Proceedings of the 21st National & 10TH ISHMT-ASME Heat and Mass Transfer Conference

December 27-30, 2011, IIT Madras, India

Paper ID: ISHMT_USA_013

TRANSIENT AIR TEMPERATURE MEASUREMENTS IN A DATA CENTER

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ABSTRACT

The rapidly increasing power density of computing and telecommunication equipment emphasizes the importance of an energy-efficient data center design. The thermal design requires analyses of multi-scale transport processes both under a steady-state condition and various dynamic conditions, which can be created by varying parameters such as cooling airflow rate and computing heat loads. To monitor transient temperature fields inside a data center laboratory facility, we developed a thermocouple network deployed in a three-dimensional telescopic mechanism. In the current study, measurements of rack-inlet temperatures for a representative case study characterize rack-level transient heat transfer processes.

Keywords: Data Center, transient temperature measurement, multi-scale transport processes.

INTRODUCTION

A data center is a mission-critical facility housing large numbers of heat-dissipating information technology (IT) equipment organized in rows of standard-size units called racks, arranged in cold aisle/ hot aisle layout. To avoid overheating and possible performance and reliability degradation, heat-dissipating IT equipment must sufficiently be cooled with an optimal cooling scheme. Most data centers are air cooled: a computer room air conditioning unit (CRAC), which includes a heat exchanger coil connected to a chilled water loop, supplies chilled air to a raised-floor plenum from where it flows into cold aisles through perforated tiles. Thereafter, air is driven through servers by server fans. The fan-driven airflow cools hot server chips by forced convection. For the high power racks, hot exhaust air from the server outlets is primarily cooled by chilled-water rear-door heat-exchangers before being dislodged into a hot aisle, from where hot air returns to CRACs through an overhead plenum. Sustaining such a forced convection-based cooling system requires external power to support cooling apertures such as CRAC blowers, server fans. Benchmarking studies have revealed that cooling systems in a typical data center consumes as much as 30-40% of the total facility power, and the life-cycle cost for cooling is fast becoming comparable to that of IT equipment [1]. The optimization of the cooling cost requires a dynamic allocation scheme of cooling resources. In turn, such an allocation scheme requires an accurate monitoring of transient temperature evolution.

In a data center, the characterization of multi-scale heat transfer processes, which encompasses heat generation in the chip-scale (length~ mm and time~ ms) and forced convective cooling by turbulent airflow in the facility-scale (length~ 10 m and time~ s), involves a high-dimensional sampling space. Therefore, an experimental estimation of the temperature field inside a data center requires a distributed sensor network suitably resolved into multiple scales [2]. Furthermore, a transient characterization requires a sufficiently small measurement time-scale—fast enough to measure time-varying physical processes. Although several experimental studies exist for a characterization of a data center [3-5], a few studies deal with transient evolutions [6]. To exploit an opportunity of improving power usage effectiveness (PUE) in a data center, an optimal cooling design must incorporate an analysis of common transient scenarios in a data center. For one, Shields et al. [7] have studied the transient thermal response to a sudden power failure in a data center. Other possible physical situations that promote a transient heat transfer scenario include facility-level upgrades, dynamic server heat loads, and time-varying CRAC fan speeds. This paper describes a grid-based thermocouple network, deployed in a three-dimensional telescopic mechanism, which is suitable for measuring a rack-level temperature field. The thermocouple network, equipped with digital circuitries, is capable of measuring transient temperatures.

EXPERIMENTAL MEASUREMENTS

The experiments were conducted in the Consortium for Energy Efficient Thermal Management (CEETHERM) Data Center Laboratory at Georgia Tech. Figure 1 shows the test cell facility which is a raised-floor facility with the floor area of $56\,\mathrm{m}^2$.

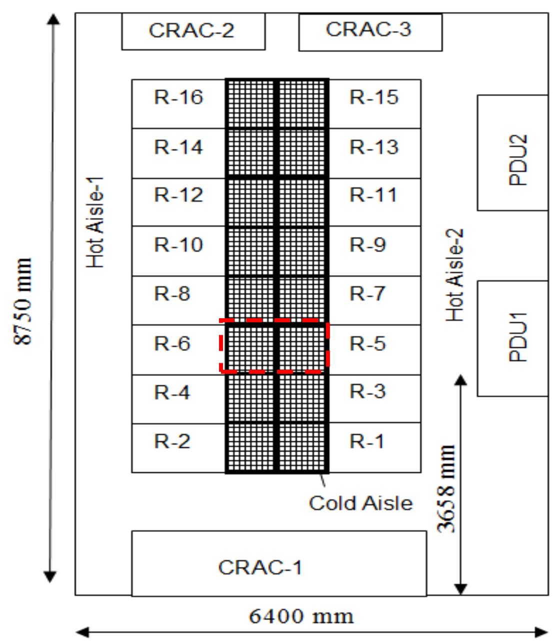

Figure 1: Test cell plan view (Tile: 610 mm x 610 mm with 56% porosity, Rack Height: 2,100 mm , 2,712 mm drop ceiling height: 2712 mm, under-floor plenum: 914 mm, and drop ceiling plenum: 1524 mm). The

temperatures were measured in the cold aisle between R-5 and R-6, as shown by the red box.

As shown in Figure 1, the setup is populated with 16 racks, organized in two rows, in an 8x2 cold aisle/hot aisle arrangement. Table (1) specifies racks in the test setup:

Table 1: Specifications of the racks in the computational zone of the CEETHERM Laboratory

Rack	Heat Load (kW)	Comment
R1	5.2	Network
R2	5.2	Storage
R3	8.48	IBM Blade Center
R4	6.4	IBM Blade Center
R5	10.08	IBM Blade Center
R6	10.08	IBM Blade Center
R7	8.8	IBM Blade Center
R8	10.72	IBM Blade Center
R9	9.6	IBM Blade Center
R10	6.4	IBM Blade Center
R11	9.6	IBM Blade Center
R12	0	Empty
R13	10.48	IBM Blade Center
R14	0	Empty
R15	0	Empty
R16	0	Empty

Each rack is 0.534 m wide, 1.067 m deep and 2.134 m high. In the present study, we focus on the cold-aisle region between Racks R-5 and R-6. Both R-5 and R-6 are populated with horizontally arranged IBM blade centers: an IBM blade center is an advanced high-density computing device which includes 14 computing units, each with two central processing units (CPUs). Figure 2 describes the configuration of a typical blade center [8]. The heat dissipation from computing equipment is cooled by airflow driven from CRACs by CRAC fans. The CRAC fan speed, or effectively cooling airflow rate, is controlled by variable frequency drives (VFDs). In the current set-up, only CRAC-1 is active.

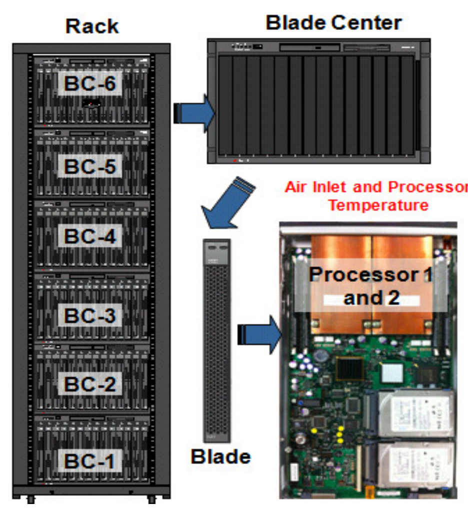

Figure 2: Schematic of an IBM Blade Center.

We performed thermocouple-based temperature measurements of three-dimensional temperature fields with an accuracy of $\pm 0.2\ ^0C$. As shown in Figure 3, geometrical features of the tool are designed such a way that it is particularly useful in capturing temperature data in a cold aisle between two racks. The tool consists of 12 layers, each of which is populated with 21 T-type copper-constantan thermocouples made from 28 gauge thermocouple wire (0.321 mm in diameter). The decision of the thermocouple-wire choice is governed by two optimization parameters: the response time for transient temperature measurements and the mechanical durability of sensors. A 28 gauge thermocouple wire provides a response time of 20 ms to be useful for a transient characterization of rack-level temperatures of time-scale~ 1s and sufficient mechanical durability for manual handling. The temperature data obtained are processed by a data acquisition system and subsequently, transmitted to I/O devices by a router. Besides the rack-level temperature field, we measure the temperature of IBM blade central processing units (CPUs).

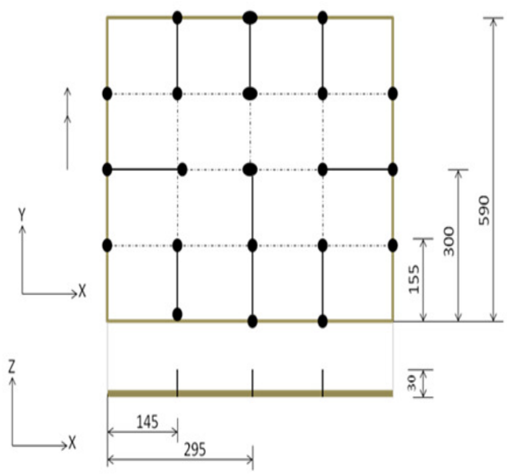

Figure 2: Thermocouple-based temperature measurement grid. All units are in mm.

RESULTS AND DISCUSSION

In this study, we analyze the transient introduced by a periodic variation of CRAC fan speed. We begin our study at a steady-state with 100% CRAC fan speed. As shown in Figure 3, we subject a series of step-changes in the CRAC fan speed: a step-down from 100%-80% at 410s, a further step-down from 80%-60% at 735s; thereafter, a step-rise from 60%-80% at 950s, and a subsequent step-rise from 80%-100% at 1250s. The four step-changes in CRAC fan speed variation create four transient evolutions as follows, Transient-1: 410-735s, Transient-2: 735-950s, Transient-3: 950-1250s, and Transient-4: 1250-1500s.

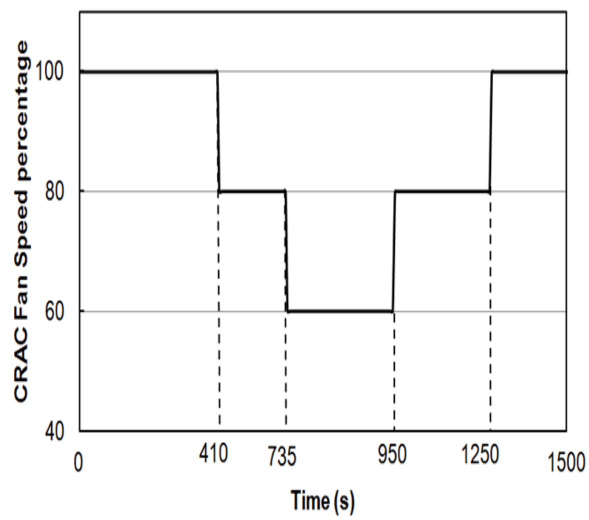

Figure 3: Variations of CRAC Fan Speed with Time.

The modulation in the CRAC fan speed changes cooling airflow into the plenum, as described in Table 2.

Table-2: Mass flow rates at different CRAC fan speeds

CRAC Fan Capacity	Mass Flow Rate
100%	4.6
80%	3.7
60%	2.8

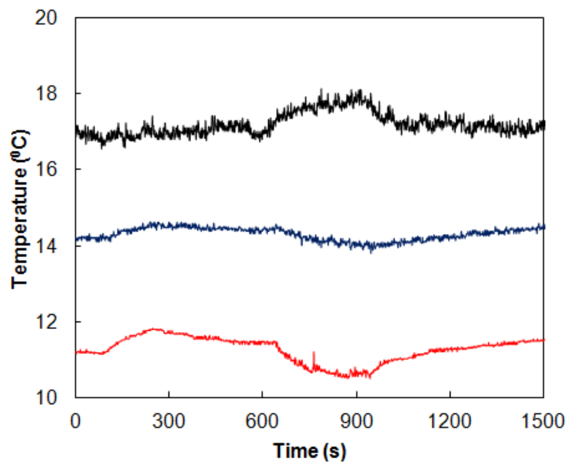

Figure 4: Transient characteristics of temperatures at R-5 Inlet. Black line indicates transient temperatures near the top of R-5, blue line at the mid-height, and red line near the perforated tile surface.

Air temperatures were measured in the cold aisle between R-5 and R-6. Figure 4 shows transient air temperatures in the cold-aisle near R-5. Three different heights are examined: near the perforated tile surface, at the mid-rack height, and near the top of the rack. As expected, Figure 4 indicates temperatures are increasing during the first two transients, i.e., 409-946s and decreasing during the next two transients, i.e., 949-1507s. Such a trend relates to the CRAC airflow modulation: lower cooling air supply increases server inlet temperatures. Evidently, Figure 4 indicates mean inlet air temperature increases along the rack height--recirculation of hot exhaust air from hot aisles increases air temperatures near the top of R-5. The fluctuations in Figure 4 can be attributed to the measurement error on the order of $\pm 0.2^0 C$ and statistical uncertainties due to turbulent fluctuations.

While the temperature measurement tool captures air temperature data, the software platform *PI* monitors CPU temperature data. Figure 5 shows the transient evolution for a CPU temperature in the third blade center from the bottom of rack, R-5. Like air temperatures, CPU temperatures increase during the first two transients and decrease during the last two transients. The similarity indicates a tight coupling between air temperatures and CPU temperatures

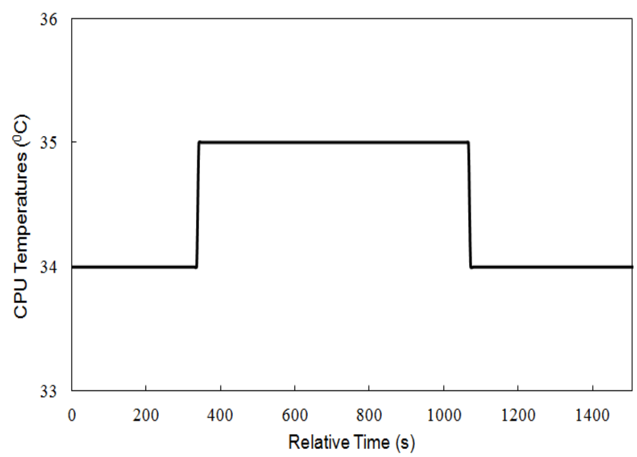

Figure 5: Transient temperatures of a CPU inside R-5.

To map rack-level temperature data, we use the temperature measurement tool. As shown in Figure 6, we map the rack-inlet temperature fields for R-5 at different time instants: 650s for transient-1; 900s for transient-2; 1100 s for transient-3; and 1400s for transient-4.

A comparison between Figure 6.a and 6.b indicates average temperatures at R-5 inlet are increasing which is consistent with decreasing cooling airflow. Another observation reveals that rack-inlet air temperature distributions also vary with time.

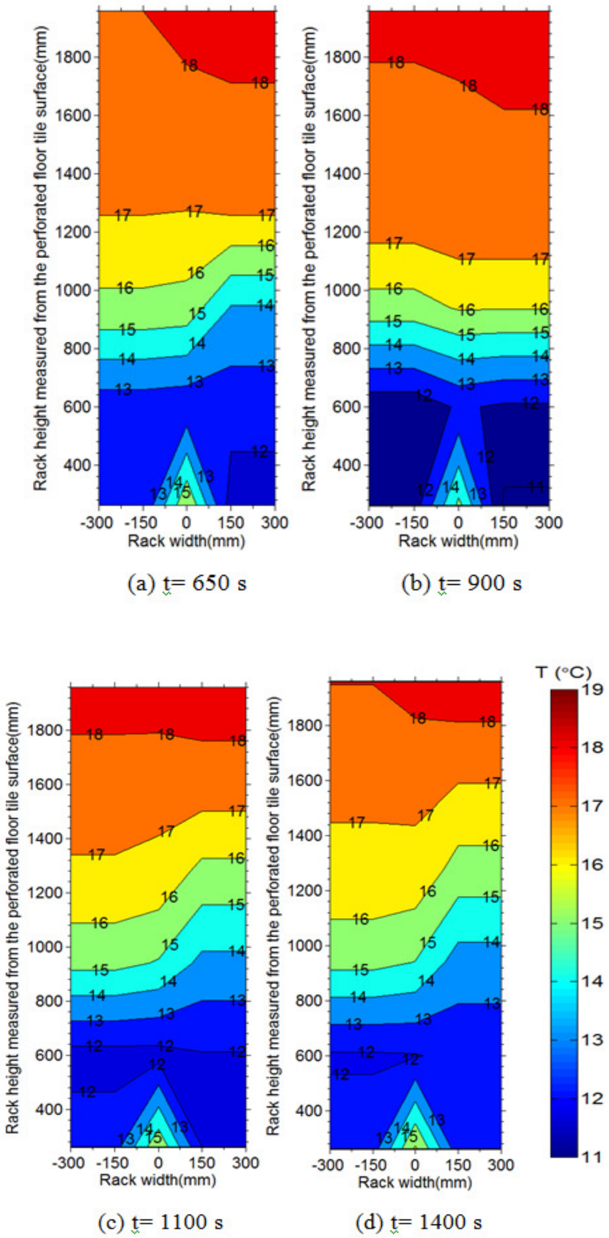

Figure 6: Rack-inlet temperature field for R-5 at (a) t= 650 s, (b) t= 900 s, (c) t= 1100 s, and (d) t= 1400 s.

With decreasing cooling airflow, more hot air from the hot aisle is drawn into the cold aisle, increasing air temperatures near the top of the rack and modifying rack-inlet temperature distributions. A comparison between Figure 6.c and 6.d suggests increasing airflow reduces the average rack-inlet temperature. With higher momentum, cooling airflow can rise further from the perforated tile surface, significantly changing local convective temperature fields.

CONCLUSION AND SUMMARY

We designed and built a grid-based temperature measurement capability, particularly suitable in capturing rack-level air temperature data. Following a periodic CRAC fan speed modulation, we measured transient temperatures at rack-inlets.

In summary, the current study demonstrates that a tight coupling exists between the cooling air-flow rate and the CPU temperature via convective heat transfer. We have demonstrated how rack-inlet air temperatures vary in a series of transient scenarios which are created by the variation of the CRAC fan speed. In addition, the coupling between the CPU temperature and the local rack-level air temperature field is studied.

ACKNOWLEDGEMENT

The authors acknowledge support for this work from IBM Corporation, with Dr. Hendrik Hamann as the technical monitor. Acknowledgements are also due to the United States Department of Energy as the source of primary funds. An additional support from the National Science Foundation award CRI 0958514 enabled the acquisition of some of the test equipment utilized.

REFERENCES

[1] Belady, C.L., 2007, In the data center, power and cooling costs more than the it equipment it supports. Available: http://www.electronics-cooling.com/2007/02/

[2] Nelson,G.M., 2007, Development of an Experimentally-Validated Compact Model of a Server Rack, Masters Thesis, Georgia Institute of Technology, Atlanta 2007.

[3] Hamann, H.F., Lacey, J.A., O'Boyle, M., Schmidt, R.R., and Iyengar, M., 2008, Rapid Three-Dimensional Thermal Characterization of Large-Scale Computing Facilities, Components and Packaging Technologies, IEEE Transactions on, vol. 31, pp. 444-448.

[4] Sharma, R., Bash, C., Patel,C., and Beitelmal, M., 2004, Experimental investigation of design and performance of data centers, ITherm, Las Vegas, NV, USA, pp. 579-585 Vol. 1.

[5] Shrivastava, S.K., Iyengar, M., Sammakia, B.G., Schmidt, R., and VanGilder, J.W., 2006, Experimental-Numerical Comparison for a High-Density Data Center: Hot Spot Heat Fluxes in Excess of 500 W/ft2, ITherm, pp. 402-411.

[6] Somani, A., 2009, Advanced thermal management strategies for energy-efficient data centers, Masters Thesis, Georgia Institute of Technology, Atlanta, USA.

[7] Shields, S., 2009, Dynamic thermal response of the data center to cooling loss during facility power failure, Masters Thesis, Georgia Institute of Technology, Atlanta, USA.

[8] Desai, D., Bradicich, T., Champion, D., Holland, W., and Kreuz, B., 2005, BladeCenter system overview, IBM Journal of Research and Development, vol. 49, pp. 809-821.