EXPERIMENTAL CHARACTERIZATION OF TRANSIENT TEMPERATURE EVOLUTION IN A DATA CENTER FACILITY

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Abstract

Rapidly increasing energy usage in data centers, triggered by escalating power densities of information technology (IT) equipment, has made energy efficiency a major concern. Depending on the air flow and temperature distribution, the power consumed by the cooling system can be as high as 33% of the total input power the data center. Although several computational studies have been carried out to characterize the air flow and temperature distributions in data centers, only a few experimental studies are available in the literature. In this paper, we present transient temperature measurements inside a data center cell, employing a raised-floor plenum to distribute cold air from the Computer Room Air Conditioning (CRAC) units to the computing racks, and a ceiling plenum to return hot air back to the CRAC unit. The temperature field is measured using a grid-based thermocouple network, deployed in a 3-D telescopic mechanism. The measurements reveal transient characteristics for transport phenomena in a typical data center facility.

INTRODUCTION

One of the most critical problems in electronic packaging industry is thermal management of data centers (Belady, 2001, Belady and Malone, 2006). A data center is a mission-critical facility housing large numbers of computing equipment organized in rows of standard size units called racks or cabinets. To avoid overheating and possible performance and reliability issues, waste heat from the IT equipment must be effectively removed. Most data centers are cooled by direct air cooling: a computer room air conditioner (CRAC)-unit, which includes a blower unit and heat exchanger coil connected to a chilled water loop, supplies cold air to a raised-floor plenum, The plenum is used to distribute cooling air into the data center cold aisles through perforated tiles. The heated air after passing through the racks is returned to the CRAC inlets via the alternating hot aisles. In the cold aisles, air is driven into servers by server fans. The hot exhaust air from the server outlets in the current study is pre-cooled by chilled water cooled rear-door heat-exchangers prior to its return to the overhead plenum. Sustaining such forced convection-based cooling requires external power to support cooling apparatuses such as CRAC blowers, and server fans. The cooling system in a data center can consumes as much as 30-40% of the total facility power, and the life-cycle cost of cooling is fast becoming comparable to that of the IT hardware (Belady, 2007). The optimization of the cooling cost is a complex problem

(Pakbaznia and Pedram, 2009). One way to facilitate the optimization is dynamic allocation of cooling resources that requires a detailed characterization of the transient evolution of convective transport phenomena in a data center. Transient events are pervasive in data centers mainly due to power outages in data centers. Table (1) cites recent power outages in data centers.

Table-1: Recent power outages in data centers*

Date	Event
8/21/2011	BigCommerce System Administrators data center fails
8/18/ 2011	Thunderstorm takes down Google data center
8/18/ 2011	Power outage brings US VoIP provider Ooma's services down
8/11/2011	Power outage at Colo4 Data Center
5/5/2011	Air conditioning failure brings bank's IT down
6/7/2010	Dallas data center failure

*Source: http://www.datacenterdynamics.com/

In general, a high-fidelity transient characterization of a data center facility would facilitate dynamic power routing, saving massive capital costs incurred in power redundancies. A prominent feature of the transient characterization of a data center facility is its inherent multi-scale nature: significance of transport processes across several scales--spanning from chip-level ~O(mm) and time scale~O(ms) , to room-level ~O(10m) and time scale~O(10 s). The involvement of multiple length and time scales makes the characterization of a data center significantly complex and requires resolution of multi-scale transport phenomena. Common approaches for the characterization include CFD/HT-based numerical models (Abdelmaksoud et al.) and experimental investigations (Hamann et al., 2008). However, most of these studies pertain to steady-state transport phenomena in a data center. Only recently have transient effects been explored (Gondipalli et al., 2010, Shields, 2009). In this paper, we investigate transient temperature fields at the rack-level in a section of a ~130 m^2 Data Center Laboratory. The transient scenario is created by varying airflow rate from the CRAC unit.

EXPERIMENTAL SETUP and MEASUREMENTS

The experiments were conducted in Consortium for Energy Efficient Thermal Management (CEETHERM) Data Center Laboratory at Georgia Tech. Figure (1) shows the test cell for the present study. As shown in Figure 1, the test cell with the floor area of $57\,\mathrm{m}^2$, equipped with eight heat-dissipating racks, three CRAC units, one Power Distribution Unit (PDU), and one Chilled-water Distribution Unit (CDU). Table (2) describes experimental conditions—heat loads in different racks and airflows from different CRAC units. CRAC units are equipped with variable frequency drives (VFDs) for precise airflow control. CRAC-1, the only active CRAC unit for these experiments, supplies downward cooling airflow to the raised-floor plenum at a volumetric flow rate of $6.7\,\mathrm{m}^3/s$ at 100% capacity, or $5.05\,\mathrm{m}^3/s$ at 60% capacity.

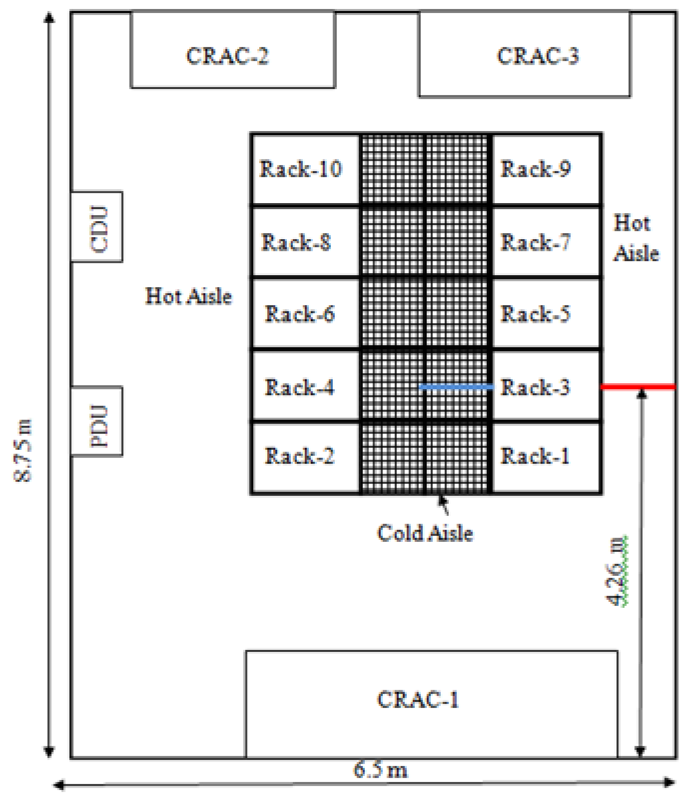

Table-2: Experimental Conditions

Part	Specification
Rack-1	Heat load~ 12 kW
Rack-2	Heat load~ 6 kW
Rack-3	Heat load~ 6 kW
Rack-4	Heat load~ 6 kW
Rack-5	Heat load~ 6 kW
Rack-6	Heat load~ 6 kW
Rack-7	Inactive
Rack-8	Heat load~ 6 kW
Rack-9	Inactive
Rack-10	Inactive
CRAC-1	Downward
CRAC-2	Inactive
CRAC-3	Inactive

Figure 1: Test cell plan view (610 mm x 610 mm with 56% porosity, 2,000 mm rack height, 2,712 mm drop ceiling height, 914 mm under-floor plenum, and 1,524 drop ceiling plenum). The heavy lines adjacent to Rack 3 indicate temperature measurement planes in the aisles.

In the present study, we focus on Rack-3, which is 0.534 m wide, 1.067 m deep, and 2134 m high, and is populated with 42 1-U servers, each dissipating 6 kW. The planes for the hot and cold aisle temperature measurements are shown in Fig. 1. A grid-based thermocouple network (Nelson, 2007), is deployed in a three-dimensional telescopic mechanism, capable of mapping temperatures with an accuracy of $\pm 0.2\,^0C$. As shown in Figure (2), the geometry of the thermocouple grid is designed such that it is particularly suitable for capturing rack-level temperature data. For a given rack, we have six layers of the thermocouple grid, each consisting of 21 T-type Copper-Constantan thermocouples made from 28 gauge thermocouple wire. The choice of the thermocouple wire size is governed by the optimal response time for transient temperature measurement without compromising the mechanical sustainability of sensors. A 28 gauge thermocouple wire (wire diameter 0.907 mm provides a response time of 20 ms to be suitable for transient characterization, and sufficient mechanical durability for manual handling. The temperature data obtained by thermocouples is processed by a data acquisition system and subsequently transmitted to I/O devices by a router.

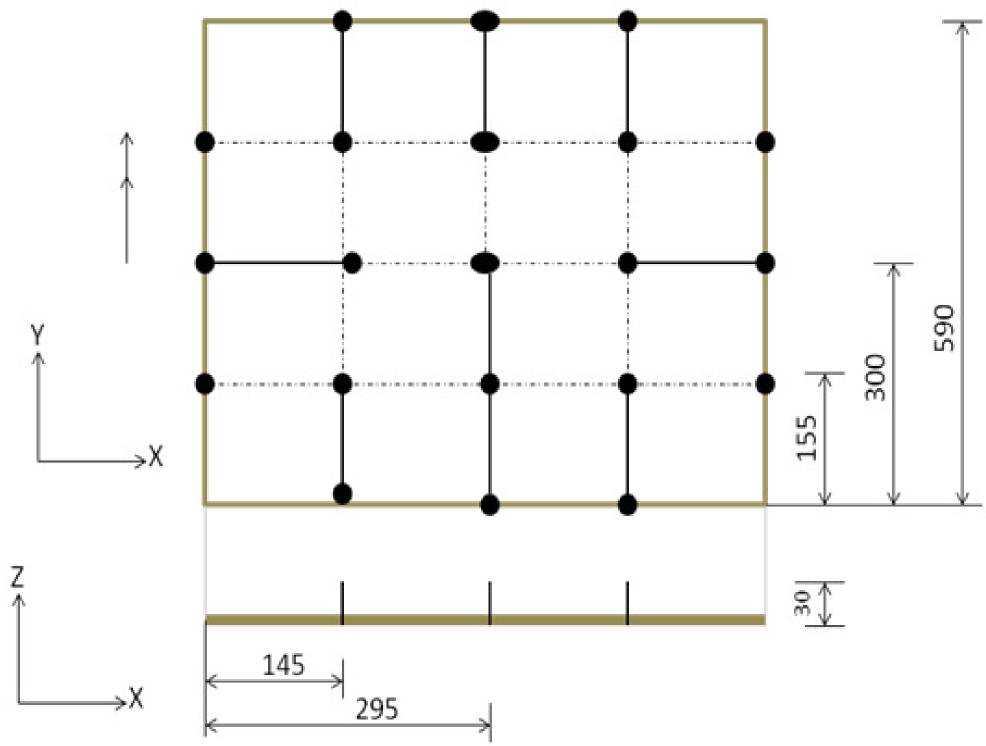

Figure 2: Thermocouple-based temperature measurement grid. All units are in mm.

RESULTS and DISCUSSION

In the present investigation, we analyze the transients resulting from variations of the CRAC fan speed. We begin our experiment from a steady-state condition with racks dissipating heat fluxes equal to the specified values in Table 2 and the CRAC running at 100% capacity. Figure (3) shows rack-level temperature fields in cold and hot aisles in steady-state, at 100% CRAC fan speed. From the cold aisle, air is drawn into the servers by server fans. Inside the servers, the convective transport from the heat-dissipating components increases the bulk air temperature. Thereafter, the heated air expelled out into the hot aisle. Moreover, Figure 3 suggests a stratified air temperature distribution. In the cold aisle, the coolest zone exists at the half-rack height. Near to the perforated tile the Venturi effect dominates the transport phenomena: the pressurized cold air emerging from the perforated tile suddenly expands into the cold aisle, leading to local negative pressure gradients near the rack inlet. As a result, the hot air from the hot aisle is pulled into the cold aisle to resolve the imbalance in pressure field in the cold aisle. This influx of hot air leads to a formation of a local hot spot as illustrated in Figure (3). The Venturi effect gradually decreases along the rack height resulting in lower rack inlet temperatures. However, near the top of the rack, an increase in inlet temperature is observed due to hot air recirculation. Moving in the hot aisle, local air temperature gradually increases with height. At the top, a somewhat precipitous rise in temperature occurs because hot air recirculation into cold aisle increases the air temperature going into the server.

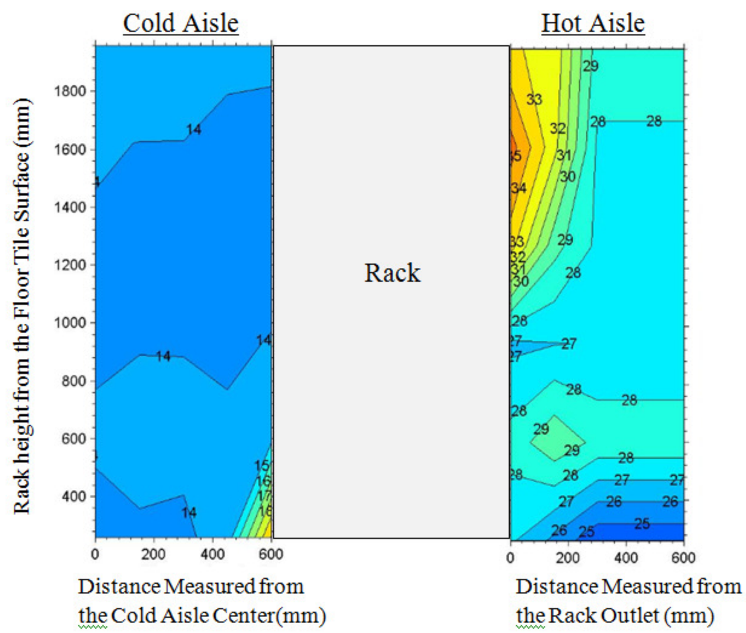

Figure 3: Steady-state Rack-level Temperature Field with 100% CRAC Fan Speed

Using a variable frequency drive, we suddenly reduce the CRAC fan speed from 100% to 60%, and we investigate the resulting transient. Figure 4 describes the transient temperature fields at t= 150s, 300s, and 450s following the step change in the CRAC fan speed. The evolution of rack-level temperature field is complex multi-physical process. A reduction in the CRAC fan speed decreases the influence of the Venturi effect. A gradually expanding pocket of hot air is observed at the top-right corner. The observation can be explained as follows: with reduction in cooling air momentum, the local temperature field at the top of the rack is dominated by hot air recirculation from the hot aisle. Furthermore, a close scrutiny of the hot aisle temperature field suggests a gradual reduction in temperature gradients; fewer stratified layers can be seen with time. Such a trend indicates the temperature field is gradually progressing towards a steady state.

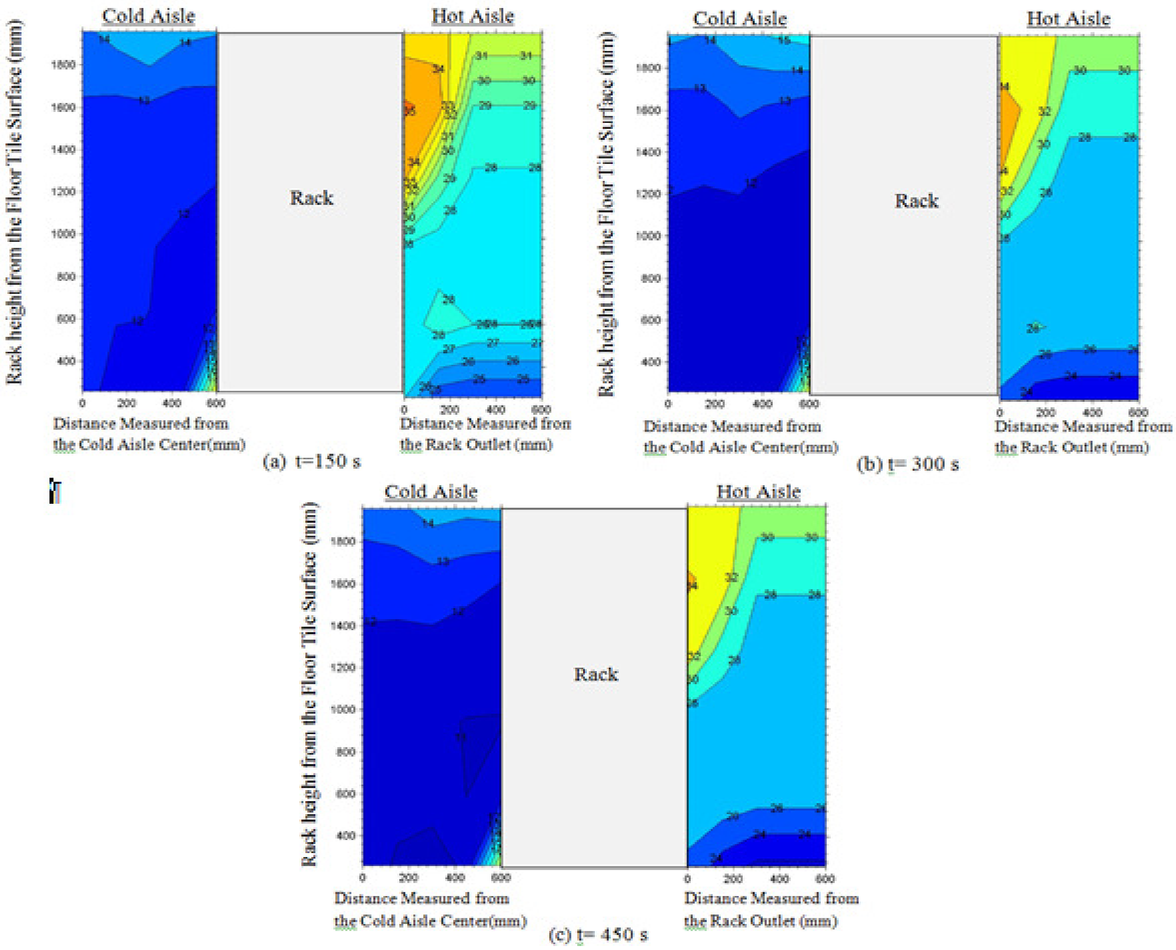

Figure 4: Rack-level Temperature Fields at different time instants, (a) t=150 s, (b) t=300 s, and (c) t=450 s, during a transient scenario induced by changing CRAC Fan Speed from 100% to 60% at t= 0

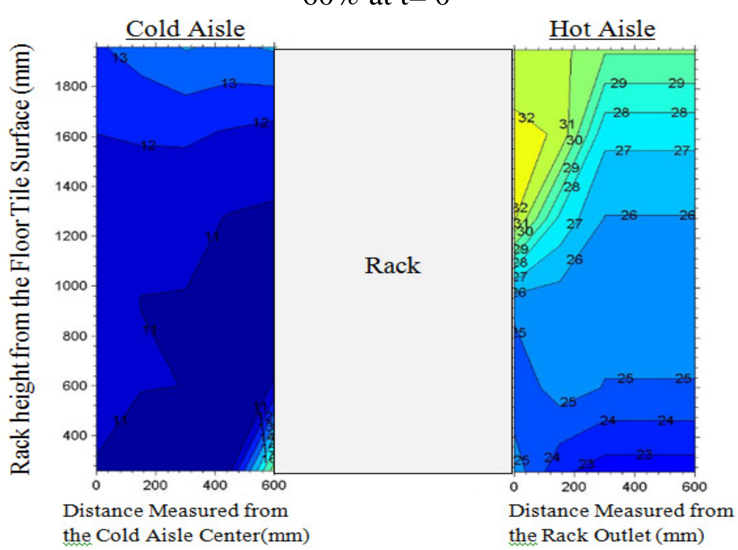

Figure 5: Steady-state Rack-level Temperature Field with 60% CRAC Fan Speed

As par our expectation, temperature fields subsequently reach their steady-state, as shown in Figure 5. At 60% CRAC fan speed, a significantly smaller hot zone near the perforated tile confirms a reduction in the Venturi effect. Subsequently, we increase the CRAC fan speed from 60% to 100% capacity. Resultant transient temperature fields are observed at t=150 s, t=300 s, and t=450 s, as shown in Figure 6. Furthermore, Figures 7 shows the temperature field at t=1500 s with 100% CRAC fan speed. As we previously described, Figure 3 shows the steady state temperature plot at 100% CRAC fan speed. A comparison between Figure 7 and Figure 3 demonstrates a similarity in the air temperature distributions, suggesting that the system is gradually approaching a steady state after 1500 s.

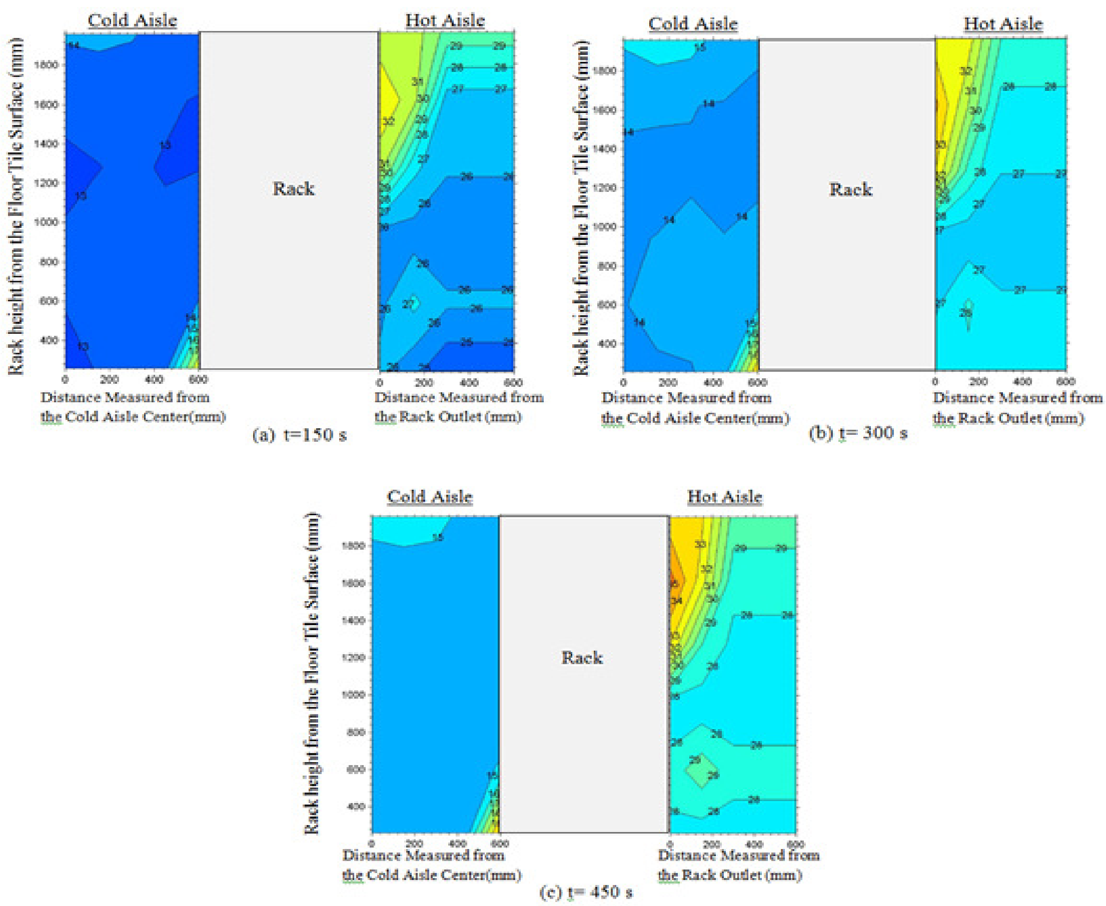

Figure 6: Rack-level Temperature Fields at different time instants, (a) t=150 s, (b) t=300 s, and (c) t=450 s, during a transient scenario induced by changing CRAC Fan Speed from 60% to 100% at t=0

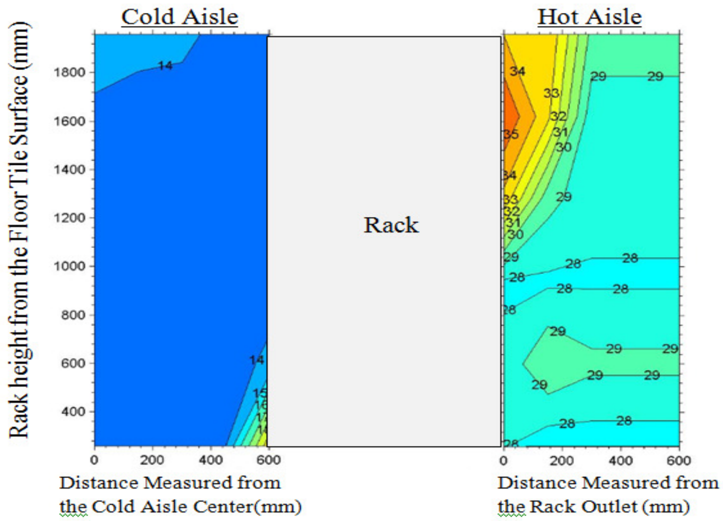

Figure 7: Rack-level Temperature Field after t= 1500 s after a Step Rise in CRAC Fan Speed from 60% to 100% at t=0.

SUMMARY and CONCLUSION

The purpose of the paper was to investigate the dynamic evolution of rack-level temperature pertaining to a CRAC fan speed modulation. For temperature measurements, a thermocouple-based data acquisition system is developed. Two transient scenarios were examined: a step-down of the CRAC fan speed and a step-rise of the CRAC fan speed. The resulting transient scenarios are examined. In general, the paper describes rack-level temperature response to facility power modulation.

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