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Method for Optimizing Equipment Cooling Effectiveness and HVAC Cooling Costs in Telecom and Data Centers

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ABSTRACT
Today's critical high-density electronic equipment environments need adequate equipment (rack) cooling without excessive energy usage. This paper presents a methodology for optimizing the rack cooling effectiveness and HVAC cooling costs in telecom and data centers. Since raised-floor air distribution is the most common way of cooling data centers, this scheme is used here to demonstrate the methodology. Two key design parameters are evaluated: The supply air temperature and the supply airflow rate. These parameters not only impact the rack cooling effectiveness but also the energy costs for cooling the space. A leading Computational Fluid Dynamics (CFD) code is used to establish the temperature field and airflow pattern for various combinations of these parameters in a typical data center with hot and cold aisles. A new function was developed within the CFD code to compute the Rack Cooling Index (RCI) for evaluating the thermal equipment environment. This Index is designed to be a measure of how effectively equipment racks are cooled and maintained within industry thermal guidelines and standards. In addition, hypothetical cost functions are introduced based on chiller and fan energy costs. Based on the RCI results and the energy cost functions, recommendations are given for optimizing the supply temperature and airflow. Specifically, the overall performance is improved by modifying the temperature and airflow to values higher than traditionally thought useful. When the RCI algorithm has been incorporated into commercial CFD codes (or used manually), engineers and architects will have a new practical tool to design and evaluate telecom and data centers for optimal equipment rack cooling effectiveness and HVAC cooling costs.

INTRODUCTION
Recent research suggest that conventional under-floor cooling in data centers may have some inherent challenges in adequately cooling electronic equipment (Herrlin and Belady 2006; Herrlin 2005; Sorell et al. 2005). Computational Fluid Dynamics (CFD) modeling compared this system with a conventional over-head system as well as with a modular over-head solution. The three references theorize that the lack of mixing in the cold aisle is one of the key reasons for the observed difficulties for under-floor cooling to provide an adequate thermal environment. If correct, the selection of supply temperature and airflow rate should be critical. A modeling study could help shed some light on the most appropriate combination.

Two prerequisites are necessary to proceed: (1) a measure of the rack cooling effectiveness and (2) a measure of the associated costs. The Rack Cooling Index (RCI) is a measure of how effectively equipment racks are cooled and maintained within industry thermal guidelines and standards (Herrlin 2005). The Index is designed to help evaluate the equipment room "health" for managing existing environments or designing new ones. It is also well suited as a design specification for new data centers. The Index was used in two of the references given above to evaluate the cooling effectiveness of over-head and under-floor air-distribution systems.

In the present paper, different combinations of supply temperature and airflow rate are analyzed for the impact on the rack cooling effectiveness as expressed by the RCI. For each combination, an established CFD code is used to determine the airflow and temperature distributions in the entire data center, including the rack intake temperatures (Fluent 2006). These data were subsequently analyzed by a new user function in the code to compute the RCI.

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Cost functions are finally developed to assign the costs/savings of improving the RCI. In this particular case, the cost functions are based on the main energy costs to cool the data center. More advanced functions can be developed to take first costs into consideration or ultimately a life-cycle approach. Although difficult, costs can also be assigned to the risk of equipment failure at certain RCI levels. This first attempt, however, should highlight the potential of combining the RCI with cost functions to provide comprehensive design information for the data center owner and/or consultant.

RACK COOLING INDEX (RCI)

The following is a brief overview of the Rack Cooling Index (RCI) to provide the necessary understanding how to interpret the Index. For a complete description of the RCI, the reader is referred to the original work by Herrlin (2005) and published by ASHRAE.

The Index deals with rack intake temperatures—the conditions that air-cooled equipment depend on for its continuous operation. The “allowable” equipment intake temperature limits in Figure 1 represent the equipment test range whereas the “recommended” limits refer to target facility operation. Over-temperature conditions exist once one or more intake temperatures exceed the maximum recommended temperature. The total over-temperature represents a summation of over-temperatures across all rack inlets. Similarly, under-temperature conditions exist when intake temperatures drop below the minimum recommended. The numerical values of these limits depend on the applied guideline (e.g., ASHRAE 2004) or de-facto standard (e.g., Telcordia 2001; Telcordia 2006). In other words, the RCI is a measure of the conformance with a given specification.

The RCI has two parts, describing the equipment room health at the high (HI) end and at the low (LO) end of the temperature range, respectively. Figure 1 provides a graphical representation of the RCI_{HI}. An analogous Index is defined for temperature conditions at the low end of the temperature range, RCI_{LO}.

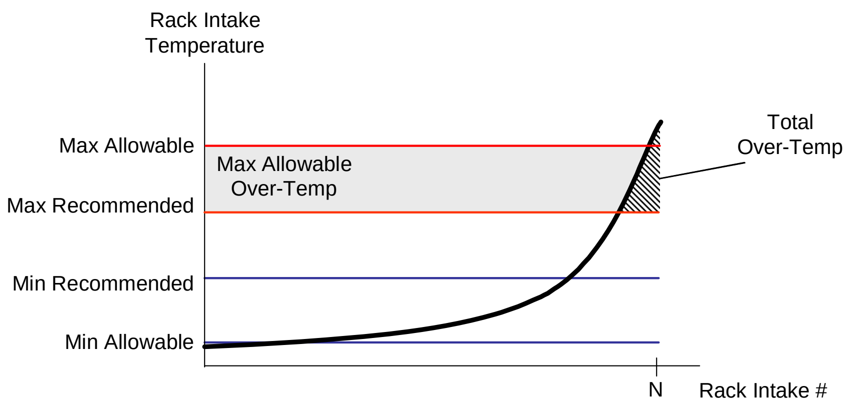

Figure 1. Intake temperature distribution and graphical representation of RCI_{HI}

The RCI_{HI} definition is as follows:

$$RCI_{HI} = \left[1 - \frac{\text{Total Over-Temp}}{\text{Max Allowable Over-Temp}}\right] 100\ \% \qquad (1)$$

The hands-on interpretation of the Index is as follows:

$RCI_{HI} = 100\%$ All intake temperatures $\leq$ max recommended temperature
$RCI_{HI} < 100\%$ At least one intake temperature > max recommended temperature
$RCI_{HI} < 0\%$ At least one intake temperature > max allowable temperature

The RCI_{HI} is a measure of the absence of over-temperatures; 100% means that no over-temperatures exist (ideal). The lower the percentage, the greater probability (risk) that equipment experiences temperatures above the maximum allowable temperature. The Index for the hypothetical temperature distribution shown in Figure 1 is approximately RCI_{HI} = 95%. Based on numerous studies, a value at or above 95% is a sign of a good system design.

CFD analysis provides a convenient tool for computing and analyzing the RCI at various levels of detail. The RCI can be calculated using all intake temperatures or any subset thereof, down to a single equipment intake. While analyzed with CFD modeling, the temperature for a single intake is the average of all computational cells' temperatures across that opening. By studying the individual intakes' RCI values, the variation of the RCI across all air intakes can be determined.

PARAMETER STUDY

The modeled 1400 ft^2 (300 m^2) data center is shown in Figure 2. The equipment room has a 9-foot (2.7 m) ceiling and a 2-foot (0.6 m) raised floor. There are 48 equipment racks—12 per equipment line-up—each with 4 kW of heat dissipation. Thus, the total space load is 192 kW or 137 W/ft^2 (1475 W/m^2). The cooling airflow entering each rack is 640 cfm (1090 m^3/hr) with total rack airflow of 30,720 cfm (52,190 m^3/hr).

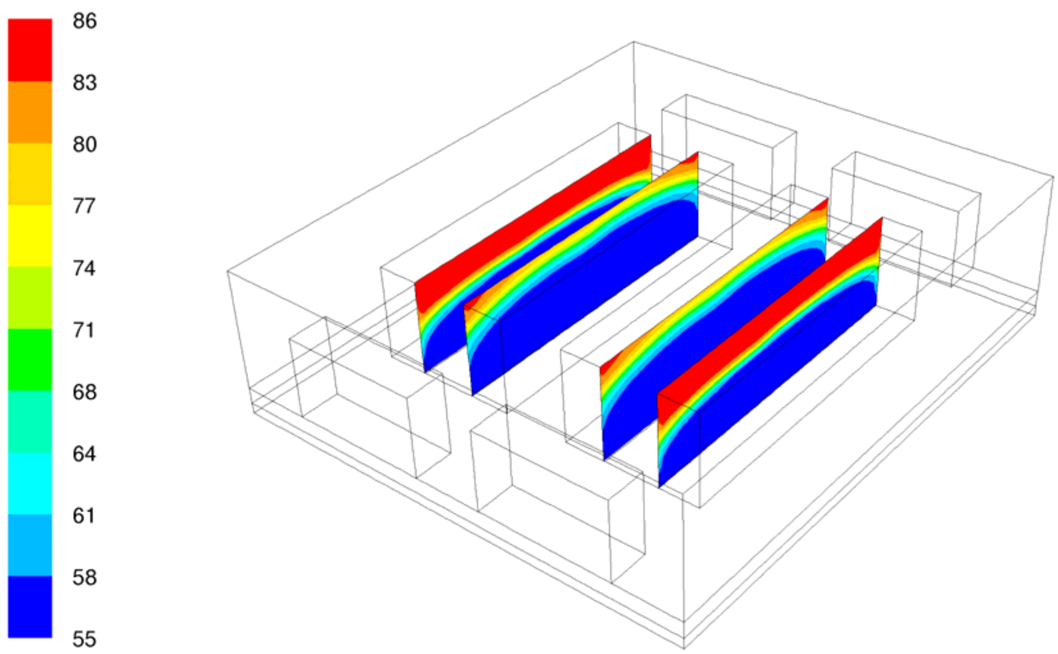

Figure 2. Data center layout showing electronic equipment and CRAC units.
Equipment air intake temperature distribution at SAT=55°F (13°C) and SAQ=80%.

There are four Computer Room Air Conditioning (CRAC) units with a capacity of 17 ton (60 kW) cooling each. The supply temperature (SAT) is 55°F (13°C), 60°F (16°C), 65°F (18°C), or 70°F (21°C). The supply airflow rate (SAQ) is 80%, 100%, 120%, or 140% of the total rack airflow rate. Forty-eight 25% (open area) perforated floor tiles deliver air from the raised-floor plenum into the cold aisle in front of the equipment.

In the present paper, ASHRAE (2004) "Class 1" data center environment is used for the RCI calculations. In this specification, the recommended equipment intake temperature range is 68°–77°F (20°–25°C) and the allowable range is 59°–90°F (15°–32°C).

COST FUNCTIONS

Ultimately, the costs/savings associated with improving the RCI need to be known. In this section, simple cost functions are developed to assign costs/savings based on the main energy costs to cool the space. More advanced functions could be developed in a similar manner, taking first costs into consideration or deploying a life-cycle approach. Although difficult, costs could also be assigned to the risk of electronic equipment failure. Nevertheless, this first attempt should highlight the potential of combining the RCI with cost functions to provide comprehensive design information for the data center owner and/or consultant.

Energy costs for conditioning and distributing the air are mainly associated with chiller and fan energy, respectively. Increasing the supply air temperature allows operating the chiller at a higher evaporator temperature and—in turn—higher chiller efficiency and Coefficient of Performance (COP). Increasing the supply airflow rate, on the other hand, requires more fan energy to move air between the air-handler and the data center. Clearly, both cost functions need to be evaluated when the supply air temperature and supply airflow are changed.

For the modeled data center in Figure 2, four typical CRAC units remove the equipment heat dissipation of 192 kW. The COP was estimated at selected supply temperatures between 55°F (13°C) and 70°F (21°C) based on manufacturers' data. Figure 3 shows the resulting chiller cost function, not including the evaporator fan energy. The annual energy cost assumes an energy price of $0.08/kWh. These assumptions may or may not be applicable to a specific application or geographic location. Specifically, the chiller cost function is a bit more complicated since the chiller efficiency also is a function of the CRAC airflow. For clarity, however, this effect is not included to demonstrate the use of cost functions.

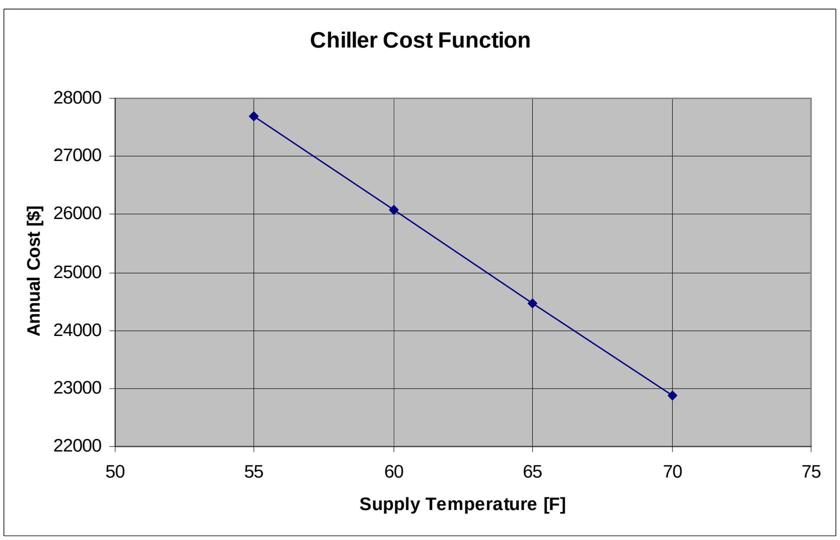

Figure 3. Hypothetical cost function--chiller

Eight fans (two per CRAC unit) transport the air between the units and the data center. Figure 4 shows the resulting annual fan cost as a function of airflow. One-hundred percent represents 30,720 cfm (52,190 m^3/hr) per the discussion above. A total pressure drop of 1.5 in of water (373 Pa) was assumed as well as a fan efficiency of 75%. Again, these values may or may not apply to a specific application or geographic location.

Figure 3 indicates that a supply temperature reduction of 5°F (3°C) results in a cost penalty of $1,600 whereas Figure 4 points out that an airflow rate increase of 10 percentage points adds $500. These two hypothetical cost functions suggest that a supply temperature change has a greater impact on the operating costs than does an airflow rate change. Having such cost functions at hand, a designer can evaluate different designs with regard to both RCI and operating costs.

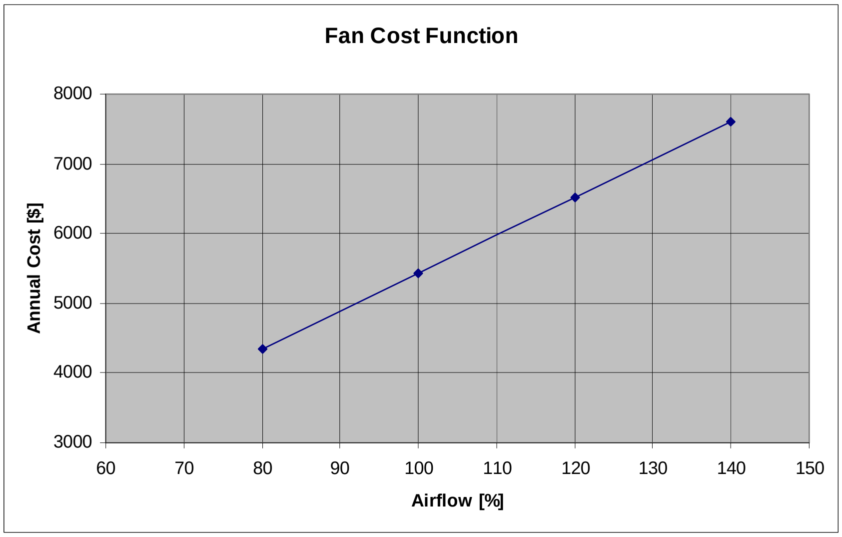

Figure 4. Hypothetical cost function—fan

When the "sweet spot" has been established based on the RCI and costs, say, a supply temperature of 65°F (18°C) and an airflow of 120%, it can be used as the starting point when modifying the cooling design to further improve the RCI. Essentially, two design parameters have been fixed and thus removed from the design process.

RESULTS

Tables 1 and 2 show the RCI values for sixteen parameter combinations. Supplying an airflow rate that matches the rack airflow rate (100%) and supplying the air at a "customary" 55°F (13°C) temperature produce excellent thermal conditions at the high end of the temperature range (RCI_{HI} of 100%) but very poor conditions at the lower end (RCI_{LO} of −20%). Indeed, numerous intakes draw air below the minimum allowable temperature of 59°F (15°C). Generally, this is not acceptable since it may be outside the manufacturer's specifications. Note that an "*" indicates that one or several intake temperatures are outside the allowable temperature range.

How can the performance of the raised-floor system be improved? If both the RCI_{HI} and RCI_{LO} are considered equally important (if a range is specified, both should matter), a high supply flow rate combined with a high supply air temperature should be evaluated. If the RCI_{LO} is of little interest, on the other hand, a combination of 65°F (18°C) supply temperature and 100% airflow may provide an adequate environment. A lower supply temperature or higher airflow will not significantly improve the thermal conditions.

By incorporating the proposed cost functions, the data center owner and/or consultant can assign a dollar amount to improving the RCI values. Increasing the "customary" 55°F (13°C) supply temperature to 70°F (21°C) would result in better chiller efficiency. On an annual basis, this would save about 17% of the chiller energy or $4,800. Note however, that high return temperatures may cause problems for many CRAC units. Increasing the airflow rate from 100% to 140% on the other hand, would increase the fan operating costs by 40% or $2,200. Increased airflow rates may exceed the available capacity of the raised floor plenum and the perforated tiles. These calculations assume unchanged system pressure drop by design.

Table 3 shows the net effect in percent of total annual chiller and fan energy, with the 55°F (13°C) and 100% as an (arbitrary) reference. As can be seen, the combination of supply temperature and airflow that provides ideal intake conditions (70°F (21°C) and 120%) also provides an energy cost saving of 11%, a true win-win situation.

Table 1: RCI_{HI}

		SUPPLY AIR TEMPERATURE			
SUPPLY %	**CFM (m^3/hr)**	**55°F (13°C)**	**60°F (16°C)**	**65°F (18°C)**	**70°F (21°C)**
80	24,580 (41,760)	88	78*	68*	56*
100	30,720 (52,190)	100	98	95	91*
120	36,860 (62,630)	100	100	100	100
140	43,010 (73,070)	100	100	100	100

Table 2: RCI_{LO}

		SUPPLY AIR TEMPERATURE			
SUPPLY %	**CFM (m^3/hr)**	**55°F (13°C)**	**60°F (16°C)**	**65°F (18°C)**	**70°F (21°C)**
80	24,580 (41,760)	10*	48	83	100
100	30,720 (52,190)	-20*	30	77	100
120	36,860 (62,630)	-38*	18	72	100
140	43,010 (73,070)	-40*	16	71	100

Table 3: Net Savings/Costs by Changing Supply Temperature and/or Airflow Rate.

		NET ENERGY SAVINGS			
SUPPLY %	**CFM (m^3/hr)**	**55°F (13°C)**	**60°F (16°C)**	**65°F (18°C)**	**70°F (21°C)**
80	24,580 (41,760)	3%	8%	13%	18%
100	30,720 (52,190)	**$33,120**	5%	10%	15%
120	36,860 (62,630)	(3%)	2%	6%	11%
140	43,010 (73,070)	(7%)	(2%)	3%	8%

The RCI_{HI} and RCI_{LO} numbers shown in Tables 1 and 2 are based on all rack intakes temperatures in the data center. A visual representation of the RCI distribution is sometimes desirable, including maximum and minimum values. Such distributions are shown in Figures 5 and 6 as computer-generated RCI maps for two parameter combinations: 55°F (13°C)/80% (base case) and 65°F (18°C)/100%. Since the figures have the same RCI scale (0% to 100%) it is easy to compare the effect of changes to the supply temperature and/or supply airflow rate.

The figures highlight the substantial improvement of the thermal equipment environment by modifying the supply temperature and the airflow rate. In this case, the combination of 65°F (18°C) supply temperature and 100% flow rate was considered as a reasonable compromise between the rack cooling effectiveness, cooling costs, and practical considerations. The RCI_{HI}/RCI_{LO} improved from 88%/10% to 95%/77% while the cooling cost was reduced by 7%.

The design methodology presented in this paper is a new tool for optimizing the rack cooling effectiveness and cooling costs in telecom and data centers. Each user, however, needs to determine the “correct” balance between the rack cooling effectiveness, various costs, and other considerations.

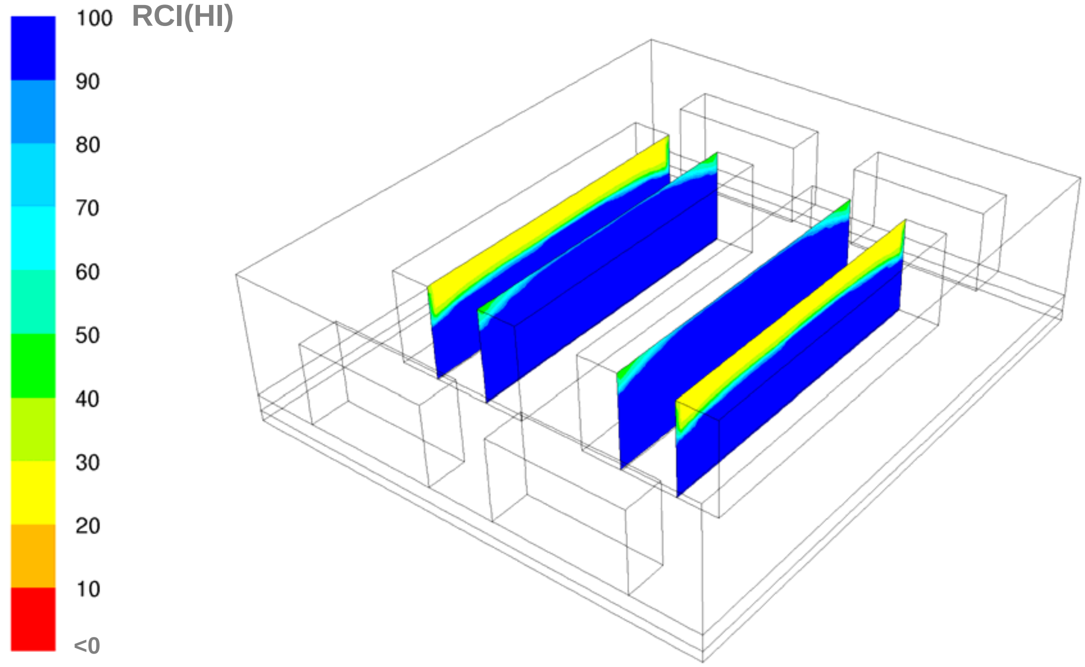

Figure 5a. RCI_{HI} distribution across equipment air intakes at SAT=55°F (13°C) and SAQ=80%.

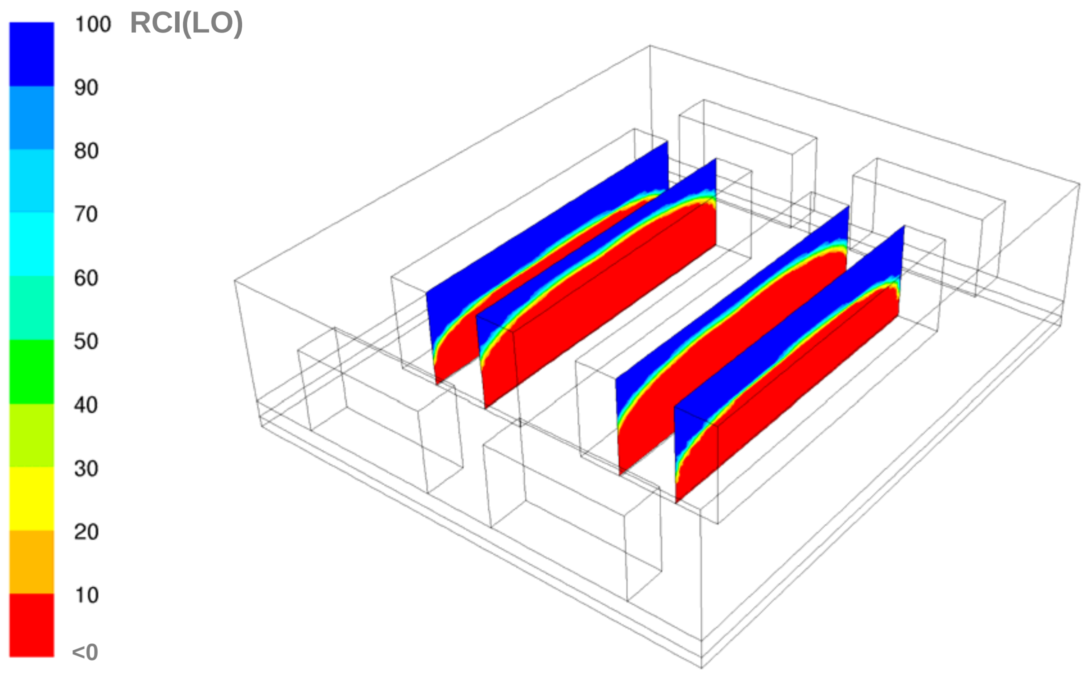

Figure 5b. RCI_{LO} distribution across equipment air intakes at SAT=55°F (13°C) and SAQ=80%.

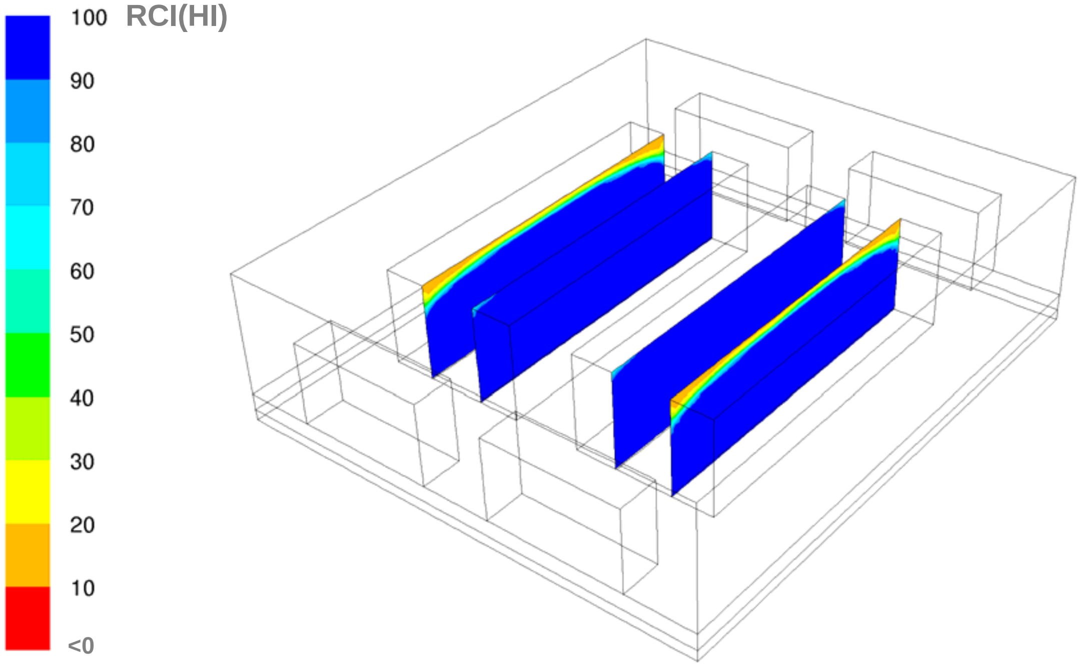

Figure 6a. RCI_{HI} distribution across equipment
air intakes at SAT=65°F (18°C) and SAQ=100%.

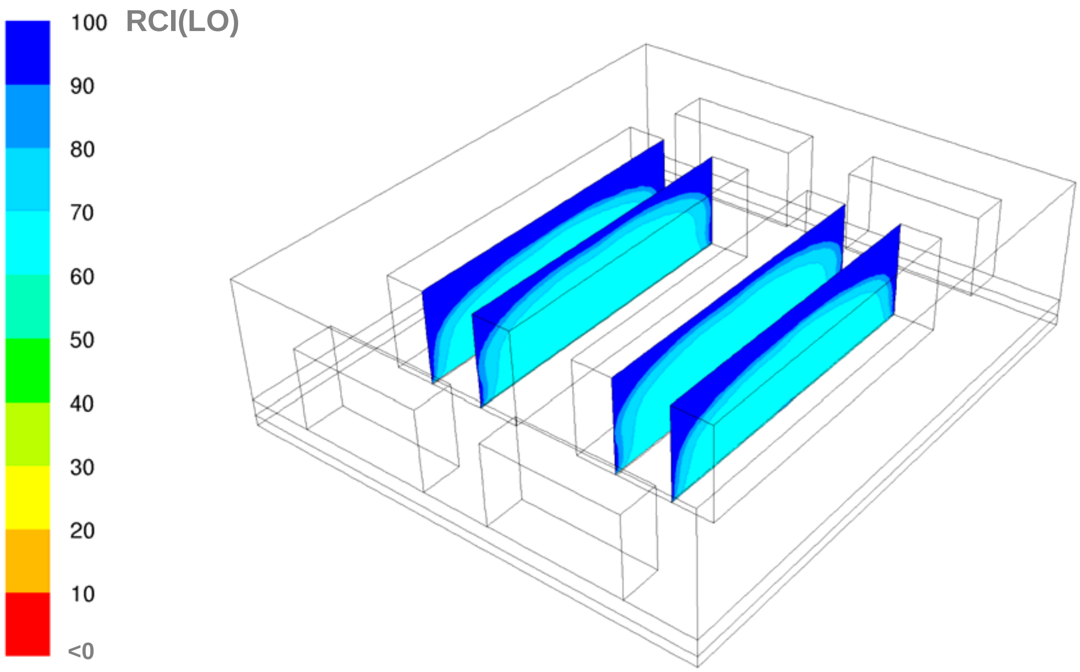

Figure 6b. RCI_{LO} distribution across equipment
air intakes at SAT=65°F (18°C) and SAQ=100%.

SUMMARY

This paper has presented a methodology for optimizing the equipment rack cooling effectiveness and HVAC cooling costs in telecom and data centers. By combining the Rack Cooling Index (RCI) with cost functions, current or planned equipment room designs can be evaluated. The Rack Cooling Index (RCI) was developed to be a measure of how effectively equipment racks are cooled and maintained within industry thermal specifications. Since the costs/savings associated with improving the RCI needs to be known, the concept of cost functions was developed based on costs to condition the equipment space.

Given that raised-floor air distribution is the most common way of cooling data centers, this scheme was used to demonstrate the methodology. The RCI was computed with Computational Fluid Dynamics (CFD) modeling to evaluate the thermal equipment environment for different supply temperatures and supply airflow rates. A new user function for calculating the Index was developed and incorporated into the computer code. Additionally, two hypothetical energy cost functions were worked out, one for the chiller and one for the supply fan. These functions estimated the energy costs/savings associated with improving the thermal equipment environment.

Specifically, it was shown how the performance of the raised-floor system could be improved by modifying the supply temperature and airflow rate to values higher than traditionally used. Color maps depicting RCI distributions provided a visual representation of the benefits of changing the supply air conditions. And, it was shown that the change also reduced the energy consumption of the CRAC units. This analysis points out the fact that improving the equipment environment and saving energy are not mutually exclusive.

The methodology outlined in this paper was shown to constitute a practical tool for making better and more informed design decisions. Since all necessary information is readily available, the methodology can immediately be included in the analysis. When the RCI algorithm has been incorporated into CFD codes, engineers and architects will have yet another tool to evaluate and design telecom and data centers. Until then, manual calculations of the RCI can easily be performed.

REFERENCES

ASHRAE. 2004. Special Publication, *Thermal Guidelines for Data Processing Environments*.

Fluent. 2006. *Fluent 6.2 User's Guide.*

Herrlin, M. K. and C. Belady. 2006. "Gravity-assisted air mixing in data centers and how it affects the rack cooling effectiveness." *IEEE-ITherm 2006, San Diego, CA, May 30–June 2, 2006.*

Herrlin, M. K. 2005. "Rack cooling effectiveness in data centers and telecom central offices: The Rack Cooling Index (RCI)." *ASHRAE Transactions, Volume 111, Part 2.*

Sorell, V., S. Escalante, and J. Yang, 2005. "A comparison of under-floor and above-floor air delivery systems in a data center environment using CFD modeling." *ASHRAE Transactions, Volume 111, Part 2.*

Telcordia. 2006. Generic Requirements NEBS GR-63-CORE, *NEBS Requirements: Physical Protection*, Issue 3, March 2006.

Telcordia. 2001. Generic Requirements NEBS GR-3028-CORE, *Thermal Management in Telecommunications Central Offices*, Issue 1, December 2001.