By Magnus K. Herrlin, Ph.D. ANCIS Incorporated
Christian Belady, P.E., Hewlett-Packard Company

UNDERSTANDING GRAVITY'S ROLE IN THE DATA CENTER:

HOW IT COULD HELP IMPROVE THE COOLING DESIGN

As power and heat densities continue to increase, the behavior of the data center environment grows in importance. As a result, there has been a continued interest in understanding the performance of various in-room cooling solutions. Many factors affect the behavior of these solutions but little attention has been given to the effect of gravity. This poses the question: Does gravity play a role in forced convection environments such as data centers?

The purpose of this article is to determine whether gravity plays a role in the data center environment and examine the phenomenon by analyzing what we call "gravity-assisted" air mixing using Computational Fluid Dynamics (CFD) modeling and a metric called the Rack Cooling Index (RCI). We compare a bottom-up system widely used in data centers, and alternative modular top-down system, and a hybrid system. The RCI is used to gauge how effectively the equipment racks are cooled and maintained within thermal guidelines or standards.

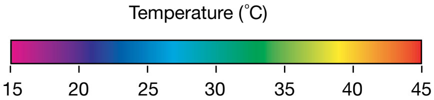
Example 1: Reverse Gravity

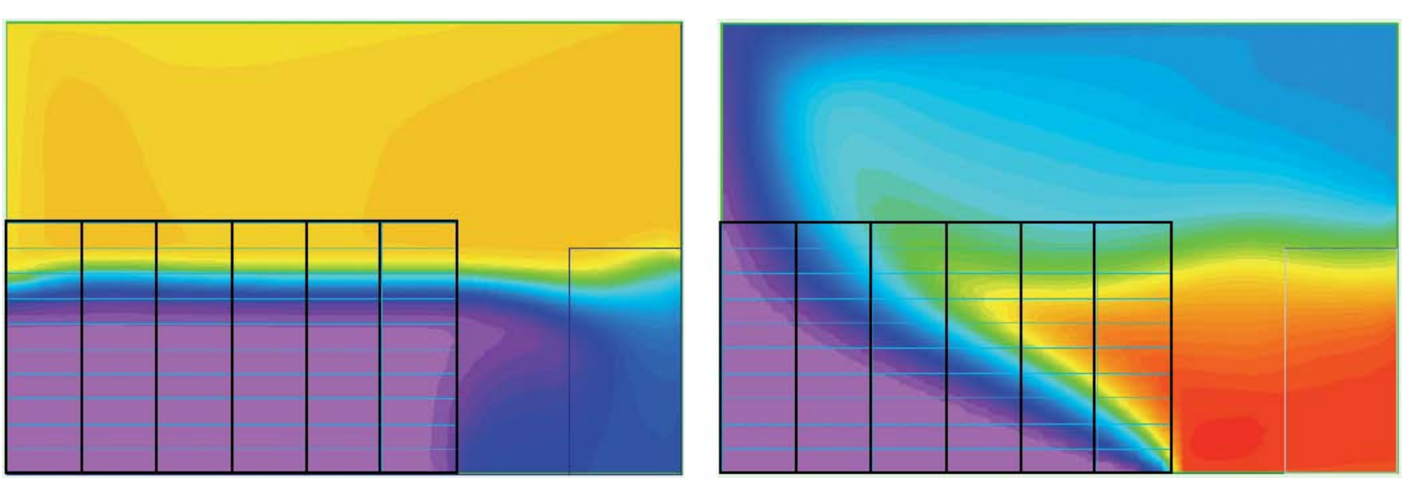
To demonstrate the impact of gravity on a system seemingly dominated by forced convection, the following is a discussion centered round "reverse gravity." In this example, conventional raised floor cooling is modeled with normal gravity and then with reverse gravity. Although this is not something that can be done in the real world, it is a simple idea that demonstrates the impact of gravity. If the results of the models are different, then we may need to consider gravity in our design and analysis.

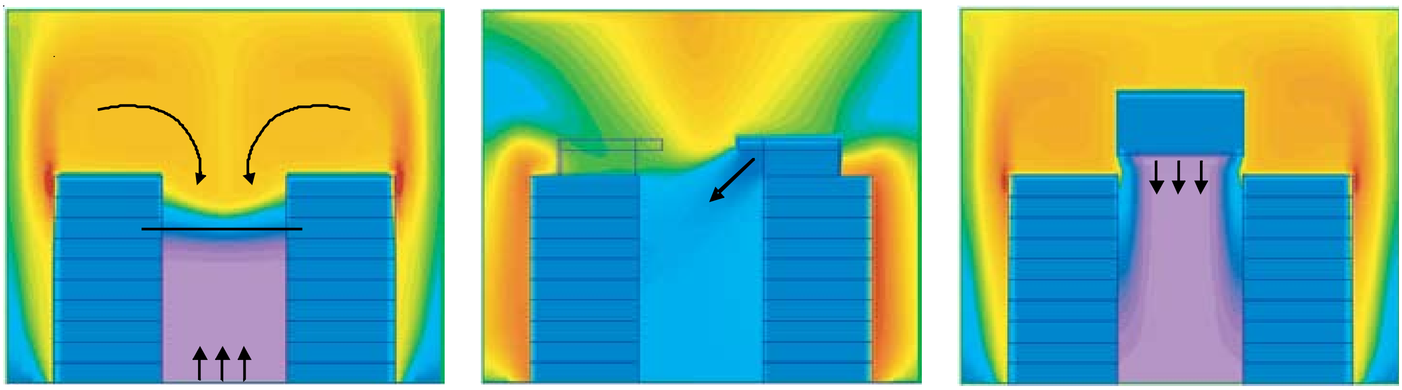
Figure 1 shows a cross-section along an equipment aisle in the data center. A characteristic distinct interface between hot and cold air is developed towards the top of the server racks. One would think that this environment is dominated by the forced air from the floor tiles. However, by simply reversing the gravity field, the temperature distribution looks quite different, not only in the room at large but also in the equipment aisle. Clearly, gravity plays a role.

This is a key finding, but it is shown under idealized conditions. How does this finding relate to more realistic set-ups? We explore this next where three different cooling systems are compared.

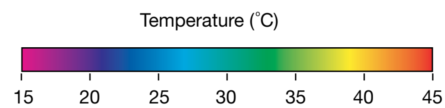
Figures 1 and 2.
Normal Gravity and Reverse Gravity







Figures 3-5. Bottom-up, Top-down, and Reverse-Tile Systems



Example 2: Comparing Technologies

The bottom-up system **(Figure 3)** is based on a raised floor with perforated floor tiles. The tile airflow is uniform assuming an even pressure distribution in the under-floor plenum. The supply temperature is 60°F (16°C).

The top-down system **(Figure 4)** consists of modular cooling units installed above selected equipment racks. Built-in fans and cooling coils move and condition the air. The supply temperature is 65°F (18°C) to ensure dry coil operation.

The reverse-tile system **(Figure 5)** is essentially a reversed raised floor environment. The supply temperature is identical to the bottom-up system, that is, 60°F (16°C).

The three systems are applied to a data center with hot and cold aisles. For the bottom-up system and the reverse-tile system, the entire cold aisles have perforated floor tiles. The reverse-tile system and the top-down system do not require a raised floor. Each equipment rack holds ten servers. The equipment has front-to-rear cooling (F-R), the temperature rise is 27°F (15°C), and the heat dissipation is 3kW per rack. For all three systems, the supply airflow matches the equipment cooling airflow.

According to **Figures 3-5,** the systems produce significantly different temperature conditions. For the bottom-up system, re-circulation occurs at the top of the racks; the interface between cold and hot air is distinct (highlighted by a black bar). The top-down system, on the other hand, produces a well mixed cold aisle and the servers draw air with uniform temperature. Finally, the reverse-tile system also results in fairly uniform conditions. Although CFD modeling allows visualization of temperatures, determining the cooling effectiveness of the systems can be challenging. What matters most for the health of the air-cooled equipment is the intake temperature. This temperature is typically monitored by the equipment to ensure that air is provided within the specified limits for reliable operations. However, these sensors are not easily available for feedback to the in-room cooling system.

Recommended Thermal Conditions

The thermal conditions that may occur in a data center are depicted in Figure 6. First, facilities should be designed and operated to target the recommended range. Second, electronic equipment should be designed to operate within the extremes of the allowable operating environment. Prolonged exposure to temperatures outside the recommended range can result in decreased equipment reliability and longevity; exposure to temperatures outside the allowable range may lead to catastrophic equipment failures.

The recommended range and the allowable range vary with the guideline or standard used. For the recommended temperatures, the telecom standard NEBS suggests 65°-80°F (18°-27°C) whereas ASHRAE Thermal Guideline lists 68°-77°F (20°-25°C) for a "Class 1" environment.

The rack Cooling Index (RC)

The RCI is a metric that allows us to gauge the thermal health of the electronic equipment (Herrlin, 2005). Specifically, the RCIHI is a measure of the absence of over-temperatures (under-cooled conditions); 100% means that no over-temperatures exist, and the lower the percentage, the greater probability that equipment experience excessive intake temperatures. RCI values below 80% are generally considered "poor."

About the Authors:

Magnus K. Herrlin, Ph.D.

Dr. Magnus K. Herrlin is President of ANCIS Incorporated, a San Francisco, California, based consultancy providing advanced indoor environmental and energy solutions for data centers, telecom central offices, and other mission critical facilities. Magnus holds a Ph.D. in Mechanical Engineering and is a Certified Energy Manager (CEM) by the Association of Energy Engineers.

Christian Belady, P.E., Distinguished Technologist

Christian Belady is an executive-level technologist in HP's High Performance System Lab in Richardson, Texas, where he is responsible for the power & cooling strategy of the center's high-end computers. He is also a Fellow and Lifetime Member of the International Microelectronics and Packaging Society (IMAPS) as well as a Fellow of ASME. Christian currently holds 42 US patents and several international patents.

The RCIHI is defined as follows:

$$\text{RCIHI} = \left[1 - \frac{\sum (T_x - T_{max\text{-}rec})_{T_x > T_{max\text{-}rec}}}{(T_{max\text{-}all} - T_{max\text{-}rec})\, n}\right] 100\ \%$$

where

T_x	**Mean temperature at intake x [°F or °C]**
n	**Total number of intakes [–]**
$T_{max\text{-}rec}$	**Max recommended temp. per some guideline or standard [°F or °C]**
$T_{max\text{-}all}$	**Max allowable temperature per some guideline or standard [°F or °C]**

An analogous index is defined at the low end of the temperature range. The RCILO is a complement to the previous index especially when the supply conditions are below the minimum recommended temperature.

$$\text{RCILO} = \left[1 - \frac{\sum (T_{min\text{-}rec} - T_x)_{T_x < T_{min\text{-}rec}}}{(T_{min\text{-}rec} - T_{min\text{-}all})\, n}\right] 100\ \%$$

where

T_x	**Mean temperature at intake x [°F or °C]**
n	**Total number of intakes [–]**
$T_{min\text{-}rec}$	**Min recommended temp. per some guideline or standard [°F or °C]**
$T_{min\text{-}all}$	**Min allowable temperature per some guideline or standard [°F or °C]**

The significance of a low RCILO is the potential for harmful relative humidity levels and that the equipment may not be qualified at low temperatures. Internal timing of data packages may be affected and thus contribute to data corruption.

The comprehensive CFD data generated by modeling are condensed by the RCI and the results are shown in Figure 7 using ASHRAE Class 1 recommended and allowable temperature ranges. The indices clearly highlight differences in the rack cooling effectiveness of the three systems.

Discussion

The results in Figure 7 show that the top-down system is significantly better than the other two for the assumptions outlined earlier. Contributing factors are "gravity-assisted" mixing in the cold aisle, limited entrainment of hot ambient air, and modestly cool supply air. The top-down system provides intake temperatures that match the ASHRAE Class 1 environment with both RCI values near 100%.

The conventional bottom-up system has the worst performance. Due to the low supply temperature of 60°F (16°C) and the lack of air mixing in the aisle, the RCILO is 40%. A higher supply temperature would improve the RCILO but hurt the RCIHI. The performance of the reverse-tile system is in between the two other systems.

Gravity-assisted mixing is a combination of longer jet throw and natural convection. For overhead cooling systems, the cold downward air jets will be subjected to the benefits of gravity-assisted mixing.

The jets will entrain some surrounding air while traveling downwards from the diffuser. Towards the end of the throw, colder air is located above hotter air which results in natural convection. Such convection is driven by gravity and differences in air densities. The result is a well-mixed aisle.

The temperature distribution in the cold aisle looks significantly different for the typical bottom-up system. Cold air is supplied upwards from perforated floor tiles. While the cold air is traveling upwards, air flows out at the end of the aisles. In this system, throw and natural convection are reduced rather than assisted by gravity.

Summary

This article demonstrates that gravity does in fact play a role in the temperature distribution in data centers. As a result, it is important to consider the effect of gravity in the choice of cooling system. In addition, it is shown that the Rack Cooling Index (RCI) can be used to grade the cooling effectiveness of various data center cooling technologies.

The RCI is a measure of the absence of over- and under temperatures at the air intakes of the equipment, where 100% indicate ideal conditions. Based on the data presented, the following observations can be made:

- **The modular top-down system provides intake temperatures that match the ASHRAE environmental Class 1. It has RCI values at or near 100% (ideal).**

- **The conventional raised-floor system has the lowest RCI values indicating that many servers are operating outside their specifications.**

These observations are pointing to some very significant differences in rack cooling effectiveness when gravity-assisted mixing is allowed to thrive. This leads to our hypothesis that there are intrinsic performance differences between overhead cooling and under-floor cooling. We started this article with one question and we end with another: Why are most data centers designed with raised-floor cooling?

This article is based on "Gravity-Assisted Air Mixing In Data Centers And How It Affects the Rack Cooling Effectiveness" by Magnus K. Herrlin, Ph.D. and Christian Belady, P.E. which appears in the Proceedings of the IEEE-ITherm 2006 conference, San Diego, CA, May 30 - June 2, 2006.

The full ITherm paper (Herrlin and Belady, 2006) can be downloaded for free from ANCIS' website at www.ancis.us The ASHRAE paper "Rack Cooling Effectiveness in Data Centers and Telecom Central Offices: The Rack Cooling Index (RCI)" (Herrlin, 2005) is also available for downloading.

Figure 6. Temperature Distribution (hypothetical), Thermal Ranges, and Thermal Limits

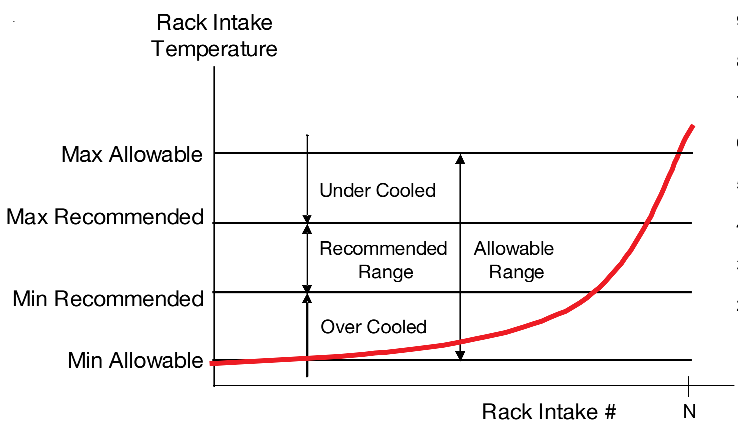


Figure 7. RCI Comparison of the Three Systems at 150 W/ft2 (1,615 W/m2)