The Use of Ceiling-Ducted Air Containment in Data Centers

White Paper 182

Revision 0

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Executive summary

Ducting hot IT-equipment exhaust to a drop ceiling can be an effective air management strategy, improving the reliability and energy efficiency of a data center. Typical approaches include ducting either individual racks or entire hot aisles and may be passive (ducting only) or active (include fans). This paper examines available ducting options and explains how such systems should be deployed and operated. Practical cooling limits are established and best-practice recommendations are provided.

Introduction

Hot exhaust airflow recirculation and cold supply airflow bypass are more likely to occur with high and non-uniform rack densities due to mismatches between IT and local cooling supply airflow (e.g., from perforated floor tiles). Air containment can virtually eliminate such recirculations thereby improving the reliability and energy efficiency of data centers. Both "hot" and "cold" air containment strategies are common and are discussed in greater detail in White Paper 153, Implementing Hot and Cold Air Containment in Existing Data Centers and White Paper 135, Impact of Hot and Cold Aisle Containment on Data Center Temperature and Efficiency. Ceiling-ducted containment systems, the topic of this white paper, are "hot air" containment strategies in which the hot IT exhaust is ducted directly into a drop ceiling plenum and subsequently drawn out of the plenum by CRAH (Computer Room Air Handler) or other cooling units. Like all hot air containment strategies, ducted systems provide the following primary advantages over cold air containment strategies:

- Comfortable working conditions and better cooling of equipment located around the periphery of the data center; and
- Greater energy efficiency due to increased temperature difference between the hot return air and the ambient.

Ceiling-ducted containment systems deserve examination in greater detail here because of their unique reliance upon a drop ceiling system. As will be discussed, it is the performance of the ceiling plenum, specifically, the ability to provide a slightly negative pressure (relative to the room) which dominates the cooling performance of ducted equipment. When properly utilized, ducted containment is a reasonable option for new facilities and a particularly attractive option for improving the efficiency and extending the life of existing facilities.

Classification of ducted air containment

The defining characteristic of ducted containment systems is that they physically duct hot IT exhaust into a drop ceiling. **Figures 1** and **2** show typical examples in which passive rack ducting is used with traditional CRAH units and passive hot-aisle ducting is used with high-efficiency cooling units located outside of the building, respectively. In both cases, the design intent is that all hot IT exhaust is captured and directed into the ceiling plenum thereby eliminating recirculation back to equipment inlets. Of course, such systems are not perfectly sealed and generally cannot provide perfect separation of cold and hot airflow streams. Ultimately, there must be an airflow mass balance and, any mismatch between IT and CRAH airflow rates must be made up by leakage either into or out of the plenum. We will discuss the ceiling plenum airflow and pressure in more detail later in this paper. First, this section provides a brief overview of the types of ducting systems considered here. See White Paper 153, Implementing Hot and Cold Air Containment in Existing Data Centers, for additional details.

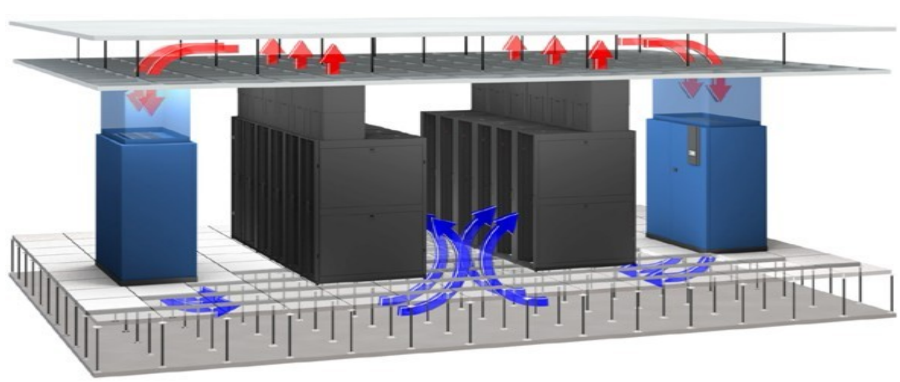


Figure 1

Example of drop ceiling plenum and passive ducted racks in a typical perimeter CRAH application (Schneider Electric Vertical Exhaust Duct Used)

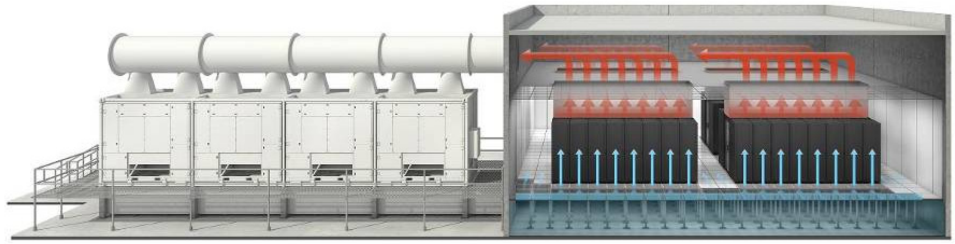


Figure 2

Ducted HACS used in combination with Schneider Electric EcoBreeze

Passive individually-ducted rack

Figure 1 shows an example of passive individually-ducted racks. This air containment strategy involves rack-by-rack ducting to the ceiling plenum. In addition to the ducting itself, solid panels are installed in the rear door and sometimes the un-ducted portion of the roof to minimize leakage airflow. Deeper racks may be preferred for use with passive individually-ducted-rack containment, particularly with higher densities, to provide a larger unrestricted airflow path for IT exhaust.

Active individually-ducted rack

Figure 3 shows an example of an active individually-ducted rack. The fans in this active ducting system allow for rack densities up to about 12 kW and can overcome some adverse plenum pressure or pressure drops resulting from very dense cabling at the server exhausts. However, active systems can easily create unintended consequences elsewhere in the data center and should be employed with particular care. The solution shown in **Figure 3** adds approximately 10 in (250 mm) to the overall depth of the rack which likely will add to the pitch between adjacent rows of racks. Active systems also consume power and require monitoring and maintenance.

Figure 3

Example of active ducted rack air containment
(Schneider Electric Air Removal Unit shown)

Ducted hot aisle containment system (Ducted HACS)

Figure 4 shows an example of a ducted hot aisle containment system (HACS). This passive system encloses the entire hot aisle with solid panels and, sometimes, plastic curtains at the end of rack rows. Customized containment solutions may be required due to building column constraints, vendor-compatibility issues, or mismatched row lengths. While a specific rack orientation and configuration is required, rack rear doors and internal side panels are unnecessary with a ducted HACS. The shared hot aisle provides a large unobstructed volume for IT exhaust airflow which allows this solution to be effective at very high rack densities.

Figure 4

Example of ducted hot aisle containment system
(Schneider Electric EcoAisle shown)

Cooling performance of ducted containment

The cooling performance of ducted systems strongly depends on the configuration of the entire data center. Parameters like the amount of excess cooling (relative to IT) airflow, “leakiness” of the dropped ceiling system, ceiling plenum depth, rack density, and the physical layout of equipment typically affect cooling performance more than the specific construction details of the ducting systems themselves. If the data center design naturally creates a sufficient vacuum (favorable) pressure above the ducted equipment, then very high density racks can be supported with practically any ducting architecture. On the other hand, if the aggregate design results in only a neutral or even positive (adverse) pressure above the ducted equipment, cooling performance will be poor as recirculation back to the IT inlets may be the “path of least resistance” for hot IT exhaust.

First, we discuss the primary factors that affect ceiling plenum pressure then discuss airflow within the (attached) passive ducted systems. After establishing cooling performance limits of passive ducted systems (at a given ceiling plenum pressure), we discuss how specific (favorable) ceiling plenum pressures may be achieved in practice. Finally, we conclude this section with a brief discussion of active ducted systems.

Ceiling plenum airflow and pressure

Figure 5 shows an example of a complex, but typical, ceiling plenum airflow pattern. Air enters the plenum from ducted equipment and, possibly, perforated ceiling tiles which serve to capture the hot exhaust from un-ducted equipment and exits where it is drawn out by ducted CRAH units. Often, due primarily to imbalances between IT and CRAH airflow, overly leaky drop ceilings, and shallow ceiling plenums, the pressure distribution inside the ceiling plenum will be either “unfavorable” (higher than room pressure) and/or highly non-uniform. As a result, the cooling performance of ducted equipment may vary from location-to-location even for otherwise-identical groups of equipment in the same data center. Furthermore, hot exhaust airflow may enter the room as a result of "backflow" through perforated ceiling tiles and leakage paths. The airflow physics associated with a ceiling plenum is similar to that of a floor plenum[1]. Fortunately, ceiling plenums tend to be naturally deeper than floor plenums (as a consequence of clearance for building structural members and other infrastructure) which helps pressure uniformity. Additionally, relatively "tight" drop ceiling systems and regular/symmetric data center layouts help minimize plenum pressure variations.

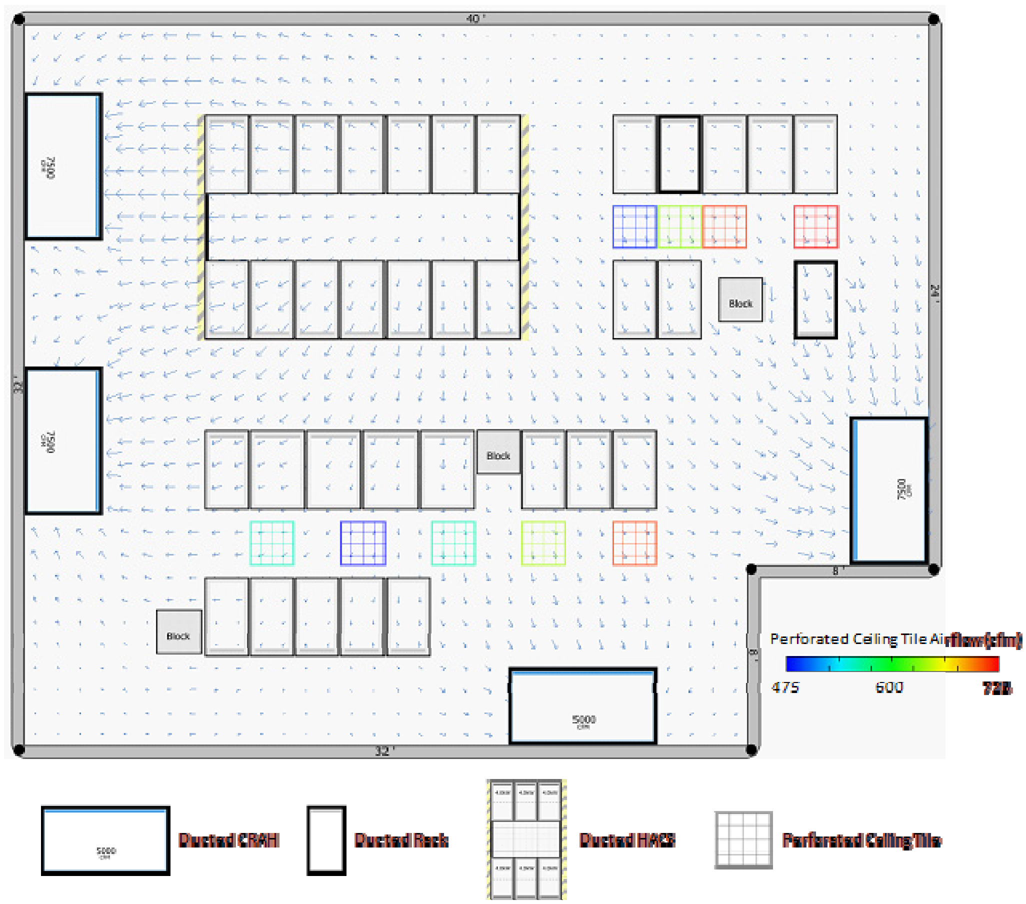


Figure 5

Example airflow pattern in ceiling plenum (Schneider Electric EcoStream CFD software)

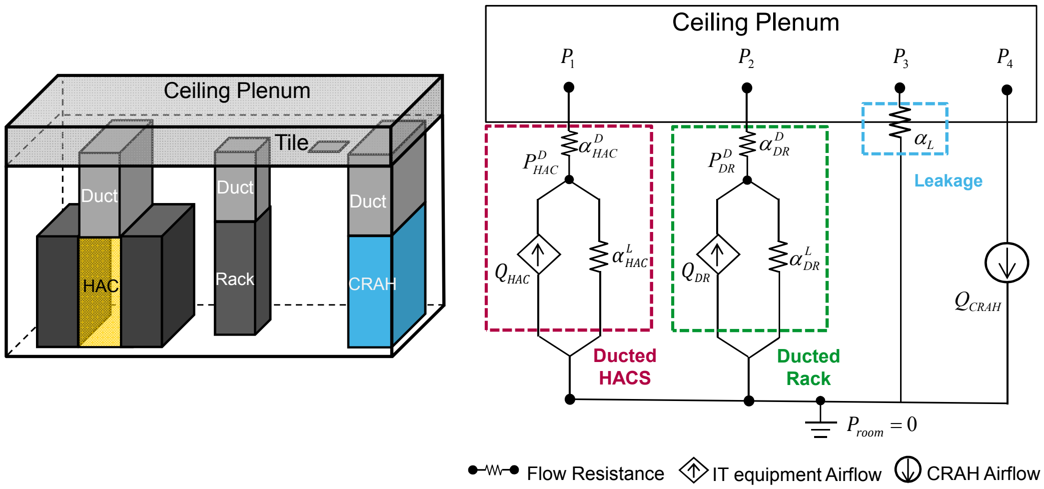
Cooling performance of passive ducted systems

The airflow physics of passive ducted systems is most easily understood with reference to a flow network diagram in which airflow sources and resistances to airflow are drawn in analogy to a simple electric circuit. **Figure 6** shows an example data center architecture with its corresponding flow network diagram; more complex architectures simply add more ducted HACS, ducted racks, and CRAHs. Unlike a simple electric circuit, however, the pressure drop across a flow resistance typically does not vary linearly with airflow rate; relationships somewhere between linear and quadratic are typical. As an example, the pressure drop across a perforated ceiling tile varies nearly with the square of the airflow rate which passes through it. In the flow network diagram, **Figure 6b**, airflow rates (e.g., in cfm or m^3/s) are designated with Q, pressure (e.g., in inH_2O or Pa) with P, and flow resistance (e.g., in inH_2O/cfm^2 or $Pa/(m^3/s)^2$ for quadratic elements) with α.

[1] VanGilder, J. and Schmidt, R., 2005, "Airflow Uniformity Through Perforated Tiles in a Raised Floor Data Center", Proceedings of InterPACK, July 17-22, San Francisco, California.

Figure 6

Example data center with passive ducting: 1 ducted rack and 1 ducted HACS



a) Physical Layout   b) Flow Network Diagram

In the flow network model, ducted HACS clusters are idealized as an aggregate of all racks within the HACS combined with the physical structure which contains the hot aisle and ducts it to the ceiling plenum. For each ducted HACS cluster, the total rack airflow is represented by a single flow source (Q_{HAC}) in parallel with a flow resistance ($\alpha^L{}_{HAC}$) which characterizes all possible paths taken by leakage airflow passing from the hot aisle into the room (or vice versa) through openings in the racks and the containment system structure. Additionally, a “duct resistance” ($\alpha^D{}_{HAC}$) represents the flow resistance between the IT equipment exhaust and the ceiling plenum.

Ducted racks are represented by similar flow source (Q_{DR}) and leakage path ($\alpha^L{}_{DR}$) elements; however, the “duct resistance” ($\alpha^D{}_{DR}$) is generally much greater. The “duct resistance” is primarily associated with server exhaust airflow rapidly decelerating as it approaches the solid rear door of the rack, being redirected vertically, and, finally, being forced through a small space between the rear of the servers and the rear of the rack. Note that, although we refer to this resistance as “duct resistance” for brevity, the actual resistance inside the containment duct itself is fairly negligible.

CRAHS are idealized as fixed airflow sources (Q_{CRAH}) while leakage airflow through the ceiling and, if present, perforated ceiling tiles, are idealized as additional flow paths (with resistance α_L). Because the plenum pressure distribution is highly case dependent, the preferred design approach is to analyze the airflow in the ducted equipment and attached ceiling plenum using computational fluid dynamics (CFD) software. Schneider Electrics' EcoStream CFD software, for example, embeds the flow network model shown above into the model of the room airflow and relies on experimentally-measured flow resistance data to characterize the various leakage paths. This software is used internally within Schneider Electric to assist in data center design and is available commercially as part of StruxureWare™ Data Center Infrastructure Management (DCIM) software[2]. Other references provide more details on the coupling of the flow network and CFD models and the analyses presented here[3,4].

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[2] http://www.schneider-electric.com/sites/corporate/en/solutions/struxureware/struxureware-applications.page (accessed 2/17/2014)

[3] Zhang, X., VanGilder, J., Healey, C., and Sheffer, Z., 2013, “Compact Modeling of Data Center Air Containment Systems”, Proceedings of InterPACK, July 16-18, Burlingame, California.

[4] VanGilder, J., and Zhang, X., 2014, “Cooling Performance of Ceiling-Plenum-Ducted Containment Systems in Data Centers”, Submitted for Publication. Proceedings of IEEE ITHERM Conference, May 27-30, Orlando, Florida.

While we have stressed that the ceiling plenum system should generally be considered when designing passively-ducted systems, it is instructive to see how the different ducting systems perform relative to one another at a given ceiling pressure. In the analysis which follows, we assume IT equipment airflow is 125 cfm/kW [212 m^3/hr/kW], racks are uniformly populated up to the 30-U position, and blanking panels are installed elsewhere. HACS clusters are assumed to be comprised of 20 total racks and ducted racks provide for 8 in (200 mm) of clearance between the rear of the server and the rear door for the rack.

Figure 7 shows the cooling performance of ducted racks and ducted HACS as a function of ceiling plenum pressure and rack power density under the assumptions outlined above. “Good”, “Marginal”, and “Bad” cooling performance is based on the amount of IT exhaust recirculation. “Good” means that all of the IT-exhaust airflow is captured by the ceiling plenum and the Good/Marginal interface corresponds to a neutral pressure environment for the servers – with neither backpressure nor additional suction. “Bad” signifies at least 10% recirculation with 90% or less of the IT exhaust captured by the ceiling plenum. With reference to **Figure 7**, we draw the following two main conclusions:

Cooling performance is strongly linked to the ceiling plenum pressure. Both ducted HACS and individually-ducted racks can potentially accommodate reasonably high rack densities but only when appropriate plenum vacuum pressures can be achieved.
Ducted HACS can adequately cool much higher densities than individually-ducted racks at a given ceiling vacuum pressure. For example, at a vacuum pressure of 0.03 inH_20 (7.5 Pa), individually-ducted racks are limited to about 8 kW while ducted HACS systems can support up to about 16 kW. Furthermore, ducted HACS systems provide at least “marginal” cooling performance far into the “bad” range for individually-ducted racks.

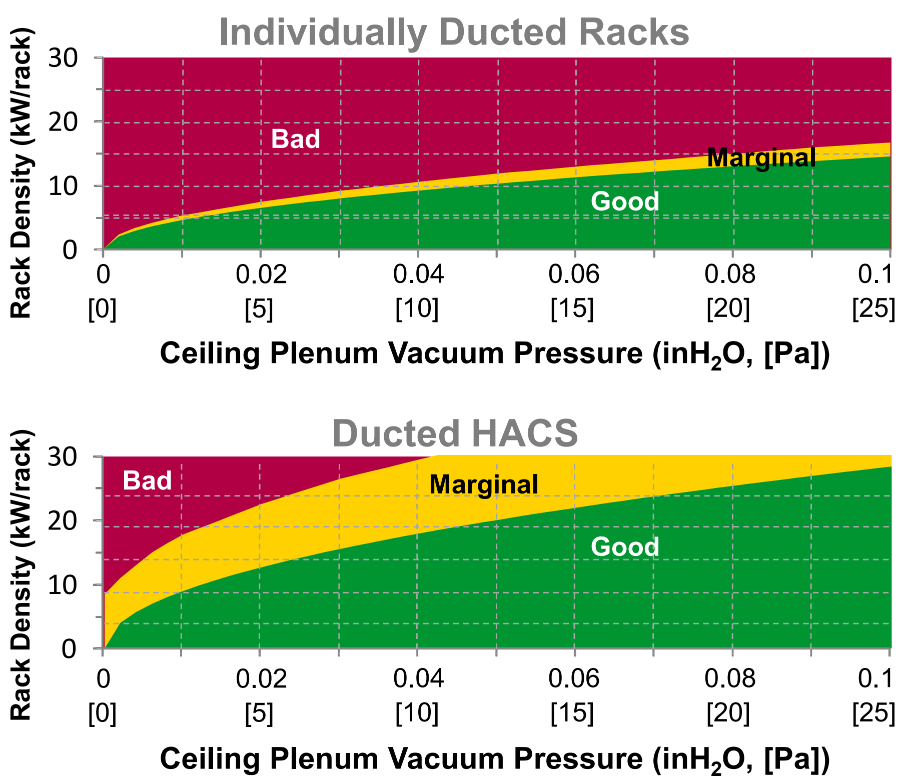

Figure 7

Cooling performance of passive ducted systems as a function of ceiling plenum pressure and rack density

Figure 8 summarizes the maximum rack density limits of **Figure 7** and facilitates a more direct comparison of performance between ducted racks and ducted HACS. Ideally, ceiling plenum pressure should be maintained at just the values indicated by the curves of **Figure 8** as these are the neutral-pressure operating points for the IT equipment. Lower values of ceiling vacuum result in some hot-exhaust recirculation while higher values imply wasted cooling power as room (bypass) air is drawn into the ceiling plenum. Also indicated in **Figure 8**, is the practicality of achieving specific plenum pressures. Ceiling vacuum of greater than 0.03 inH2O (7.5 Pa) can be achieved by minimizing cutouts, employing more restrictive (or eliminating) perforated tiles, and selecting lighting fixtures that do not introduce substantial leakage paths. As ceiling vacuum increases beyond about 0.06 inH_2O (15 Pa) or so, typical-density ceiling tiles begin to lift with the resulting leakage airflow limiting further increase in vacuum pressure.

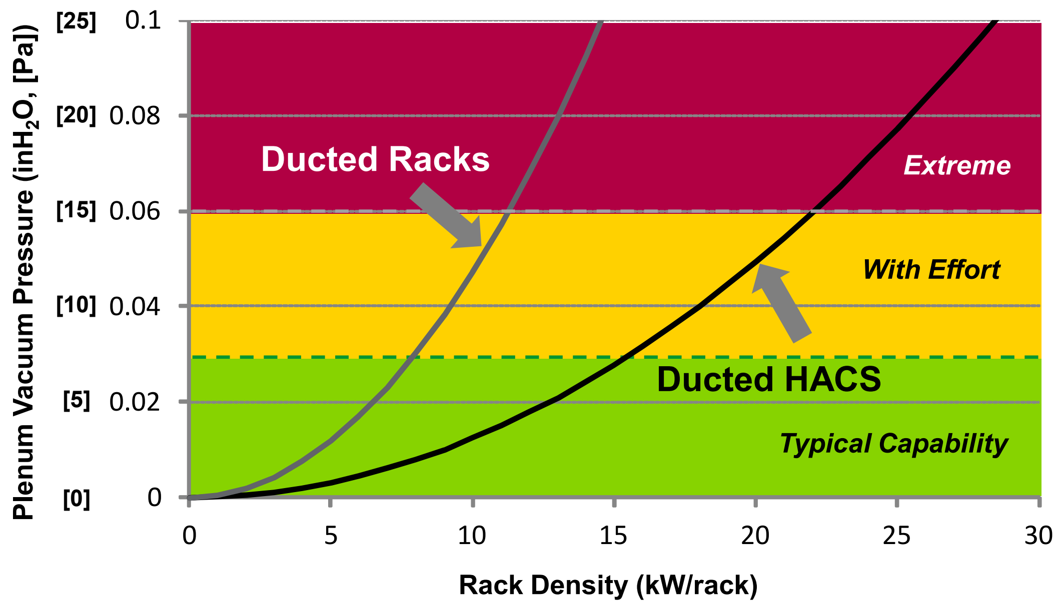

Figure 8

Target ceiling plenum set point pressure as a function of rack density

Cooling analysis including entire ceiling plenum

If CRAHs are controlled based on ceiling plenum pressure, then **Figures 7** and **8** give the information the data center designer or operator needs to assure good cooling performance. But, without active ceiling pressure control, how can we be sure that a given design is capable of achieving the required plenum vacuum? Although, this question is best answered by performing a design-specific analysis, we give general design guidance here based on CFD analyses of a typical data center layout[5]. The layout includes four rows of 10 racks; 20 racks on one side of the room are individually ducted while the other 20 racks form one ducted HACS cluster. Four CRAHs are placed at the ends of the hot aisles. CFD simulations cover the following design values:

- Cooling-to-IT airflow ratio: 0.8, 1.0, 1.2
- Ceiling leakiness: “leaky”, “typical”, “well sealed”
- Ceiling plenum depth: 12, 18, 24, 36, 48, 60 in (0.30, 0.46, 0.61, 0.91, 1.22, 1.52 m)
- Rack density: 2, 6, 12 kW

Summarizing the CFD results, average cooling performance is a fairly weak function of plenum depth and rack density; with deeper plenums and lower density yielding somewhat better performance. Cooling performance is moderately affected by drop-ceiling leakiness with “tighter” being generally better though “typical” plenums perform much closer to “well sealed” than “leaky”. Finally, cooling performance is a strong function of cooling-to-IT airflow

[5] VanGilder, J., and Zhang, X., 2014, “Cooling Performance of Ceiling-Plenum-Ducted Containment Systems in Data Centers”, Submitted for Publication. Proceedings of IEEE ITHERM Conference, May 27-30, Orlando, Florida.

ratio with higher values better. For the latter, values of one are generally acceptable for ducted HACS but ducted racks may require cooling-to-IT airflow ratios of 1.2 or higher.

While *average* cooling performance is only a weak function of plenum depth, the *uniformity* of cooling performance (i.e., rack-to-rack variations) does depend on plenum depth. **Figure 9** shows the rack-to-rack uniformity in cooling performance for typical design conditions (cooling-to-IT airflow ratio of 1 and "Typical" ceiling leakiness) of ducted HACS. Note that uniformity is good with plenums deeper than 18-24 in (0.46-0.61 m). Furthermore, cooling uniformity is not strongly affected by rack density with even 12 kW racks (and higher) yielding "good" uniformity provided this minimum plenum depth is provided. Cooling uniformity for ducted racks (not shown) is even slightly better than that for ducted HACS due to the more-isolated nature of individual rack ducting.

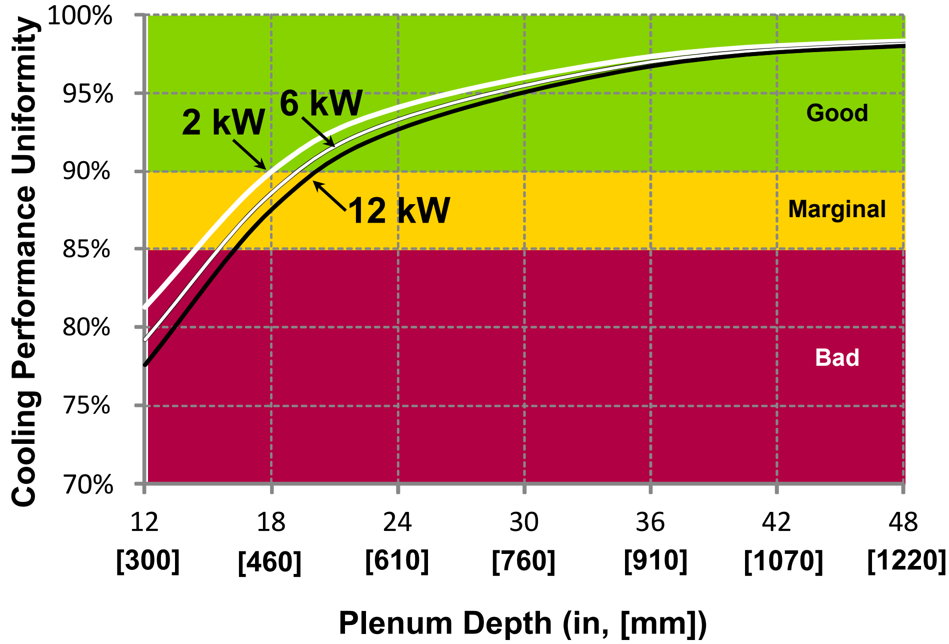

Figure 9

Cooling performance uniformity as a function of ceiling plenum depth for Ducted HACS

Cooling performance of active ducted systems

With an understanding of the airflow physics of passive systems we now provide a brief discussion of active systems. Although active-ducted systems, i.e., those with fans to force the airflow into the ceiling plenum may be able to overcome adverse plenum pressures, they may do so at the expense of other areas of the data center. In simple terms, whatever airflow gets pushed into the ceiling plenum has to find a way out and, if CRAH airflow is insufficient or the plenum is too restrictive, hot air will simply be forced back out elsewhere – through perforated ceiling tiles, leakage paths, and even other ducted equipment. For this reason, it is recommended that active systems be deployed following the same design guidelines as for passive systems, e.g., **Figures 7** and **8** and in the "Guidance for implementation" section below. Additionally, the reader should refer to the product literature related to the maximum airflow of the active system under consideration.

Comparison of ducting options

Table 1 summarizes the primary considerations when selecting a specific ceiling-ducted architecture. Capital cost is similar for the passive systems but substantially higher for the active ducted rack. Because the active systems draw fan power, they will also cost more in operating costs which will negatively offset some of the energy saving benefit of containment.

The primary limitation of passive ducted HACS is that a specific floor layout is required for its implementation. However, since the standard hot/cold aisle architecture has been a best-practices standard for many years, this may not be a real limitation. Where ducted HACS can be implemented, it offers the best performance with the highest density IT equipment while not adding to rack depth or requiring specific racks or adapter hardware. However, if only a sparse distribution of racks requires ducting or the layout required for ducted HACS is impractical, individual-rack options might be employed. In any case, passive ducted racks are a good overall choice especially with "shorter" servers up to moderate densities, e.g., up to about 8 kW/rack or even higher if the required ceiling plenum vacuum pressure can be achieved.

Active ducted systems may offer an advantage in the case where ducted HACS are impractical due to layout and passive ducted racks are too limited in density at the maximum achievable ceiling plenum vacuum. However, the general use of active ducted systems to compensate for undesirable plenum pressure is not recommended due to the likelihood of creating cooling problems elsewhere in the data center. The preferred approach is to first address ceiling plenum pressure problems (e.g., by increasing ducted cooling airflow, improving ceiling "tightness", and/or increasing plenum depth) before deploying ducted equipment of any kind.

Additional considerations may also guide the selection of particular ducted-containment architecture. These include the possible interference with fire suppression and lighting, cooling performance under emergency conditions, and noise. The reader is also reminded that there are other cold and hot-aisle containment options available beyond the plenum-ducted options discussed here. See the references noted in the Introduction for more information.

Table 1

Comparison of ducted air containment architectures

Consideration	Ducted air containment		
	Passive ducted rack	Active ducted rack	Ducted HACS
Capital cost	$500 - 700 / rack	$1,800 - 2,000 / rack	$500 - 1,000 / rack
Works with any floor layout	Yes	Possibly[1]	No
Works with all racks without special hardware	No	No	Yes
Maintenance and monitoring free (power feed not required)	Yes	No	Yes
Allows for normal (minimum) row pitch	Possibly[2]	No	Yes
Best choice for high density (⩾6kW) or low plenum vacuum pressure	No	No	Yes

[1]May require wider row pitch
[2]Deeper racks are recommended for use with deeper servers and higher densities

Guidance for implementation

Ensure adequate ceiling plenum vacuum pressure

Ideally, the proposed new design or retrofit should be simulated using CFD software to ensure that adequate vacuum and reasonably uniform pressures can be achieved throughout the ceiling plenum. At a minimum, the following best-practices should be observed:

- Ceiling plenums should be at least 18 in (450 mm) deep in all cases while deeper is better when practical.
- Ducted cooling airflow should exceed ducted IT airflow by a minimum 10% for most cases or 20% when passive ducted racks are employed with relatively leaky drop ceiling systems.
- Ceiling plenum vacuum should be maximized:
    - Minimize and seal leakage paths in the drop ceiling
    - Minimize the number of perforated ceiling tiles and use more restrictive tiles
- Ducted equipment should be configured in reasonably uniform (with respect to geometric configuration and IT density) layouts to maximize plenum pressure uniformity. Note that, un-ducted equipment does not necessarily need to conform to this guideline as it does not affect ceiling plenum airflow dynamics.

Minimize leakage paths in containment systems

Sealing leakage paths in containment systems as much as practical helps ensure that the ceiling plenum remains the “path of least resistance” for rack exhaust airflow. Follow these best practices:

- Fill empty rack spaces with blanking panels or brush strips to minimize recirculation from the back to the front of the rack.
- Cover as many openings in the rack enclosure as possible and, in the case of passive ducted racks, also seal the rear door of the rack.
- Keep the space behind IT equipment as free and clear of cabling and other obstructions as possible. With passive ducted racks, ensure at least about 8 in (200 mm) of space between the rear of the server and rack rear door. Use deeper racks if necessary to achieve this.
- For passive ducted racks, install deeper IT equipment lower in the rack to avoid choke points for the exhaust airflow.

Employ active ducted containment with caution

For configurations which include active containment systems, verifying the performance of the intended application in advance with CFD is even more attractive. With active systems there is the risk that, while the active ducted equipment will perform well – apparently “fixing” a hot spot, problems will be created elsewhere in the data center. Such problems may not be readily apparent or easy to troubleshoot. In any event, increase the likelihood of a successful implementation by following the best practices recommended above even with active systems.

Conclusion

Ducted air containment can simultaneously improve the energy efficiency and reliability of data centers. Since all ducted equipment, ducted cooling units, and the ceiling plenum function as a single entity, the use of CFD modeling is recommended for new deployments particularly when design constraints are close to the best-practice limits established here. In any case, deployment advice centers on ensuring an adequate and fairly uniform vacuum pressure in the ceiling plenum. This, in turn, can be achieved by providing sufficient ducted cooling airflow, creating a relatively “tight” ceiling system, employing deeper ceiling plenums, and sealing unnecessary leakage paths in racks and containment structures.

About the authors

Jim VanGilder is responsible for Schneider Electric’s data-center Computational Fluid Dynamics (CFD) software development and related research. He has authored or co-authored more than 40 peer-reviewed technical papers and holds more than 15 patents in the field of data center cooling. He is an active American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) member where he is a recent Chair of Technical Committee 4.10, Indoor Environmental Modeling. Jim is a registered professional engineer in the state of Massachusetts. He has master’s degree in mechanical engineering from Duke University and over 20 years experience using and developing CFD tools.

Simon Zhang is a Sr. Research Engineer with APC by Schneider Electric working on data center design, operation, and management software platforms. He has extensive experience with real-time cooling predictions & indoor airflow simulations, and has author/co-authored 12 patents (granted or pending) and over a dozen peer-reviewed technical papers on data center cooling and energy assessment techniques. He is actively involved in data center communities and has chaired and organized many technical sessions of ASME and IEEE conferences. He received his M.S. in Mechanical Engineering at Syracuse University in 2006 and an MBA degree from Boston University in 2013.

Paul Lin is a Senior Research Analyst at Schneider Electric's Data Center Science Center. He holds a Bachelor’s degree in Mechanical Engineering from Jilin University where he majored in Heating, Refrigeration, and Air Conditioning. He also holds a Master’s degree in Thermodynamic Engineering from Jilin University. Before joining Schneider Electric, Paul worked as the R&D Project Leader in LG Electronics for several years. He is now designated as a “Data Center Certified Associate”, an internationally recognized validation of the knowledge and skills required of a data center professional.

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