Energy Efficient Cooling for Data Centers: A Close-Coupled Row Solution

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Executive Summary

The trend of increasing heat densities in data centers has held consistent with advances in computing technology for many years. As power density increased, it became evident that the degree of difficulty in cooling these higher power demand loads was also increasing. In recent years, traditional cooling system design has proven inadequate to remove concentrated heat loads (up to and greater than 20 kW per rack). This has driven an architectural shift in data center cooling. The advent of a newer cooling architecture that was designed for the higher densities has brought with it increased efficiencies for the data center. This article discusses the efficiency benefits of row-based cooling compared to two other common cooling architectures.

Energy-Efficient Data Centers

A Close-Coupled Row Solution

By John Bean, Member ASHRAE; and **Kevin Dunlap**

The predominant architecture for cooling data centers since the inception of the mainframe has been raised floor air delivery from perimeter computer room air handlers (CRAH). In this approach, CRAHs are placed around the perimeter of the room, and they distribute cold air through a raised floor with perforated floor tiles or vents to direct the air into the room (*Figure 1*). At lower densities (1 to 5 kW/rack) adequate cooling is provided to sensitive IT equipment, despite the mixing of air throughout the room.

A similar air delivery system that has been used to cool data centers is central air-handling units (CAHU) (*Figure 2*). These systems use much larger, more centralized cooling units with similar air delivery to perimeter CRAH cooling of either raised floor or custom overhead ductwork.

As rack power grew beyond 5 kW, air delivery and heat removal challenges with use of CRAH and CAHU systems became evident. The major obstacle in these architectures is the length scale of air delivery. Distance between the cooling units and the heat load make it difficult to properly remove the heat generated from IT equipment without mixing with supply air. This separation results in hot spots and a complicated design approach to air distribution.

To add to this problem, the airflow demands of the IT equipment also increases with power density. Since CRAH and CAHU systems use a plenum for supply air delivery (and warm air return in certain designs), a significant amount of fan horsepower is required to pressurize the plenum and overcome resistances in the air-distribution system. Additionally, to overcome the effects of mixing the net volume of air circulated is significantly greater than actual air volume required

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by IT equipment further compounding energy consumed by fans.

To address the air delivery and heat removal challenges of CRAH and CAHU systems, row-based cooling systems have begun to appear in many data center designs (*Figure 3*). To address the separation of cooling units and heat loads, row-based designs place the air-conditioning units in the row of rack enclosures. Incorporating a hot/cold aisle design, heat is removed from the hot aisle as it is dispelled from the IT equipment. The hot air is then cooled and discharged to the cold aisle.

While row-based designs addressed the issue of proper heat removal and cold air supply, they also brought with them inherent energy-efficiency advantages. The first of these was a reduction in fan power requirement to move the air. Close coupling to the heat load allows for a much shorter air delivery and heat removal path. This represents a shift in the mindset of data center air distribution from cold air supply to heat removal. Removal of heat from the hot aisle before it has a chance to mix with surrounding air in the room makes the remaining areas in the room a large volume of supply air. With this in mind, the length scale for air delivery in row-based systems is only a few feet (varies with number of racks and air-conditioning units).

In most CAHU and CRAH implementations it is necessary to maintain a fixed fan speed to deliver the necessary pressure for uniform airflow through delivery vents. In close-coupled designs, such as row-based, the static pressure requirement is significantly less, with only the cooling unit resistance to overcome. Without the requirement for constant pressure, row-based designs allow for variable air volume to scale back fan speed with heat load demand. This feature boosts the energy efficiency through part-load operation with increasing gains at lower loads as shown in *Figure 4*.

Eliminating mixing of hot and cold airstreams produces another energy benefit resulting from much warmer return air temperatures to the cooling units. Some advantages to warmer air return temperatures are:

- An increase in cooling capacity per unit that reduces the overall cooling footprint. The warmer return air temperatures provide a higher temperature differential to the cooling coil over rooftop and perimeter systems, and, therefore, more heat removal.
- More effective capture of hot air enables a much warmer supply temperature (no need to overcool the air to compensate for mixing).
- Limited or no condensate removal, reducing makeup humidification requirement.

Several row-based configurations are available in the market, which use varying placement of the cooling unit in the row and different methods of heat rejection. While these approaches to row-based cooling can be compared for the best energy efficiency, the real energy gain is with the row-based architecture over distributed air delivery systems like perimeter CRAH and CAHU systems. The following comparison of these different architectures illustrates the energy-efficiency advantage of the row-based architecture.

Data Center Cooling Architecture Efficiency Comparison

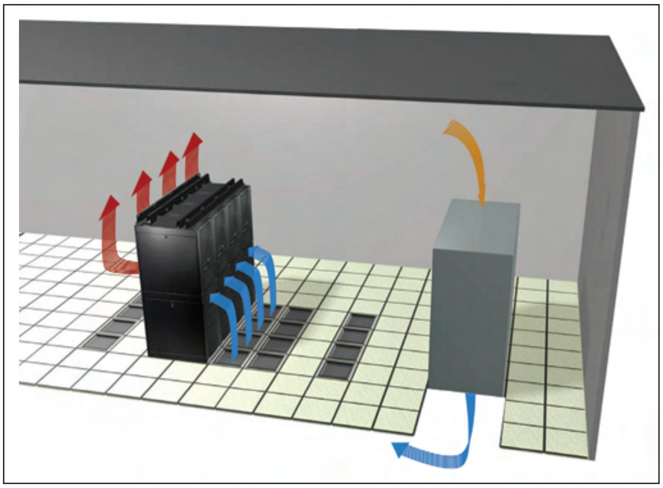
Let's compare three cooling architectures for the cooling of a mission critical information technology space. The key metric for this comparison shall be power consumed by the cooling infrastructure versus power dissipated by information technology equipment. This comparison attempts to understand and account for all power consumed across the entire length scale of thermal transport (IT rack exhaust to outdoor ambient).

$$\text{Efficiency}_{\text{Metric}} = \frac{\text{Cooling Power}\left[\text{kWh}\right]}{\text{IT Power}\left[\text{kWh}\right]} \tag{1}$$

The general format of the metric equation, from above, yields the ratio of cooling power to IT power. Proper understanding of this metric reveals that the lower the value, the more energy efficient the cooling architecture.

Symbols and Constants Used

Cp_{Air} = Specific Heat Air, 1.022 kJ/kg·°C
Cp_{Water} = Specific Heat Water, 4.188 kJ/kg·°C
ρ_{Air} = Density Air, 1.173 kg/m^3
ρ_{Water} = Density Water, 999.7 kg/m^3
η = Fan or Pump Efficiency
η_{Pump} = Pump Efficiency, 0.65
$\dot{V}$ = Volumetric Flow Rate (m^3)
H = Head Loss (m)
g = Gravitational Acceleration 9.81 m/^{2}
$\dot{Q}_{NetSensible}$ = Net Air Handler Cooling Power (kJ·sec)



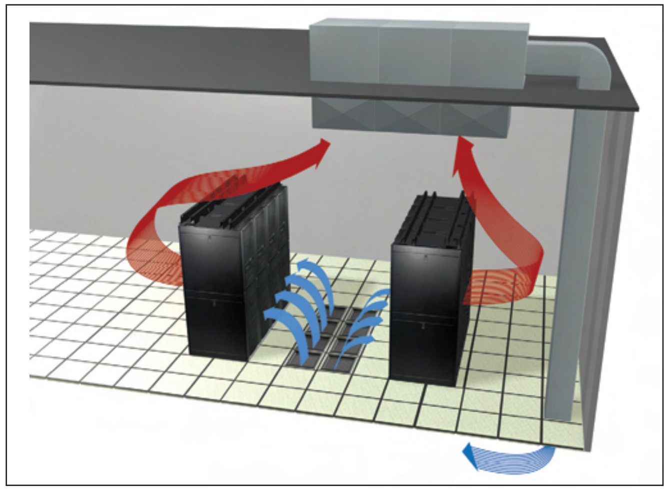


Figure 1 (left): Perimeter computer room air handlers (CRAH). Figure 2 (right): Rooftop units.

$\dot{Q}_{Demand}$ = Architecture Specific Total Chiller Load (kWh)
λ_J = Power Ratio Chiller, Consumed/Load (kWh/kWh)
β_J = Bin Data Condenser Water Temperature (hr)

Equations Used

$\text{Power}_{\text{Shaft}} = \left(\dot{V}_{Air} \cdot \rho \cdot g \cdot H\right) / \left(\eta \cdot 1000\right) [\text{kW}]$ applies to fans or pumps (2)

$$\text{LAT} = \text{EAT} - \dot{Q}_{NetSensible} / \left(\dot{V}_{Air} \cdot \rho \cdot Cp_{Air}\right) {}^{\circ}\text{C}\left({}^{\circ}\text{F}\right) \quad (3)$$

$$\text{Power}_{\text{Chiller}} = \sum_{J=1}^{8} \left(\dot{Q}_{Demand} \cdot \beta \cdot \lambda_J\right) / 8,760 \; [\text{kW}] \quad (4)$$

General Considerations for Comparison

The architectures considered here include CAHUs, perimeter floor mounted CRAHs, and in-row air handlers (IRAHs). This study focuses only on sensible cooling requirements for the IT equipment and excludes considerations regarding space humidity control (dehumidification and or humidification).

The reader should be cautioned that architectures using CAHU and CRAH equipment have lower sensible heat ratios than the IRAH, and likely require additional energy consumption to maintain space humidity requirements.

Ultimately, the primary metric driver becomes the characteristic efficiencies of the three air delivery and distribution methods used by the specific architectures.

The theoretical data center used for this evaluation has an actual heat release by IT equipment and lighting set at 0.75 MW. The chilled water cooling source for the IT loads, lighting, and air-handlers is supported by a vapor compression chiller, using screw compressor technology outfitted with an inverter drive. This chiller supplies a constant 45°F (7°C) chilled water supply for all three architectures considered. The heat of rejection of said chiller is removed by cooling tower water.

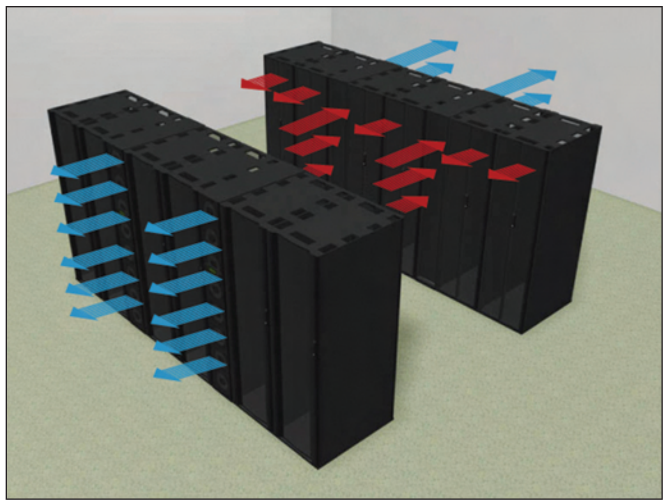


Figure 3: Row-based cooling. Row-based cooling architecture, as depicted, uses a free air discharge without ducting or any containment of hot or cold airstreams.

The water temperature from the cooling tower can track ambient environmental wet-bulb temperature down to a minimum tower leaving fluid temperature of 55°F (13°C). The leaving tower temperature for given wet-bulb bin temperatures is determined from cooling tower performance curve for 100% design flow with 10°F (–12°C) temperature range line.[1] The combination of inverter compressor drive and lower condenser water temperatures allows for significant chiller efficiency gains during periods of low chiller lift.

For the purpose of this comparison, the bin wet-bulb hours for St. Louis shall be considered. The resulting condenser water leaving fluid temperature bin hours are depicted in *Table 1*.

While many condenser water systems may vary the condenser water flow as a function of chiller load, this study shall maintain full design condenser water flow to further enhance performance/efficiency of the chiller. The duty cycle of the

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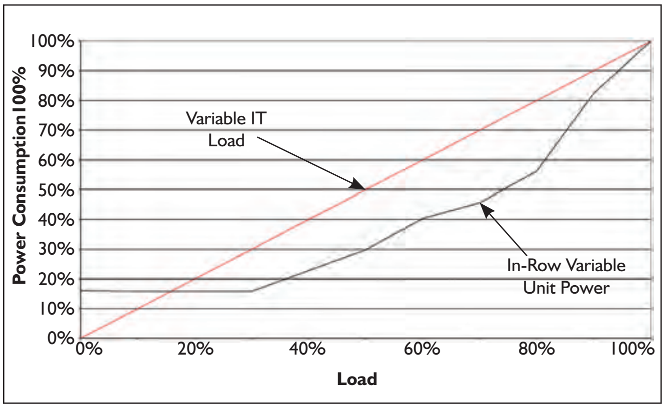

Figure 4: Variable speed fan electrical consumption. Note: Energy savings from variable airflow may not be recognized by all row-based cooling systems. This feature is specific to systems incorporating a variable speed control algorithm.

°F	J	Hours β_J
85.1 – 90.0	1	194
80.1 – 85.0	2	916
75.1 – 80.0	3	1,353
70.1 – 75.0	4	894
65.1 – 70.0	5	1,041
60.1 – 65.0	6	932
55.1 – 60.0	7	1,234
55.0	8	2,196
Total		8,760

Table 1: Condenser water bin hours.

cooling tower fans shall be adjusted accordingly to the demand factor placed upon the chiller by the various cooling architectures considered.

Table 2 establishes the performance of the central chiller in terms of kWh consumed versus kWh load. The particular chiller selected has exceptionally high part load and low lift efficiencies. This was a deliberate choice to avoid possible exaggeration of downstream efficiency gains between the various cooling architectures. Less efficient selections downstream of the air handler (chiller, pump, and cooling tower) will magnify overall power consumed by increased fan loads. Chiller power ratios (λ) with condenser water temperature greater than 85°F (29°C) have been extrapolated. Errors introduced by this method are minimal, as operating hours beyond this temperature account for only 3% of total hours.

The chilled water circulating loop shall have a base loss of 40 ft (12 m) of head allowed for facility piping and chiller, and shall be summed with the air-handler losses for the specific cooling architectures. The chilled water flow rates shall be set at the value required for the specific cooling architecture.

In-Row Air-Handler (IRAH)

As previously mentioned, an alternate method and emerging cooling architecture for IT loads is to intersperse air-handling units within rows containing racks housing the IT loads. These air handlers are designed for this application with special control algorithms to maximize the stability of the thermal environment. Typically, these air handlers are small, allowing nearly ideal capacity resolution versus IT loads. Additionally, placement within the IT

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°F	J	λ_J
85.1 – 90.0	1	0.18
80.1 – 85.0	2	0.16
75.1 – 80.0	3	0.14
70.1 – 75.0	4	0.12
65.1 – 70.0	5	0.11
60.1 – 65.0	6	0.09
55.1 – 60.0	7	0.08
55	8	0.07

Table 2: Chiller performance versus water temperature.

Cooling Component	IRAH	CRAH	CAHU	Units
AHU Fan Power	30.6	88.0	83.2	kW
Chilled Water Pump Power	10.2	11.0	11.1	kW
Mean Chiller Power (from *Equation 4*)	83.9	94.7	94.2	kW
Condenser Pump Power	18.5	18.5	18.5	kW
Cooling Tower Power	16.2	18.3	18.2	kW
Mean Total Cooling Power	159.30	230.50	225.10	kW
$Efficiency_{Metric}$ (from *Equation 1*)	0.21	0.31	0.30	
Annual Cooling Operating Cost	139,572	201,878	197,211	$ USD

Table 3: Cooling infrastructure power consumption.

rows minimizes the mixing of air and allows a much greater percentage of air delivered from the air handler to have first-pass opportunity through the IT loads.

IRAH Unit Specifications[2]

- 2,900 cfm (1369 L/s) at free discharge
- Sensible Cooling: 25.2 kWh at 95°F DB and 67.7°F WB (35°C DB and 20°C WB)

- Sensible Heat Ratio: 1.0
- Chilled Water Flow: 17.9 gpm at 25 ft of head (1.13 L/s) at 8 m of head)
- Leaving Air Temperature: 67.4°F (19.7°C) (from Equation 3)
- Fan Power: 1 kWh (published manufacturer data, all losses included)
- CW Pump Power: 0.34 kW (from Equation 2)

The theoretical data center load of 0.75 MW would require 30 IRAH units, adding an additional 30.6 kW fan power plus 10.2 kW chilled water pump power above and beyond the 750 kW IT and lighting load. This scenario yields a total chiller load of 791 kW.

Computer Room Air Handler (CRAH)

Presently, common practice for reducing first-time capital expense of perimeter cooling solutions leverages the largest practical and commercially available cooling equipment. An unfortunate consequence of using large capacity boxes is a reduction in capacity resolution.

An additional consideration for CRAH units is the fan placement within the air-distribution path. These fans are placed in the bottom of the CRAH unit with little or no outlet transition into the raised floor plenum. The consequence is a fan outlet system effect[3] that adds a significant static effect on fans. This effect is a function of blast area, outlet area, velocity, and transition length. The outlet system effect is often overlooked and frequently may result in products as installed delivering less than anticipated airflow quantities.

The theoretical CRAH depicted below has a net sensible cooling capacity of 102 kWh versus the 750 kWh for the combined IT and lighting load. In this case, full capacity without redundancy would require 7.3 CRAH units per the below specification. The IT load being considered requires eight CRAHs with an immediate over-provisioning factor of 1.09 times the base load.

CRAH Unit Specifications

- 17,100 cfm at 0.3 in. w.c. (8070 L/s at 75 Pa) floor pressure
- Sensible Cooling: 113 kWh at 75°F (24°C) DB, 45% RH, 61°F (16°C) WB
- Sensible Heat Ratio: 0.95
- Chilled Water Flow: 81 gpm at 18 ft of head (5 L/s at 6 m of head)
- Fans (3x) $Power_{Shaft}$: 3.2 kWh each (from Equation 2)
- Forward Curve 15 in. × 15 in. (38 cm × 38 cm) double inlet, double-width (DIDW)
  - Blast Area = 0.81 ft × 1.55 ft = 1.26 ft^2 (0.25 m × 0.47 m = 0.12 m^2)
  - Outlet Area = 1.32 ft × 1.55 ft = 2.05 ft^2 (0.40 m × 0.47 m = 0.19 m^2)
  - BA/OA = 1.26 ft^2/2.05 ft^2 = 0.61 (0.38 m^2/0.62 m^2 = 0.61)
  - Static Efficiency: 0.59
  - Outlet Velocity: 2,800 fpm (14 m/s)
  - Outlet System Effect: 0.6 in. w.c. (149 Pa)
  - Floor Pressure: 0.3 in. w.c. (75 Pa)
  - Filter Loss: 0.75 in. w.c. (187 Pa)
  - Coil Loss: 0.65 in. w.c. (162 Pa) (wet)
  - Cabinet Loss: 0.5 in. w.c. (125 Pa)
- Motor Power: 11.0 kW (0.92 motor efficiency × 1.05 drive loss)
- Net Sensible Cooling: 102 kW
- Leaving Air Temp: 56°F (13°C) (from Equation 3)
- Chilled Water Pump Power: 1.4 kW (from Equation 2)

The above eight CRAH units combined would add an additional 88 kW fan power plus 11.2 kW chilled water pump power above and beyond the 750 kW IT and lighting load. This scenario yields a total chiller load of 893 kW at a sensible heat ratio of 0.95.

CAHU

Most applications using central air handlers will have custom air handler units designed and built for the specific project. The wide variation of design practices and component selection make it difficult to express performance data in absolute terms. The values used herein are for purpose of comparison and are believed to reasonably represent nominal values. However, some variation should be anticipated.

The reader may notice that a significant contribution to the CRAH fan losses from above, outlet system effect, is missing in the below CAHU example. This is possible due to physical geometry of custom air handlers allowing better practice regarding fan placement and operation. Unfortunately, in many cases the gains from reducing and or eliminating blower outlet system effects are frequently offset by increased pressure losses in delivery system: ducting, elbows, and diffusers.

The theoretical data center load of 0.75 MW will require a quantity of four CAHUs per the below specification without any redundancy. With the CAHU being custom built equipment the amount of over provisioning can be carefully controlled allowing only for the desired factor of safety.

CAHU Specifications

- 34,000 cfm at 1.0 in. w.c. (16 046 L/s at 249 Pa) external static pressure
- Sensible Cooling: 220 kWh at 75°F (24°C) DB, 45% RH, 61°F (16°C) WB
- Sensible Heat Ratio: 0.95
- Chilled Water Flow: 158 gpm at 20 ft of head (10 L/s at 6 m of head)
- Fans (2x) $Power_{Shaft}$: 9.1 kW each (from Equation 2)
  - 76 cm backward-inclined, double-width (BIDW)
  - Outlet Velocity: 1,825 fpm (9 m/s)
  - Static Efficiency: 0.66
  - Return Air Duct: 0.3 in. w.c. (75 Pa)
  - Filter Loss: 0.75 in. w.c. (187 Pa)
  - Coil Loss: 0.60 in. w.c. (149 Pa) (wet)

– Cabinet Loss: 0.35 in. w.c. (87 Pa)
– Supply Duct Loss: 1 in. w.c. (249 Pa)

- Motor Power: 20.8 kW (0.92 motor efficiency × 1.05 drive loss)
- Net Sensible Cooling: 56.8 tons (200 kW)
- Leaving Air Temperature: 56.3°F (14°C) (from Equation 3)
- Chilled Water Pump Power: 2.8 kW (from Equation 2)

The above four CAHUs combined would add an additional 83.2 kW fan power plus 11.2 kW chilled water pump power above and beyond the 750 kW IT and lighting load. This scenario yields a total chiller load of 888 kW at a sensible heat ratio of 0.95.

Conclusion

The annual electrical cost of three cooling architectures: IRAH, CRAH, and CAHU are given respectively $139,572, $201,878, and $197,211 (at $0.10/kWh). Of course, the magnitude of savings would vary due to chiller plant efficiency, utility cost, and base IT and lighting loads. The row-based cooling architecture versus the other two choices affords a two-thirds reduction in fan power consumed by cooling equipment, with additional savings compounded throughout the entire downstream cooling infrastructure.

Although row-based cooling has a sizable advantage in operational cost savings, it will not be a silver bullet for all applications. Certainly, there are far more existing data centers than new ones being built, and it is likely that a mix of cooling architectures, including all of the above mentioned, will be deployed within the same data center. As data centers evolve and densities increase, a hybrid approach to cooling various density heat loads is the likely result. However, new data center space (whether expansion or entirely new) should always consider row-based cooling for the best energy efficiency and predictability whenever possible.

Acknowledgments

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Kevin has participated on numerous power management and cooling panels, as well as on industry consortiums and ASHRAE committees for thermal management and energy efficient economizers.