Indirect Air-Side Economizer Cycle

Data Center Heat Rejection

By Keith Dunnavant, P.E., Member ASHRAE

The electric power consumed to manage our digital dependency is growing, and so is the resulting by-product: heat. HVAC engineers are tasked with selecting mechanical systems that strike a balance between high reliability and low life-cycle cost. This article explores a cooling/heat rejection strategy that is gaining acceptance and achieves a balance of reliability and energy efficiency.

Indirect Air-Side Economizer

The indirect air-side economizer (IASE) cycle uses outdoor air to reject heat, but the outdoor air never enters the process or space. The IASE uses an air-to-air heat exchanger (HX) to transfer data center heat to a separate outdoor airstream ("scavenger air"). *Figure 1* illustrates one type of IASE system that uses a plate-type air-to-air HX.

In *Figure 1* scavenger outdoor air enters the unit and flows through one side of an air-to-air HX (enters from lower right). Warm air from the data center hot aisles enters from the other side (upper left) of the unit and flows through the opposite side of the air-to-air HX, completely separated from the scavenger air by sealed HX plates. As the hot-aisle air flows through the HX, it transfers heat to the cooler scavenger outdoor air. The scavenger air may be used untempered, or the scavenger air may be evaporatively cooled prior to entering the HX. Evaporative precooling (*Figure 1*) significantly enhances heat rejection potential when a wet-bulb depression (difference between the dry-bulb and wet-bulb temperature) exists of 10°F (5.6°C) or more.

Why Indirect?

Intuition suggests it's more efficient to use a direct air-side economizer and introduce outdoor air directly into the data hall. The IASE provides some key advantages that may not be readily apparent. Refer to the IASE system in *Figure 2* as you read the following list of benefits.

Benefits of the IASE

Because the data hall air is recirculated and cooled with IASE systems, and no outdoor air is introduced into the data center by the heat rejection units, filters may be eliminated from some or all of the heat rejection air-handling units (AHUs). Particulate removal may be accomplished by using a side-stream filtration unit, or filters may be included in some of the IASE units, such that the room air is filtered at a rate of perhaps 6 to 10 air changes per hour (ach). This approach results in reduced filter, maintenance, and fan power costs compared to installing filters on all of the heat rejection units,

---

About the Author

Keith Dunnavant, P.E., is a sales engineer and data-center cooling specialist for Munters, Buena Vista, Va.

which often have air turnover rates in excess of 100 ach.

Since outdoor air is not introduced into the space by the heat rejection units, there is reduced risk of outdoor air pollutants[1] adversely affecting the information and communication technologies (ICT) equipment. Also, space humidity and pressure are not impacted, resulting in the potential to lower humidification costs and maintain more stable moisture levels in the data hall.

Single, or multiple makeup air units, with MERV 8 and MERV 13 filters, equipped with dehumidification and humidification capability as required by the local climate, provide the recommended ventilation[2] (0.25 ach has been recommended as the minimum) and humidity control. Humidification may be accomplished using direct evaporative media with heat from the return air. The IASE units are laser focused on one objective: heat rejection.

Unlike water-side[3] and wet-bulb[4] economizer systems, IASE systems may operate dry during cooler ambient conditions, resulting in lower annual water consumption and elimination of freeze concerns. IASE systems are able to achieve 100% heat rejection operating dry when outdoor air temperature is below 48.5°F (9.2°C) using HXs that are 50% effective, or 66.2°F (19°C), using HXs that are 75% effective (based on a hot aisle temperature of 101.5°F [38.6°C], cooling to 75°F [23.9°C]).

Modulating mixed air dampers and relief fans/dampers are not required as part of the heat rejection cycle. IASE systems achieve supply temperature control by varying scavenger fan flow and staging/modulating DX or modulating chilled water valves.

IASEs, using scavenger air evaporative cooling, require about one-third of the water flow rate of conventional water-side economizer systems, and operate with less pump head, resulting in annual pump power savings. IASE systems, using wetted HXs (described later in the article), require a maximum recirculating water flow rate of 2 gpm (0.13 L/s) per 1,000 cfm (471.9 L/s) of supply air and require a pump head of 30 ft (9.1 m). IASE systems using dry HXs with direct evaporative media installed in the scavenger airstream have even lower flow rate and pump head requirements. IASE systems require no pump energy during cooler ambient conditions. Contrast this with an open water-side economizer (direct tower to coil), providing 25°F (13.9°C) of air-side sensible cooling, taking a water-side temperature rise of 10°F

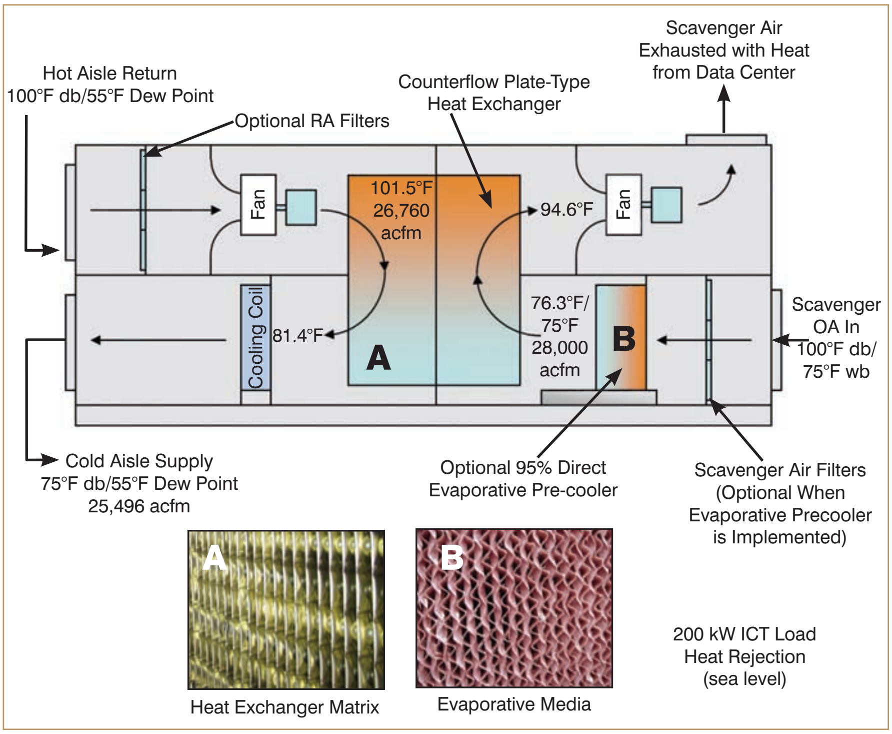

Figure 1: Indirect air-side economizer (dry HX).

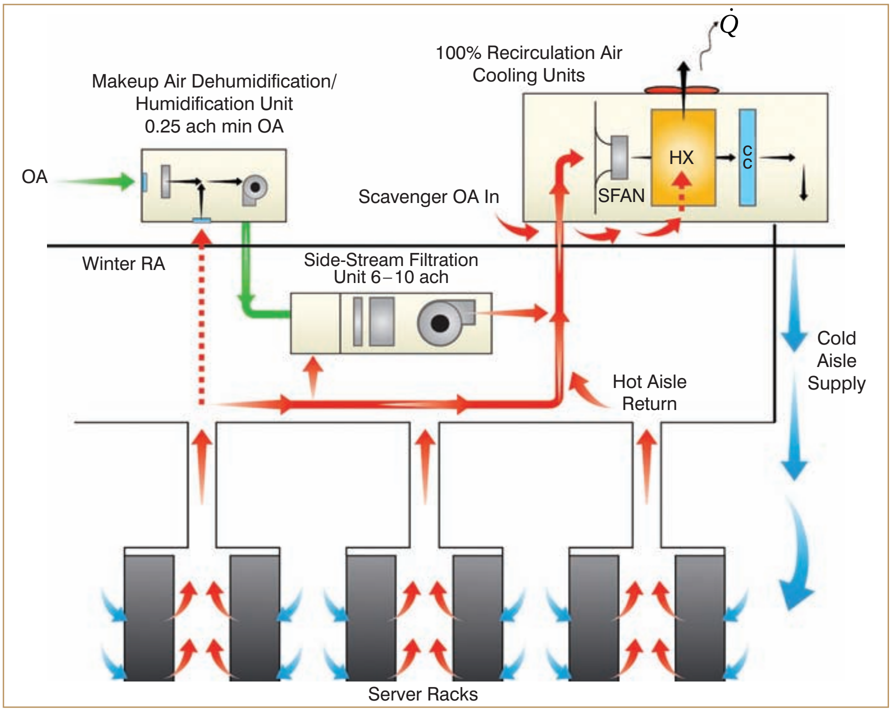

Figure 2: Data center air management.

(5.6°C). Such a water-side economizer requires approximately 5.5 gpm (0.35 L/s) per 1,000 cfm (471.9 L/s) at sea level and may require 100 ft (30.5 m) of pump head, or more, depending on the installation.

When integrated with scavenger air evaporative cooling, refrigeration capacity may be significantly reduced on IASE systems in virtually all climates, which is not true of conventional direct air-side economizers or wet-bulb economizer installations that require supply air dew point to be maintained below the current allowable value for Class I environments of 63°F (17.2°C).

IASE units have a rapid restart after power outage with little delay reaching full heat rejection potential.

Scavenger Air Entering HX			Scavenger Air		Supply Air
Dry-Bulb (°F)	**Wet-Bulb (°F)**	**Flow (cfm)**	**Leaving HX Dry Bulb (°F)**	**HX Pressure Drop (In. w.c.)**	**Leaving HX* (Dry Bulb [°F])**
90	85	28,000	98.5	0.61	92.4
80	78	28,000	95.7	0.63	84.4
70	69	28,000	92.8	0.65	76.3
65	64	22,500	94.4	0.44	75
60	59	18,100	96.3	0.30	75
50	49	13,350	98.3	0.18	75
40	39	10,665	99.3	0.12	75
30	29	8,875	99.9	0.09	75
20	19	7,580	100.3	0.07	75
10	9	6,585	100.6	0.06	75
0	–1	5,800	100.8	0.05	75
–10	–11	5,160	100.9	0.04	75
–20	–19	4,625	101.0	0.03	75
–30	–30.5	4,175	101.1	0.03	75

Note: Hot-aisle entering (including fan heat) = 101.5°F; 200 kW ICT load heat rejection; supply airflow entering HX = 26,760 acfm; supply-side HX pressure drop = 0.56 in. w.c.
* Scavenger airflow varies to maintain target supply air dry bulb = 75°F

Table 1: Dry HX performance at various ambient conditions.

Dry HX IASE System

Referring back to *Figure 1*, when a HX with an effectiveness of 80% is selected and a 95% efficient direct evaporative pre-cooler is used, most of the ICT load from a data center may be rejected to ambient air through the HX, even during a hot and humid ambient condition as indicated on the figure. Given a 100°F (37.8°C) hot-aisle temperature and 75°F (23.9°C) target cold-aisle temperature, whenever the outdoor air dry-bulb temperature is 68.4°F (20.2°C) or lower, the IASE cycle can reject 100% of data center heat (assumes 1.5°F [0.83°C] rise across supply fan). Similarly, when a 95% efficient scavenger air evaporative pre-cooler is included, 100% of data center heat may be rejected by the IASE cycle if the ambient wet-bulb temperature is 65°F (18.3°C) or lower, regardless of how hot the corresponding ambient dry-bulb temperature may be.

Table 1 shows how the counterflow plate-type HX IASE system performs at various ambient conditions. Note that the required scavenger airflow falls rapidly with decreasing ambient dry-bulb entering temperature. At an ambient dry-bulb temperature of only 50°F (10°C), the scavenger flow has dropped by more than 50% of its design flow, and corresponding scavenger-fan motor power is reduced to less than one-eighth of the power consumed at design condition.

Table 2 shows the annual hours in a typical year (as defined by TMY2 weather data) where an 80% effective HX augmented with a 95% efficient scavenger air evaporative pre-cooler can cool hot-aisle air from 101.5°F (38.6°C), including supply fan heat, to 75°F (23.9°C). Note that the IASE cycle rejects 100% of data center heat for almost 80% of annual hours in Atlanta. In Salt Lake City, the IASE cycle rejects 100% of data center heat for 99.98% of annual hours. If server inlet temperatures are allowed to occasionally rise to the upper end of the recommended range, refrigeration may be eliminated from data center heat rejection systems in many cities around the globe.

City	Hours	Percent of Annual Hours
Albuquerque, N.M.	8,759	99.99%
Atlanta	6,943	79.26%
Baltimore, Md.	7,416	84.66%
Boise, Idaho	8,760	100.00%
Boston	8,302	94.77%
Chicago	8,085	92.29%
Boulder, Colo.	8,759	99.99%
Fort Worth, Texas	5,937	67.77%
Las Vegas	8,474	96.74%
Los Angeles	8,697	99.28%
Minneapolis	8,104	92.51%
Phoenix	7,391	84.37%
Portland, Ore.	8,742	99.79%
Salt Lake City	8,758	99.98%
San Francisco	8,755	99.94%
Seattle	8,755	99.94%

Note: Computed from TMY2 weather data. 101.5°F (allows for 1.5°F of fan heat) hot aisle cooling to 75°F cold aisle.

Table 2: Annual hours where an IASE using an 80% efficient dry HX with a 95% efficient DEC scavenger air pre-cooler rejects 100% of data center heat.

Polymer-Tube Indirect Air-Side Economizer

Another type of IASE uses a horizontal polymer-tube heat exchanger[5] (*Figure 3*). With this design, outdoor scavenger air is drawn across the exterior of elliptical tubes, which are wetted by a recirculation water pump. The elliptical shape of the heat exchanger tubes maximizes the allowable surface area for heat rejection and is sufficiently elastic such that its subtle expansion and contractions, resulting from normal operation, aid in the shedding of residual solids that are a by-product of evaporation. With scavenger air flowing over the wet exterior tube surfaces, evaporative heat transfer efficiently cools the data center hot aisle air flowing through the inside of the tubes.

Although only 45% to 51% effective when operating dry, when the outside of the polymer-tube HX (*Figure 3*) is wetted, the HX is able to provide 70% to 80% wet-bulb depression effectiveness (WBDE), as an indirect evaporative cooler. WBDE is a measure of the approach of the hot-aisle dry-bulb temperature to the outdoor air wet-bulb temperature. Using a 75% WBDE HX design, 100% of data center heat may be rejected solely using indirect evaporative cooling (IEC) whenever the ambient wet-bulb temperature is 66.2°F (19°C) or lower, based on a hot aisle temperature, after recirculation fan heat, of 101.5°F (38.6°C) cooling to a target cold-aisle temperature of 75°F (23.9°C).

Figure 4 shows the scavenger-side pressure drop and WBDE as a function of the HX's rated flow for the condition of recirculation air entering at 101.5°F (38.6°C) dry bulb at 55°F (12.8°C) dew point and with scavenger air entering at 73°F (22.8°C) dry bulb at 65°F (18.3°C) wet bulb (HX designed for a target 70% WBDE). When the HX operates with recirculation and scavenger air flowing at design (1 times rated value), the scavenger-side pressure drop is 0.33 in. w.c. (82.1 Pa), and the WBDE is 70.2%. Holding the recirculation flow constant at design, if the scavenger airflow is reduced to 0.4 times design, the resulting scavenger-side pressure drop will be just over 0.06 in. w.c. (14.9 Pa), and the WBDE will be just over 52.5%. Because the WBDE declines slowly as scavenger flow is reduced, the scavenger fan flow and corresponding power consumption rapidly drop as the ambient wet-bulb temperature falls.

The scavenger fans operate at low capacity for most operating hours. To better quantify this statement, consider an IASE system operating in Chicago, with a hot-aisle condition (after supply fan heat) of 101.5°F (38.6°C) dry bulb at 55°F (12.8°C) dew point, and with a target cold-aisle deliv-

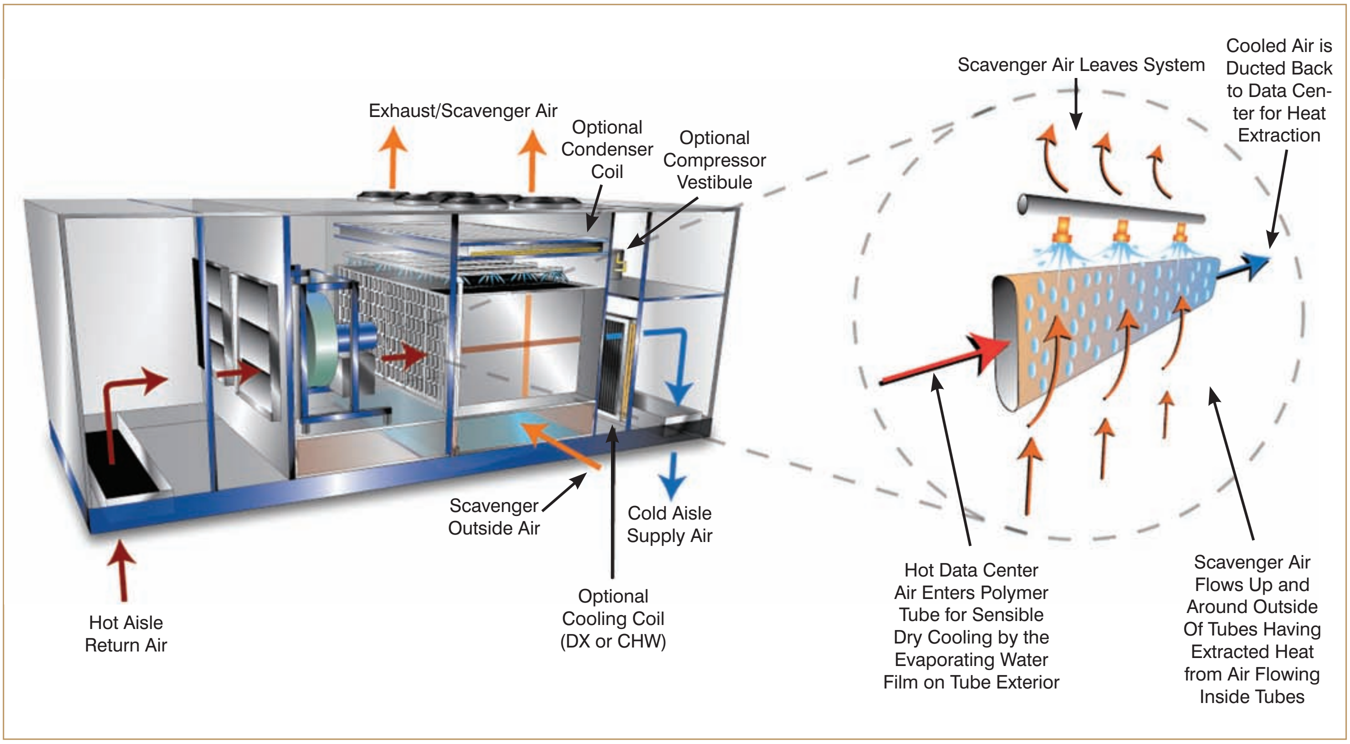

Figure 3: Polymer-tube indirect air-side economizer (wet HX).

ery condition of 75°F (23.9°C) dry bulb. For this system, the scavenger fans operate at less than 75% of design flow for a calculated 79.7% of annual hours, and at less than 50% of design for 41.6% of annual hours. Fan power reduces approximately in relation to the cube of the flow, so at 50% of flow, the bhp is reduced to one-eighth of the design value. Since the scavenger-side pressure drop at design is a very low 0.33 in. w.c. (82.1 Pa), the scavenger fan motors consume less power than relief fan motors consume with many conventional direct air-side economizer designs.

System Design and Energy Modeling

To facilitate IASE system design, and to predict annual cost of operation, including water consumption, a detailed mathematical model is required. There are four elements of power consumption that must be accounted for in modeling an IASE system:

- Power to circulate the primary air;
- Power to transport the scavenger air that rejects the heat from the system;
- Pump power (when evaporative cooling is used); and
- Power for supplemental refrigeration, DX or chilled water (when required).

In addition to the electrical power, water consumption including evaporation, bleed, and periodic sump flush cycles must all be taken into account.

Figure 5 shows how the scavenger fan flow for an IASE system using a wetted polymer-tube HX is predicted to vary with the ambient wet-bulb temperature for a 1,500 kW data center operating in Chicago. The hot-aisle temperature applicable to this figure is 101.5°F (38.6°C) after fan heat, and the target cold-aisle temperature is 75°F (23.9°C). At the 47°F wet-bulb bin condition, the scavenger fans are operating at a predicted 34% of maximum speed, and 239 annual hours are at this bin condition, based on TMY2 weather data.

Figure 6 applies to the same 1,500 kW data center operating in Chicago. This figure shows the power consumption as a function of ambient WB for each component in the horizontal polymer-tube IASE system. At the peak ambient wet-bulb bin of 79°F (26.1°C), which occurs at a mean coincident dry-bulb (MCDB) temperature of 85.8°F (29.9°C), refrigeration is the greatest single consumer of power. In this example, the refrigeration is assumed to operate at a fixed rate of 0.8 kW/ton. At this operating point, the indirect evaporative coolers reject 293.7 tons (1033 kW) and the total supplemental refrigeration required is 159.2 tons (560 kW). Note that even at this high wet-bulb condition, the HX is still rejecting 64.8% of the total load. Upon reaching the WB bin of 65°F (18.3°C), which occurs at a MCDB of 73°F (22.8°C), refrigeration is off.

Continuing with *Figure 6*, there are 334 annual hours at the wet-bulb bin of 59°F (15°C), and the total power consumption is calculated to be 109.7 kW. At this point, the IASE system is rejecting 1,500 kW of ICT load using only 109.7 kW. This results in a system EER of 49.6. By computing the EER at each bin condition, and weighing that against the number of operating hours at that bin, it is possible to calculate a SEER for the IASE system, which in this example is 49.3, when operating with N units. Under normal conditions

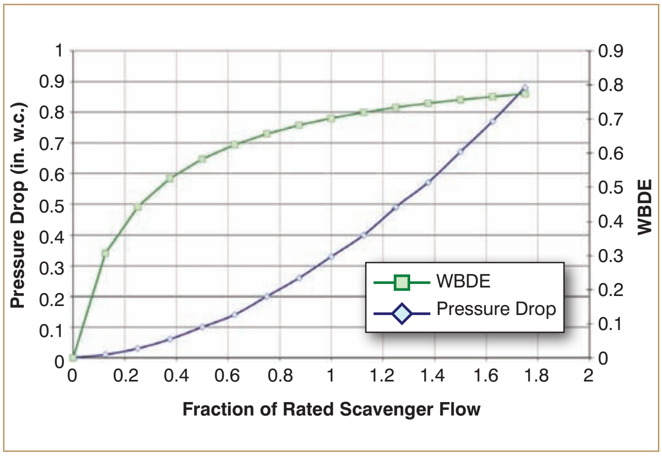

Figure 4: Polymer HX performance (wet for IEC) vs. fraction of design rated flow.

with N+1 units operable, the SEER increases resulting from the lower pressure drop and greater efficiency from having the redundant and essential units run in tandem.

A more meaningful metric of heat rejection effectiveness applicable to data centers is the coefficient of performance (COP), obtained by multiplying the EER by 0.293, or if fan heat is neglected, simply by dividing the ICT power by the power consumed by the heat rejection equipment to reject this heat. Using the above example, 1,500 kW ICT load divided by 109.7 kW to reject the heat = 13.7 = COP neglecting fan heat. When fan heat is included in the computation, the COP increases to 14.5.

It is apparent from *Figure 6* that the supply fan motors are the largest single contributor to the total power consumed in rejecting the data center heat. The total static pressure for the supply fans in this example is 2.59 in. w.c. (644.5 Pa), which is the sum of the HX pressure drop (0.74 in. w.c. [184 Pa]), the cooling coil (0.15 in. w.c. [37 Pa]), AHU system losses (0.2 in. w.c. [50 Pa]), and the external static pressure resulting from the return and supply connected ductwork (1.5 in. w.c. [374 Pa]). Filter pressure drop is not included here for reasons already explained. The supply fan static efficiency is 74% in this example, and the supply fan motors operate at 93% efficiency.

The above internal pressure drops are the values that result when a unit is down for servicing, and the system is operating with N units in an N+1 configuration. When all units are operational, the internal pressure drops and resulting power is lower, the specific reduction amount being dependent on the number of units installed. Clearly, the best way to improve the efficiency of an IASE system, or any data center cooling system, is to design the heat exchanger and duct system for low pressure drop.

Figure 6 shows that the power contribution from the scavenger fan motors is very low for most of the operating hours. In this example, scavenger fans have been selected with a static efficiency of 70%, and the motors operate at 90% efficiency at full speed. The power consumed by the water pumps is conservatively estimated at 0.052 kW per 1,000 cfm (471.9 L/s) of process (supply) air. In this model, the pumps are deactivated at a dry-bulb temperature of 35°F (1.7°C).

Polymer-tube IASE operating in Chicago; 1,500 kW ICT load, 75°F cold-aisle/101.5°F hot-aisle (after supply fan heat). 452.9 tons of total heat rejection, supply fan heat included.

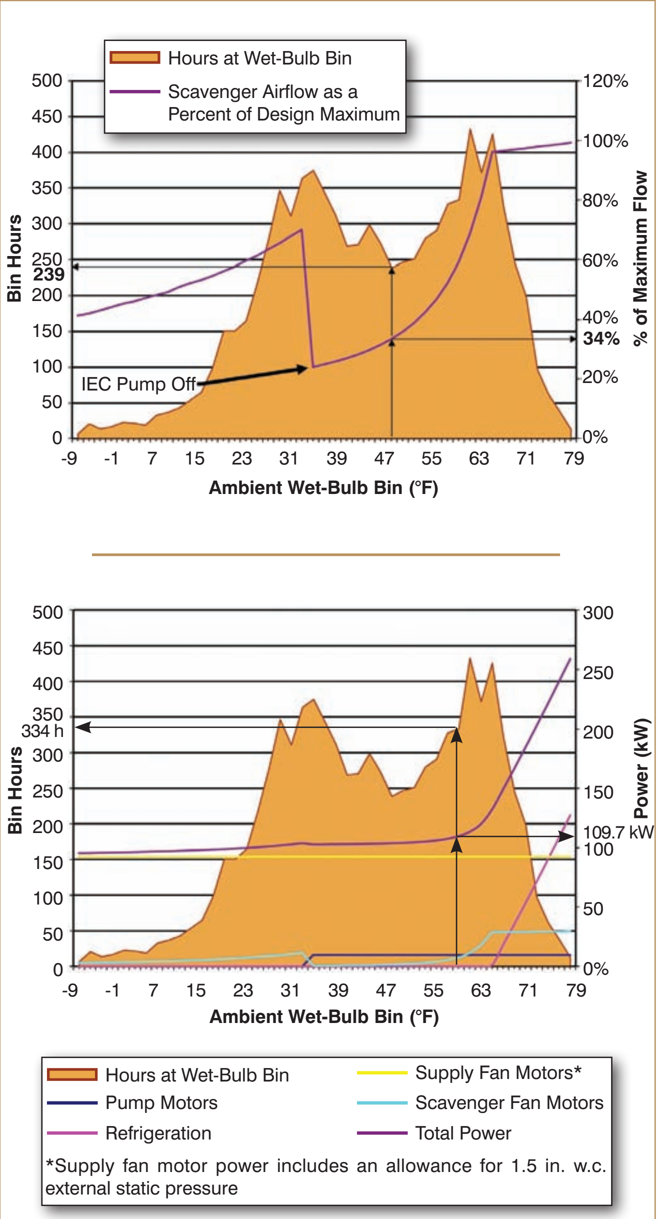

Figure 5 (top): IASE scavenger airflow (percent of design maximum) versus ambient wet-bulb temperature. **Figure 6 (bottom):** IASE power consumption versus ambient wet-bulb temperature.

The total annual energy used by the IASE system as described in *Figure 6*, rejecting the 1,500 kW ICT load operating 24/7, is predicted to be 996,900 kWh. At a cost of $0.10/kWh, this translates to an annual electric power cost of $99,690.

Cooling Coil and Refrigeration Sizing

Figure 7 shows the design performance of the polymer-tube IASE system operating to reject an ICT load of 1,500 kW in Chicago. Five units total are selected for the duty, operating in an N+1 configuration. The system design is based on N units active, which for this example equals four. 51,272 acfm (24 198 L/s) of hot-aisle return air at 100°F (37.8°C) dry bulb at 55°F (12.8°C) dew point enters each of the four IASE units. The hot aisle air enters the supply fan, resulting in a 1.5°F (0.83°C) rise in dry-bulb temperature, before entering the polymer-tube HX. Operating at a selected design ambient condition of 95°F (35°C) dry bulb/82°F (27.8°C) wet bulb, the wetted HX cools the air to 86.5°F (30.3°C), rejecting 64.3 tons of load per unit. This heat is transported away by 56,574 acfm (26 700 L/s) of scavenger air per unit leaving at a predicted condition of 87.3°F (30.7°C) db /90% RH. The combination of water evaporated and bleed off water, based on three cycles of concentration, is 198.5 gph (751.4 L/h) per unit at this operating condition. Water evaporated is 132.3 gph (500.8 L/h) per unit, which equates to 2.06 gph (7.8 L/h) per ton of heat rejected by the indirect evaporative coolers.

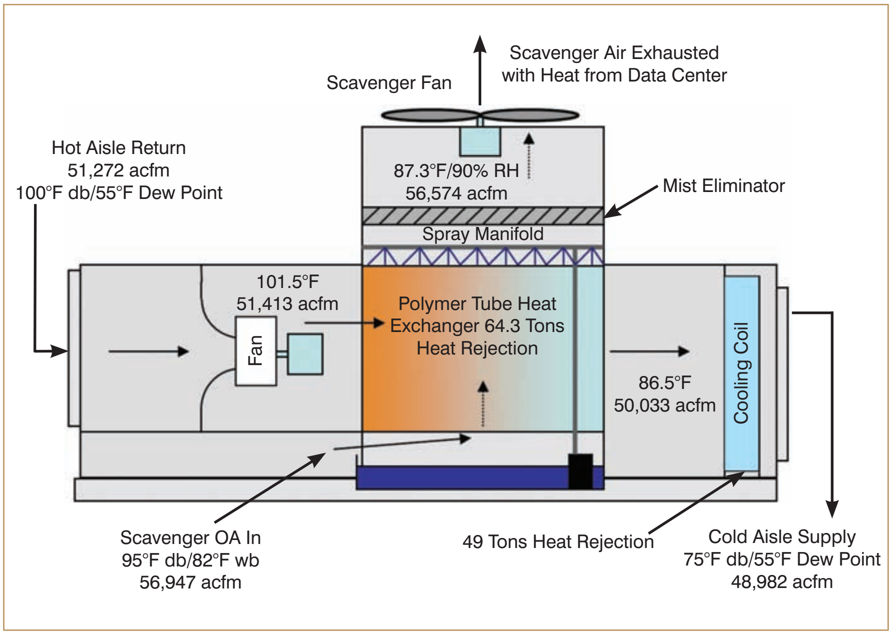

Figure 7: Polymer tube IASE system operating in Chicago (673 ft [205 m] elevation) 75°F (23.9°C) cold aisle/100°F 37.8°C) hot aisle. Four units operating to reject a 1,500 kW ICT load. Performance data above applies to one unit.

After leaving the HX, the process air enters the cooling coil, where an additional 49 tons (172.3 kW) of sensible heat rejection per unit must occur to cool the supply air to 75°F (23.9°C). Sizing the refrigeration component based on this conservative Chicago ambient design condition results in a comfortable margin of safety. Note that in the event of a complete failure of the refrigeration system, the polymer-tube IASE HX is still capable of rejecting the full ICT load. The equilibrium point of operation occurs at a predicted hot-aisle return temperature of 114.9°F (46.1°C) and a corresponding cold-aisle temperature of 89.9°F (32.2°C), which is still in the range of what is allowable for Class I environments.[6] Some cutting edge data centers already are operating with server inlet temperatures of up to 90°F (32.2°C), and one manufacturer has published a white paper on its experience operating at this condition.[7]

Side Stream Filtration

By configuring IASE units with blow-through, direct drive supply fans, the 100% recirculation air flowing within the air handlers is predominantly under positive pressure, and there is no belt dust generated. As a result, it is not necessary to have air filters within each IASE unit. A better, more energy efficient approach is to install filters into 20% of the units (or as required to ensure filtration at 6 to 10 ach) or integrate the old practice of side stream filtration (SSF) into data center air management. *Figure 2* presents a schematic of a total air management system using IASE heat rejection with the addition of SSF, filtering the data center air at a proposed rate of 6 to 10 ach using a separate AHU with fan and filters. An SSF system, implemented with pre-filters plus MERV 16 filters, has the potential to achieve a more energy efficient filtration system while providing better particulate removal than recommended by ASHRAE.[1] It is suggested that the outdoor air be independently filtered with MERV 8 + MERV 13 filters and then ducted into the SSF system prior to entry into the data center.

The removal of air filters within the IASE units relieves a burden of what is typically estimated at 1 in. w.c. (248.8 Pa) of pressure drop from these heat rejection work horses; this results in a significant reduction in power consumption, amounting to at least 1.65 kW/10,000 cfm (assumes fan static efficiency of 75% and motor efficiency of 95%). Since conventional air-side economizer units must use filtration (ASHRAE recommends MERV 8 + MERV 11 or MERV 13 filters), the recirculating air IASE heat rejection units typically consume less supply fan power than direct air-side economizer units because the total internal static pressure within the polymer-tube IASE units (including the HX and supplemental coil) is typically less than 1 in. w.c. (248.8 Pa). The filters used in the recirculating airstream of an IASE system also load more slowly than those installed in direct air-side economizers,[8] and there are far fewer to change, leading to savings in the annual cost of replacement filters and the labor to change them.

Conclusion

The merits of the IASE strategy presented here are applicable to data centers in almost any locale and are not limited for use in areas perceived to be cold or dry climates. The IASE strategy may be used even when cooler cold-aisle conditions are desired. The 100°F (37.8°C) hot-aisle and 75°F (23.9°C) cold-aisle conditions were used in this article solely as a point of reference, since modern data centers are designed to similar or more aggressive conditions. Clearly, the maximum benefit of the IASE strategy is derived when implemented with hot- or cold-aisle containment, with warmer hot-aisle and warmer cold-aisle temperatures.

Acknowledgments

This article is dedicated to Nick Des Champs, Ph.D., P.E., Fellow ASHRAE, and Mike Scofield, P.E., Fellow ASHRAE. Nick developed the finite-difference heat and mass transfer indirect evaporative cooler model that is an integral part of the system model used to produce the data presented. Mike provided the kick-off of the original effort, and provided encouragement needed to bring the effort to completion. Both contributed ideas and provided valuable support and feedback that helped make this work possible.

Thanks also to Mark Fisher for providing valuable collaboration and assistance with the figures and modeling code, and to Jacqueline McIlrath, Denise Salinas, and Doug Des Champs for assistance with the figures.

References

1. ASHRAE. 2009. “Particulate and Gaseous Contamination Guidelines for Data Centers.” ASHRAE Technical Committee 9.9.

2. Shields, H., C. Weschler. 1998. “Are indoor pollutants threatening the reliability of your electronic equipment?” *Heating/Piping/Air Conditioning Magazine* (5):46 – 54.

3. Yury, Y.L. 2010. “Waterside and airside economizers, design considerations for data center facilities.” *ASHRAE Transactions* 116(1).

4. Scofield, M., T. Weaver. 2008. “Using wet-bulb economizers, data center cooling.” *ASHRAE Journal* (8):52 – 58.

5. Scofield, M., T. Weaver, K. Dunnavant, M. Fisher. 2009. “Reduce data center cooling cost by 75%.” *Engineered Systems*.

6. ASHRAE. 2009. *Thermal Guidelines for Data Processing Environments*, second edition.

7. Atwood, D., J. Miner 2008. “Reducing Data Center Cost with an Air Economizer.” Intel.

8. Quirk, D., V. Sorell. 2010. “Economizers in datacom—risk mission vs. reward environment?” *ASHRAE Transactions* 116(2):9, para.2.⬣