Case Study:

Cabinet Cooling Using a Water and Refrigeration System

Escalating computing capabilities and shrinking chip packages are leading to corresponding increases in server and rack power densities. Cooling the new higher-powered racks is a serious challenge to system designers and data center managers. In the past, designers tried such methods as cabinets with better airflow configurations, adding central air conditioning systems, raising floors and using cold-aisle and hot-aisle layouts. Today, engineers are turning their attention to water-cooled techniques and refrigeration technology to solve cabinet overheating problems.

Many liquid-cooled cabinets are available on the market, based on different cooling methods. IBM has a patented rear door heat exchanger design. Emerson manufactures both water-cooled and refrigeration-cooled cabinets. HP's Modular Cooling System uses chilled water to dissipate heat. This paper will not discuss which company has the best technique for cabinet cooling; rather, it addresses the concept of a liquid-cooled cabinet by simple calculation and comparison.

Consider a cabinet, with dimensions of 2200 x 800 x 1200 mm, containing multiple servers which generate 30 kW of waste heat. The cabinet has a fan tray which delivers 5000 m^3/h (2940 CFM) of airflow to the servers and dissipates 1 kW of heat to move the air. The air temperature at the cabinet inlet is 20˚C (68˚F). The cabinet is supplied with chilled water whose temperature is 12˚C (54˚F) at the inlet. To cool this cabinet, what are the requirements for the heat exchanger and water supply system? If the refrigeration system is used, what are its advantages?

1. A Cabinet with an Integrated Air-Water Heat Exchanger

This configuration sets the baseline of liquid cooling and includes the following cases:

1)A rear-door, air-water heat exchanger which cools the hot air from the cabinet to 20˚C (Figure 1(a)).

2)A sealed cabinet with an air-water heat exchanger inside (Figure 1(b)).

Figure 1 shows the simplest water-cooled cabinet. The rear door heat exchanger design was developed by IBM Corporation. The Figure 1(b) represents the water-cooled cabinet with internal air circulation.

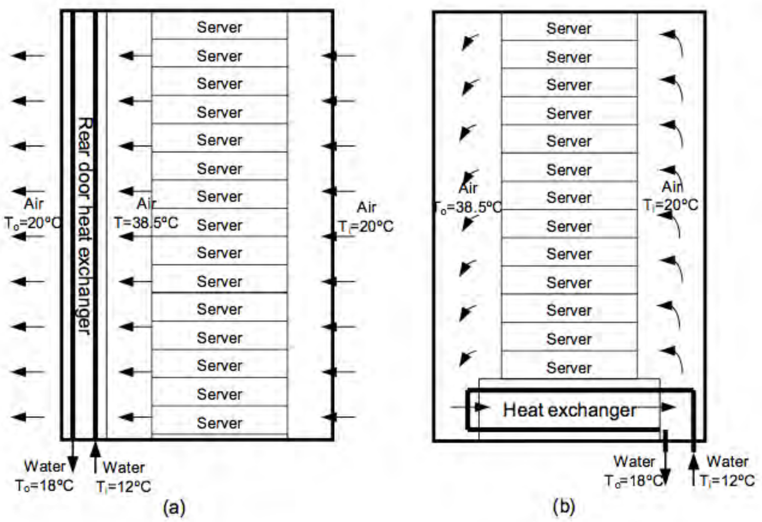

Figure 1. Schematics of a Cabinet with Different Integrated Air-Water Heat Exchangers.

The total heat dissipation of the cabinet (from servers and fan tray) is 31 kW. The average air temperature at the servers' exit is

$$T_{a\_o} = \frac{q}{\rho m_v C} + T_{a\_i} = \frac{31000}{1.2 \times 5000 / 3600 \times 1005} + 20 = 38.5^\circ C$$

Assuming the water temperature at the outlet is 18˚C (64.5˚F), the water flow rate needed to cool the cabinet is,

$$m_V = \frac{q}{\rho C(T_{w\_o} - T_{w\_i})} = \frac{31000}{1000 \times 4200 \times (18-12)} = 0.00123 m^3/s (19.5GPM)$$

The efficiency of the air-water heat exchanger depends on both air and water properties and on the temperature.

For air:

$$C_a = \rho m_V C = 1.2 \times (5000/3600) \times 1005 = 1675 W/°C$$

For water:

$$C_w = \rho m_V C = 1000 \times 0.00123 \times 4200 = 5166 W/°C$$

So the maximum heat the heat exchanger can dissipate is:

$$q_{max} = C_a(T_{a\_i} - T_{w\_i}) = 1675 \times (38.5 - 12) = 44.4kW$$

The heat exchanger's effectiveness is:

$$\varepsilon = \frac{q}{q_{max}} = \frac{31000}{44400} = 0.70$$

With

$$\frac{C_a}{C_w} = \frac{1675}{5166} = 0.32$$

The NTU (number of transfer units) of the heat exchanger (according to [1]) is:

$$NTU = \frac{h_a A_a}{C_a} = \frac{h_w A_w}{C_w} = 1.7$$

Assuming the average heat transfer coefficient between air and heat exchanger fin is:

$$h_a = 50 W/m^2.°C$$

The total surface area needed for the fins is:

$$V = \frac{m_V}{4A_{tube}} = \frac{0.00123}{4 \times 3.14 \times 0.005^2} = 3.9 m/s$$

For the water, assume four parallel tubes with internal diameter of 10 mm are used for the air-water heat exchanger.

The average water velocity inside tube is:

$$V = \frac{m_V}{4A_{tube}} = \frac{0.00123}{4 \times 3.14 \times 0.005^2} = 3.9 m/s$$

The Reynolds number is:

$$Re = \frac{VD}{\gamma} = \frac{3.9 \times 0.01}{1.2 \times 10^{-6}} = 32500$$

The Nusselt number for fully developed turbulent flow is:

$$Nu = 0.023 Re^{4/5} Pr^{0.4} = 0.023 \times 32500^{4/5} \times 7.6^{0.4} = 211$$

The heat transfer coefficient of tube is:

$$h_w = \frac{Nuk}{D} = \frac{211 \times 0.6}{0.01} = 12660 W/m^2.°C$$

The total surface area needed for the tubes is:

$$A_w = \frac{C_w NTU}{h_w} = \frac{5166 \times 1.7}{12660} = 0.69 m^2$$

The length of each tube is:

$$L = \frac{A_w/4}{\pi D} = \frac{0.69/4}{3.14 \times 0.01} = 5.49m$$

The friction factor of the tube is:

$$f = 0.184 Re^{-1/5} = 0.184 \times 32500^{-0.2} = 0.023$$

The estimated pressure drop for each straight tube is:

$$\Delta P = \frac{1}{2}\rho V^2 f \frac{L}{D} = \frac{1}{2} \times 1000 \times 3.9^2 \times 0.023 \times \frac{5.49}{0.01} = 96000Pa(13.9PSI)$$

From the calculation we find that a total of 0.00123 m^3/s (19.5GPM) of water is needed to cool this cabinet. The estimated water pressure drop across the heat exchanger is 96000 Pa (13.9 PSI). This cooling solution has minimum impact on the CRAC (Computer Room Air Condition) system because, in theory, there is no heat dissipation from cabinet to the ambient.

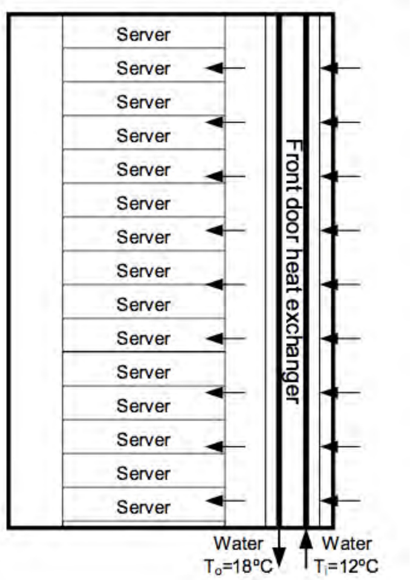

Figure 2. Schematic of a Cabinet with a Front Integrated Air-Water Heat Exchanger.

In general, it is not advisable to put an air-water heat exchanger in the front of a cabinet, as shown in Figure 2. This configuration has very low heat exchanger efficiency because the temperature difference between the inlet air and inlet water is very small. In this case, it is only 8˚C. In the best scenario, the air can only be cooled down to about 12˚C after passing through the heat exchanger.

2. A Cabinet with an Integrated Refrigeration System

Using a refrigeration system to cool electronic components has been applied in the field for long time. Today, this technique is used by companies such as Emerson Corporation for cabinet cooling. It gives the cabinet more flexibility and more potential to reach higher power densities. It also makes the cabinet more complex and adds cost.

In this study, the integrated refrigeration system calculation covers the following cases:

1) A rear-door air-refrigerant heat exchanger which cools the hot air from the cabinet to 20˚C (Figure 3(a)).

2) A sealed cabinet with an air-refrigerant heat exchanger and an refrigerant-water heat exchanger inside (Figure 3(b)).

Assume R134a is used as refrigerant. The refrigeration system can be simplified as a heat transfer system with two heat exchangers, as shown in Figure 4.

For this system, assume the coefficient of performance (COP) of refrigeration is 4:

$$COP = \frac{q}{W_c} = 4$$

So the power of compressor is:

$$W_c = \frac{q}{COP} = \frac{31}{4} = 7.8kW$$

The total power generated by cabinet and compressor is 38.8kW.

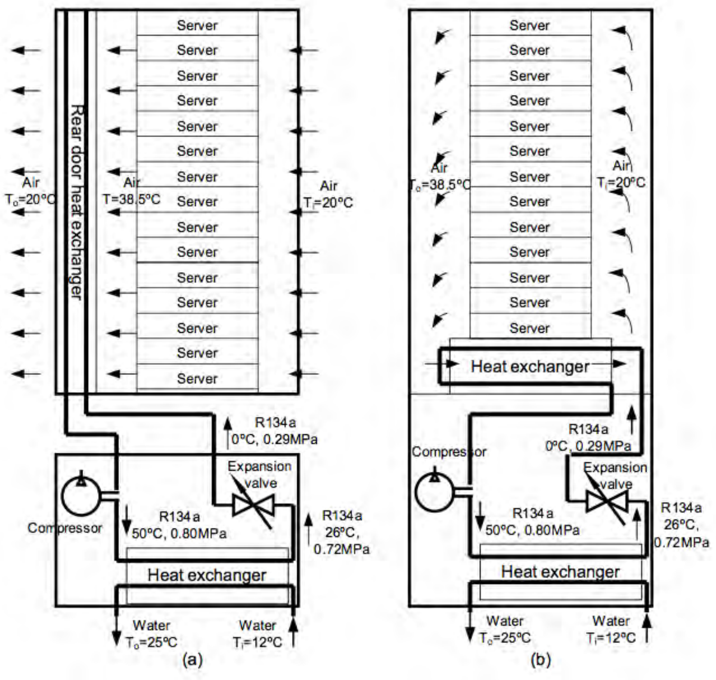

Figure 3. Schematics of Cabinets with Integrated Air-Refrigerant Heat Exchangers.

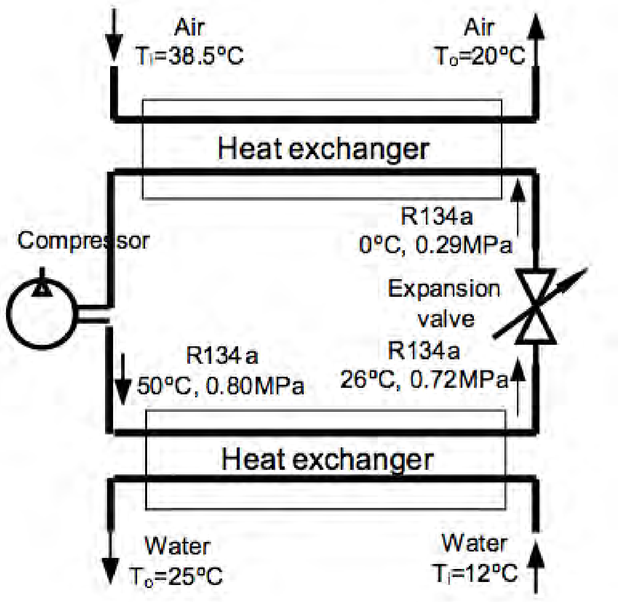

Figure 4, Illustration of a Cabinet with a Refrigeration System.

The flow rate of refrigerant R-134a needed is:

$$m_r = \frac{q}{h} = \frac{31}{162.6} = 0.191 kg/s$$

For R134a in the air-refrigerant heat exchanger:

$$C_r = mC = 0.191 \times 198600 = 37930 W/°C$$

So maximum heat the heat exchanger can dissipate is:

$$q_{max} = C_a(T_{a\_i} - T_{r\_i}) = 1675 \times (38.5 - 0) = 64.5kW$$

The effectiveness of air-refrigerant heat exchanger is:

$$\varepsilon = \frac{q}{q_{max}} = \frac{31}{64.5} = 0.48$$

With

$$\frac{C_a}{C_r} = \frac{1675}{37930} = 0.044$$

The NTU (number of transfer units) of the air-refrigerant heat exchanger (according to [1]) is:

$$NTU = \frac{h_a A_a}{C_a} = \frac{h_r A_r}{C_r} = 1.7$$

Assume the average fin heat transfer coefficient is:

$$h_a = 50W/m^2.°C$$

The total surface area needed for the fins is:

$$A_a = \frac{C_a NTU}{h_a} = \frac{1675 \times 0.7}{50} = 23.5m^2$$

Compared to the air-water heat exchanger, the required fin surface area of the air-refrigerant heat exchanger is reduced by more than half. A more compact heat exchanger can be used for this configuration.

For the refrigerant-water heat exchanger, the total heat transferred from R134a to water is 38.8 kW. Assume that the temperature of the water leaving the tube-to-tube heat exchanger is 25˚C.

The water flow rate needed is:

$$m_V = \frac{q}{\rho C(T_{w\_o} - T_{w\_i})} = \frac{38800}{1000 \times 4200 \times (25 - 12)} = 7.1 \times 10^{-4} m^3/s(11.3GPM)$$

And:

$$C_w = \rho m_V C = 1000 \times 0.00071 \times 4200 = 2982 W/℃$$

For R134a at condenser:

$$C_r = mC = 0.191 \times 8283 = 1582 W/℃$$

So the maximum heat the refrigerant-water heat exchanger can dissipate is:

$$q_{max} = C_r(T_{r\_i} - T_{w\_i}) = 1582 \times (50 - 12) = 60kW$$

Heat sink effectiveness is:

$$\varepsilon = \frac{q}{q_{max}} = \frac{38.8}{60} = 0.65$$

With:

$$\frac{C_r}{C_w} = \frac{1582}{2982} = 0.53$$

The NTU (number of transfer units) of the refrigerant-water heat exchanger (according to [1]) is:

$$NTU = \frac{h_w A_w}{C_w} = \frac{h_r A_r}{C_r} = 1.7$$

For water, assume four parallel tubes with an internal diameter of 10 mm are used for tube-to-tube refrigerant-water heat exchanger.

The average water velocity is:

$$V = \frac{m_V}{4A_{tube}} = \frac{0.00071}{4 \times 3.14 \times 0.005^2} = 2.3m/s$$

The Reynolds number is:

$$Re = \frac{VD}{\gamma} = \frac{2.3 \times 0.01}{1.2 \times 10^{-6}} = 19170$$

The Nusselt number for fully developed turbulent flow is:

$$Nu = 0.023 Re^{4/5} Pr^{0.4} = 0.023 \times 19170^{4/5} \times 7.6^{0.4} = 138$$

The heat transfer coefficient of tube is,

$$h_w = \frac{Nuk}{D} = \frac{138 \times 0.6}{0.01} = 8280 W/m^2.℃$$

The total surface area needed for the tubes is:

$$A_w = \frac{C_w NTU}{h_w} = \frac{2982 \times 1.7}{8280} = 0.61m^2$$

The length of each tube is:

$$L = \frac{A_w/4}{\pi D} = \frac{0.61/4}{3.14 \times 0.01} = 4.86m$$

The friction factor is:

$$f = 0.184 Re^{-1/5} = 0.184 \times 19170^{-0.2} = 0.026$$

The estimated pressure drop for straight tube is:

$$\Delta P = \frac{1}{2}\rho V^2 f \frac{L}{D} = \frac{1}{2} \times 1000 \times 2.3^2 \times 0.026 \times \frac{4.86}{0.01} = 33400Pa(4.8PSI)$$

In this configuration, 7.1 x 10^{-4} m^3/s (11.3 GPM) of water are needed to cool this cabinet. The estimated pressure drop for water is 33400 Pa (4.8 PSI). Compared to the cooling system illustrated in Figure 1, this system requires less water and pumping power. But, it requires a bigger chiller at the data center's cooling system.

One possible configuration for the refrigeration system is to put the air-refrigerant heat exchanger in front of the servers, as shown in Figure 5. This design will enable the cabinet to provide sub-ambient temperature airflow to the servers. Because the air-refrigerant heat exchanger works as an evaporator for R134a, the air temperature after the heat exchanger can be very uniform irrespective of location. The air-refrigerant can be quite efficient because the refrigerant evaporating temperature is regulated by a compressor.

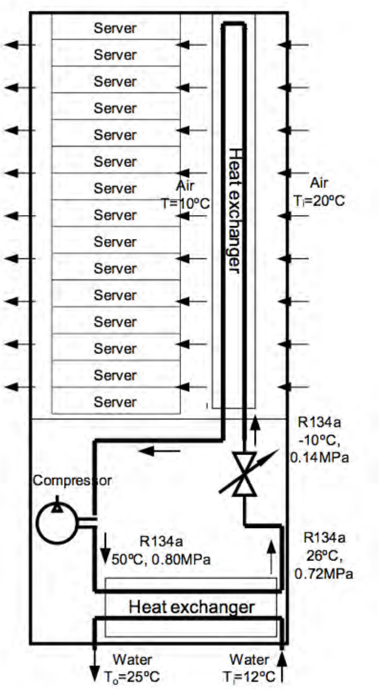

Figure 5. Schematic of a Cabinet with a Front-Integrated Air-Refrigerant Heat Exchanger.

Compared with other liquid-cooled cabinets, the cabinet with a simple air-water heat exchanger is the most energy efficient. It transfers the waste heat from the cabinet to a central chiller, with no additional work required for cooling. A cabinet with a refrigeration system adds an extra heat load to central chiller, but it also brings advantages of better cabinet cooling, a less sophisticated heat exchanger design and less requirements of the water delivery system. Choosing a liquid-cooled cabinet with the right cooling technique and configuration depends on the customer's requirements, including the rack power density, water supply system, CRAC system and budget. The configuration must be selected on an individual basis. With the continuing increase of power dissipation we are sure to see more liquid-cooled cabinets in data centers.

Reference

1. Incropera F. and DeWitt D., Fundamentals of Heat and Mass Transfer, 5th Edition, John Wiley & Sons, 2002.

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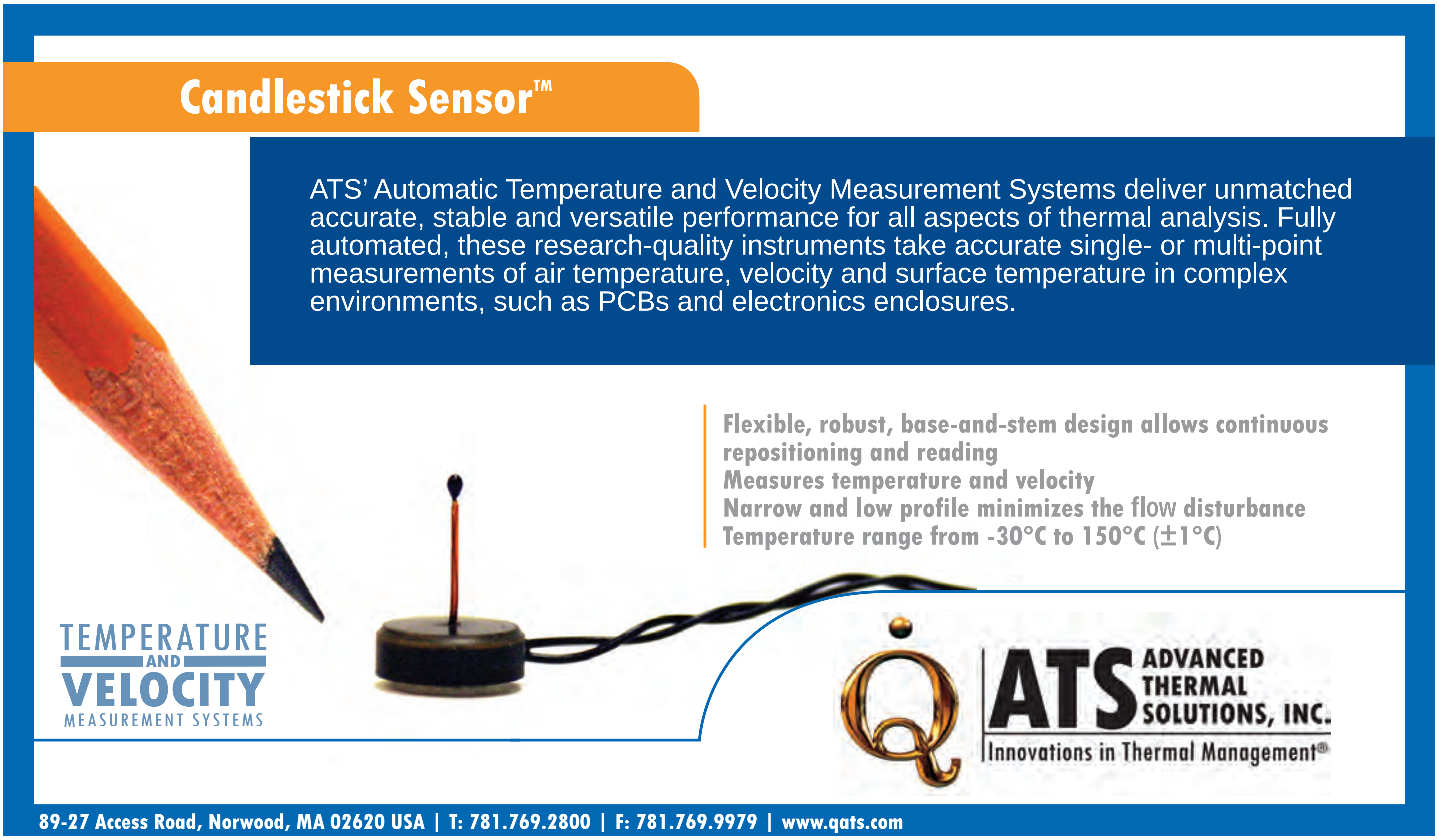

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