液冷式綠色機房設計趨勢與解決方案

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Outline

- 背景
- 常見之液冷系統
- ***Economizer (free cooling)***
- ***Fundamentals – Heat Transfer for Cold Plate & Fin-and-tube Heat Exchanger***
- 液冷設計之基本準則 /Green tips for Liquid Cooling
- Coolant Distribution Unit/Piping
- Short Summary
- Appendix 1 - 近年機房機櫃方之液冷專利介紹
- Appendix 2 : The Different Technologies for Cooling Data Centers

Major References..

- Liquid Cooling Guidelines for Datacom Equipment Centers. 2006, ASHRAE.
- Thermal Guidelines for Data Processing Environments. 3rd ed., 2012, ASHRAE.
- Datacom Equipment Power Trends and Cooling Applications. 2nd ed., 2012, ASHRAE.
- Thermal Guidelines for Liquid Cooled Data Processing Environments. 2011, ASHRAE TC 9.9
- Design Considerations for Datacom Equipment Centers. 2nd ed., 2009, ASHRAE.
- Green Tips for Data Centers. 2010, ASHRAE.
- APC White Paper
- Relevant Published Papers.

Data Center

- Highly energy-intensive and rapidly growing
- Consume 10 to 100 times more energy per area than a typical office building
- Large potential impact on electricity supply and distribution
- Used about 45 billion kWh in 2005 (USA)
- At current rates, power requirements could double in 5 years.

More Facts…

- Servers, including its infrastructure, account for **1.2% electricity consumption (US).**
- **Every Watt of electricity consumed by IT equipment, an extra 1.5 Watts is needed for infrastructure to support IT equipment**.
- **Most servers require 1 Watt of cooling for every watt of power used** in moderately dense server system.
- **High dense servers requires 2 Watts of cooling for every watt** used in the system.

Worldwide electricity used in data centers Environ. Res. Lett. 3 (2008)

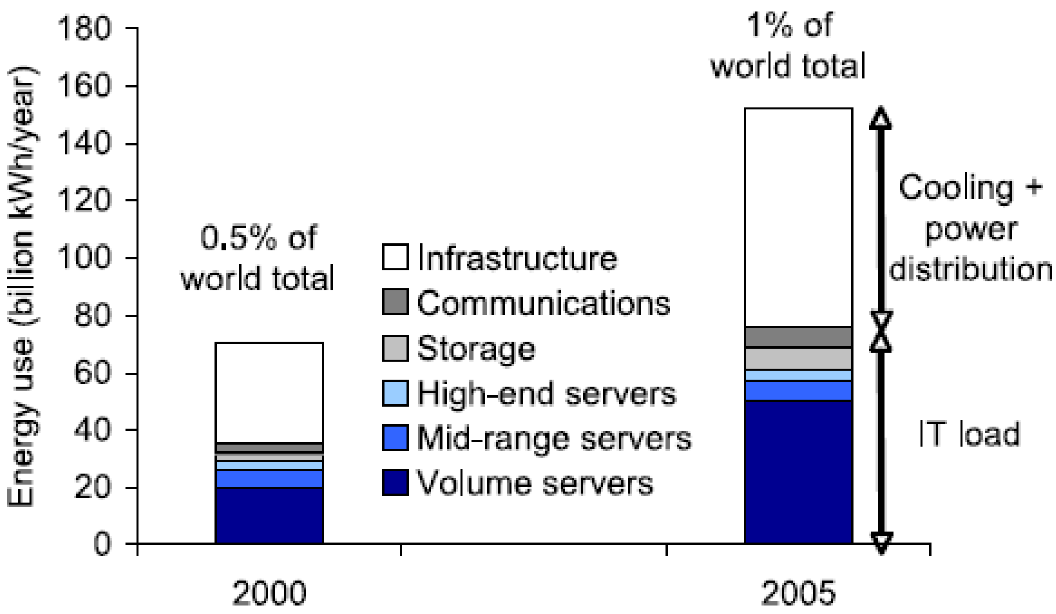


Figure 1. Total electricity use for data centers in the US and the world in 2000 and 2005, including cooling and auxiliary equipment. Total world electricity consumption was 13 238 billion kWh in 2000 and 15 747 billion kWh in 2005, according to the data in table 6.2 of the US Energy Information Administration's *International Energy Outlook*, downloadable at http://www.eia.doe.gov/iea/elec.html. Data center communications electricity use includes only that for networking equipment internal to data centers—it does not include the electricity use of the networks connecting data centers to the Internet as a whole or to the other parts of that broader network.

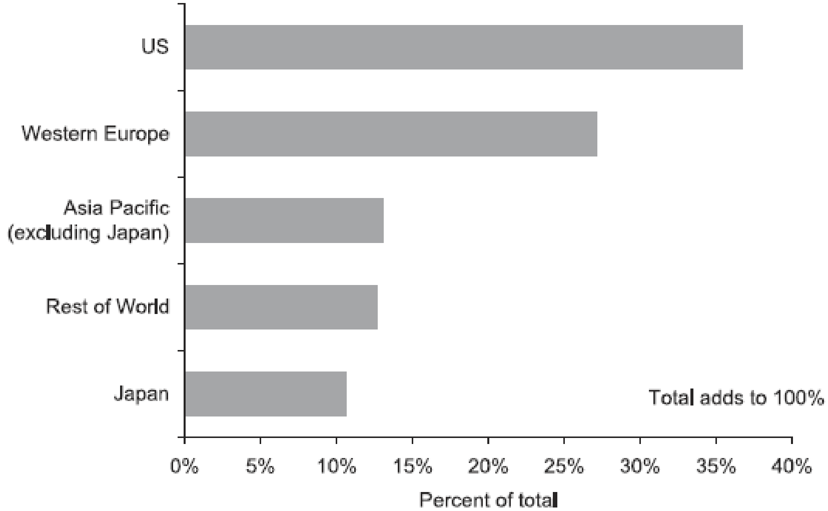
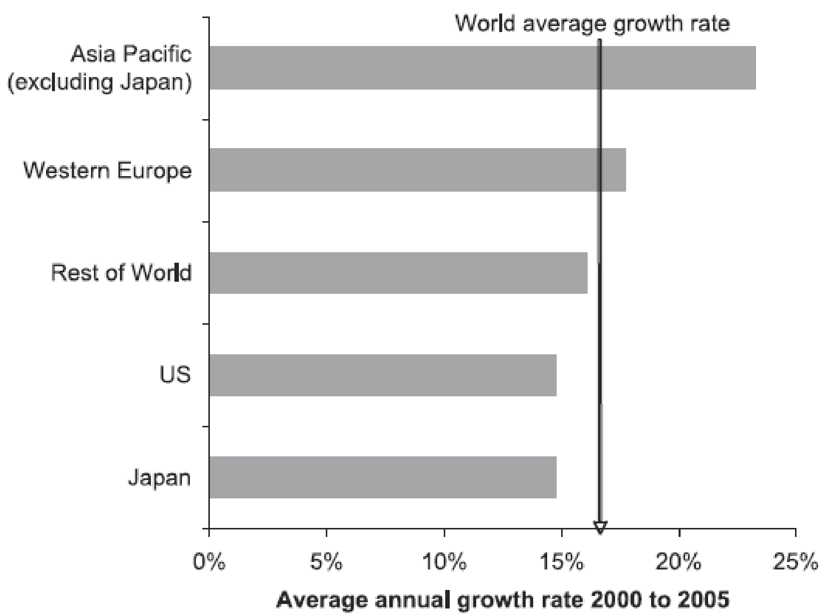


Figure 2. Regional distribution of electricity use for data centers in 2005.



. Average annual percentage growth rates in data center electricity use by major world region, 2000–2005.

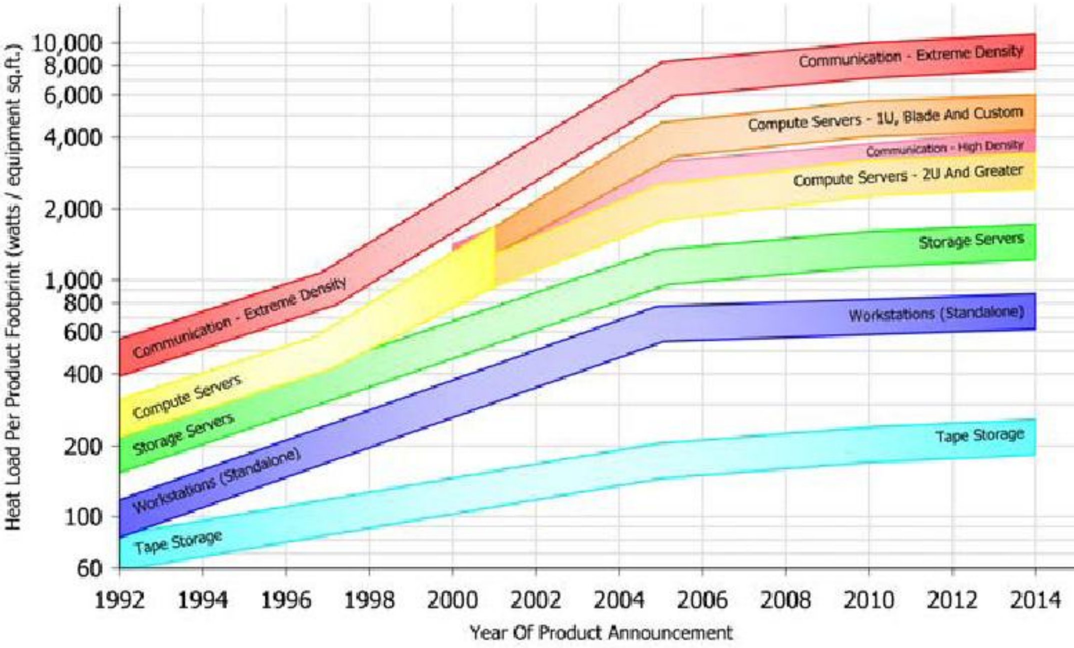
Table 1. Installed base and server power per unit in 2000 and 2005 by major world regions.

Installed base	Units	Volume	Mid-range	High-end	Total/avg
2000					
US	Thousands	4 927	663	23	5 613
Western Europe	Thousands	3 332	447	15	3 794
Japan	Thousands	1 140	250	15	1 405
Asia Pacific (ex. Japan)	Thousands	1 416	132	4	1 552
Rest of World	Thousands	1 425	317	8	1 750
Total	Thousands	12 240	1808	66	14 114
2005					
US	Thousands	9 897	387	22	10 306
Western Europe	Thousands	6 985	356	15	7 355
Japan	Thousands	2 361	185	12	2 558
Asia Pacific (ex. Japan)	Thousands	3 553	137	4	3 694
Rest of World	Thousands	3 162	199	7	3 368
Total	Thousands	25 959	1264	59	27 282
Average power used per server	**Units**	**Volume**	**Mid-range**	**High-end**	**Total/avg**
2000					
US	Watts/server	186	424	5534	236
Western Europe	Watts/server	181	422	4517	227
Japan	Watts/server	181	422	4517	271
Asia Pacific (ex. Japan)	Watts/server	181	422	4517	212
Rest of World	Watts/server	181	422	4517	246
Total	Watts/server	183	423	4874	236
2005					
US	Watts/server	219	625	7651	250
Western Europe	Watts/server	224	598	8378	258
Japan	Watts/server	224	598	8378	289
Asia Pacific (ex. Japan)	Watts/server	224	598	8378	247
Rest of World	Watts/server	224	598	8378	263
Total	Watts/server	222	607	8106	257

Note: (1) Installed base for US and World taken from Koomey (2007b). Non-US installed base by region was not available from IDC, so it was approximated using IDC shipments data by region and multipliers characterizing the relationship between installed base and shipments for all non-US regions in the aggregate (Koomey 2007a). This approach assumes that installed base for each non-US region grows in the same manner as does the sum of those regions. (2) Average power used per server for US and World taken from Koomey (2007b). Non-US average power per server calculated for non-US regions using the differences between US and World installed base and direct electricity consumption from Koomey (2007b).

Background – General Trend

Datacom equipments power trends and cooling applications ASHRAE 2005



New ASHRAE updated and expanded power trend chart.

IDC Report – Cost Structure and Trends

2005 Predicted trend

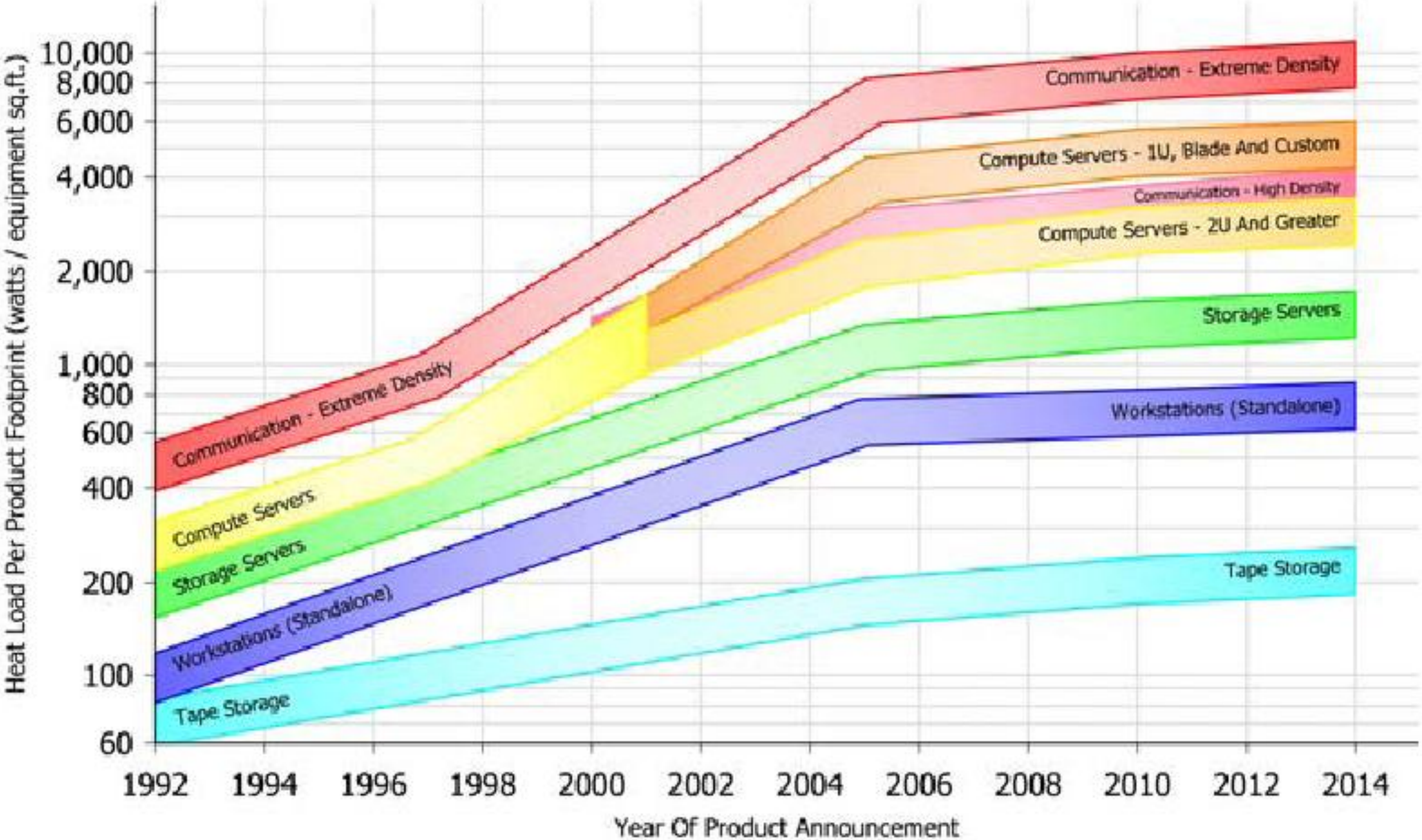


Figure 3-10 New ASHRAE updated and expanded power trend chart.

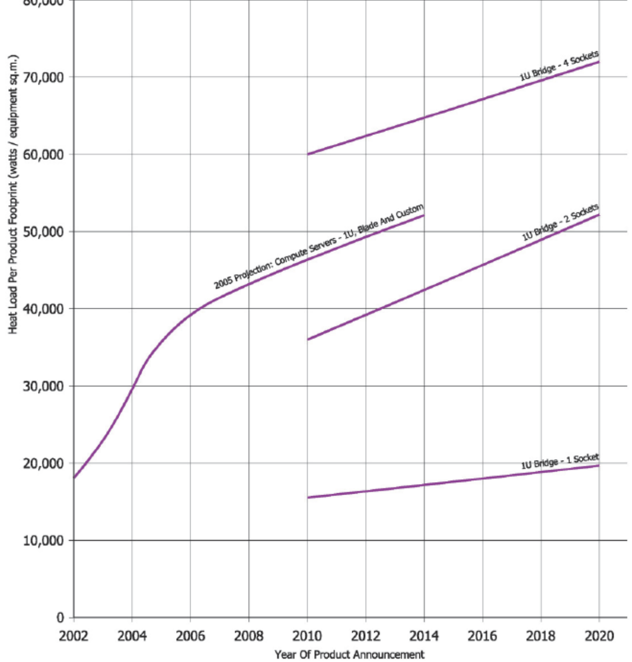


Figure B.9 1U Servers—2005 and 2012 trends (non-log scale, SI units).

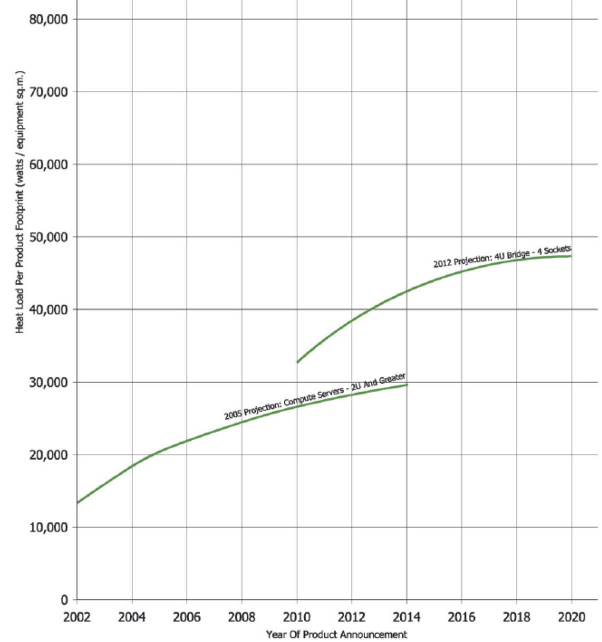


Figure B.11 4U Servers—2005 and 2012 trends (non-log scale, SI units).

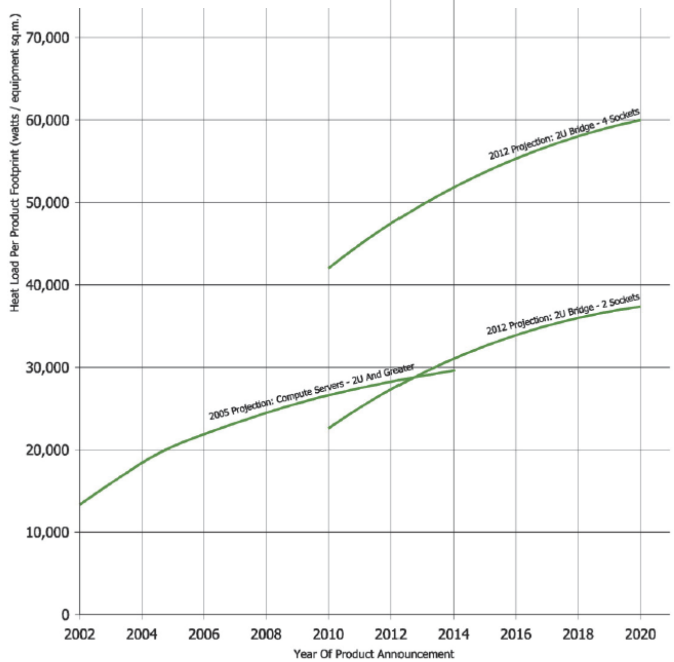


Figure B.10 2U Servers—2005 and 2012 trends (non-log scale, SI units).

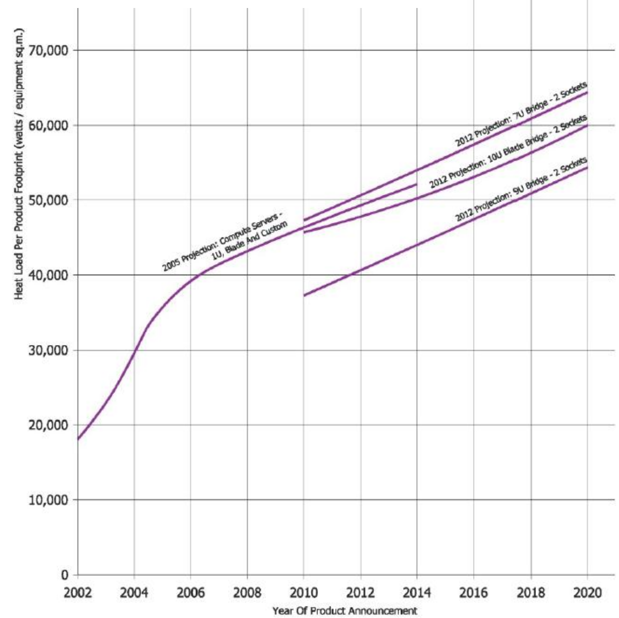


Figure B.12 Blade servers (7U, 9U, and 10U)—2005 and 2012 trends (non-log scale, SI units).

- This chart is based on ***maximum measured load***.
- The data shown in the power trend chart provide a ***general overview of the actual power consumed and the actual heat dissipated by data processing and telecommunications equipment***.
- The data **emulate the most probable level of power consumption assuming a fully configured**, highly utilized system in the year the product was first shipped.
- Finally, the intent of the trends is that they are to be used **as a forecasting and planning tool by providing guidance for the future implementation** of the different types of hardware.
- ***Not all products will fall within the trend lines*** on the chart at every point in time.

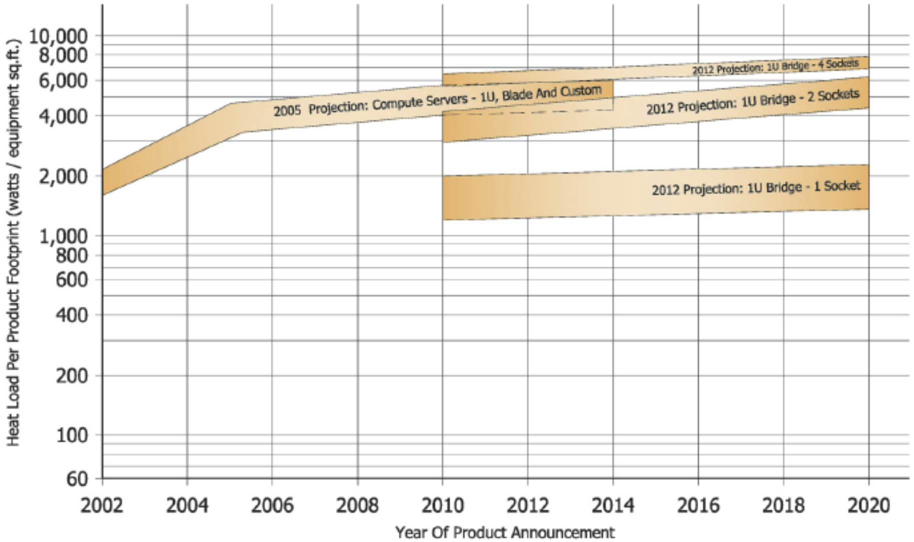


Figure 4.4 1U servers—2005 and 2012 trends.

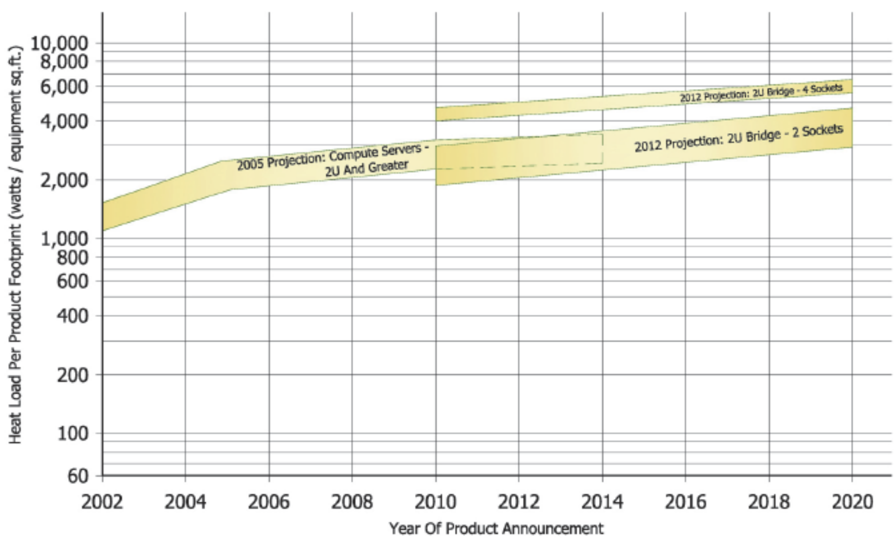


Figure 4.5 2U servers—2005 and 2012 trends.

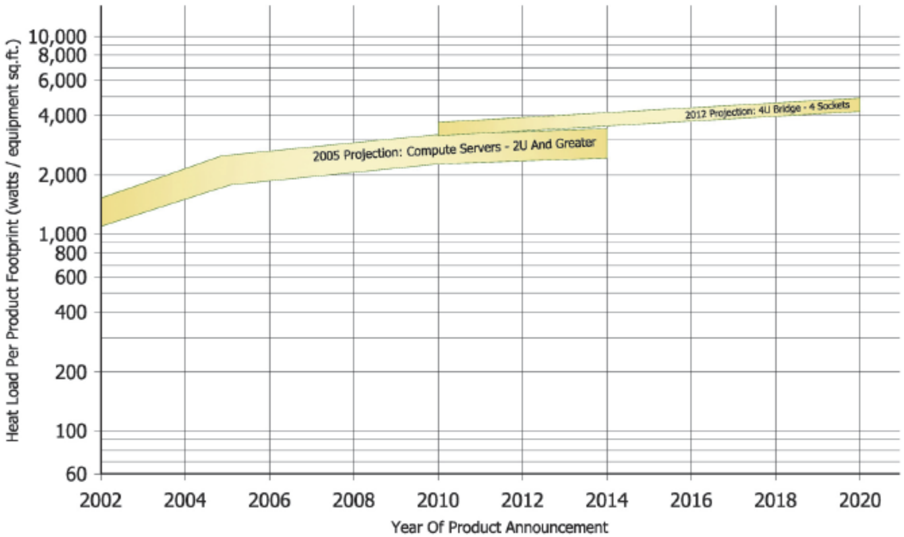


Figure 4.6 4U servers—2005 and 2012 trends.

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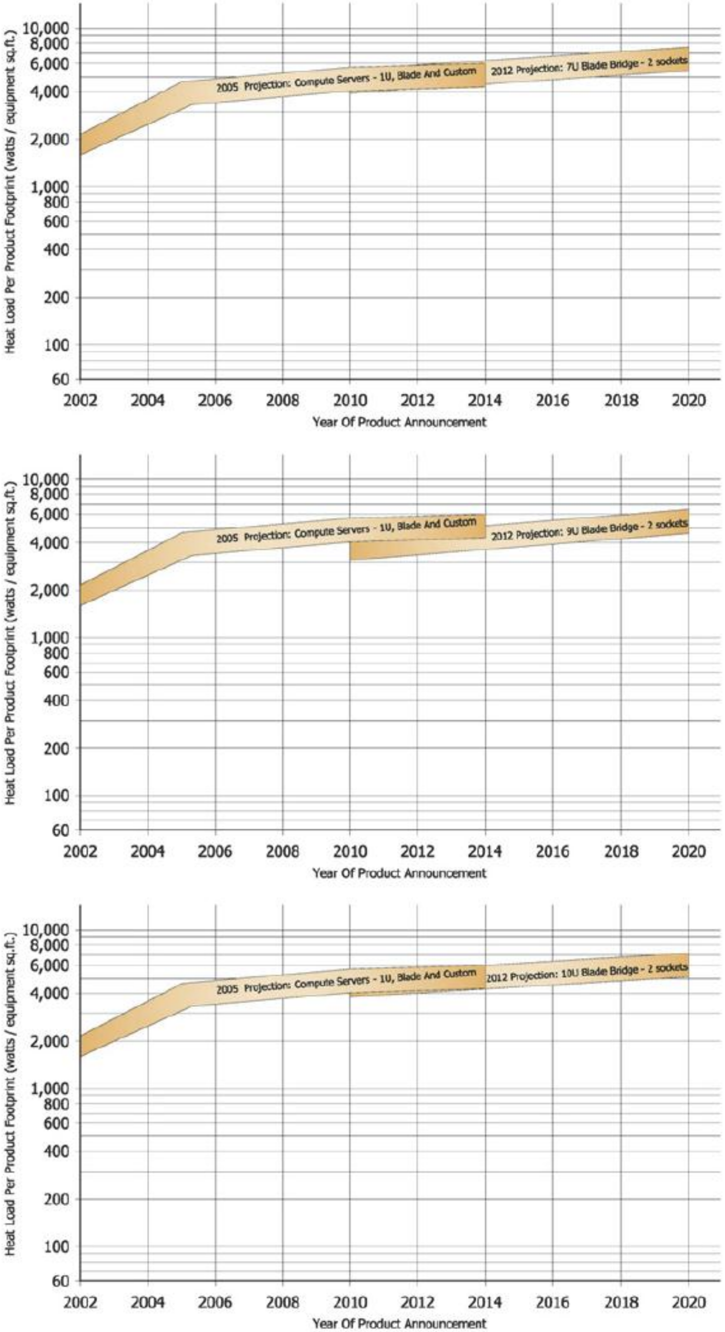


Figure 4.7 Blade servers (7U, 9U, and 10U)—2005 and 2012 trends.

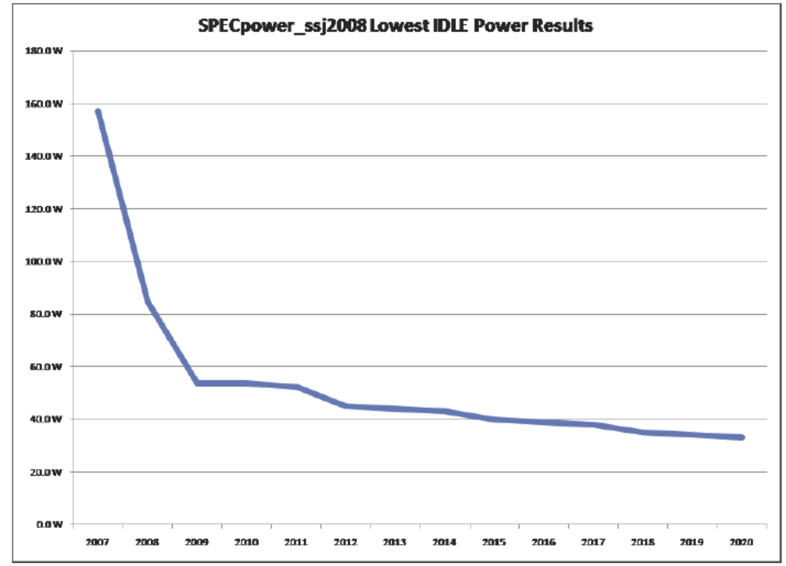


Figure 4.8 SpecPower trend in idle power.

Table 4.2 Power Trends of Nonstandard-Planform Equipment

Type	Range of Average Heat Loads	Range of Footprints, ft^2 (m^2)	Heat Load per Product Footprint, W/ft^2 (W/m^2)		
			2010	2015	2020
Storage Servers	±15%	6 to 13.5 (0.6 to 1.3)	700 (7500)	850 (9150)	1,100 (11,850)
Tape Storage	±30%	10 to 12 (0.9 to 1.1)	200 (2150)	200 (2150)	200 (2150)
Communications	±20%	6 to 12 (0.6 to 1.1)	2000 (21,500)	2550 (27,500)	3000 (32,300)

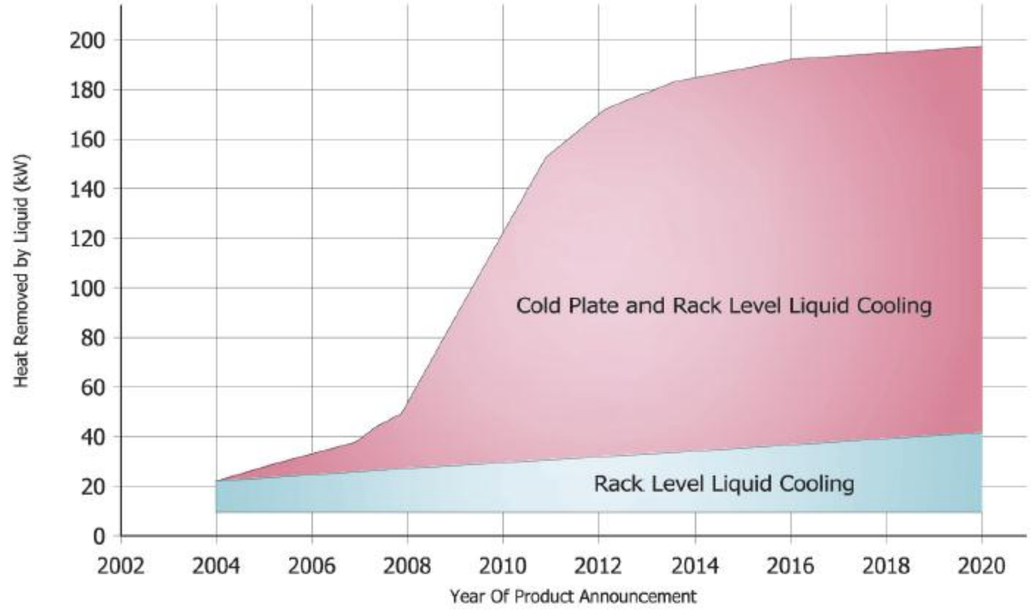
Cooling Technology in Datacom

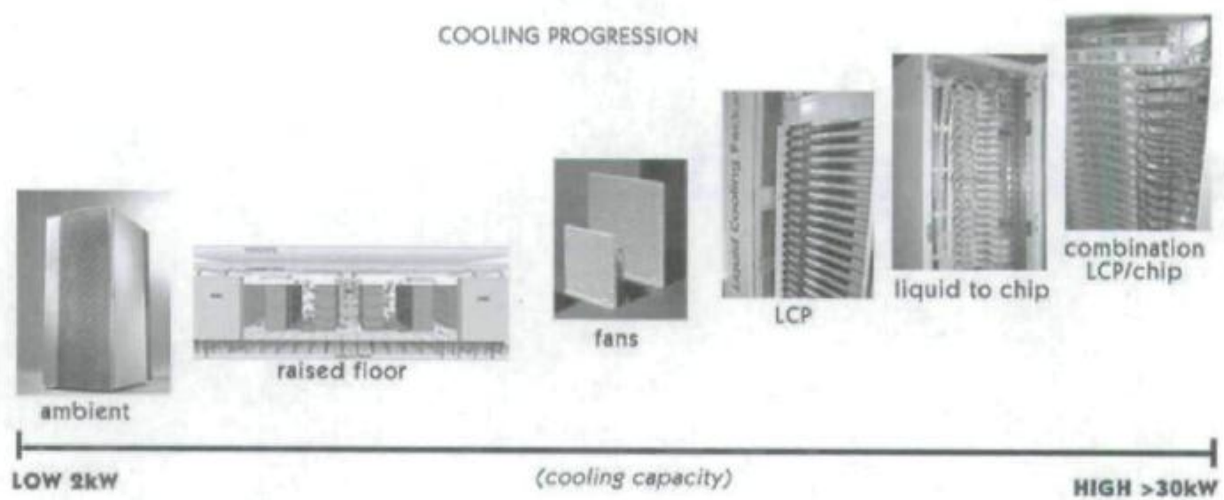
- Air cooling

Air Cooling – Conditioned air is supplied to the inlets of the rack / cabinet for convection cooling of the heat rejected by the components of the electronic equipment within the rack. It is understood that within the rack, the transport of heat from the actual source component (e.g., CPU) within the rack itself can be either liquid or air based, but the heat rejection media from the rack to the terminal cooling device outside of the rack is air.

- Liquid cooling

Liquid Cooling – Conditioned liquid (e.g., water, etc., and usually above dew point) is channeled to the actual heat-producing electronic equipment components and used to transport heat from that component where it is rejected via a heat exchanger (air to liquid or liquid to liquid) or extended to the cooling terminal device outside of the rack.





Cooling progression.

LCP (Liquid Cooling package)

Figure 2 Liquid cooling package LCP.

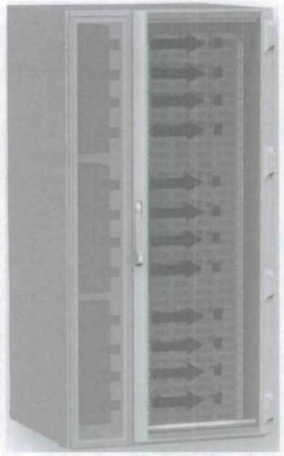


Figure 3 Liquid cooling package LCP.

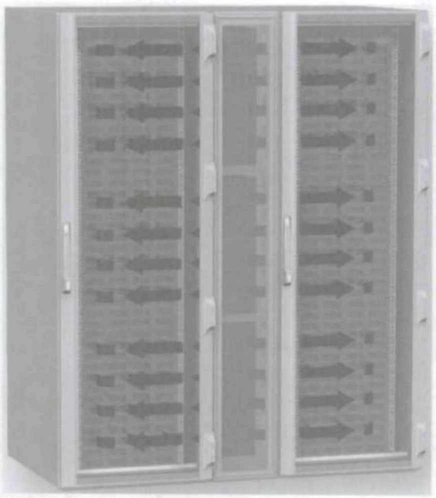


Figure 4 Supply and return lines installed.

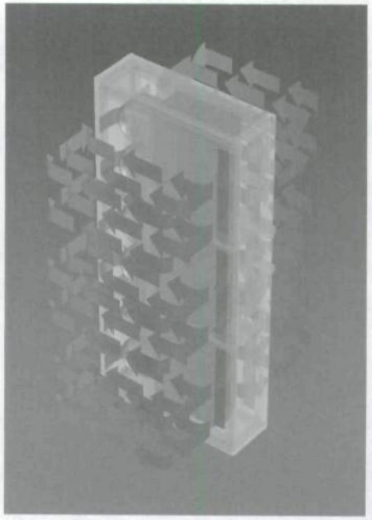
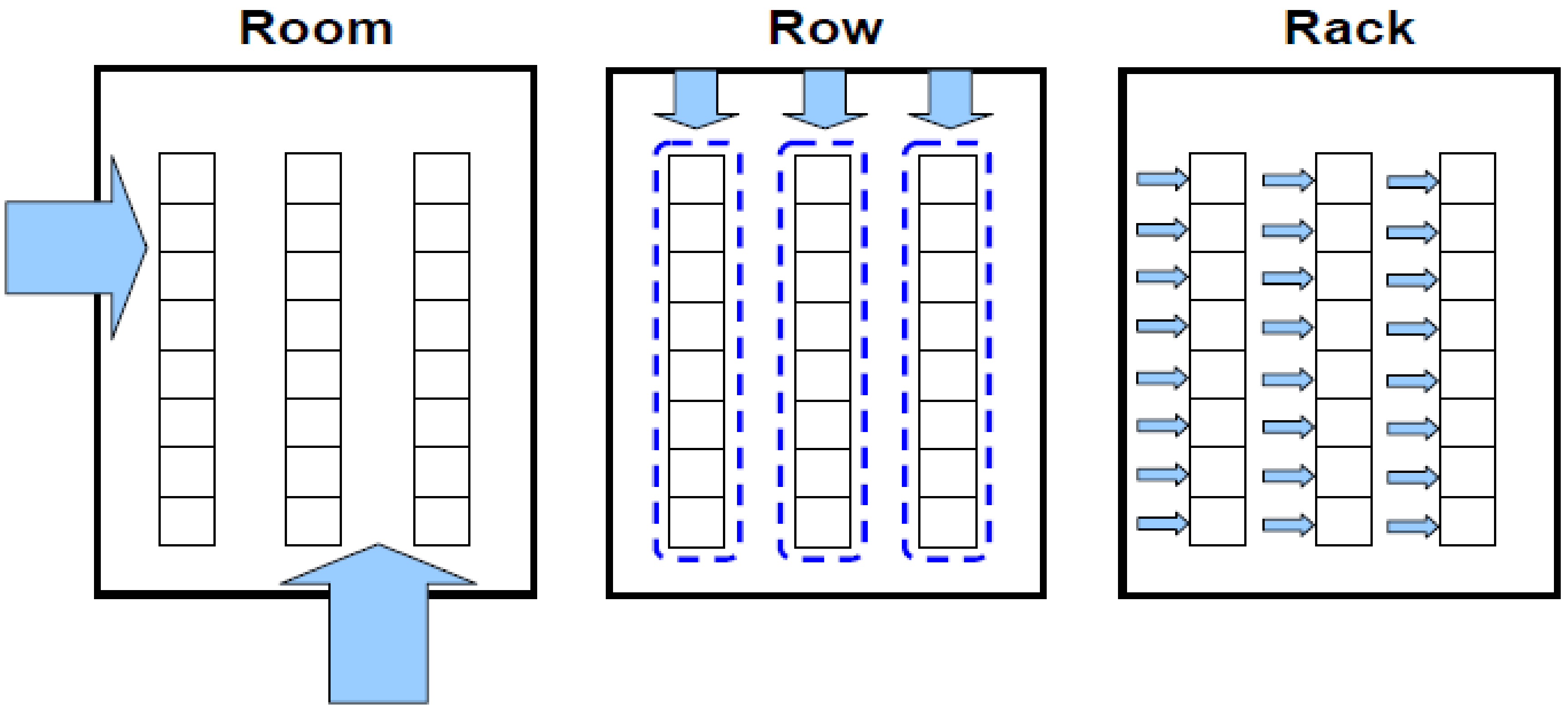


Figure 5 Supply and return lines installed.

Room, row, and rack based cooling architectures

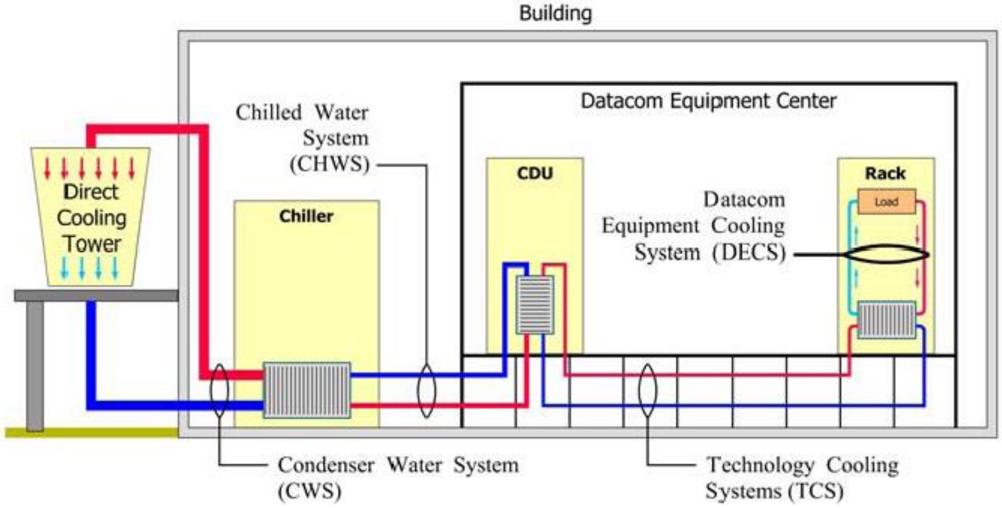
APC White paper #130

***Figure 1** – Floor plans showing the basic concept of room, row, and rack-oriented cooling architecture. Blue arrows indicate the relation of the primary cooling supply paths to the room.*



LIQUID COOLING SYSTEMS

- **Datacom equipment cooling system (DECS):** This system does not extend beyond the IT rack. It is a loop within the rack that is intended to perform heat transfer from the heat-producing components (CPU, memory, power supplies, etc.) to a fluid cooled heat exchanger also contained within the IT rack. Some configurations may eliminate this loop and have the fluid from the coolant distribution unit (CDU) flow directly to the load. This loop may function in single-phase or two-phase heat transfer modes facilitated by ***heat pipes, thermosyphon, pumped fluids, and/or vapor compression cycles***.

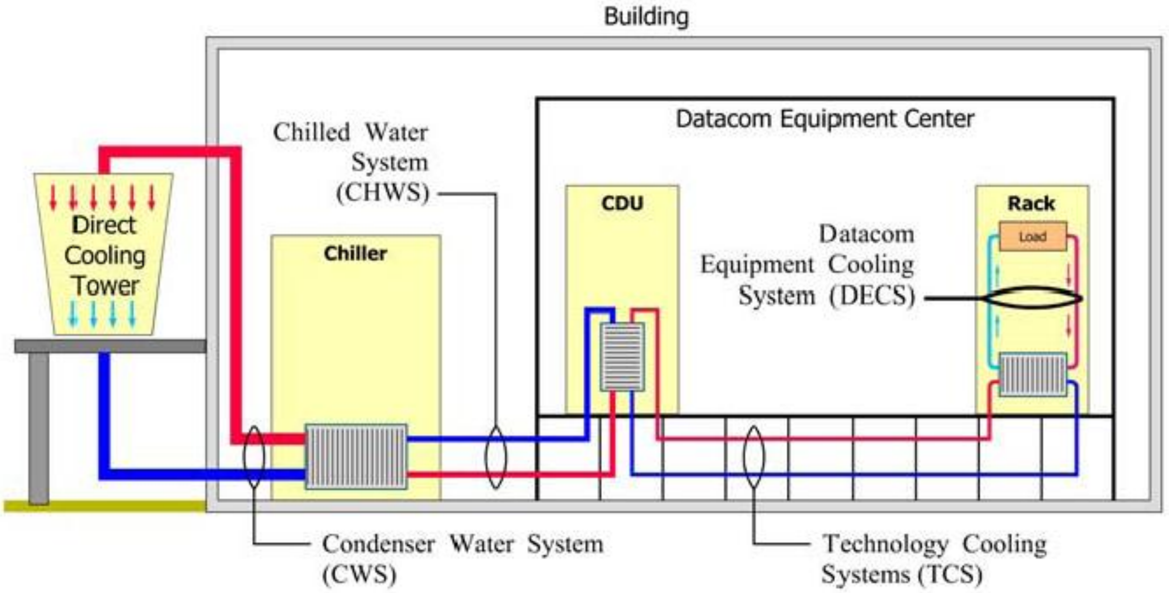


- ***Technology cooling system (TCS):*** This system would not typically extend beyond the boundaries of the IT space. The exception is a configuration in which the CDU is located outside the data center. It serves as a dedicated loop intended to perform heat transfer from the datacom equipment cooling system into the chilled-water system. This loop is highly recommended, as it is needed to address specific fluid quality issues regarding temperature, purity, and pressure as required by the heat exchangers within the datacom equipment cooling systems.
- ***Chilled-water system (CHWS):*** This system is typically at the facility level and may include a dedicated system for the IT space(s). It primarily consists of the system between the data center chiller(s) and the CDU. ***The chilled-water system would include the chiller plant, pumps, hydronic accessories, and necessary distribution piping at the facility level***.

- **Condenser-water system (CWS):** This system consists of the liquid loop between the cooling towers and the data center chiller(s). It is also typically at the facility level and may or may not include a dedicated system for the IT space(s). ***Condenser water loops typically fall into one of two fundamental categories: wet-bulb-based or dry-bulb-based system***. The ***wet-bulb-based loops function on an evaporative process***, taking advantage of lower wet-bulb temperatures, thereby providing cooler condenser-water temperatures. ***The dry-bulb-based loops function based upon the difference of condenser-water loop temperature versus ambient dry-bulb temperature***.

Liquid Cooling Overview – The coolants

- Fluorinerts™ (fluorocarbon liquids)
- Water (or water/glycol mixtures)
- Refrigerants (pump & vapor compression systems)



Liquid cooling systems/loops within a data center.

Dielectric Fluids

- Dielectric fluids exhibit properties that make an attractive heat transfer media for data processing applications. Foremost is ***an ability to contact the electronics directly*** (eliminating some of the intermediary heat exchange steps), as well as the transfer of high heat loads (via an evaporative cooling methodology). This technology ***has containment concerns, metallurgical compatibility exposures, and tight operating tolerances***. Dielectric liquids are not to be confused with chlorinated fluorocarbons (CFCs), which are subject to environmental concerns.

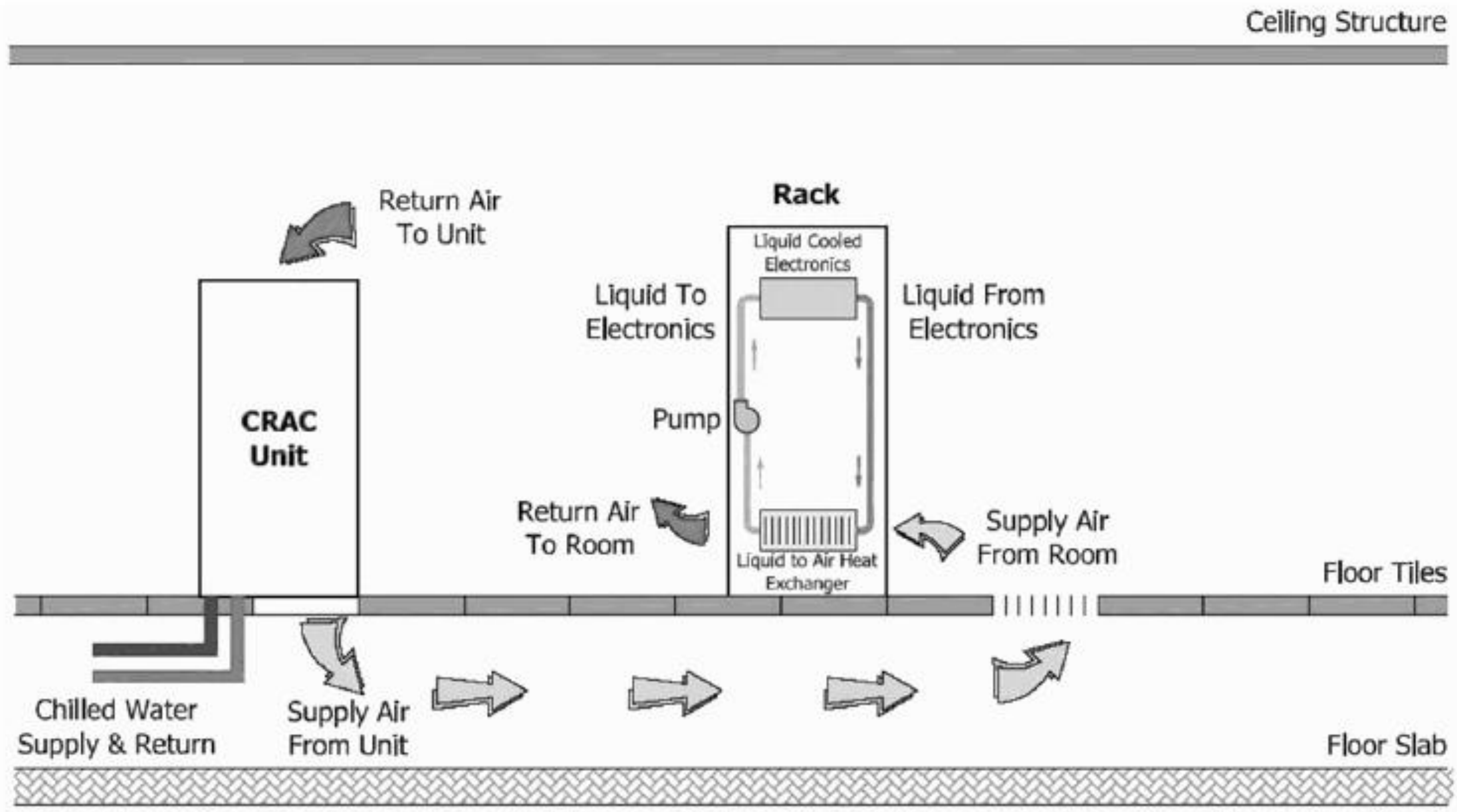


Figure 6.1 Internal liquid cooling loop restricted to within rack extents.

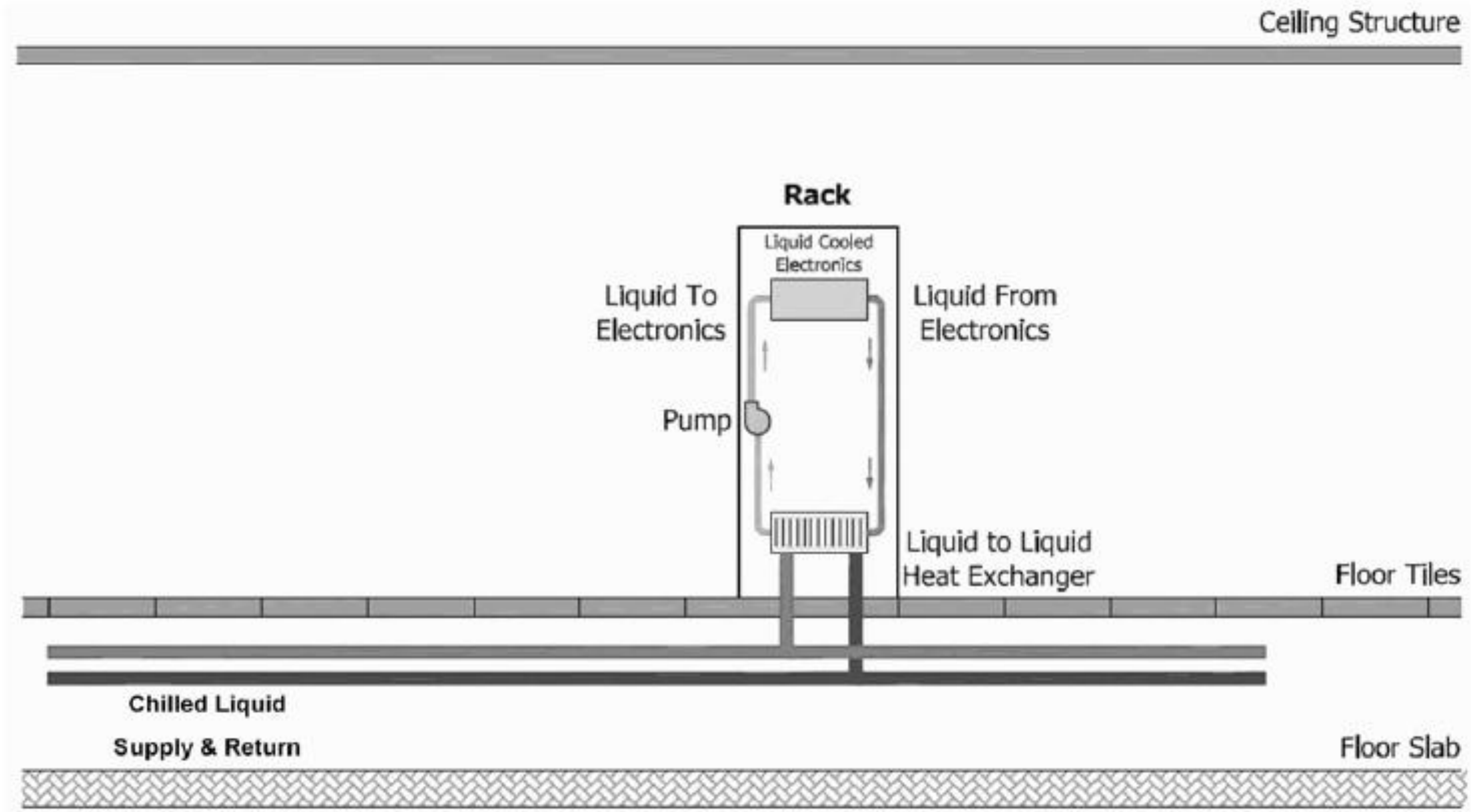


Figure 6.2 Internal liquid cooling loop within rack extents and external liquid cooling loop to racks.

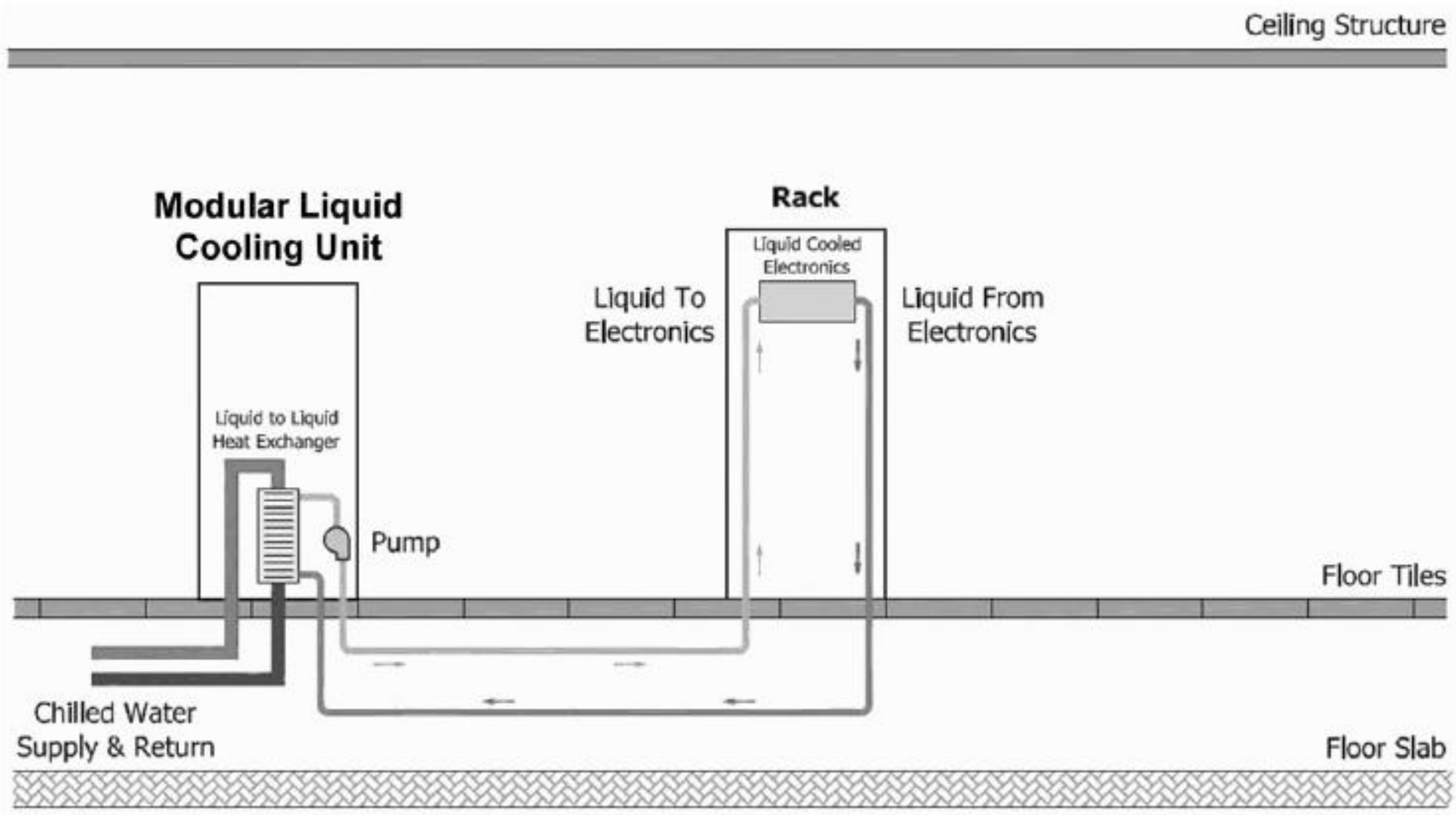


Figure 6.3 Internal liquid cooling loop extended to liquid-cooled external modular cooling unit.

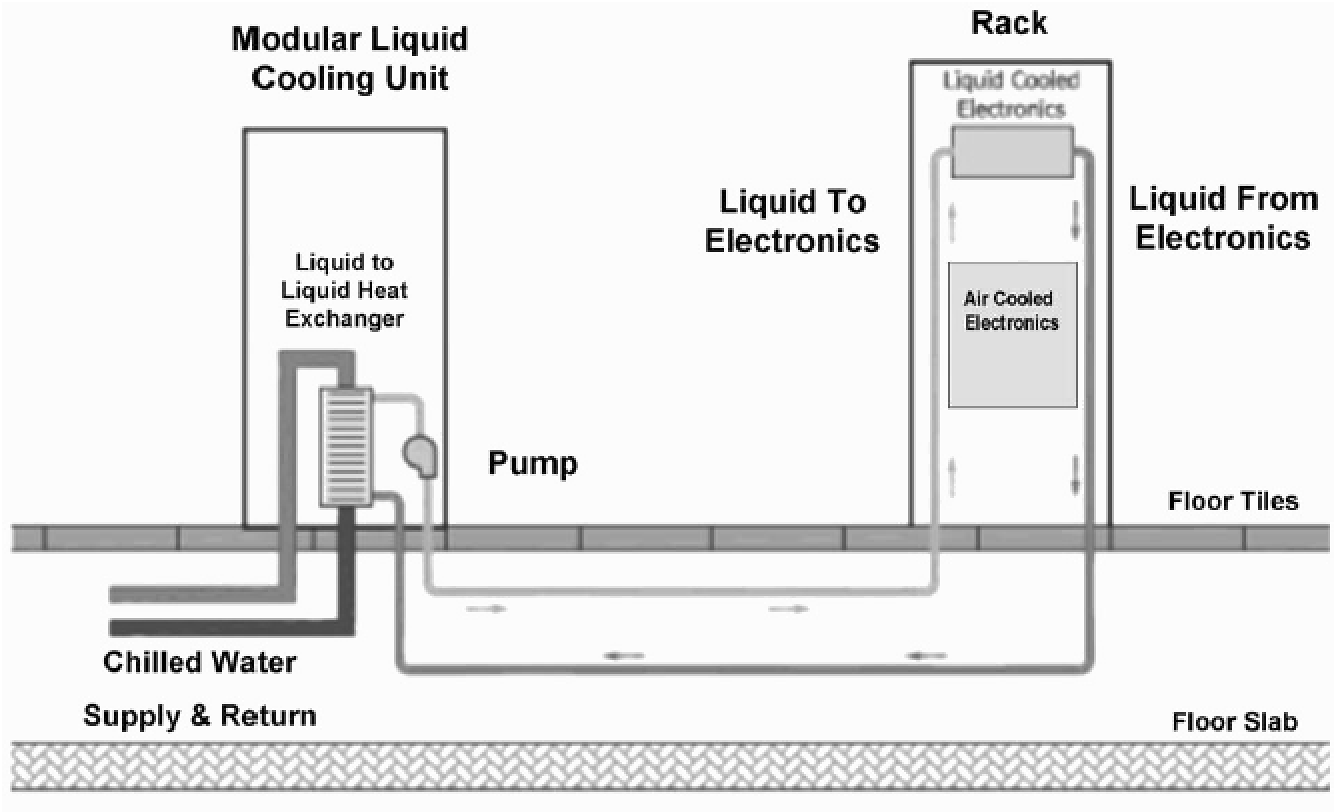


Figure 6.4 Hybrid rack cooling system—internal liquid cooling loop extended to liquid-cooled external modular cooling unit and rack air-cooled components.

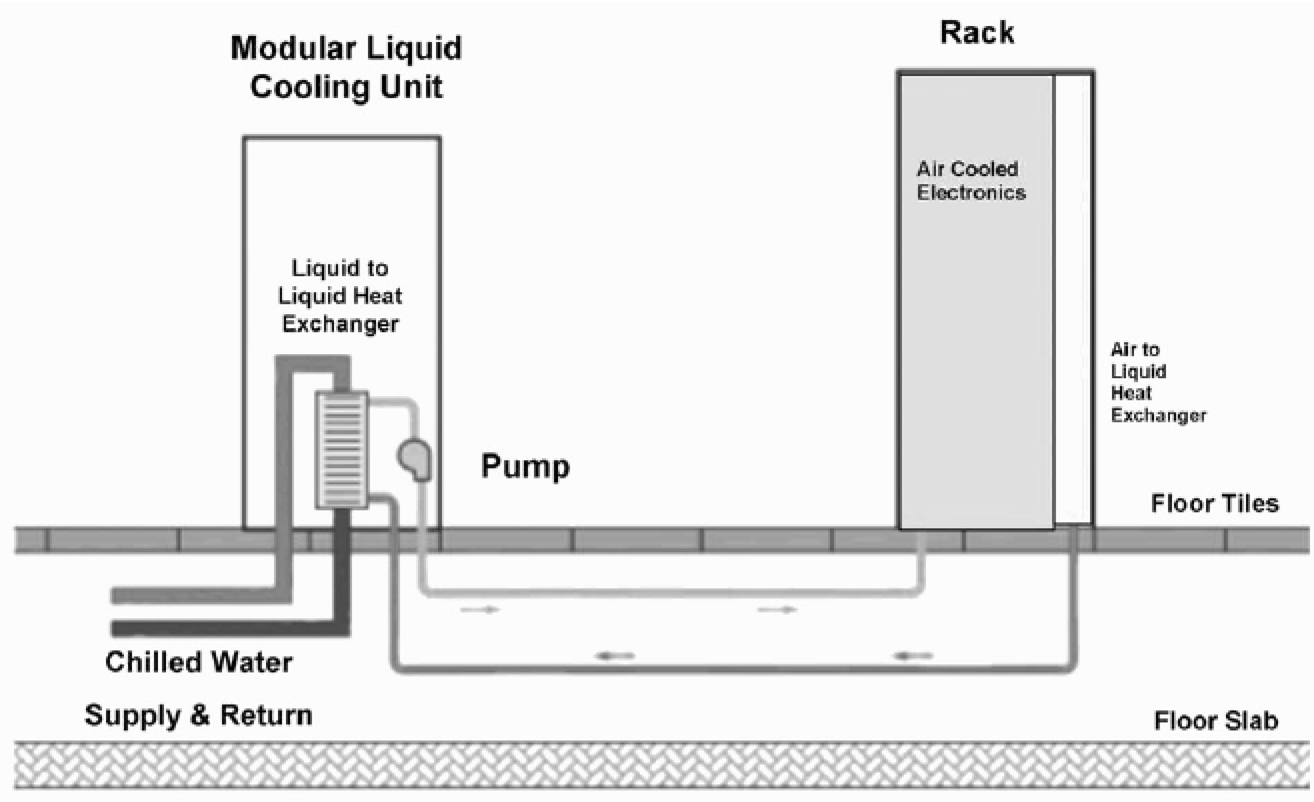


Figure 6.5 Hybrid rack cooling system—rack level liquid cooling loop extended to liquid-cooled external modular cooling unit and rack air-cooled components.

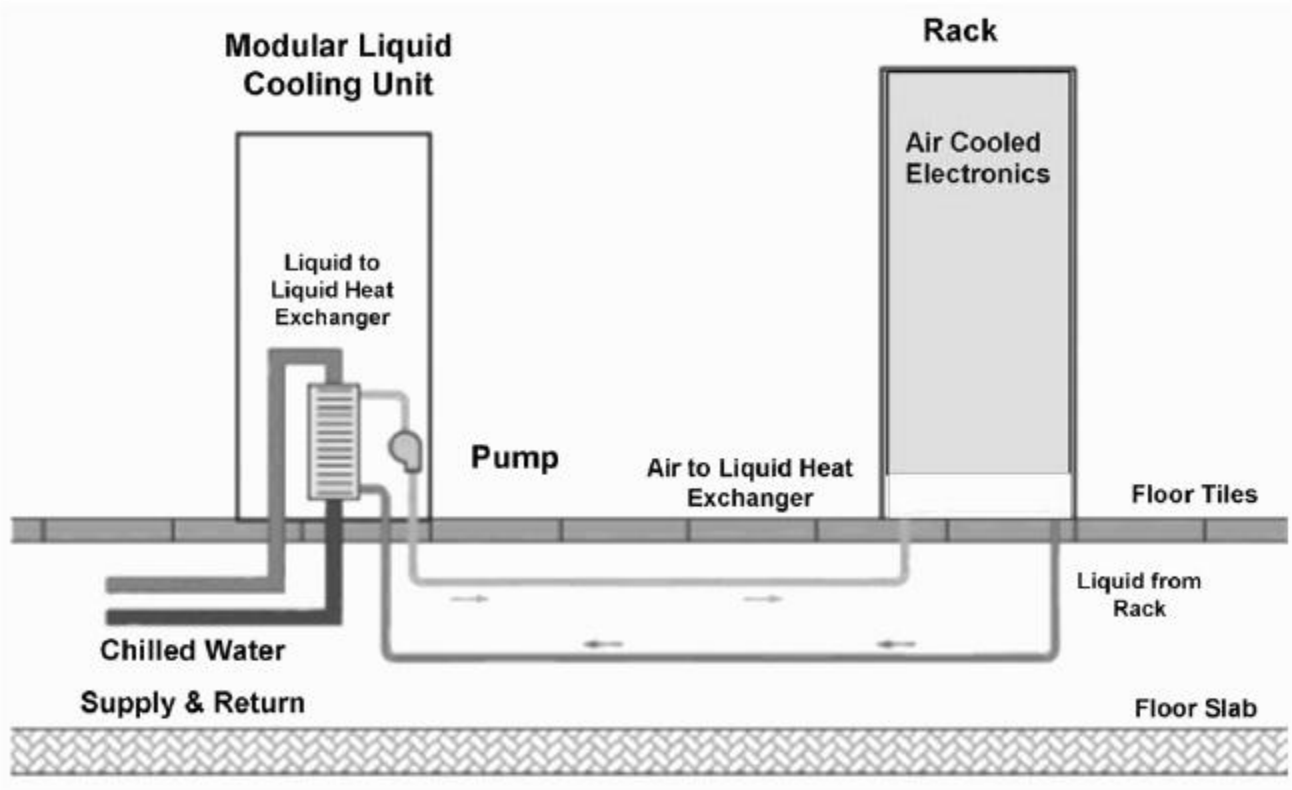


Figure 6.6 Hybrid rack cooling system—rack level liquid cooling loop extended to liquid-cooled external modular cooling unit and rack air-cooled components.

Reasons for choosing a dielectric liquid cooling strategy

- **Less conversion losses** (fewer steps between the heat load and the ultimate heat sink). The heat transfer path could be from the electronic circuit to dielectric liquid to central plant chilled water.
- **Heat transfer capacity of dielectric liquids is several orders of magnitude higher compared to air**.
- **Minimal acoustical concerns**.
- ***More compact***.

Water

- **Less conversion losses** (fewer steps between the heat load and the ultimate heat sink). The heat transfer path would be from the electronic circuit to component interface, to water, to central plant chilled water.
- Heat transfer capacity of water compared to dielectric liquids and air (water has several times and several orders of magnitude higher specific heat capacity compared to dielectric liquid and air, respectively.
- Minimal acoustical concerns.
- ***More compact than air or dielectric liquid cooling***.

Refrigerants

- Refrigerants can be used either in a ***pumped loop technique or vapor compression cycle***. The advantages of using refrigerants are similar to those of dielectric liquids in that ***they can contact the electronics without shorting out any of the electronics.***
- In the ***pumped loop methodology, the refrigerant is at a low pressure such that, when passing through an evaporator, the liquid evaporates or passes into a two-phase flow situation*** and then passes onto the condenser where the cycle begins again. ***If lower than ambient temperatures are desired, then a vapor compression cycle may be employed***.

General Requirements of Facility of Liquid Cooling

- **Flexibility**
- **Scalability**
- **Ease of Installation, Commissioning, and Operation**
- **Ease of Maintenance and Troubleshooting**
- **Availability and Reliability**

Flexibility

- Data center cooling systems should be designed with features that will **minimize or eliminate system outages associated with new equipment installation**.
  - **Valved and capped piping connections for future equipment**, such as water-cooled racks, central station air handlers, CRACs, and central plant equipment.
  - **The central plant should be configured to add additional chillers, pumps, and cooling towers** as the load increases.
  - **Overall flexibility is often limited by the pipe sizes** used in the central plant and distribution system.
  - After a data center is online, **changing pipe size to increase capacity is typically prohibitive from both outage risk and implementation cost perspectives**.

Scalability

- The building cooling systems should be designed to **accommodate future load growth of the computer equipment.** Unless adequately planned growth and expansion is included in the data center, it will be obsolete in a very short time.
  - Building piping architecture (CWS and CHWS) should be designed to **support a future building cooling load density**.
  - The central plant should have **enough space for future chillers, pumps, and cooling towers**.
  - **Sizing piping for the full buildout or future growth will save energy and allow smaller active components** during the early life of the building.

Ease of Installation, Commissioning, and Operation

- Cooling service equipment should be designed such that it can be installed in **easy, visible, and readily accessible locations**. Commissioning is an effective strategy to verify that the cooling systems are operating as intended in the original building design and should be considered for every project.
  - Commissioning plan includes **factory acceptance tests, field component verification, system construction verification, site acceptance testing, and integrated systems testing**.
  - Commissioning **at full load (full flow) to prove hydraulic capacity should be a requirement**.
  - The control center should house all of the building operations systems, such as **security monitoring, energy management and control systems, system control and data acquisition systems, building automation systems, and fire alarms**.
  - **Power and cooling loads on facility equipment, such as UPS, chillers, and electrical feeders**, should be monitored to determine load growth and available capacity.

Ease of Maintenance and Troubleshooting

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- The ease of maintenance and the ability to troubleshoot problems quickly and accurately are essential elements of a high-availability datacom facility.
  - **Maintain adequate working clearance around cooling equipment**.
  - Manufacturers’ recommendations for **working clearances should be used as a minimum for serviceability areas**.
  - Building owners should consider a computerized maintenance management system (CMMS) to help manage equipment maintenance. These systems can record maintenance history and automatically dispatch work orders for future maintenance.
  - **Energy management and control systems (EMCS) or building automation systems (BAS) sensors and device outputs can be trended over time and used for system diagnostics and troubleshooting**.
  - Load growth over time can be compared to chilled-water capacity, **and this information can be used to project time frames for plant expansion or increase in individual component capacity, i.e., replace an 800 ton chiller with a 1200 ton chiller.**

Availability and Reliability

- A key to having a reliable system and maximizing availability is **an adequate amount of redundant equipment to perform routine maintenance.** If *N* represents the number of pieces to satisfy the normal cooling capacity, then often reliability standards are considered in terms of redundant pieces compared to the baseline of *N*.
  - *N* + 1—full capacity plus one additional piece
  - *N* + 2—full capacity plus two additional pieces
  - 2*N*—twice the quantity of pieces required for full capacity
- 2(*N* + 1)—full capacity plus one additional piece and the entire assembly repeated again (backup site)
- **A critical decision is whether *N* should represent just normal conditions or whether *N* includes full capacity during offline routine maintenance**.

Comparison of Cooling Fluids Based on Cooling Solution Requirements

National Chiao Tung University

Cooling Solution Requirement	Refrigerant Technology	Water Based Technology
Capacity to Cool High Heat Densities	★★★ Phase changing of the fluid in the system yields higher capacities in limited space.	★★ One-phase fluid in the system can limit capacity.
Flexibility to Equipment Reconfiguration and Changed Room Layout	★★ Pre-piped room and quick connect couplings can allow flexibility to reconfigure.	★ Pre-piped room and quick connect couplings can allow flexibility to reconfigure. However, reconfiguration cannot be done without introducing water-related risks to the data center.
Energy Efficiency	★★★ Phase changing of the fluid in the circuit yields very good energy efficiency due to smaller pumps and less pressure drop in the heat exchangers located close to the heat source.	★★ Pumping water to the heat exchangers, located close to the heat source, yields good energy efficiency.
Provide Thermal Ride Through in Case of a Failure	★★★ Due to the phase changing of the fluid contained in the piping circuit, thermal ride through time can be achieved.	★★ The water (one-phase fluid) contained in the piping circuit, can yield some thermal ride through time.
Floor Space Efficiency	★★★ Refrigerant technology enables floor space-saving overhead solutions.	★★ With water based technology, non-overhead solutions are typically used because of water related risks.
Low Complexity of Cooling Redundancy	★ Heat exchangers close to the heat source increase complexity of cooling redundancy.	★ Heat exchangers close to the heat source increases complexity of cooling redundancy.
Avoid Possibility for Water Leaks in the Data Center	★★★ No water introduced in the middle of the data center.	★ Requires careful piping layout, piping containment/ trays, detection and isolation to minimize the possibility of a water leak.
Possibility to Implement as Retrofit	★ Requires space for distribution piping (and heat exchangers) to implement.	★ Requires space for distribution piping (and heat exchangers) to implement.
Known and Comfortable Technology	★★ Direct expansion refrigerant technology is very well known since many years. Pumped refrigerant technology is known but in a relatively new application when used for data center high heat density cooling.	★★ Water based cooling was more common 20 years ago. The technology is slowly becoming used again because of increasing heat densities.

★ Fair ★★ Good ★★★ Excellent

ASHRAE Transactions 2010, Vol. 116, Part 1, pp. 24-31

Green Tips for Cooling Plant
(Liquid Cooling)

- **INSTALL VARIABLE-SPEED DRIVES**
  - The typical data center load is fairly constant but grows over time. Therefore, VSDs can be utilized to respond to the load growth and still improve the efficiency of the data center cooling system
  - The fan and pump affinity laws indicate that the ***rotational speed is directly proportional to the fluid volume rate***, thus the frequency of the motor is directly proportional to the fluid volume rate of the fluid, cfm (m^3/s) or gallons per minute, gpm (L/min). An example shows that a reduction of ***20% in fan speed and airflow volume results in a 49% reduction in energy from the maximum operating point.***

INSTALL VARIABLE-SPEED DRIVES..

- WHEN/WHERE IT IS APPLICABLE
  - VSDs can be used on cooling supply air fans (such as those in CRAC units), outdoor air/ventilation supply fans, exhaust fans, chilled-water pumps, condenser water pumps, cooling tower fans, air-cooled condenser fans, drycooler fans, and certain compressors.
  - The VSDs on the fans can also help coordinate the volume of cool supply air from the CRAC units by changing the volume of air flowing through the IT equipment.
  - When located on pumps, VSDs can ensure that the correct flow rate is maintained after piping changes are made or after CRAC units are added in a data center.

INCREASE WATER EFFICIENCY

- Evaporative Cooling Systems
  - Many datacom facilities use evaporative cooling systems (such as water-cooled chillers coupled with cooling towers). For every 1 MW of cooling, the annual water consumption of these systems is roughly equivalent to the annual water usage of 50 households. Consequently, the primary focus of increasing water efficiency in data centers is on reducing the amount of water used by the evaporative cooling system, specifically the cooling towers.

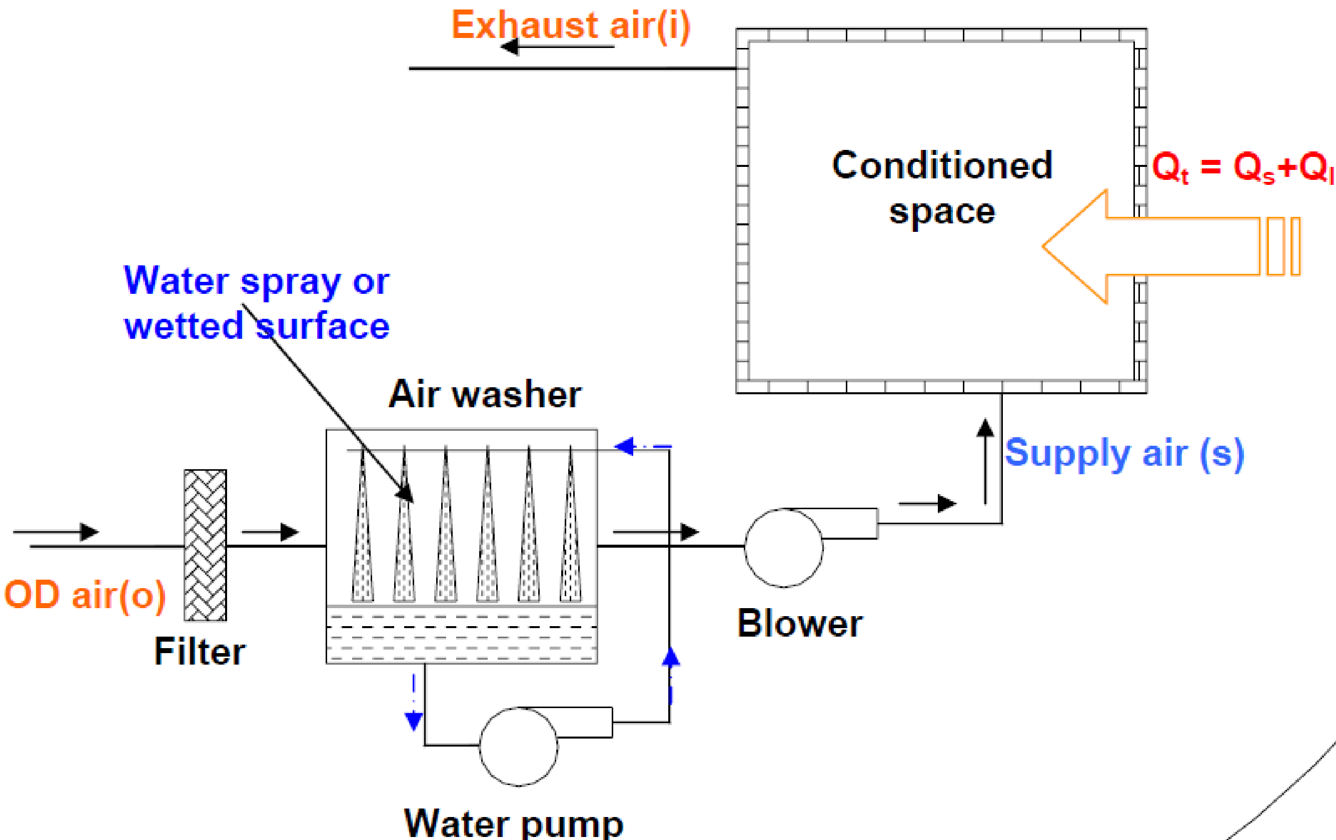
Evaporative air conditioning systems

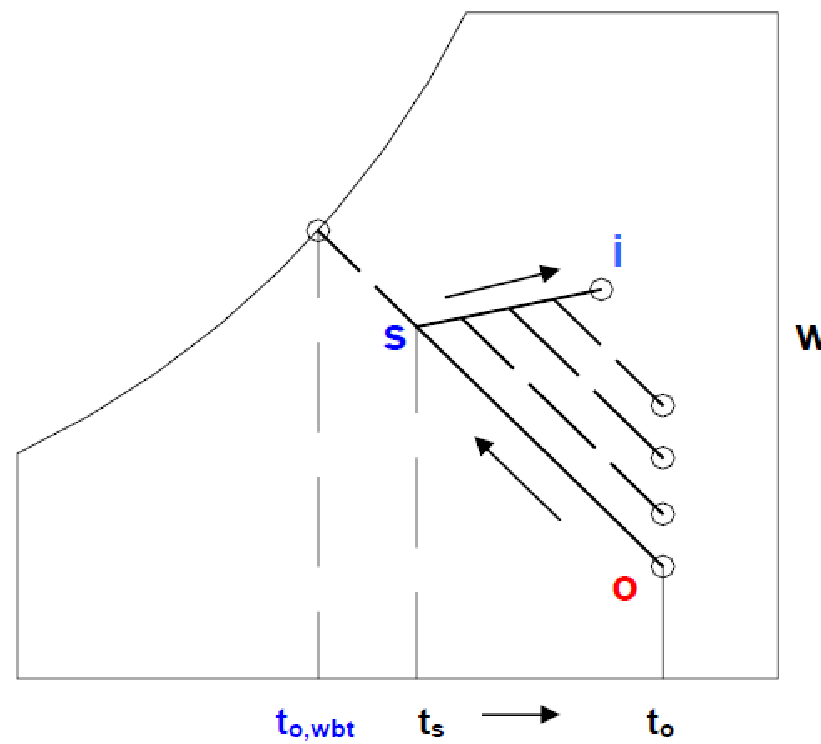
- Evaporative cooling has been in use for many centuries for cooling and for providing thermal comfort in hot and dry regions. This system is based on the principle that when moist but unsaturated air comes in contact with a wetted surface whose temperature is higher than the dew point temperature of air, some water from the wetted surface evaporates into air. The latent heat of evaporation is taken from water, air or both of them. In this process, the air loses sensible heat but gains latent heat due to transfer of water vapor. Thus the air gets cooled and humidified.

Type of evaporative cooling systems

- Direct evaporation process
- Indirect evaporation process, or
- A combination or multi-stage systems

Direct Evaporative system

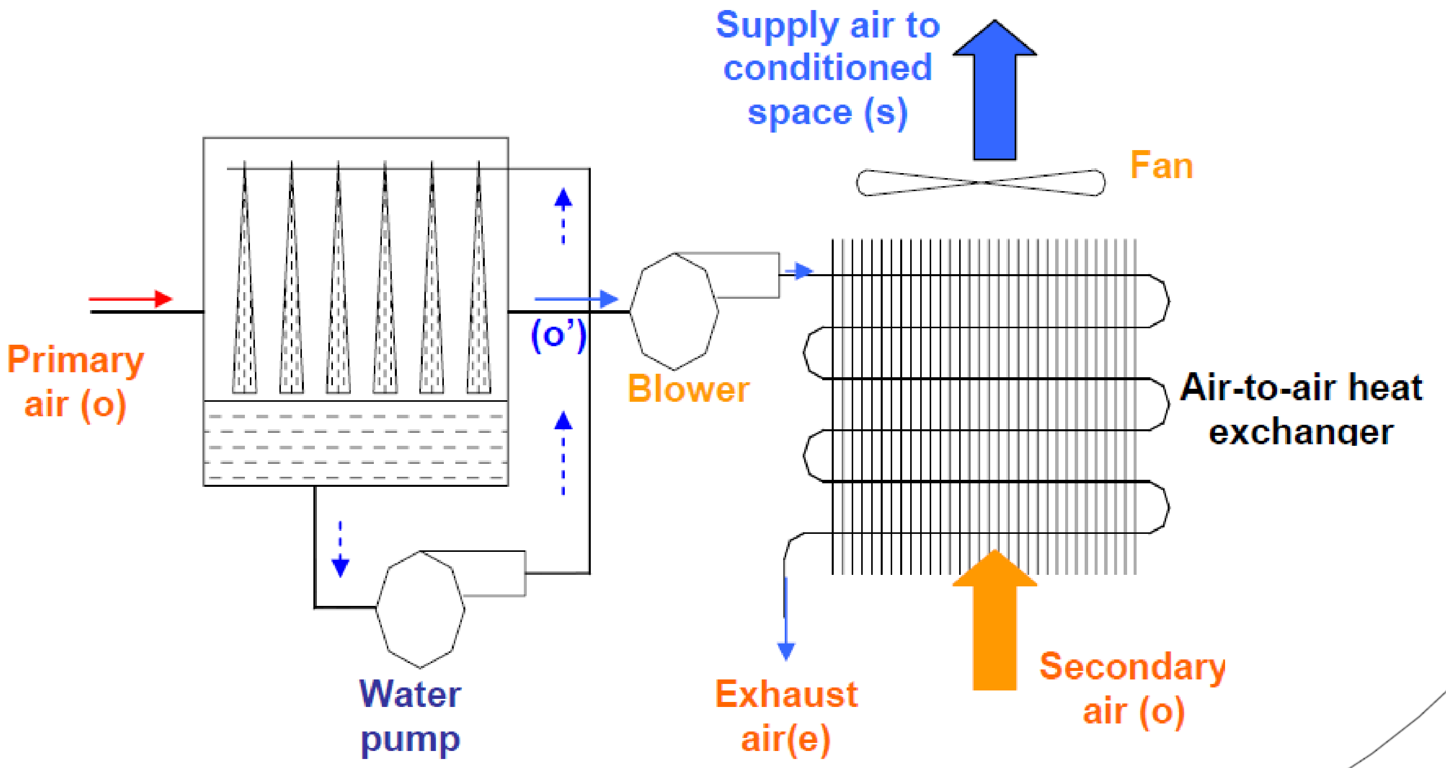


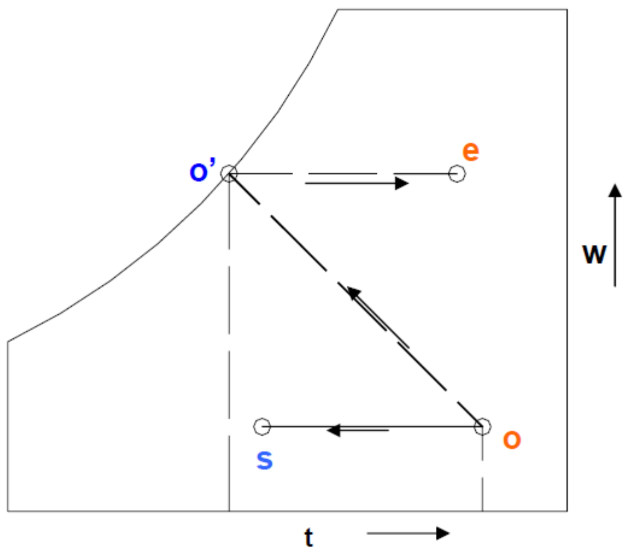


- the saturation efficiency or effectiveness of the evaporative cooling system ε as:

$$\varepsilon = \frac{(t_o - t_s)}{(t_o - t_{o,wbt})}$$

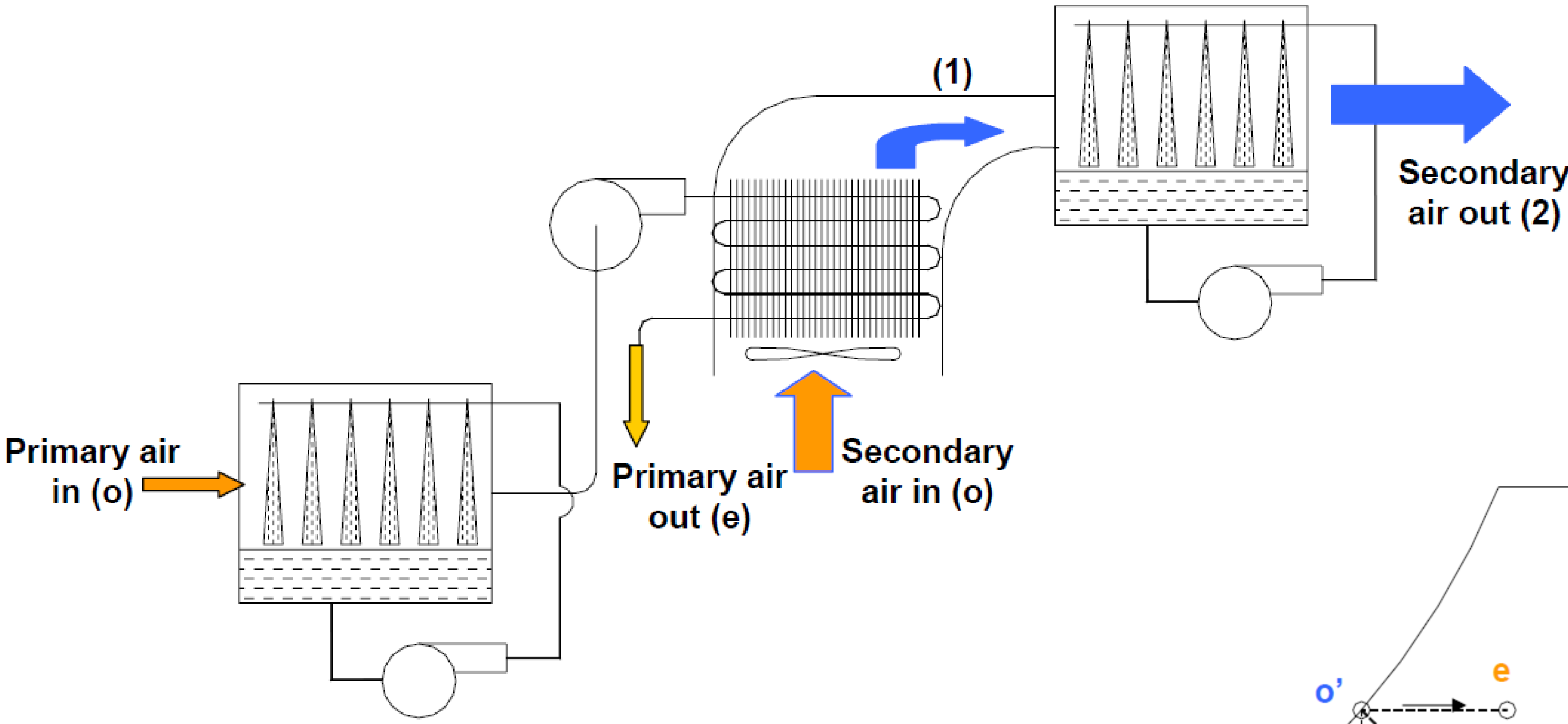
Indirect evaporative cooling system





Multi-stage evaporative cooling systems

- Several modifications are possible which improve efficiency of the evaporative cooling systems significantly. One simple improvement is to sensibly cool the outdoor air before sending it to the evaporative cooler by exchanging heat with the exhaust air from the conditioned space. This is possible since the temperature of the outdoor air will be much higher than the exhaust air. It is also possible to mix outdoor and return air in some proportion so that the temperature at the inlet to the evaporative cooler can be reduced, thereby improving the performance. Several other schemes of increasing complexity have been suggested to get the maximum possible benefit from the evaporative cooling systems. For example, one can use multistage evaporative cooling systems and obtain supply air temperatures lower than the wet bulb temperature of the outdoor air. Thus multistage systems can be used even in locations where the humidity levels are high.


(1)
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Secondary
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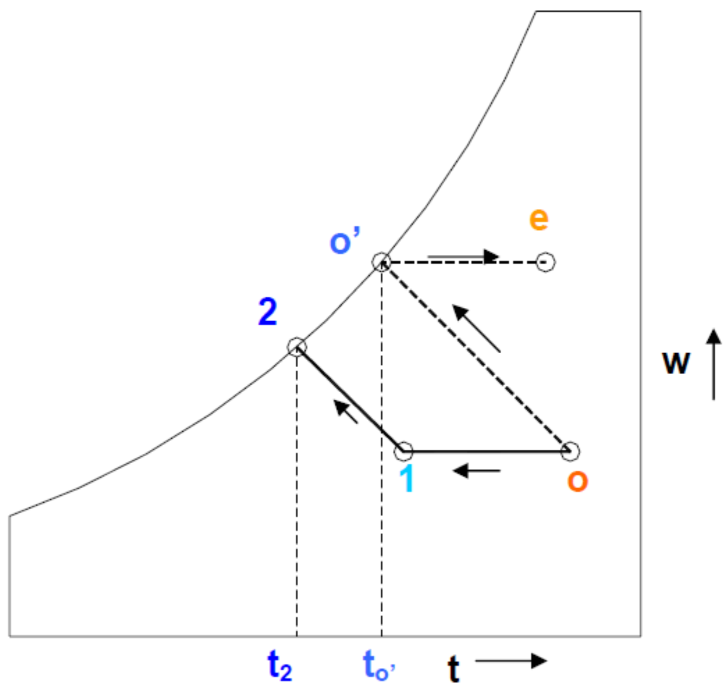
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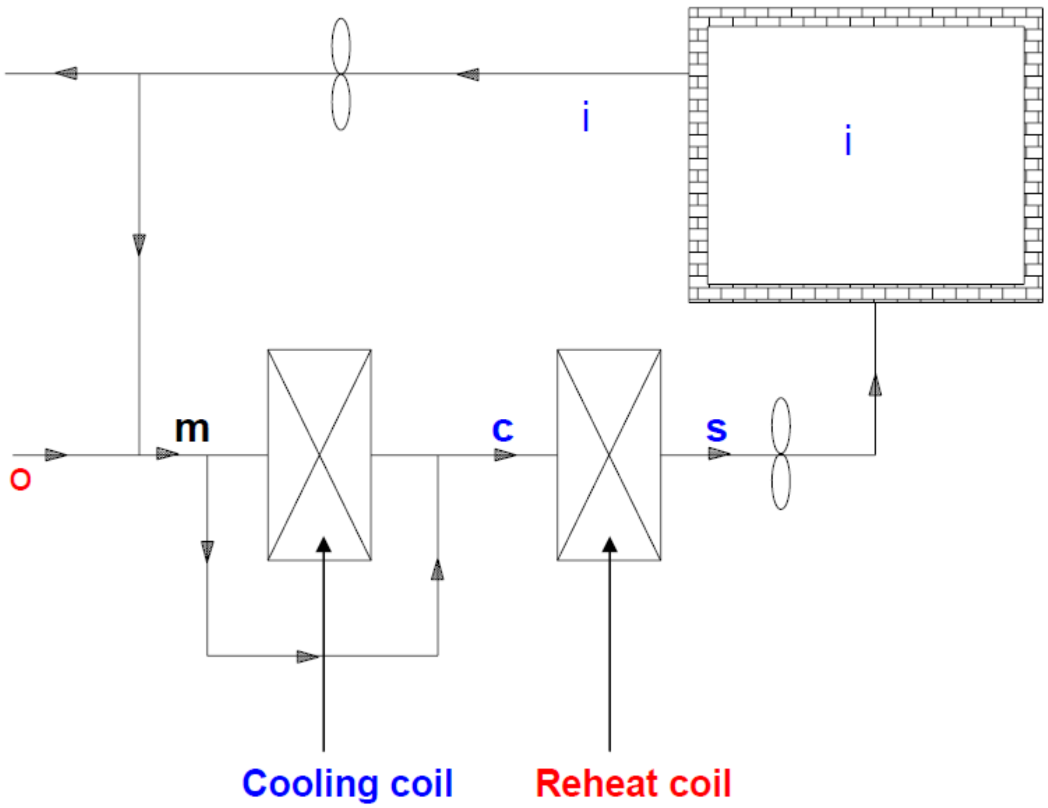
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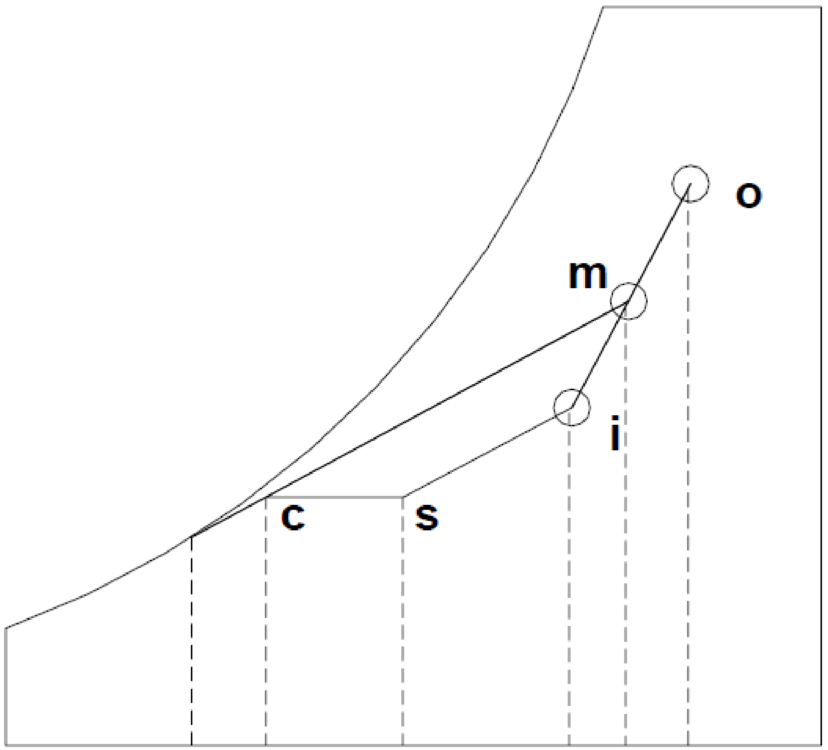
Reheat coil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Applicability of evaporative cooling systems

- One of the older rules-of-thumb used in USA specifies that evaporative cooling systems can be used wherever the **average noon relative humidity during July is less than 40%**. However, experience shows that evaporative coolers can be used even in locations where the relative humidity is higher than 40%. A more recent guideline suggests that evaporative cooling can be used in locations where the **summer design wet bulb temperatures are less than about 24^{o}C (75^{o}F)**. It is generally observed that evaporative coolers can compete with conventional systems when the noon relative humidity during July is less than 40%, hence should definitely be considered as a viable alternative, whereas these systems can be used in places where the noon relative humidity is higher than 40% but the design WBT is lower than 24^{o}C, with a greater sacrifice of comfort.

- Evaporative air conditioning systems can also be used over a broader range of outdoor conditions in factories, industries and commercial buildings, where the comfort criteria is not so rigid (temperatures as high as 30^oC in the conditioned space are acceptable). Evaporative air conditioning systems are highly suitable in applications requiring large amounts of ventilation and/or high humidity in the conditioned space such as textile mills, foundries, dry cleaning plants etc.
- Evaporative cooling can be combined with a conventional refrigeration based air conditioning systems leading to substantial savings in energy consumption, if the outside conditions are favorable. Again, a number of possibilities exist. For example, the outdoor air can be first cooled in an evaporative cooler and then mixed with the re-circulating air from the conditioned space and then cooled further in the conventional refrigerant or chilled water coil.

Advantages and disadvantages of evaporative cooling systems

- Lower equipment and installation costs.
- Substantially lower operating and power costs. Energy savings can be as high as 75 %.
- Ease of fabrication and installation.
- Lower maintenance costs.
- Ensure a very good ventilation due to the large air flow rates involved, hence, are very good especially in 100 % outdoor air applications.
- Better air distribution in the conditioned space due to higher flow rates.
- The fans/blowers create positive pressures in the conditioned space, so that infiltration of outside air is prevented.
- Very environment friendly as no harmful chemicals are used.

Disadvantages

- The moisture level in the conditioned space could be higher, hence, **direct evaporative coolers are not good when low humidity levels in the conditioned space is required**. However, the indirect evaporative cooler can be used without increasing humidity.
- **Since the required air flow rates are much larger, this may create draft and/or high noise levels in the conditioned space**.
- **Precise control of temperature and humidity in the conditioned space is not possible**.
- May lead to health **problems due to micro-organisms** if the water used is not clean or the wetted surfaces are not maintained properly.

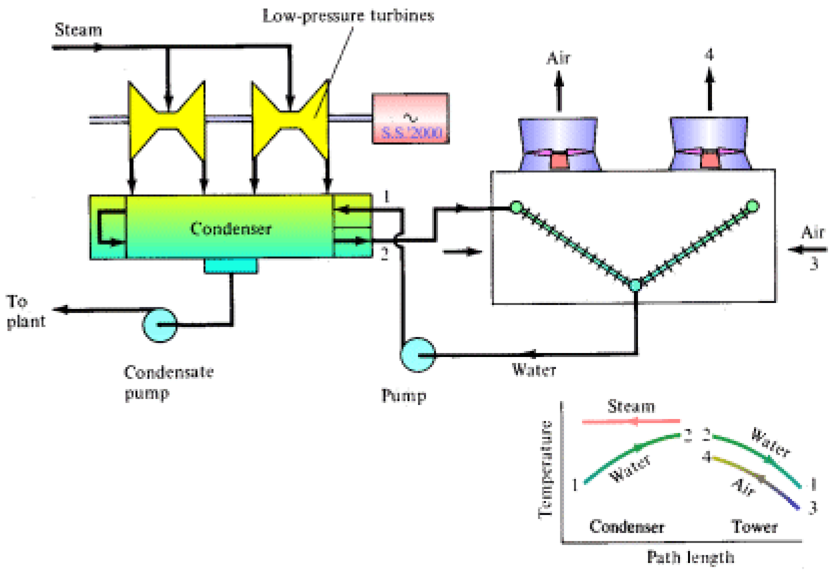
Cooling Towers

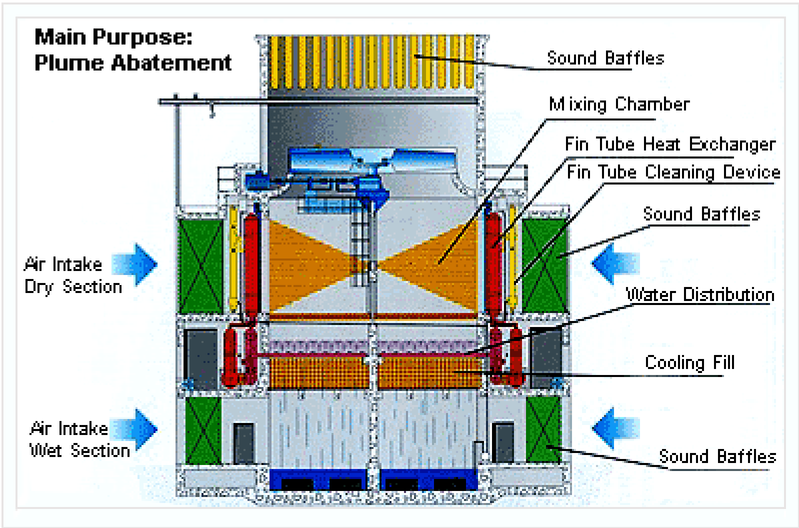
– Some Concerns

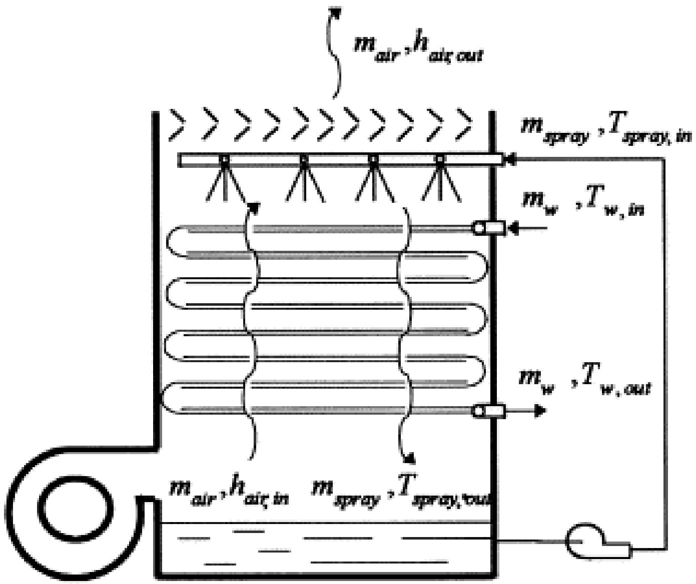
- **The water used by a cooling tower** can be broken into three components: **evaporation, drift, and blowdown**. The evaporative effect of the cooling tower represents the useful cooling process, and it is reasonable to consider this a fixed value.
- Drift is the entrainment of water droplets in the discharge vapor and does not produce useful cooling. **Drift losses are estimated to be less than 0.2% of the total water consumption when the cooling tower is properly specified and operated**.
- As water is evaporated from the cooling tower during the normal course of heat transfer, the soluble salts are left behind in the cooling tower circulating water and increase the proportion of solids to water. **The only way to reduce this proportion is to introduce more makeup water and to blowdown some of the circulating water. The amount of blowdown should be minimized while maintaining the required water quality parameters.**

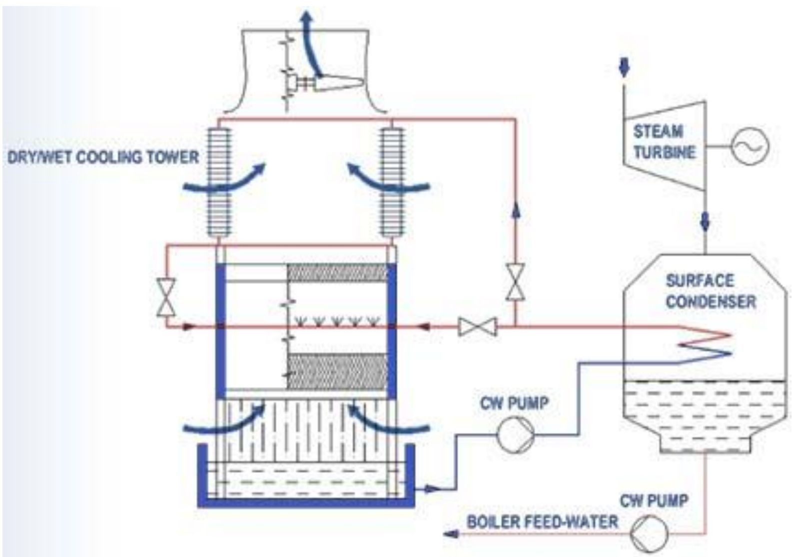
Cooling Tower

- Drycooler, wet cooling tower, and hybrid tower









Some methods to improve blow-down

- Develop an **optimized water treatment and blowdown strategy**; influencing factors include the hardness of the water, the location of cooling tower, the material of the piping, and the type of tower.
- **The water that is drained from cooling equipment to remove mineral build-up is called “blow-down” water or “bleed” water**.
- Use **monitoring and automatic controls to optimize the blowdown volume** and interval based on the water conductivity.
- Install a **filtration system** (such as a rapid sand filter or high-efficiency cartridge filter) to cleanse the water. This enables the system to operate more efficiently with less water and fewer chemicals.
- Install a **makeup water softening system** when hardness is driving the amount of blowdown.
- Install covers to **block sunlight penetration**. Reducing the amount of sunlight on tower surfaces can significantly reduce biological growth. Consider installing proven alternative water treatment technologies (such as ozonation or ionization systems) that keep solids entrained in water for longer periods of time.

Alternative Water Efficiency Strategies

- Determine the **feasibility of using non-potable water as makeup water in the cooling towers**. The source of the non-potable water can vary from regional gray-water distribution systems to storm-water reuse (e.g., through the collection of rainwater from the roof of the facility) to local bodies of water (such as canals, rivers, etc.).
- **Using a combination of drycoolers and evaporative cooling towers** that can be sequenced based on cooling load, the time of year, and the water usage impact.
- Using **hybrid cooling towers**.
- Using **adjacent bodies of water** (e.g., rivers, lakes, oceans, etc.) or ground wells (i.e., a geothermal system) for heat rejection.

OPTIMIZE PUMPING CONTROL

Availability and Maintainability Considerations

- All redundant components are **on-line with water pumped through them at full flow. This approach is the least efficient from a pumping energy standpoint**.
- All redundant components are on-line with water pumped through all system **components at a proportionally reduced flow rate**.
- **All redundant components are off-line with no water pumped through them** (the operation of redundant and active components may be cycled to balance component runtimes). Although this option may be the most energy efficient, the control method and the time it takes to bring redundant components online in the event of a component failure need to be carefully evaluated to ensure the cooling system availability goals are met.

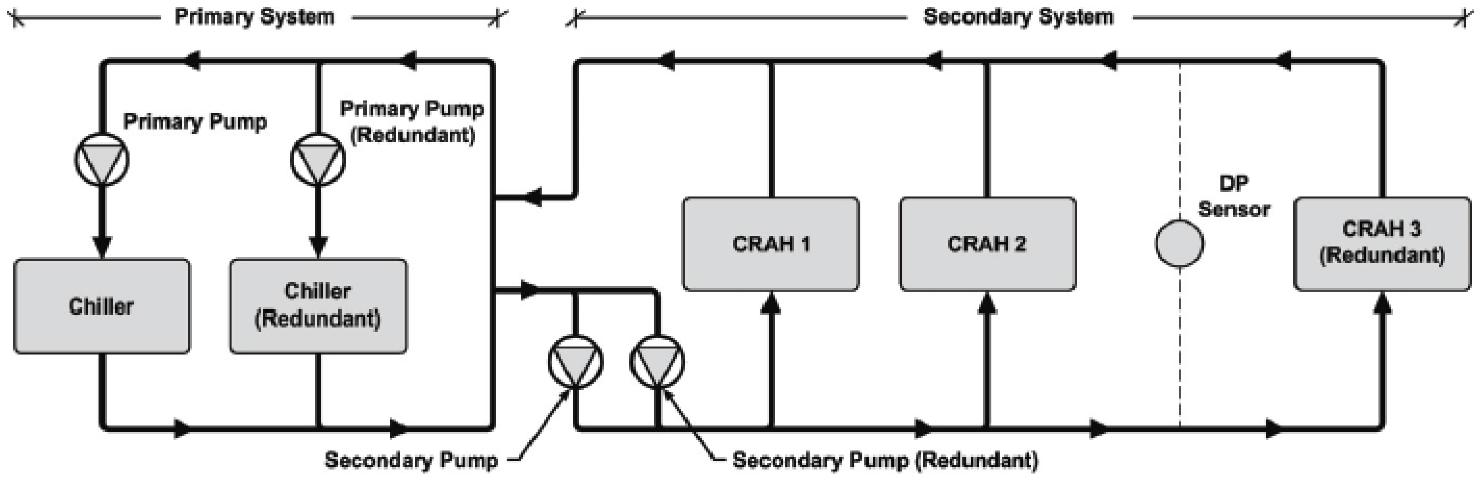
Preferred operational sequence for a power outage

- **Pumping system components are considered to be nonessential and are not provided with generator backup. This is uncommon in datacom facilities** but should be reviewed if the data center is located in a multiuse facility.
- **Pumping system components are considered to be essential and are provided with generator backup.** It should be noted that there will be a short-duration power interruption whenever the transfer to the generator occurs.
- **Pumping system components are considered to be critical and are fed by UPS units and provided with generator backup.** Used for an uninterruptible cooling system and may prove to be the least complex from a pumping controls standpoint since there should essentially be no change in state as the result of a power failure.

Piping System Configurations

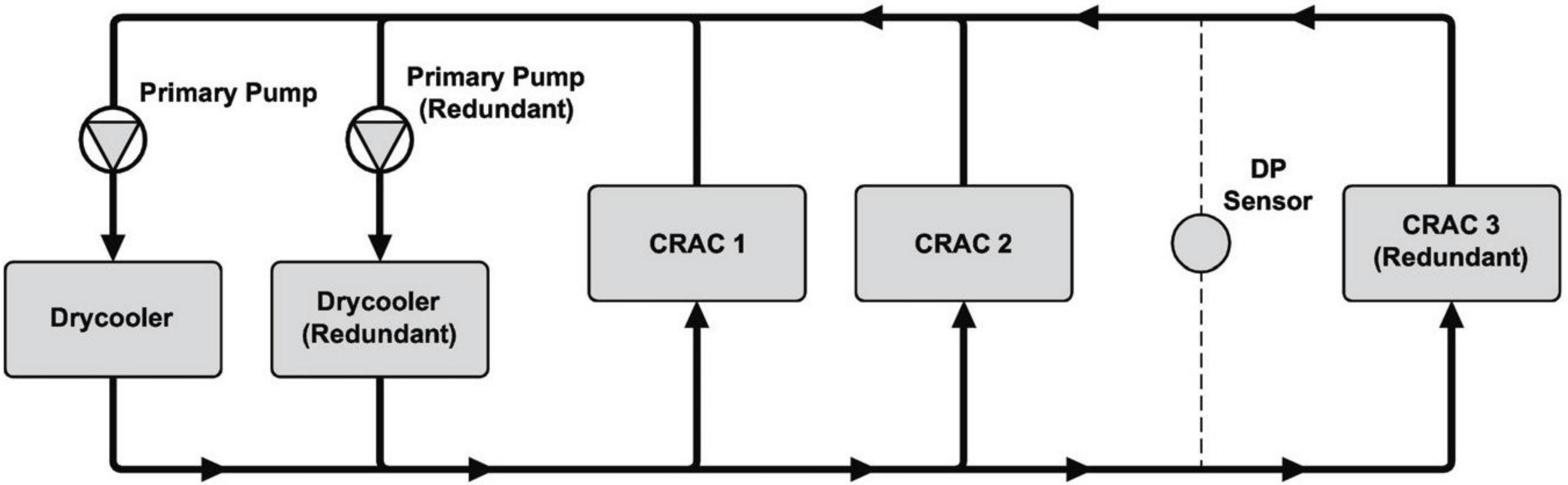
Primary-secondary systems

- **Primary-secondary systems have primarily been used when a constant flow is required through the cooling plant equipment** (such as chillers, cooling towers, etc.) to ensure proper equipment operation and that the cooling load is variable. **The two loops can be considered to be hydraulically decoupled and the primary loop is often constant flow, whereas the secondary loop may be constant flow or variable flow.**



Primary-only system

- **Typically for the condenser water to flow through the drycoolers and the water-cooled DX CRAC units**. However, improved chiller technology, which allows wider variances in evaporator water flow, has made primary-only pumping systems more viable for chilled water systems.
- **The use of primary-only pumping systems for data centers can reduce energy use and increase availability**.



Primary-only systems vs. primary-secondary systems:

- Total annual plant energy: 2% to 5%
- First cost: 4% to 8%
- Life-cycle cost: 3% to 5%
- Also, fewer pumps, piping, valves, and controls are required in a primary-only system, which reduces the complexity of the system, the number of bypass devices required (for concurrent maintenance and fault tolerance), the first cost, and the energy consumption.

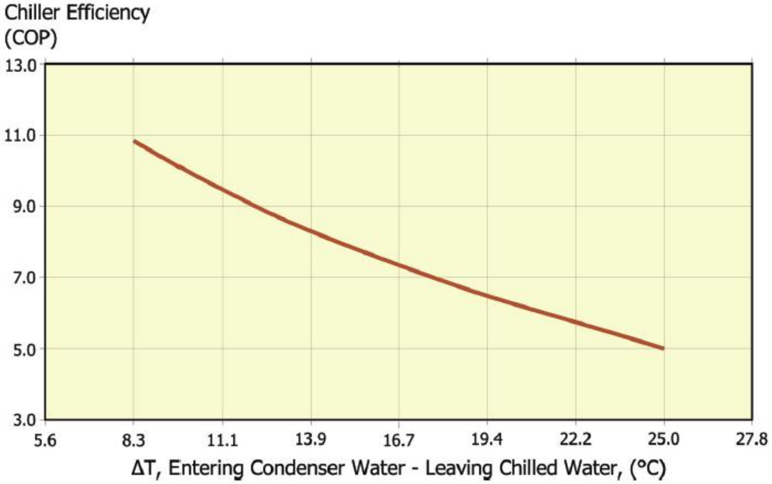
Pumping System Flow Control

- The most energy-efficient method for handling part-load conditions is **reducing the pumping system flow rates using VSDs**.
- VSDs offer the ability to run the pump motors at low speeds, therefore reducing the flow while reducing the power consumption of the pumping system.

OPTIMIZE CHILLED-WATER AND CONDENSER-WATER SUPPLY TEMPERATURES

- Chilled water temperatures:
  - Chilled-water temperature **optimization focuses on providing the highest practical temperature that will still enable the CRAH units to meet the IT equipment inlet air temperature requirements**.
  - The optimized **chilled-water set point is between 55˚F and 60˚F (12.8˚C and 15.6˚C).** This is consistent with the ASHRAE recommended temperature range (ASHRAE 2009a) **for supply air into servers of 64.4˚F to 80.6˚F (18˚C to 27˚C).**

- **Condenser-Water Temperature**
  - Condenser-water temperature optimization strategies for water-cooled chillers should aim to **provide the coolest possible temperature based on the ambient wet bulb temperature**. The cooling tower operational parameters, such as **approach temperature and part-load performance, will influence the condenser water temperature**. **Cooling towers are relatively low-cost items when compared to chillers, so using oversized cooling towers that facilitate lower approach temperatures should be evaluated.**



Sample cooling equipment efficiency of water-cooled chillers (SI).
Adapted from ASHRAE (2009b), Figure 3.5b.

- A practical objective for the optimized condenser water set point is $5^{\circ}F$ ($2.8^{\circ}C$) below the ambient wet-bulb temperature. **Water-side economizer operation should be initiated whenever the condenser water temperature is low enough to precool the chilled-water return.** Full water-side economizing is achieved when the condenser water temperature is able to cool the chilled water to its set point.
- It should be noted that as condenser-water temperatures approach the chilled water temperatures, some form of condenser head pressure control will be required to allow the chiller to continue to operate.
- **Significant chiller compressor energy savings can be realized, often by simply adjusting operating set points**.
- **Lower condenser-water temperature requirements can increase cooling tower first cost**.
- The addition of condenser-water reset controls increases first cost and system complexity.

Selection of Optimum Liquid Temperature for Heat Rejection—Air-Cooled Equipment

- In order to deliver air at the low end of that thermal envelope, say 68°F (20°C), the chilled water temperature delivered to the chilled water coil should be in the range of 55°F to 60°F (12.8°C to 15.6°C), depending on the actual coil selection. For these air-cooled devices, these chilled water temperatures would actually lead to very efficient chiller operation, especially when compared to the more conventional chilled water supply temperatures of 42°F (5.6°C), as is typically found for comfort cooling (these air-cooled racks will be converted to liquid-cooling after the comparison is completed).

Selection of Optimum Liquid Temperature for Heat Rejection—Liquid-Cooled Equipment

- For the device level cooling solution being discussed, **the temperature of the liquid sprayed on or in contact with the chip can be 104˚F (40˚C) or even higher**. In order to deliver a liquid at that temperature, **the water fed to the CDU can be approximately 86˚F (30˚C). At such a supply temperature, there is no reason to use chilled water;** instead water delivered straight from a closed-loop fluid cooler can provide all the cooling necessary.

IMPROVE PUMPING EFFICIENCY

- Rightsizing the pump selection when considering the **number of pumps**, the **impeller type**, and the **motor rotational speed and efficiency saves energy**.
  - It is highly recommended that **pump selection software be used in selecting the pump**. This software will allow for a comprehensive review of pump types, pumping configurations, and pump-motor speeds.
- **Multiple pumps for efficiency** are complementary to redundancy design goals.
- Properly selected pumps will be more energy efficient and/or easier to maintain.

- **Selection of Chilled-Water Pumps & Condenser Water Pumps**
  - **Optimized for the operating point**. Check several manufacturers and pump models to find the most efficient pump for the application.
  - **The delta T of the chilled water should be optimized**. A greater delta T will result in lower flow and, thus, lower pumping energy consumption but potentially lower chiller efficiency or larger chilled-water coils.
  - **Premium efficiency motors and, where applicable, variable-speed drives** should be specified.

DIRECT-EXPANSION (DX) VS. CHILLED-WATER SYSTEMS

- **An air-cooled direct expansion (DX) system might be better suited for a desert climate**; a shortage of water and cool night temperatures improve the DX system energy performance and make the DX system a better overall fit in such climates. Another example is in **cold climates where the energy penalty for the cost of freeze protection could offset the energy saving of a chilled-water system**.
- Advanced-design **water-cooled chilled-water systems can have power consumption figures that are 40%–50% less than air-cooled DX systems**. As system sizes increase, the yearly energy savings from water-cooled chilled-water systems increase to the point that the savings will provide an acceptable return on investment.

Cooling System Overview

- **DX systems are ideal for small data centers and supplemental cooling solutions**.
- **DX systems are also better in extreme environmental conditions**. Chilled-water systems lend themselves to larger data centers.

<table>
<tr><th>System Type</th><th>Heat Rejection</th><th>Mechanical Cooling Equipment</th><th>Terminal Equipment</th></tr>
<tr><td rowspan="2">Chilled Water</td><td colspan="2">Chiller (air-cooled)</td><td>CRAH (chilled water)</td></tr>
<tr><td>Cooling tower</td><td>Chiller (water-cooled)</td><td>CRAH (chilled water)</td></tr>
<tr><td rowspan="4">Direct Expansion (DX)</td><td>Condenser</td><td colspan="2">CRAC (DX)</td></tr>
<tr><td>Drycooler</td><td colspan="2">CRAC (water/glycol)</td></tr>
<tr><td colspan="2">Condensing unit</td><td>Air handler (DX)</td></tr>
<tr><td colspan="3">Self-contained AC unit/rooftop unit</td></tr>
</table>

- DX Systems
  - **Unitary equipment can be sized for the load to run at its best efficiency**.
  - An advance in displacement compressor technology has improved small system energy efficiency.
  - Efficiency improves for air-cooled DX systems in cooler climates.
- Chilled-Water Systems
  - **Large-capacity systems can produce cooling at the lowest power input per ton (kW)**.
  - **Water-side economizers** can be added for cool-weather energy savings.
  - Maintenance is minimized on the data center floor.

Concerns..

- DX Systems
  - Impractical for large data centers.
  - Increased maintenance due to multiple compressors, fans, and controls.
  - Can have higher energy consumption than chilled-water systems, especially at larger cooling capacities.
- Chilled-Water Systems
  - Impractical for small data centers.
  - Winterization and freeze protection costs could negate energy savings.
  - Water-cooled chillers require more building infrastructure.

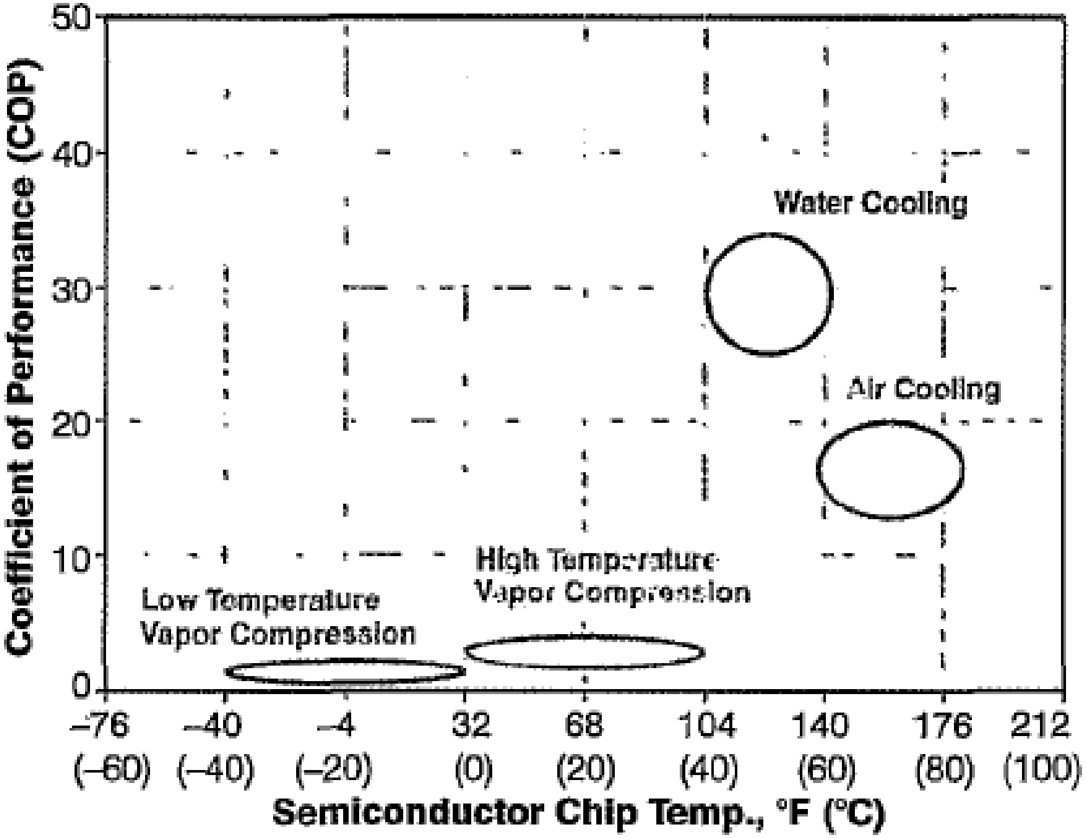
- **Thermodynamic efficiency of vapor compression cycles can be increased:**
  - Raising the space temperature allows the vapor compression cycle to run with a smaller temperature differential. This increases the thermodynamic efficiency of the cycle. With chilled-water plants, **the rule-of-thumb increase in efficiency is 1%-3% for every 1°F (0.6°C) rise in evaporator temperature**.
  - Chiller **part-load efficiencies in the range of 0.20 kW/ton are possible with 60°F (16°C) chilled water and concurrent low condenser water temperature.** In many climates, it may be possible to produce 60°F (16°C) water through evaporative cooling without the use of chillers for many hours of the year.

Advantages for Liquid Cooling General

- Sorell and Rodgers (2006) evaluated eight different cooling scenarios, including the currently entrenched computer room air handler-based solutions (CRAHs), as well as upcoming in-chassis cooling solutions that use liquid-cooled cold plates on hot components.
- Sorell and Rodgers conclude that the **in chassis liquid cooling solutions provide the most energy efficient cooling solution** for data centers.

ASHRAE J., Dec. 2004

- **The speed of the circuits increase at a rate of approximately 2% for every 1 0˚C (1 8˚F) reduction in chip temperature.**
- COP = cooling load/power input to cooling system



- **Lower noise levels**.
- The choice of liquid-cooled versus air-cooled generally has more to do with factors other than efficiency.
- **Close control of electronics temperatures**.
  - However, liquid in electronic equipment raises a **concern about leaks**. This is an issue because maintenance, repair, and replacement of electronic components result in the need to disconnect and reconnect the liquid carrying lines.

New Construction

- For a new data center, the cooling architect must consider a number of factors, including **data center workload**, **availability of space, location-specific issues, and local climate.**
- If the data center will have an economizer, and **the climate is best suited to air-side economizers because of mild temperatures and moderate humidity, then an air-cooled data center may make the most sense**. Conversely, **if the climate is primarily dry**, **then a water-side economizer may be ideal**, with the cooling fluid conveyed either to the racks or to a coolant distribution unit (CDU).

- **Liquid cooling more readily enables the reuse of waste heat**.
- For adequately planned from the beginning, **reusing the waste energy from the data center may reduce energy use of the site or campus. In this case, liquid cooling is the obvious choice because the heat in the liquid can most easily be transferred to other facilities that house them.** To meet this challenge, **the use of direct water or refrigerant cooling at the rack or board level** is now being deployed.

Expansions

- **For adding or upgrading equipment** in an existing data center (normally do not have large raised floor heights, or the raised floor plenum is full of obstructions such as cabling), **if ITE requires higher power density than the existing raised floor air-cooling can support, liquid cooling can be the ideal solution**.
- Current typical **air-cooled rack powers can range from 6 to 30 kW**. In many cases, rack powers of 30 kW are well beyond the capability of air cooling. Liquid cooling to a datacom rack, cabinet-mounted chassis, cabinet rear door, or other localized liquid cooling system can make these higher-density racks nearly room neutral by cooling the exhaust temperatures down to room temperature levels.

High Density and HPC (high-performance computing)

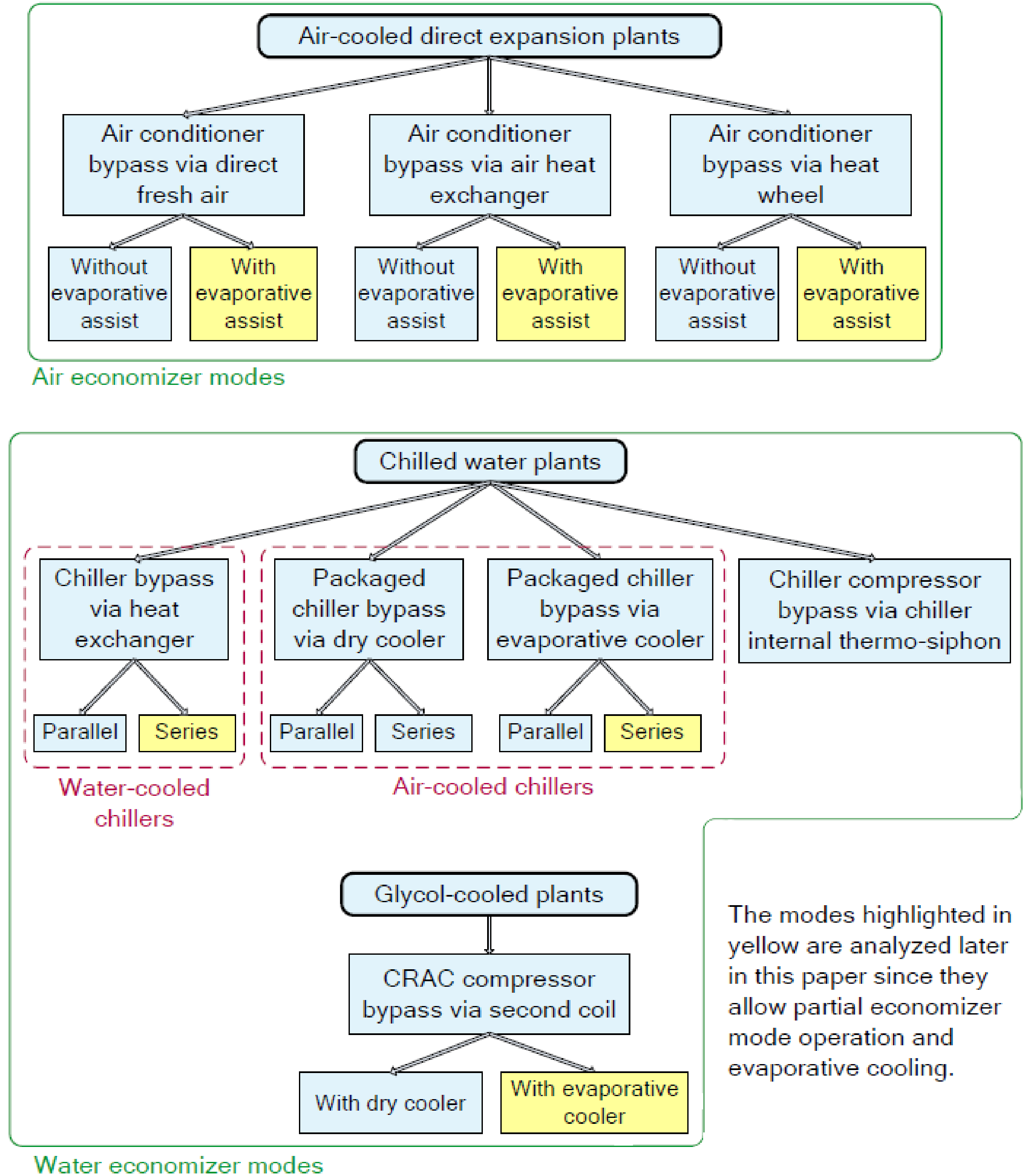
- Because of the energy densities found in many **HPC applications and next-generation high-density routers**, liquid cooling can be a very appropriate technology if the room infrastructure is in place to support it. One of the main cost and performance drivers for HPC is the node-to-node interconnect.
- Because of this, HPC typically is driven toward higher power density than is a typical enterprise or internet data center. **Thirty-kilowatt racks are typical, with densities extending as high as 80 to 120 kW**. These higher powers would be very difficult if liquid cool is not implemented. **The advantages of liquid cooling increase as the load densities increase**.

Economizer (free cooling)

Economizer mode

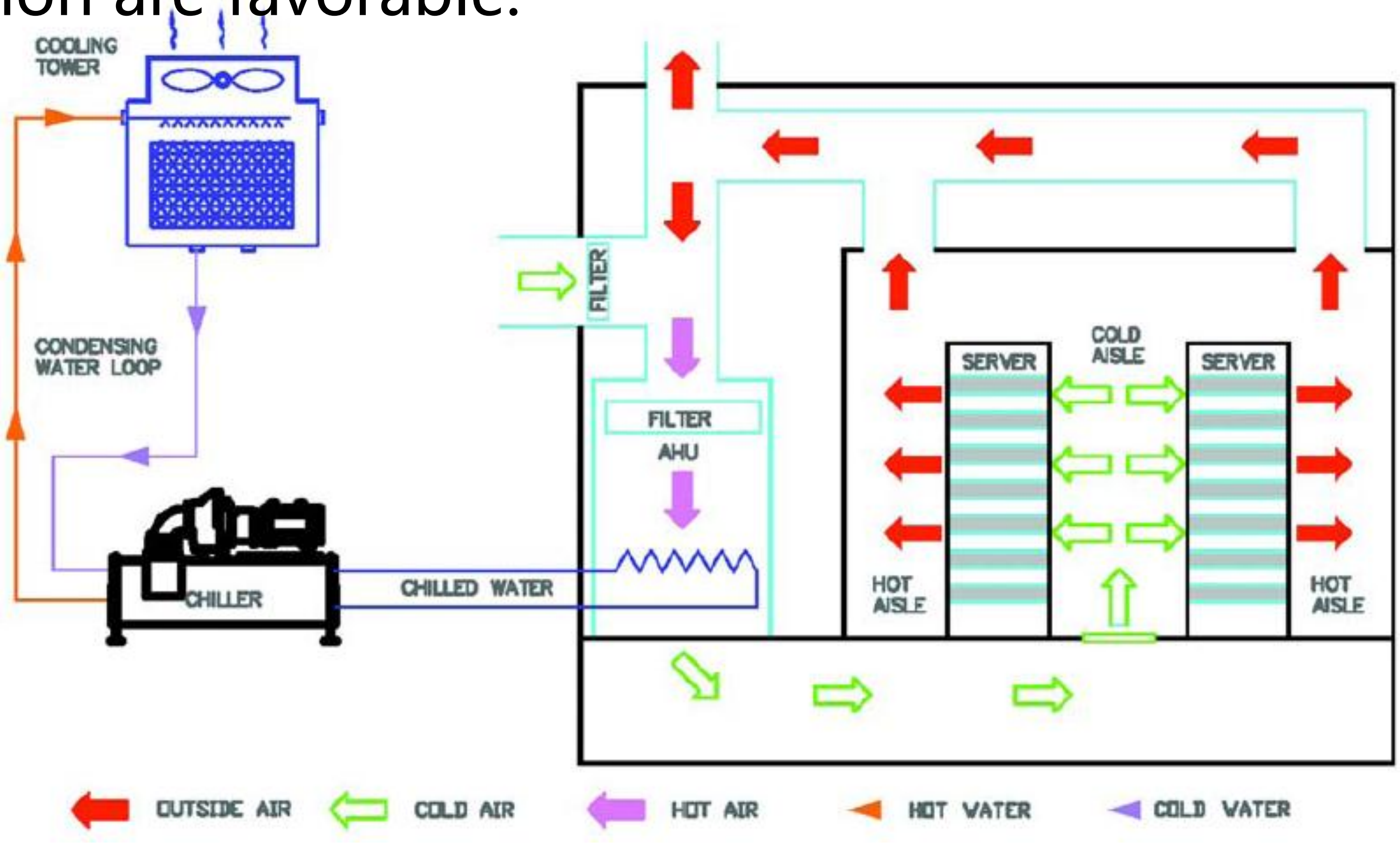
- **In an economizer mode, the compressor function is fully or partially bypassed**, eliminating or reducing its energy use. The compressor is used to move heat from within the data center to the outdoor environment when the outdoor temperature is greater than the data center temperature.
- **Economizer modes are sometimes referred to as "free cooling".** Most systems using economizer modes spend most of the time in a partial bypass mode, so part of the cooling energy is saved, **but the cooling is not "free".**

- **The operation of data center at partial loads increases the benefit of economizer modes**, and **more designers recognize that data centers spend a considerable fraction of their life at light load.**
- The trend toward operation of data centers at **higher IT air return temperatures has a dramatic effect on the percent of time economizer mode operation** is possible, especially in warmer climates.
- **Most new implementations of economizer modes can now operate in a "partial" economizer mode**, which greatly increases the amount of energy saved in almost all cases.
- The tools available for quantifying the energy saved by implementing economizer modes are now improved and frequently predict significant savings possibilities with excellent ROI.
- Real-world experience with economizer modes and improvement of controls and monitoring systems, have increased confidence that **these modes do not adversely affect the reliability of data centers.**

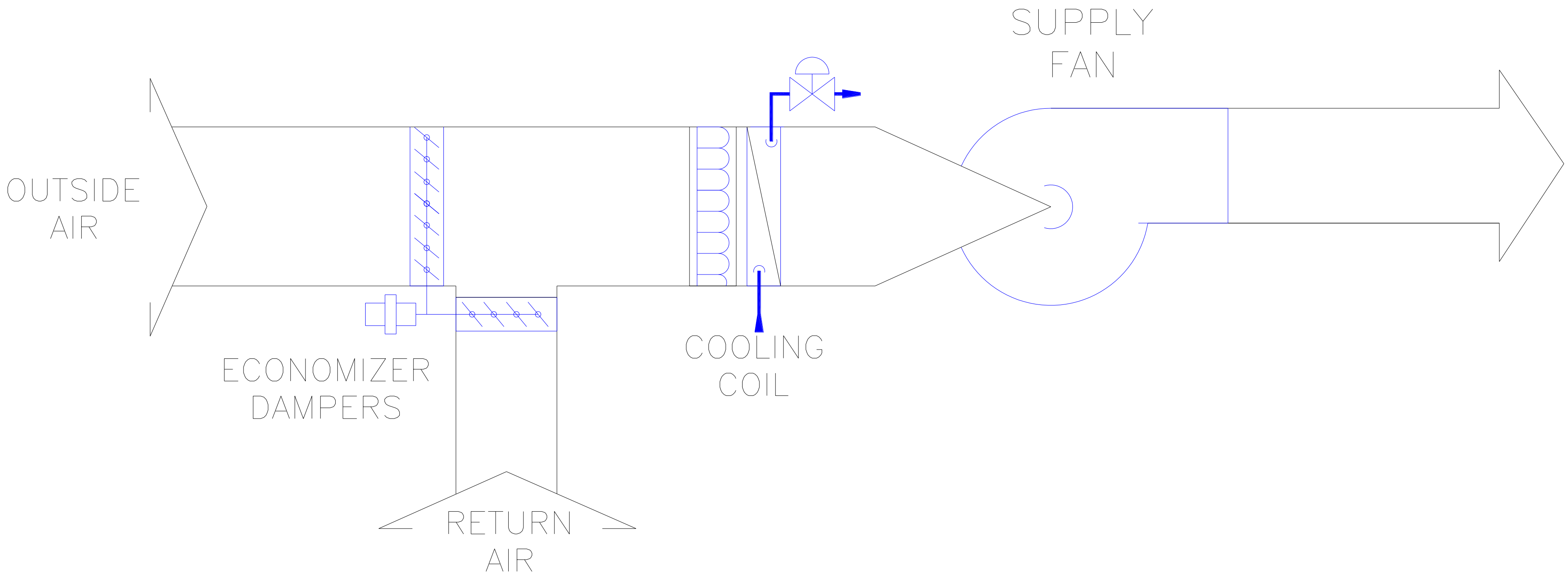

Air-cooled direct expansion plants
Air conditioner bypass via direct fresh air
Air conditioner bypass via air heat exchanger
Air conditioner bypass via heat wheel
Without evaporative assist
With evaporative assist
Without evaporative assist
With evaporative assist
Without evaporative assist
With evaporative assist
Air economizer modes
Chilled water plants
Chiller bypass via heat exchanger
Packaged chiller bypass via dry cooler
Packaged chiller bypass via evaporative cooler
Chiller compressor bypass via chiller internal thermo-siphon
Parallel
Series
Parallel
Series
Parallel
Series
Water-cooled chillers
Air-cooled chillers
Glycol-cooled plants
CRAC compressor bypass via second coil
With dry cooler
With evaporative cooler
The modes highlighted in yellow are analyzed later in this paper since they allow partial economizer mode operation and evaporative cooling.
Water economizer modes

Typical Airside economizer

The concept of an airside economizer is to capture outside air with low heat content to replace internal heat gain from occupants, lighting and equipment when outdoor weather condition are favorable.



Air-side economizer



Air-Side Economizer Design conditions

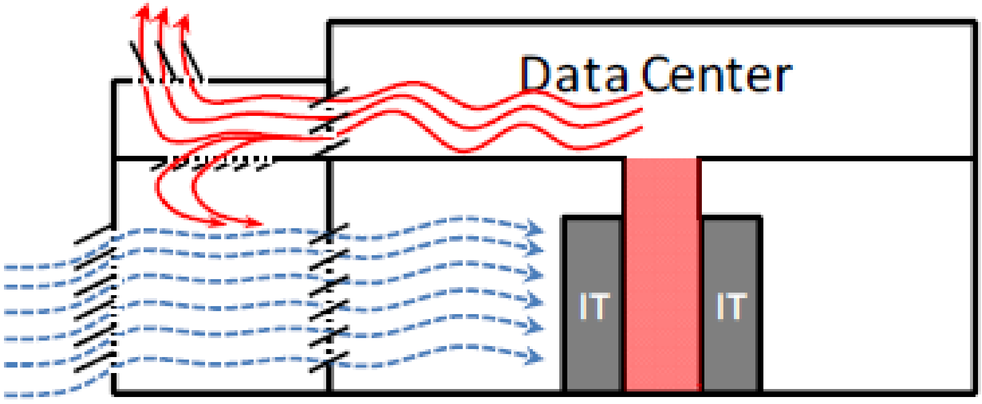
Table 2.1
Class 1, Class 2 and NEBS Design Conditions

Condition	Class 1 / Class 2		NEBS	
	Allowable Level	Recommended Level	Allowable Level	Recommended Level
Temperature control range	59°F – 90°F[a,f] (Class 1) 50°F – 95°F[a,f] (Class 2)	68°F – 77°F[a]	41°F – 104°F[c,f]	65°F – 80°F[d]
Maximum temperature rate of change	9°F. per hour[a]		2.9°F/min. [d]	
Relative humidity control range	20% - 80% 63°F. Max Dewpoint[a] (Class 1) 70°F. Max Dewpoint[a] (Class 2)	40% - 55%[a]	5% to 85% 82°F Max Dewpoint[c]	Max 55%[e]
Filtration quality	65%, min. 30%[b] (MERV 11, min. MERV 8)[b]			

[a]These conditions are inlet conditions recommended in the ASHRAE Publication *Thermal Guidelines for Data Processing Environments* (ASHRAE, 2004).
[b]Percentage values per ASHRAE *Standard* 52.1 dust-spot efficiency test. MERV values per ASHRAE Standard 52.2. Refer to Table 8.4 of this publication for the correspondence between MERV, ASHRAE 52.1 & ASHRAE 52.2 Filtration Standards.
[c]Telecordia 2002 GR-63-CORE
[d]Telecordia 2001 GR-3028-CORE
[e]Generally accepted telecom practice. Telecom central offices are not generally humidified, but grounding of personnel is common practice to reduce ESD.
[f]Refer to Figure 2.2 for temperature derating with altitude

Air conditioner bypass via direct fresh air

- A fresh air economizer mode (sometimes referred to as direct air) uses fans and louvers to draw a certain amount of cold outside air through filters and then directly into the data center when the outside air conditions are within specified set points.



Air conditioner bypass via air heat exchanger

- An air conditioner bypass via air heat exchanger mode (sometimes referred to as indirect air) uses outdoor air to *indirectly* cool data center air when the outside air conditions are within specified set points.

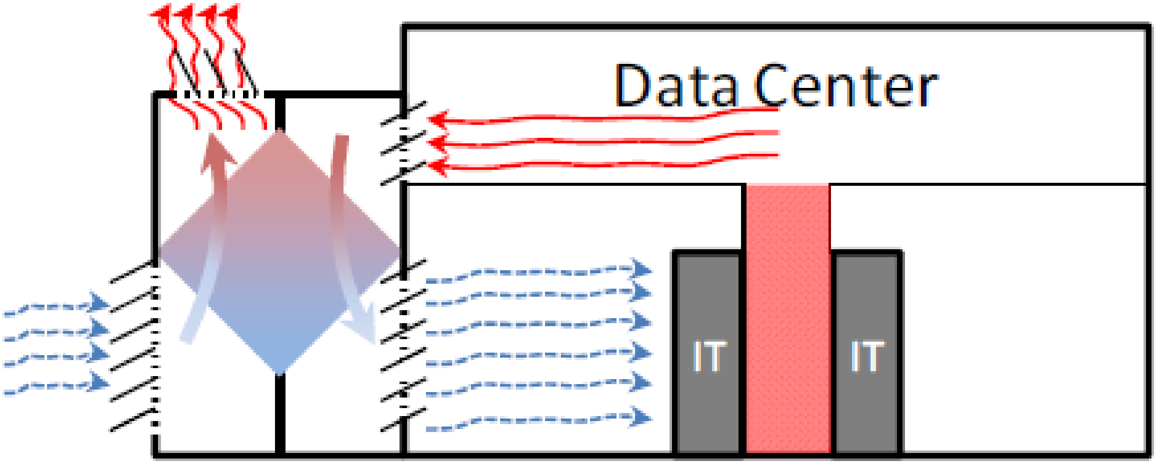
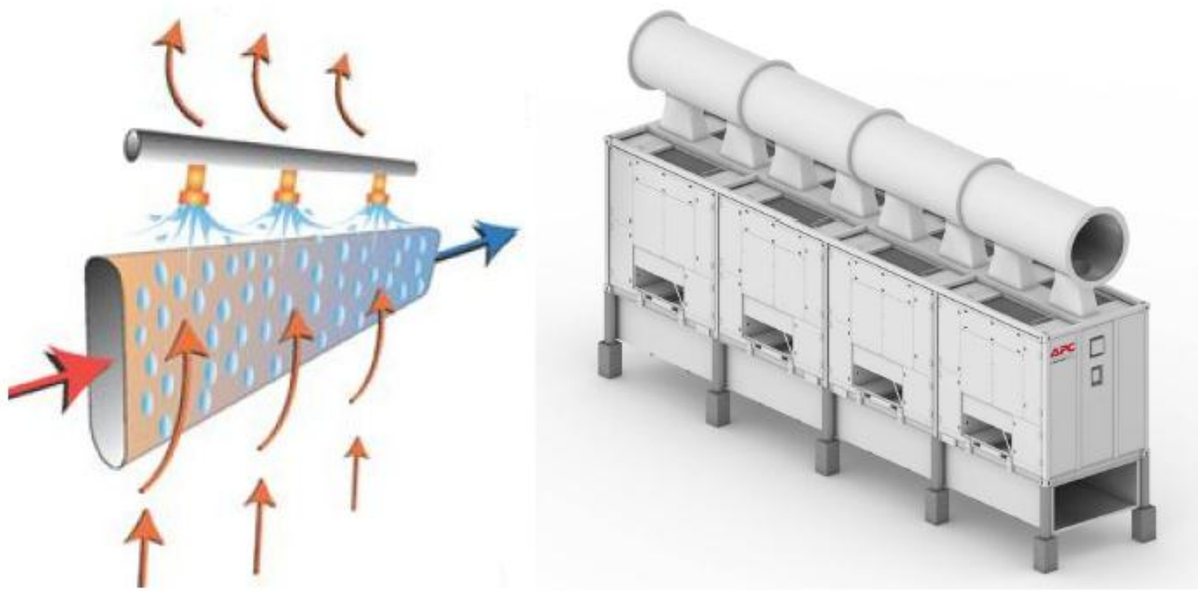


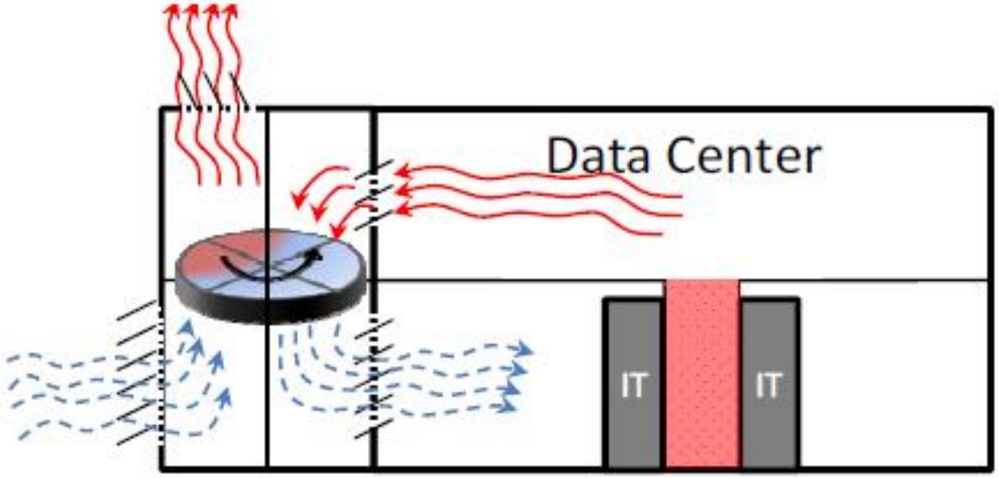
Figure 3b

Illustration of an air-to-air heat exchanger with evaporative assist (left) and an example of a complete cooling system with an integrated air conditioner bypass via air heat exchanger mode (right)



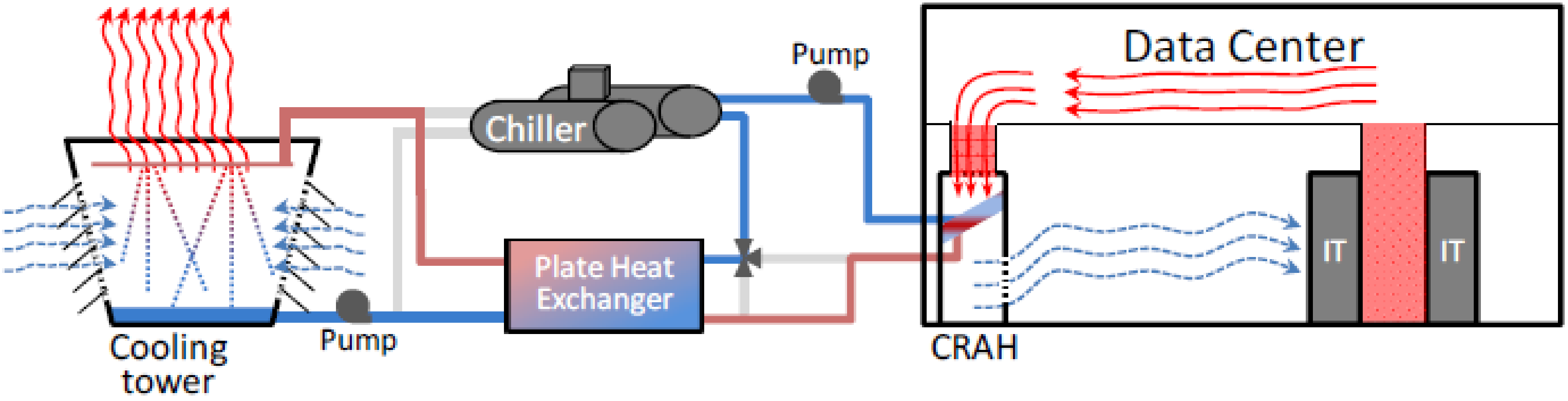
Air conditioner bypass via heat wheel

- An air conditioner bypass via heat wheel mode uses fans to blow the cold outside air through a rotating heat exchanger which preserves the dryer air conditions of the data center space



Chiller bypass via heat exchanger

- A chiller bypass via heat exchanger economizer mode uses the condenser water to indirectly cool the data center chilled water when the outside air conditions are within specified set points.



Chiller compressor bypass via chiller internal thermo-siphon

- Some chillers offer a thermo-siphon economizer mode option that allows the compressor to be turned off when the outside air conditions are within specified set points. **In this mode, the chiller acts like a simple heat exchanger. The principle of thermo-siphon causes the hot refrigerant to naturally move toward the cold condenser coil where is it cooled.** The cold refrigerant then relies on gravity or a pump to travel back to the evaporator coil where it cools the data center chilled water.

Packaged chiller bypass via dry cooler (or via evaporative cooler)

- A packaged chiller bypass via dry cooler economizer mode uses a heat exchanger known as a dry cooler to directly cool the data center chilled water when the outside air conditions are within specified set points.

Figure 6a

Packaged chiller bypass via dry cooler mode

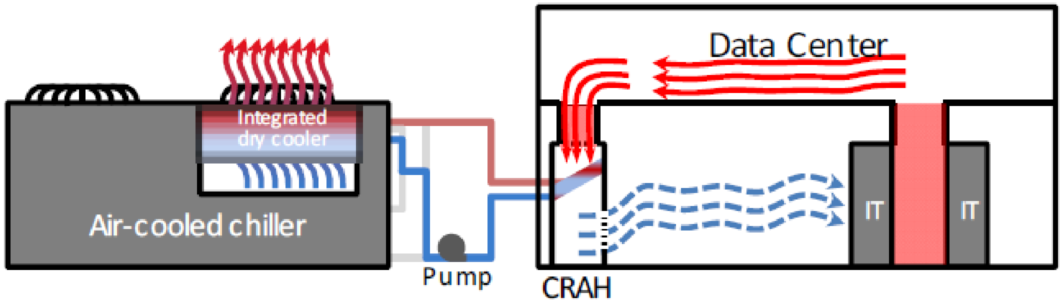


Figure 6b

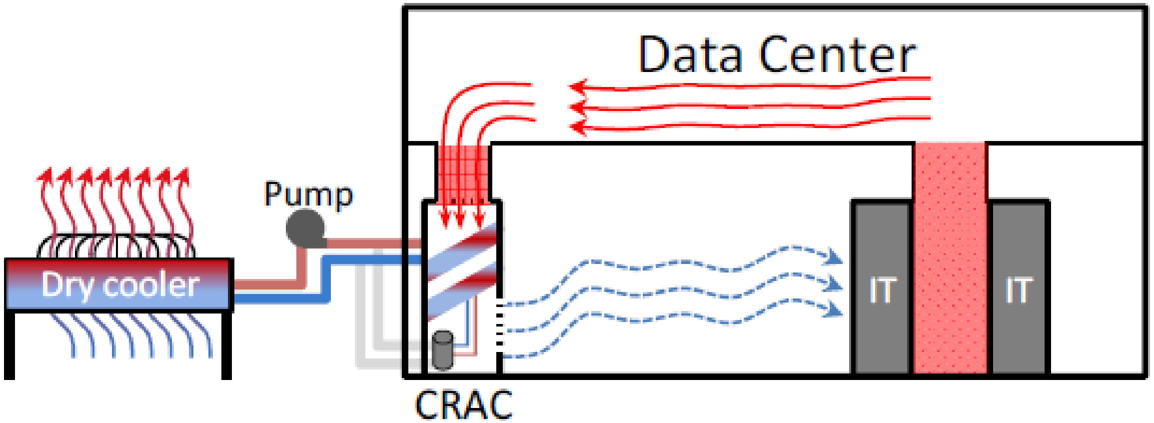
Example of a packaged chiller with integrated dry cooler

CRAC compressor bypass via second coil

- In this type of economizer mode**, the direct expansion (DX) CRAC includes an independent second coil that uses the condenser water during economizer mode**

Figure 7

CRAC compressor bypass via second coil mode



Comparison of the different economizer modes

Table 1

Qualitative comparison between types of economizer modes (blue cells indicate best performer for that attribute)

Economizer mode attribute	Air economizer modes: Air conditioner bypass via direct fresh air (w/ evap assist)	Air economizer modes: Air conditioner bypass via air heat exchanger (w/ evap assist)	Air economizer modes: Air conditioner bypass via air heat wheel (w/ evap assist)	Water economizer modes: Chiller bypass via heat exchanger [3]	Water economizer modes: Packaged chiller bypass via evaporative cooler [3]	Water economizer modes: CRAC compressor bypass via second coil (w/ evap assist)
Building shell compatibility	May require building shell modification	May require building shell modification	May require building shell modification	No issue with building shell	No issue with building shell	No issue with building shell
Ability to retrofit	Not logical to retrofit into existing system	Not logical to retrofit into existing system	Not logical to retrofit into existing system	Practical if space available	Practical if space available	Requires swapping out CRAC unit
Complexity of controls	Fewer devices to control	Fewer devices to control	Fewer devices to control	Most devices to control	Moderate number devices to control	Moderate number devices to control
Data center humidity control	Dependent on outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity	Independent of outdoor humidity
Life expectancy	20-40 years on heat exchanger	20-40 years on heat exchanger	20-40 years on heat exchanger	10-15 yrs on plate heat exchanger	10-20 years on evaporative cooler	10-20 years on cooling unit
Availability risks -loss of cooling water - poor air quality - fire suppression	Highly susceptible to outdoor air quality Shutdown required with clean agent suppression	Low downtime risk due to water loss. No risk due to poor air quality, or fire suppression	Low downtime risk due to water loss. No risk due to poor air quality, or fire suppression	Downtime due to loss of make-up water for cooling tower	No downtime due to water loss, poor air quality, or fire suppression	No downtime due to water loss, poor air quality, or fire suppression
Footprint	0.41 ft^2 / kW 0.038 m^2 / kW	0.788 ft^2 / kW 0.073 m^2 / kW	1.72 ft^2 / kW 0.16 m^2 / kW	1.94 ft^2 / kW 0.18 m^2 / kW	3.34 ft^2 / kW 0.31 m^2 / kW	2.02 ft^2 / kW 0.19 m^2 / kW
Need for backup refrigerant mode	Fully sized backup in case of poor outdoor air quality	Partially sized for extreme climates	Partially sized for extreme climates	Partially sized for extreme climates	Partially sized for extreme climates	Partially sized for extreme climates

Table 2

Quantitative comparison between types of economizer modes

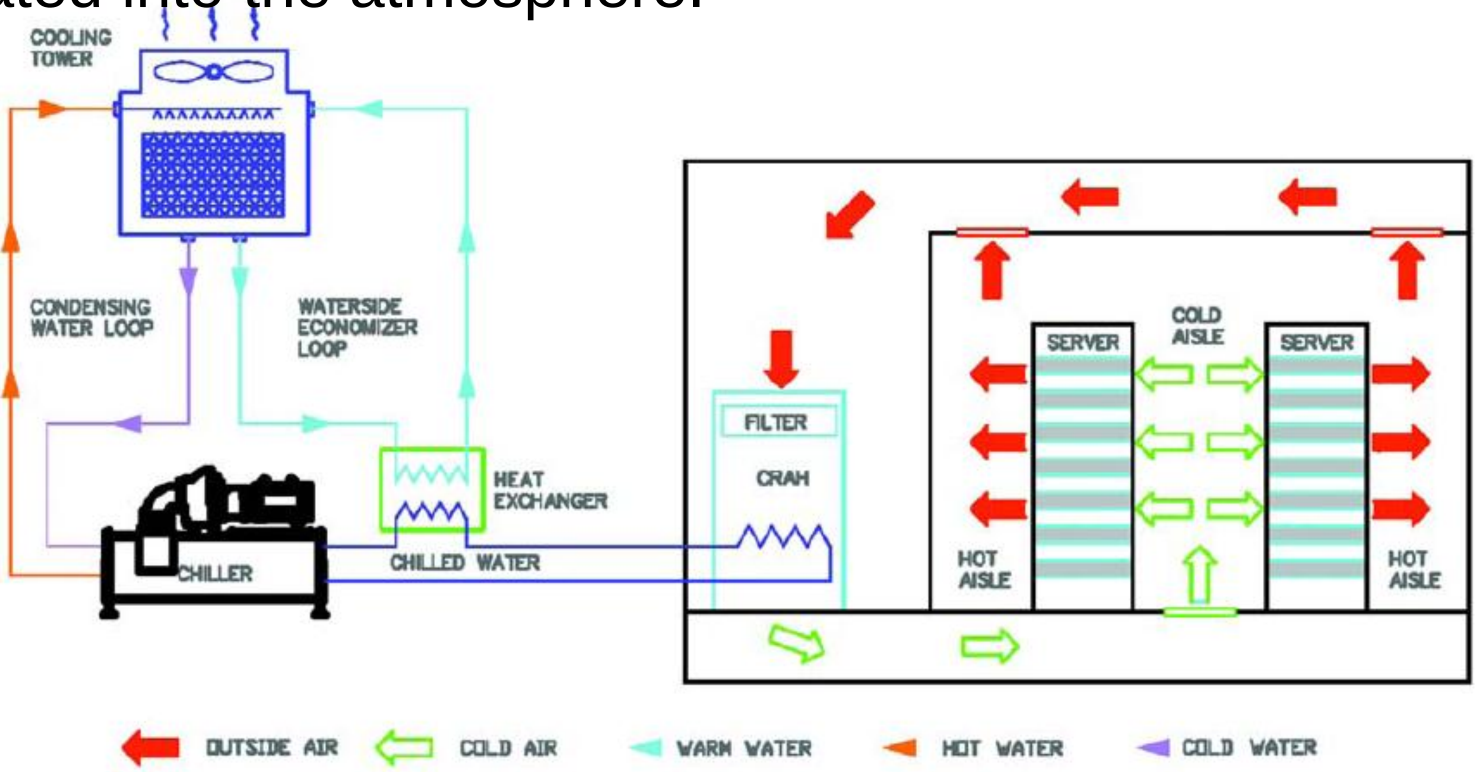
Economizer mode attribute	Air economizer modes: Air conditioner bypass via direct fresh air (w/ evap assist)	Air economizer modes: Air conditioner bypass via air heat exchanger (w/ evap assist)	Air economizer modes: Air conditioner bypass via air heat wheel (w/ evap assist)	Water economizer modes: Chiller bypass via heat exchanger [5]	Water economizer modes: Packaged chiller bypass via evaporative cooler [5]	Water economizer modes: CRAC compressor bypass via second coil (w/ evap assist)
The following attributes are based on a 1MW data center at 50% IT load, located in St. Louis, MO, U.S. See side bar for all assumptions.						
Annual water consumption	100 gal 379 L	1,262,000 gal 4,777,000 L	257,000 gal 973,000 L	7,000,000 gal 26,000,000 L [6]	128,000 gal 485,000 L	128,000 gal 485,000 L
Capital cost of entire cooling system	$2.2 / watt	$2.4 / watt	$2.8 / watt	$3.0 / watt	$2.3/ watt	$2.0 / watt
Annual maintenance cost of entire system [7]	75%	75%	83%	100%	100%	92%
Total cooling energy	737,506	340,365	377,625	589,221	736,954	960,974
Annual hours - full economizer mode	5,723	7,074	5,990	4,705	5,301	4,918
Annual hours - partial economizer mode	0	1,686	2,770	3,604	1,773	3,800
Est. annual PUE	1.34	1.25	1.26	1.31	1.34	1.39

Economics of evaporative assist

- The cost of evaporative coolers and evaporative assist in general include the material cost, water usage, and water treatment.
- These costs must be considered when deciding upon a data center cooling system.
- Evaporative assist is most effective in dry climates such as Las Vegas and Dubai. The cost of an evaporative cooler must be balanced against its effectiveness in climates that are more humid.
- It is possible to spend more on evaporative cooling than is saved on cooling system energy.

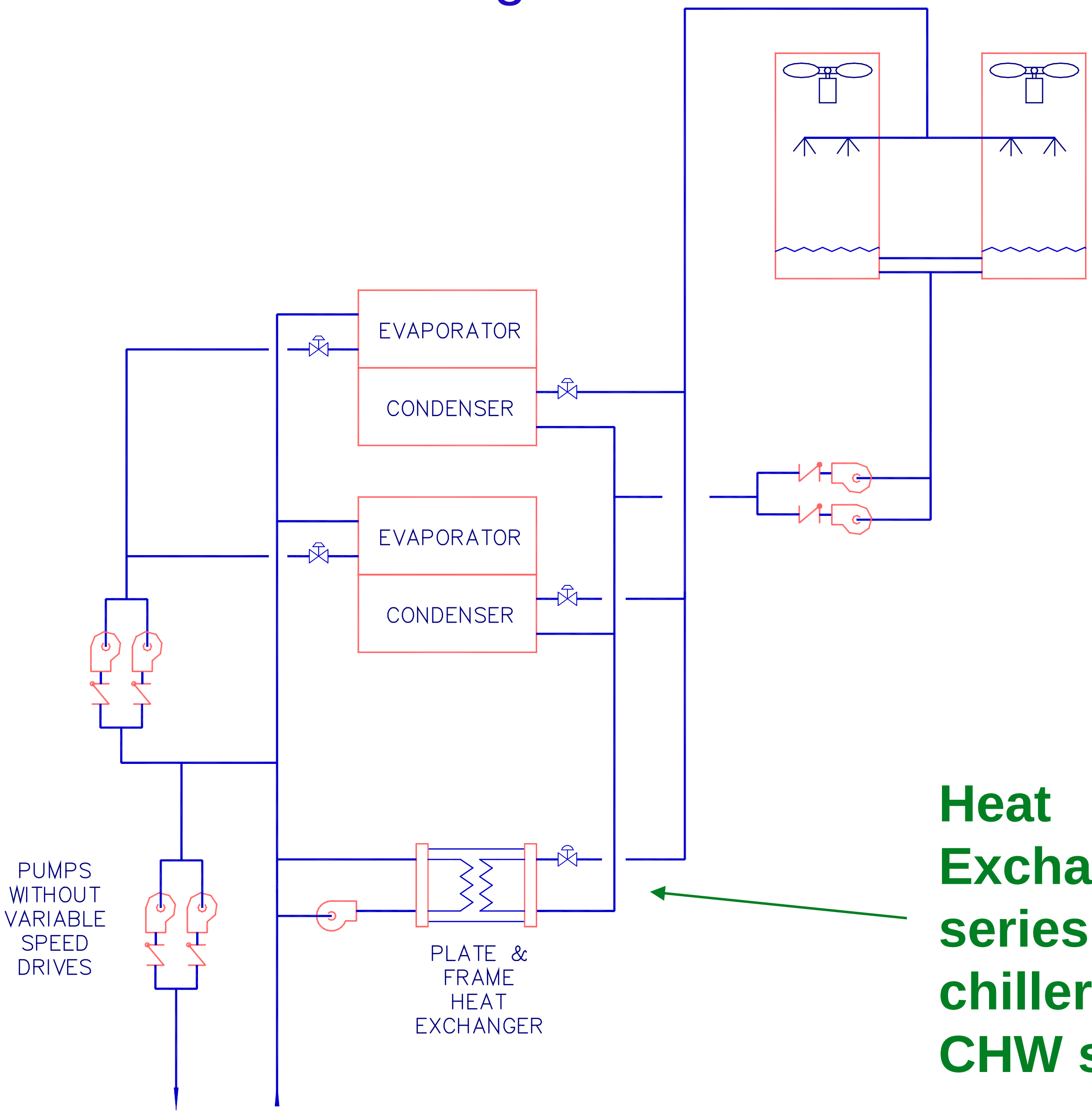
Water side economizer

The basic principle of **waterside economizer is to pre-cool some or all of the return water in a chilled water loop with the cooling tower**, substantially reducing or even eliminating the need of mechanical cooling. Through the use of plate and frame heat exchangers, building heat is transferred from the chilled water loop into the cooling tower loop and eventually dissipated into the atmosphere.



Water-Side Economizer

Integrated

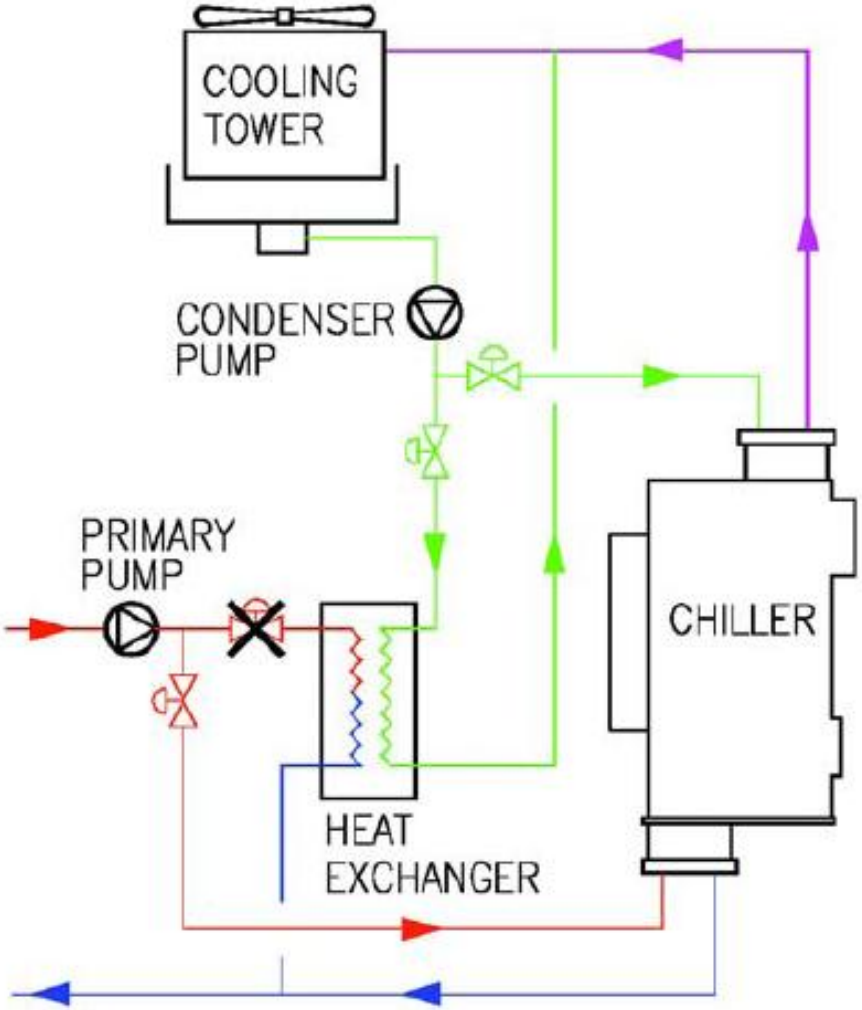


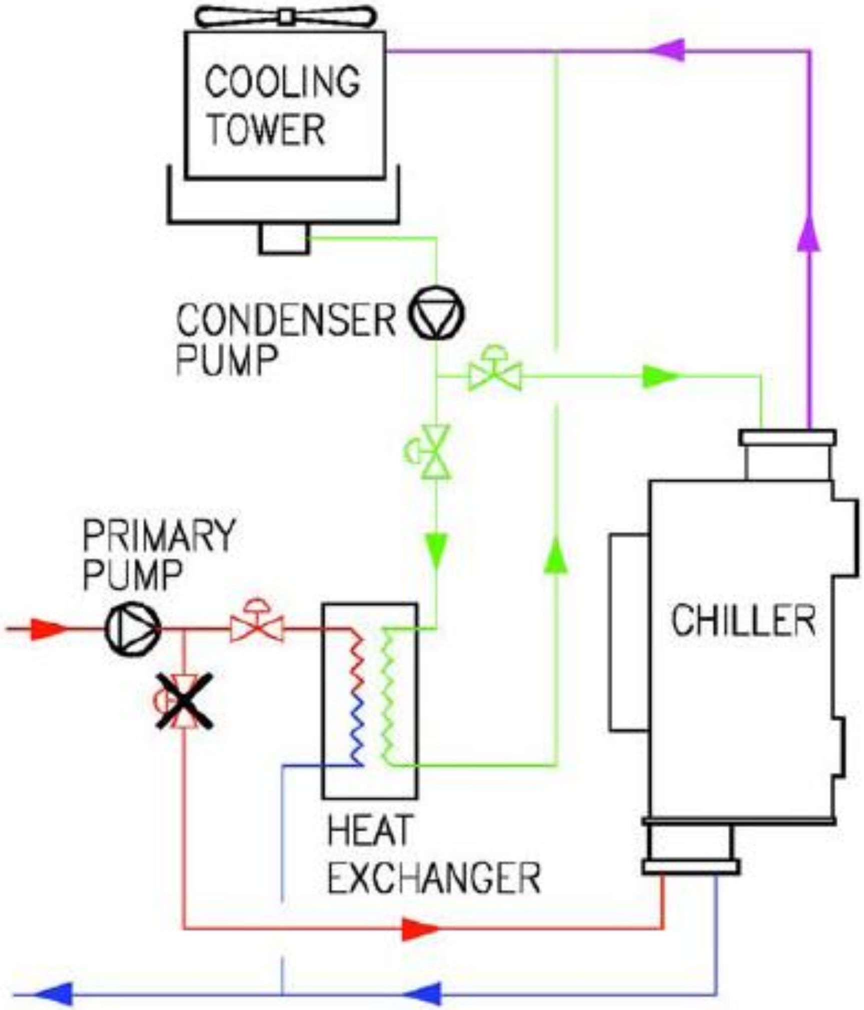
Heat Exchanger in series with chillers on CHW side

Series / Parallel Operation for Economizer

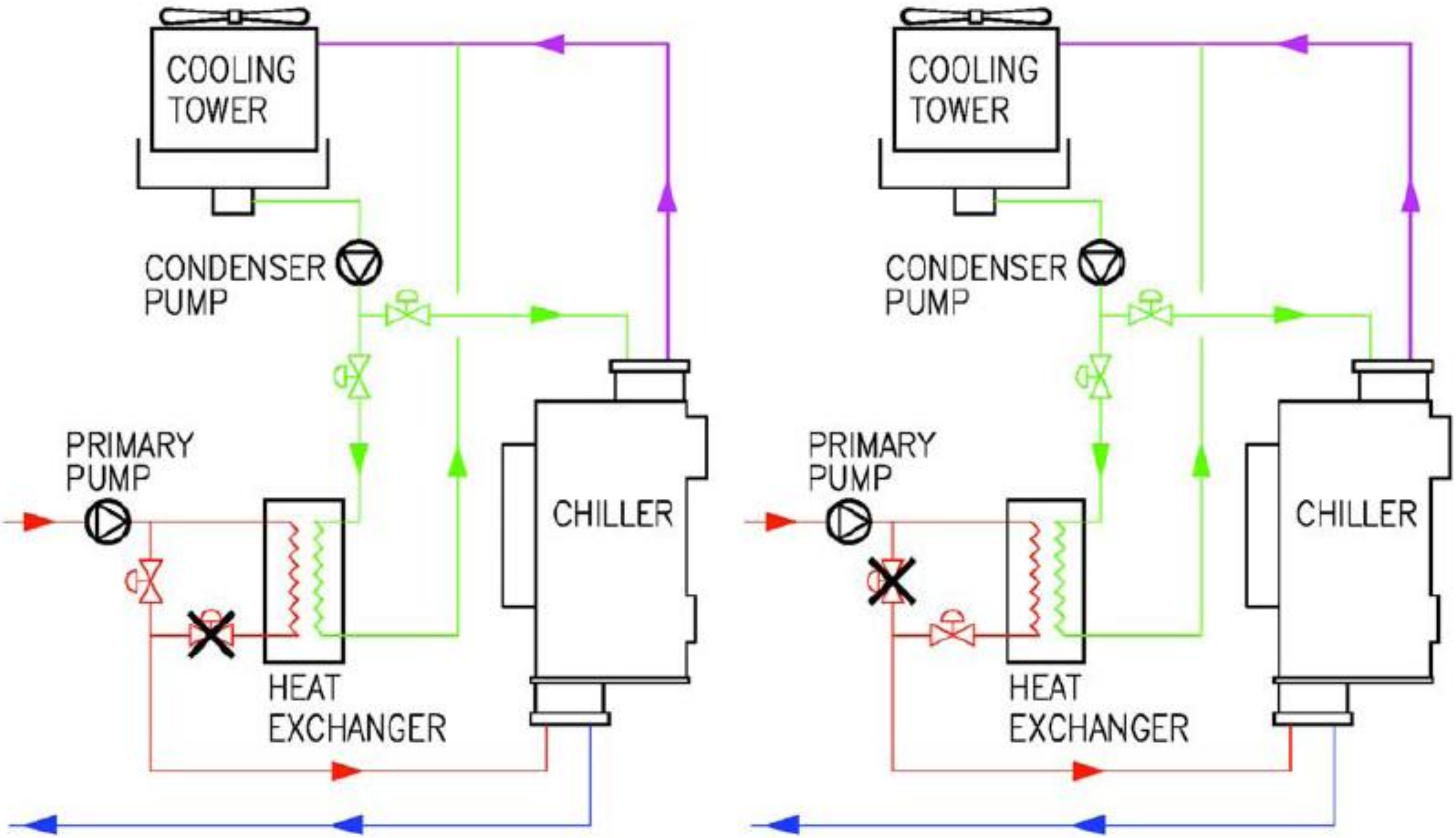
- In a series configuration, the component that bypasses the compressor (e.g. plate-and-frame heat exchanger) is installed in series with the compressor. This configuration allows for partial economizer mode where the heat exchanger "pre-cools" the air or water. This reduces the total heat energy that the compressor must reject, saving a significant amount of energy.
- In a parallel configuration, the component that bypasses the heat pump is installed in parallel with the heat pump. This configuration prevents the ability to operate in partial economizer mode. **This "all or nothing" approach fails to capitalize on the significant energy savings available by operating in partial economizer mode**.

*Typical **parallel waterside economizer** (PWSE) flow diagram in normal operation (left) and **economizer operation** (right).*





Typical **series waterside economizer** (SWSE) flow diagram in normal operation (left) and economizer operation (right)



Economizer Summary

Air-Side Economizers

- **Provides free cooling when dry-bulb temperatures are below 78˚F-80˚F (25.5~27°C).**
- May increase particulates (LBNL research indicates this is of little concern).
- Should be integrated to be most effective.
- Improves plant redundancy!
- Can work in conjunction with water-side economizers on data centers!
- Need to incorporate relief.

Water-Side Economizers

- **Provides low energy cooling when wet-bulb temperatures are below 55˚F-60˚F (12.8~15.6°C)**.
- Avoids increased particulates (and low humidity if that concerns you).
- Should be integrated to be most effective.
- Improves plant redundancy!
- Can work in conjunction with air-side economizers on data centers!

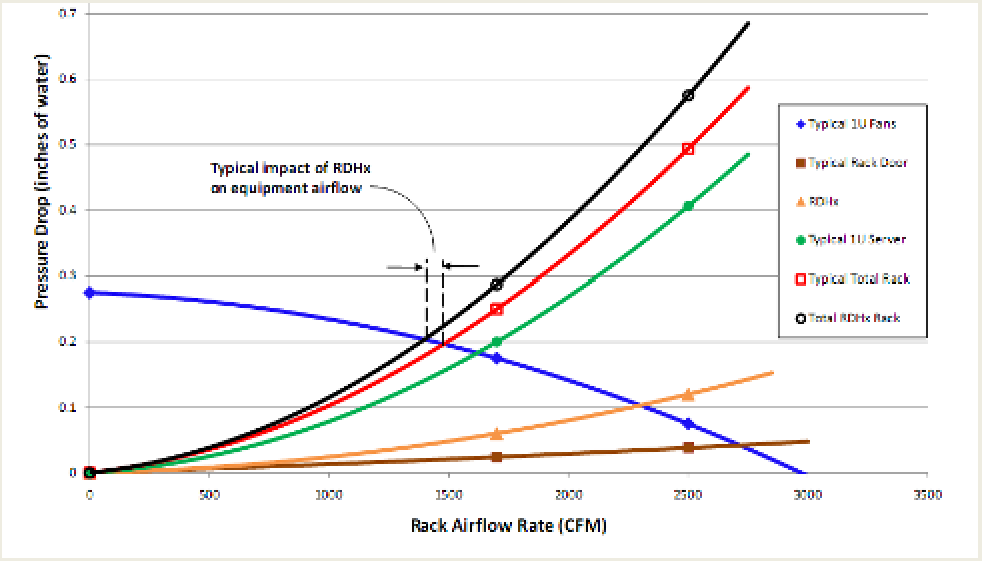
Both are proven technologies on data centers!

Liquid Cooling Deployment

- **Rear-door, in-row, or above-rack heat exchanger** that removes a large percentage of the ITE waste heat from air to liquid.
- **Totally enclosed cabinet that uses air as the working fluid and an air-to-liquid heat exchanger**.
- **Direct delivery of the cooling fluid to the components in the system using cold plates** directly attached to processors, application-specific integrated circuit, memory, power supplies, etc. in the system chassis or rack, whether they be servers or telecom equipment.
- **Note that new options, such as single- and two-phase immersion baths**, are becoming available that may become more prevalent in the near future.

Water-based Cooling

- Cooling system design by Vette Corp.
- Heat removal of up to 30 kilowatts
- Rear door closed loop liquid heat exchanger designed by IBM
- Currently available only for IBM Enterprise Rack
- Available from Rittal for retro-fit designs

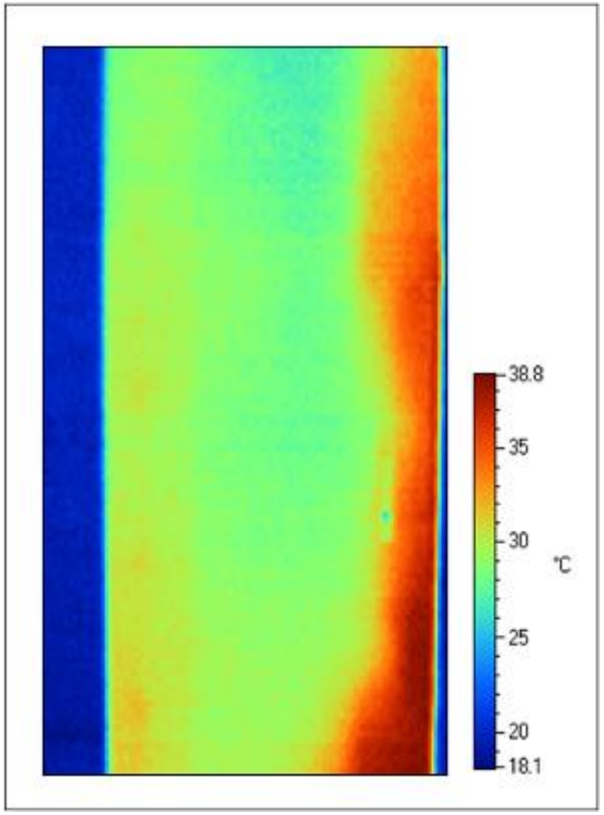


Pressure drop across the heat exchanger for a typical 1U fan setup

IBM Rear Door Heat Exchanger

Images: www.vette-corp.com

Water-based Cooling



Temperature Distribution inside the Rack

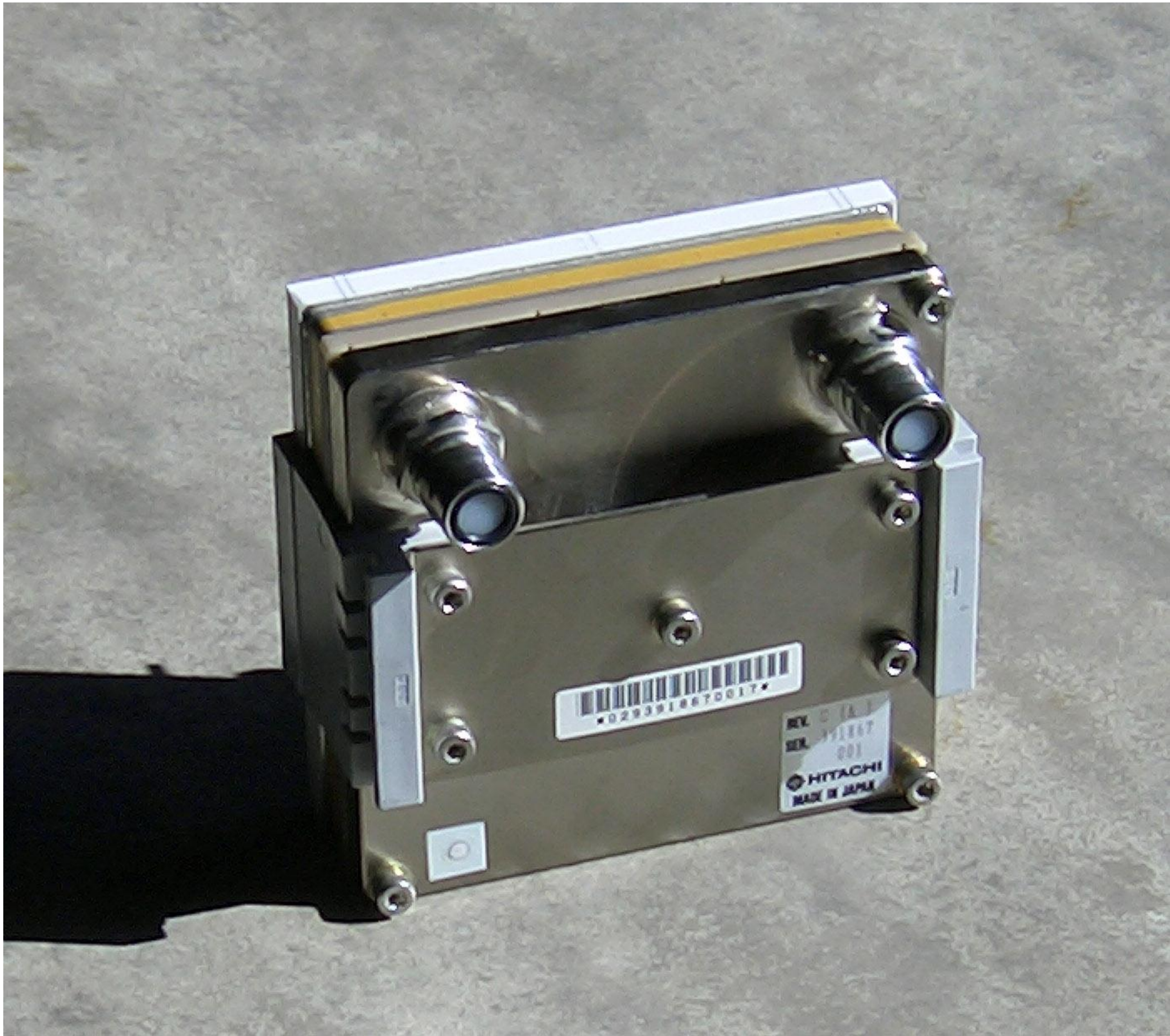
Water-based Cooling (in-row cooling)

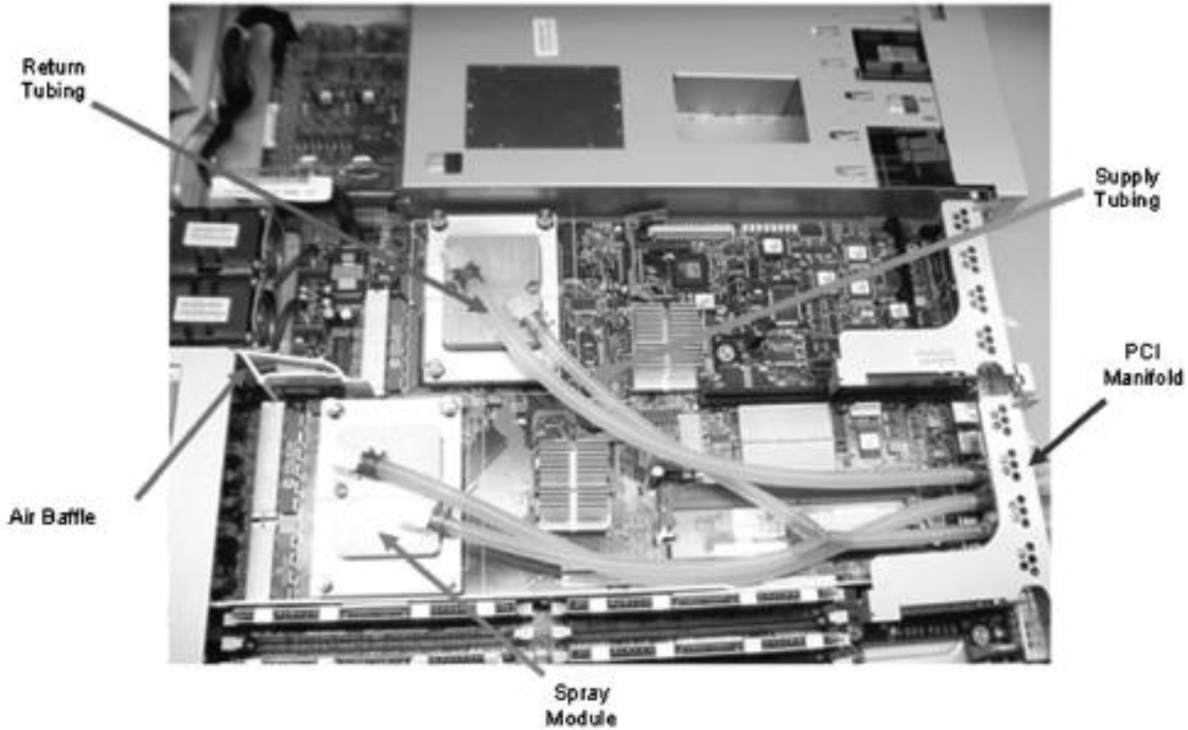
- Cooling system design by APC.
- Heat removal of up to 70 kilowatts
- Controlled in-row cooling
- Row air containment
- Modularity
- Similar designs from HP (35 kilowatts)
- Similar concepts available from Rittal (30 kilowatts)
- Similar concepts available from Liebert (8 kilowatts and 17 kilowatts)

Heat Exchanger and Fan Assembly | Front View | Rear View

Images: www.apc.com

Typical Cold Plate





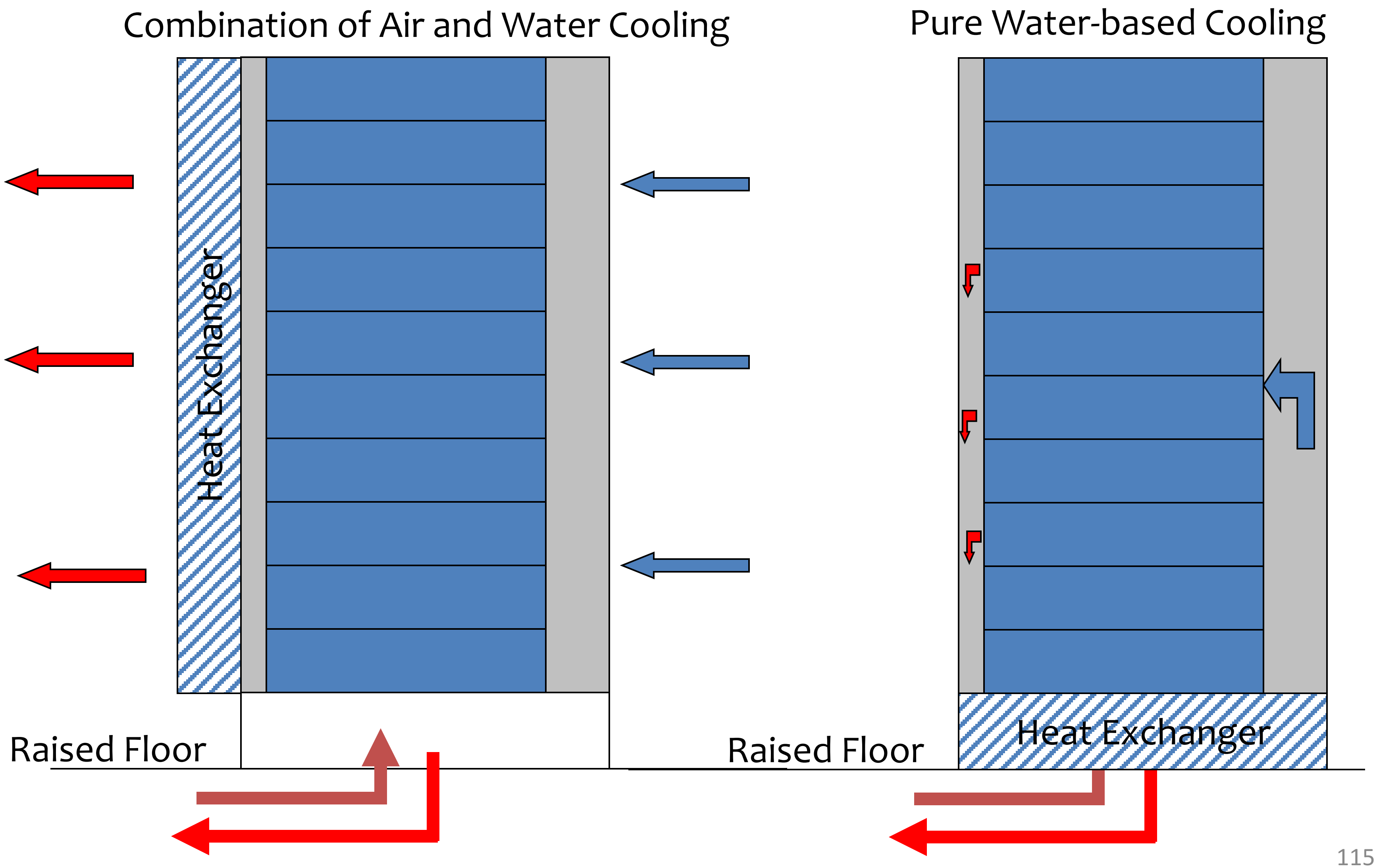
Photograph of a liquid-cooled IBM x3550 server.

Water-based Cooling

- Basis: $Q_{LOAD} = mC_p \Delta T$

  (Water has 3000 times higher heat carrying capacity than air)
- Chilled water from building supply
- Cooling high density servers up to 70 kilowatts per rack
- Lower energy cost as some of the CRAC units can be removed
- Avoid hotspots due to high power-density equipment
- Possible to have redundant systems (Chillers, pumps, piping, and power supply) to avoid downtime
- Importance of CDU
- Electrically conductive, corrosiveness and high flow rates

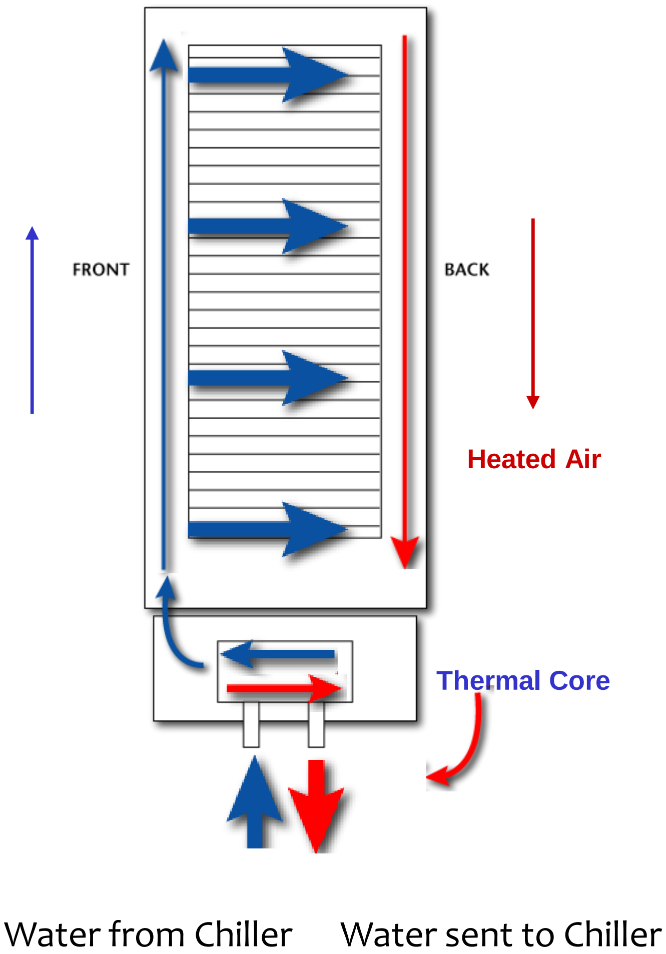
Water-based Cooling



Water-based Cooling

- Heat removal of 20+ kilowatts
- Closed liquid loop with bottom mounted fin and tube heat exchanger
- Thermal test done with 5 blade servers

Inputs	Heat Load	24.0	kW
	Water Temp	12.8	degC
	Water Flow	0.76	l/sec
Results	Cold Air Supply	22.8	degC
	Hot Air Disch	49.8	degC
	Air DT	27.0	degC
	Water Rise	7.1	degC
	Water Disch	19.9	degC
	Water P.D.	48.3	kPa
Background	Server Fans	1680	CFM
	Fan Power	700	watts

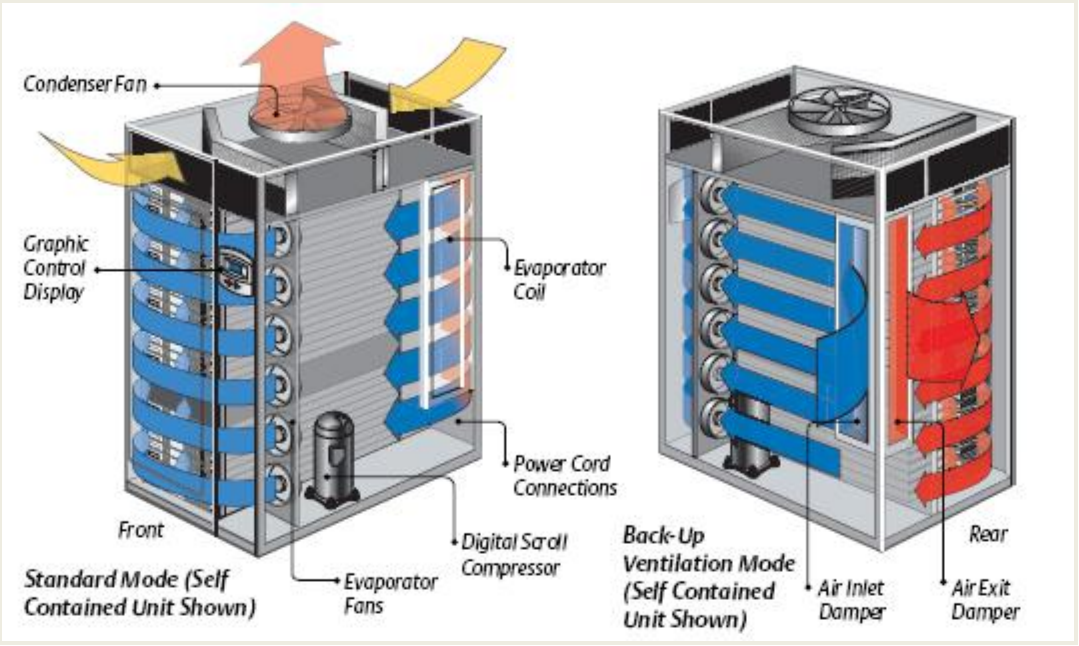


Refrigerant-based Cooling

- Phase change (latent heat transfer)
- Electronics-safe
- Low flow rates and non-corrosive
- Some systems are stand-alone and hence flexible
- CRAC units are the most common ones
- Chilled water from building supply may be used for supplemental cooling
- Expensive (comparable to water+ additives)

Refrigerant-based Cooling

- Cooling system design by Liebert
- XDF- Cooling capacity of 14 kilowatts
- Stand-alone unit



Liebert XDF Self Contained Unit

Images: www.liebert.com

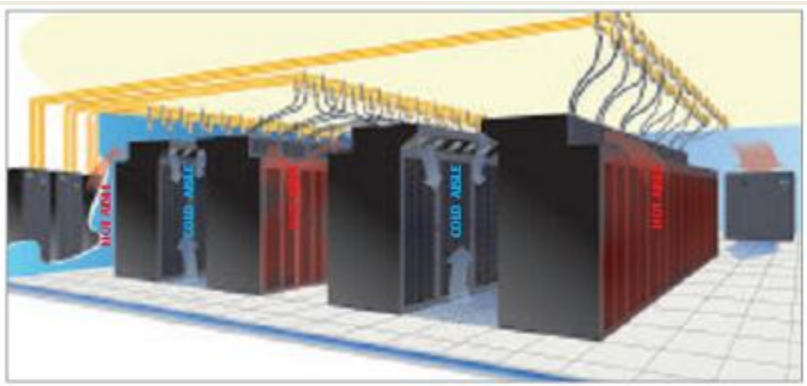
Refrigerant-based Cooling

- Cooling system design by APC.
- Heat removal of up to 43 kilowatts
- Modularity
- Rack air containment

APC In-Row Cooling

Refrigerant-based Cooling

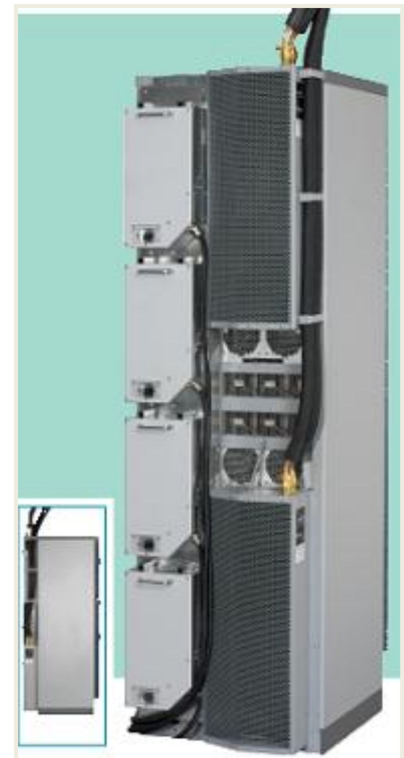
- Cooling system design by Liebert
- XDV- Rack mount air conditioners (10 kilowatts) - Almost no floor space required
- XDH-Rack Cooling capacity up to 30 kilowatts
- Also available from Rittal



The Liebert XDV works extremely well with the "hot aisle-cold aisle" approach.

Liebert Roof Mount Cooling

Liebert In-Row Cooling



Rittal Rear Door Hx

Images: www.liebert.com

Water/Refrigerant-based Touch Cooling

- Direct contact cooling combined with chip cooling
- Remove heat at the source

Cold plate with Liquid Cooling

Images: www.rittal-corp.com

Liquid Cooling of Boards

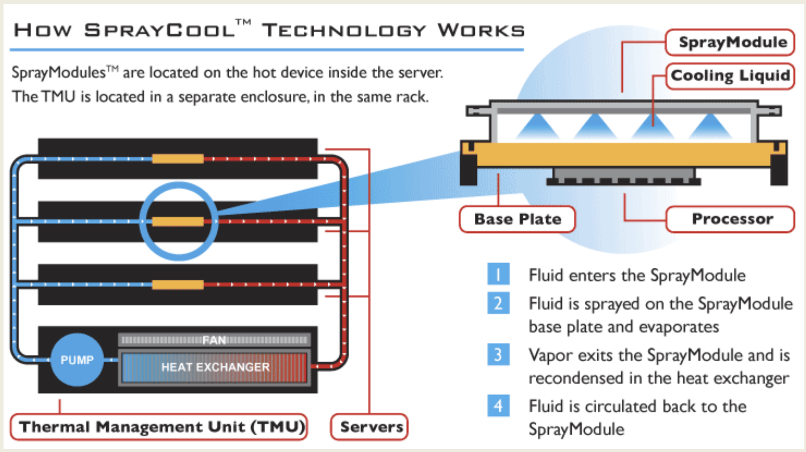
Images: www.ibm.com

Available from:

Clustered Systems

Rittal (Power electronics)

SprayCool (20 to 30KW)



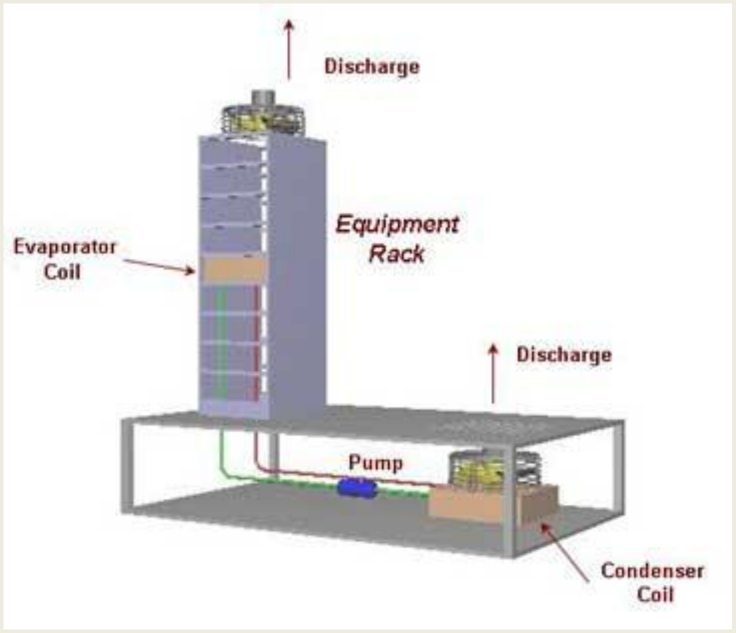
Spray Cooling

Images: www.spraycool.com

Refrigerant-based Touch Cooling

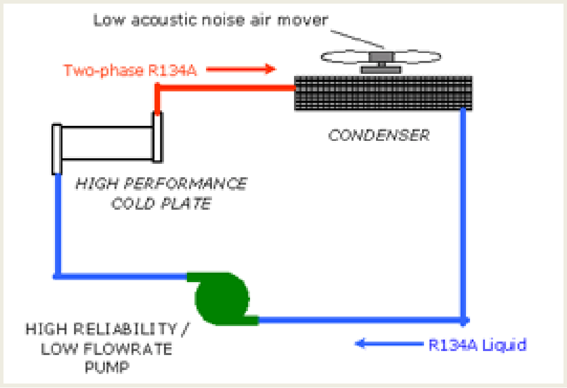
- Cooling system design by Thermal Form and Function
- Pumped liquid multiphase cooling
- Heat removal of up to 10 kilowatts

  per evaporator (Modular)
- Designed for retro-fit applications
- Air/Water cooled condenser unit can be used



Thermal Form and Function Refrigeration Unit

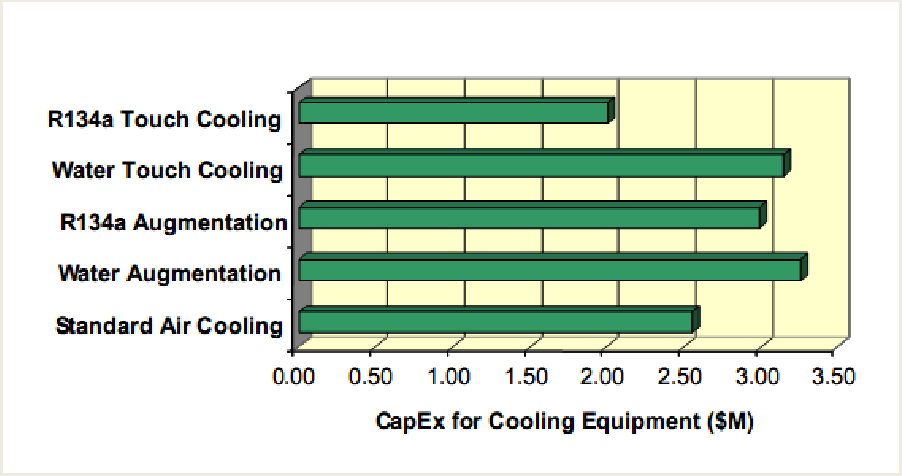
Images: http://www.thermalformandfunction.com/



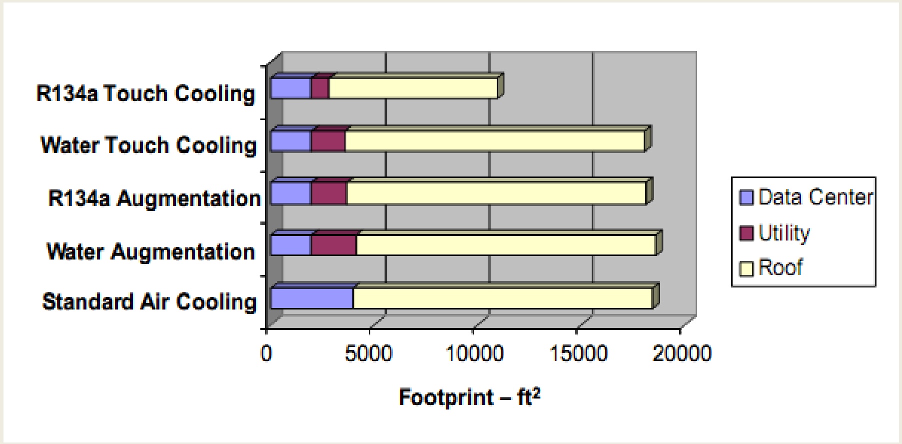
Two Phase Flow

Comparative Analysis

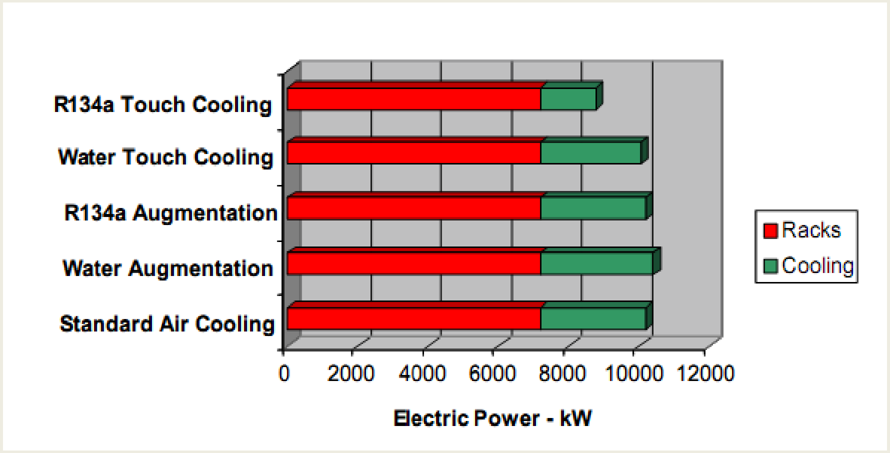
- Study by Hannemann and Chu – Interpack '07
- Comparative study of cooling technologies with a model datacenter



Capital Expenditure of Cooling Equipment

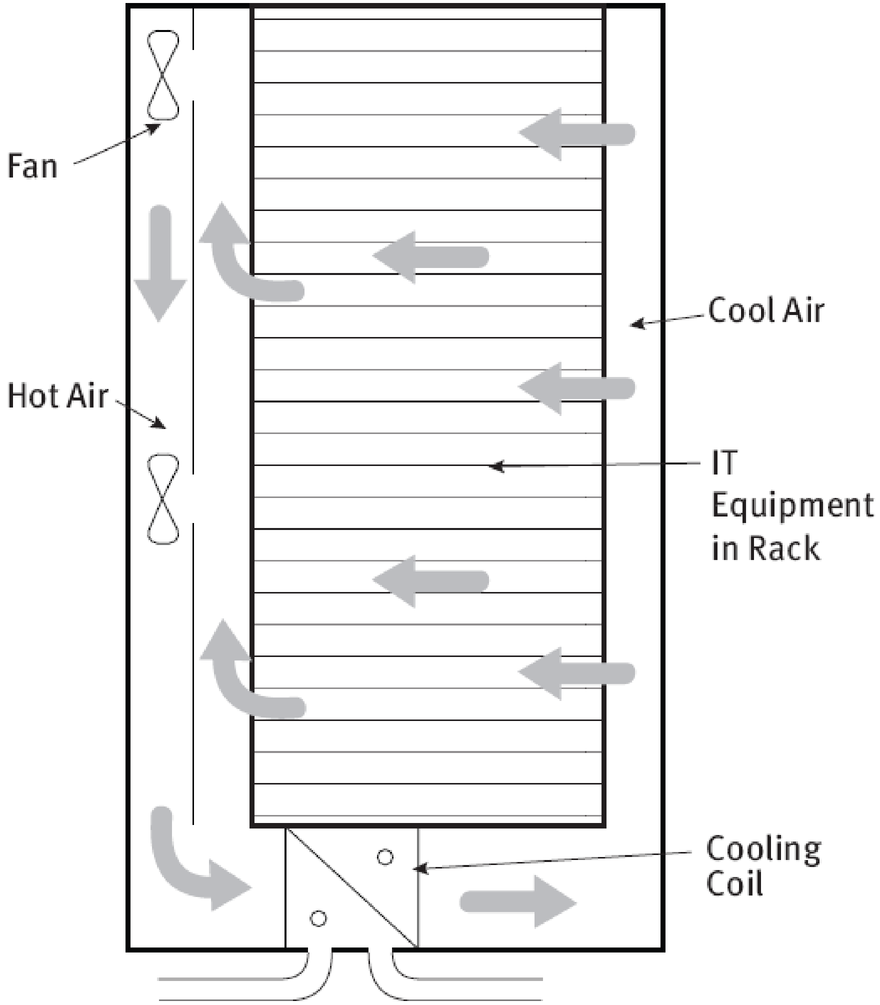


Area required for Cooling Equipment



Power Consumption of Cooling Equipment

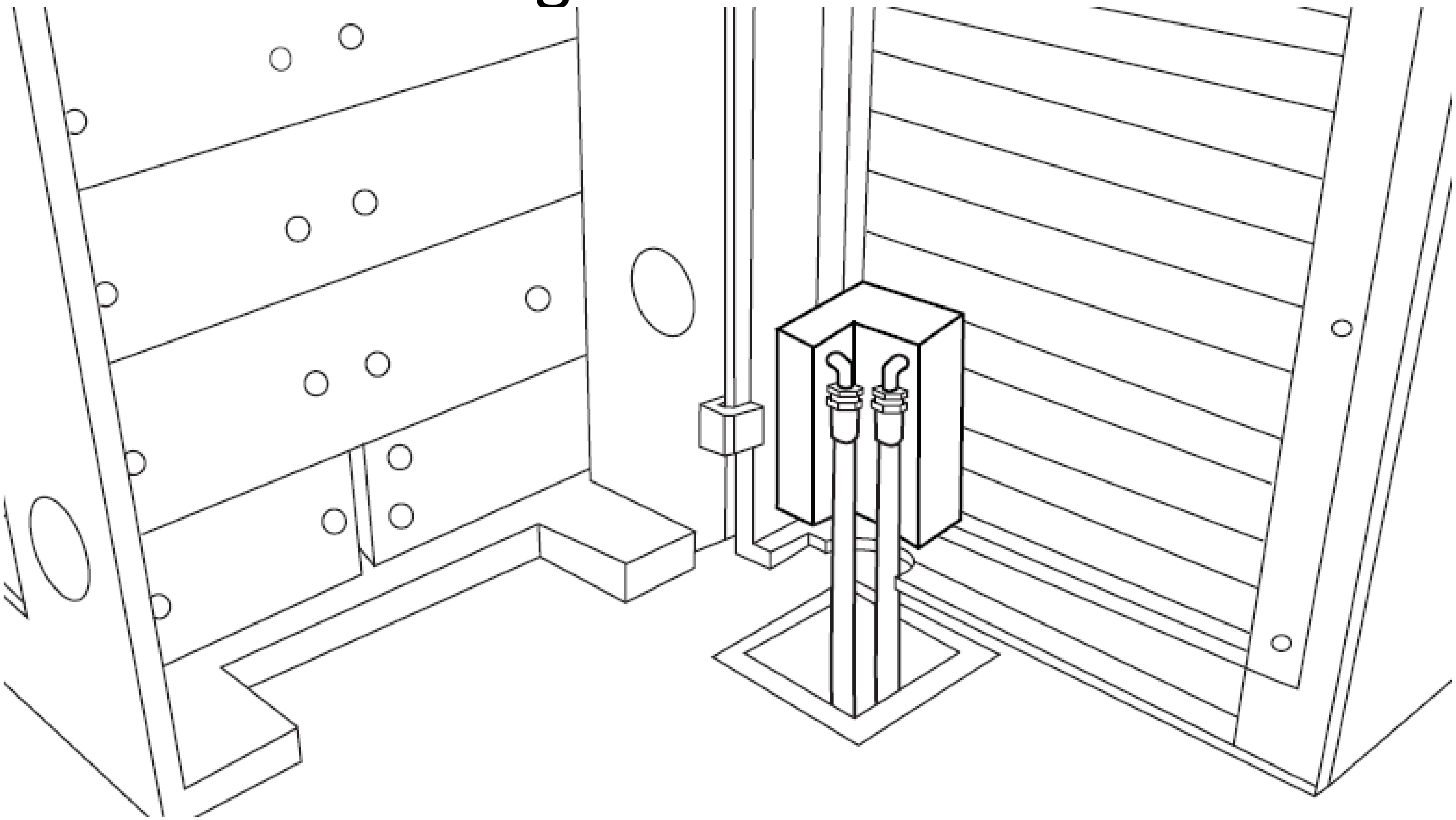
Liquid Cooling



- Closer coupling between cooling source and server

Liquid Cooled Racks

- Racks with integral coils

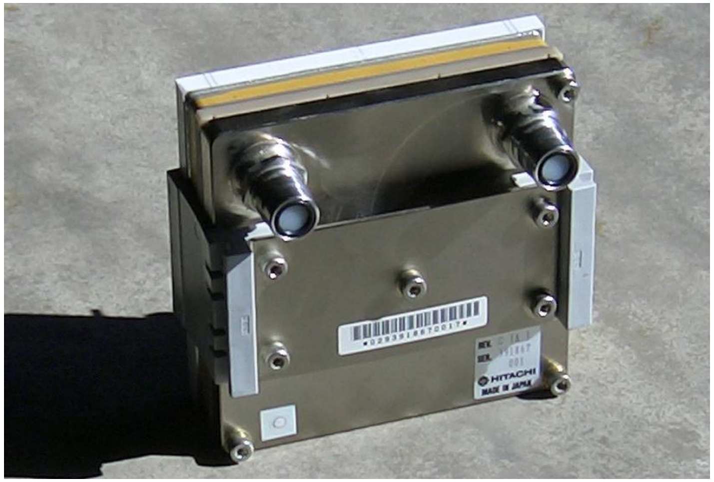


Comparison of Conventional Cooling to Liquid Cooling – 1,000 kW data center load

	Cooling Towers and Pumps	Chiller	Chilled Water Pumps	Fans	Other	Total Power (kW)	% SAVINGS
Traditional System - 45 Deg F Chilled Water	70	500	50	150	n/a	770	N/A
Liquid Cooled with Fans in the Rack - 55 Deg F Chilled Water	70	425	50	100	n/a	645	16%
Liquid Cooled without fans in the rack - 55 Deg F Chilled Water	70	425	50	0	n/a	545	29%
Liquid Cooled directly couple with CPU - 70 to 80 deg F Chilled Water	70	0	50	0	Room A/C - 245	365	53%

國立交通大學
National Chiao Tung University

Fundamentals of Heat Transfer in Cold Plate and Fin-and-tube HXs



Fundamentals:

Heat Transfer Augmentation of Cold-Plate

- Heat Transfer Augmentation ($Q = UA\Delta T_m$)

  Q : heat transfer rate,

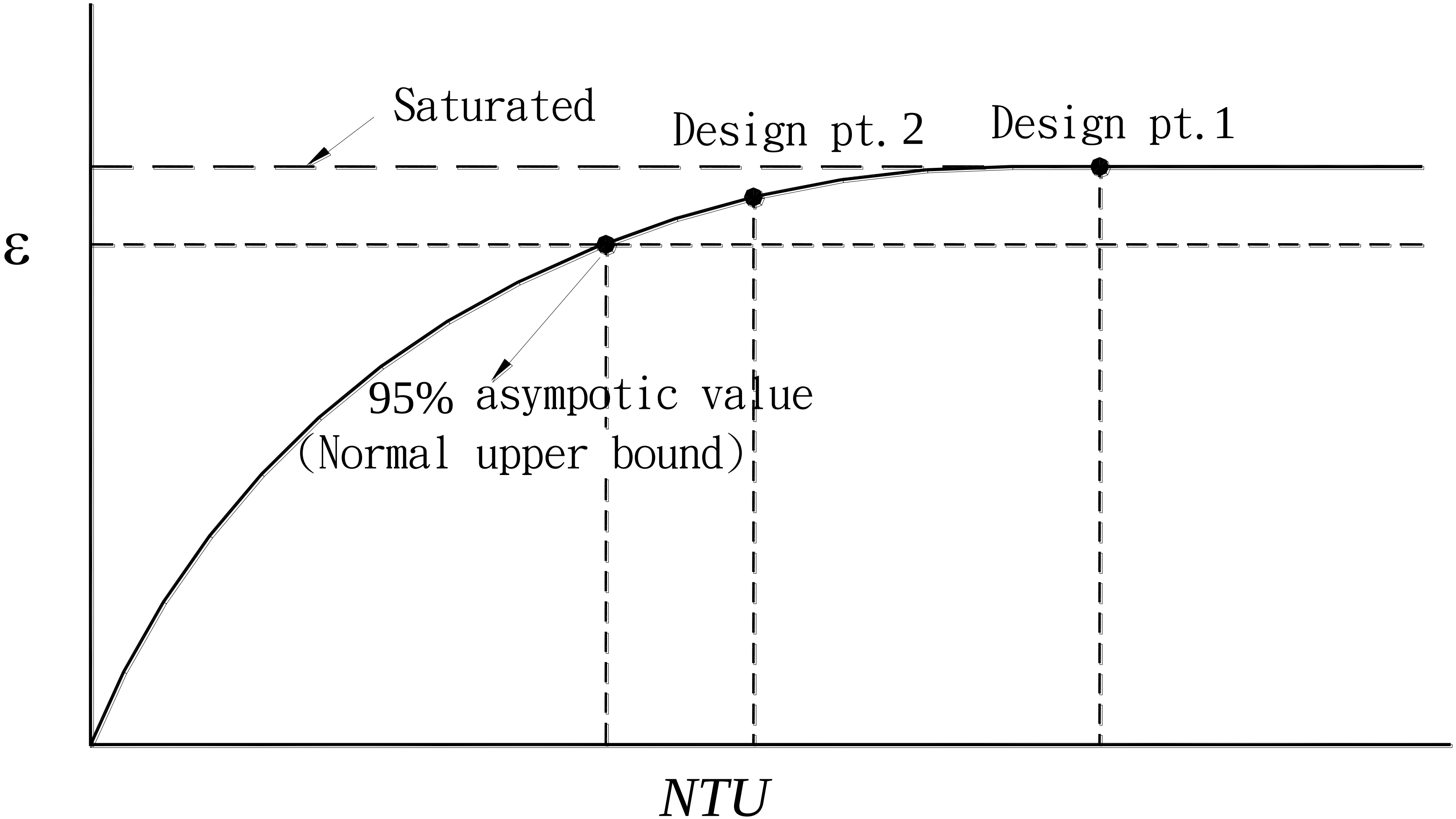
  U: overall heat transfer Coeff.

  A: Area

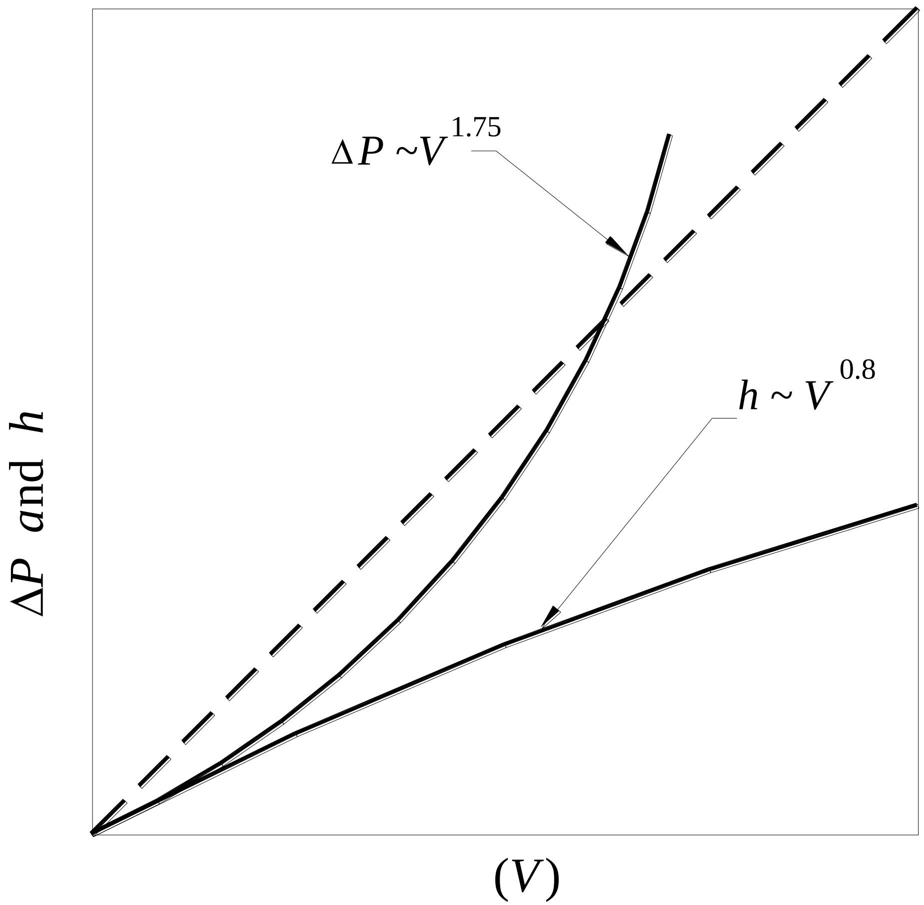
  ΔT_m: mean temperature difference

- Do we really need enhancement?
- When do we need the enhancement?
- Where should we place enhancements?
- Is it cost-effective?

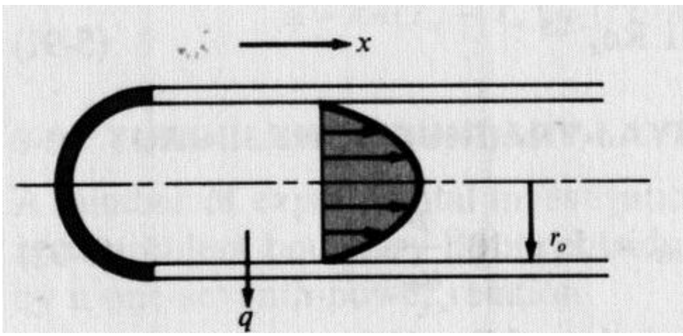
- Why enhancement? Do we really need enhancement?

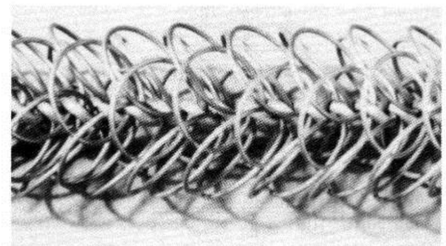


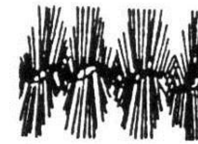
Taking into consideration about the influence of pressure drop (pumping power)

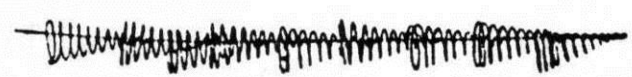


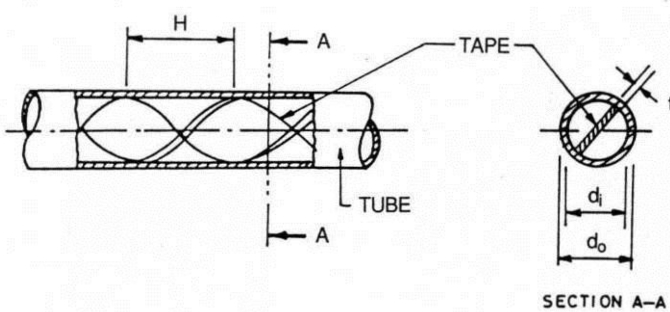
Augmentation of single-phase flow – Laminar Flow

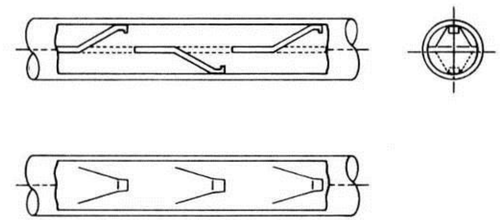


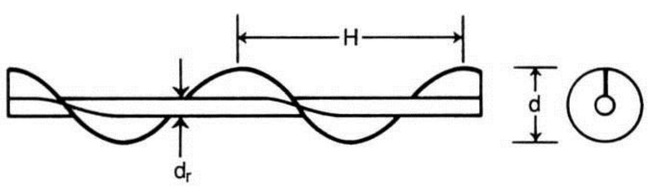


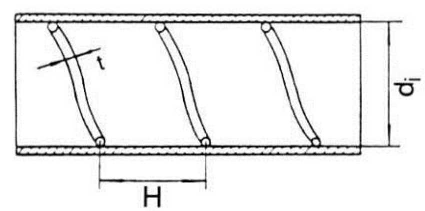




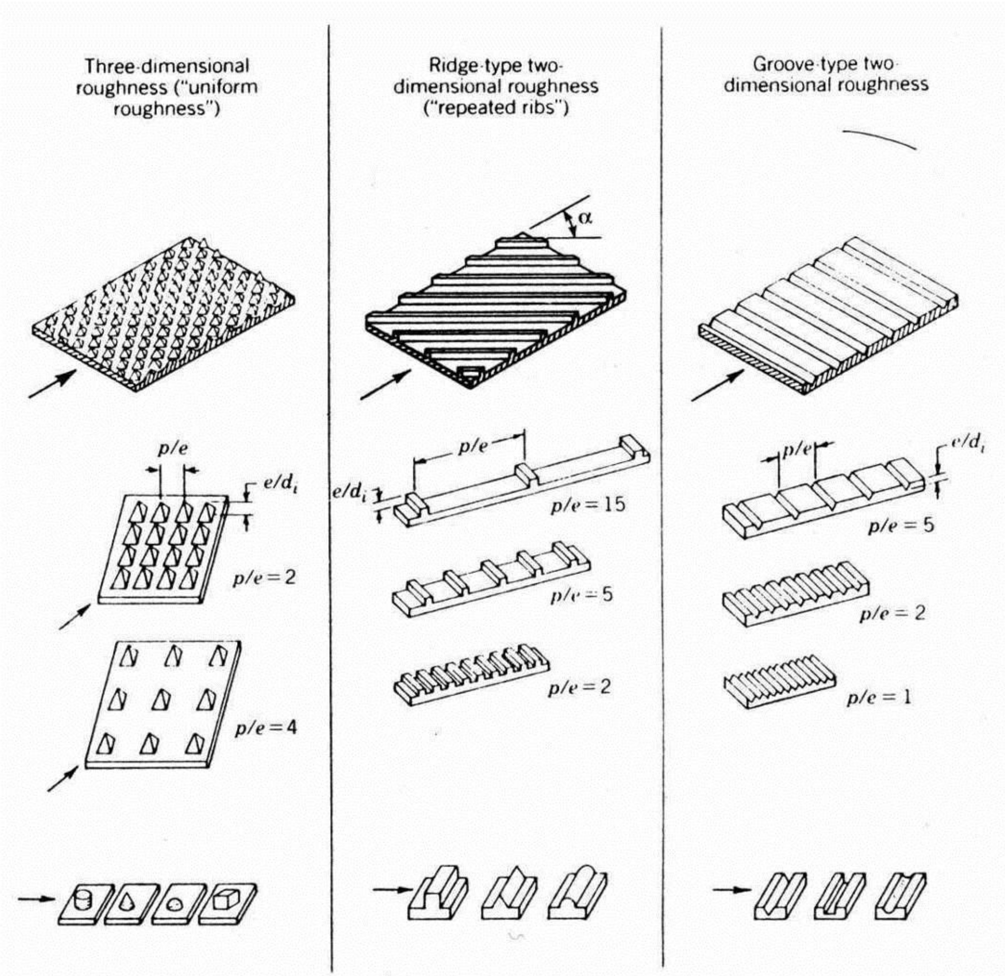


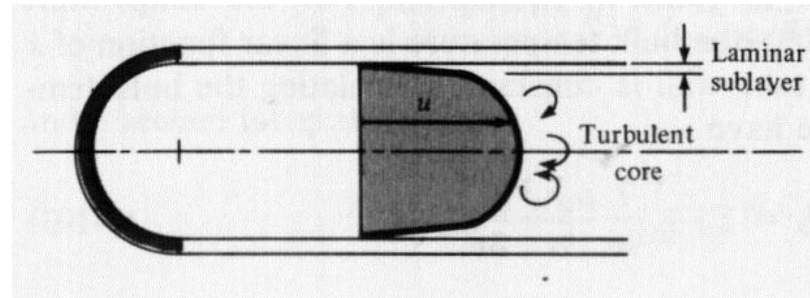


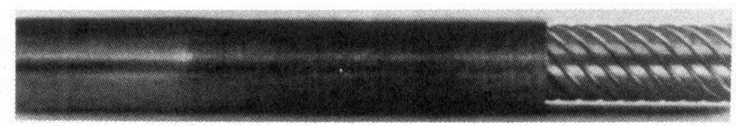


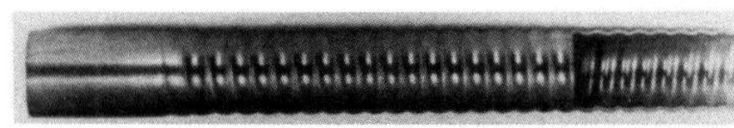


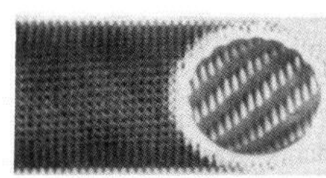
Augmentation in turbulent flow

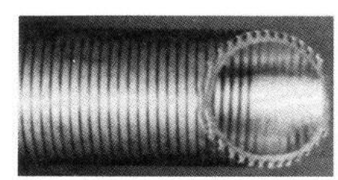








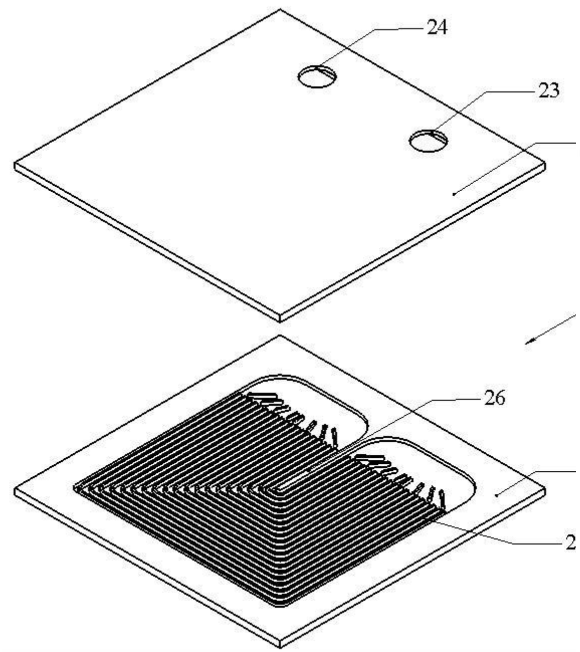




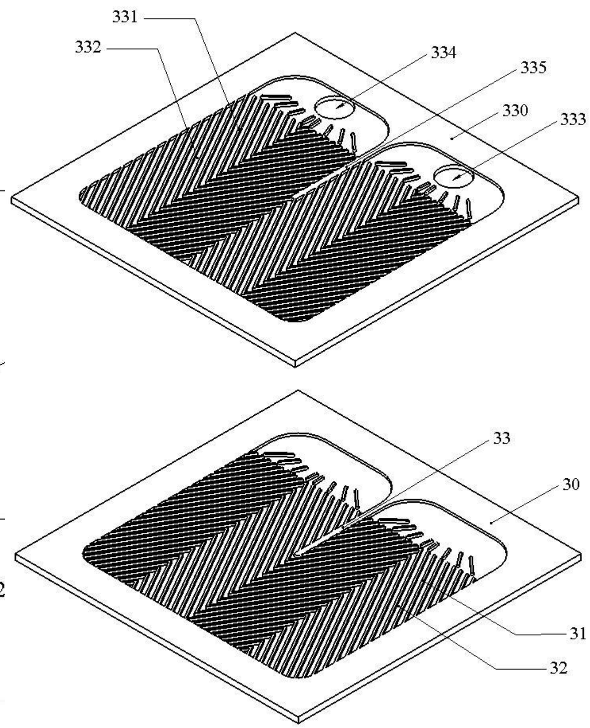
Augmentation based on plate HXs

dimension: 50 mm x 50 mm x 2 mm

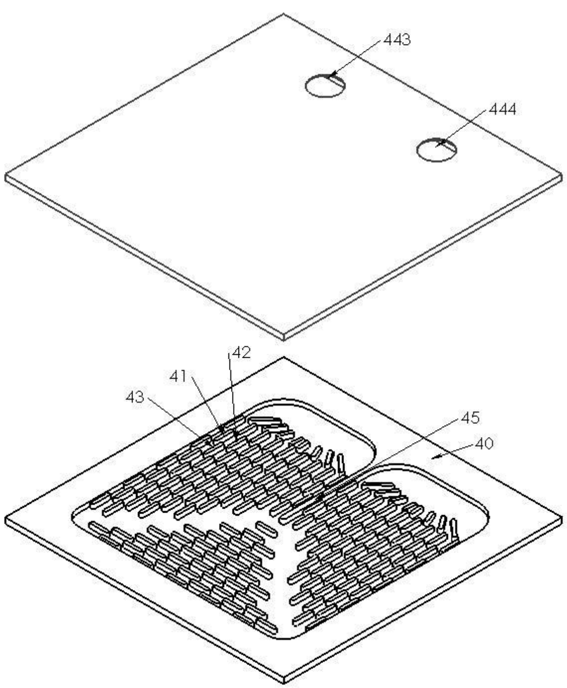
U - type



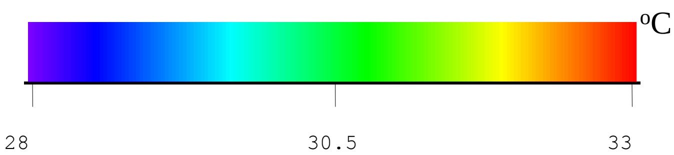
Chevron (V)



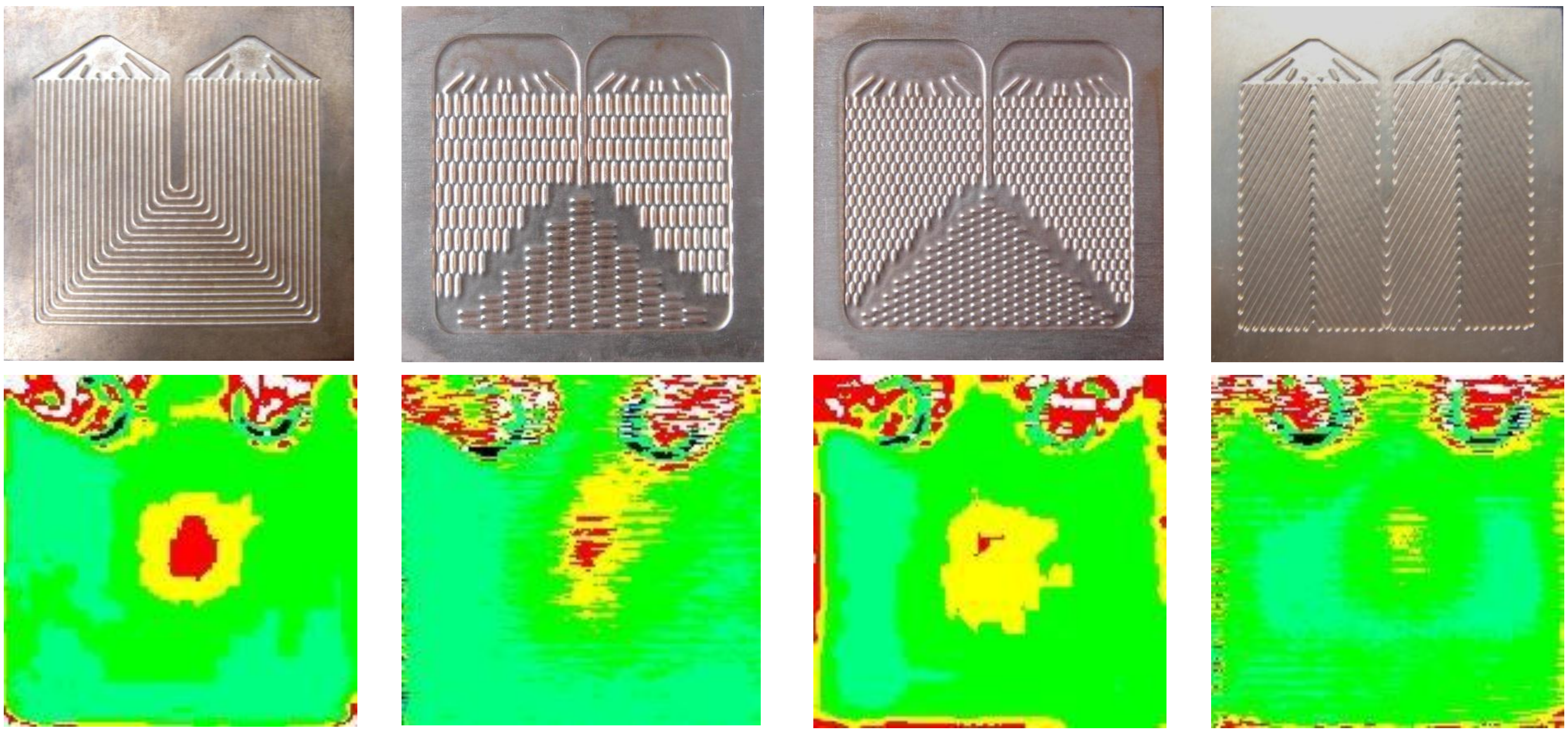
(OSF)



Temperature Distribution..



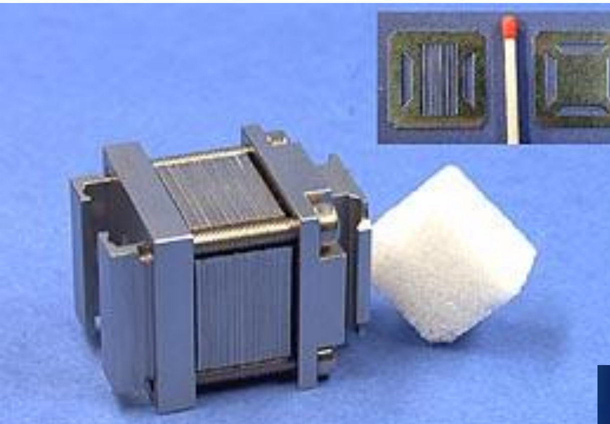
	Power	Flowrate (mL/min)	Inlet Temp.
	20	230	30 ^{o}C

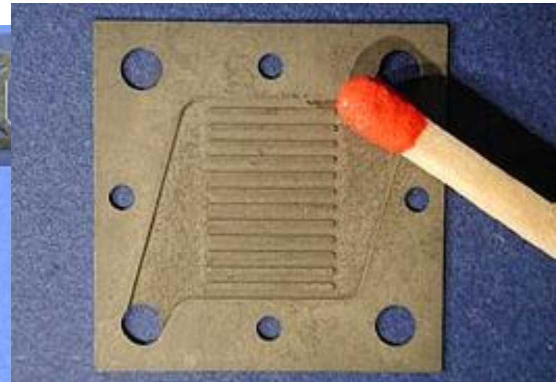


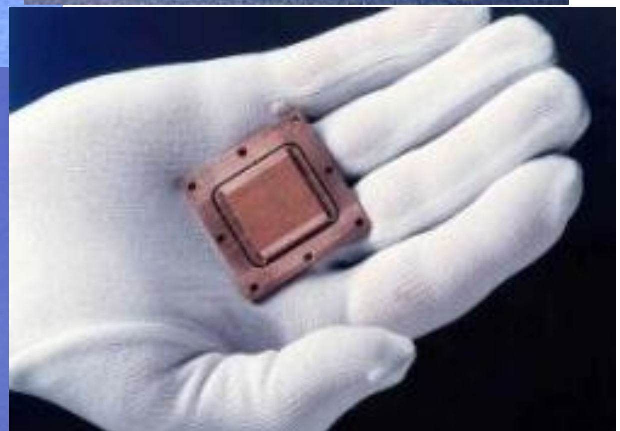
Courtesy of Prof. C.Y. Yang, Department of Mechanical Engng., NCU, cyyang@ncu.edu.tw

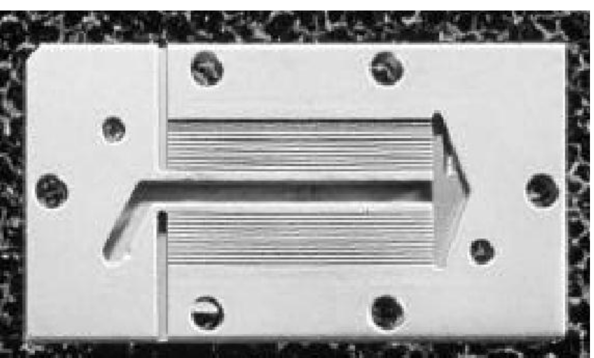
Why Microchannel?

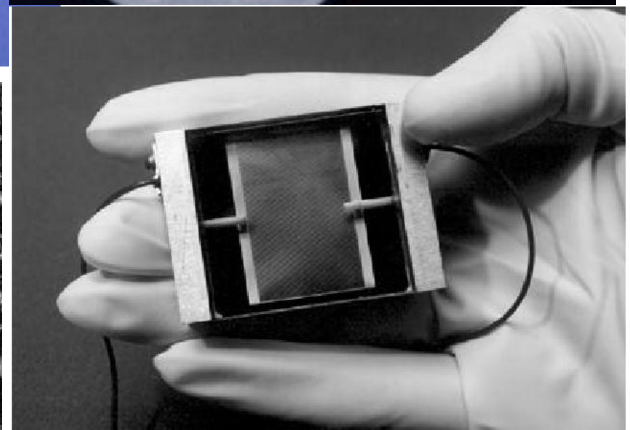
Micro-channel HXs - Exampl

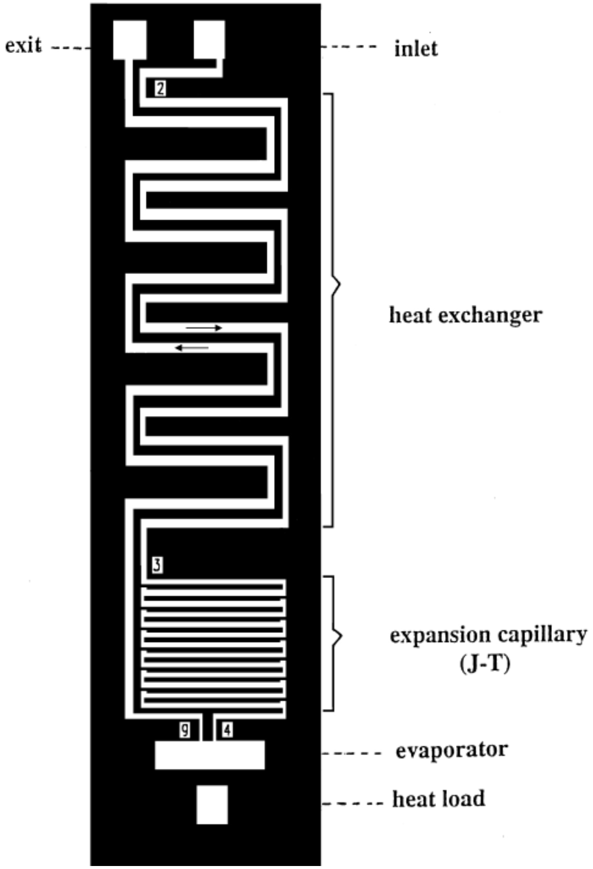


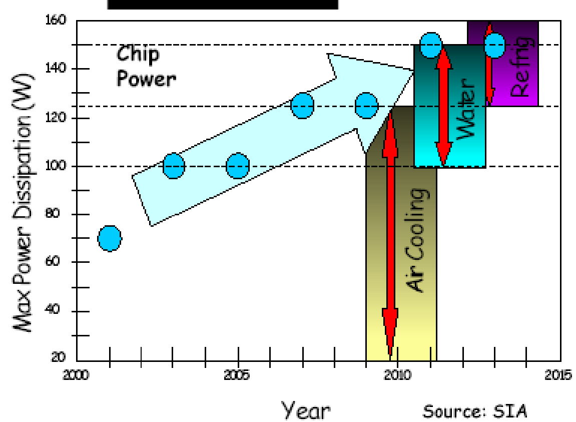












Why Use smaller Channel?

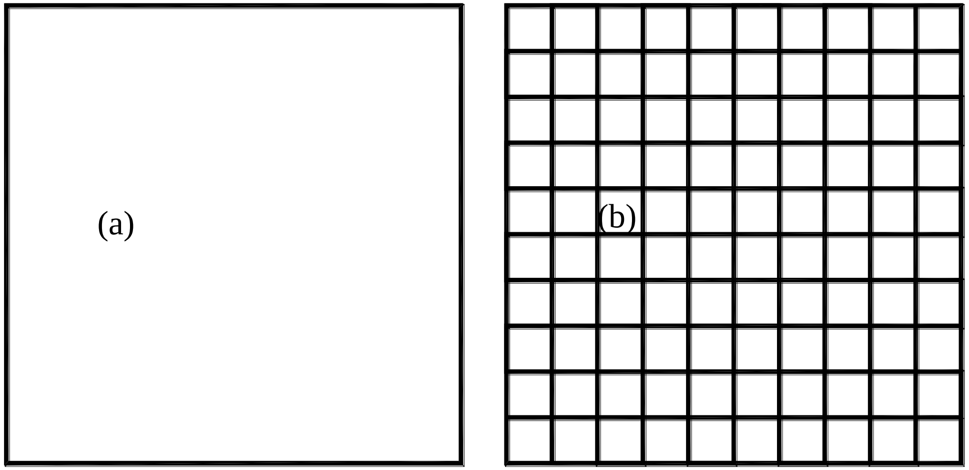
Consider a reduction of D_h with a factor of 10

- In this case, 10 times increase of heat transfer coefficient (*Nu = hD$_h$/k)*
- In this case, 10 times increase of heat surface area at the same volume)
- For the same thermal resistance, flow rate, and pressure drop constraints, the microchannel design offers 1/100 Less volume!

$$\Delta P = \frac{4L}{D_h} f \frac{1}{2}\rho u^2 = \frac{4L}{D_h} f \frac{\rho u D_h}{\mu} \frac{\mu}{D_h} \frac{1}{2} u$$

$$= \frac{2\mu u L}{D_h^2} f \,\mathrm{Re}$$

$$\Delta P \propto \frac{L}{D_h^2} \quad \rightarrow L \text{ must reduce to } \frac{1}{100} \text{ to}$$



maintain a constant ΔP, while the thermal

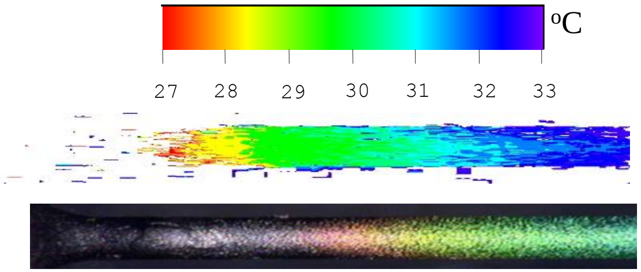
resistance $\frac{1}{hA}$ stays the same! This implies a reduction of volume to its original $\frac{1}{100}$

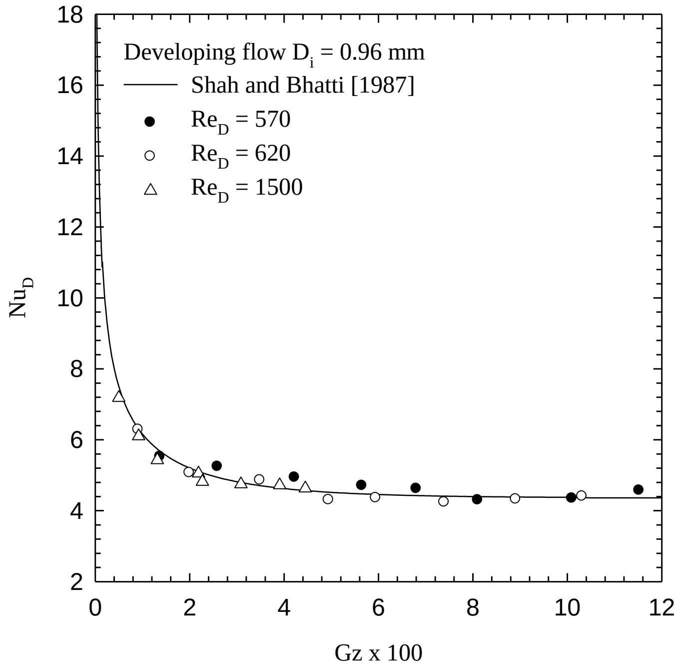
What's problem in designing Microchannels?

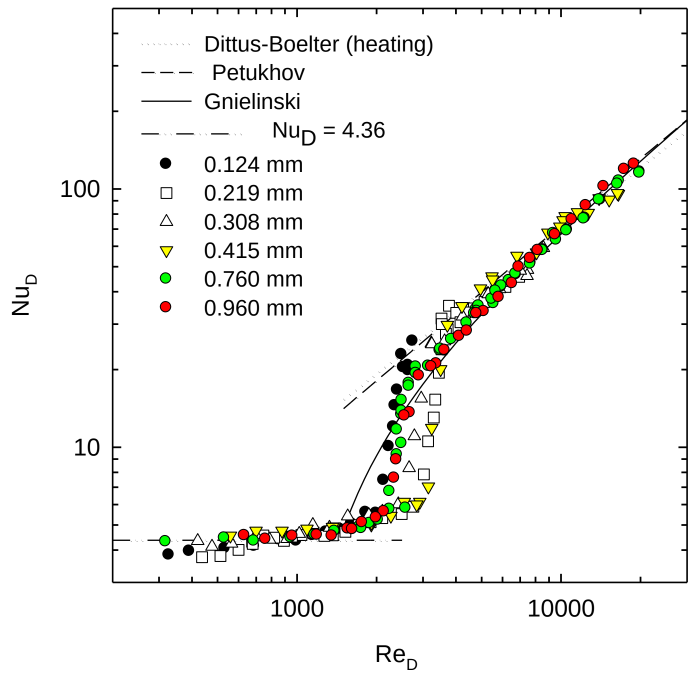
- Correct dimension (most crucial!), correct flow rate
- Effect of entrance
  - Hydraulic entrance length
  - Thermal entrance length
  - Simultaneously entrance effect
- Mostly Laminar flow
  - Depends on boundary conditions

Does the heat/flow characteristics in micro channel behaves like macro channel?

- Nu_D (= hD/k)
- For single-phase fluid in the range of 0.1 to 1.0 mm, heat transfer behaves just like macro-channels

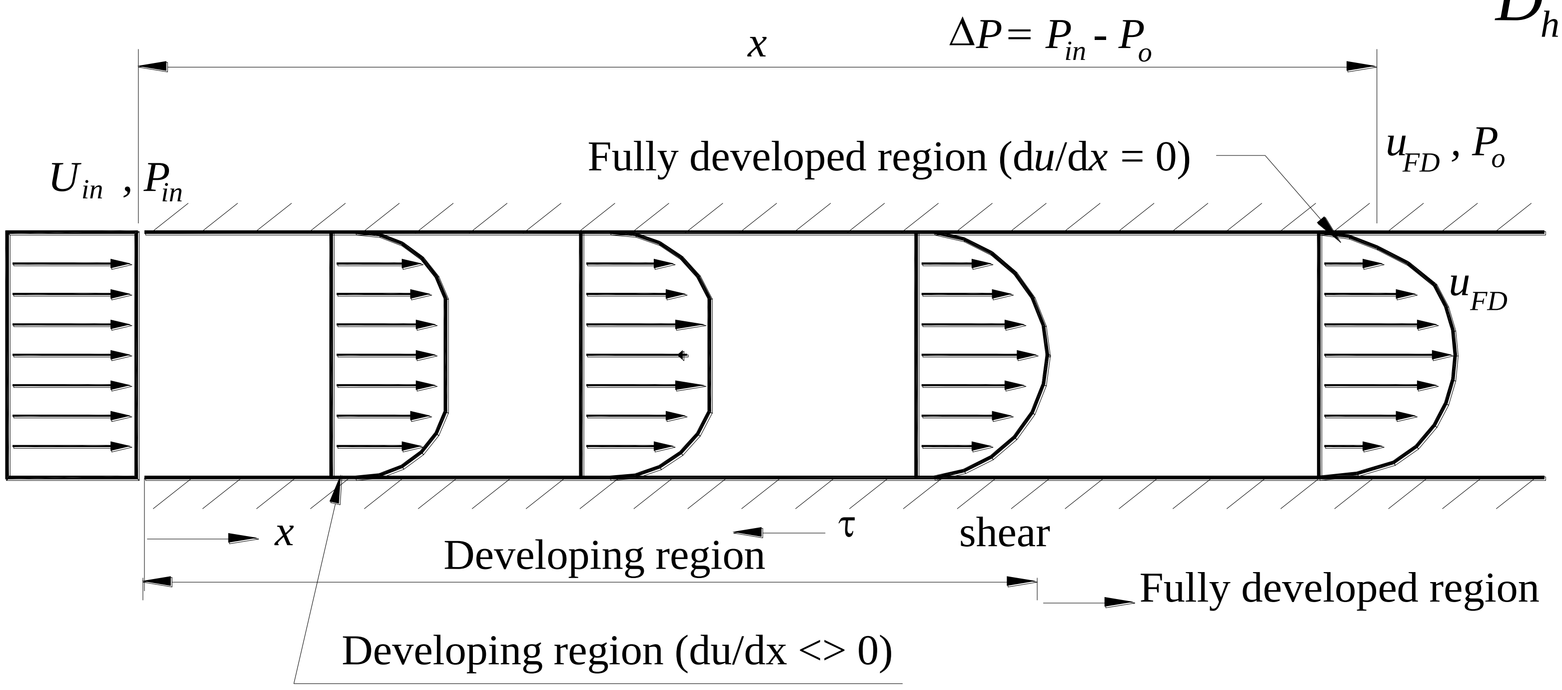






Effect of hydraulic entrance

$$L_{hy}^{+} = \frac{L_{hy}}{D_h \,\mathrm{Re}}$$



Schematic of Hydraulic Boundary Layer

$$L_{hy}^{+} \approx 0.05 \text{ (some suggests 0.06) (laminar flow)}$$

$$L_{hy}^{+} \approx 4.4\,\mathrm{Re}^{-\frac{5}{6}} \text{ (turbulent flow} \rightarrow \text{Ref : www.engineeringtoolbox.com)}$$

Example

- For a laminar flow Re = 1000, and a turbulent flow condition with Re =10000.

  Then

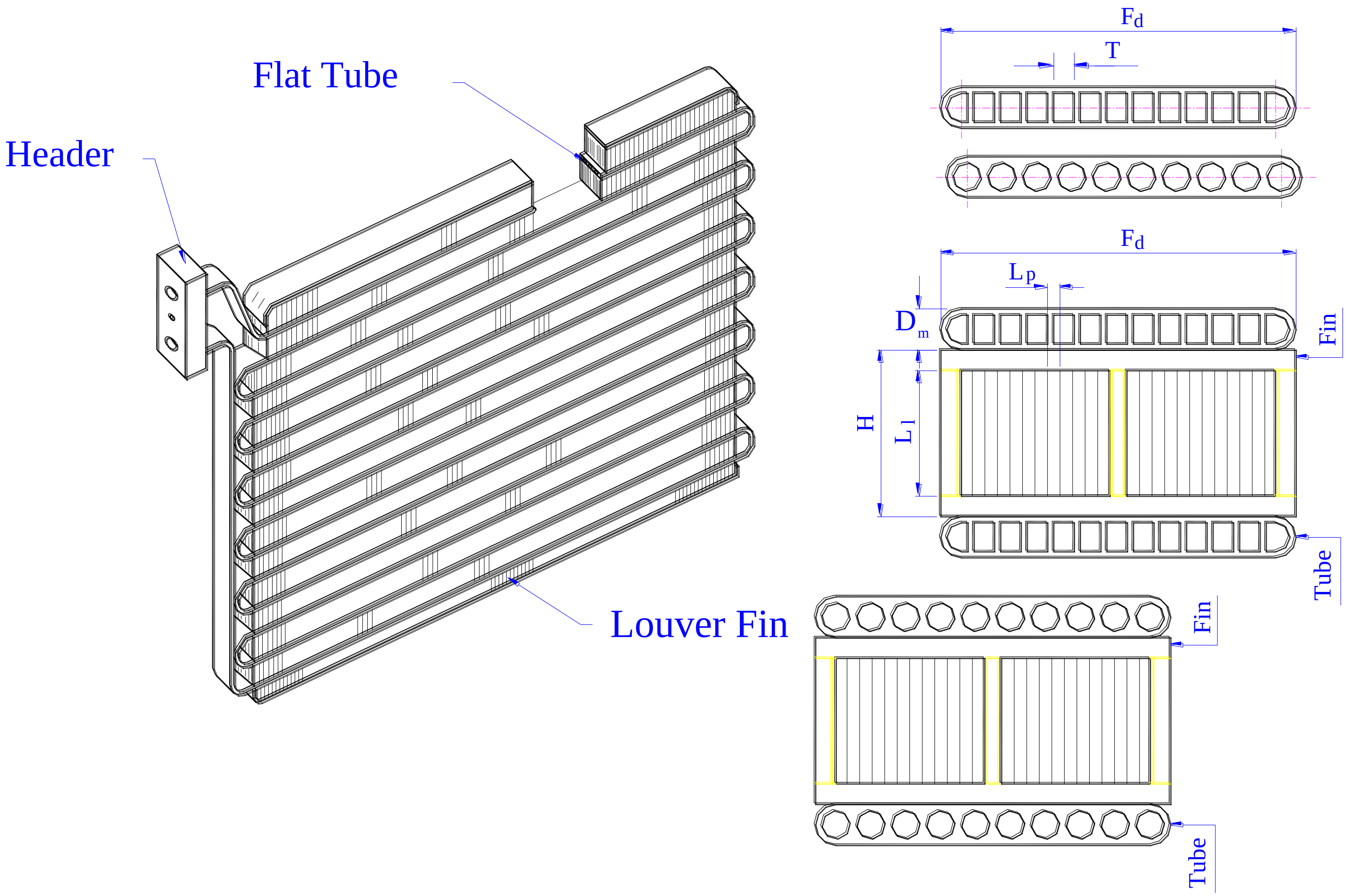
  $L_{hy,lmminar} \approx 0.05(\text{or } 0.06)\times 1000\times D_h$ = 50~60 D_h

  $L_{hy,turbulent} \approx 4.4\times 10000$^1/6$\times Dh$ = 20.5 D_h

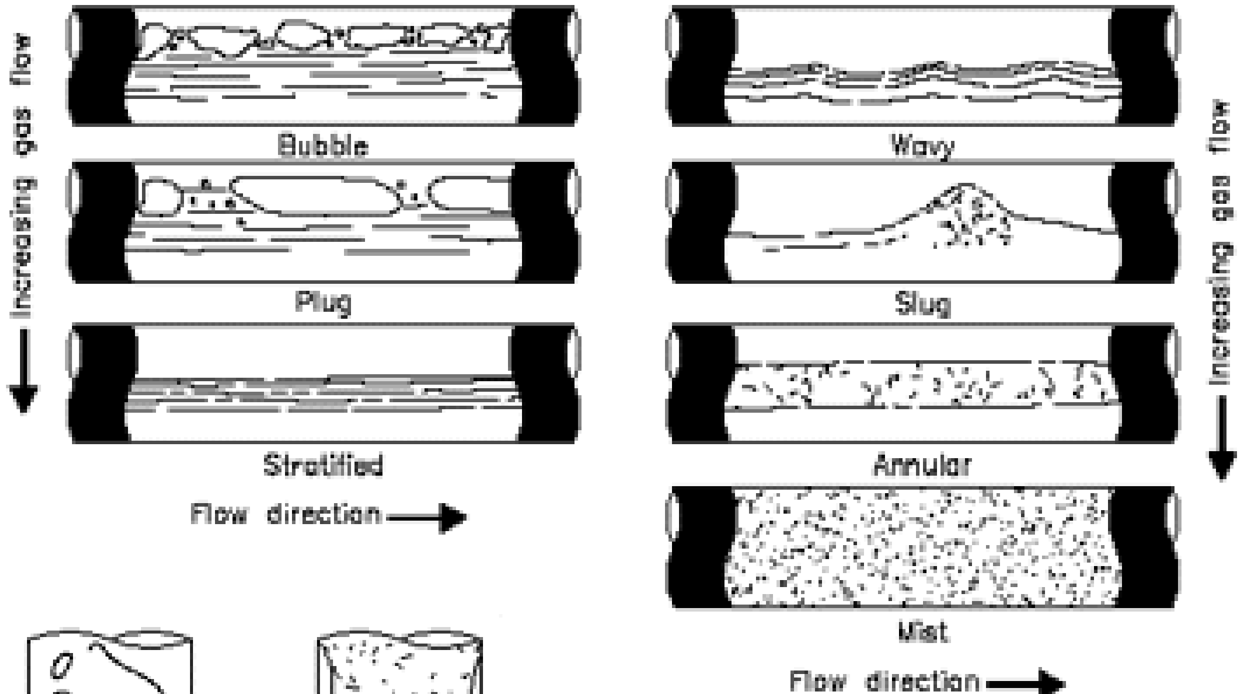
Two-phase Flow in Microchannels

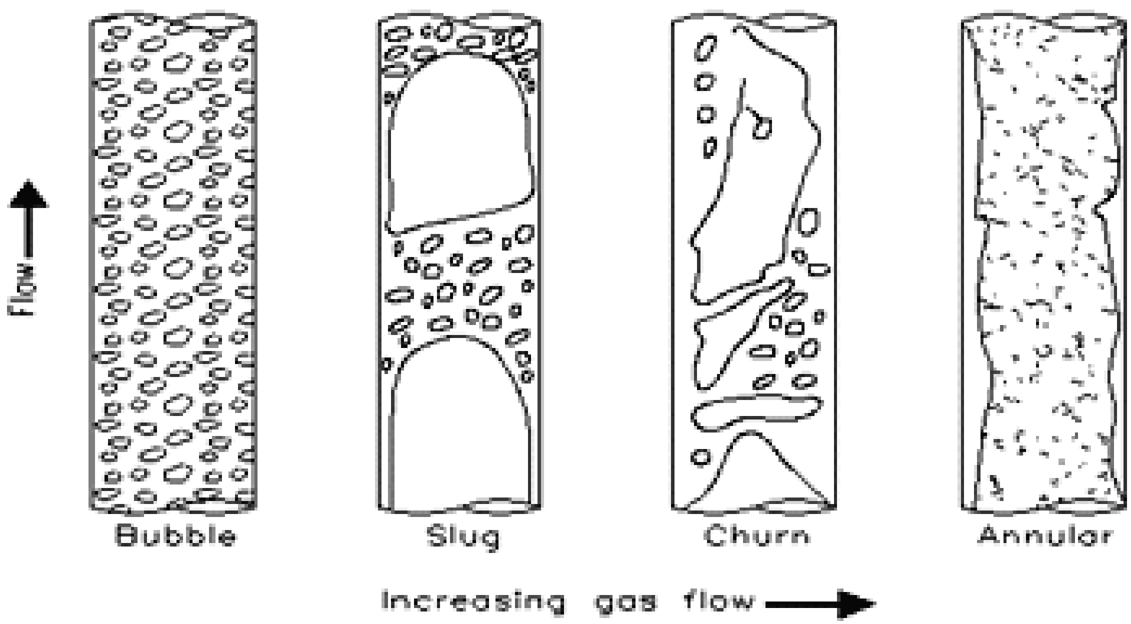
- Fact: For single phase flow, thermalfluids characteristics virtually no change either in Microchannel or conventional macrochannel.
- How about two-phase flow?

A Typical application of two-phase microchannel heat exchanger

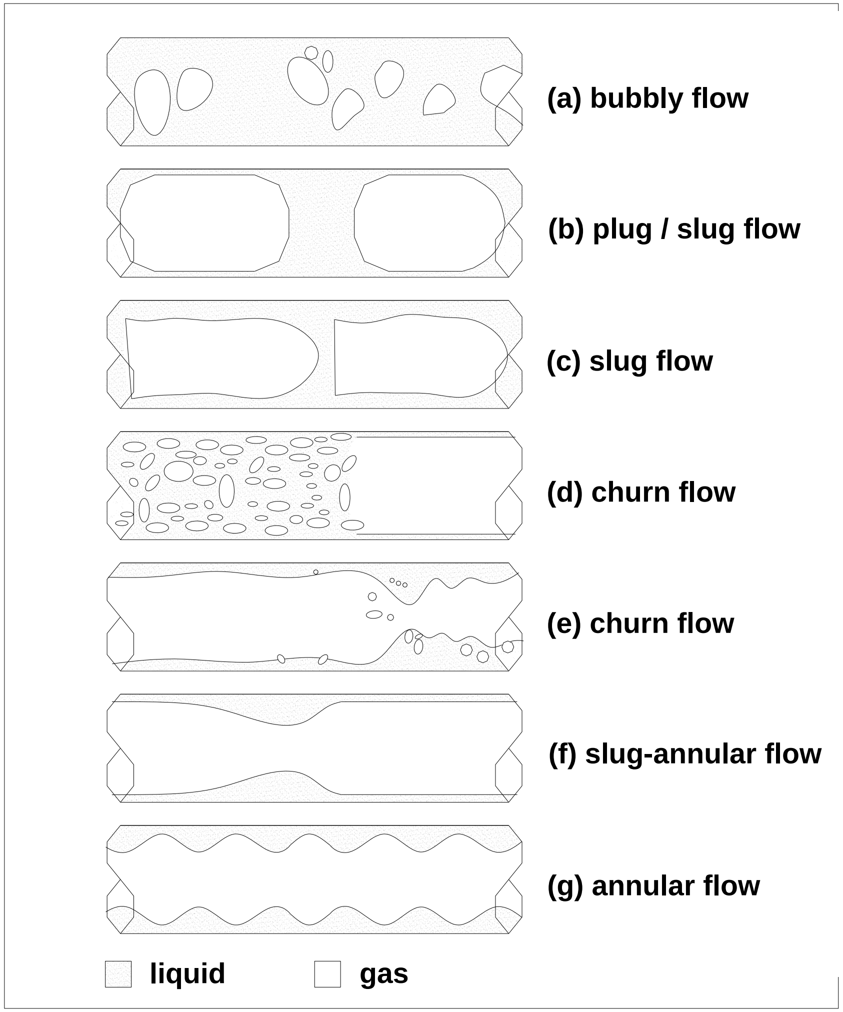


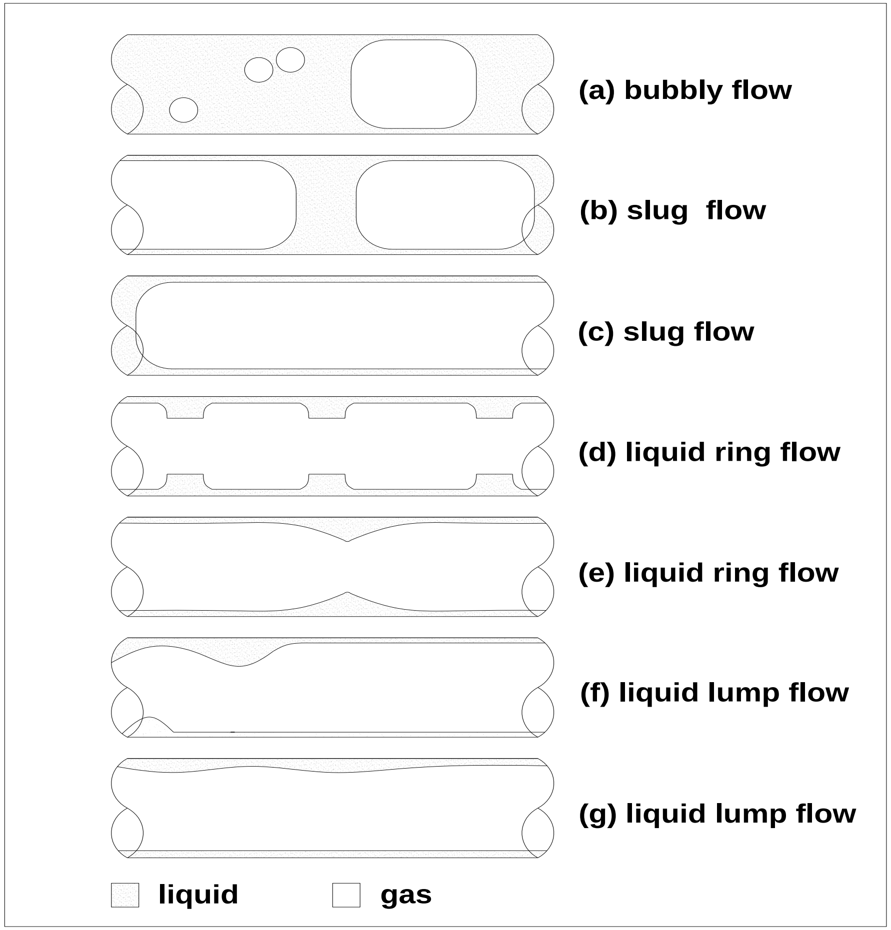
Typical flow pattern for conventional channel



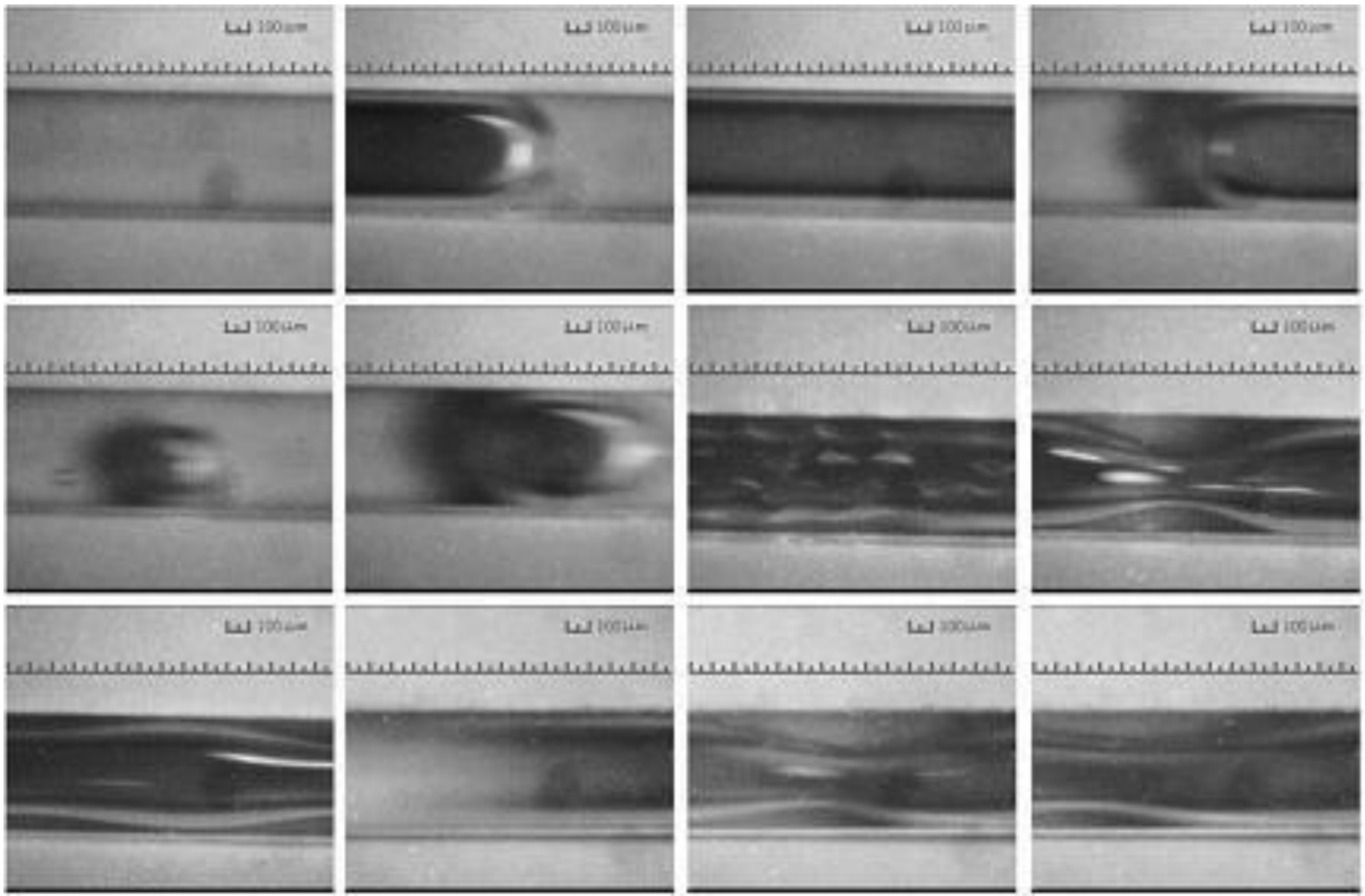


What's difference in two-phase flow pattern?

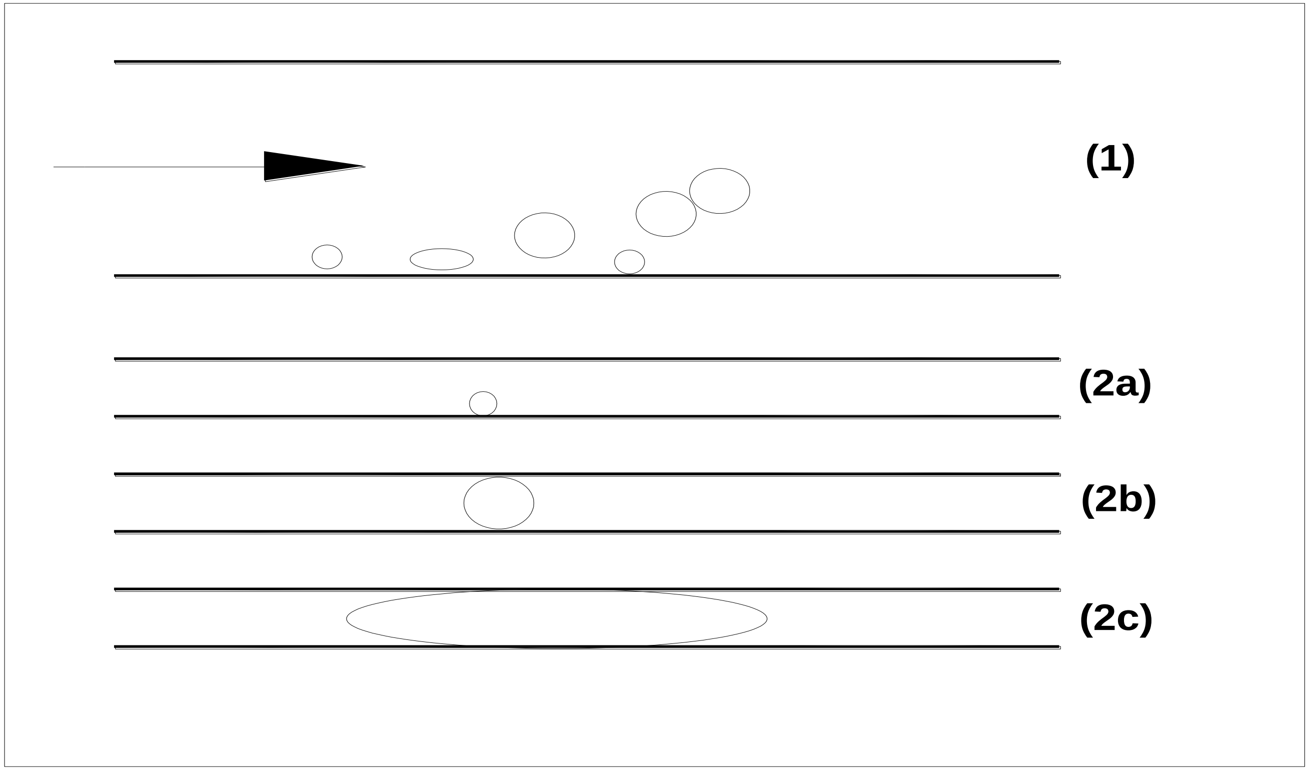


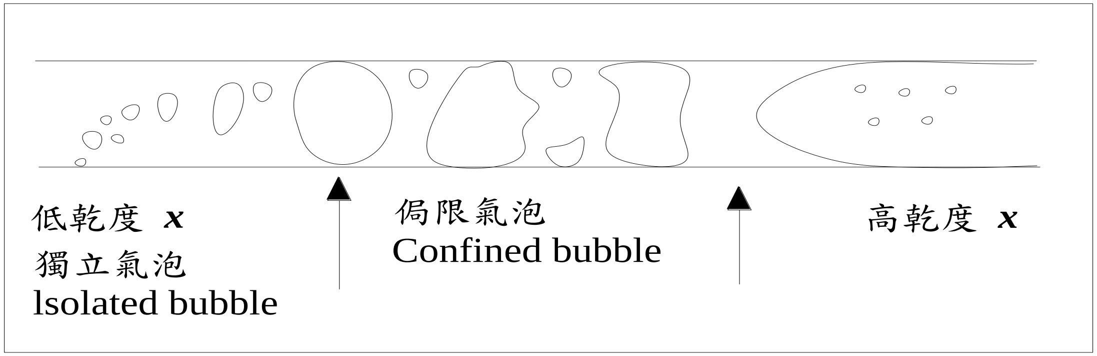


Adiabatic gas-liquid two-phase flow patterns of micro-channels plaza.ufl.edu/rxiong/research/STflow.htm



Effect of Bubble size in association with channel size



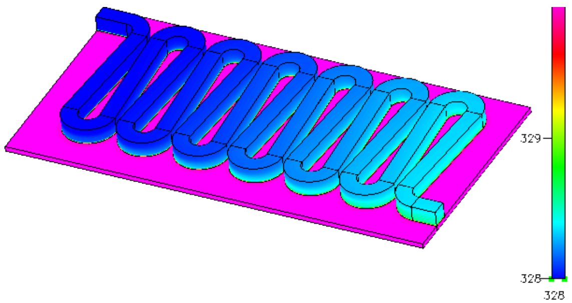


Summary of Microchannel HX

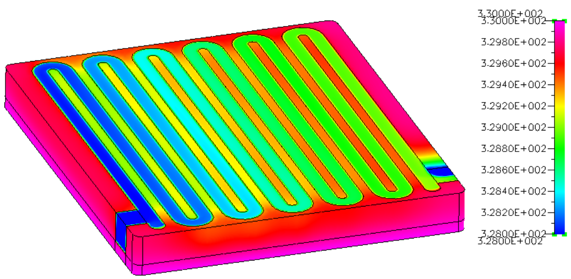
- **Microchannel HX is considered as an alternative for high-flux electronic cooling applications, and it is applicable in both single and two-phase applications.**
- **The basic heat transfer and frictional characteristics for microchannel in single phase flow is the same as that of macrochannnel. However, the two phase flow shows a considerable difference in it subject to the bubble/flow phenomena.**
- **Heat Transfer augmentation is an effective way for laminar flow cold-plate.**
- **Influence of entrance should be considered for microchannel HXs.**
- **Mal-distribution could be a concern for multiple port channel cold-plate.**
- **In two-phase flow application, contraction loss may be quite important when compared to frictional loss.**
- **The two-phase boiling heat transfer coefficient is usually increased with the rise of heat flux but shows no (or slight decrease) with vapor quality.**
- **The two-phase flow pattern for microchannel is quite different from that of macrochannel with virtually no stratified flow pattern.**

Effect of Mal-distributions..

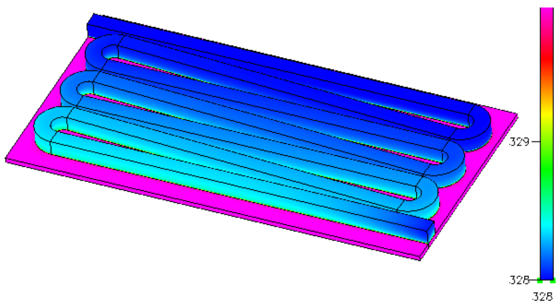
Cold Plate
Serpentine vs. multi-port design



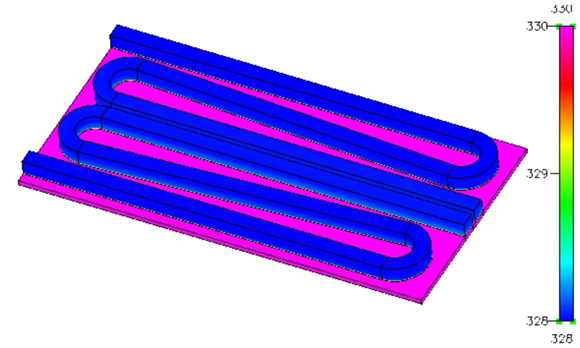
ΔP = 4.9 kPa
Q = 47.94 W



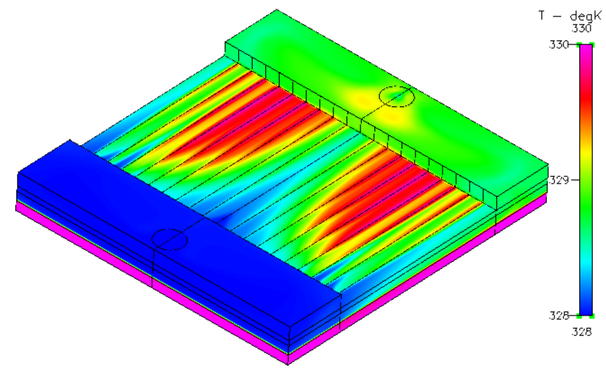
ΔP = 3.4 kPa
Q = 48.72 W



ΔP = 1.2 kPa
Q = 13.73 W

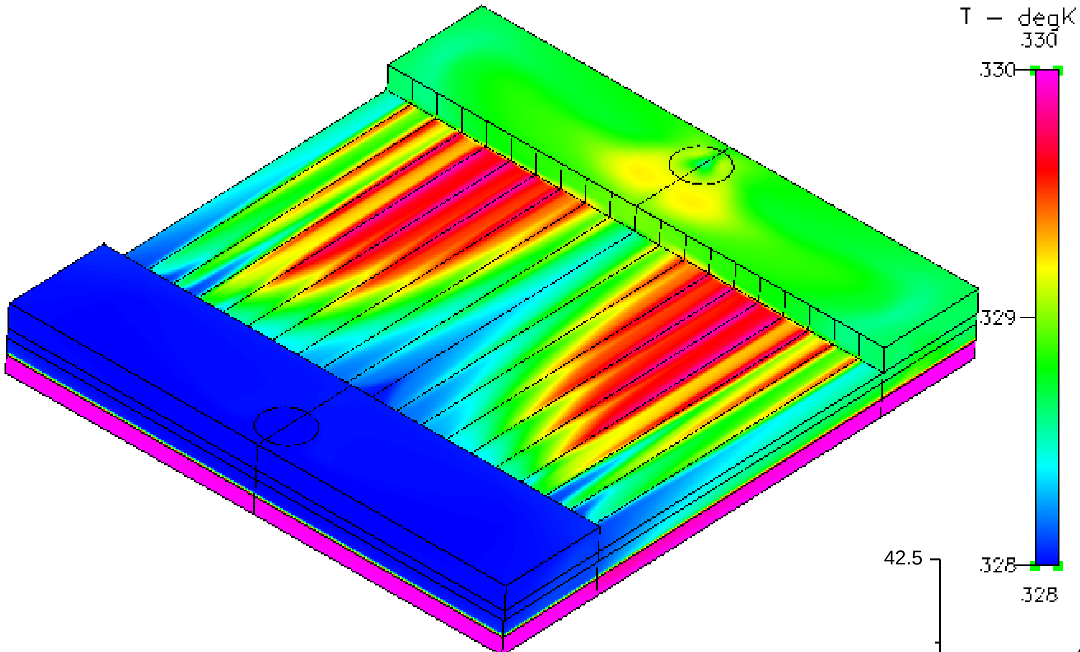


ΔP = 45.2 kPa
Q = 199.93 W



ΔP = 2.17 kPa
Q= 126.91 W

Multi-port HX



ΔP = 2.17 kPa

$\dot{Q}$ = *126.91 W*

$\dot{Q}$ X 2.7

ΔP X 0.5

(1) *ΔP = 4.9 kPa*

$\dot{Q}$ = *47.94 W*

V_{in} = 1.0 (m/s):

Flow mal-distribution:

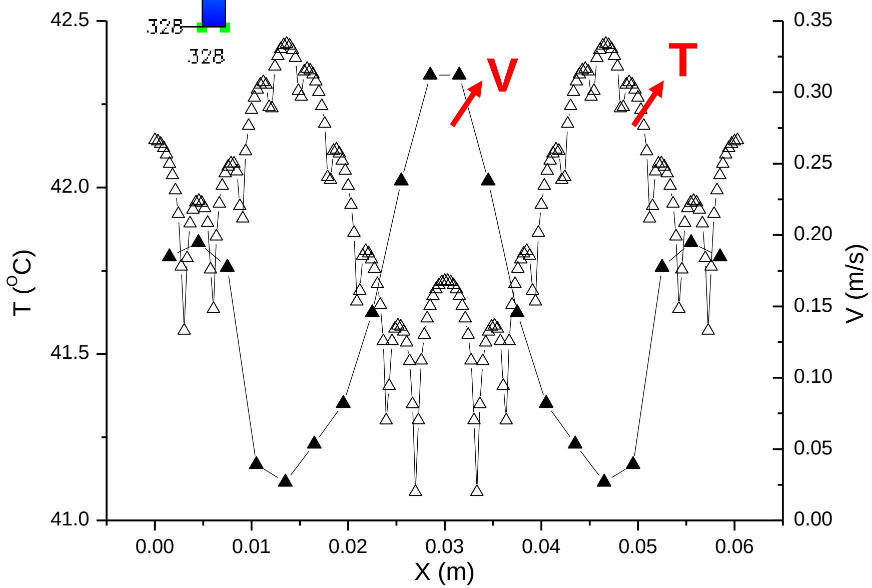
ΔV_{MAX} = 0.2852 (m/s)

Non-uniformity of Temperature field:

ΔT_{MAX} = 1.345 (°C)

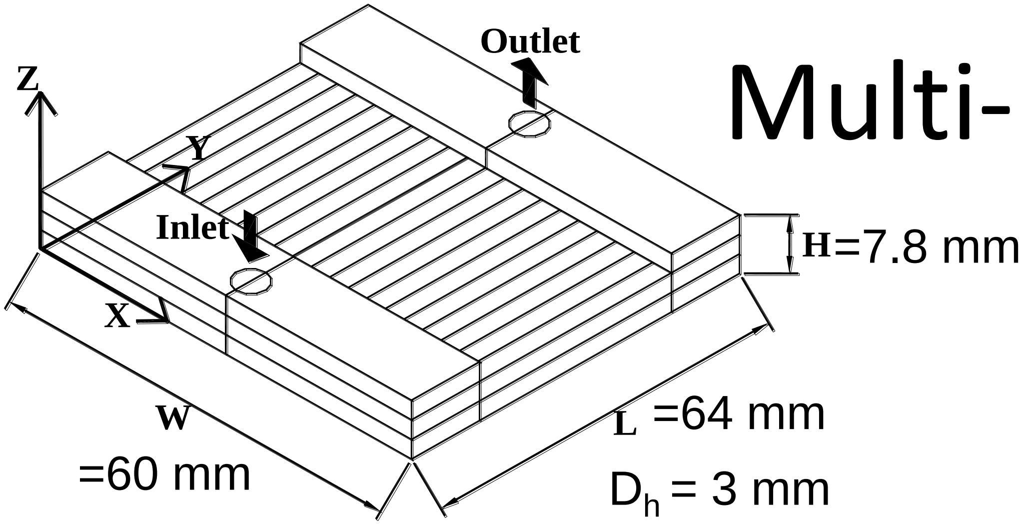
⇓

ΔQ_{MAX} = 148 (W)



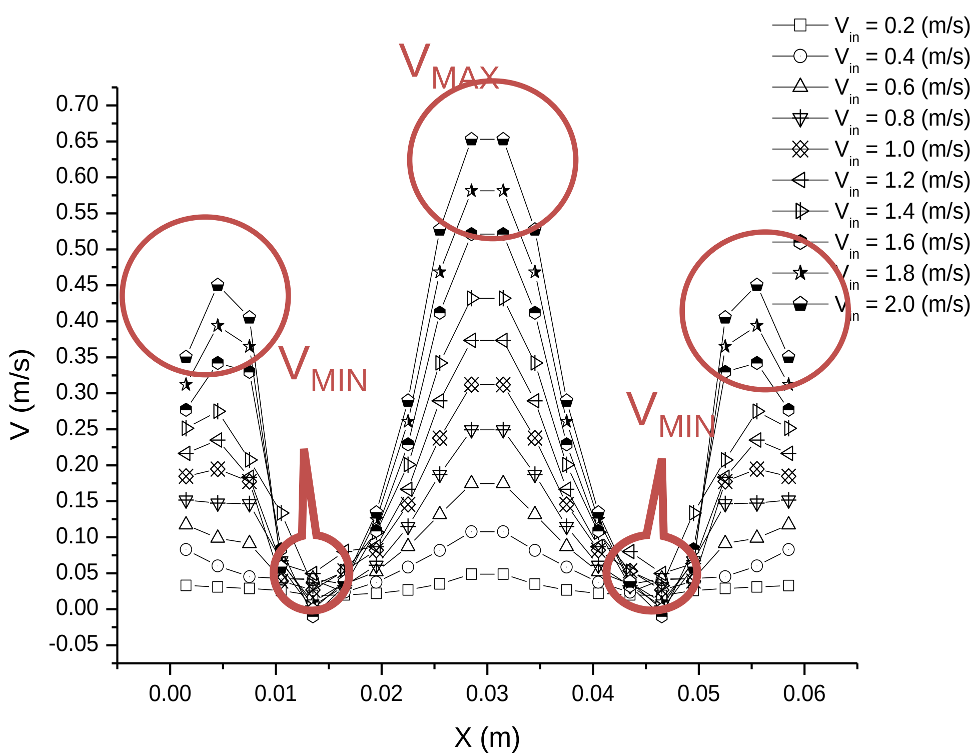
MC Lu et al., (2004)

Multi-port Cold Plate

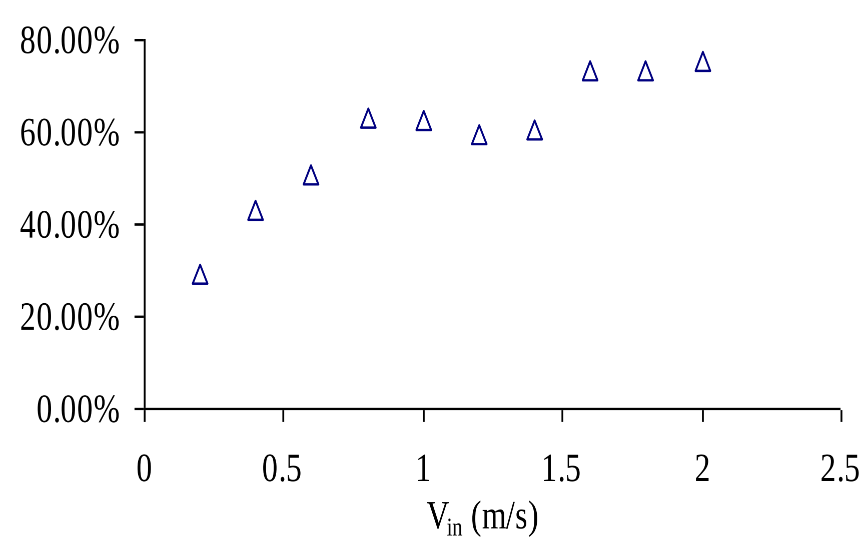


$$V_{STD} \equiv \sqrt{\frac{n\sum_i v_i^2 - (\sum_i v_i)^2}{n(n-1)}}$$

Transverse Velocity Distribution



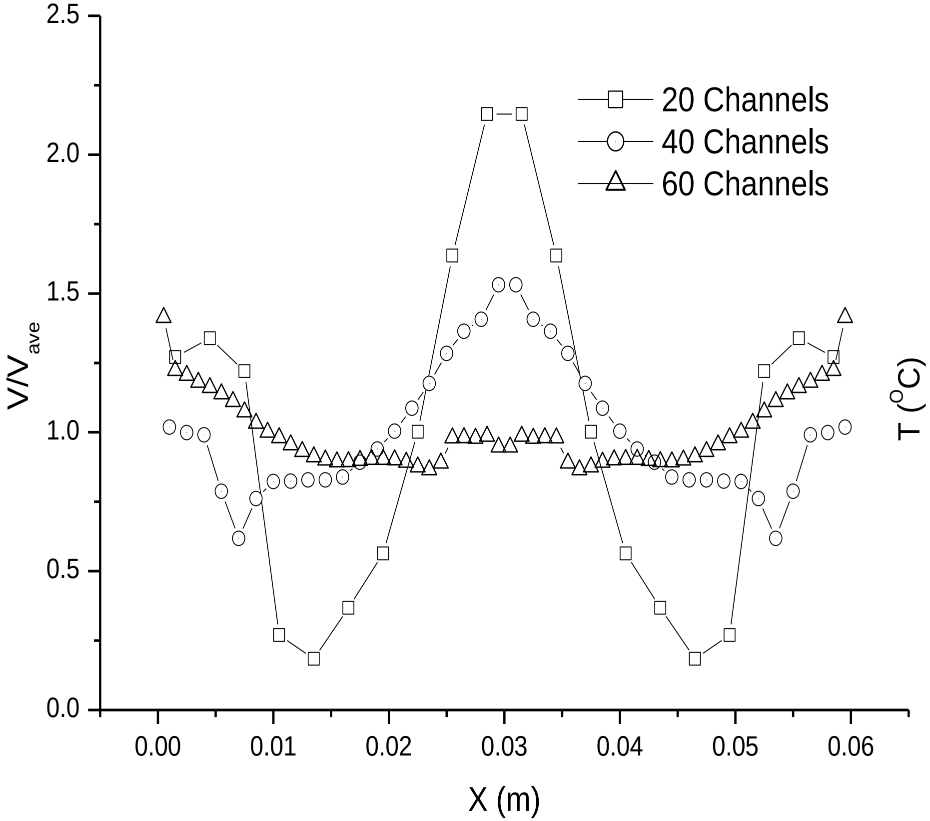
Flow Mal-distribution V_{STD}/V_{ave}



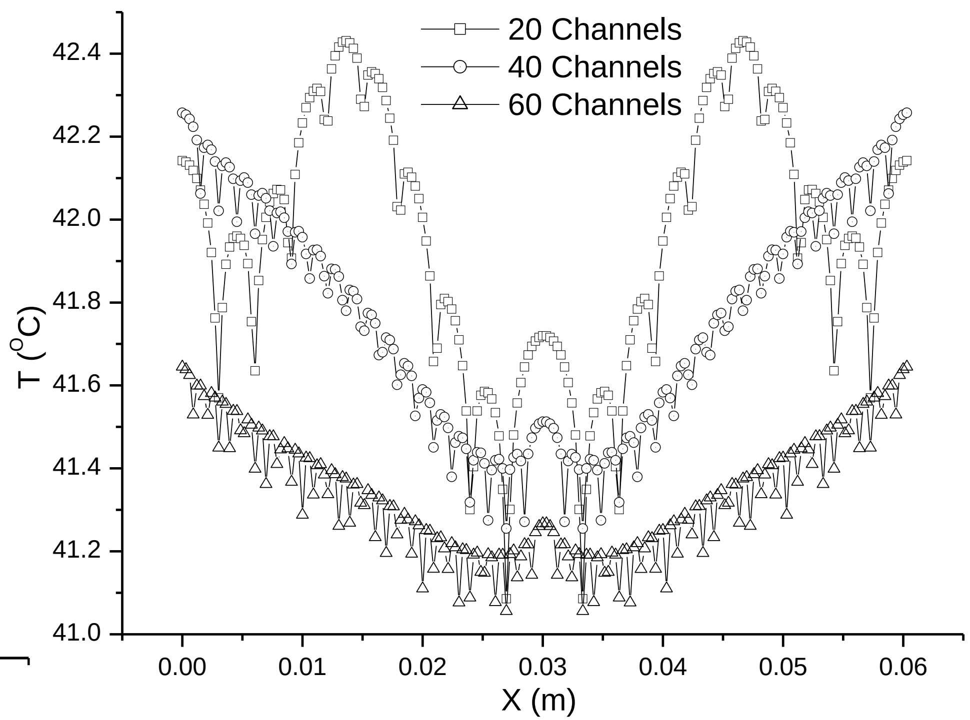
Lu and Wang, (2006)

Effect of number of port (20, 40, 60)

Velocity profiles of 20(□), 40(O) and 60(Δ) channels for Vin =1.0 m/s.



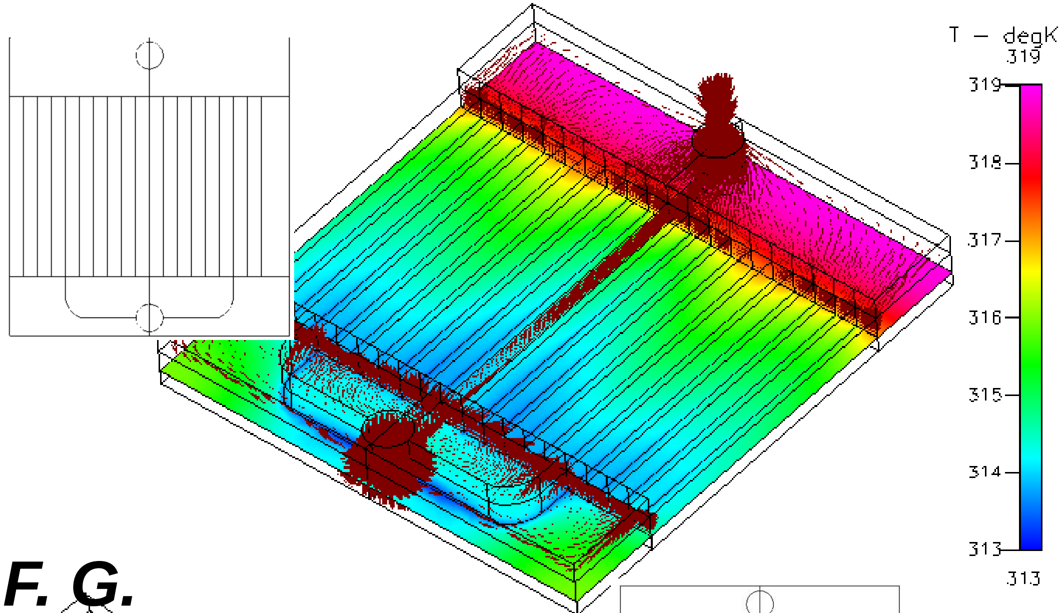
Temperature distribution of 20 (□), 40 (O)and 60 (Δ) channels cold-plates for Vin = 1.0 m/s.



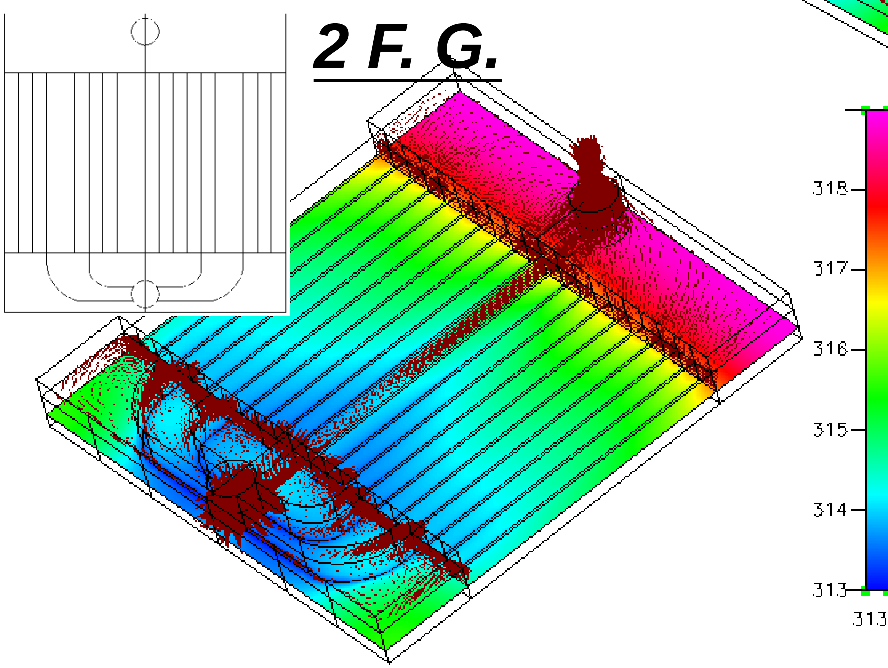
MC Lu et al., (2004)

Influence of Guide-plate

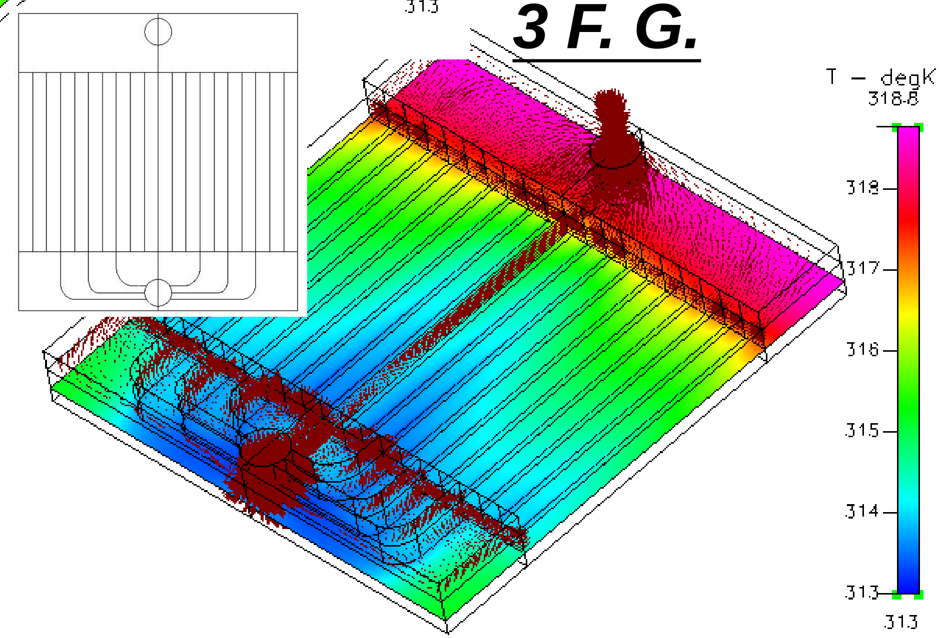
1 F. G.



2 F. G.

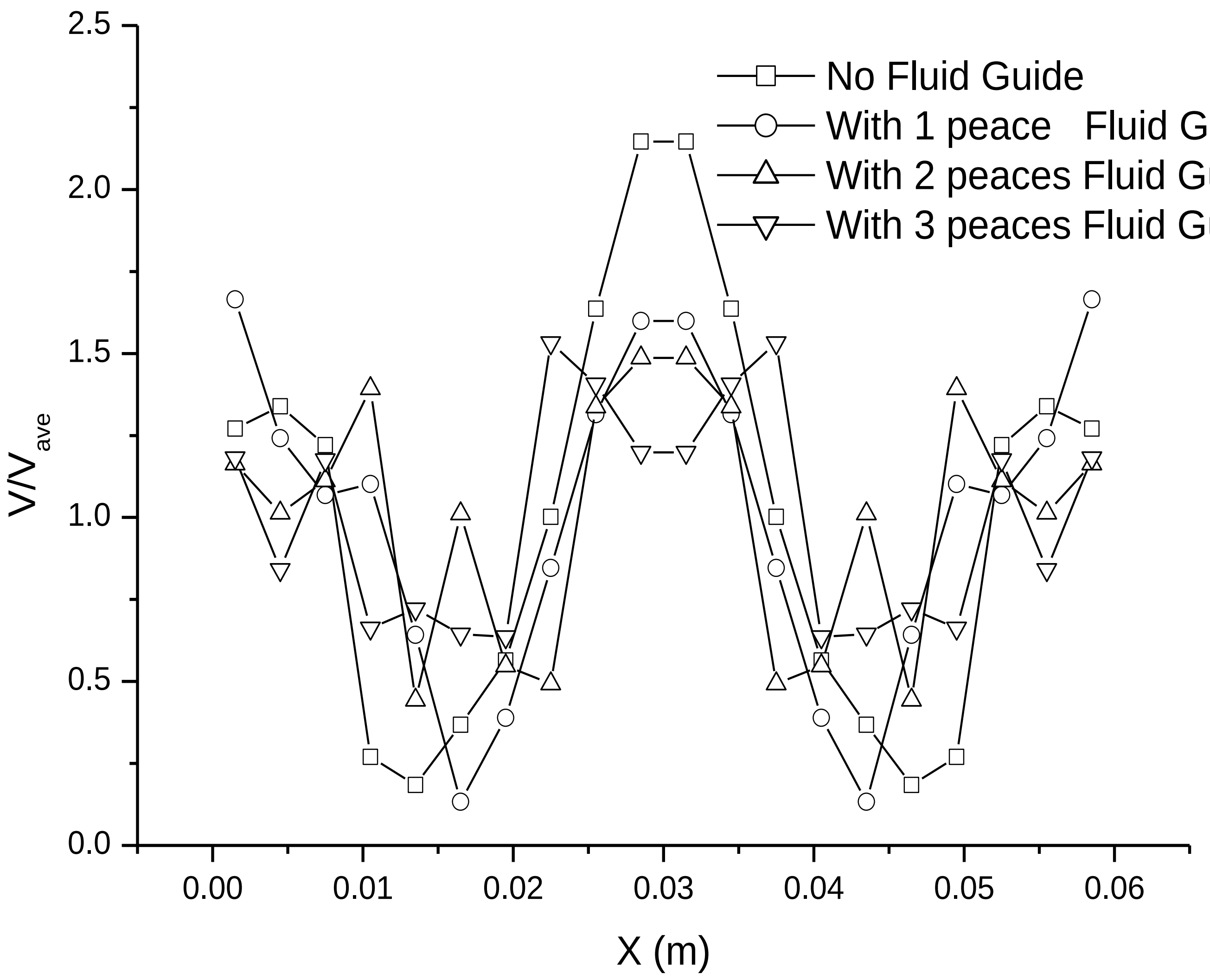


3 F. G.



MC Lu et al., (2004)

Influence of Guide Plate, Conti.



- **Flow Mal-dis.**

0 F.G. : 62.7 %

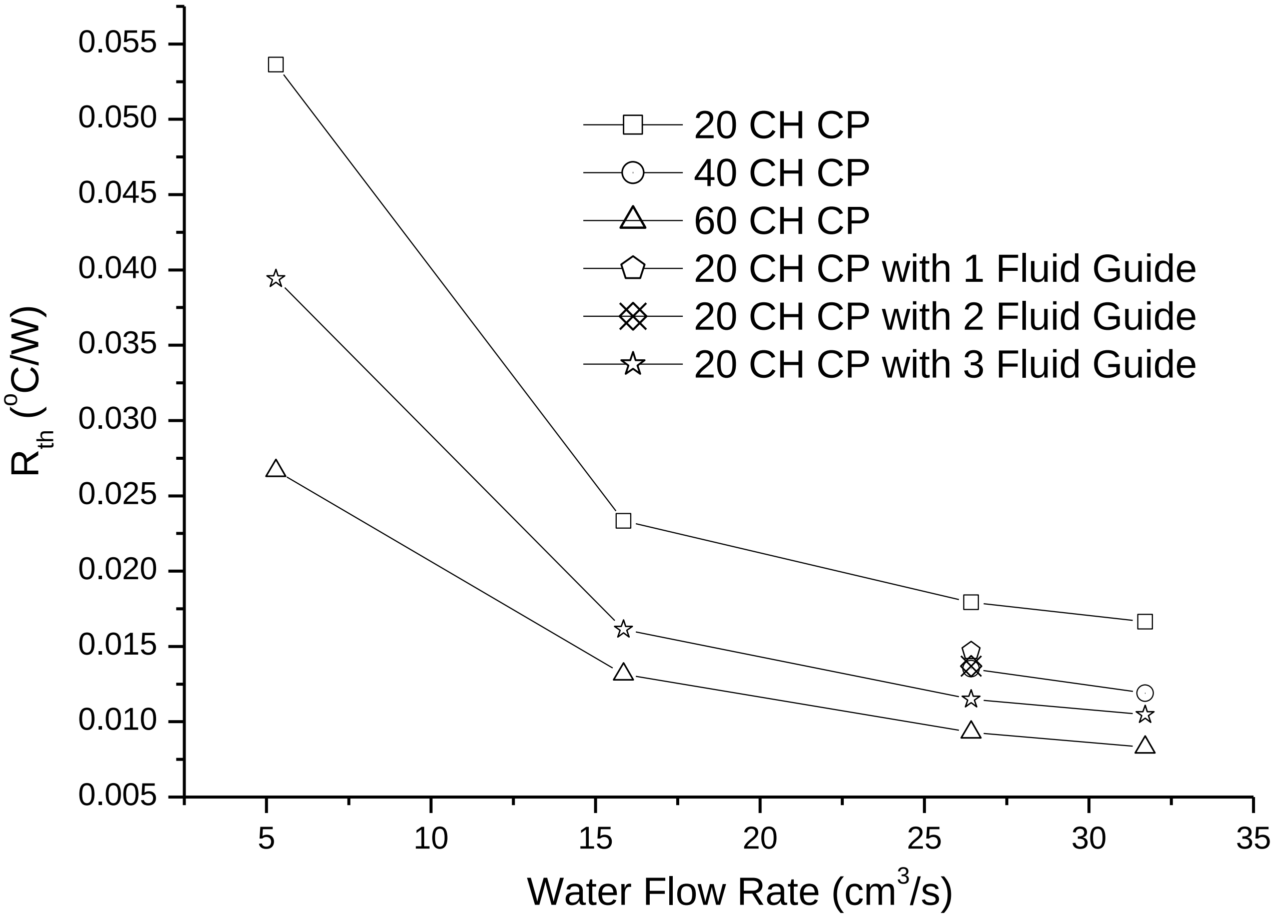
1 F.G. : 48.7 %

2 F.G. : 37.2 %

3 F.G. : 32.3 %

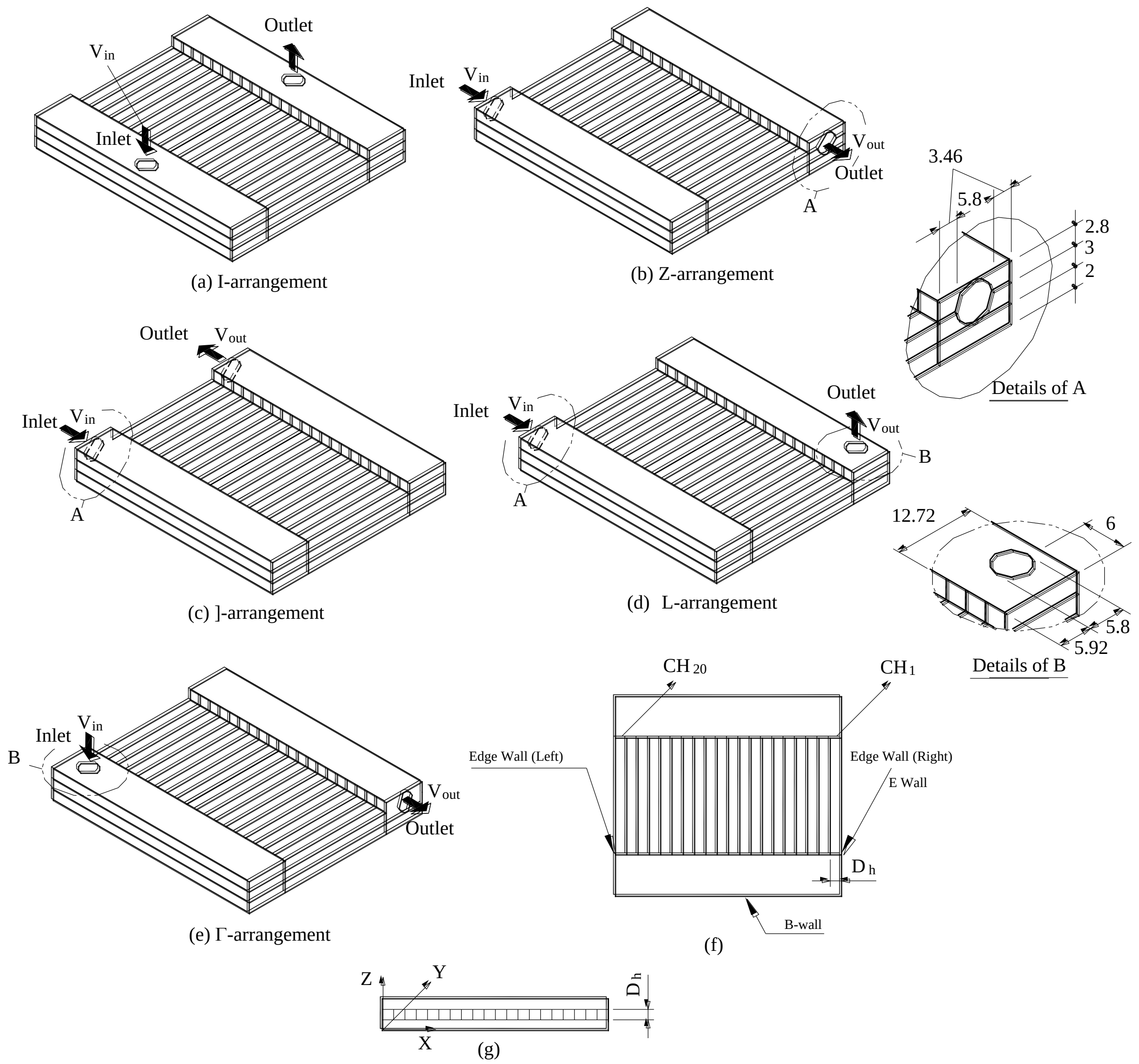
MC Lu et al., (2004)

Effect of Guide Plate – R_{th}



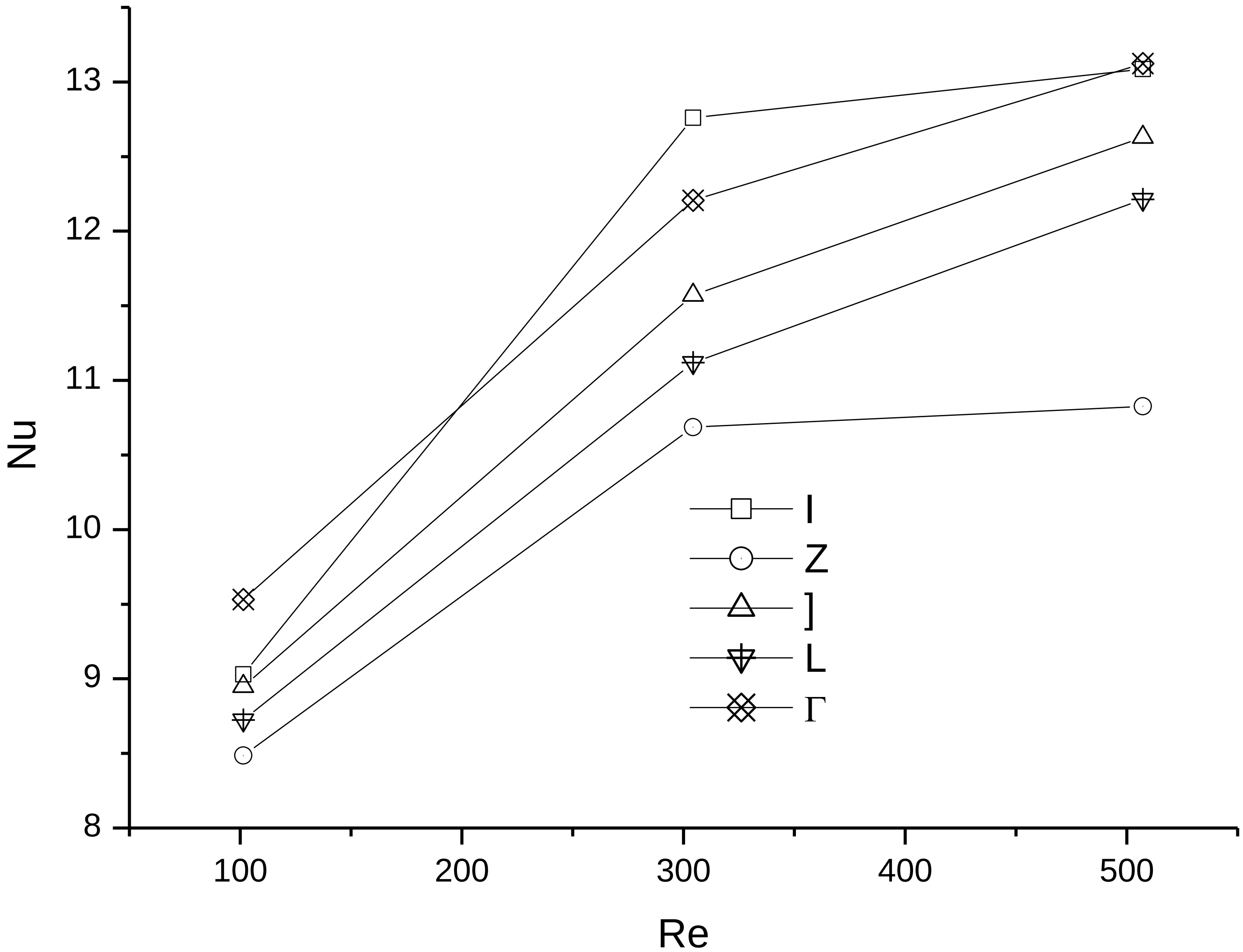
MC Lu et al., (2004)

Effect of Inlet locations



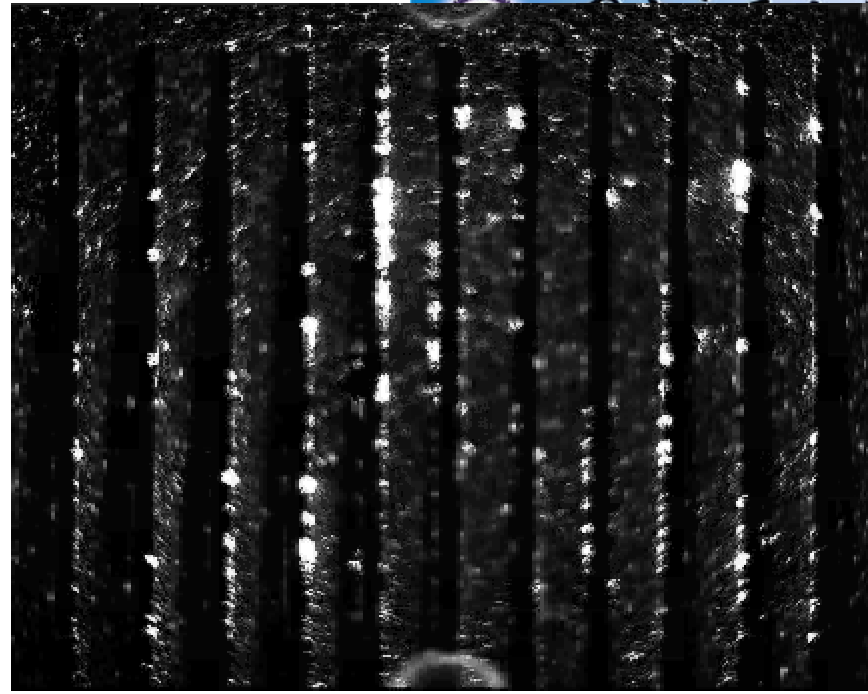
Lu and Wang, (2006)

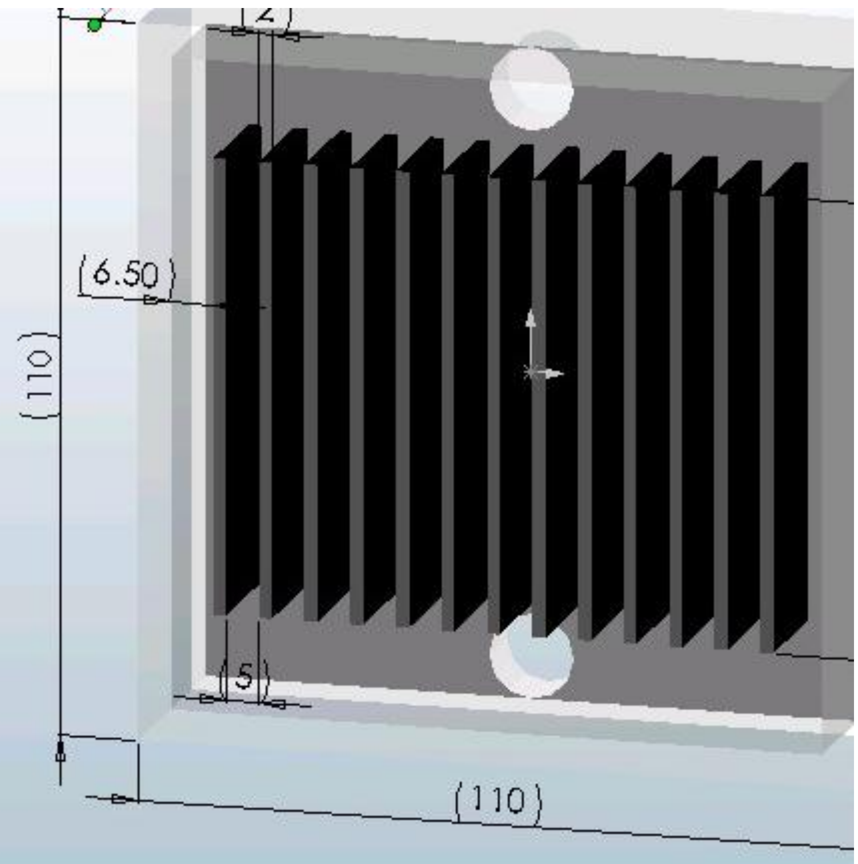
Effect of Inlet locations, Conti..

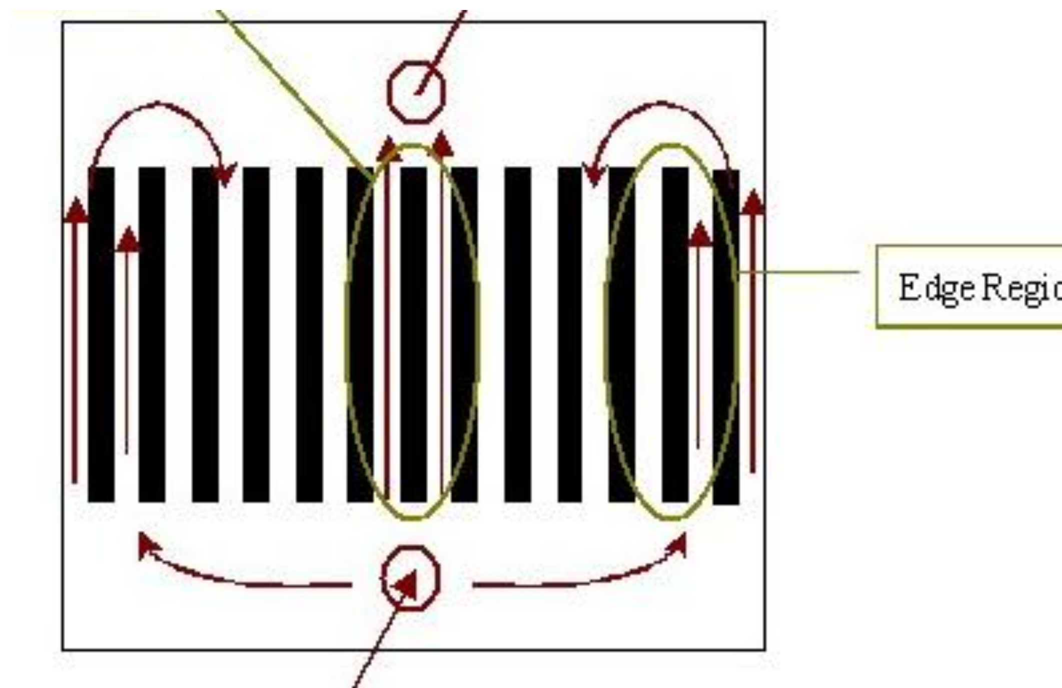


Lu and Wang, (2005)

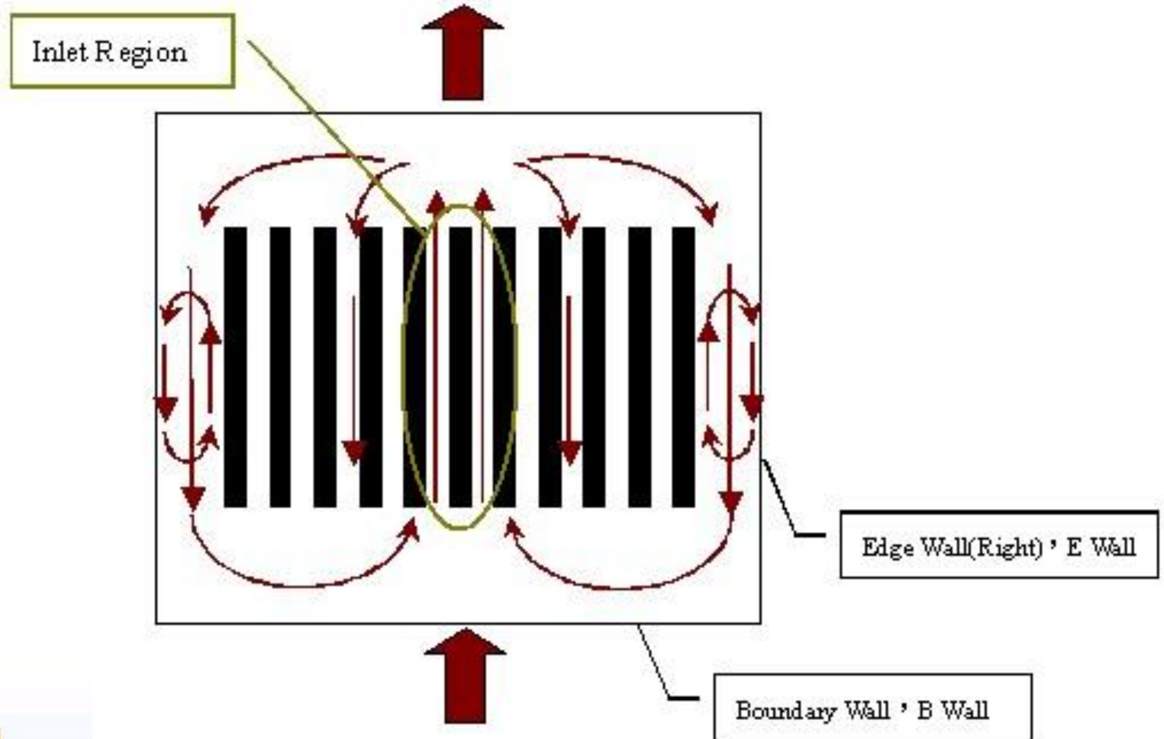
PIV Flow Visualization
: I Arrangement –Uniform Gap

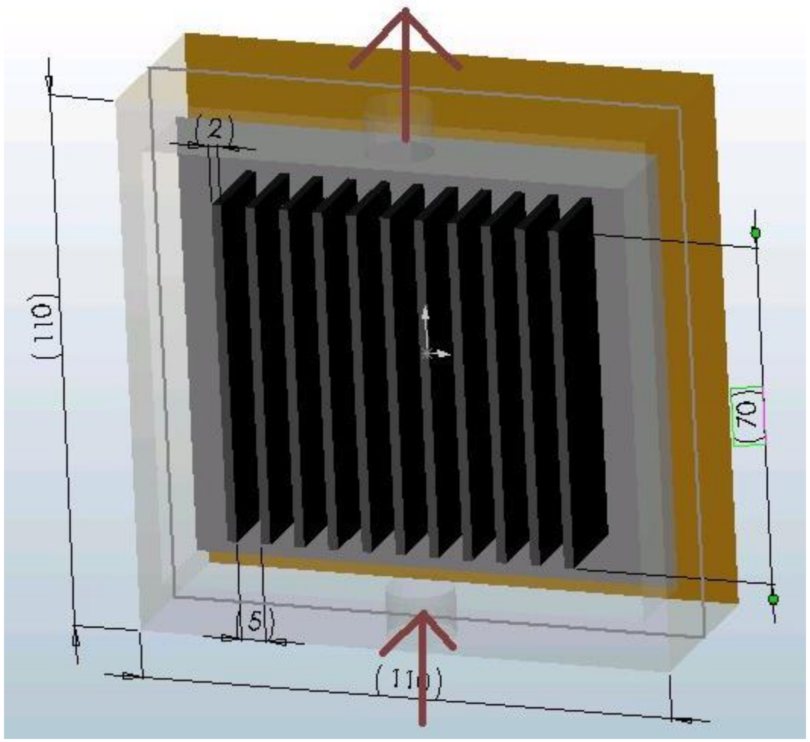


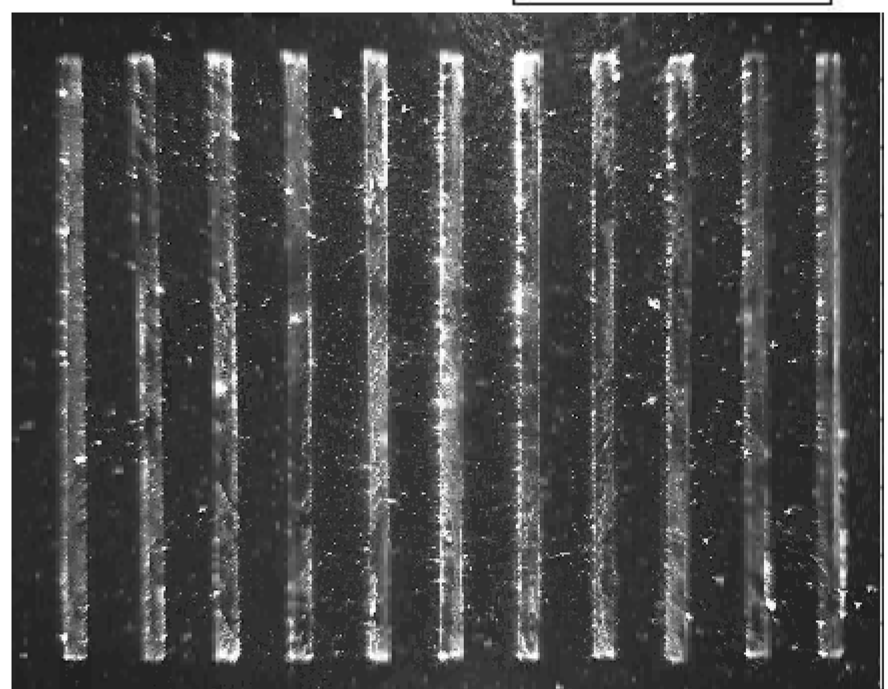




PIV
Flow Visualization







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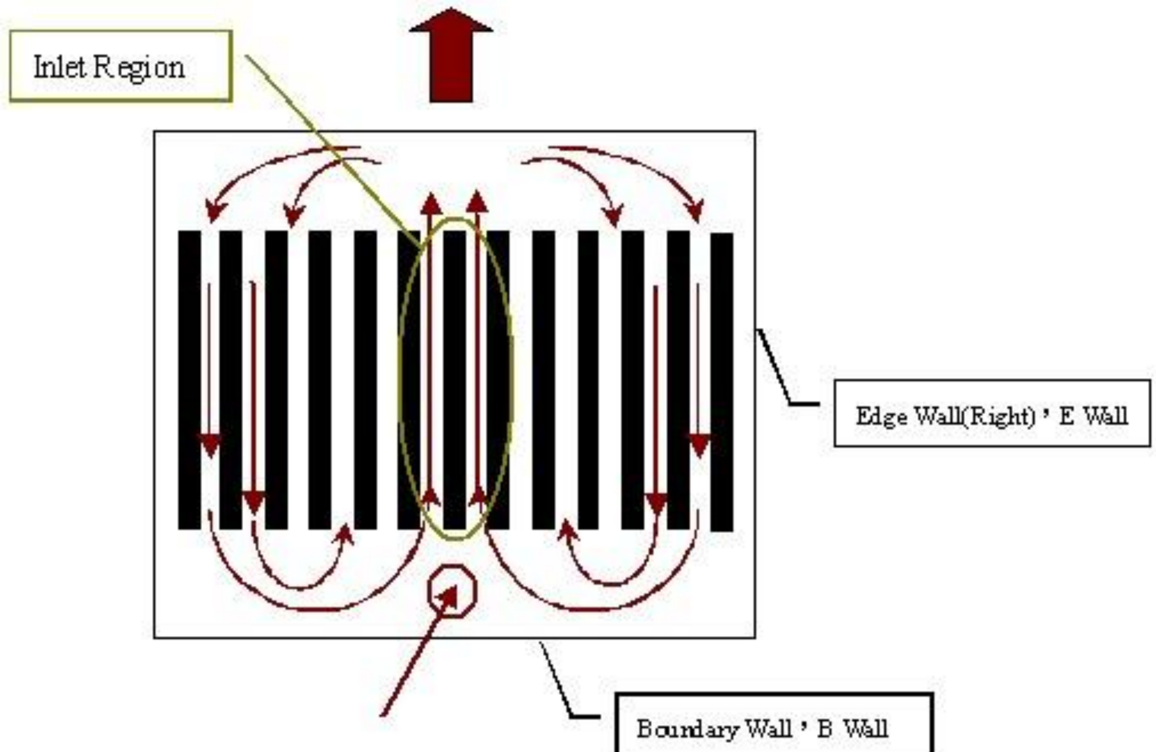

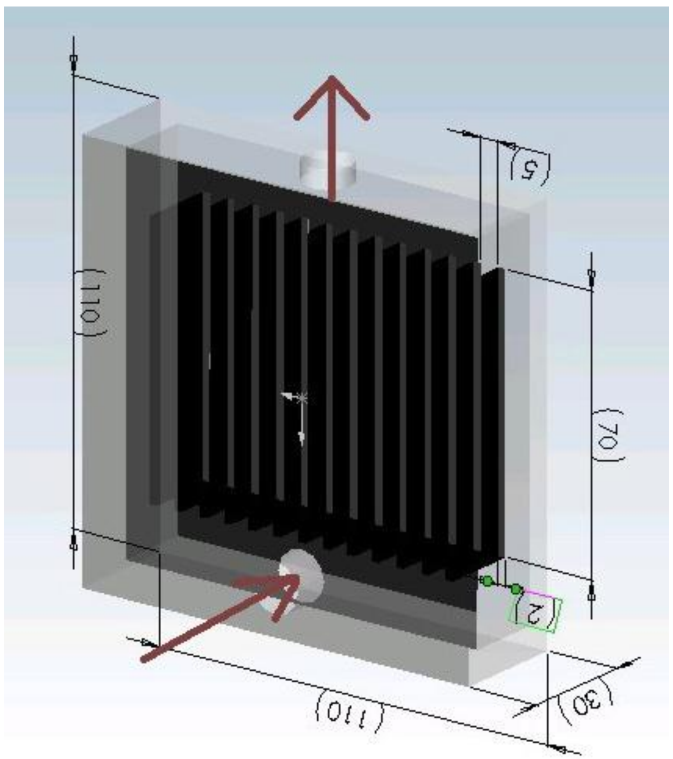

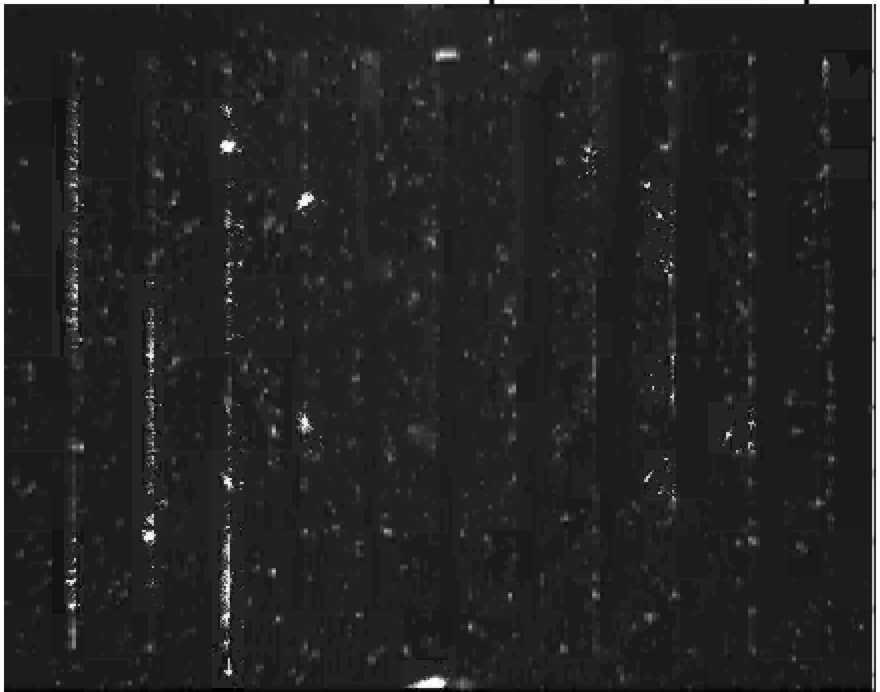

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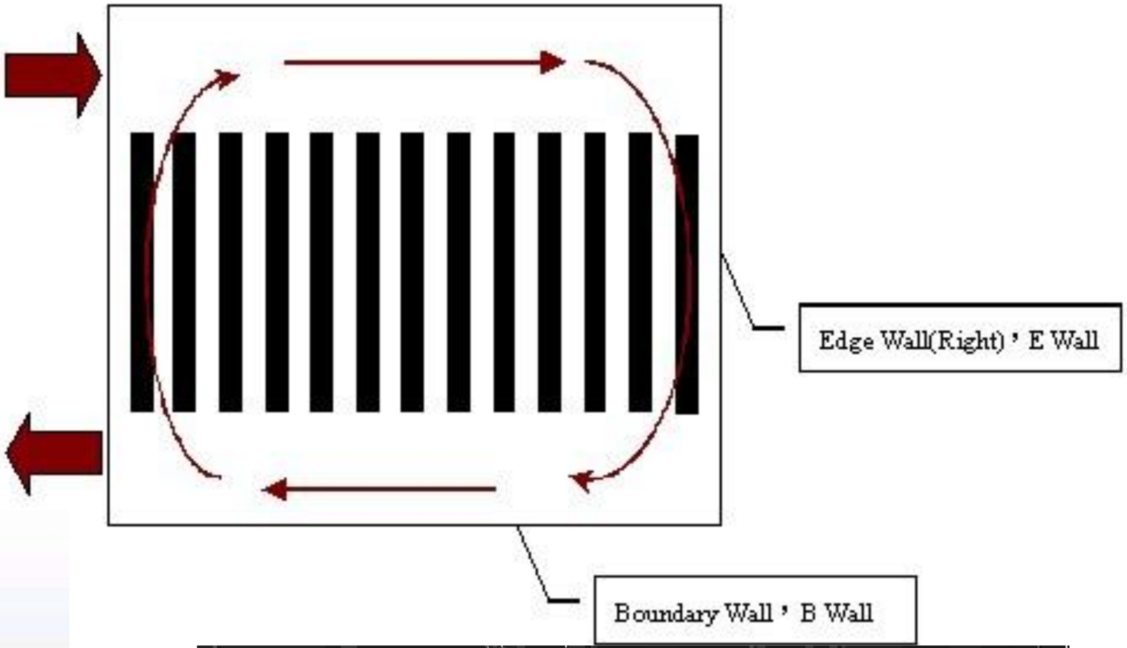

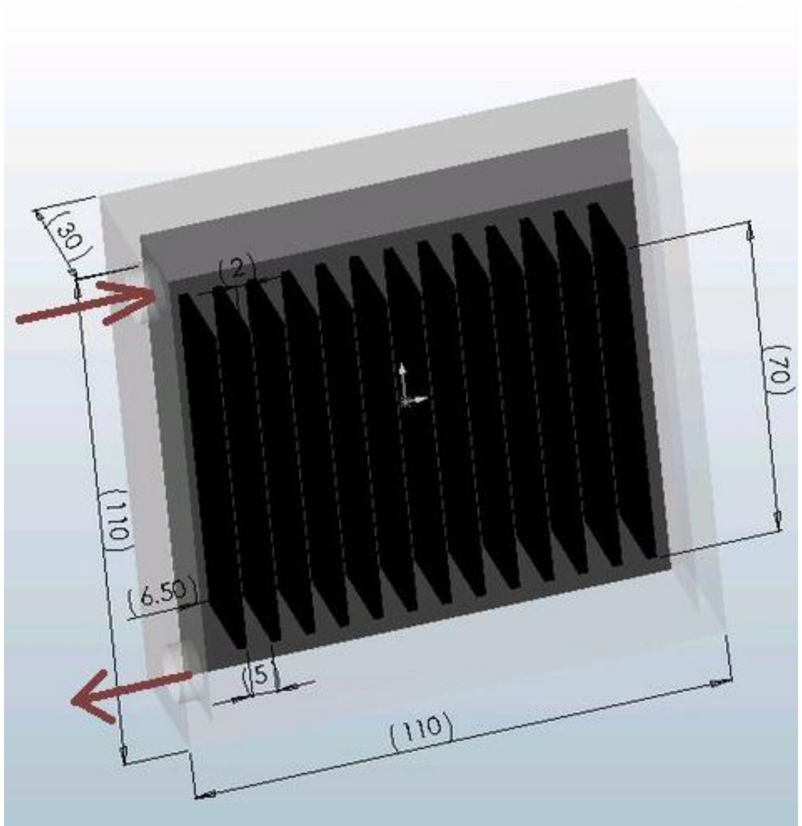

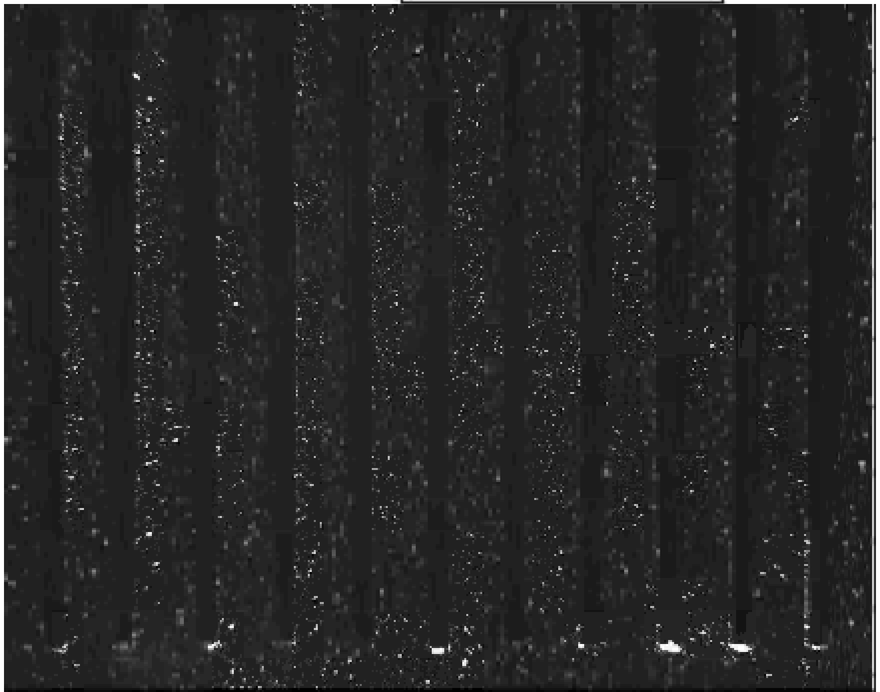

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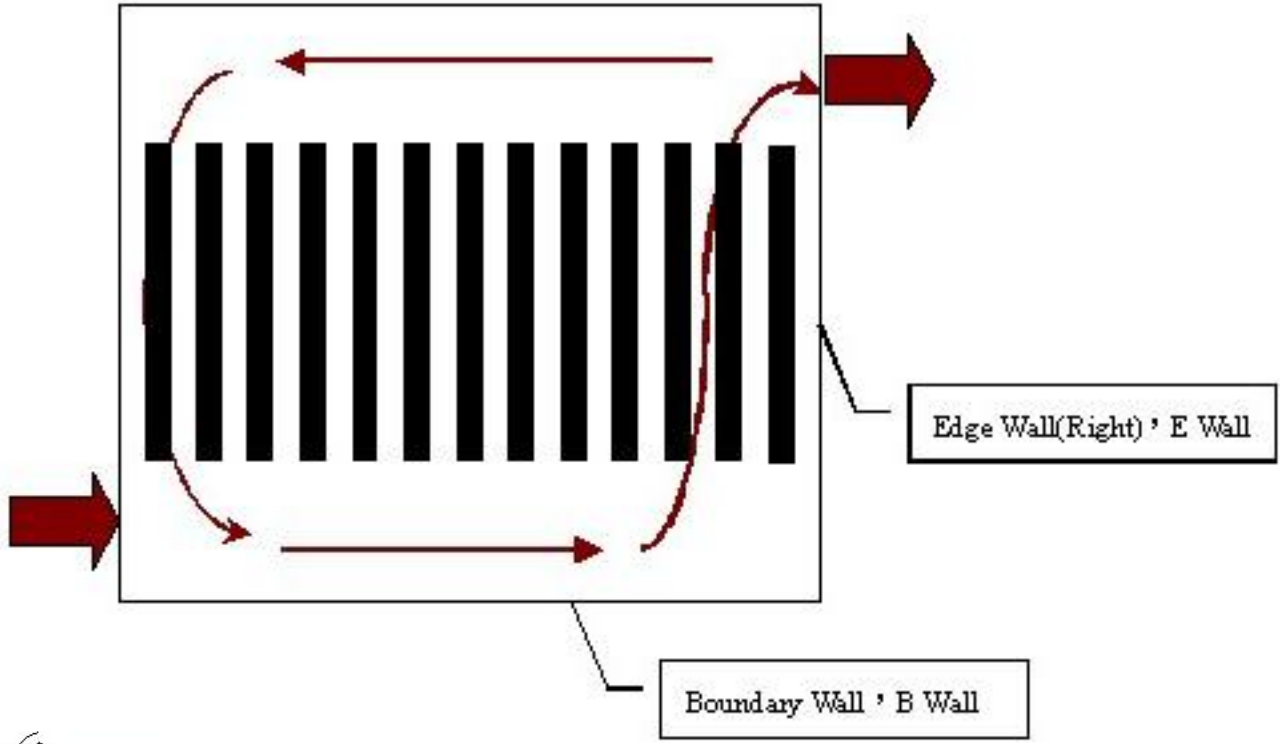

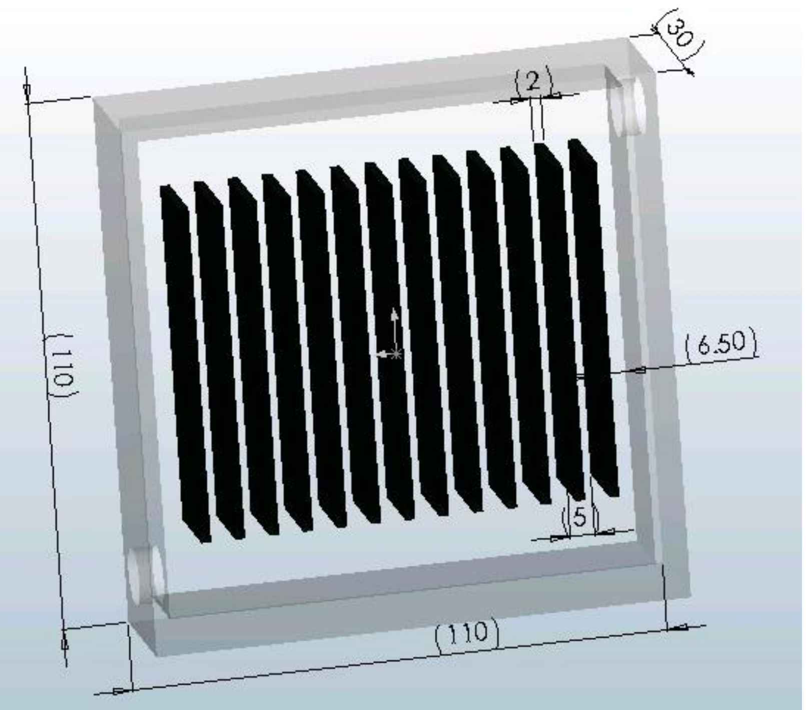

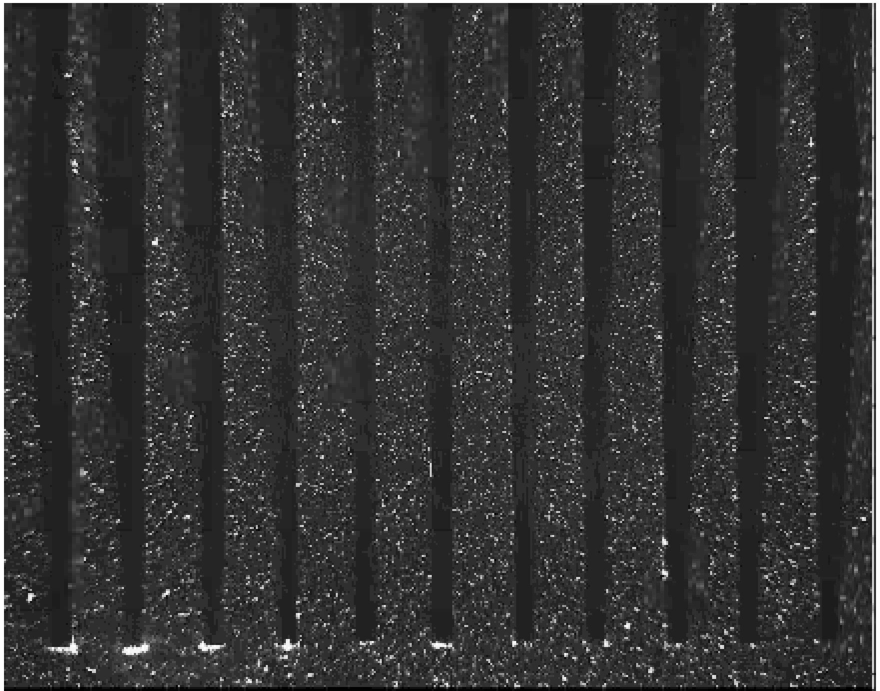


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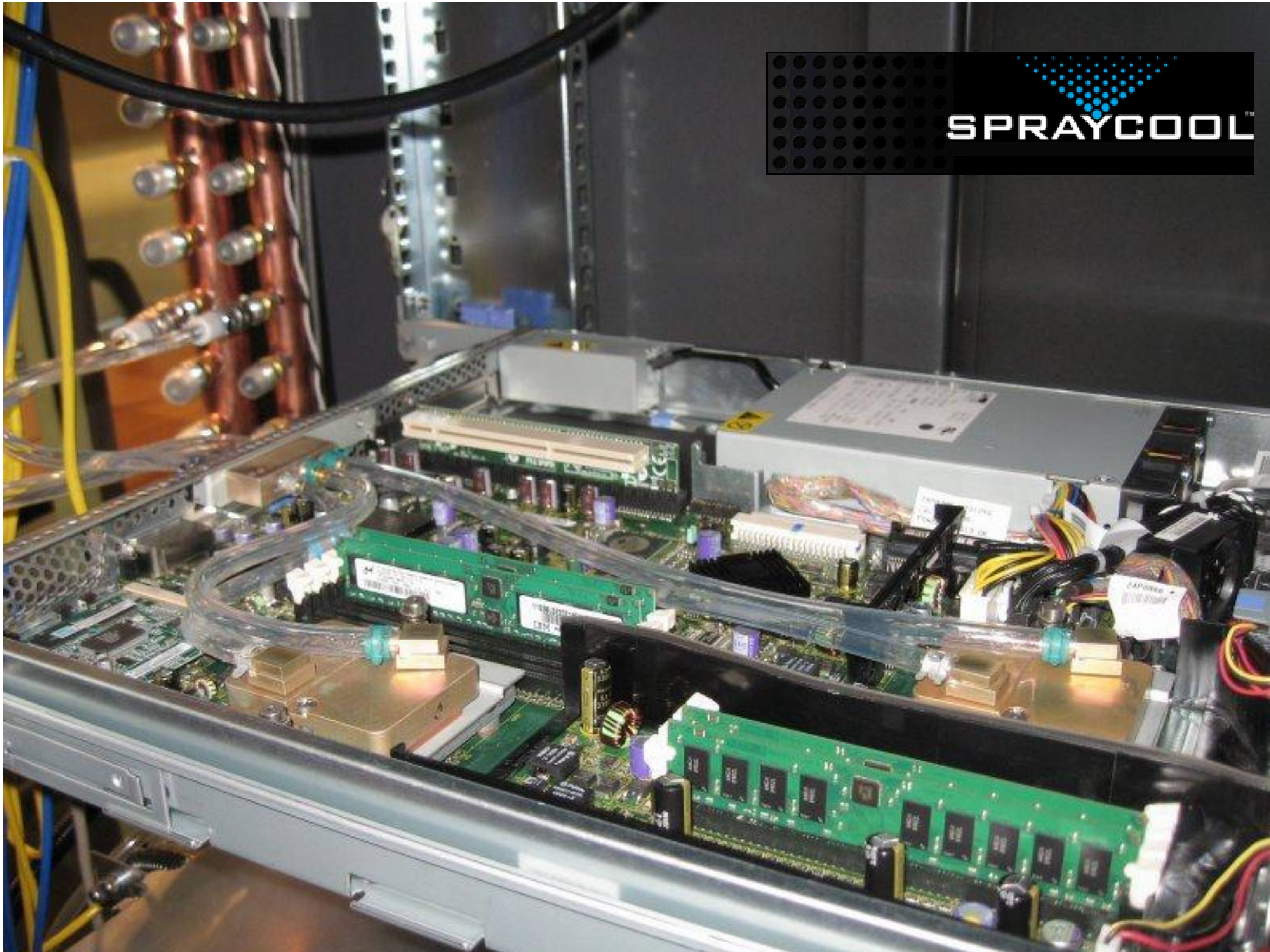
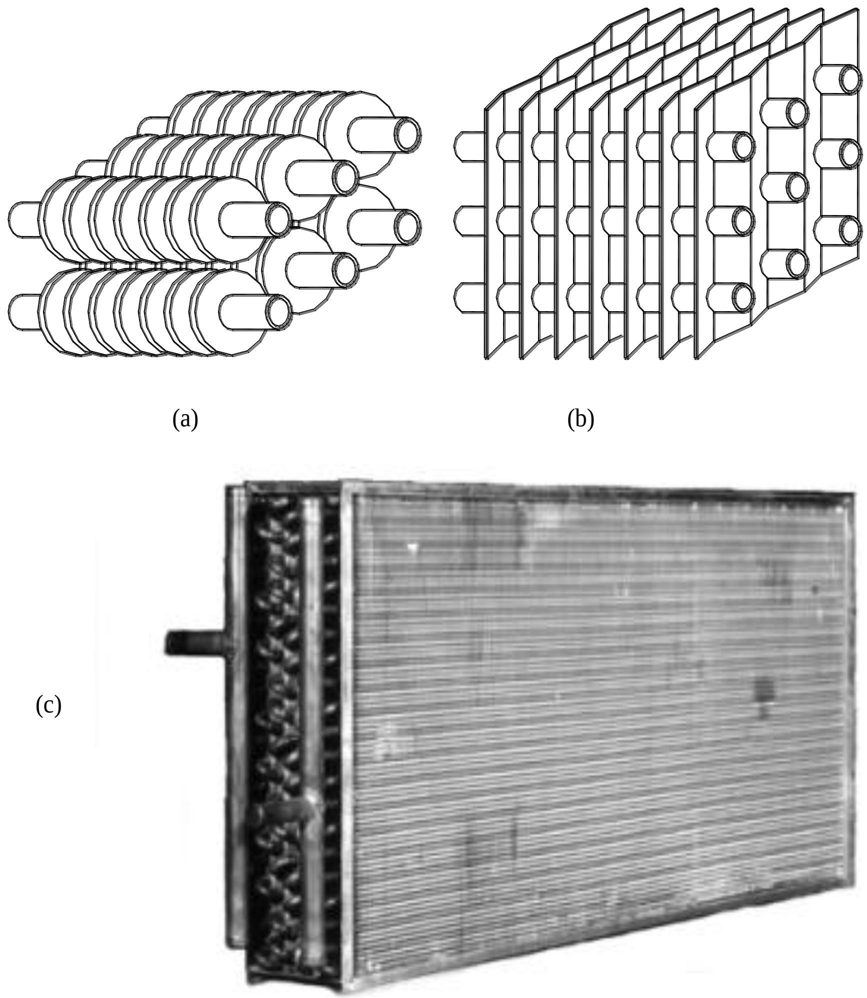
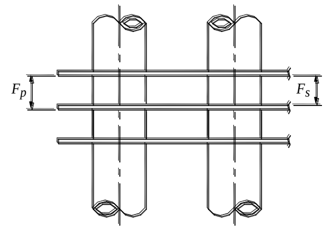
National Chiao Tung University





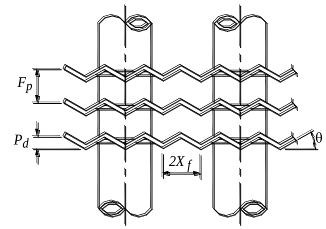
Typical fin-and-tube heat exchanger (a) individual circular fin; (b) continuous wavy fin; (c) conventional air-cooled heat exchanger

Types of Enhanced Fins



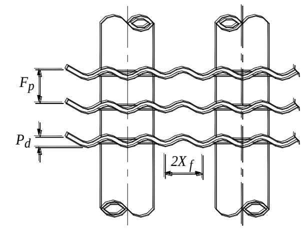
(a) 平板型

Plain fin



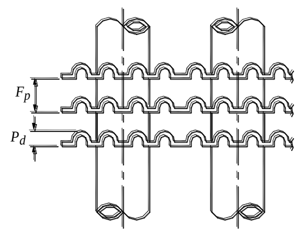
(b) 波浪型

Herringbone wavy fin



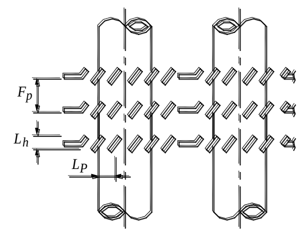
(c) 平滑波浪型

Smooth wavy fin, type (I)



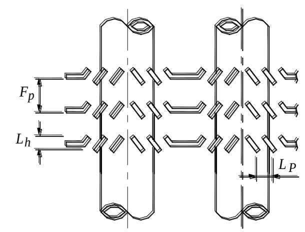
(d) 平滑波浪+平板型

Smooth wavy fin, type (II)



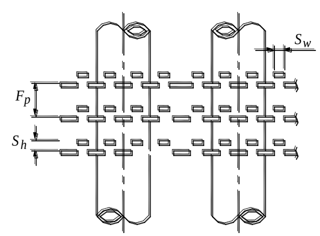
(e) 單向百葉窗型

Louver fin, one-sided



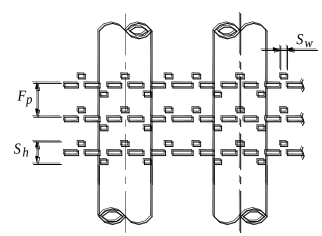
(f) 雙向百葉窗型

Louver fin, with
re-direction louver



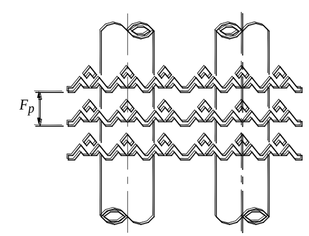
(g) 單向裂口型

Slit fin, one-sided



(h) 雙向裂口型

Slit fin, double-sided



(i) 複和百葉窗型

Convex-louver fin

Enhanced Heat Transfer

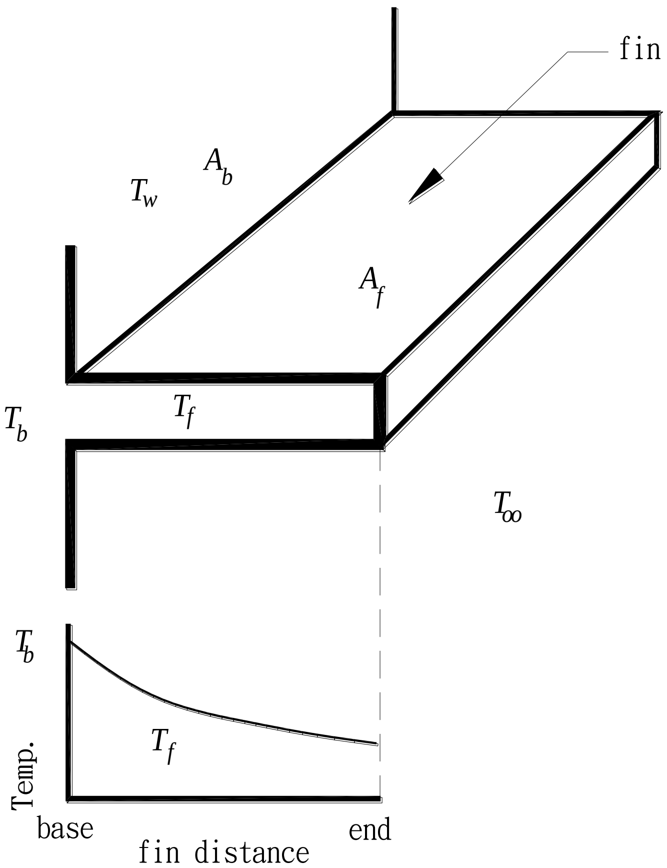
- $Q = UA\Delta T_m$
- *Q: Heat Transfer Rate*
- *A: Surface Area*
- ΔT_m: *Effective temperature Difference*

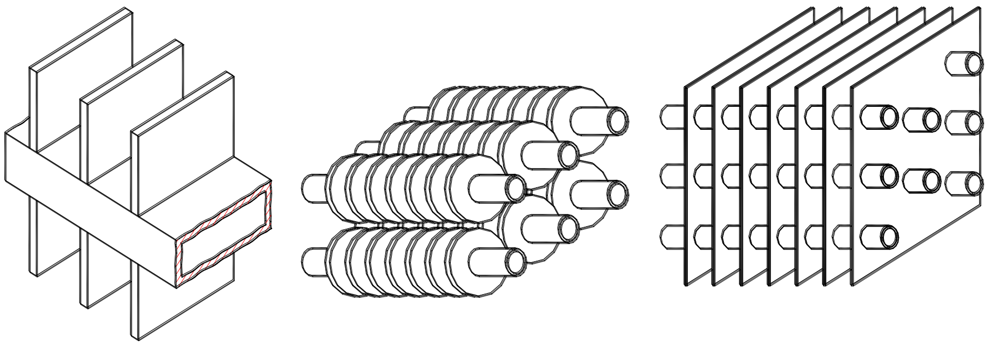
- *The most effective way is Via A, then U, and finally* ΔT_m

Stop & Think

- $Q = UA\Delta T_m$
- *Enhanced Heat Transfer always accompanied with increased pressure drops (pumping power), for fixed Q, increased pumping power is usually much higher than increased Q*
- *So, what's the benefits for increasing Q?*

Fins for Compact Surfaces





(a) plain (b) circular (c) continuous fin

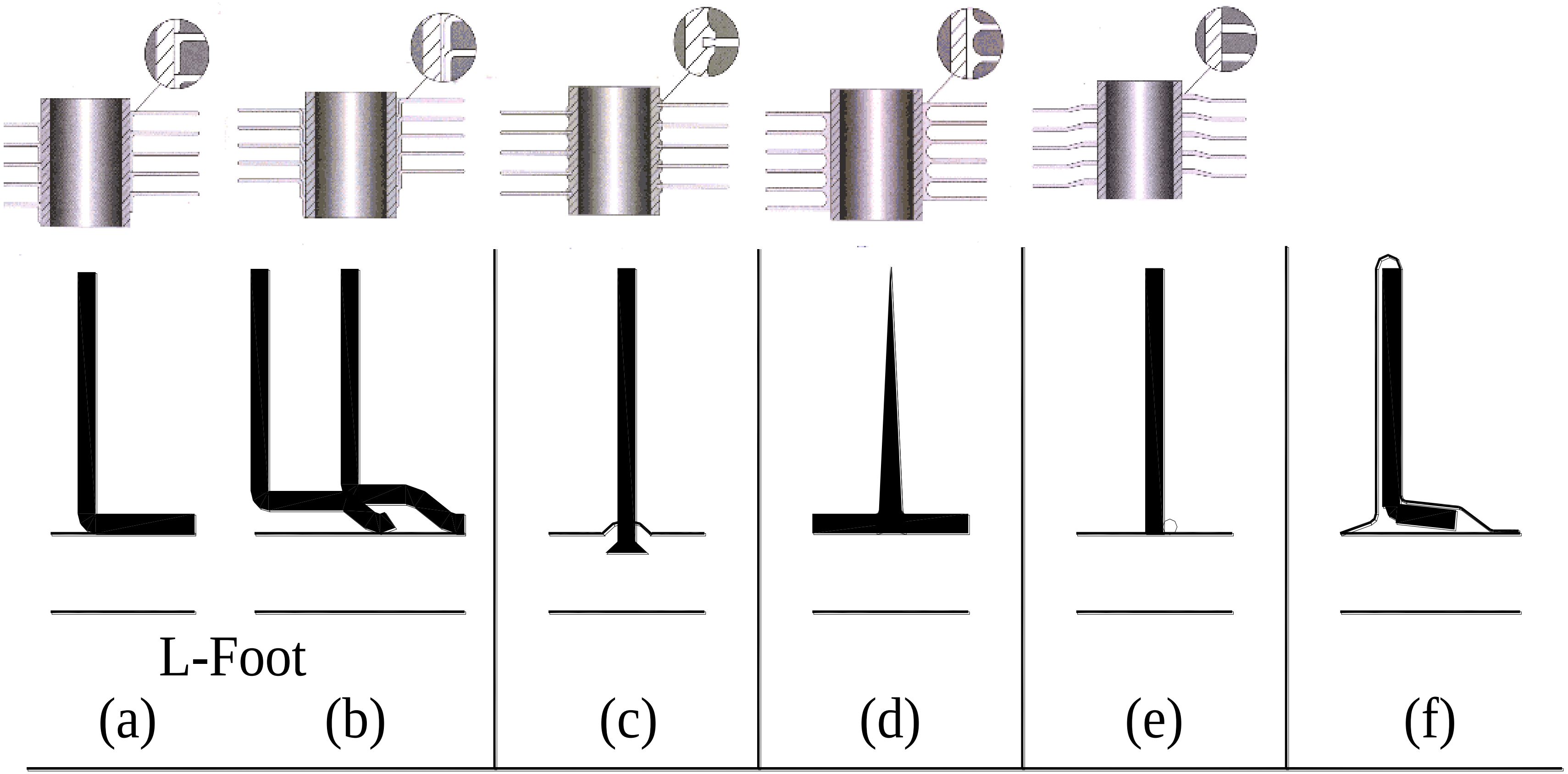
Why fins?

(a) Low thermal conductivity in the airside

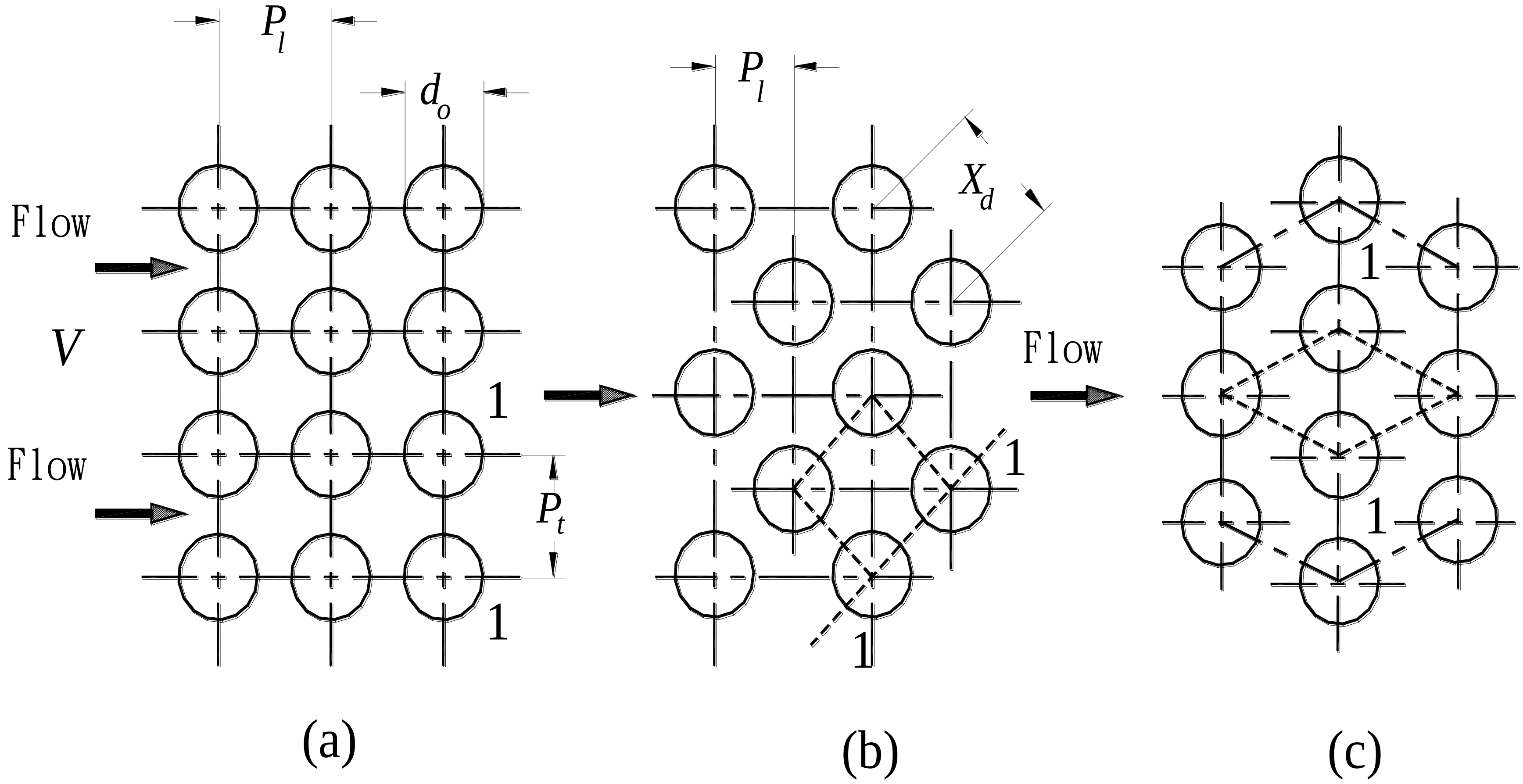
(b) Significantly increase of the surface area

(c) Increase compactness

Fin Attachment Method

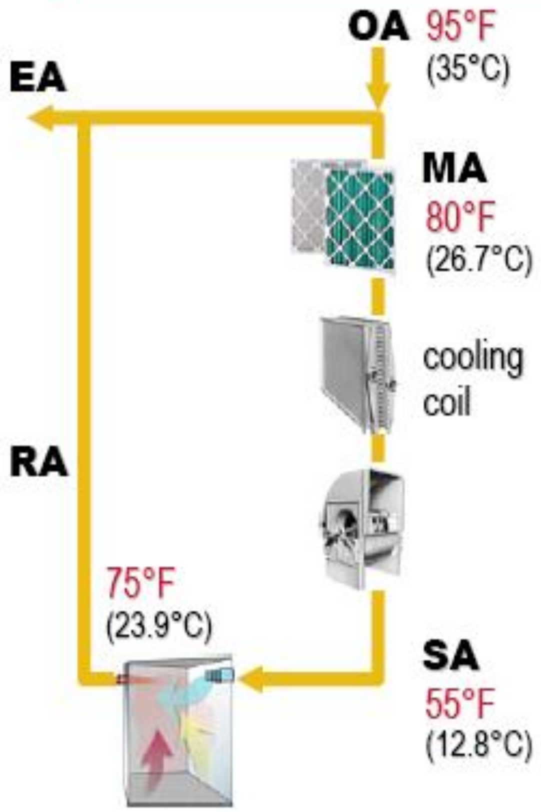


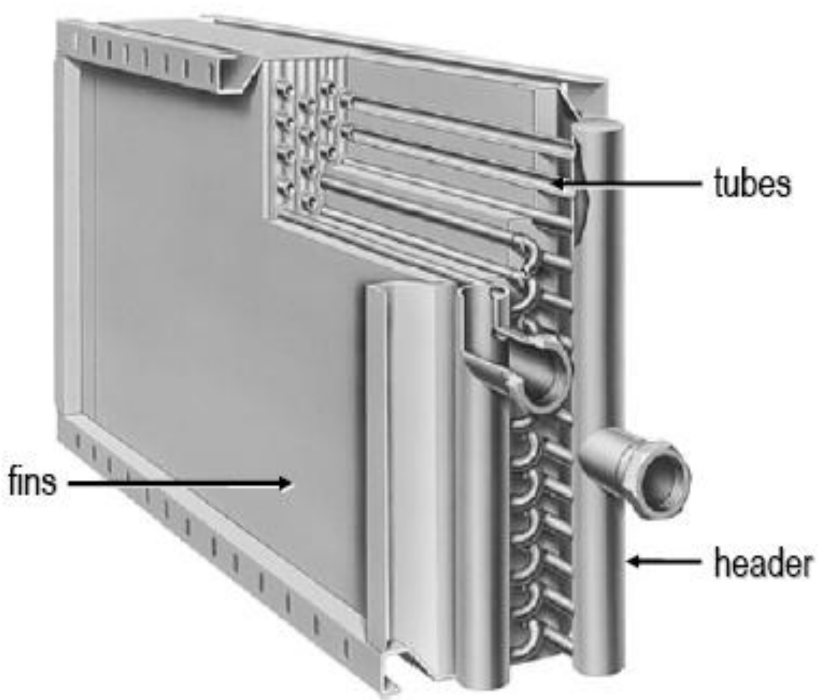
Arrangement of Fin-and-tube HX



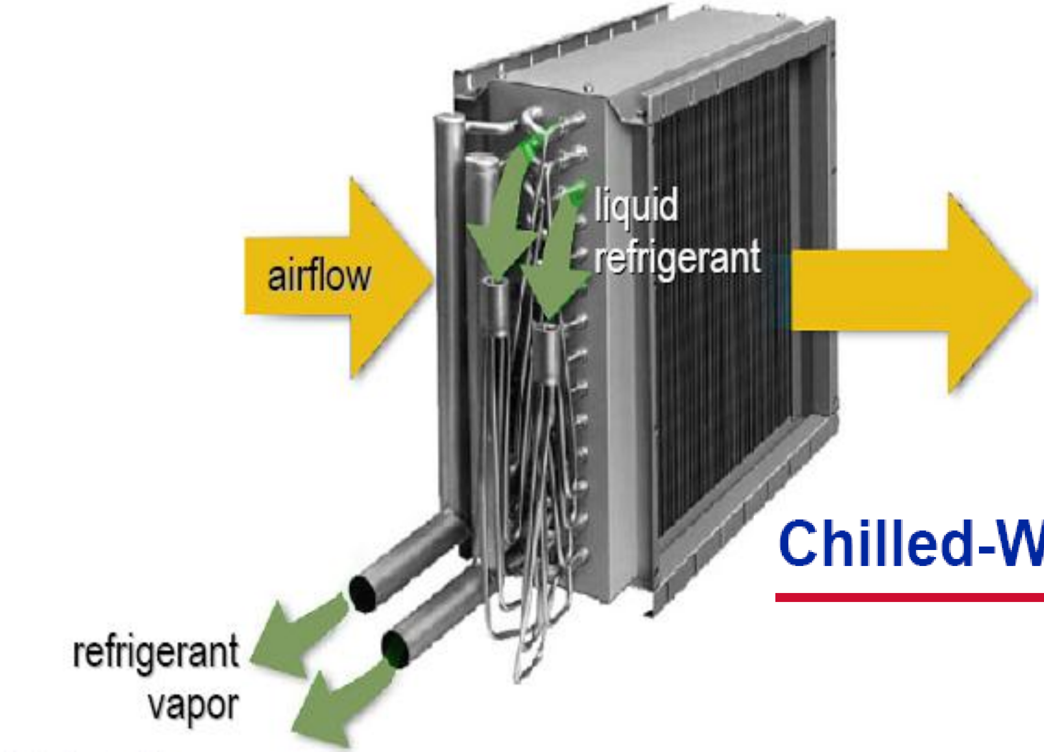
Commonly used heat exchangers in HVAC&R applications

Cooling Coil

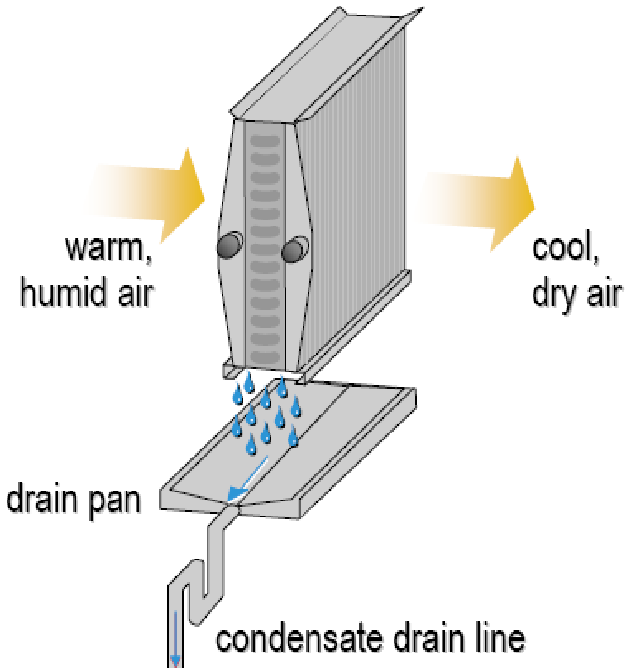




Finned-Tube Evaporator (Coil)



Chilled-Water Cooling Coil



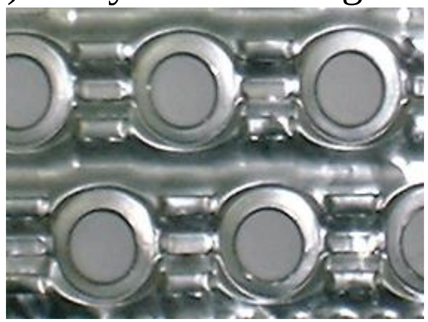

(a) Wavy fin -smooth


(b) Wavy fin – Herringbone fin


(c) Louver fin


(d)Louver fin, with redirection


(e) Copper fin


(f) Convex louver


(g) Slit – one sided


(h) Slit fin, double sided


(i) Oval Tubes


(j) Spiral fin

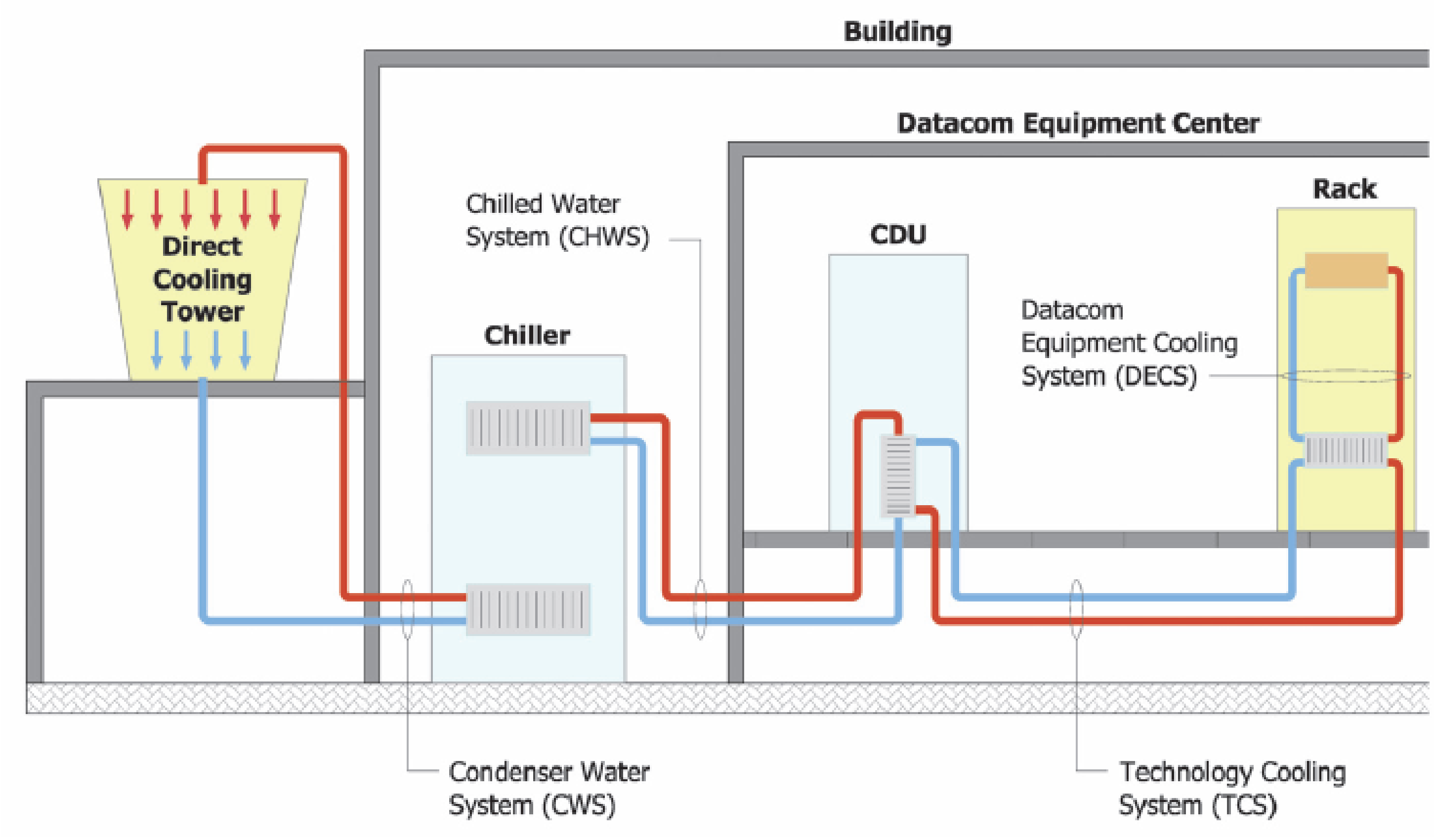

(k) Circular fin (soldered type)


(ℓ) Circular fin (L-type)

Various Enhanced Fin Surfaces

Typical Liquid Cooling System & CDU (Coolant Distribution Unit)

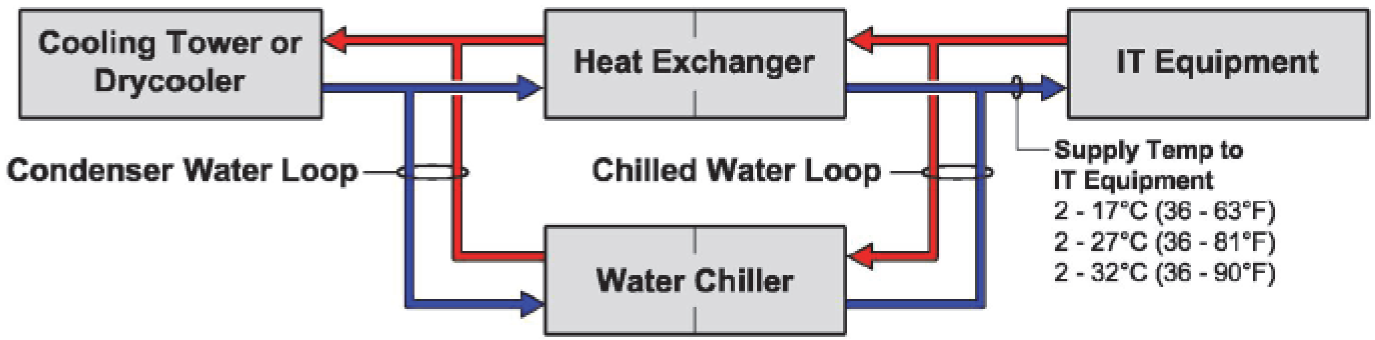
Liquid-cooling systems/loops for a data center



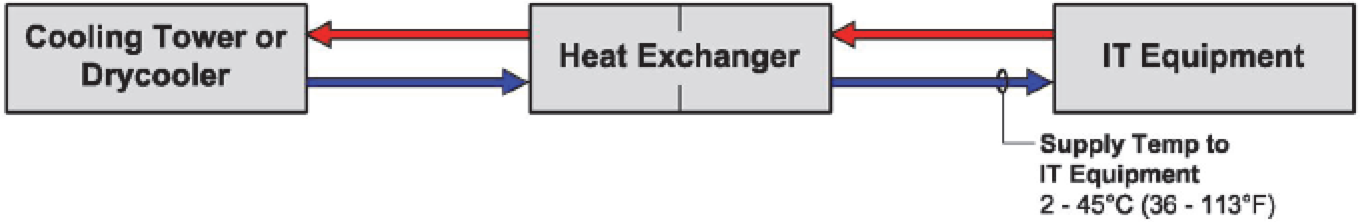
2011 ASHRAE Liquid-Cooled Guidelines

Equipment Environment Specifications for Liquid Cooling

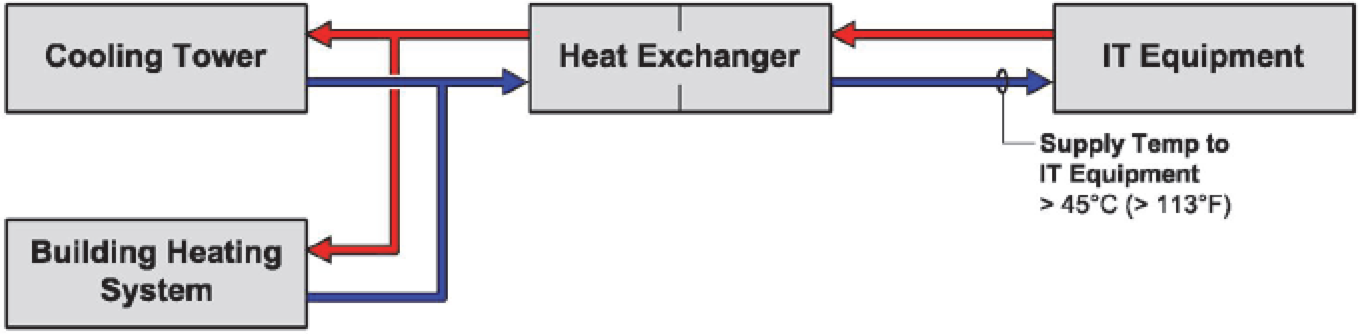
Class	Typical Infrastructure Design		Facility Supply Water Temperature, °C (°F)
	Main Cooling Equipment	Supplemental Cooling Equipment	
W1	Chiller/cooling tower	Water-side economizer	2 to 17 (35.6 to 62.6)
W2			2 to 27 (35.6 to 80.6)
W3	Cooling tower	Chiller	2 to 32 (35.6 to 89.6)
W4	Water-side economizer (with dry-cooler or cooling tower)	N/A	2 to 45 (35.6 to 113)
W5	Building heating system	Cooling tower	>45 (>113)



- Class W1/W2: **This is typically a data center that is traditionally cooled using chillers and a cooling tower, but with an optional water-side economizer to improve energy efficiency**, depending on the location of the data center
- Class W3: **For most locations, these data centers may be operated without chillers**. Some locations will still require chillers



- Class W4: **These data centers are operated without chillers to take advantage of energy efficiency and reduce capital expense.**
- Class W5: **Water temperature is high enough to make use of the water exiting the ITE to heat local buildings in order to take advantage of energy efficiency**, reduce capital expense through chillerless operation, and also make use of the waste energy.



Condensation Considerations

- Liquid-cooling Classes W1, W2, and W3 allow the **water supplied to the ITE to be as low as 2°C (36°F), which is below the ASHRAE allowable room dew-point guideline of 17°C** (63°F) for Class A1 enterprise datacom centers.
- Electronics equipment manufacturers are aware of this and are taking it into account in their designs. Data center relative humidity and dew point should be managed according to the guidelines in this book.

Operational Characteristics (W1 & W2)

- **Condensation prevention is a must.** In the chilled-water loop, insulation is typically required. In connecting loops, condensation control is typically provided by an operational temperature above the dew point.
- The **chilled-water supply temperature measured at the inlet of the datacom equipment or the CDU should not exceed a rate of change of 3°C (5.4°F)** per five-minute cycle. This may require that the infrastructure be powered by an uninterruptible power supply (UPS).
- **The maximum allowable water pressure supplied by the facility water loop to the interface of the liquid-cooled ITE should be 690 kPa** (100 psig) or less, even under surge conditions.

Operational Characteristics (W3, W4 & W5)

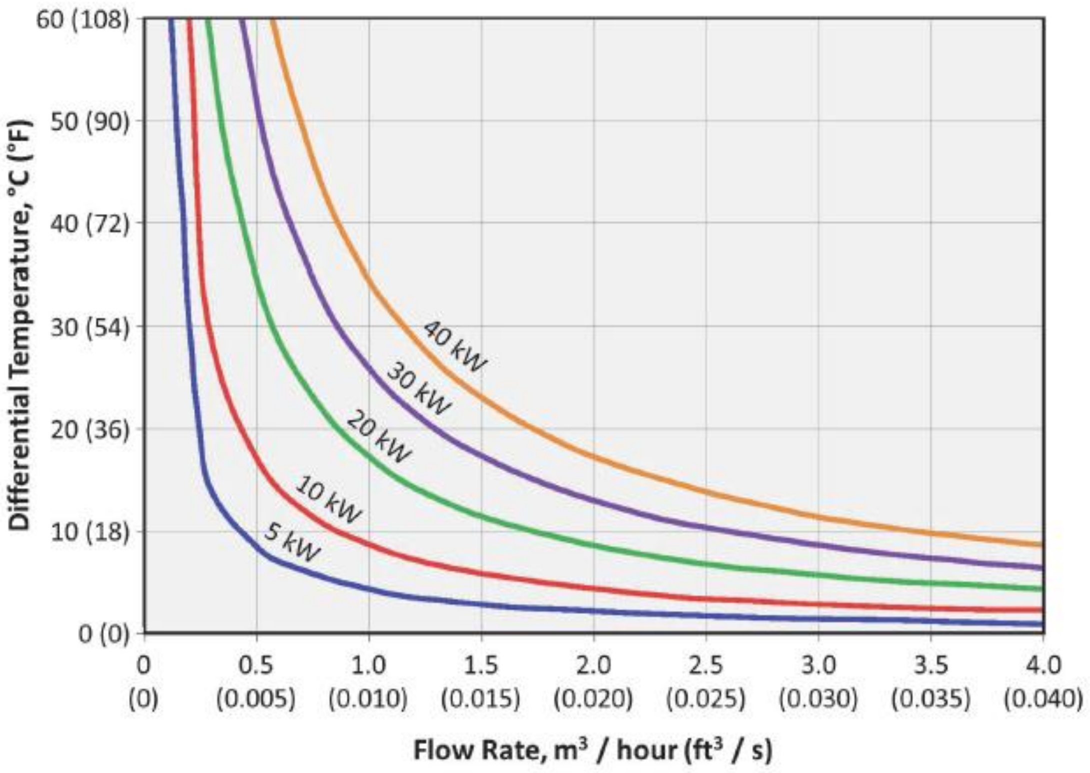
- The water temperature supplied to the water-cooled ITE will depend on the climate zone. It may be necessary in these classes to operate without a chiller installed, so it is critical to understand the limits of the water-cooled ITE and its integration within the support infrastructure. **The reliable operation of the data center infrastructure will need to accommodate the local climate, where extremes in temperature and humidity may occur.**
- The temperature of the water for Classes **W3 and W4 depends on the cooling tower design, the heat exchanger between the cooling tower and the secondary water loop, the design of the secondary water loop to the ITE, and the local climate.**
- To accommodate a large geographic region, **the range of water temperatures was chosen to be 2˚C to 45˚C (35˚F to 113˚F).**

Operational Characteristics (W5)

- For Class W5, the infrastructure will be such that **the waste heat from the warm water can be redirected to nearby buildings**.
- Accommodating water temperatures nearer the upper end of the temperature range is more critical to those applications where retrieving a large amount of waste energy is critical. **The water supply temperatures for this class are specified as greater than 45°C (113°F)** since the water temperature may depend on many parameters, such as climate zone, building heating requirements, distance between data center and adjacent buildings, etc.

Water Flow Rates/Pressures

- Water flow rates are shown in Figure for given heat loads and given temperature differences. **Temperature differences typically fall between 5°C to 10°C** (9°F to 18°F).
- Minimum facility pressure differential (drop) should not be lower than 0.4 bar.



Typical water flow rates for constant heat load

Velocity Limits

- Too high velocities lead to **erosion, sound/vibration, water hammer, and air entrainment**.
- **Particulate-free water will cause less water velocity damage** to the tubes and associated hardware.
- Guidance on maximum water piping velocities for systems that operate over 8000 hours per year. **Water velocities in flexible tubing should be maintained below 1.5 m/s** (5 ft/s).

Pipe Size, mm (in.)	Maximum Velocity (ft/s)	Maximum Velocity (m/s)
>75 (>3)	7.0	2.1
38 to 75 (1.5 to 3)	6.0	1.8
25 (<1)	5.0	1.5
All flexible tubing	5.0	1.5

Water Quality

- Water Quality Specifications Supplied to ITE
- Chapter 49, "Water Treatment," of the *ASHRAE Handbook— HVAC Applications* (ASHRAE 2011).

Parameter	Recommended Limits
pH	7 to 9
Corrosion	Inhibitor(s) required
Sulfides	<10 ppm
Sulfate	<100 ppm
Chloride	<50 ppm
Bacteria	<1000 CFUs/mL
Total hardness (as $CaCO_3$)	<200 ppm
Residue after evaporation	<500 ppm
Turbidity	<20 NTU (nephelometric)

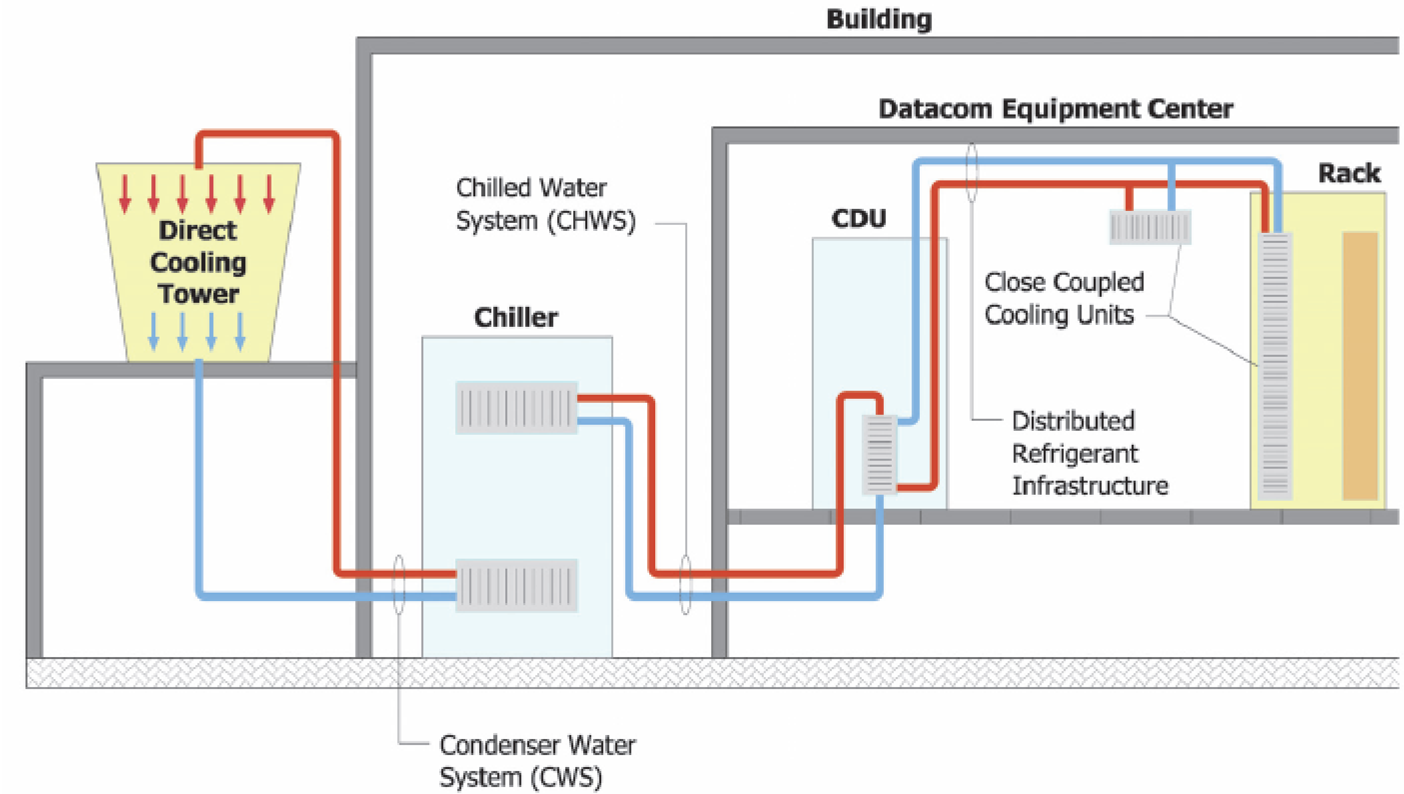
Liquid Cooling CDU & Piping

LIQUID-COOLING DEPLOYMENTS IN NEBS-COMPLIANT SPACES

- **NEBS: Network Equipment Building System**, **NEBS is a set of technical requirements and objectives that were originally developed by AT&T's Bell Labs** under the title of Technical Publications with the purpose of making network switches robust and reliable. After the 1984 divestiture of AT&T, NEBS ownership passed on to Bellcore (currently Telcordia), the research arm of Regional Bell Operating Companies (RBOC), for maintenance and upgrades. Since then Telcordia has renamed the publications Generic Requirements (GR) and published many new ones.
- **Common heat signatures of 400 to 800 W/frame are being replaced with cabinets supporting 20 kW and more.** While this range is relatively low compared to common ITE space described earlier, existing office cooling infrastructures are often unable to support the increased demand. **Liquid-cooling systems provide a bridge system that supplements existing cooling infrastructure and provides primary cooling in both greenfield and brownfield applications.**

Liquid cooling systems/loops for a NEBS space

- The backbone **cooling infrastructure up to the CDU is essentially the same for NEBS space deployment as for non-NEBS data centers.** Cooling systems presently use economizers to assist in mitigating energy use.



- **NEBS space deployments have a very strict restriction of the distribution of water within the active equipment space.** While water-side connections are permitted, **they are typically connected outside of the space to cooling units (e.g., computer room air handlers) or are restricted to the perimeter of the supported space.**
- **This limitation eliminates the risk of equipment contamination or failure due to water solutions leaking from distribution piping, connectors, and hoses.**

- The typical NEBS space is different in basic construction in **that it utilizes almost exclusively slab floor deployments with overhead cable racking and piping**.
- **This overhead piping arrangement adds to the risk factor of equipment damage due to water solution leakage.**
- The typical use of refrigerant systems provides an effective heat rejection transport medium while assuring that leaks will not cause equipment damage due to the escape of the inert gas. Other refrigerant or dielectrics may be effective in supporting the unique nature of NEBS spaces.
- The separation of a water-based cooling feed by the CDU to the refrigerant based distribution for the close-coupled cooling units also affords the option of using a direct-exchange-compressor-based cooling feed in place of the water-based cooling feed.

- The use of refrigerant-based liquid-cooling systems in NEBS spaces requires the deployment of a CDU.
- The **CDU provides a cost-effective thermal transfer point between the chilled-water supply systems and the refrigerant distribution infrastructure, including close-coupled cooling units**.
- The **CDU unit is typically placed outside of the equipment area or along the perimeter of the supported space**.
- Full leak containment is typically deployed as part of the common infrastructure.
- Multiple CDUs may be placed to provide adequate capacity and to comply with refrigerant distribution effective line length requirements. These deployments are often arranged in groups of cabinets with common power, space, and cooling capacities.

Concerns of Liquid-Cooling

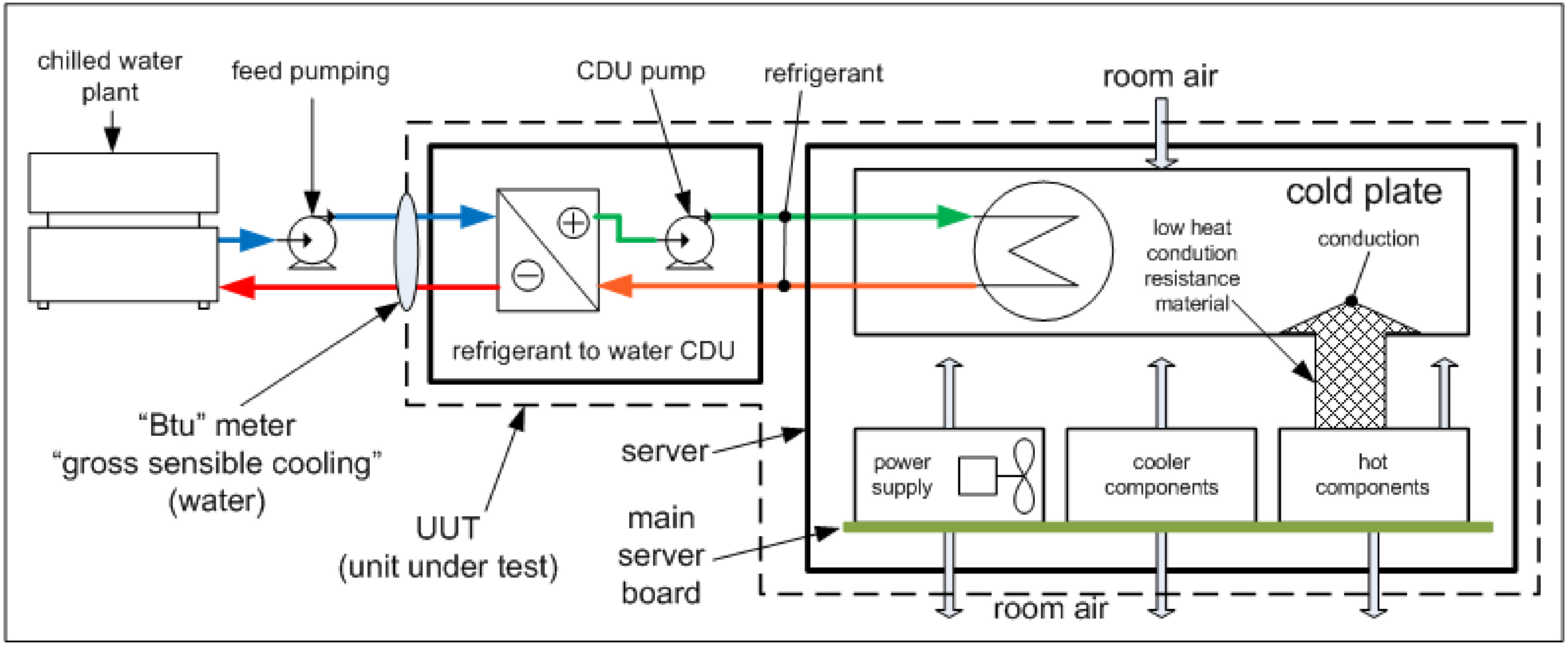
- Cost
  - with increased effort by many manufacturers, the cost of liquid-cooling equipment will continue to decrease.
- Power
  - power for pumps or compressors has traditionally been low in comparison with the heat load being removed.
- Maintenance and Serviceability
  - Liquid cooling results in a much more intensive infrastructure (particularly within the data(com equipment room.) **With air cooling, the distribution typically is a plenum space that requires little to no maintenance. Liquid cooling means that the distribution over the same path is in the form of piping, control valves, connections, etc., and there is an increased effort to access and perform maintenance on those items.**

- Redundancy
  - **With air cooling, redundancy typically is achieved with the inclusion of multiple computer room air-conditioning (CRAC) units** supplying air into a common plenum. **With the piping distribution system replacing the plenum, redundancy considerations are extended to encompass piping configurations as well**.

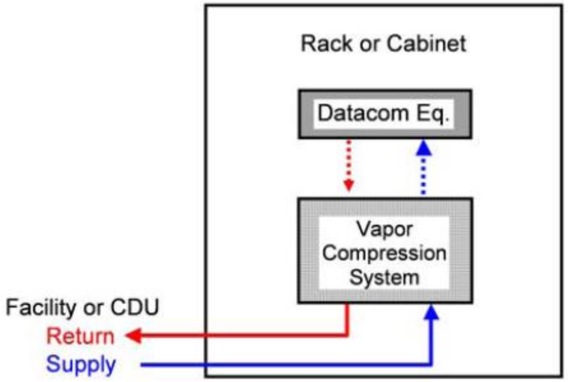
Short Summary

- Liquid has greater heat removal capacity
- Pumps are more efficient than fans
- Coupling heat removal to the source eliminates mixing
- Commercially available liquid solutions are available
- Water side free cooling provides cooling with reduced chiller

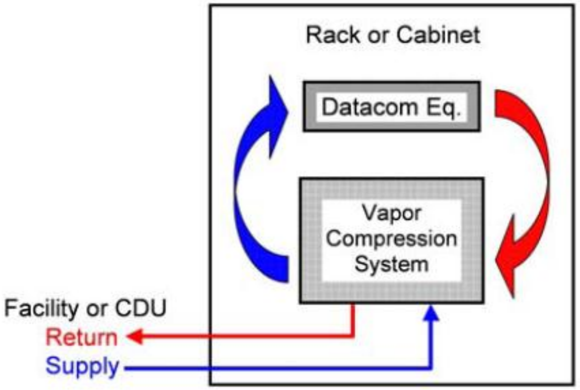
Thermal Schematic for the Clustered Systems Design



Overview of coolant distribution unit (CDU)



Liquid-cooled datacom equipment in a liquid-cooled rack using a vapor-compression system.

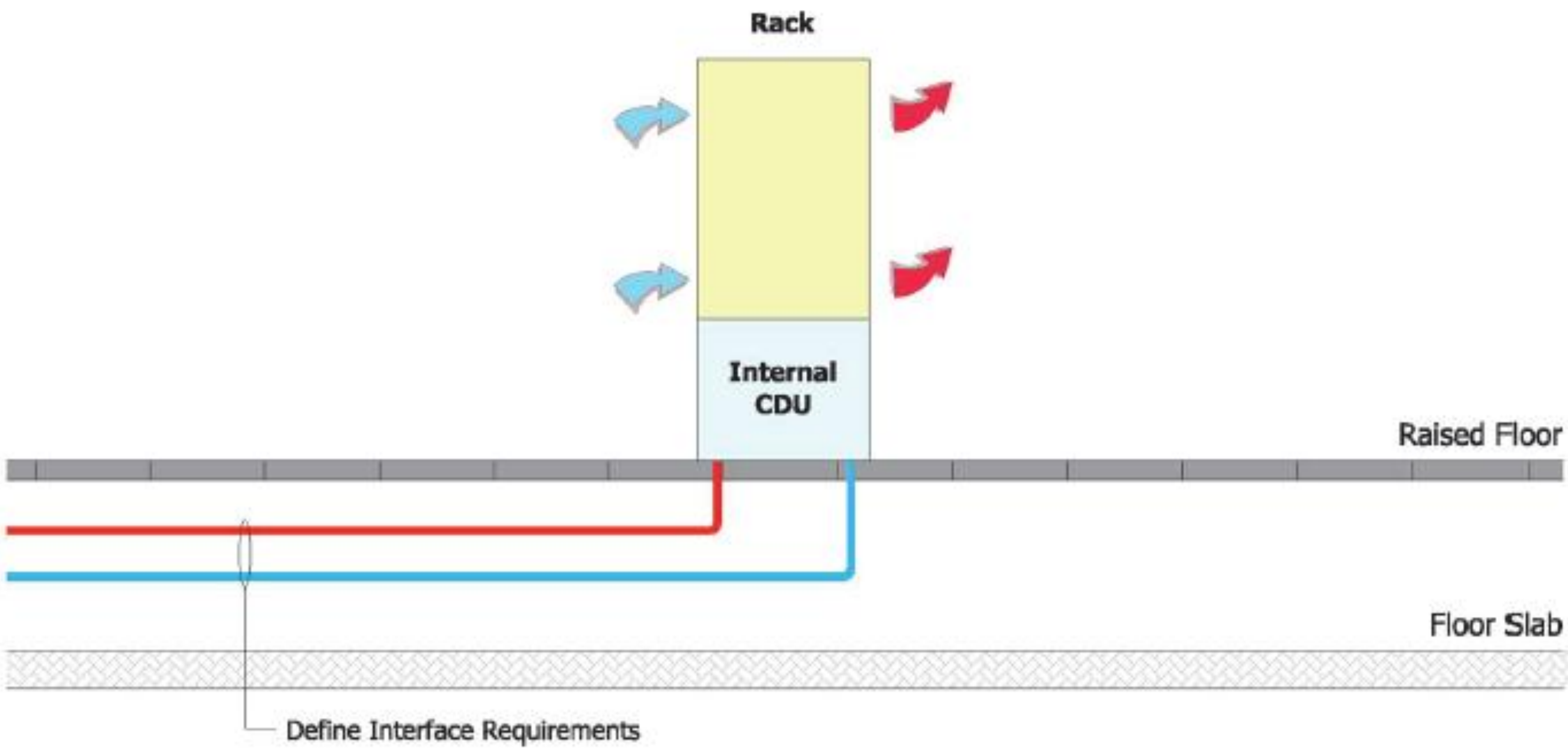


Air-cooled datacom equipment in a liquid-cooled cabinet using a vapor-compression cycle.

The CDU provides a number of important benefits, as follows:

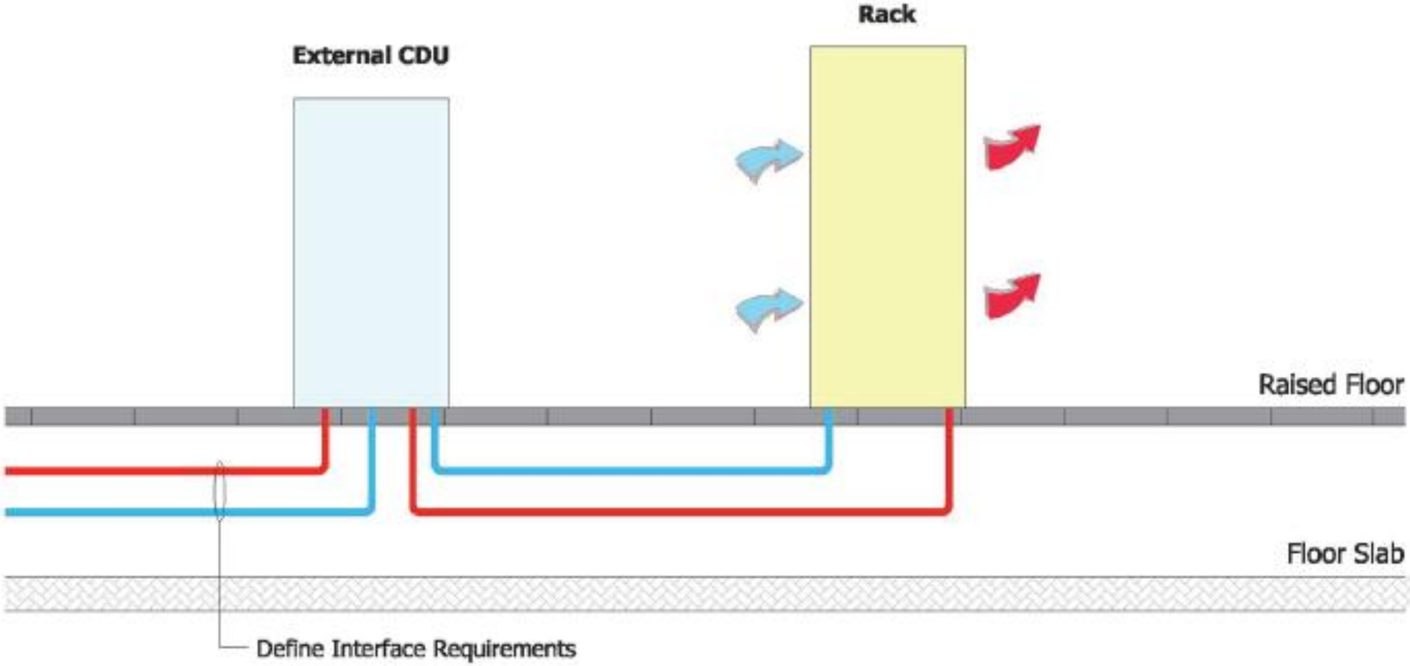
- **Prevention of condensation:** It provides an opportunity for temperature conditioning, which could allow the coolant to be delivered to the electronics above the dew point.
- **Isolation:** It may allow the electronics to be isolated from the harsher facility water in the CHWS or CWS loop. The loop supplied by the CDU also utilizes a lower volume of coolant, so a coolant leak is less catastrophic.
- **Coolant flexibility:** The separate loop associated with the CDU allows users the flexibility to use any number of coolants.
- **Temperature control:** The separate loop associated with the CDU allows users the flexibility of running the electronics at a desired temperature. This temperature can be above, at, or below the dew point.

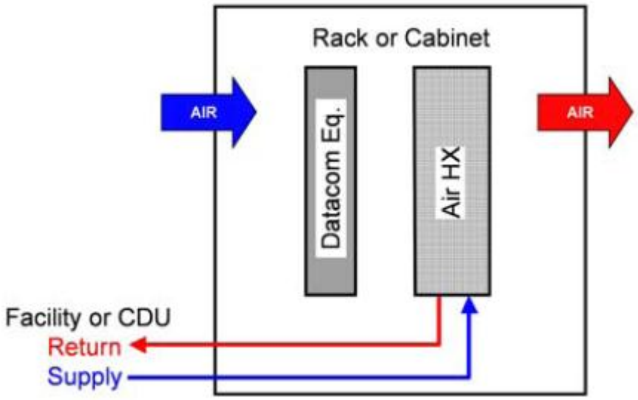
Combination air- and liquid-cooled rack or cabinet with internal CDU



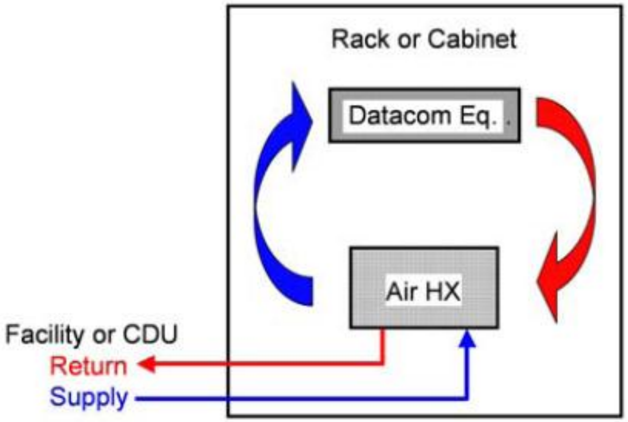
Liquid-cooled rack or cabinet with external CDU

- It is suggested **that a CDU with a heat exchanger be employed to raise the coolant temperature to at least 18˚C (64.4˚F) to eliminate condensation issues** or have an adjustable water supply temperature that **is set 2˚C (3.9˚F) or more above the dew point of the data center space**.

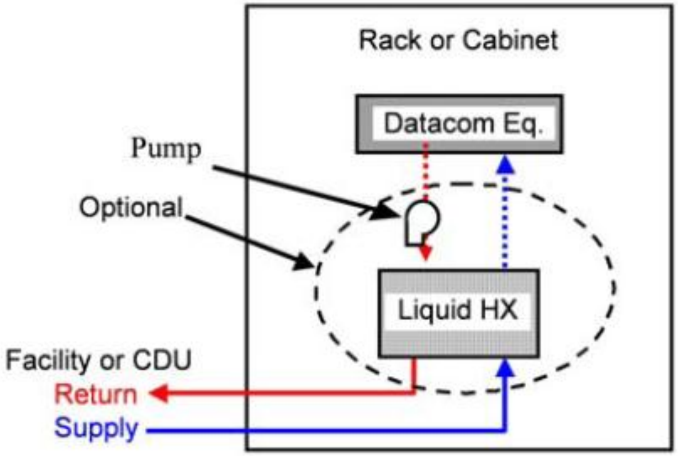




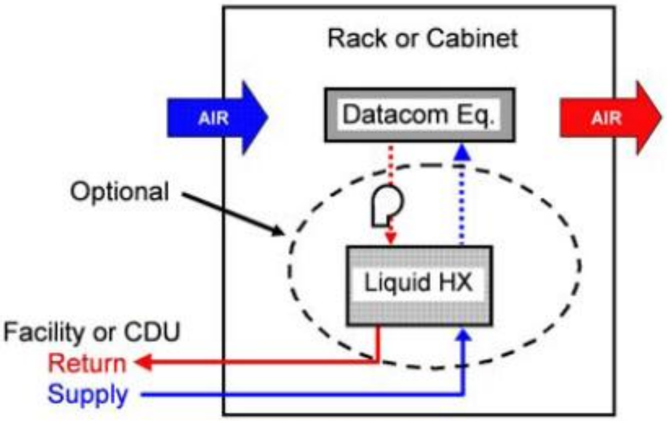
Open air-cooled datacom equipment in an air/liquid-cooled rack.



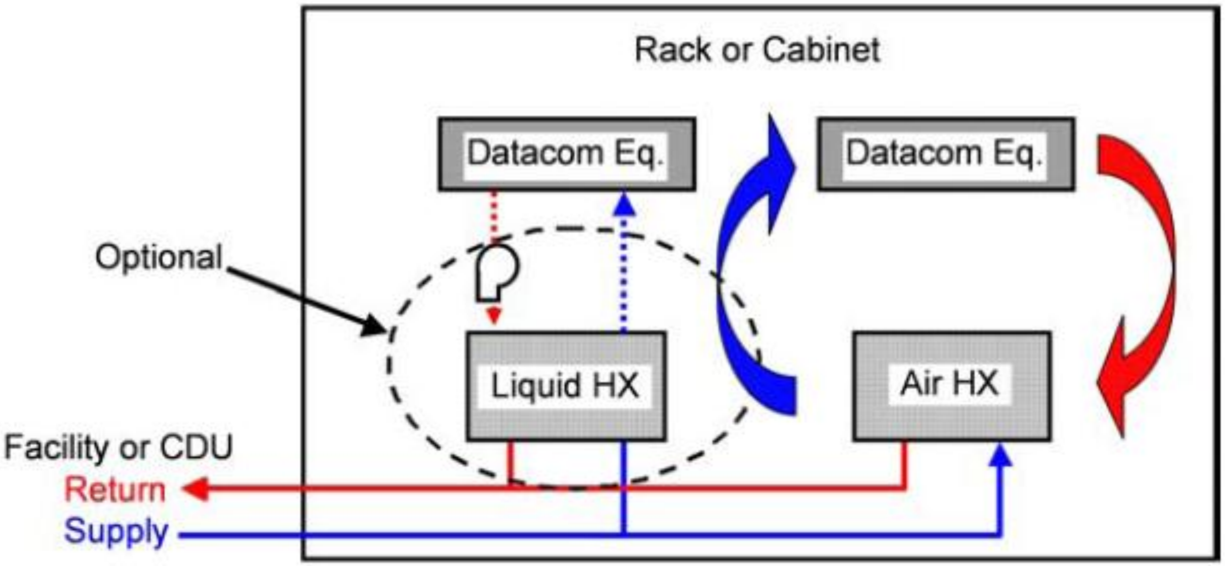
Closed air-cooled datacom equipment in a liquid-cooled cabinet.



Liquid-cooled datacom equipment in a liquid-cooled rack.



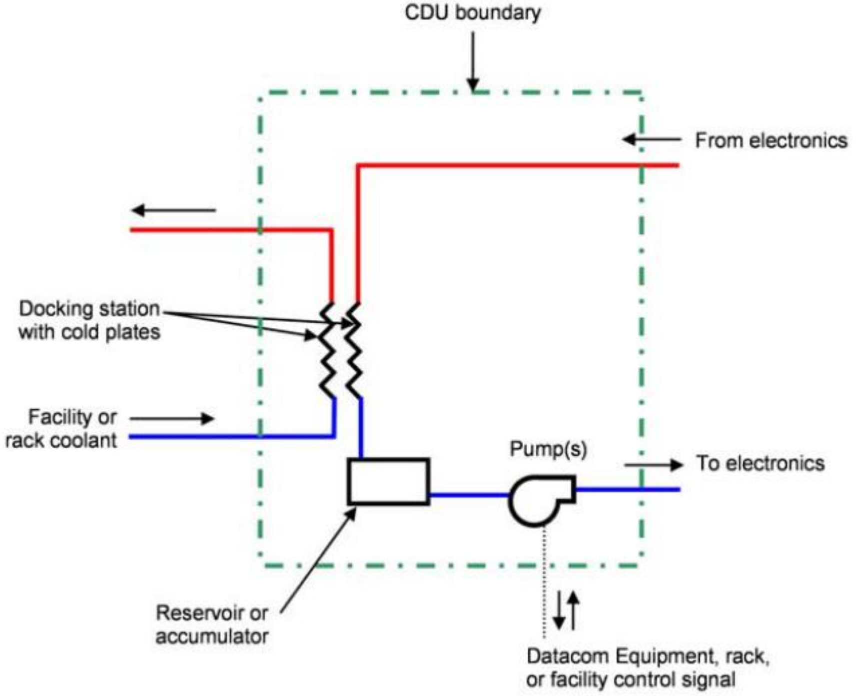
Open air- and liquid-cooled datacom equipment in an air/liquid-cooled rack.



Closed air- and liquid-cooled datacom equipment in a liquid-cooled rack.

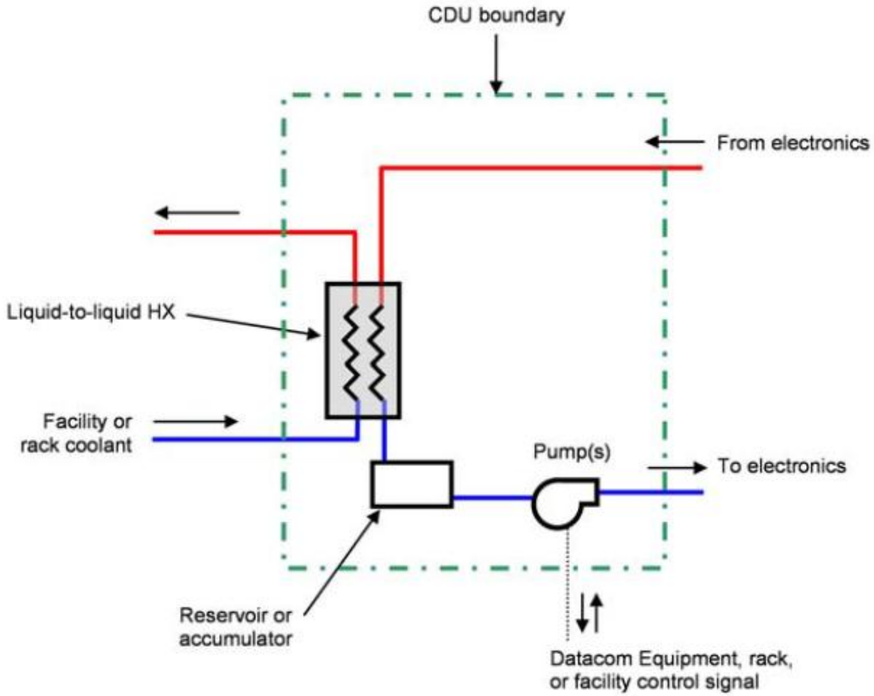
Internal datacom equipment-based CDU that utilizes a docking station and cold plates

- The datacom equipment rejects the heat from its electronics **via a cold plate that docks with another rack/cabinet-based cold plate.** At a very basic level, **the CDU consists of a cold plate, an accumulator (or a reservoir), and a pump (or multiple pumps for redundancy)**. The operation of the pump is regulated by some controllers, communicating with one or more sensors within the CDU. The data from the sensors are used to control the level of operation of the CDU.



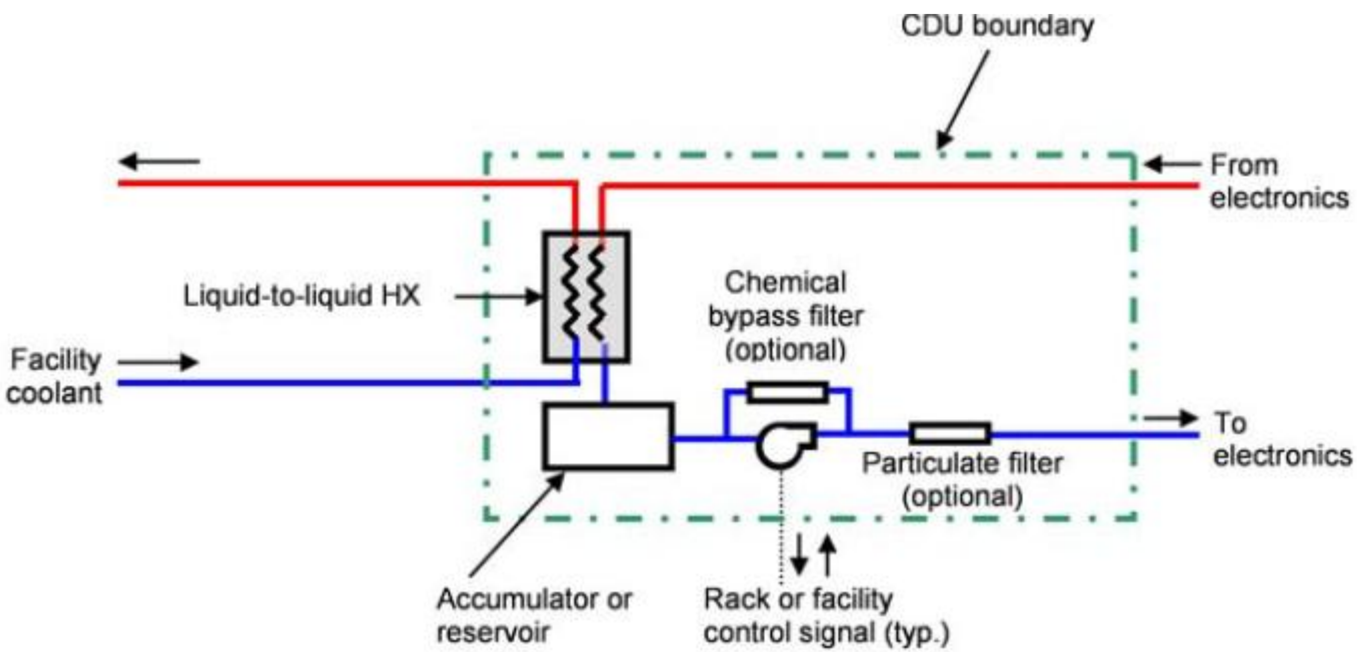
Internal datacom equipment-based CDU that utilizes a liquid to-liquid heat exchanger

- It illustrates an internal datacom equipment implementation of a CDU. The basic functionality for this implementation is similar to that previous one, with the exception of the use of a liquid-to-liquid heat exchanger to reject the datacom equipment heat. In other implementations, the CDU could deploy a liquid-to-air heat exchanger.



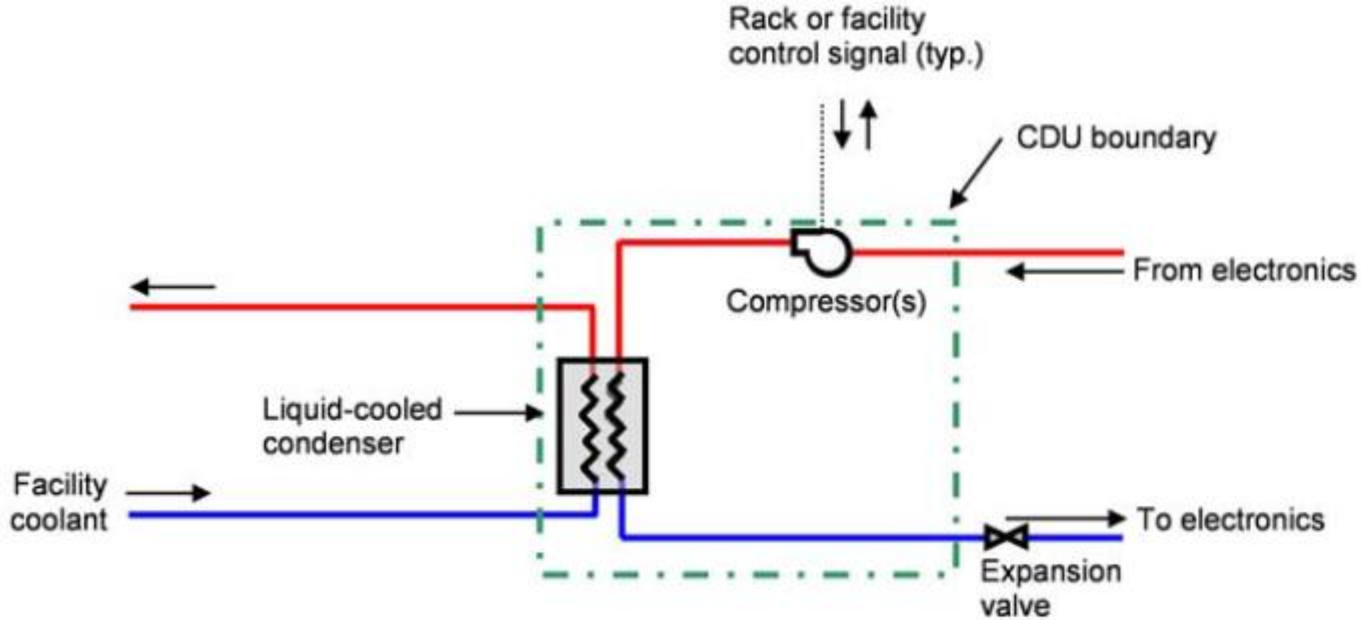
Internal rack or cabinet-based CDU that utilizes a liquid-to liquid heat exchanger

- The CDU shown consists of a liquid-to-liquid heat exchanger, an accumulator (or a reservoir), a pump (or multiple pumps for redundancy), a chemical bypass filter for solvent and water removal, and a particulate filter. Applications of an internal CDU will often use refrigerant or dielectric as cooling fluid.



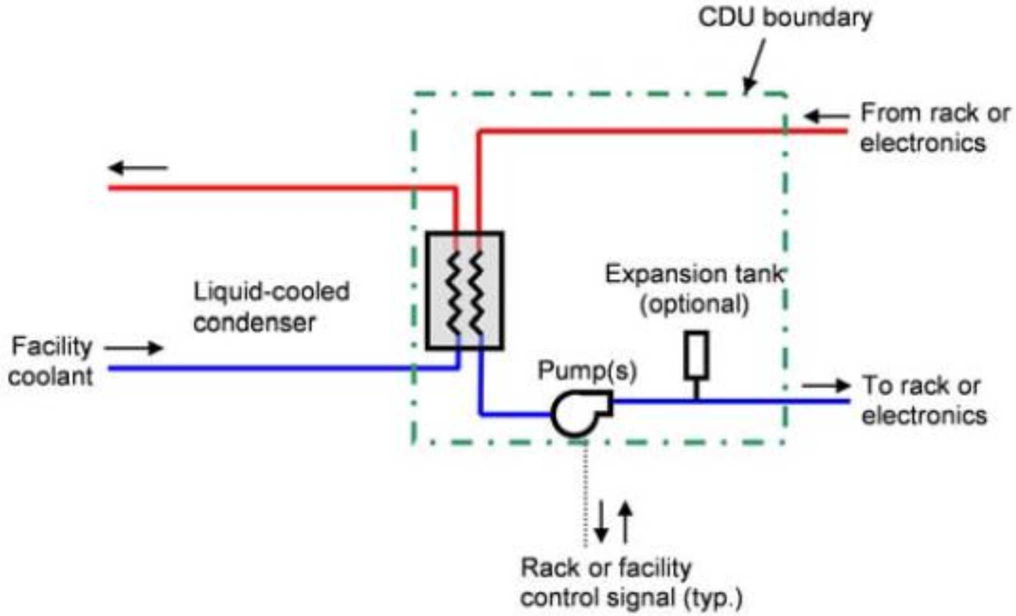
Internal rack or cabinet-based CDU that utilizes a liquid-cooled condenser and a vapor-compression system

- The basic functionality of this CDU is similar to that shown in previous Figure, with the main difference being the use of a **vapor-compression system**. **A key benefit of a vapor-compression system is that it allows the user to drop the temperature of the working coolant below that of the coolant to which it is rejecting the heat from the electronics**.



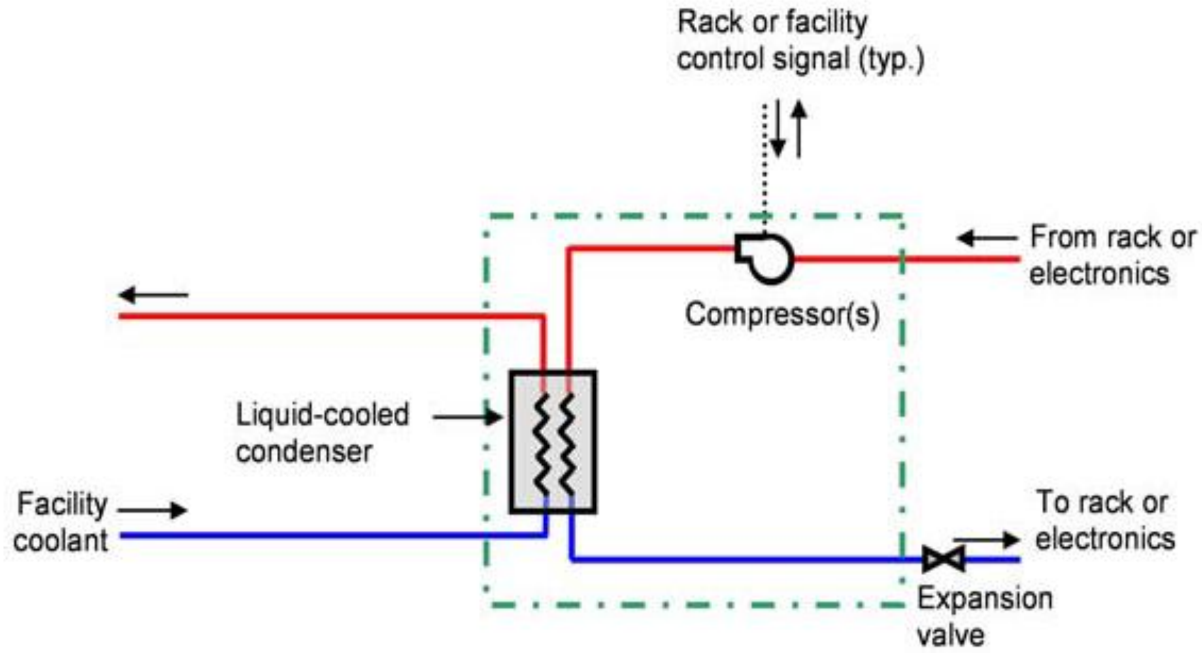
Facility-based CDU that utilizes a liquid-cooled condenser

- This form of CDU can supply cooling fluid to a single rack or a row of racks. In its most basic form, this CDU consists of a liquid cooled condenser, a pump (the additional space typically allows for redundant pumps), and an expansion tank. The CDU communicates with one or more controllers at the datacom equipment, rack/cabinet, and facility levels, which can control the operation of the CDU.



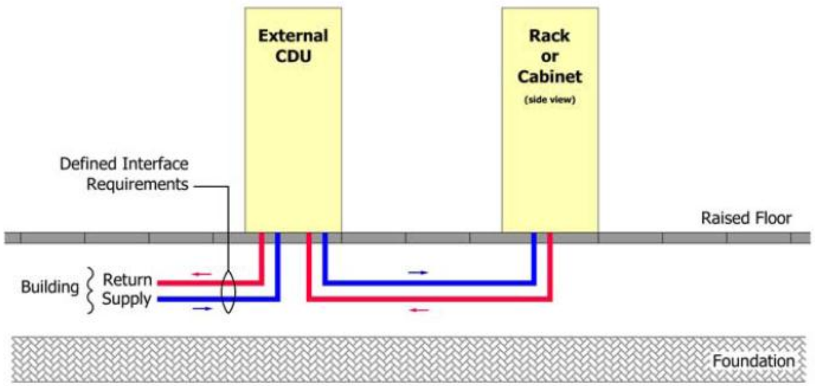
Facility-based CDU that utilizes a liquid-cooled condenser and a vapor-compression system

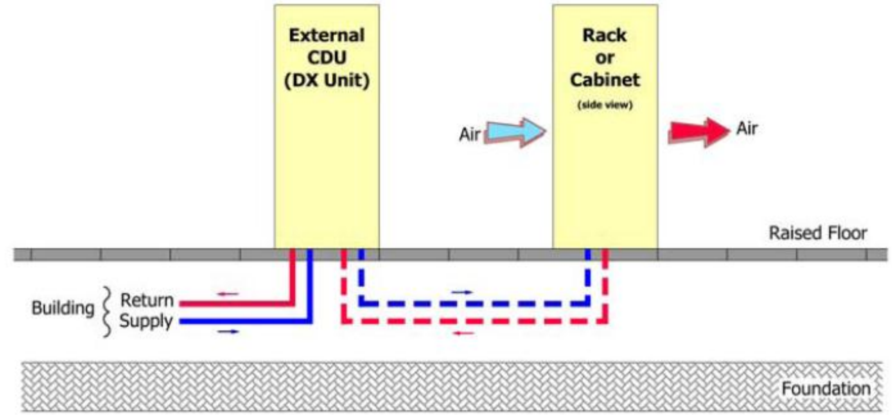
- The basic functionality is similar to that of Figure 4.19, with the key difference being the use of a vapor-compression system. Similar to previous Figure, the basic vapor-compression system uses a compressor (or multiple ones for redundancy), a liquid-cooled condenser, and an expansion valve.

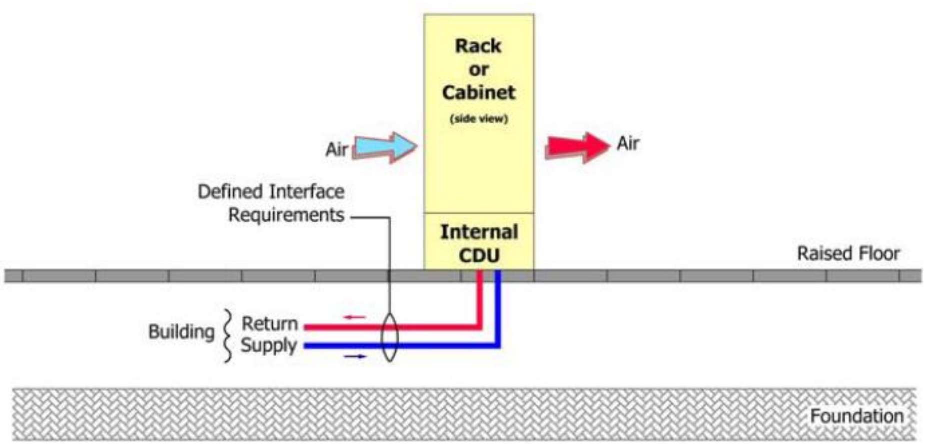


CDU vendor must design the CDU to be fault-tolerant

- For instance, **the coolant pump in the CDU is most likely the point of failure**. Most systems will have **redundant pumps**. The pump will either alternate on a relatively short-term basis (weekly or monthly) or one pump will be the primary pump and a secondary pump will be tested periodically to make sure it is operational. The pumps will likely have isolation valves so that the nonfunctional pump can be isolated for replacement without bringing the entire CDU (and associated datacom equipment) down for repair. On smaller systems that may not accommodate dual pumps, the vendor will select a pump with a long life. In this situation, it is expected that the CDU will be upgraded before the pump wears out. Power to the CDU also needs to be backed up by a UPS. This will allow the datacom equipment to continue running or to shut down gracefully in the event of a power outage.


External CDU
Rack or Cabinet (side view)
Defined Interface Requirements
Raised Floor
Building
Return
Supply
Foundation


External CDU (DX Unit)
Rack or Cabinet (side view)
Air
Air
Raised Floor
Building
Return
Supply
Foundation


Rack or Cabinet (side view)
Air
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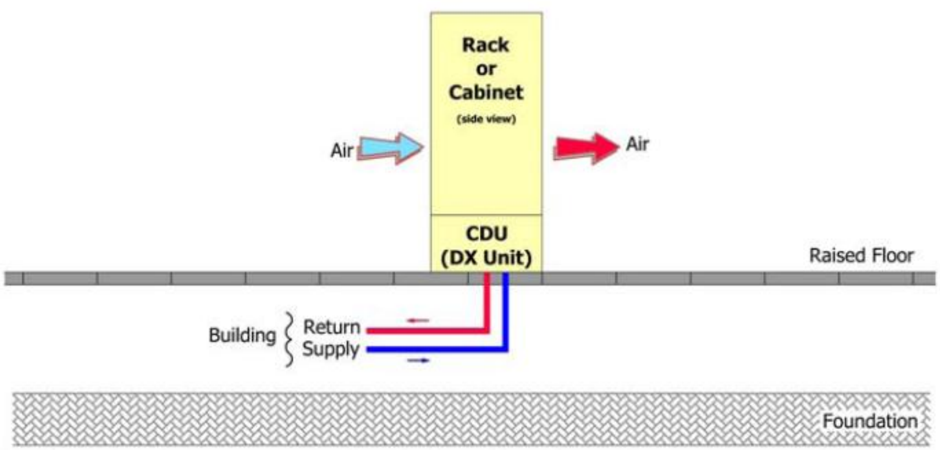
Defined Interface Requirements
Internal CDU
Raised Floor
Building
Return
Supply
Foundation


Rack or Cabinet (side view)
Air
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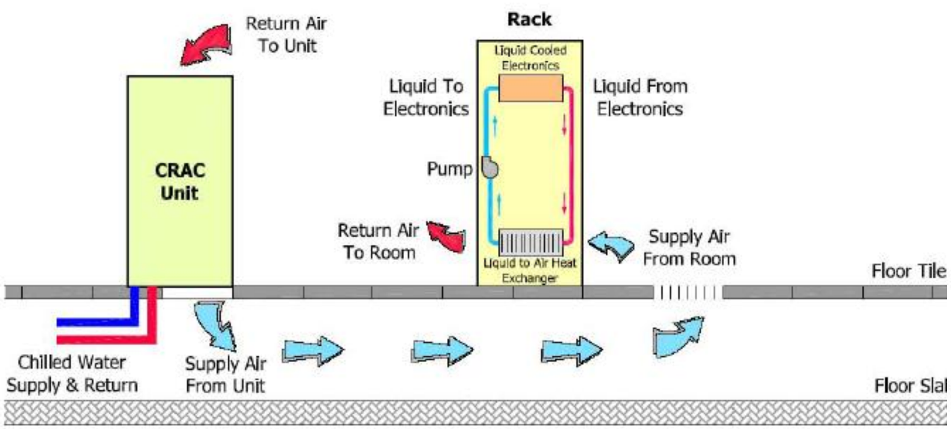
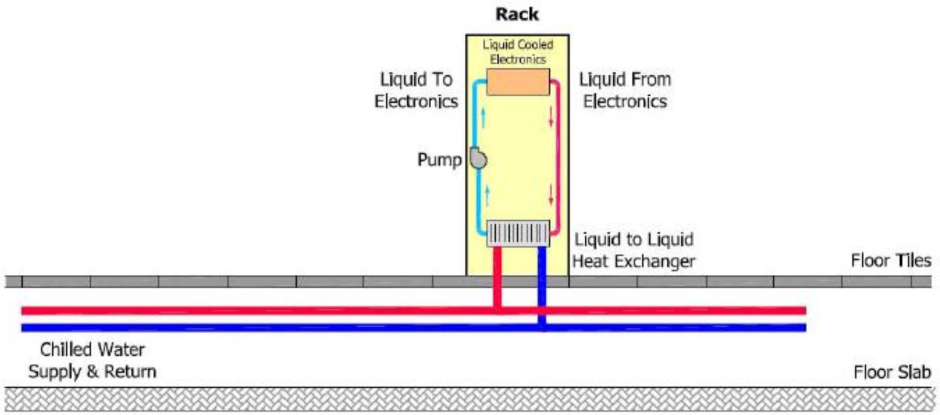
CDU (DX Unit)
Raised Floor
Building
Return
Supply
Foundation

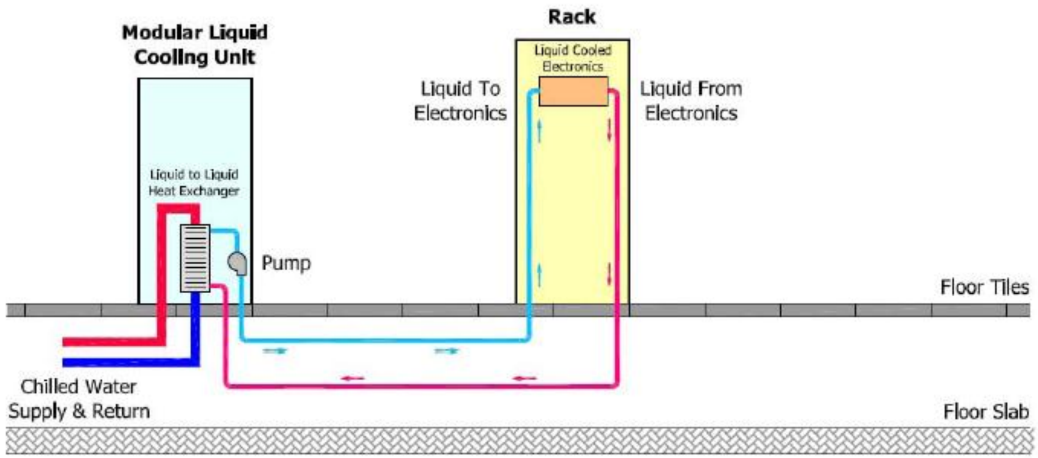
Liquid Cooling CDU



Internal liquid cooling loop restricted within rack extent.



Internal liquid cooling loop with rack extents and liquid cooling loop external to racks.



Internal liquid cooling loop extended to liquid-cooled external modular cooling unit.

Operational Requirements

- The datacom equipment should generally accommodate **chilled-water supply temperatures that range from 40˚F to 60˚F (4˚C to 16˚C)**. **The recommended nominal is 50˚F (10˚C) water.**
- The chilled-water supply temperature measured at the inlet of the datacom equipment or the CDU **should not exceed a rate of change of 5˚F (3˚C)** per five minute cycle. This may require that the infrastructure be on UPS electrical supply.
- The maximum allowable water pressure supplied to the TCS (***technology cooling system***) and DECS (***datacom equipment cooling system***) loops should be 100 psig (690 kPa) or less.

Water Quality Problems

- **Corrosion:** the dissolution of metals by water.
- **Fouling:** insoluble particulate matter in water.
- **Scale:** a deposition of water-insoluble constituents, formed directly on the metal surface.
- **Microbiological activity:** basic organisms such as aerobic bacteria, anaerobic corrosive bacteria, fungi, and algae.

- **Suspended solids and turbidity can be an indication that corrosive products and other contaminants** are collecting in the system. Excessive amounts may indicate corrosion, removal of old corrosive products by a chemical treatment program, or the contamination of the loop by another water source.
- **Suspended solids at high velocity can abrade equipment**. Settled suspended matter of all types can contribute to pitting corrosion (deposit attack). Similarly, there may be ions present that may also cause these same issues.

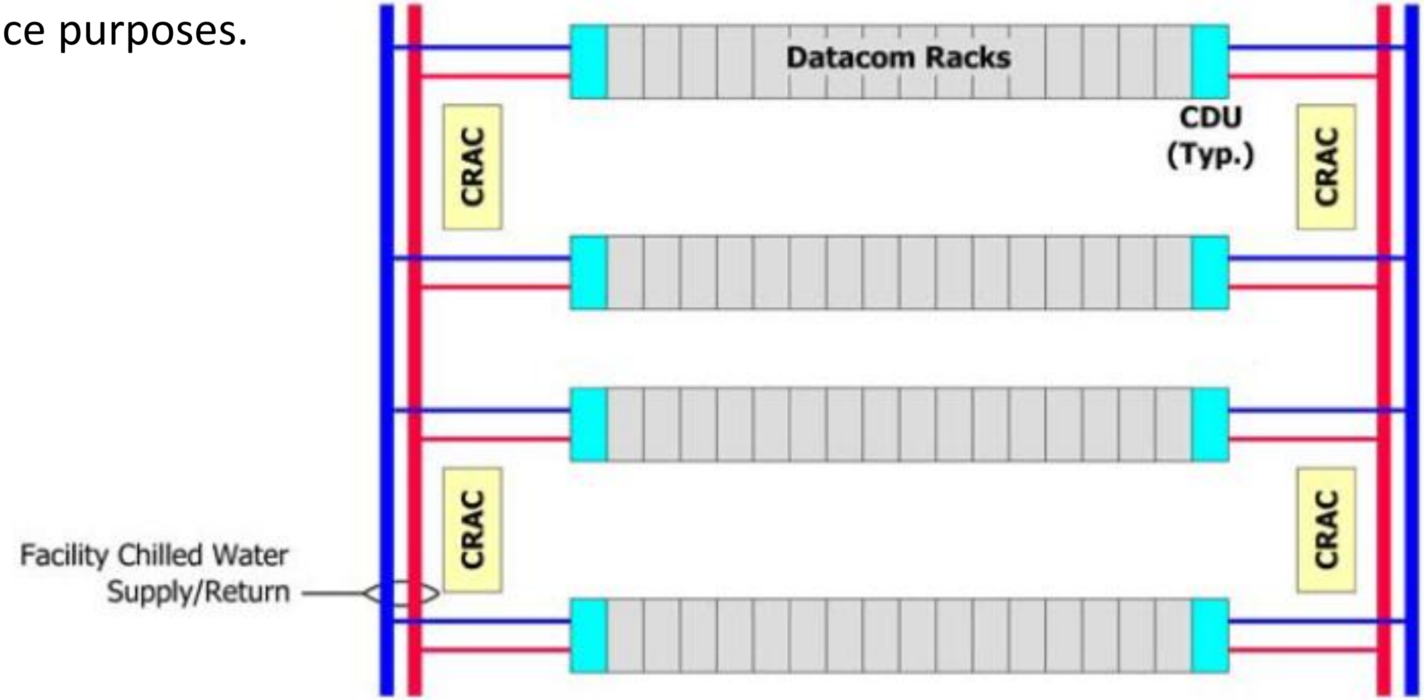
- **The presence of copper** may be an indication of increased copper corrosion and the need of a higher level of copper corrosion inhibitor.
- **Excessive iron is an indication that corrosion has increased**, existing corrosion products have been released by chemical treatment, piping has been added to the secondary loop, or the iron content has increased in the replacement water.
- The presence of **manganese** is also important if its concentration is greater than 0.1 ppm.
- Where water-softening equipment is deployed, **a total hardness of 10 ppm or greater indicates that the hardness is bypassing the softener,** that the softener regeneration is improper, or that some contamination from another system is present, such as a cooling tower or city water.
- The presence of sulfates is often an indication of a process or water tower leak into the TCS loop. High sulfates contribute to increased corrosion because of their high conductivity.

Wetted Material Requirements (CDU)

- Copper Alloys: 122, 220, 230, 314, 360, 377, 521, 706, 836, 952
- Polymer/Elastomer:
  - Acrylonitrile butadiene rubber (NBR)
  - Ethylene propylene diene monomer (EPDM)
  - Polyester sealant (anaerobic)
  - Polytetrafluroethylene (PTFE)
- Solder/Braze
  - Solder alloy: 50-50 lead-tin
  - Solder flux: Alpha OA-63, Alpha OA-64
  - Braze filler Metal: BCuP-3 or BCuP-5
  - Braze flux AWS Type 3A
- Stainless Steel
  - 300 series & 400 series
- Carbon steel
- Polypropylene or Polyethylene

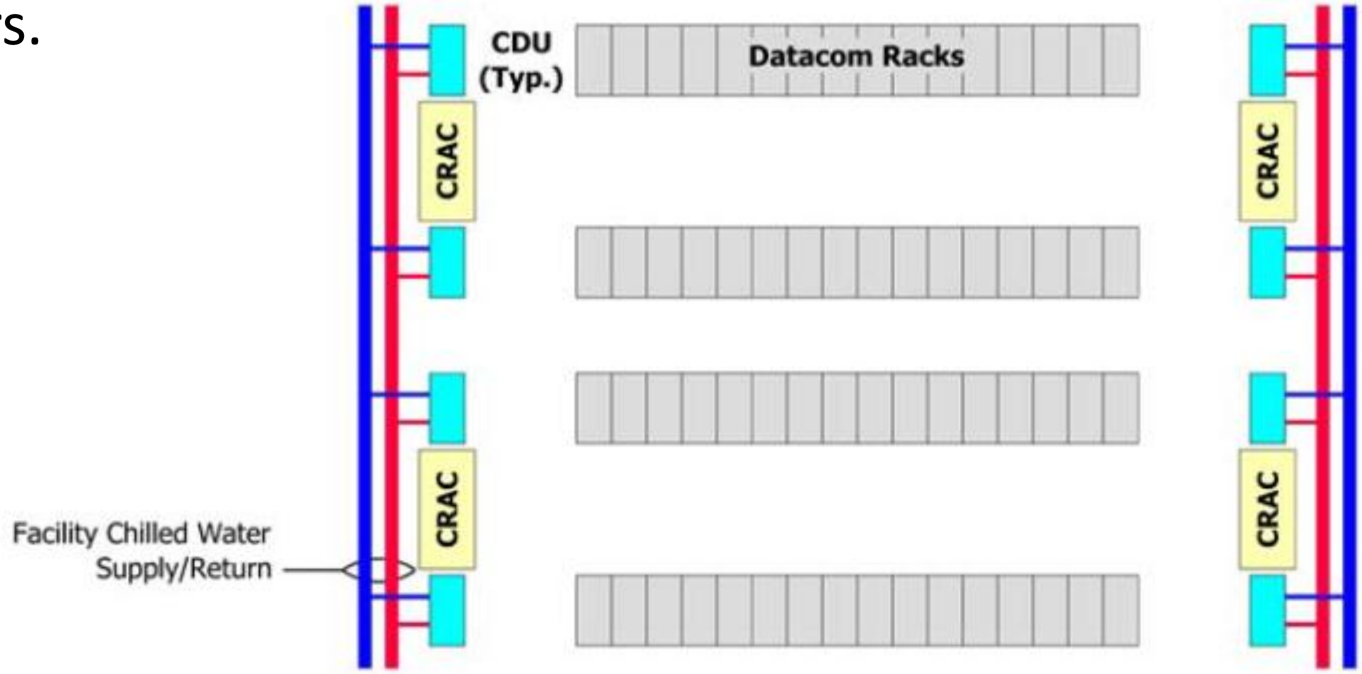
Piping Considerations

- Location of CDU units in data center—Option 1
  - **Location of the CDUs near the perimeter would concentrate any leaks from the CHWS** loop in this area and permit focus of leak detection and containment for this area.
  - **By locating the CDUs in this area, the impact on the air distribution that may be required for the racks is minimized.**
  - Hose and/or piping distribution to the racks from the CDUs can be laid out below the raised floor and below the racks parallel to the rows (of racks).
  - **Valves, strainers, or instrumentation in the piping may be easily accessed** for operation and maintenance purposes.



Location of CDU units in data center—Option 2

- The CDU units are l**ocated against the outer wall of the data center to provide increased control of leak monitoring and detection.** In addition, **this option may provide improved piping connections between the chilled-water building system and the CDUs** can be considered to be just liquid distribution units without heat exchangers.



Piping design & related problems

Basic Pipe Design Criteria

- The piping architecture **defines the relationship between the cooling source (plant) and the load** (electronic equipment). The architecture should consider **simplicity, cost, ease of maintenance, ease of upgrade/change, ease of operation, controls, reliability, energy usage**, etc.
- Analysis of plant, distribution, and terminal pipe sizes results in trade-offs between capital and operational costs. Larger pipe sizes yield lower water velocities, which, in turn, lower pumping power (smaller pumps) and operational costs. **Generally, velocities should be as high as practical without sacrificing system integrity**.

- Typically, increased pumping energy does not outweigh the lower capital cost or the space savings associated with the smaller pipe sizes. **Pipe sizing also affects how much additional cooling load can be added to the data center at a future date**. As cooling and power densities continue to grow, **data centers must be scalable to house this future growth**. **One strategy is to oversize the chilled-water piping plant mains and distribution headers to accommodate future load increases. Oversizing these will save energy and allow smaller pumps for much of the data center's life.**

SPATIAL CONSIDERATIONS

- **No overhead piping, minimal overhead piping, or no constraint on overhead piping** other than to avoid routing directly above electronic equipment.
- All piping mains and pipes above a certain size can be run in the data center or are confined to pipe galleries, chases, troughs, utility pits, etc.
- Consideration **should be given to laying out large piping first so as to minimize pressure drop**, e.g., **large radius bends, few changes of direction**, etc. Then arrange pumps, chillers, etc., to tie into the piping with minimal changes of direction. This will likely result in chillers and pumps arranged in less than a linear fashion—perhaps at 45° instead of 90°.

Characteristics of traditional hard piping methods

APC white paper #131

- **Carbon steel pipe schedule 40 and hard copper pipe type L or M are most commonly used**. Hard piping requires the use of threaded, grooved, welded or brazed fittings at every turn, at every valve, at every branch to multiple air conditioners and at every 1.8 or 6 meters (6 or 20 feet), depending on the available length of the pipe run. It is common to have multiple fittings in one pipe run from the chilled water source to the air conditioner.

Failure modes of hard piping

- Leak
- Galvanic Corrosion
- Condensation
- Mineral build-up (scaling)

Underfloor hard piping installation

***Figure 1** – Traditional underfloor chilled water piping installation with branches to different air conditioners using multiple fittings*

Overhead hard piping installation

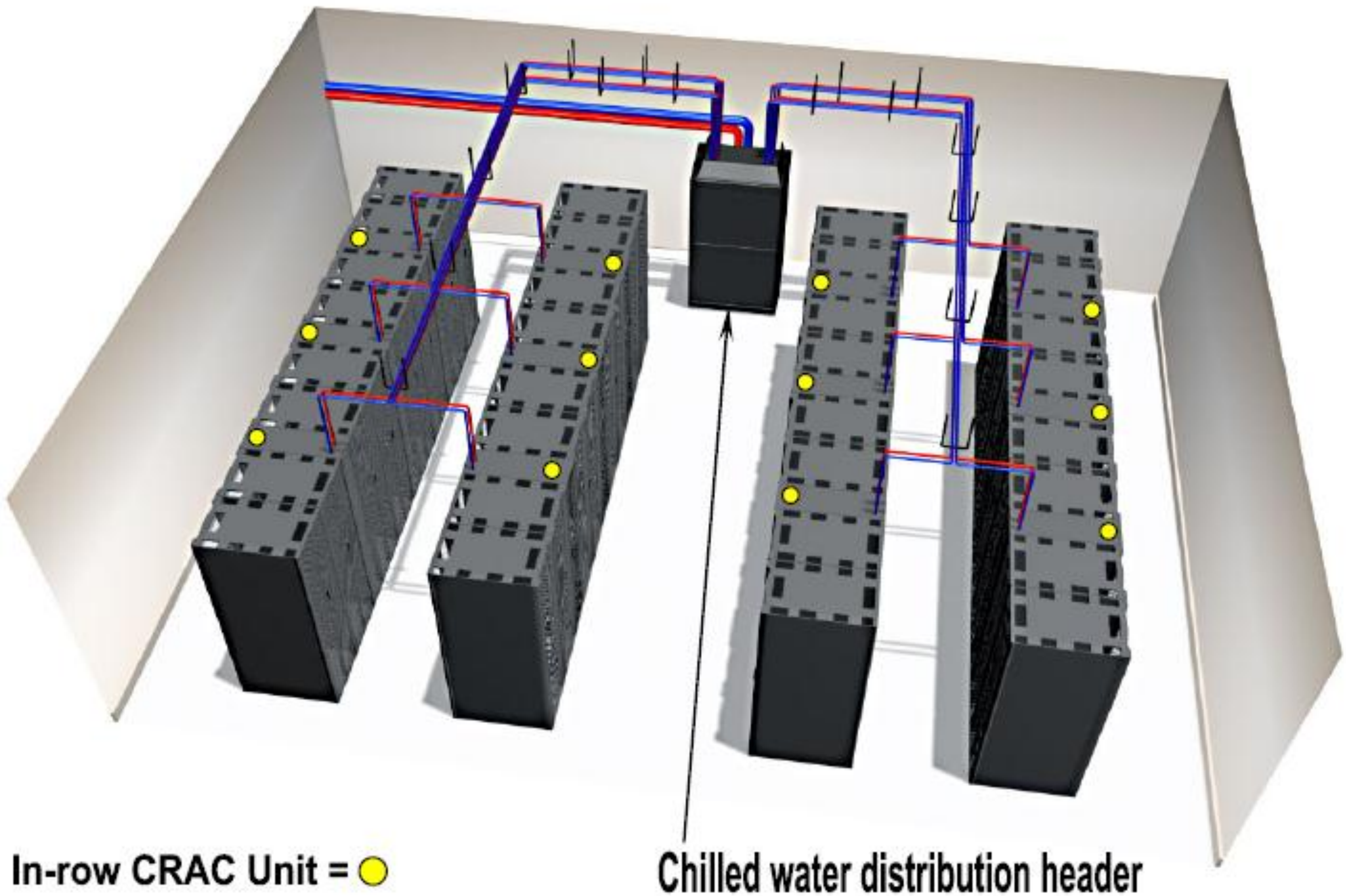
Figure 2 – *Overhead piping with drain pan above racks.*

Flexible piping methodology

- The flexible piping is a multi-layered composite tubing consisting of an aluminum tubing sandwiched between inner and outer layers of cross-linked polyethylene. **This gives the piping flexibility to be routed through the data center with the rigidity to stay in place. The cross-linked polyethylene or PEX also offers excellent protection against corrosion and the smooth interior walls and chemical properties make it resistant to mineral buildup with hard or soft water eliminating the risk of pinholes.**

Overhead flexible piping installation

Figure 4 – *Layout drawing of data center with flexible piping overhead*



Comparison Between Hard Piping and Flexible Piping

Table 1

Physical attributes of hard and flexible piping

Physical attributes	Carbon steel schedule 40	Hard copper piping type "L"	Flexible piping PEX
Pipe weight in kg per linear meter (2.54 cm nominal size pipe without water)	2.49	0.975	0.324
Pipe weight in pounds per linear foot (1" nominal size pipe without water)	1.67	0.655	0.218
Temperature rating	Up to 399°C (750°F)	Up to 204°C (400°F)	Up to 93°C (200°F)
Rated internal working pressure in megapascal	19.7 MPa @ 38°C 19.7 MPa @ 93°C	3.41 MPa @ 38°C 2.79 MPa @ 93°C	1.38 MPa @ 23°C 0.689 MPa @ 93°C
Rated internal working pressure in psi	2857 psi @ 100°F 2857 psi @ 200°F	494 psi @ 100°F 404 psi @ 200°F	200 psi @ 73°F 100 psi @ 200°F
Type of fittings	Welded, brazed, grooved or threaded fittings	Soldered, brazed, grooved or threaded fittings	Multipress threaded or compression fittings
Size range	3.2 to 660 mm (1/8" to 26")	6.4 to 305 mm (¼" to 12")	12.7 to 5.08 mm (½" to 2") in North America 12.7 to 609 mm (½" to 24") in Europe[3]
Termination connection	Welded, brazed or threaded	Soldered, brazed or threaded	Multipress threaded or compression
Corrosion resistance	Limited, depends on the relative humidity of the environment and PH of water	Very good	Excellent
Thermal conductivity	High	High	Medium to Low

	Hard piping	Flexible piping
Agility	Slow speed of deployment due to multiple brazed joints required. Balancing of system is not easily accessible either under the raised floor or above the ceiling tiles. Non-scalable expansions or relocations require one time engineering and downtime for other units.	Increased speed of deployment by 40%. Balancing of the water system is located in a centralized accessible location. Scalable, allows for moves, adds, changes, and future expansions without disturbing other units.
Availability	Leak potentials at every fitting and joint decreasing reliability.	Increased reliability by eliminating intermediate joints drastically reducing leak potential.
MTTR	If leakage occurs on the main, repair may take from hours to days depending on the leak. If leakage occurs on a distribution branch in the data center, repair may take several hours, causing shutdown for several units.	If leakage occurs from the chiller to the centralized distribution header, repair may take from hours to days depending on the leak. If leakage occurs on a flexible branch in the data center, new flexible piping can be routed and repair may take up several hours causing shutdown on one unit only.
Installation	Higher installation costs. System balancing requires more time adding cost to start-up. Brazed, threaded, or mechanical joints and fittings are used, and intermediate isolation and balancing valves are required.	Lower installation cost. System start-up and balancing is less complex with the centralized distribution system. No brazed joints, intermediate fittings, or valves are required.
Turning radius	Allows a shorter turning radius using elbow fittings.	Minimum bending radius is 5 to 7 times the outside diameter of the tube.
Maintainability	Visual checks for leaks at each joint and valve, visual check for condensation at fittings and valves and visual check at corrosion points. Water and glycol concentration measured and validated.	Less time spent in visual checking for leaks and condensation formation on valves at the centralized distribution header (all valves are in one location). Water and glycol concentration measured and validated, routine maintenance
Pressure drop	The use of elbows for turns and mineral buildup causes additional pressure drop	Smooth interior and larger radius turns without fittings reduce the pressure drop for typical piping runs
White space	Piping is run underfloor or overhead, no white space is occupied by the piping system	White space is required for the centralized distribution header in the room.
Distances	Long pipe distances can be performed with hard pipe since several pieces of pipe are joined through fittings.	Maximum distance recommended is 46 meters (150 ft) from the distribution header to the air conditioners due to the complexity that longer distances would create for the installer.
Upfront cost (installation and material)	Hard pipe cost is lower but the overall installation cost is higher due to the increased labor required for brazing and threads and system balancing requires more time adding cost to start-up.	PEX piping has a higher cost, however the overall installation may be lower due to the elimination of brazing or threaded fittings and the system start-up and balancing is less complex with the centralized distribution system.
Pipe location	Can be installed outdoors or exposed to sunlight.	PEX must not be stored or installed in areas where it is exposed to sunlight, either direct or indirect.

Table 3

Failure mode comparison of hard and flexible piping

	Hard piping	Flexible piping
Punctures	Less susceptible to leakage due to puncture by a sharp object.	More susceptible to leakage due to puncture by a sharp object.
Single point failures	Failure in a branching pipe causes loss of cooling in all CRACs connected to the branch.	Failure in a line causes loss of cooling in only one CRAC.
Joint leaks	Multiple joints and fittings in the pipe increase leak potential due to possible galvanic corrosion, failure of thread sealant over time, poor machining of the threads, gasket deterioration in grooved connections or poor quality of the threaded fittings.	Reduced amount of joints - two per line per CRAC. Multipress threaded fittings crimp the PEX-AL-PEX tube making a stronger connection than a threaded or gasketed fitting.
Earthquake / vibration	Vibration or earthquake movement can cause leakage at joints and fittings.	Less susceptible to break or leak in vibration or earthquake conditions.
Stepping on	May damage brazed or threaded fittings which can produce a leak.	Less susceptible to damage due to the flexibility of the pipe.
Insulation dripping from condensation in the data center.	More potential for condensation due to difficulty to insulate multiple valves, strainers, and fittings. Small cracks or spaces left without insulation may cause condensation.	Less potential for condensation due to the elimination of intermediate valves or fitting between the distribution system and the CRACs.
Abrasions / cuts	Resistant to exterior abrasions or cuts	Less resistant to exterior abrasions. Cut can damage the PEX piping exterior.
Pinholes and mineral buildup	Susceptible to pinholes and leakage due to mineral buildup if water is not treated periodically.	Very resistant to mineral buildup due to smooth interior walls and chemical properties.

Note: shading indicates best performance for the characteristics

- The concern of water in the data center is also reduced with a flexible piping system for three reasons:
  - **The overall piping system failure rate is greatly decreased due to the dramatic reduction in joints**
  - **The fundamental reliability of the base piping itself is higher**
  - **The potential for condensation is reduced** by not having intermediate fittings or valves to insulate, which are the main points of condensation formation in a chilled water system.

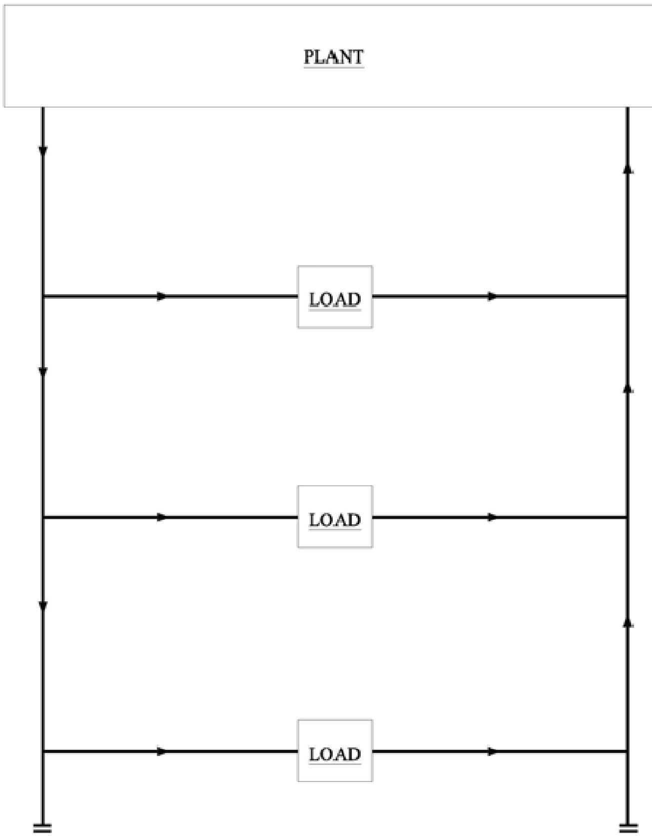
Water Quality Specifications—TCS Cooling Loop

Parameter	Recommended Limits
pH	7 to 9
Corrosion inhibitor	Required
Biocide	Required
Sulfides	<1 ppm
Sulfate	<10 ppm
Chloride	<5 ppm
Bacteria	<100 CFU/mL
Total hardness (as $CaCO_3$)	<20 ppm
Conductivity	0.20 to 20 micromho/cm
Total suspended solids	<3 ppm
Residue after evaporation	<50 ppm
Turbidity	<20 NTU (nephelometric)

Basic Piping Architecture

- Direct return

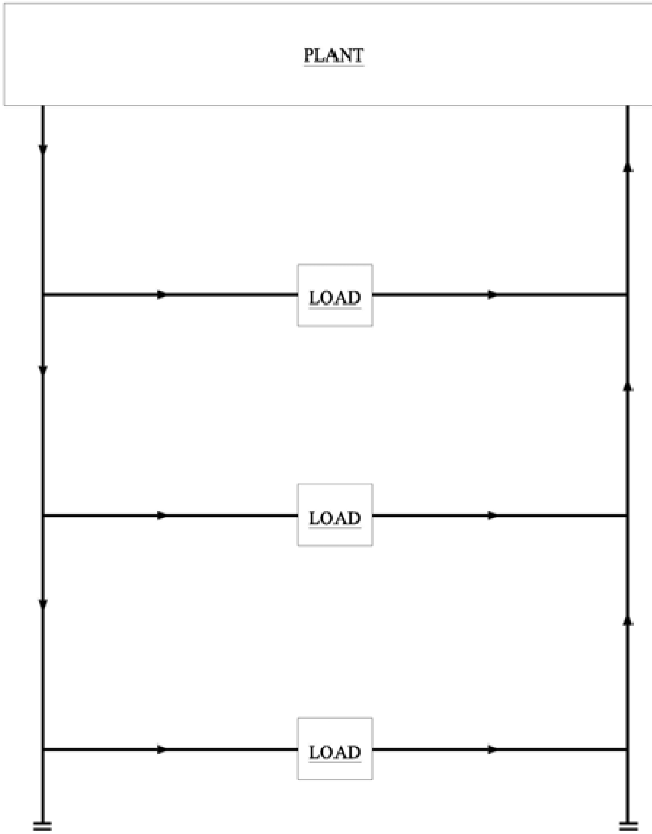
  A direct return system is the most basic type of piping system and is used in traditional HVAC design **where there are a reduced number of connection points**. In this system, the supply and return piping is fed in a radial manner and the loads that are closest to the cooling plant have the shortest supply piping lengths and the shortest return piping lengths**. It may require an excessive amount of balancing valves to ensure proper system operation.** This is due to the variation in supply and return piping lengths to a given load.



Example of direct return flow principle.

Direct Return

- Advantages
  - Least expensive to construct, uses a minimal amount of pipe, valves, and fittings.
  - Simplest to operate and understand.
- Disadvantages
  - Least reliable since only one source of cooling exists.
  - No redundancy in piping to the load. **Any pipe failure or leak or future addition could jeopardize system availability.**
  - May require additional balancing valves.

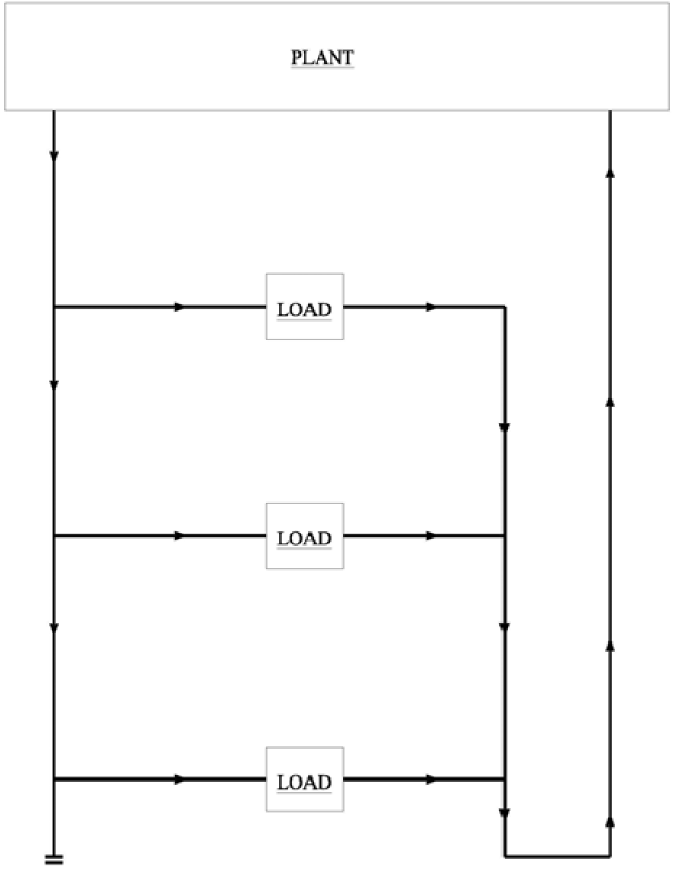


Example of direct return flow principle.

National Chiao Tung University

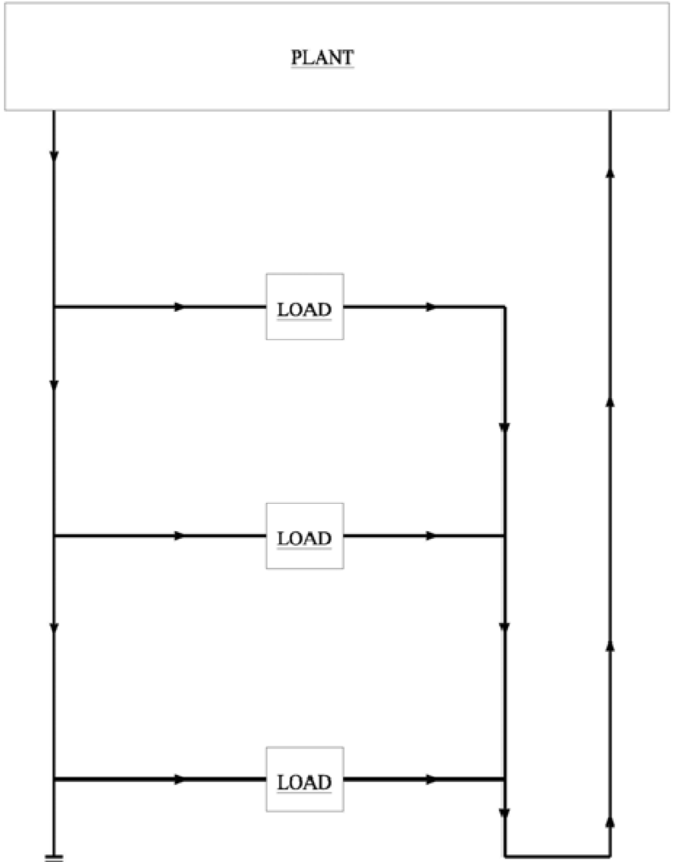
- Reverse return

Create a piping network with an element of self-balancing **by having the loads supplied by piping closest to the cooling plant also be the loads that are at the most remote end of the return piping** and vice versa. This is achieved by essentially **having the flow in the return piping parallel the flow in the supply piping** as it feeds the various loads around the building. This results in **the combined length of supply and return piping for any given load being approximately equal**, which **creates a system that can be considered self-balancing**.



Example of reverse return flow principle.

- Advantages
  - Simple to operate and understand.
  - **Self-balancing**.
- Disadvantages
  - Less reliable; again, only one source of cooling.
  - No redundancy in pipe or chilled-water routes. Routine maintenance or system expansion could require complete system shutdown.
  - A little more expensive to install than direct return (i.e., more piping required).



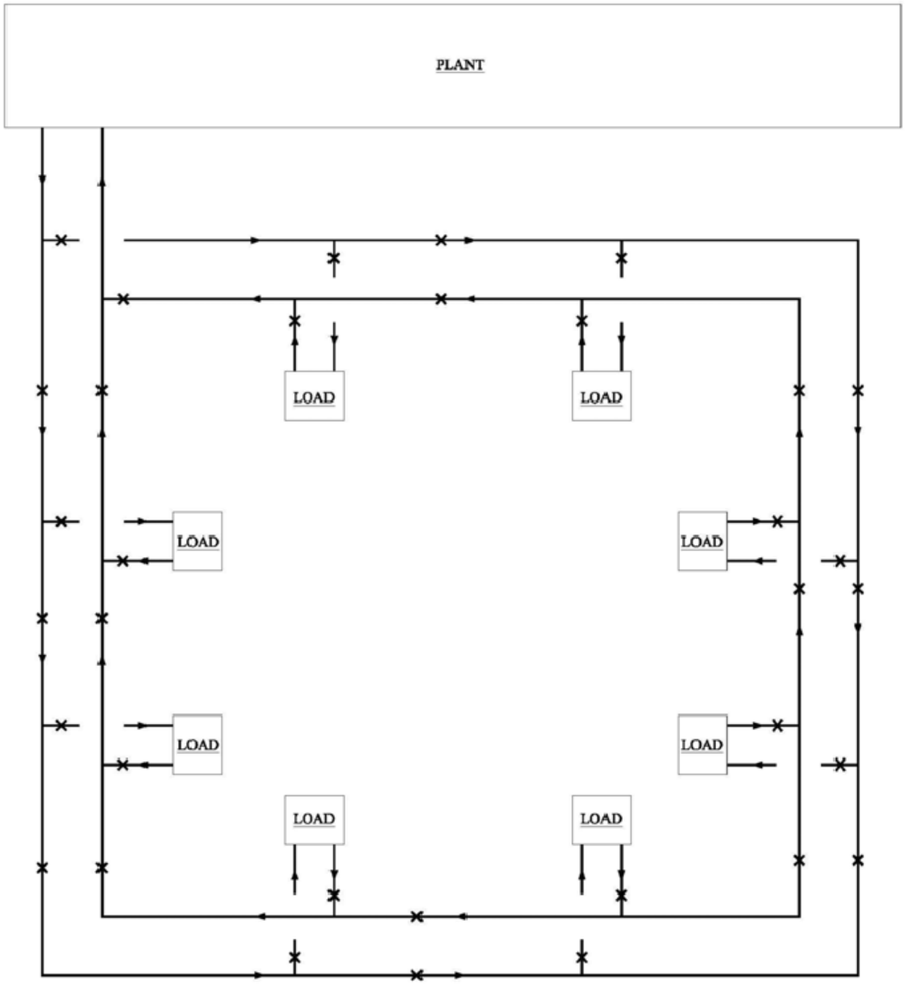
Example of reverse return flow principle.

Looped piping mains

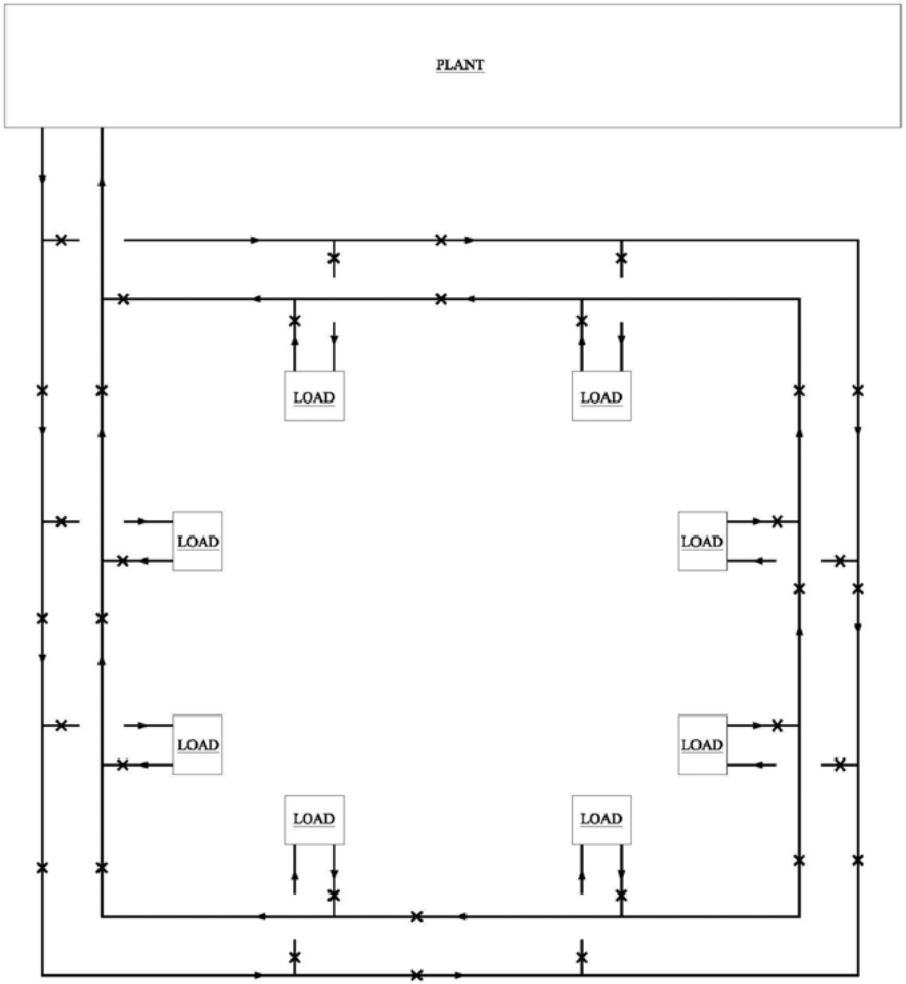
- **Involve a closed loop that is tapped at various points to feed loads. The flow of liquid within the loop can occur in two directions from the source** and, in theory, there is a “no-flow zone” near the midpoint of the loop.
- **Allows for a section of main piping to be isolated for maintenance or repair. Loads that were downstream of the isolated section can then be backfed from the other side of the looped mains to allow for greater online availability of the cooling system**.

Single ended loop with direct feed

- A single-ended loop has a single point of connection (supply and return piping) to the plant. The piping is typically looped within the datacom area and, in this particular configuration, **the loads are directly fed from the mains' loop piping.**
- A popular application of this piping architecture is for an air-cooled CRAC unit based cooling system, where CRAC units are located around the perimeter of the datacom area.

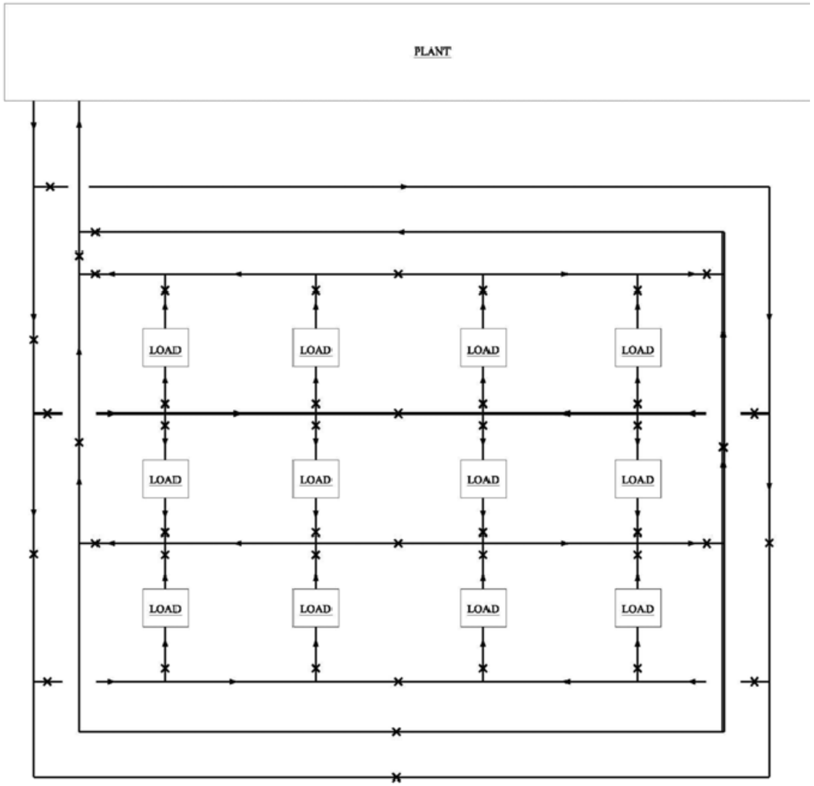


- **Advantages**
  - Self-balancing.
  - Increased reliability over direct and reverse returns systems with two piping routes to the load.
  - Individual pipe sections and future equipment installations are serviceable without system shutdown.
- **Disadvantages**
  - Increased complexity and understanding.
  - Increased installation costs.

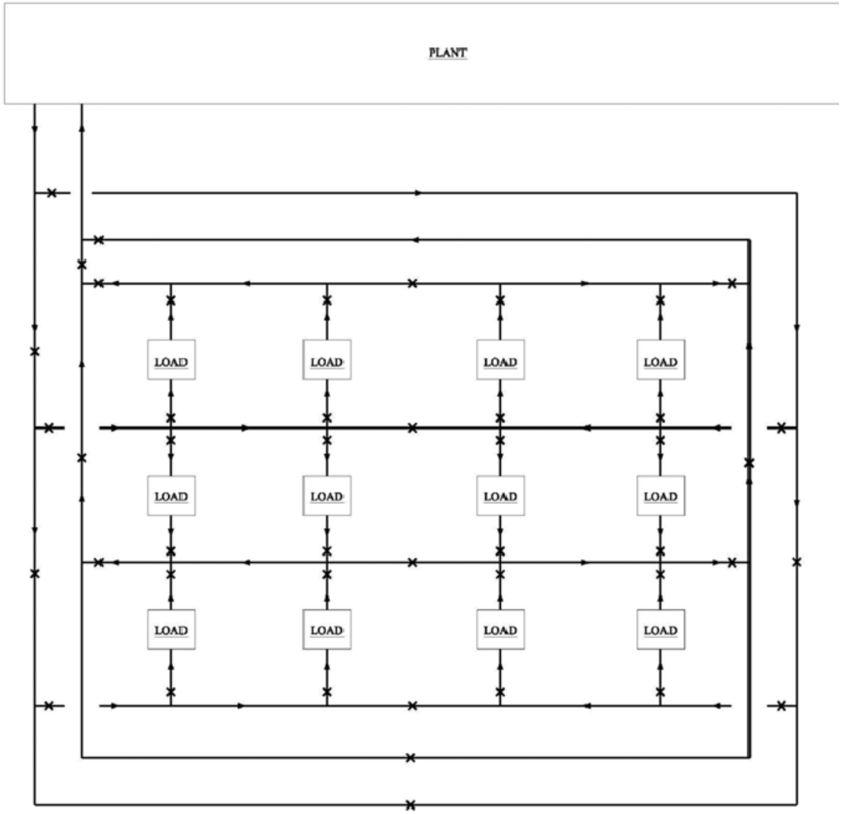


Single ended with common cross branch

- The connection of the loads are now indirectly fed from cross-branch piping connected at two locations to the mains' loop.
- **The cross-branch piping is said to be common since it is used by multiple loads on both sides of its route as a supply and return flow path.**
- **This method not only allows for a bidirectional flow of liquid in the mains but also within each cross branch.** As such, it provides **multiple paths for flow to reach the majority of the loads should a section of the mains' loop or the cross branch need to be isolated for reasons of maintenance or repair.**

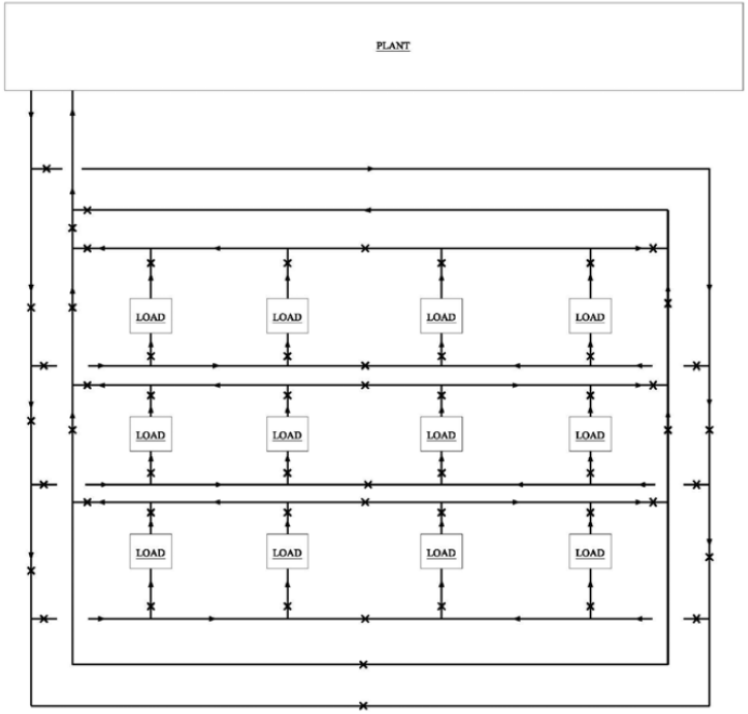


- Advantages
  - Increased reliability with multiple piping routes to load.
  - Self-balancing.
  - **Used primarily for water-cooled rack units.**
  - Individual pipe sections and future equipment installations are serviceable without system shutdown.
- Disadvantages
  - Increased installation costs.
  - Increased operational complexity.

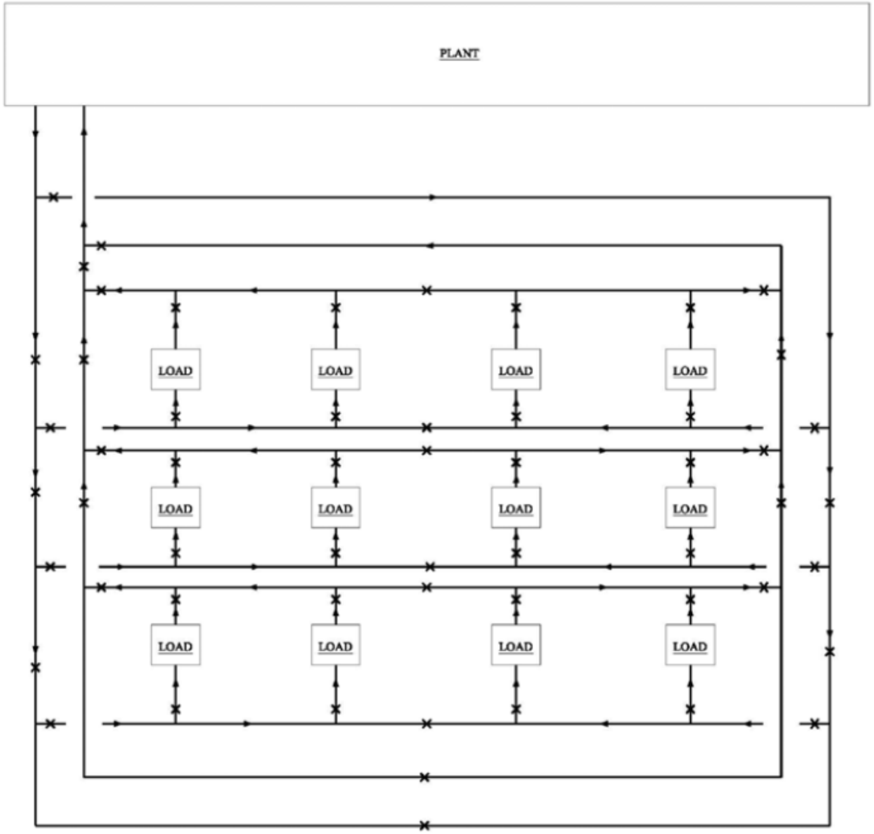


Single-Ended Loop with Dedicated Cross Branches

- The indirect connections of the loads are supplied from an increased number of cross-branch pipes. **This allows for an increase in granularity of the loads and, therefore, an increased level of reliability** (i.e., the isolation of a section of cross-branch piping will not impact as many loads since there are fewer connections per cross branch).

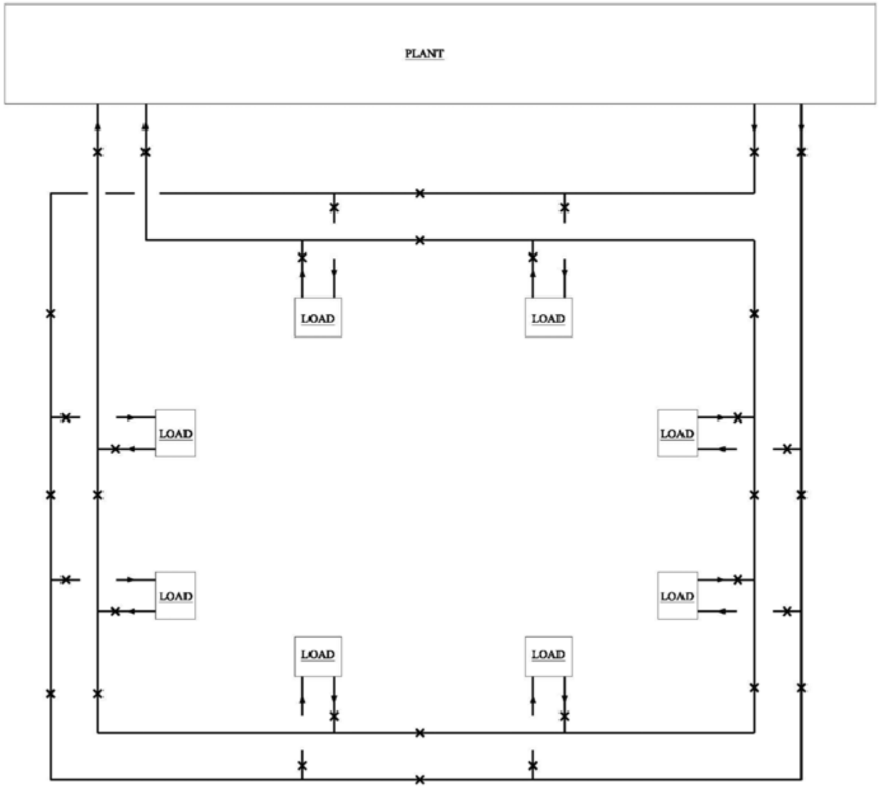


- Advantages
  - Increased reliability with multiple piping routes to load.
  - Self-balancing.
  - Individual pipe sections and future equipment installations are serviceable without system shutdown.
- **Disadvantages**
  - Increased installation costs.
  - Increased operational complexity.

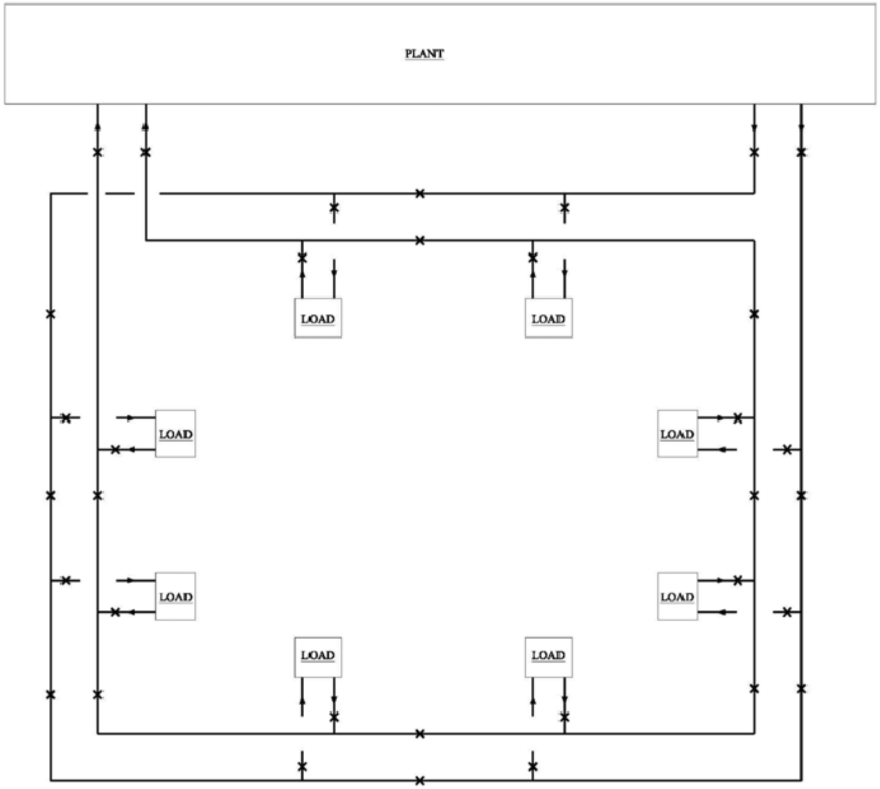


Double ended with direct feed

- The only difference between the single-ended loop and the double-ended is that **in this piping architecture there are two connections to the plant, which eliminates the single point of failure that exists for all single-ended loop piping configurations** (e.g., if a need exists to isolate the piping between the connection to the plant and upstream toward the plant itself, this method will still allow cooling to all loads via the second connection).

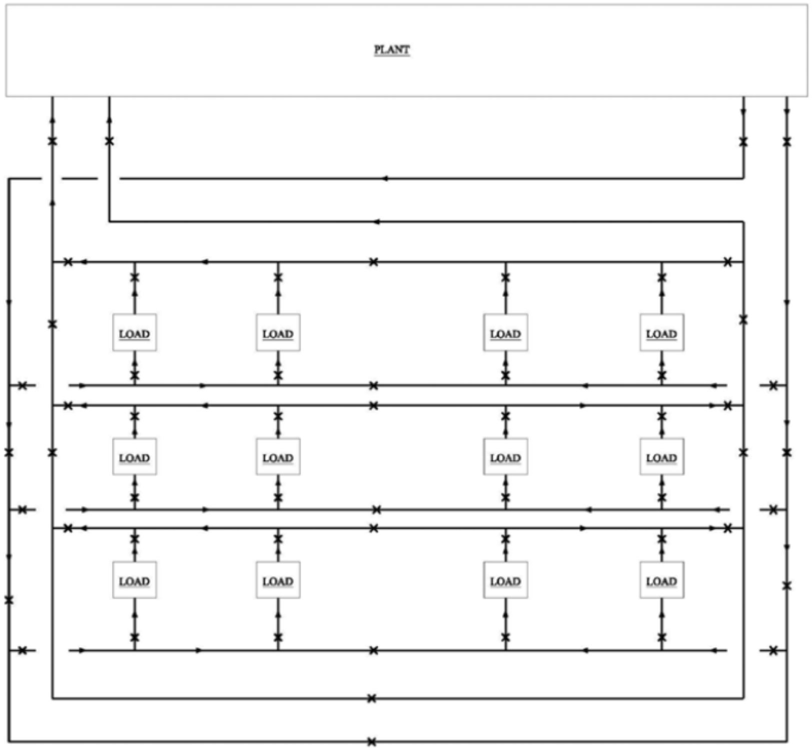


- **Advantages**
  - High reliability.
  - Redundant piping routes to load and a second cooling supply and return mains from the plant.
  - Redundant cooling supply and return piping from a second central plant.
  - Individual pipe sections and future equipment installations are serviceable
  - without system shutdown.
  - Self-balancing.
- **Disadvantages**
  - Increased installation costs.
  - Increased operational complexity.

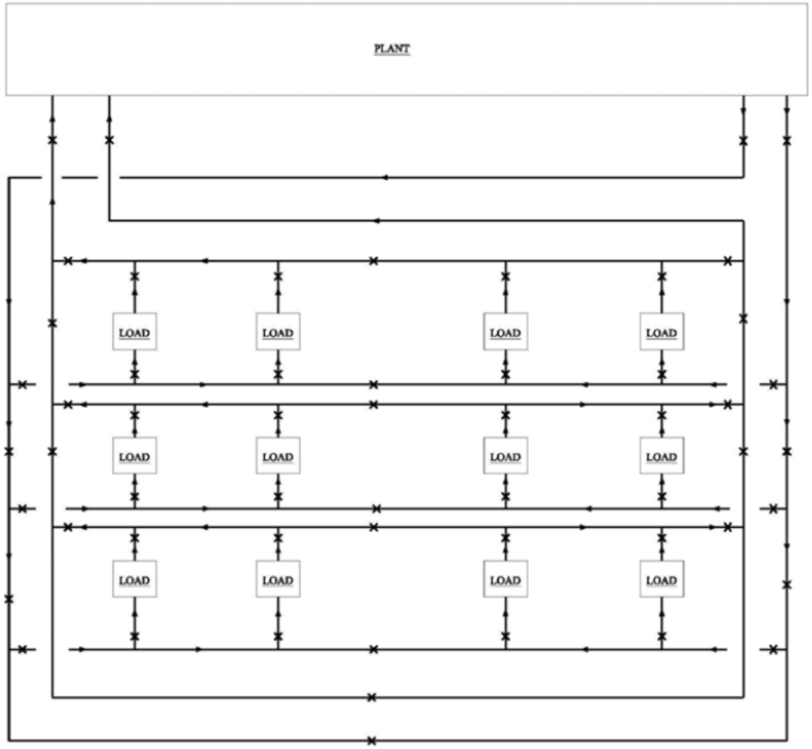


Double ended with Common Cross branch

The difference between this piping architecture and the single-ended loop with common cross branches is that two connections to the plant are made to eliminate the single point of failure.

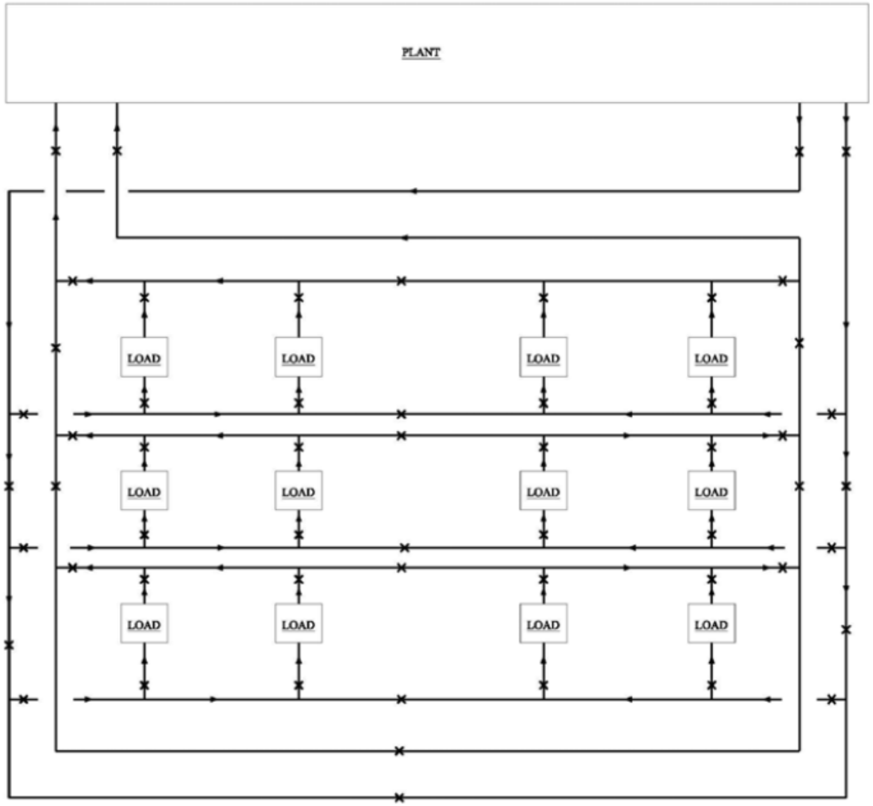


- Advantages
  - High reliability.
  - Redundant piping routes to load and a second cooling supply and return mains from the plant.
  - Redundant cooling supply and return piping from a second central plant.
  - Individual pipe sections and future equipment installations are serviceable without system shutdown.
  - Self-balancing.
- Disadvantages
  - Increased installation costs.
  - Increased operational complexity.

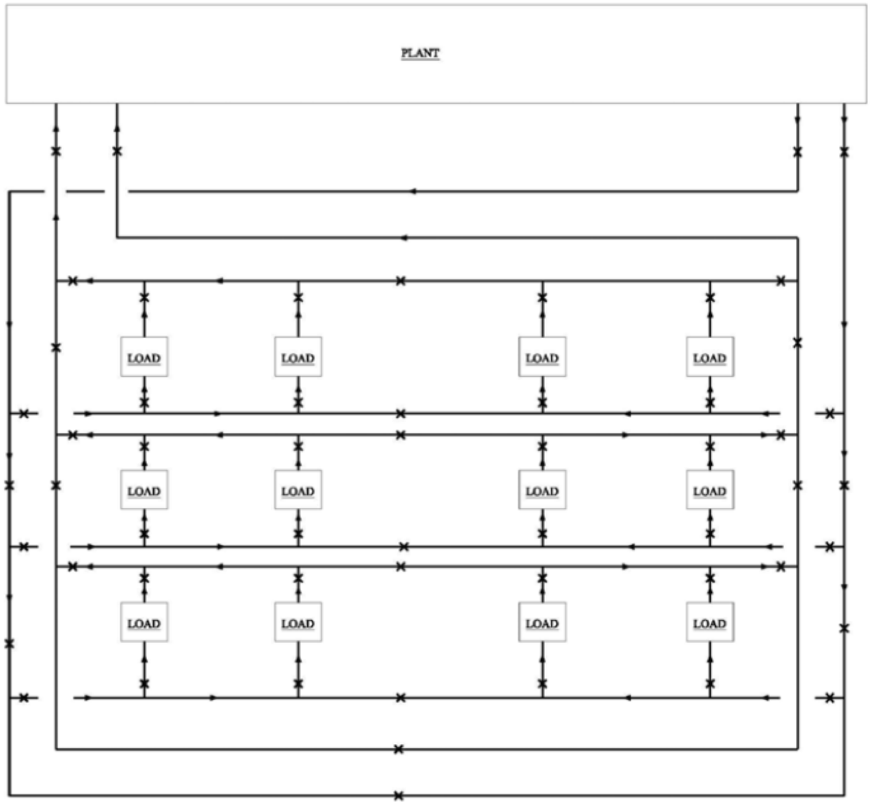


Double-Ended Loop with Dedicated Cross Branches

- The principal difference between this piping architecture and the single-ended loop with dedicated cross is that **two connections to the plant are made to eliminate the single point of failure.**



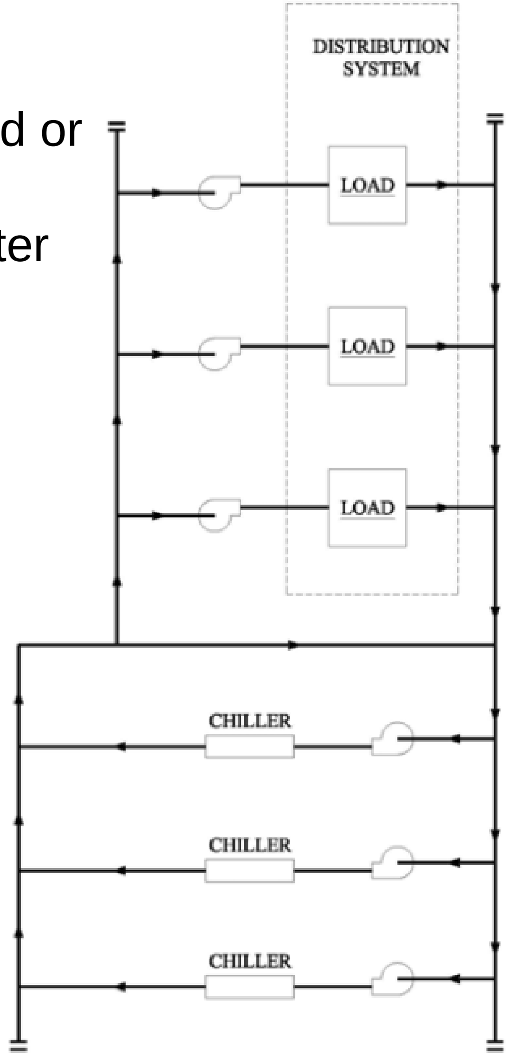
- Advantages
  - High reliability.
  - Redundant piping routes to load and a second cooling supply and return mains from the plant.
  - Redundant cooling supply and return piping from a second central plant.
  - Individual pipe sections and future equipment installations are serviceable without system shutdown.
  - Self-balancing.
- Disadvantages
  - Increased installation costs.
  - Increased operational complexity.



PIPING ARRANGEMENTS FOR THE COOLING PLANT

- **The chillers can be configured in series or parallel** and have different preferential loading schemes.
- **The pumping and flow can be configured as constant flow, stepped variable flow, or variable flow**.
- The building owner or occupant will have to **perform an engineering analysis to determine which configuration is best** for their data center.

a typical decoupled or condenser-water system/chilled-water system pumping configuration



CHWS Pipe Sizing

- Since these areas might change with new equipment over time, flexibility to **provide hotter areas with cooling must be oversized in the CHWS distribution**.
- Example: if the average load is **at a design density of 100 W/ft^2,** the CHWS distribution should be able to supply any local area of the raised **floor with 175–200 W locall**y. In today's environment of changing technology, all CHWS piping should plan for a series of additional water taps off the distribution to serve the future requirements for auxiliary cooling equipment.

Most Common Problems in Water-Cooled Systems

- **CORROSION**
  - There are various forms of corrosion: uniform, galvanic, crevice, pitting, intergranular, dealloying, erosion, environmentally induced cracking, and hydrogen damage.
  - **Uniform corrosion removes more metal than other forms of corrosion, but pitting corrosion is more insidious and difficult to predict and control**.
  - In cooling systems without adequate water-chemistry control, **steel will uniformly corrode, and copper and aluminum will also pit**.

Corrosion

– Tube and pipe surfaces, especially copper tube surfaces, should be free of contamination, such as carbon films, which is a residue from the tube drawing operations, to reduce the incidence of pitting corrosion. Stainless steel hardware must not be sensitized and must be properly passivated. Sensitized stainless steel hardware may suffer intergranular corrosion. Un-passivated stainless steel suffers superficial corrosion that may contaminate the water. Aluminum is not recommended as a wetted material in the cooling loop, but if its use is necessary a more corrosion-resistant version may be selected, including Al-clad alloys, and an aluminum-specific corrosion inhibitor must be added.

– An important water-chemistry variable is **pH. Metals corrode the least around the neutral pH range, some a little higher than pH = 7,** and some a little lower. Corrosion is also driven by high levels of chlorides, sulfides, and sulfates in the water, but one cannot make reliable predictions of corrosion rates from the water chemistry except under very extreme water-chemistry conditions.

FOULING—INSOLUBLE PARTICULATE MATTER IN WATER

- Insoluble particulate matter settles at low flow velocities or adheres to hot or slime-covered surfaces and results in heat-insulating deposits and higher pressure drops in the loop. **Deposits can consist of silt, iron rust, naturally occurring organic matter, particle matter scrubbed from the air, chemical additives due to poor control**, etc.
- **Fouling is related to the amount of particulate matter or total suspended solids in the fluid.** A full loop filtration system is not typically needed if the make-up water is of good quality. A side stream filtration system may provide adequate solids removal at a smaller capital cost.
- The operational aspect of filter monitoring and change-out frequency must be considered and a specific maintenance program established.

SCALE—PRECIPITATION OF SALTS DIRECTLY ON METAL SURFACES

- Higher temperatures promote scale formation by lowering the salts' solubility limits. **Scale typically consists of calcium carbonate and magnesium carbonate.** Hard waters, high in dissolved calcium and magnesium cations, are prone to scale formation on hotter surfaces when the water pH is high. Soft waters, low in these dissolved ions, are less prone to scale formation. **Hard waters are generally less corrosive because the scale formed on metal surfaces retards the diffusion of oxygen to the cathodic areas**. In cooling systems, closed to air, from which water is not allowed to evaporate, scale formation is generally not an issue.
- If carbon dioxide from the air is allowed to dissolve in the water, the reduced propensity to scale formation will leave the metal surfaces less protected from the cathodic half-cell reaction, thus increasing the metal corrosion rate.

MICROBIOLOGICALLY INDUCED CORROSION—CORROSION DUE TO BACTERIA, FUNGI, AND ALGAE

- Carbon steels, stainless steels, and alloys of copper and aluminum may suffer **microbiologically induced corrosion (MIC), especially in stagnant waters with a pH from 4 to 9 in the temperature range of 10°C to 50°C (50°F to 122°F).** Even if there is no recorded incident of MIC in computer closed-loop cooling waters, precautions must be taken to avoid bacteria in the water.
- **Bacteria can greatly increase the risk of pitting.** Pitting can occur at weld joints and high stress locations. Aluminum corrosion can be accelerated by microorganisms in neutral-pH water. Copper, a known toxin to bacteria, can be attacked by some types of bacteria having a high tolerance for cupric ions.

Short Summary

- With rack heat loads steadily climbing, the ability for many data centers to deliver either adequate airflow rates or sufficient chilled air is now being stretched to the limit, hence liquid cooling is a must when extremely high heat flux is encountered.
- The overall goals of the liquid implementations are to transfer as much waste heat to the facility water as possible and, in some of the implementations, to reduce the overall volume of airflow needed by the racks.
- Implementation of liquid cooling may be required to achieve higher performance of the datacom equipment through lower temperatures achieved with the cooling of microprocessors.
- This reports gives an overview of the liquid cooling technology from the aspects of application needs.

Thank You

Appendix 1

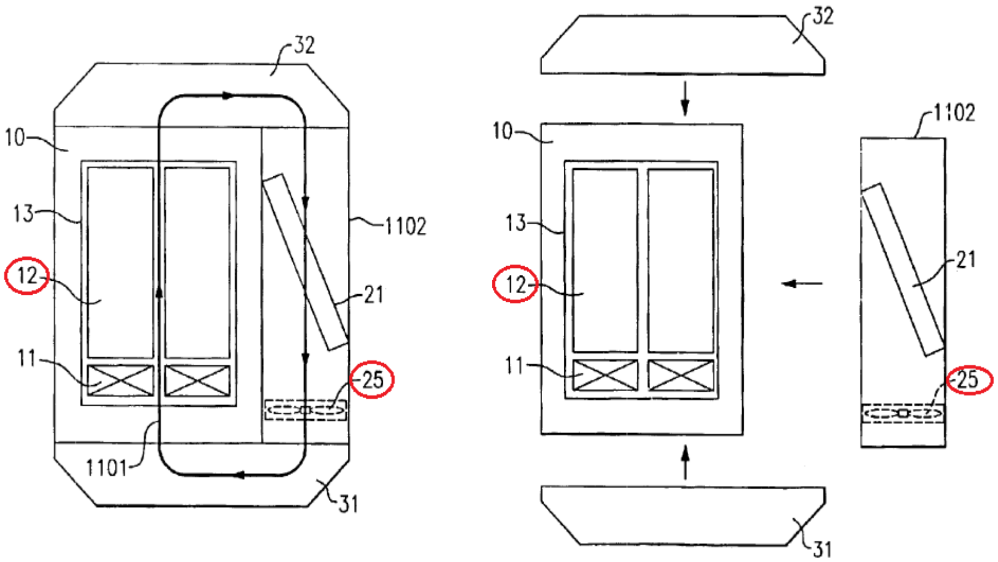
Patents related to Liquid cooling

Patent No. US 6775137

METHOD AND APPARATUS FOR COMBINED AIR AND LIQUID COOLING OF STACKED ELECTRONICS COMPONENTS

International Business Machines Corporation.2002

- An enclosure apparatus provides for combined air and liquid cooling of rack mounted stacked electronic components(12).
- Auxiliary air-moving devices(25) may be mounted within the enclosure to increase the air flow.



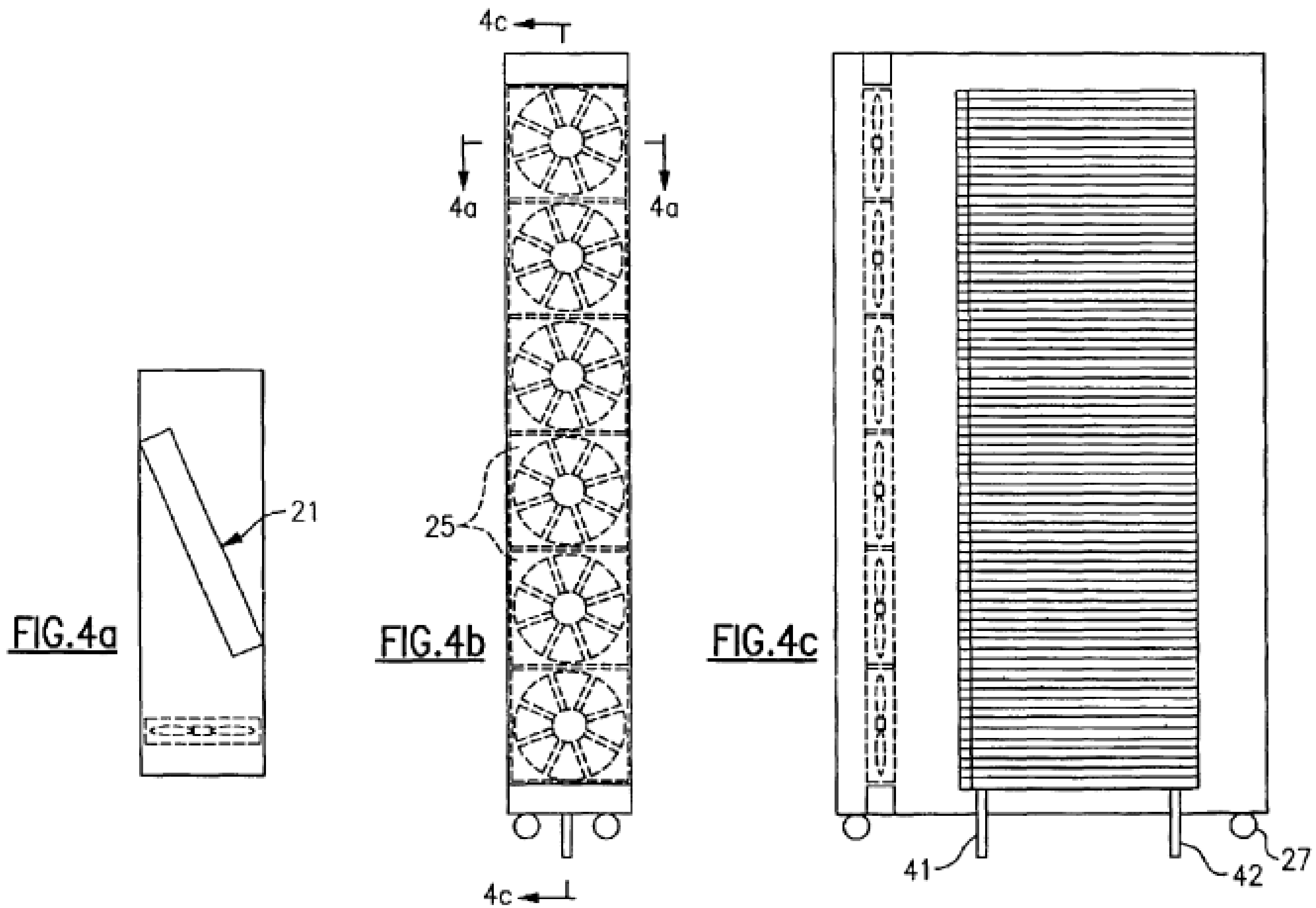


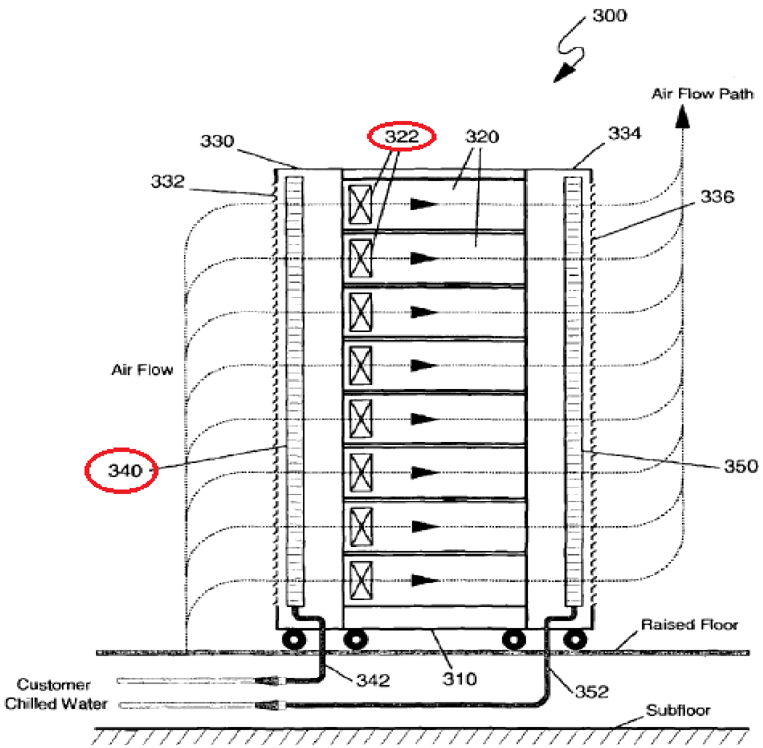
FIG.4a FIG.4b FIG.4c

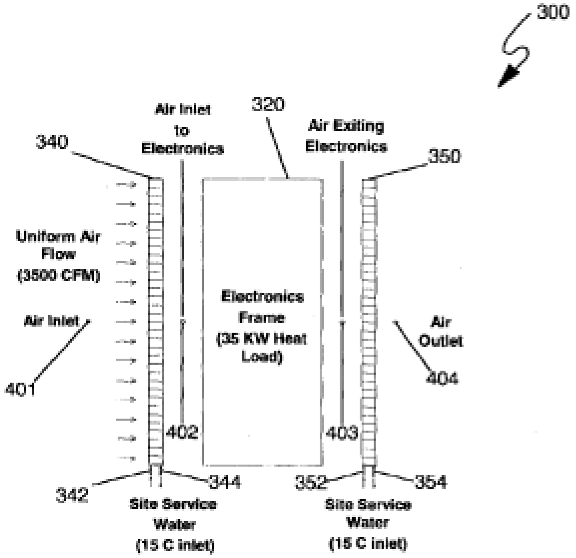
Patent No. US 6819563

METHOD AND SYSTEM FOR COOLING ELECTRONICS RACKS USING PRE-COOLED AIR

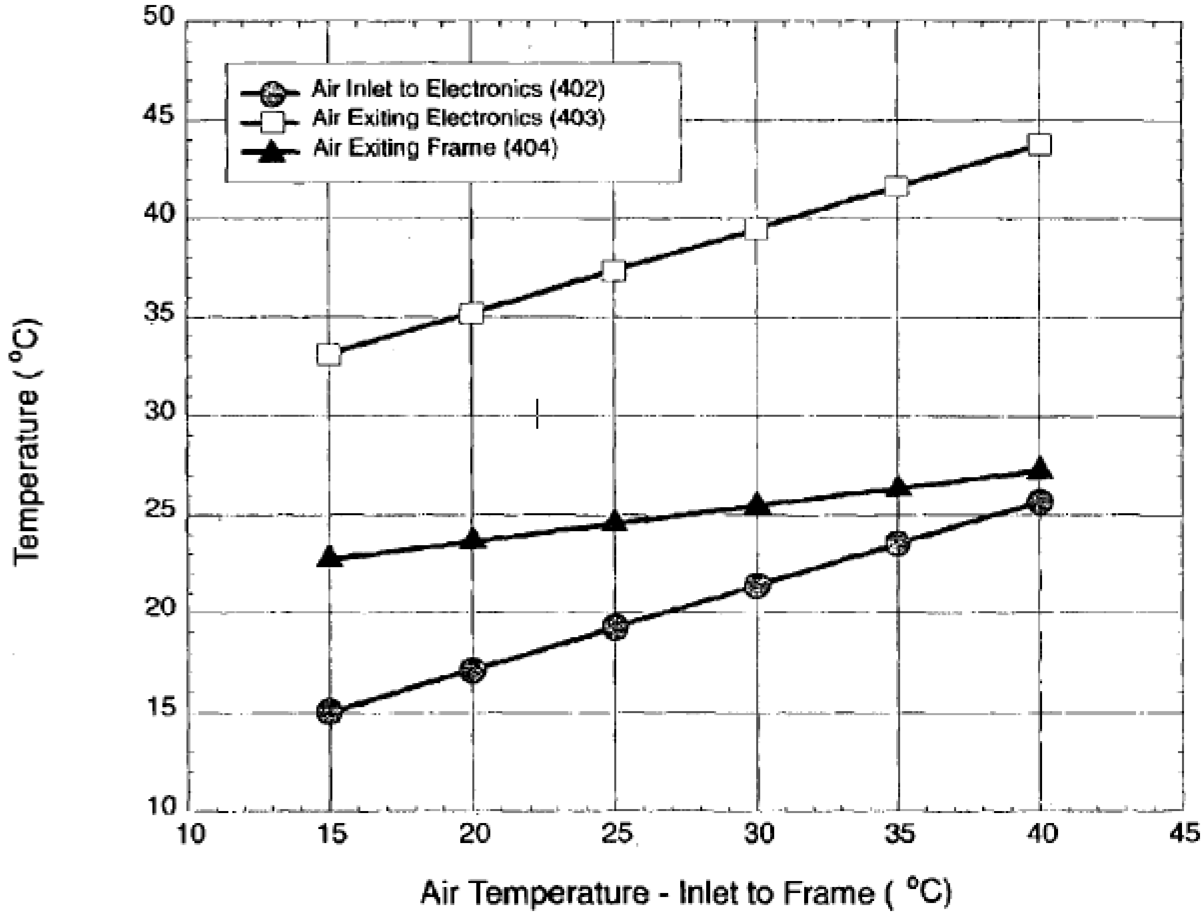
International Business Machines Corporation.2004

- A cooled electronics system includes a frame, electronics drawers, fans or air moving devices(322), and an inlet heat exchanger(340).
- A cooling fluid such as chilled water is supplied to the inlet heat exchanger, to cool incoming air below ambient temperature.



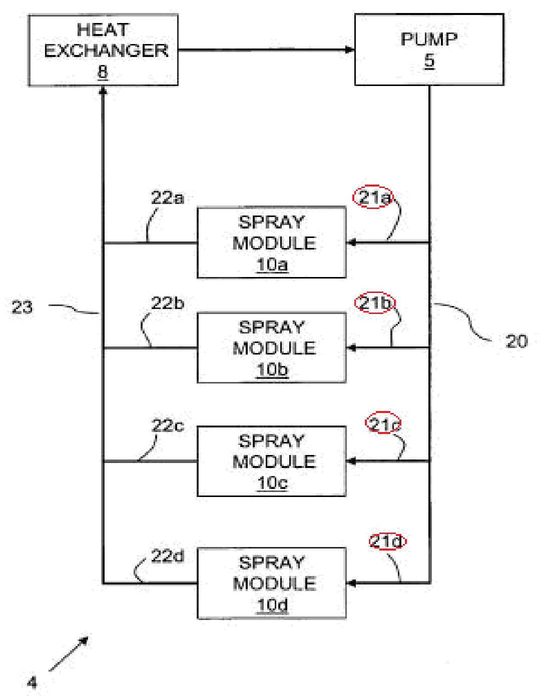


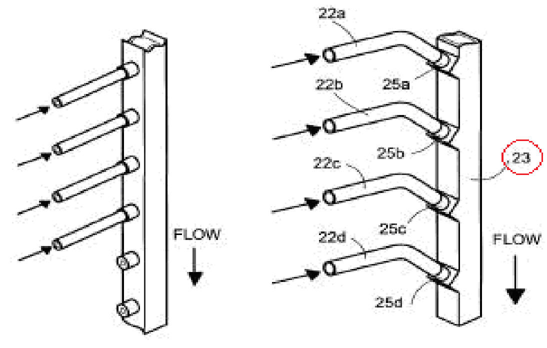
Heat Exchangers:
- Performance based published data
- 24" Wide X 73.5" high X 3.5" deep
- Water flow = 5 gpm each
- Air Flow = 3500 cfm (uniform)
- Air pressure drop = 0.05 inches water
- Water pressure drop = < 1 psi
- Inlet water temperature = 15 C



Patent No. US 6958911
LOW MOMENTUM LOSS FLUID MANIFOLD SYSTEM
Isothermal Systems.2005

- The angular transitions between the return branches(21a,b,c,d) and the return manifold (23)provides low manifold losses and a more efficient system.





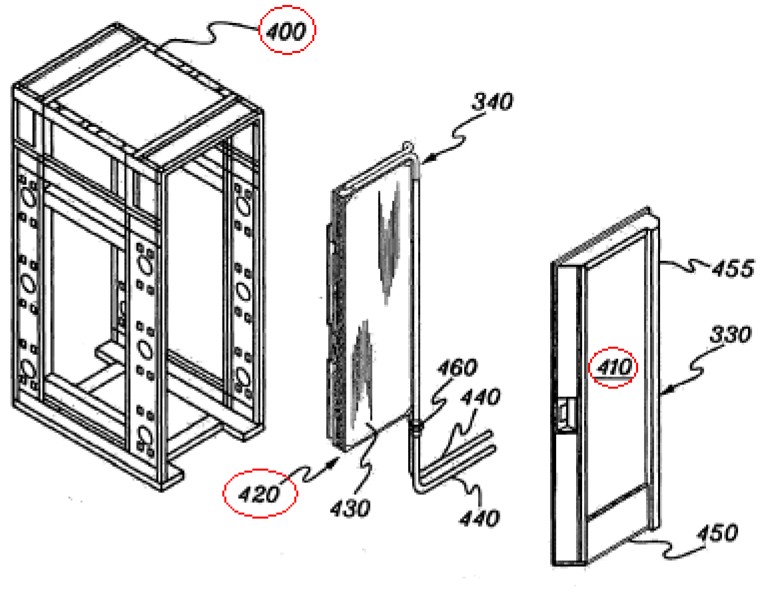
(PRIOR ART)

Patent No. US 7385810

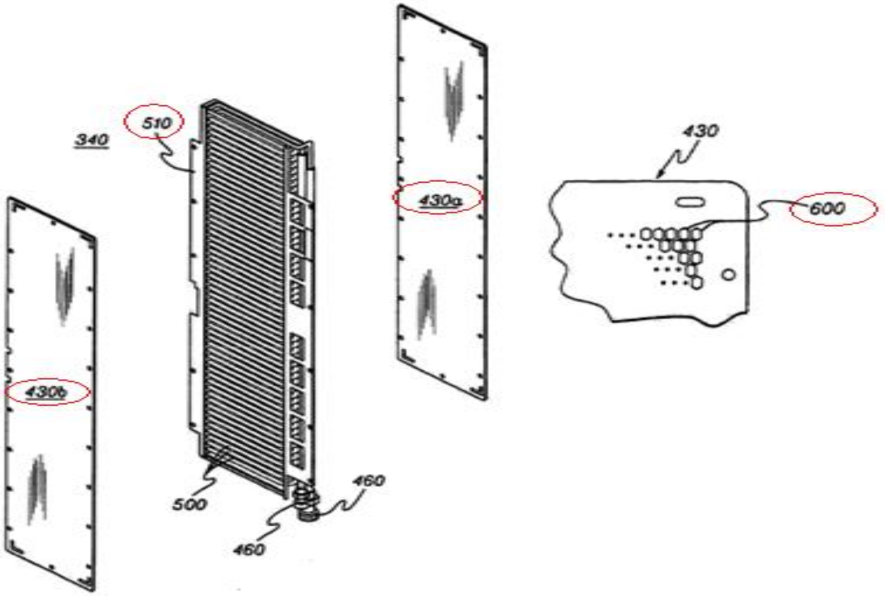
APPARATUS AND METHOD FOR FACILITATING COOLING OF AN ELECTRONICS RACK EMPLOYING A HEAT EXCHANGE ASSEMBLY MOUNTED TO AN OUTLET DOOR COVER OF THE ELECTRONICS RACK

International Business Machines Corporation.2008

- Apparatus and method are provided for facilitating cooling of an electronics rack employing a heat exchange(420) assembly mounted to an outlet door cover(410) hingedly affixed to an air outlet side of the rack(400).



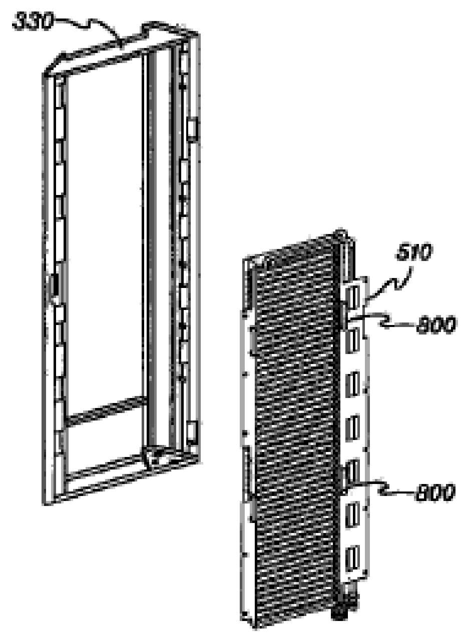
- The support frame (510) facilitates mounting of the heat exchange assembly to the outlet door cover, and first and second perforated planar surfaces (430a,430b) , for covering of heat exchanger.
- The perforated planar surfaces comprise metal plates(430) having appropriate air flow openings(600) to allow inlet-to-outlet air flow through the electronics rack.

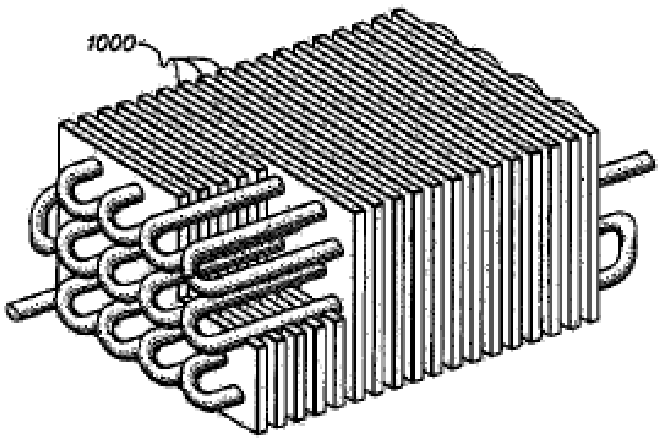


Patent No. US 7830657

APPARATUS FOR FACILITATING COOLING OF AN ELECTRONICS RACK EMPLOYING A HEAT EXCHANGE ASSEMBLY MOUNTED TO AN OUTLET DOOR COVER OF THE ELECTRONICS RACK

Vette Corp.2010



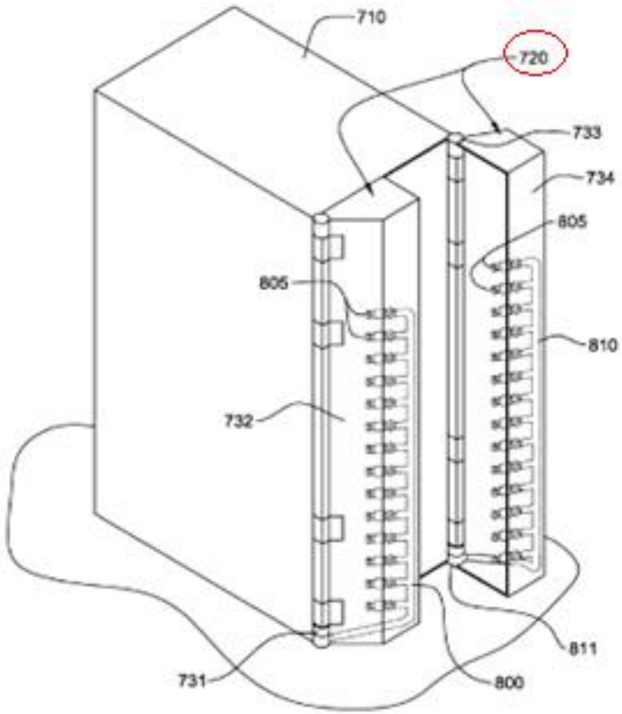


Patent No. US 74503850

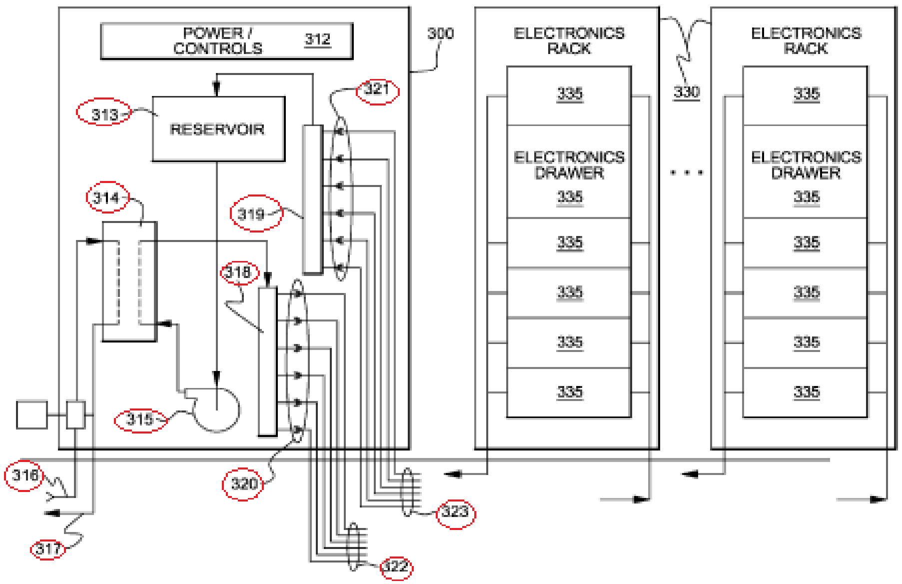
LIQUID-BASED COOLINGAPPARATUS FOR AN ELECTRONICS RACK

International Business Machines Corporation.2008

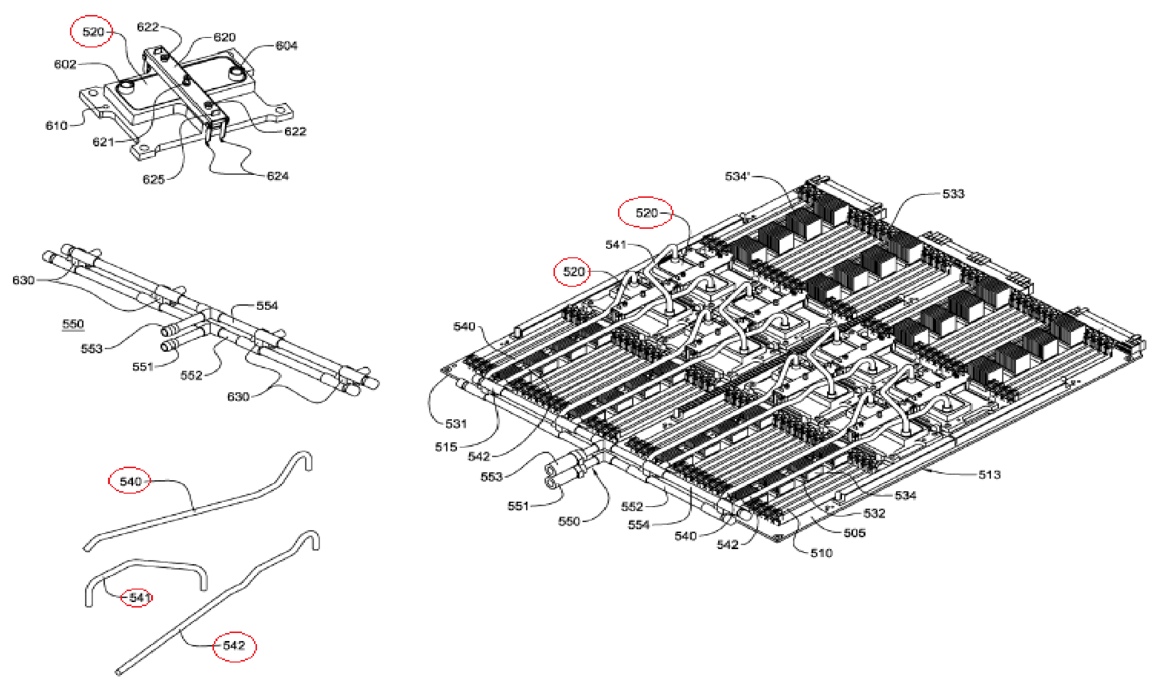
- The apparatus includes a bi-fold door(720) assembly configured for mounting to the electronics rack.



- **Within coolant distribution unit (300) is a power/control element (312) , a reservoir tank (313) , a heat exchanger (314) , a pump (315) ,inlet (316) and outlet (317) supply pipes, a supply manifold (318) directing water to the electronics frames (330) via couplings(320) and lines (322) , and a return manifold (319) directing water from the electronics frames (330) , via lines (323) and couplings (321).**

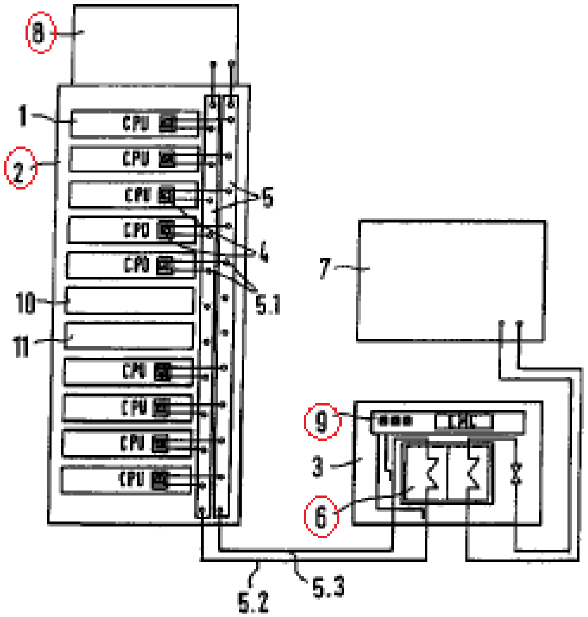


- **The cooling subsystem further includes associated coolant-carrying tubes(540,541,542) for facilitating passage of liquid coolant through the liquid-cooled cold plates and a header subassembly to facilitate distribution of liquid coolant to and return of liquid coolant from the liquid-cooled cold plates(520).**



Patent No. US 7559209
LIQUID COOLING SYSTEM
International Business Machines Corporation.2009

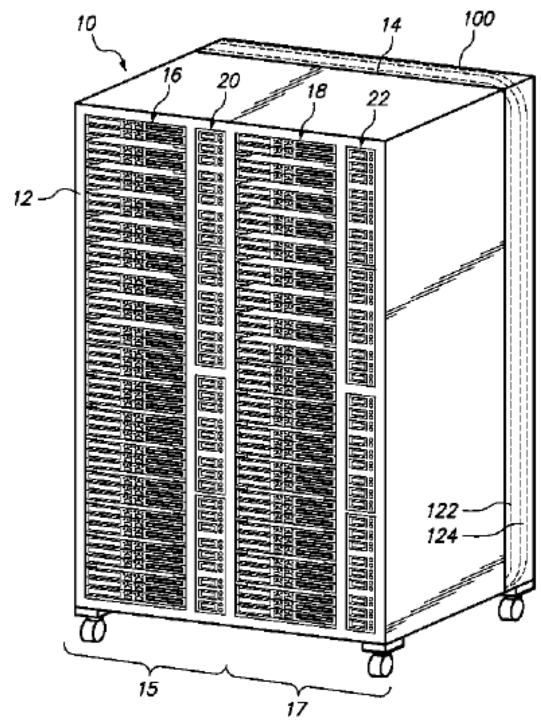
- A liquid cooling system having cooling units individually assigned to electronic component groups housed in a rack or a switchgear cabinet(2), which are to be cooled, and having a monitoring and control arrangement for monitoring a cooling temperature(9).
- water/water heat exchanger (6)
- air/water heat exchanger(8)

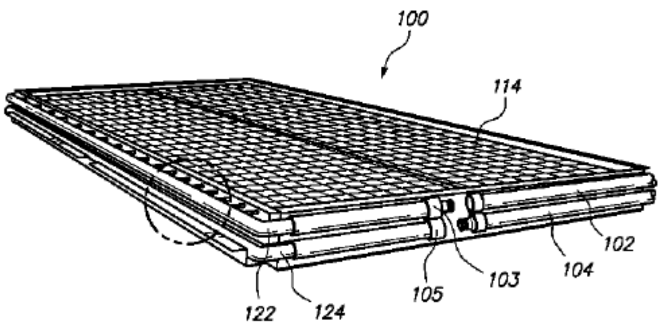


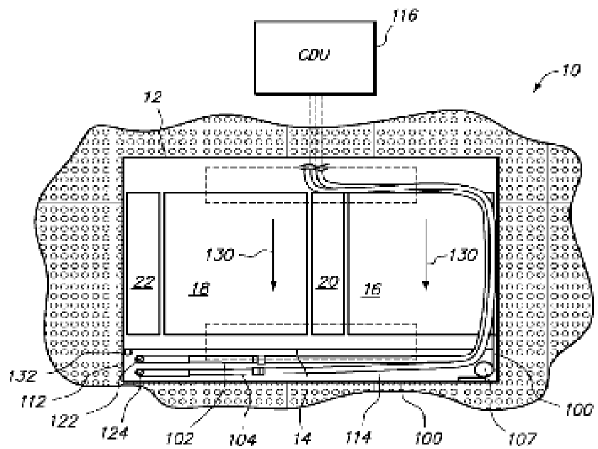
Patent No. US 7660116
RACK WITH INTEGRATED REAR-DOOR HEAT EXCHANGER

International Business Machines Corporation.2010

- The rack assembly comprises a rack providing support for one or more columns of heat-generating electronic devices and device fans for moving air from an air inlet side of the rack through the devices and through an air outlet side of the rack.



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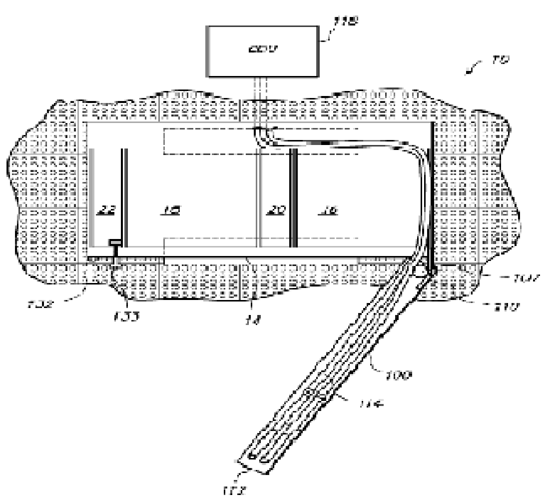
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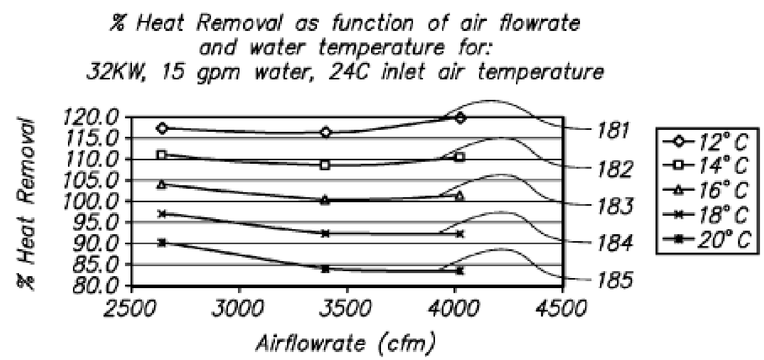
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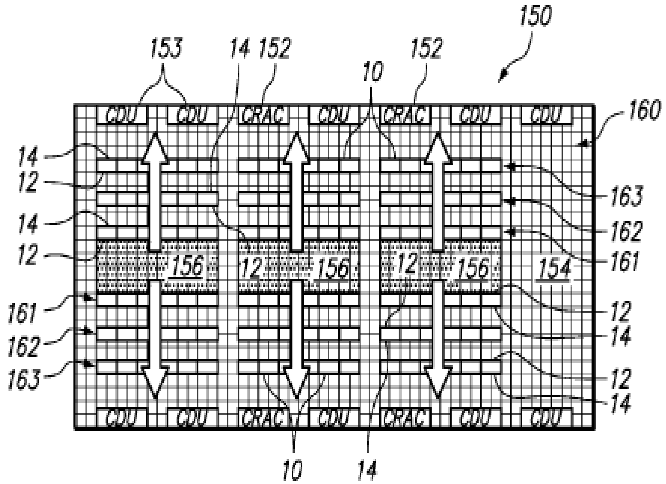
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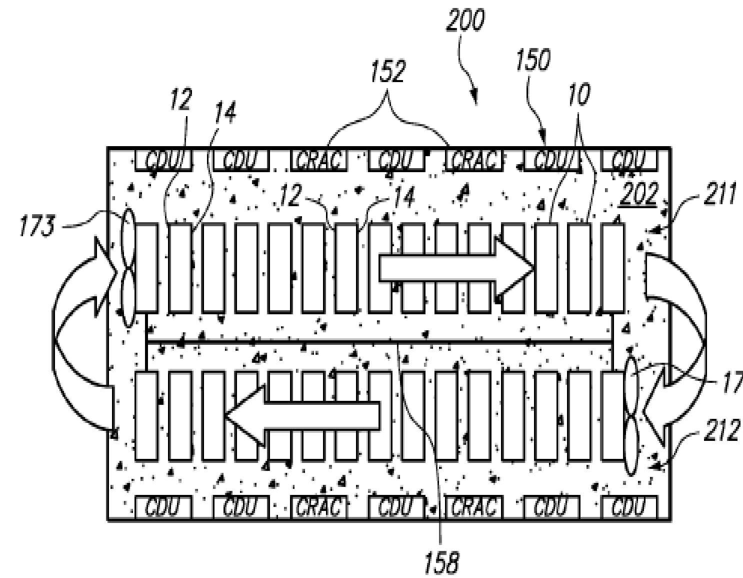
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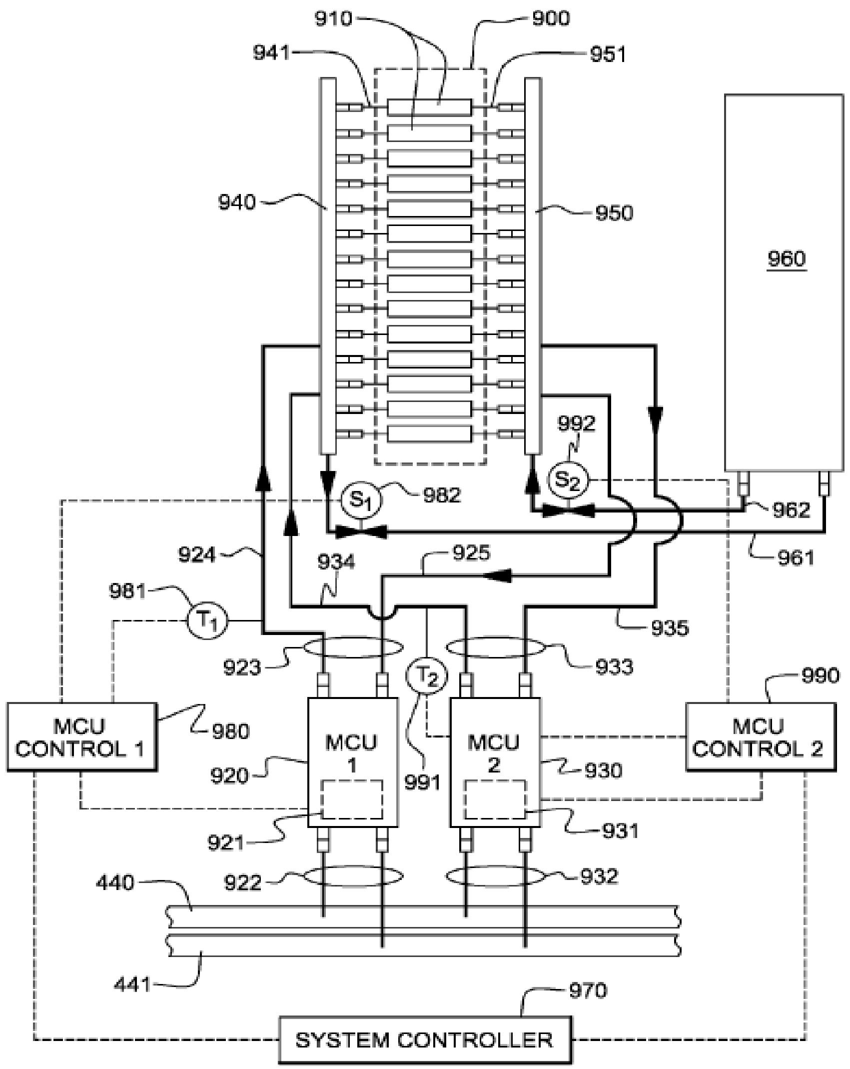
Patent No. US 7757506

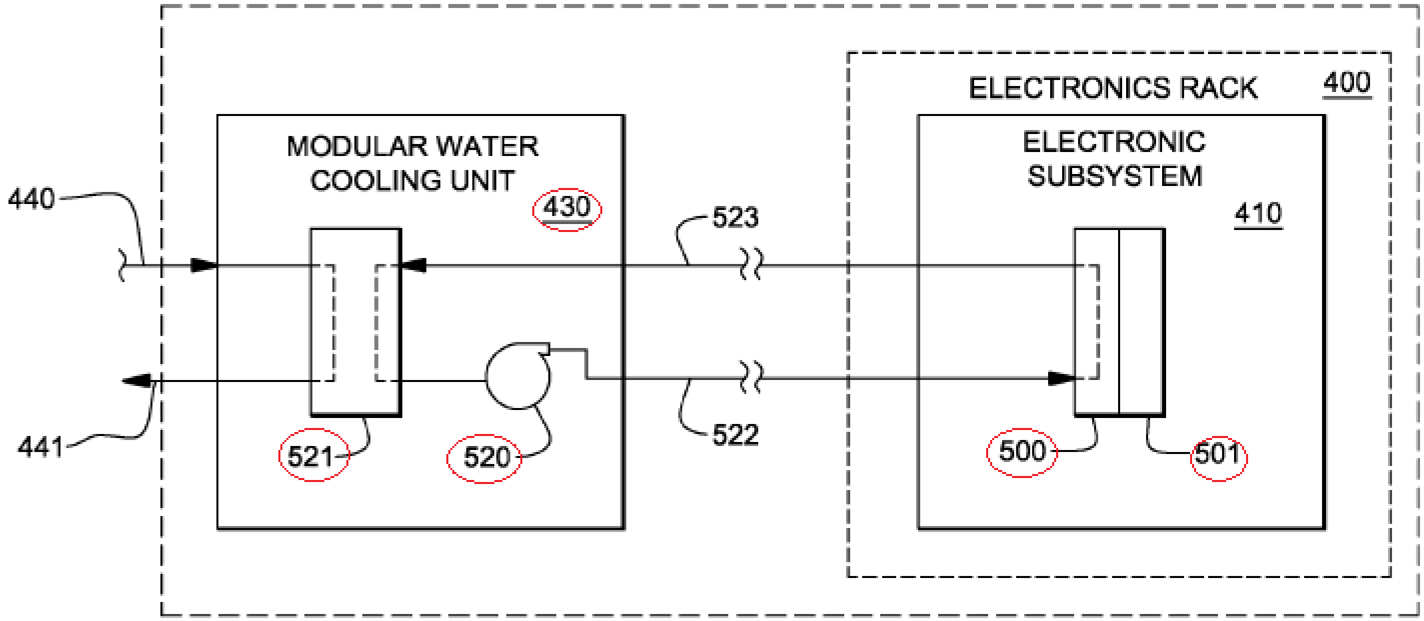
SYSTEM AND METHOD FOR FACILITATING COOLING OF A LIQUID-COOLED ELECTRONICS RACK

International Business Machines Corporation.2010

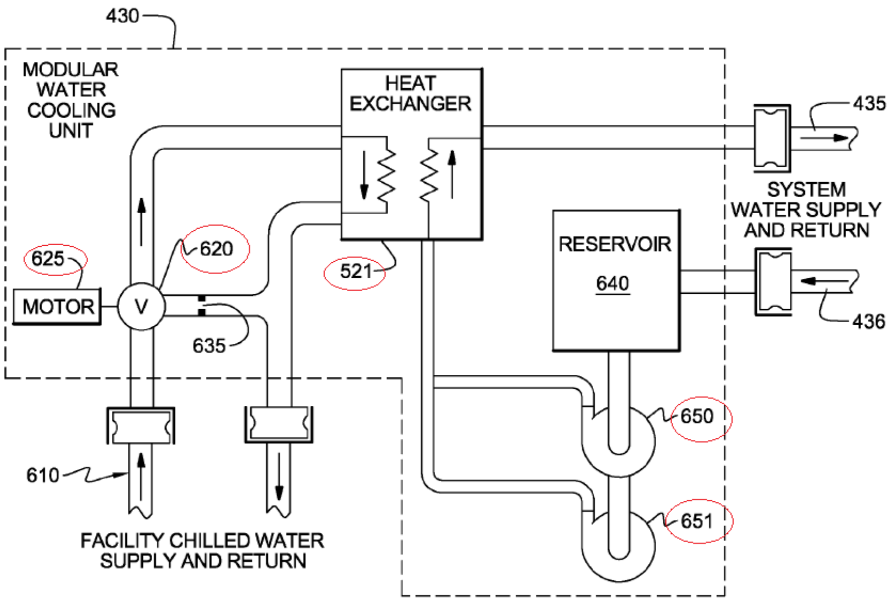


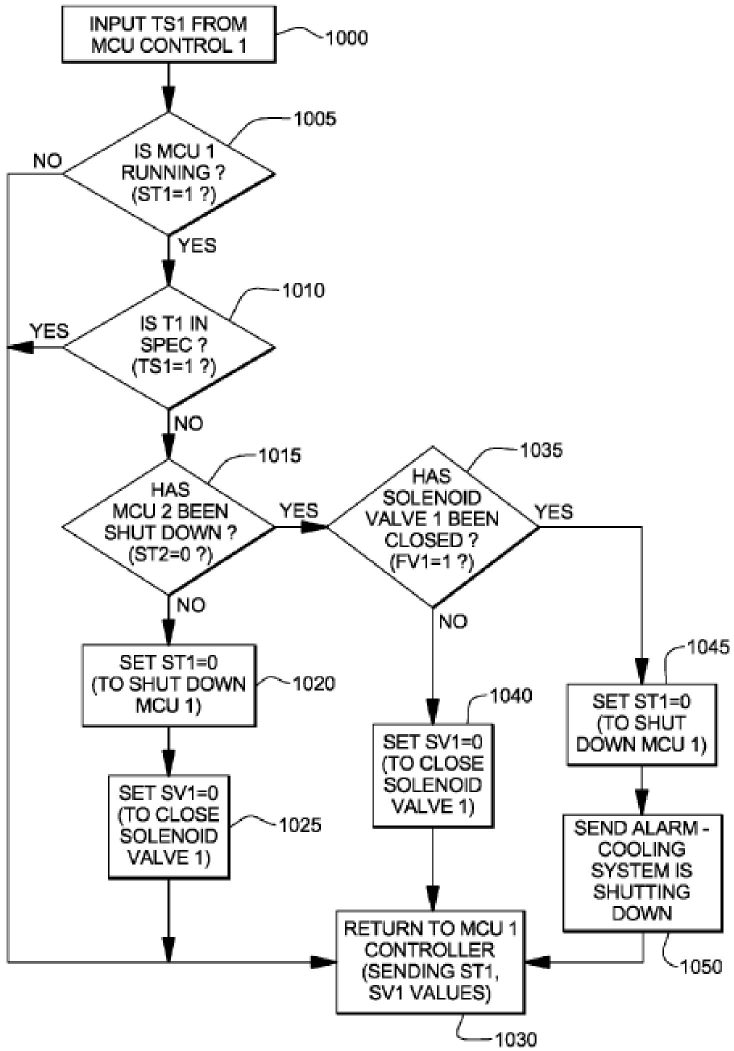
- Systems and methods are provided for cooling an electronics rack, which includes a heat-generating electronics subsystem across which air flows from an air inlet to an air outlet side of the rack.
- First and second modular cooling units (MCUs) are associated with the rack and configured to provide system coolant to the electronics subsystem for cooling thereof.

- Heat is removed from electronics module (501) via the system coolant circulated via pump (520) through cold plate (500) within the system coolant loop defined by liquid-to-liquid heat exchanger (521) of modular water cooling unit (430) and cold plate (500) .

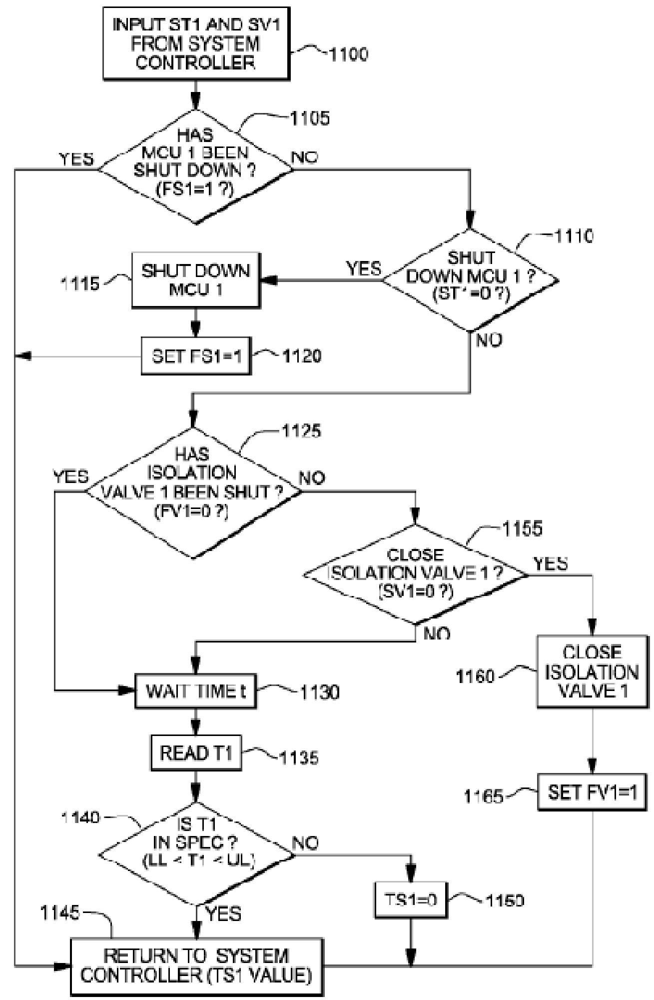


- Control valve (620)
- Motor (625)
- Heat exchanger (521)
- Pump (650,651)





INPUT TS1 FROM MCU CONTROL 1
1000
IS MCU 1 RUNNING ? (ST1=1 ?)
1005
NO
YES
IS T1 IN SPEC ? (TS1=1 ?)
1010
YES
NO
HAS MCU 2 BEEN SHUT DOWN ? (ST2=0 ?)
1015
YES
NO
HAS SOLENOID VALVE 1 BEEN CLOSED ? (FV1=1 ?)
1035
YES
NO
SET ST1=0 (TO SHUT DOWN MCU 1)
1020
SET SV1=0 (TO CLOSE SOLENOID VALVE 1)
1025
SET SV1=0 (TO CLOSE SOLENOID VALVE 1)
1040
SET ST1=0 (TO SHUT DOWN MCU 1)
1045
SEND ALARM - COOLING SYSTEM IS SHUTTING DOWN
1050
RETURN TO MCU 1 CONTROLLER (SENDING ST1, SV1 VALUES)
1030



INPUT ST1 AND SV1 FROM SYSTEM CONTROLLER
1100
HAS MCU 1 BEEN SHUT DOWN ? (FS1=1 ?)
1105
YES
NO
SHUT DOWN MCU 1 ?
1110
YES
NO
SHUT DOWN MCU 1
1115
SET FS1=1
1120
HAS ISOLATION VALVE 1 BEEN SHUT ? (FV1=0 ?)
1125
YES
NO
CLOSE ISOLATION VALVE 1 ? (SV1=0 ?)
1155
YES
NO
CLOSE ISOLATION VALVE 1
1160
SET FV1=1
1165
WAIT TIME t
1130
READ T1
1135
IS T1 IN SPEC ?
1140
NO
YES
TS1=0
1150
1145
RETURN TO SYSTEM CONTROLLER (TS1 VALUE)

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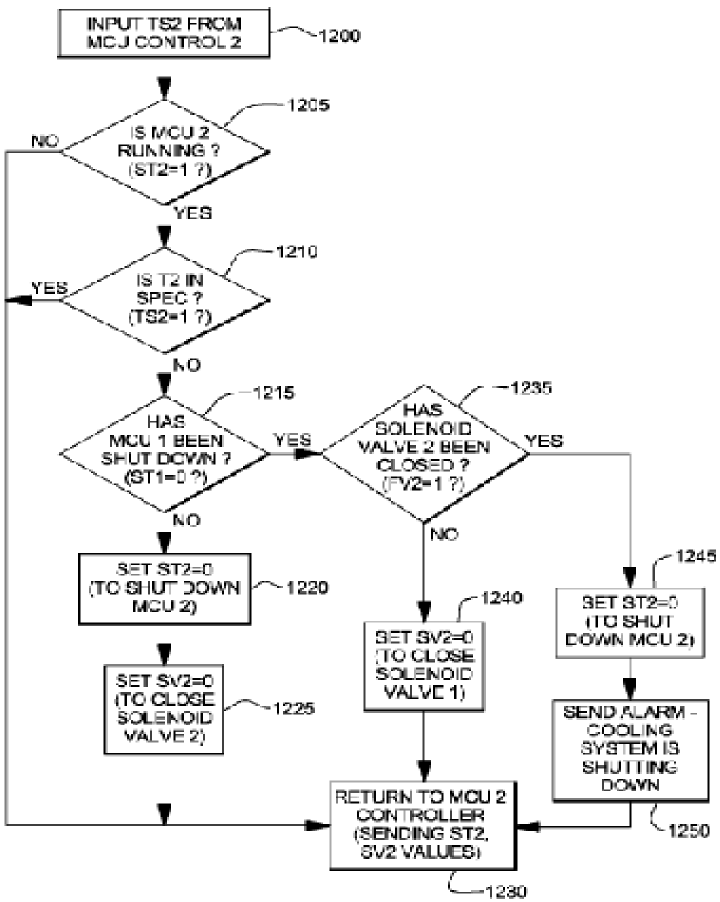
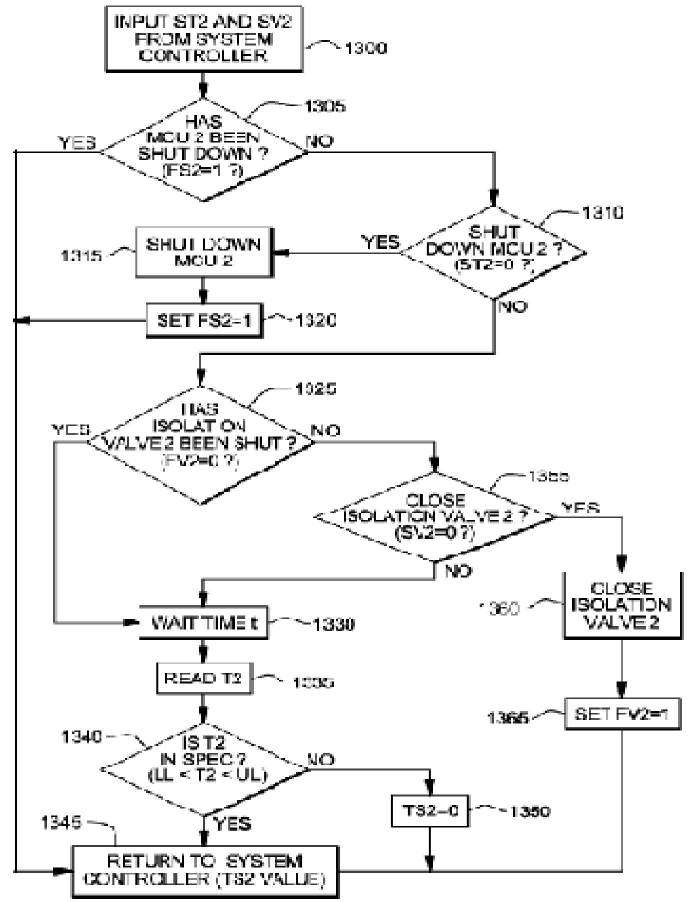
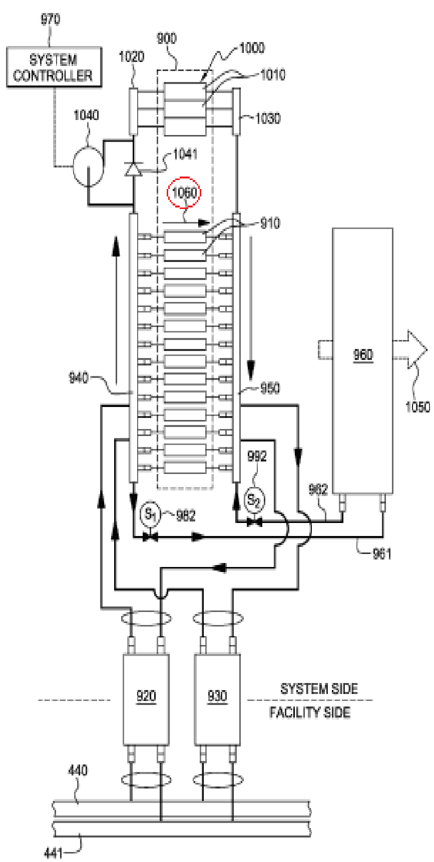
National Chiao Tung University

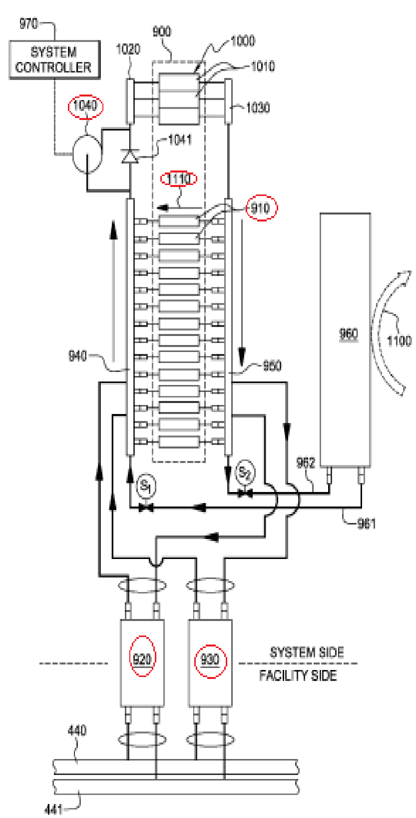




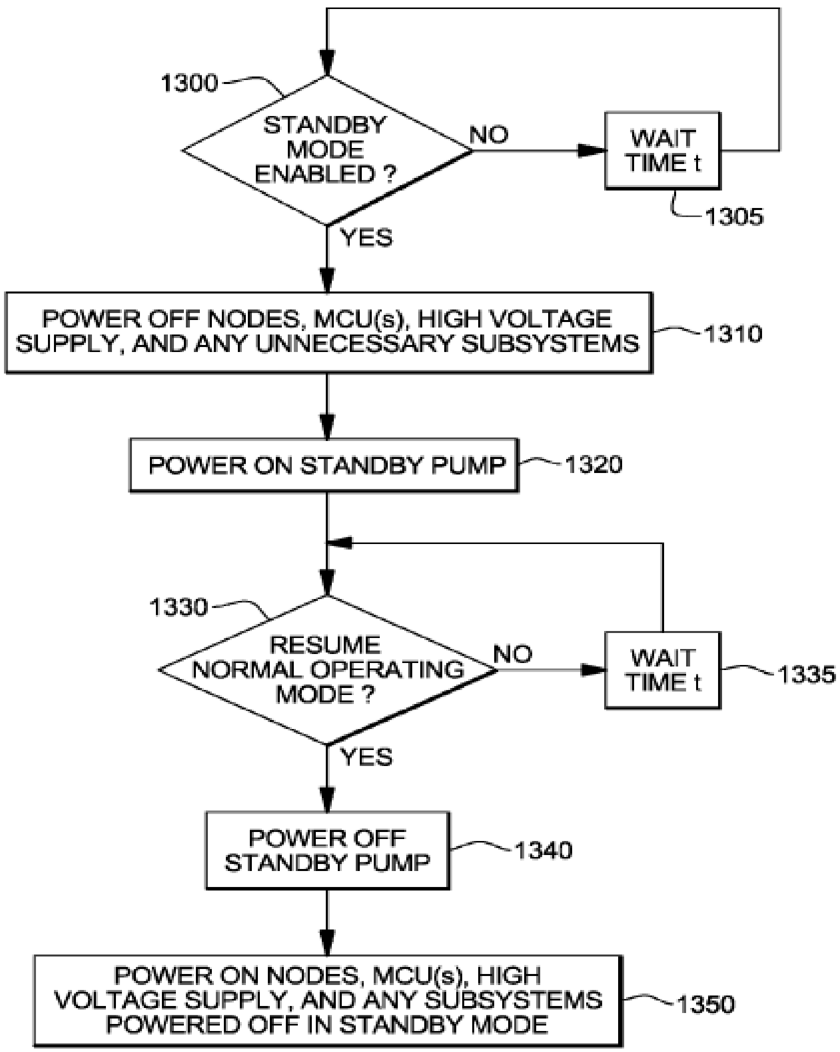
Patent No. US 7907406
SYSTEM AND METHOD FOR STANDBY MODE COOLING OF A LIQUID-COOLED ELECTRONICS RACK

International Business Machines Corporation.2011





- in standby mode, standby pump (1040) begins to impel the flow of system coolant through the system coolant loop, while minimizing the pumping power required.
- in the standby mode, the direction (1110) of system coolant flow through electronics subsystems (910) is reversed from direction (1060) of system coolant flow through the electronics subsystems in normal operating mode.
- in standby mode, it is contemplated that MCUs (920) , (930) will be off, and that electronics subsystems (910) will be powered down.

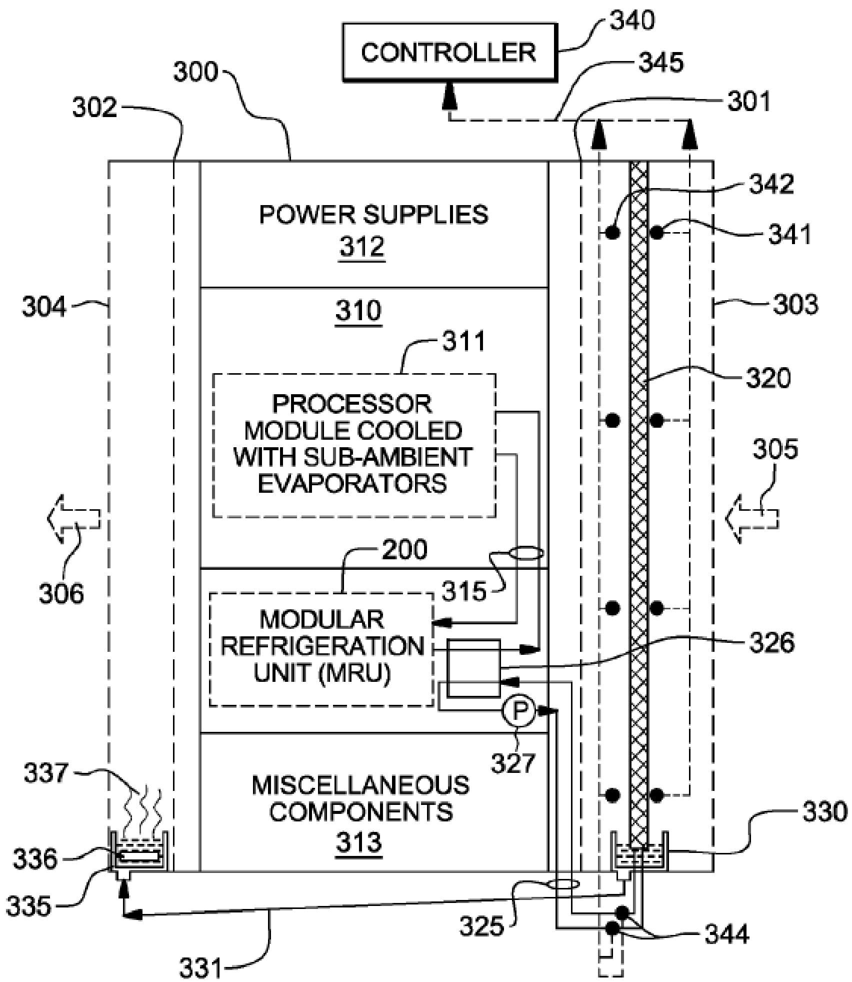


1300
STANDBY MODE ENABLED ?
NO
WAIT TIME t
1305
YES
POWER OFF NODES, MCU(s), HIGH VOLTAGE SUPPLY, AND ANY UNNECESSARY SUBSYSTEMS
1310
POWER ON STANDBY PUMP
1320
1330
RESUME NORMAL OPERATING MODE ?
NO
WAIT TIME t
1335
YES
POWER OFF STANDBY PUMP
1340
POWER ON NODES, MCU(s), HIGH VOLTAGE SUPPLY, AND ANY SUBSYSTEMS POWERED OFF IN STANDBY MODE
1350

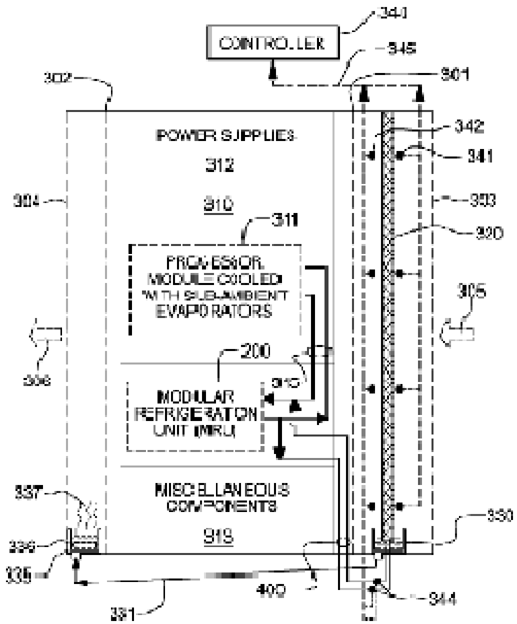
Patent No. US 7905096

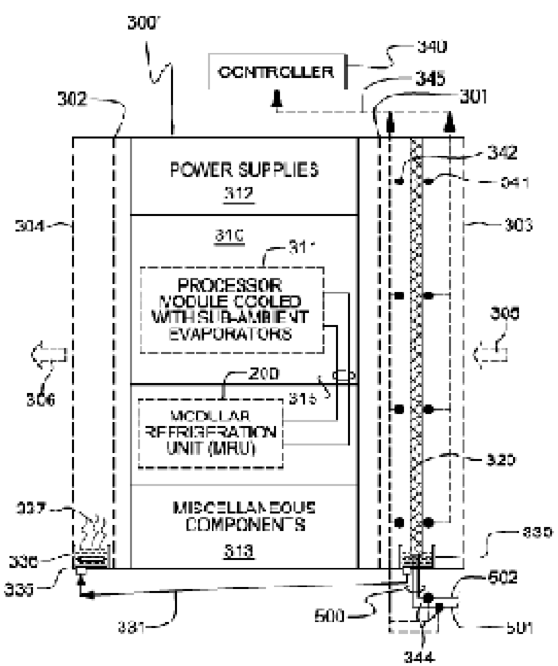
DEHUMIDIFYINGAND RE-HUMIDIFYING AIR COOLING FORAN ELECTRONICS RACK

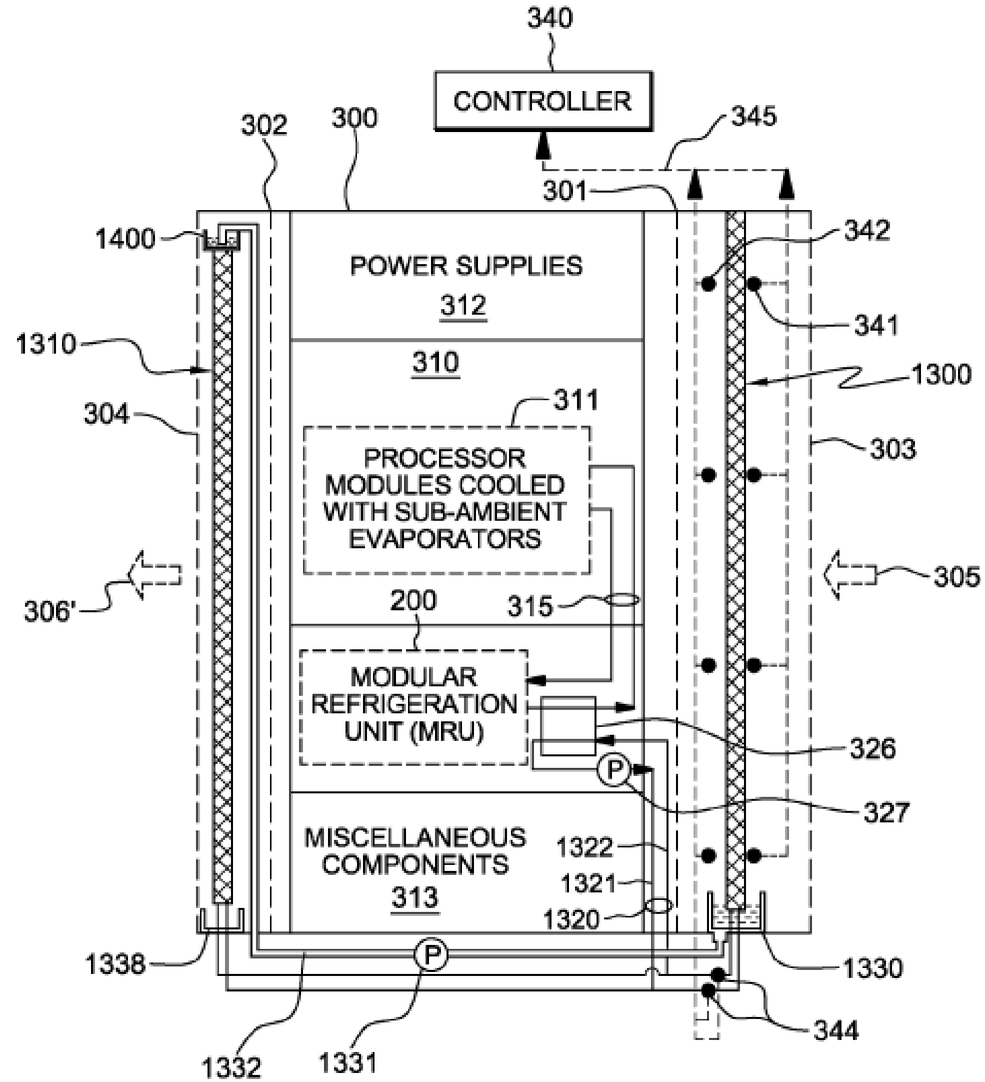
International Business Machines Corporation.2011

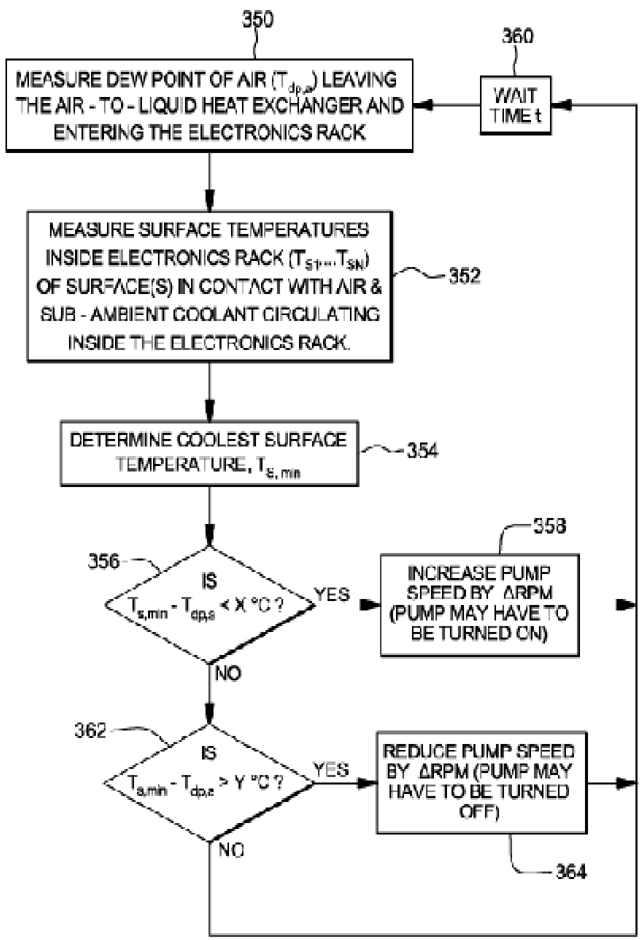


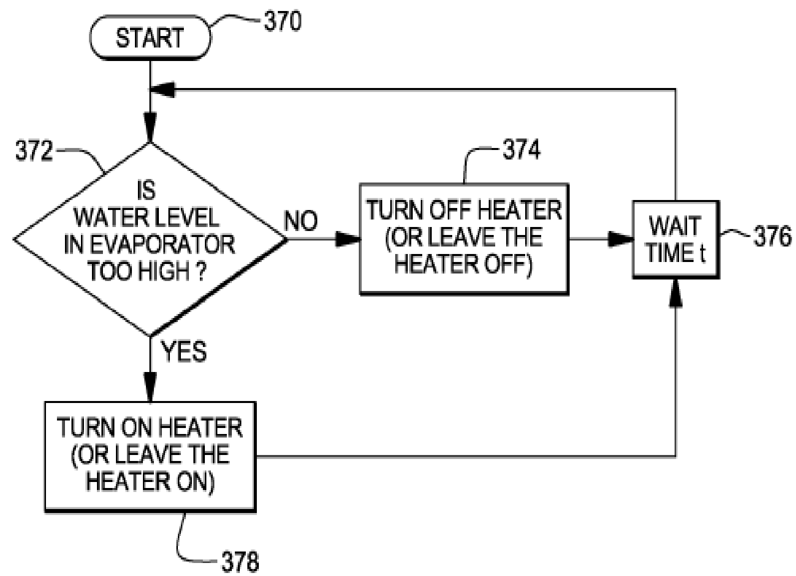
- Dehumidifying and re-humidifying cooling apparatus and method are provided for an electronics rack.
- The apparatus includes a dehumidifying air-to-liquid heat exchanger disposed at an air inlet side of the rack and a re-humidifying air-to-liquid heat exchanger disposed at an air outlet side of the rack.


CONTROLLER
340
345
301
302
POWER SUPPLIES
312
310
311
PROCESSOR MODULE COOLED WITH SUB-AMBIENT EVAPORATORS
200
MODULAR REFRIGERATION UNIT (MRU)
MISCELLANEOUS COMPONENTS
313
342
341
320
305
306
337
336
335
331
400
344
330


300'
CONTROLLER
340
345
301
302
POWER SUPPLIES
312
310
PROCESSOR MODULE COOLED WITH SUB-AMBIENT EVAPORATORS
200
MODULAR REFRIGERATION UNIT (MRU)
MISCELLANEOUS COMPONENTS
313
342
304
303
305
306
320
337
336
335
331
500
502
501
344
330


340
CONTROLLER
302
300
345
301
1400
342
POWER SUPPLIES
312
341
1310
310
1300
311
304
PROCESSOR MODULES COOLED WITH SUB-AMBIENT EVAPORATORS
303
306'
305
200
315
MODULAR REFRIGERATION UNIT (MRU)
326
P
327
MISCELLANEOUS COMPONENTS
313
1322
1321
1320
1338
P
1330
344
1332
1331

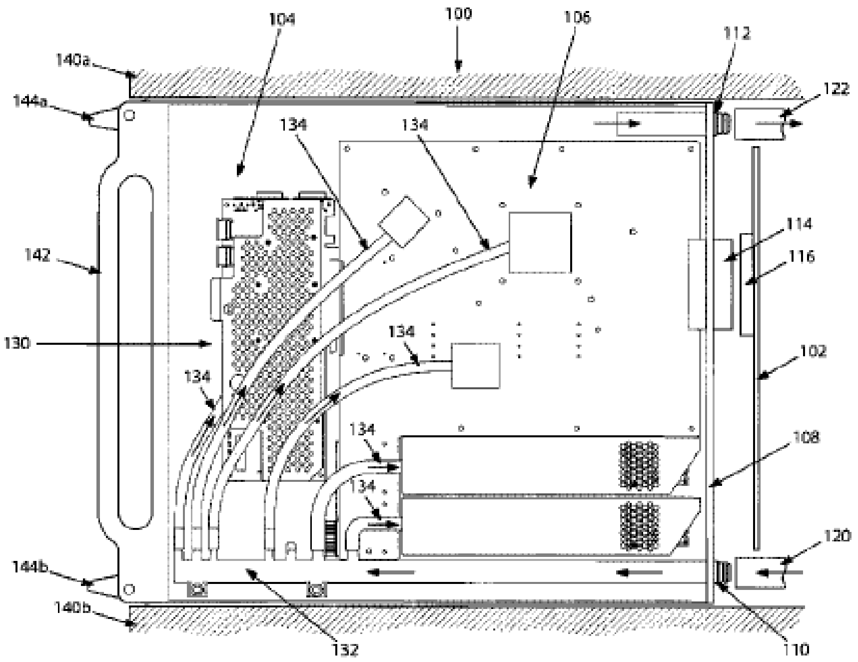

350
MEASURE DEW POINT OF AIR ($T_{dp,a}$) LEAVING THE AIR - TO - LIQUID HEAT EXCHANGER AND ENTERING THE ELECTRONICS RACK
360
WAIT TIME t
MEASURE SURFACE TEMPERATURES INSIDE ELECTRONICS RACK (T_{S1},..,T_{SN}) OF SURFACE(S) IN CONTACT WITH AIR & SUB - AMBIENT COOLANT CIRCULATING INSIDE THE ELECTRONICS RACK.
352
DETERMINE COOLEST SURFACE TEMPERATURE, $T_{S,min}$
354
356
IS $T_{s,min}$ - $T_{dp,a}$ < X °C ?
YES
NO
358
INCREASE PUMP SPEED BY ΔRPM (PUMP MAY HAVE TO BE TURNED ON)
362
IS $T_{s,min}$ - $T_{dp,a}$ > Y °C ?
YES
NO
REDUCE PUMP SPEED BY ΔRPM (PUMP MAY HAVE TO BE TURNED OFF)
364


START
370
372
IS WATER LEVEL IN EVAPORATOR TOO HIGH ?
NO
YES
374
TURN OFF HEATER (OR LEAVE THE HEATER OFF)
WAIT TIME t
376
TURN ON HEATER (OR LEAVE THE HEATER ON)
378

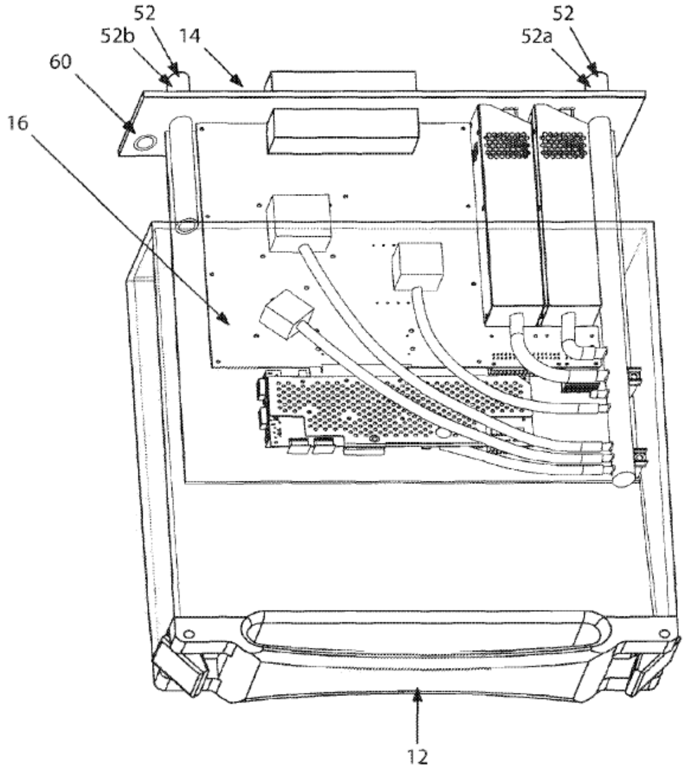
Patent No. US 7905106

CASE AND RACK SYSTEM FOR LIQUID SUBMERSION COOLING OF ELECTRONIC DEVICES CONNECTED IN AN ARRAY

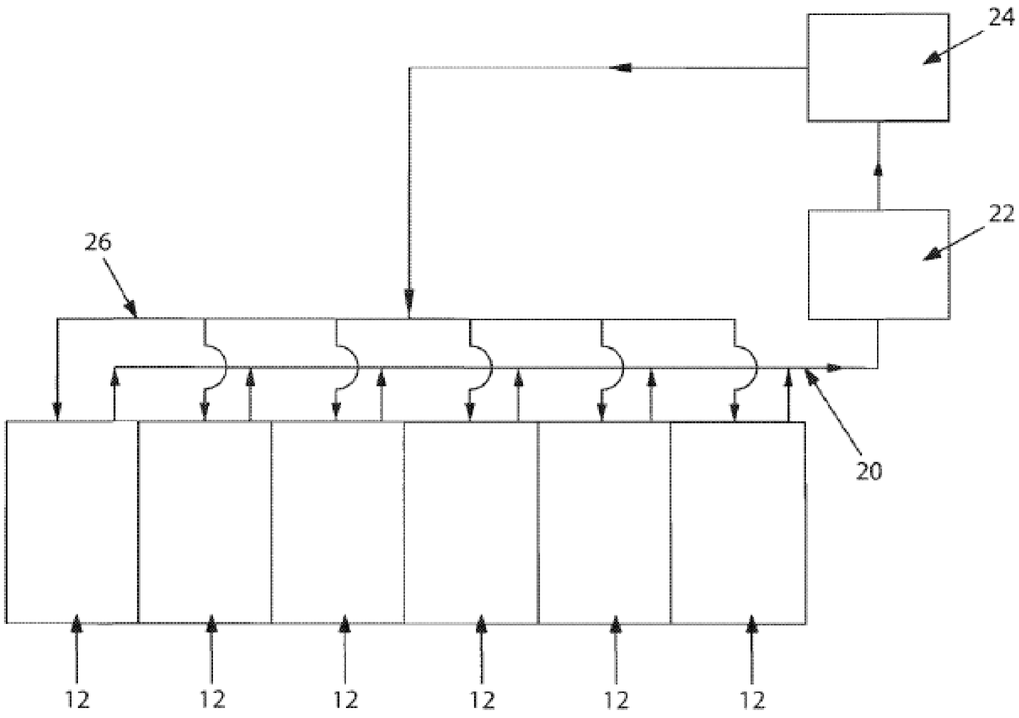
Hardcore Computer,Inc.**2011**



- A liquid submersion cooling system that is suitable for cooling a number of electronic devices in parallel using a plurality of cases connected to a rack system.
- The system cools heat-generating components in server computers and other devices that use electronic, heat-generating components and are connected in parallel systems.



52
52b
14
60
16
52
52a
12



24
22
26
20
12
12
12
12
12
12

Fig. 19A

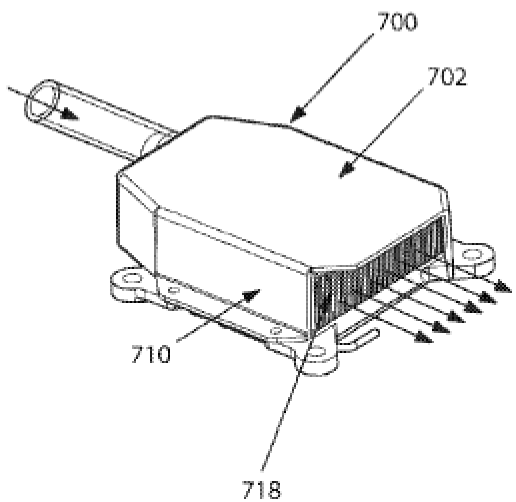


Fig. 19B

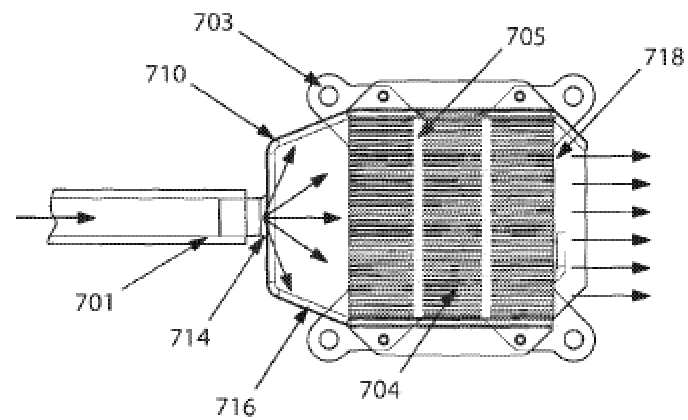
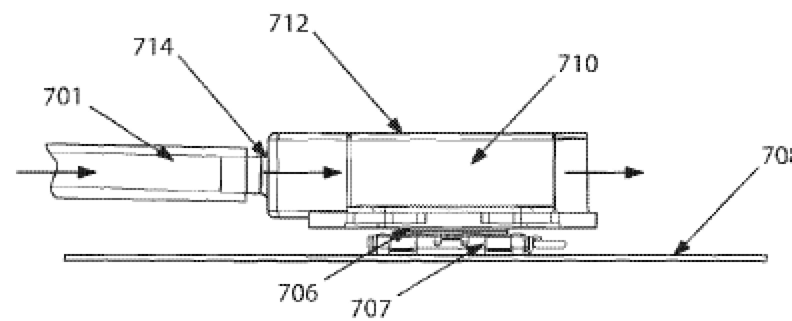


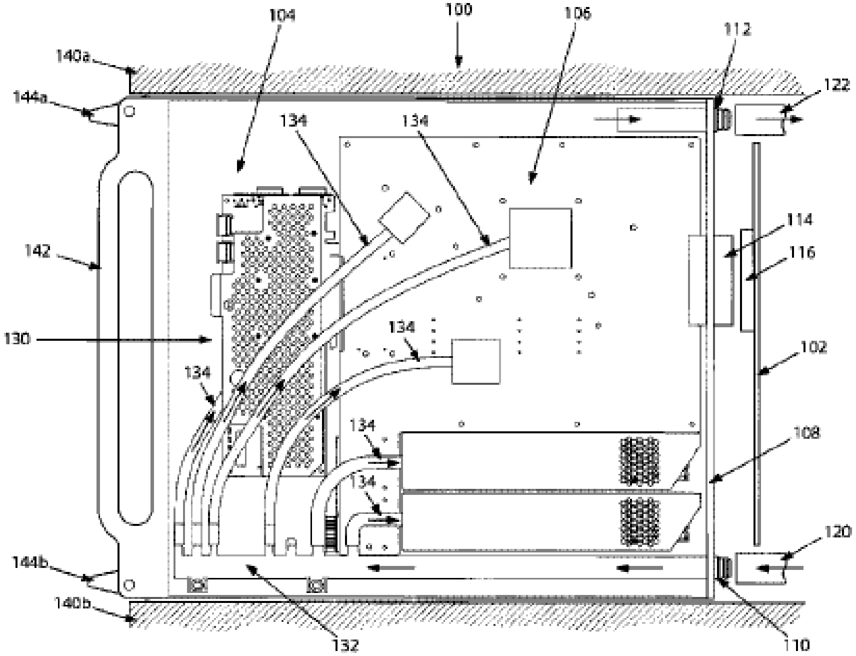
Fig. 19C



Patent No. US 7911793

CASE AND RACK SYSTEM FOR LIQUID SUBMERSION COOLING OF ELECTRONIC DEVICES CONNECTED IN AN ARRAY

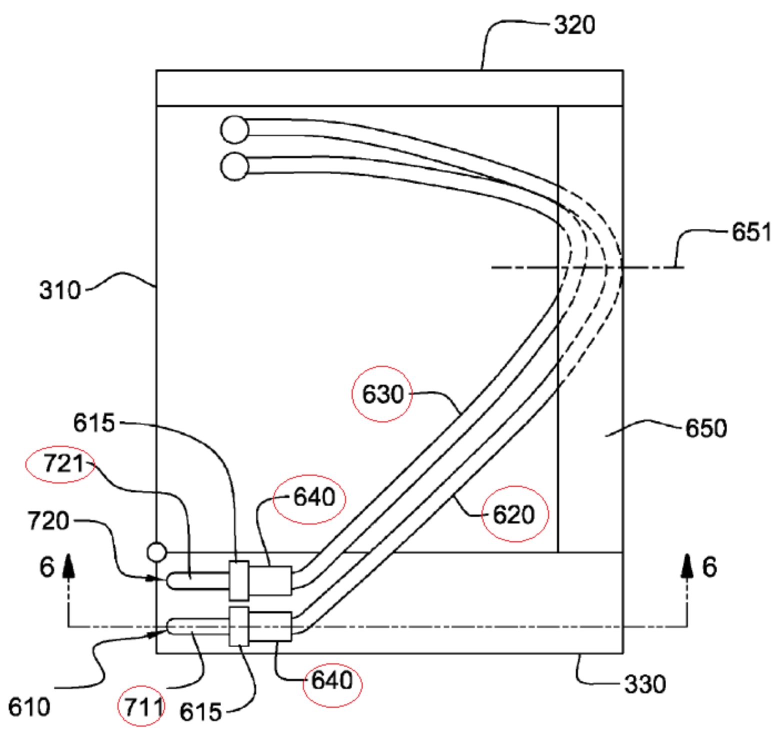
Hardcore Computer,Inc.2011



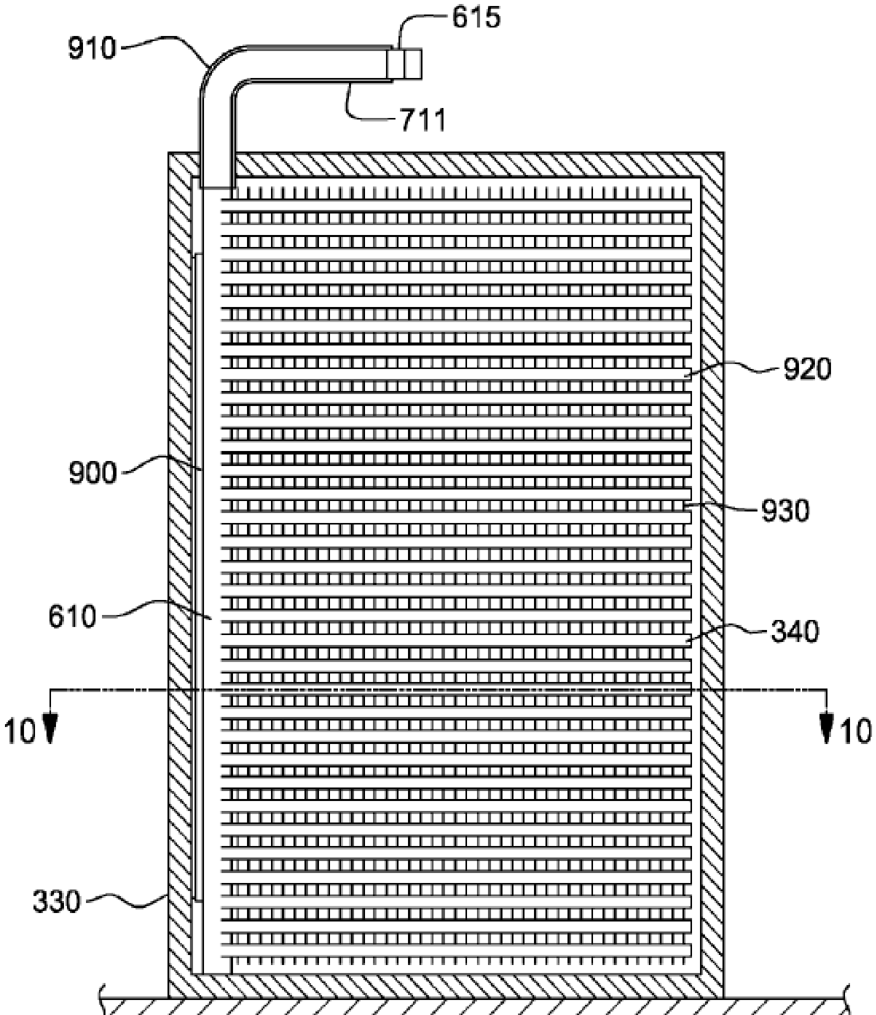
Patent No. US 7950244

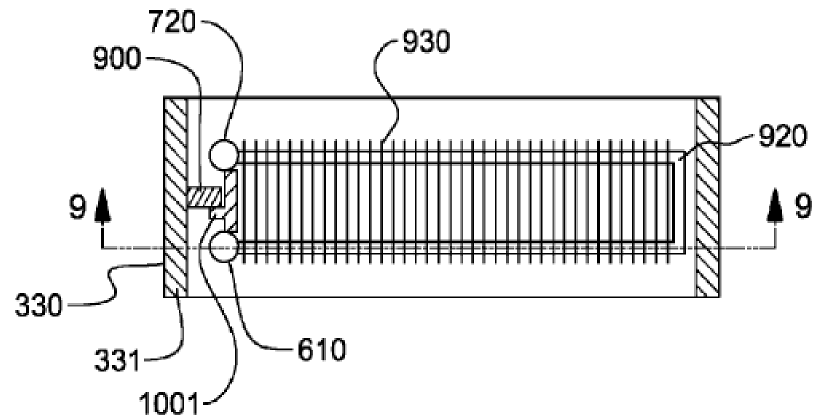
APPARATUS FOR FACILITATING COOLING OF AN ELECTRONICS RACK THROUGH THE USE OF AN AIR-TO-LIQUID HEAT EXCHANGER

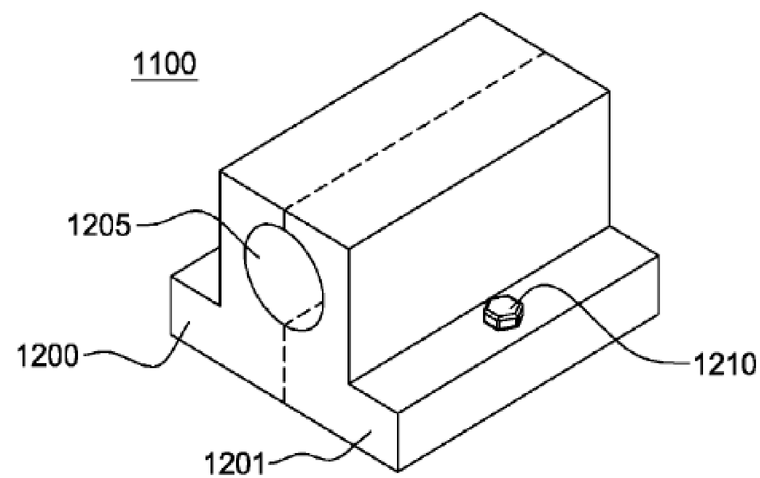
International Business Machines Corporation.2011

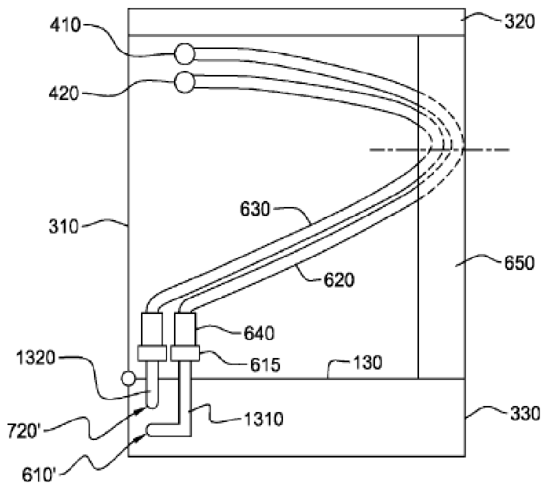


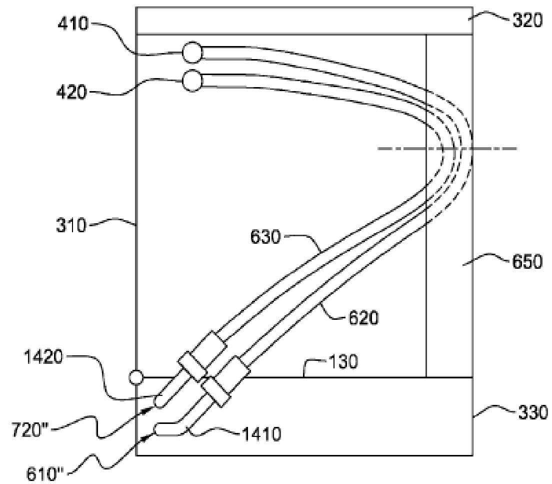
- System coolant supply (620) and return (630) hoses are disposed above the electronics rack and respectively couple in fluid communication the inlet plenum to a system coolant supply header (711) and the outlet plenum to a system coolant return header (721).
- The hoses are each flexible, partially looped and of sufficient length to allow for opening and closing of the door.
- Stress-relief structures (640) are coupled to at least one end of the hoses to relieve stress on the ends of the hoses during opening or closing of the door.

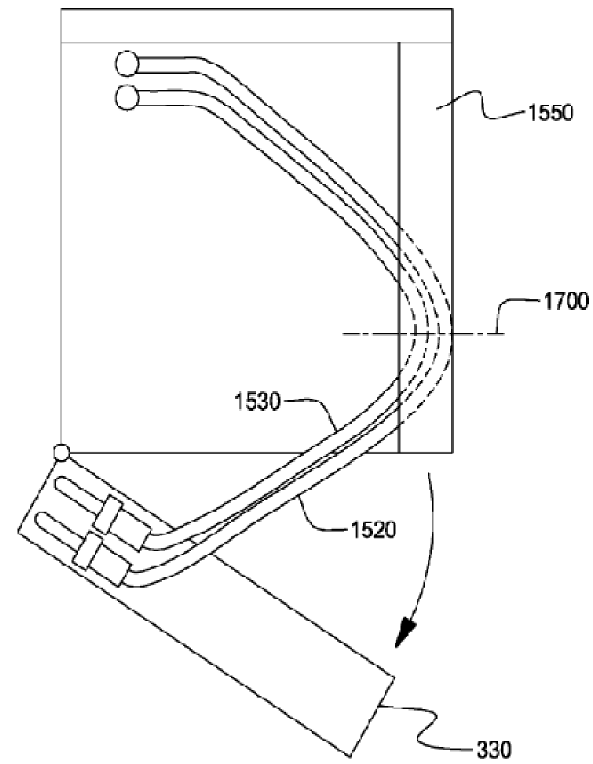

615
910
711
920
900
930
610
340
10
10
330


720
930
900
920
9
9
330
331
610
1001


1100
1205
1200
1210
1201


410
420
320
310
630
620
650
640
615
130
1320
720'
1310
330
610'


410
420
320
310
630
650
620
1420
130
720"
330
1410
610"


1550
1700
1530
1520
330

Patent No. US 7963118

VAPOR-COMPRESSION HEAT EXCHANGE SYSTEM WITH EVAPORATOR COIL MOUNTED TO OUTLET DOOR OF AN ELECTRONICS RACK

International Business Machines Corporation.2011

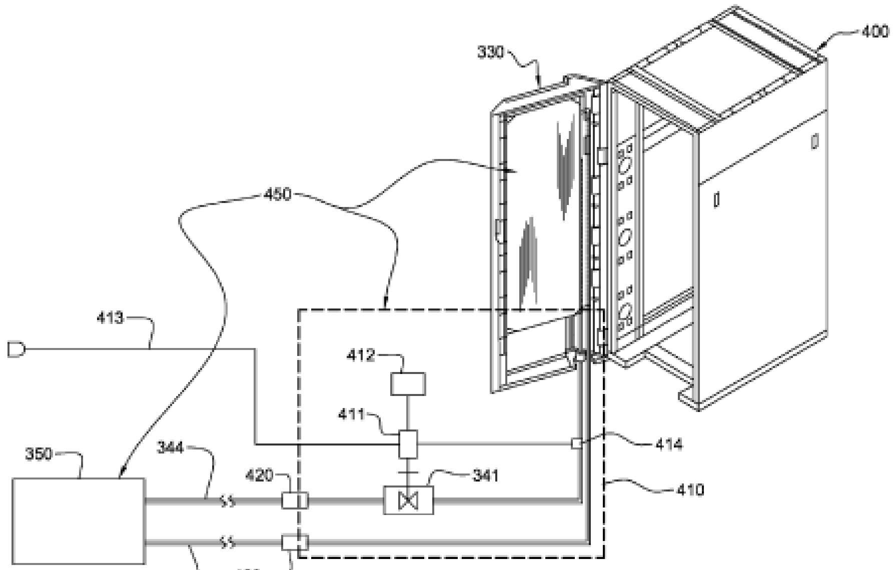
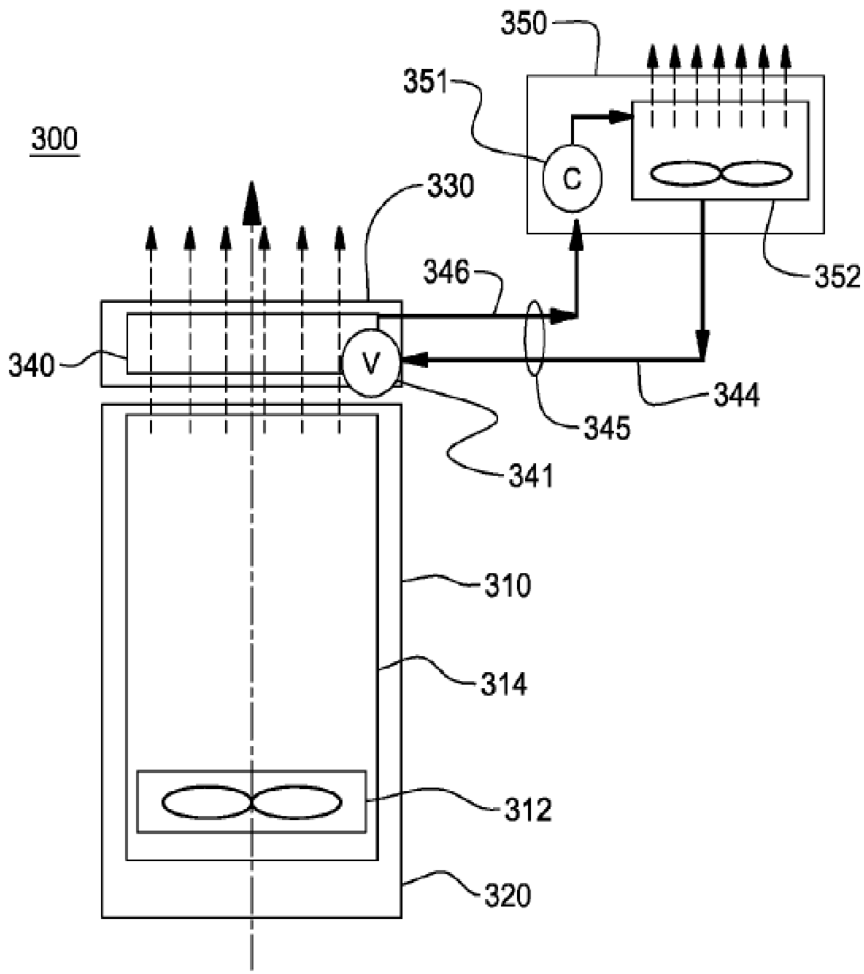
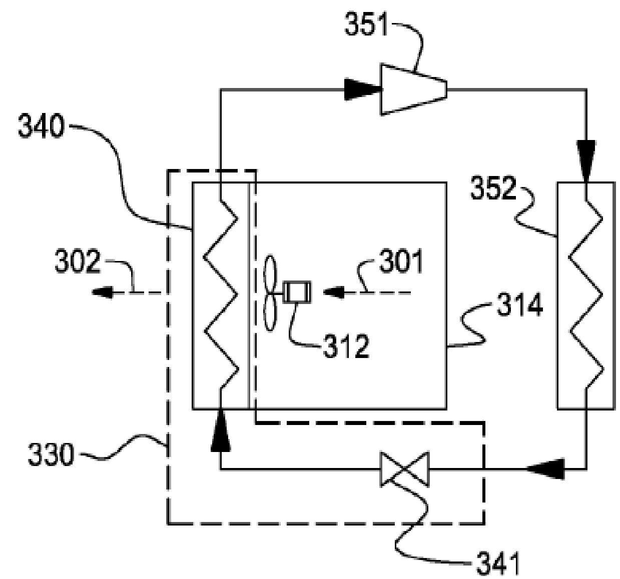


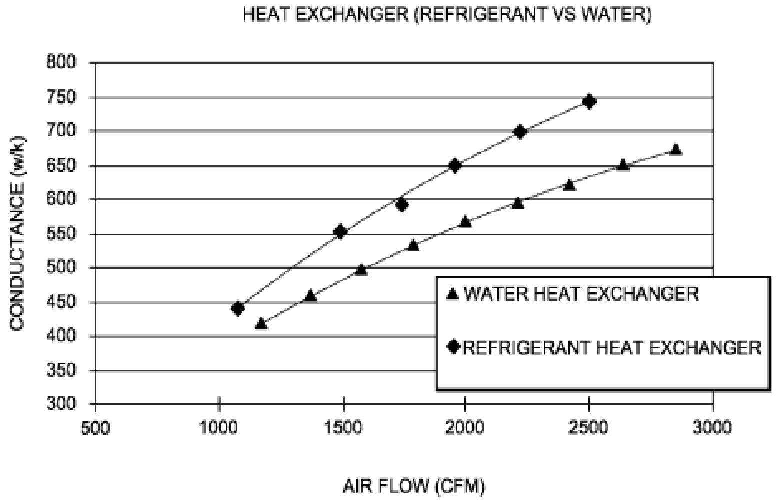
FIG. 4

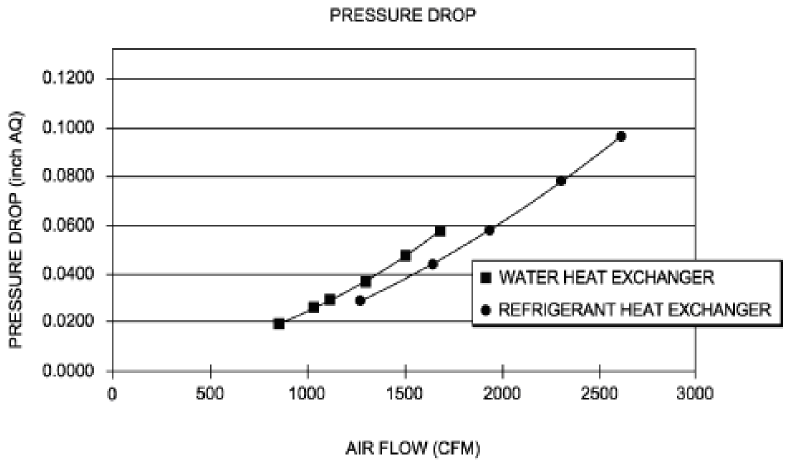
- A vapor-compression heat exchange system for facilitating cooling of an electronics rack.
- The system includes employing an evaporator coil mounted to an outlet door cover, which is hingedly affixed to an air outlet side of the rack, as well as refrigerant inlet and outlet plenums and an expansion valve also mounted to the outlet door cover and in fluid communication with the evaporator coil.


300
350
351
C
330
346
352
340
V
344
345
341
310
314
312
320


351
340
352
302
301
314
312
330
341

- The use of a refrigerant provides approximately 10% better performance compared with a water based implementation at 1500 cfm air flow volume.
- As shown, this increased performance can be achieved while still reducing the air pressure drop of a refrigerant evaporator coil compared with a water-based heat exchanger at 1500 cfm airflow volume.



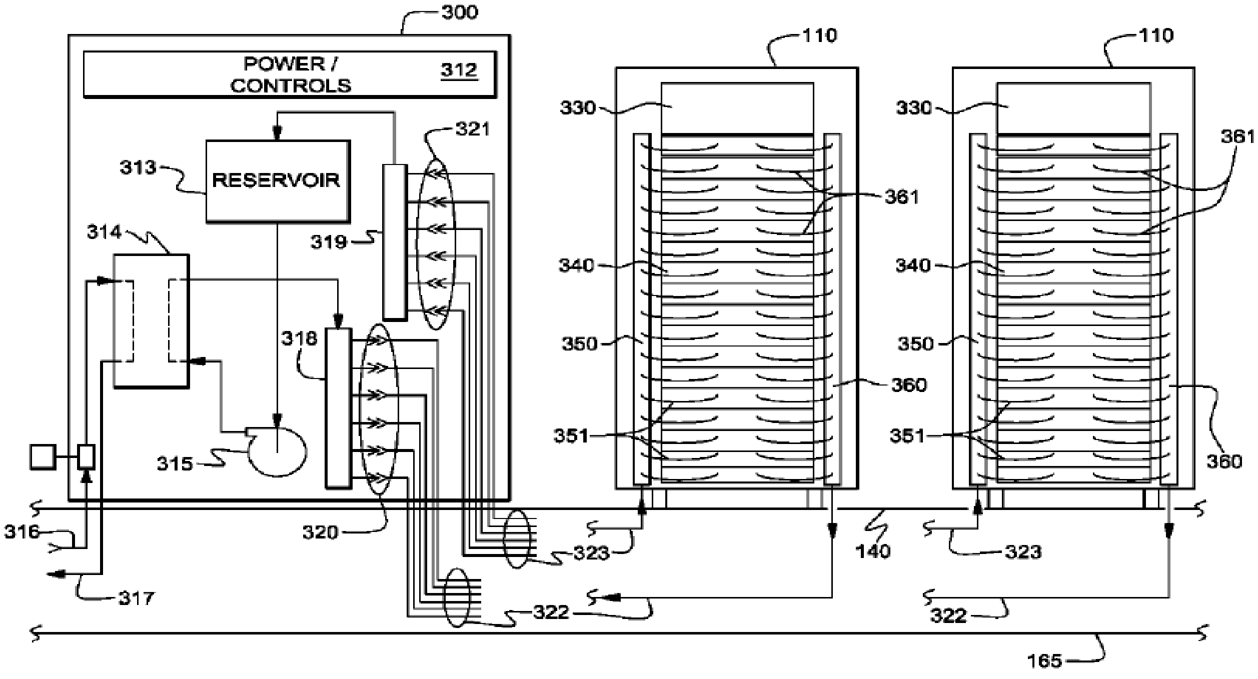


Patent No. US 7963119

HYBRID AIR AND LIQUID COOLANT CONDITIONING UNIT FOR FACILITATING COOLING OF ONE OR MORE ELECTRONICS RACKS OF A DATA CENTER

International Business Machines Corporation.2011

- A hybrid air and liquid coolant conditioning unit is provided for facilitating cooling of electronics rack(s) of a data center.



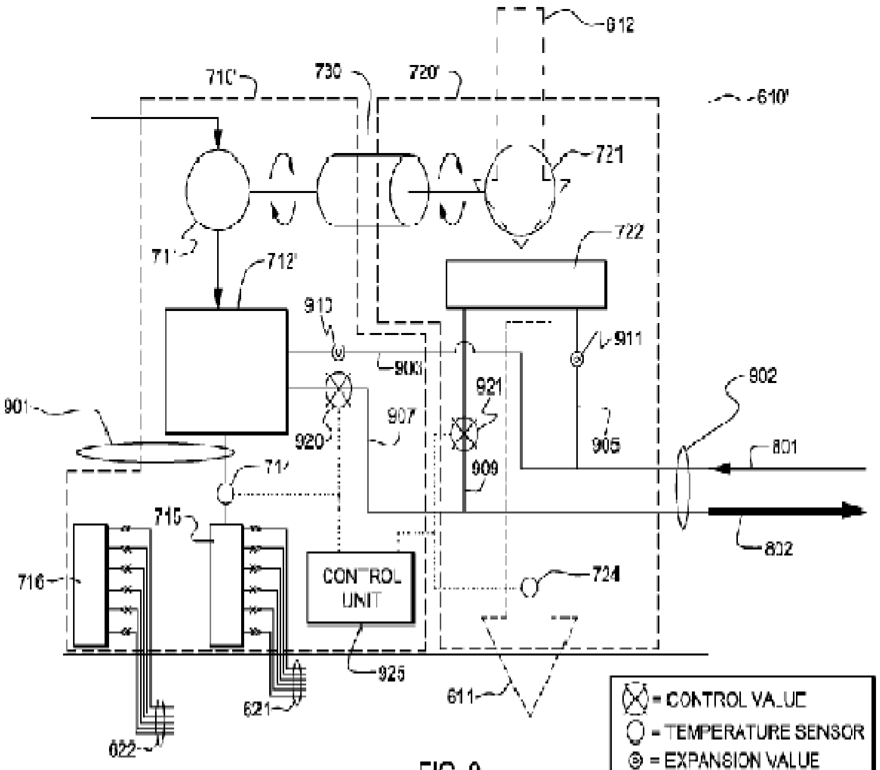

710'
730
720'
612
610'
721
71
712'
722
910
911
900
921
902
901
907
920
905
801
909
714
715
802
716
CONTROL UNIT
724
925
621
611
622
= CONTROL VALUE
= TEMPERATURE SENSOR
= EXPANSION VALUE

FIG. 9

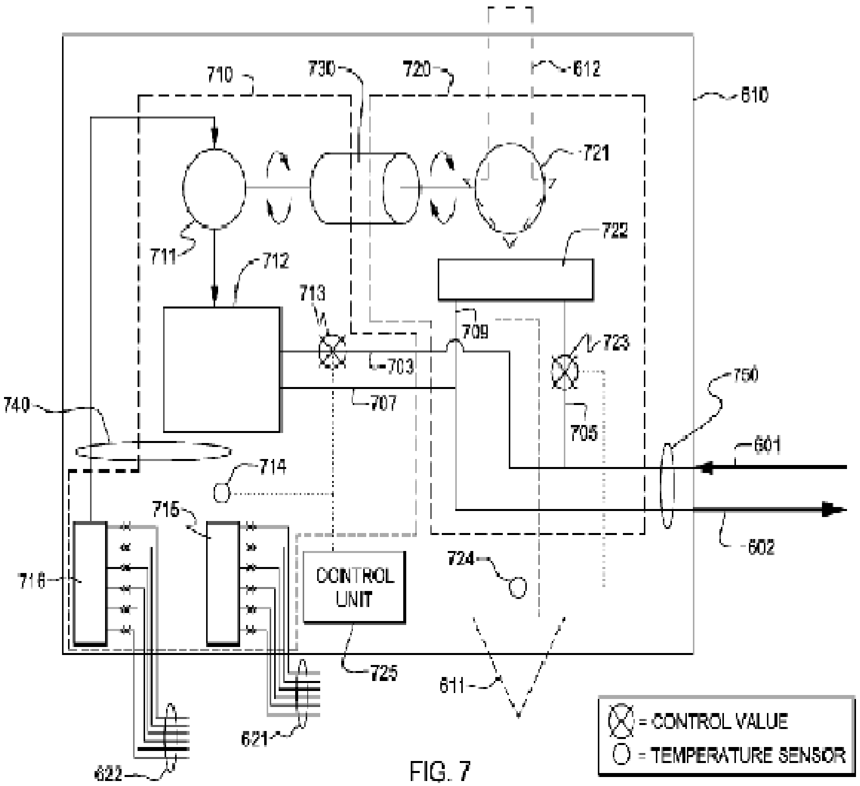

710
730
720
612
610
721
711
712
722
713
709
723
703
740
707
750
705
601
714
715
602
716
CONTROL UNIT
724
725
611
621
622
= CONTROL VALUE
= TEMPERATURE SENSOR

FIG. 7

Patent No. US 7978472

LIQUID-COOLED COOLING APPARATUS, ELECTRONICS RACK AND METHODS OF FABRICATION THEREOF

International Business Machines Corporation.2011

- Liquid-cooled electronics racks and methods of fabrication are provided wherein a liquid-based cooling apparatus facilitates cooling of electronic subsystems when docked within the electronics rack.

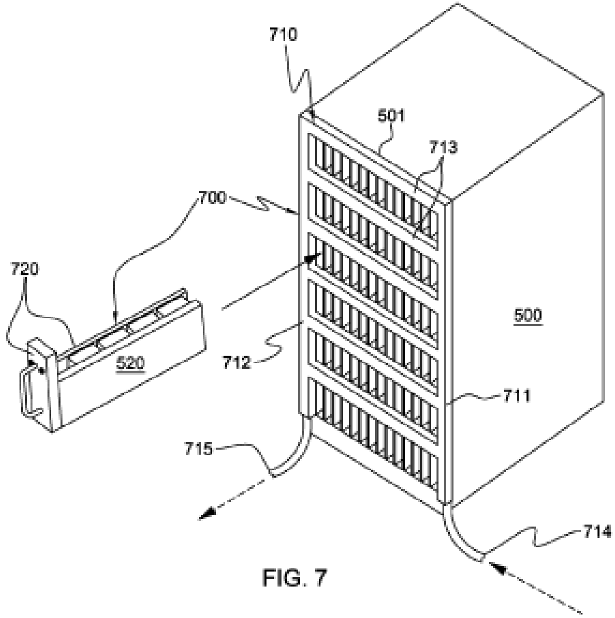


FIG. 7

- Heat flows via conduction from one or more heat-generating electronic components (522) to the heat transfer member, and then through path (1000) in the horizontally-extending heat transfer member (800) (e.g., a heat pipe), up path (1010) in the thermal interface plate (810) and across the physical interface 1020 to the wall of the horizontally-disposed, liquid-cooled cooling bar (713) , and hence to coolant flowing (1030) through the coolant-carrying channels extending therethrough.

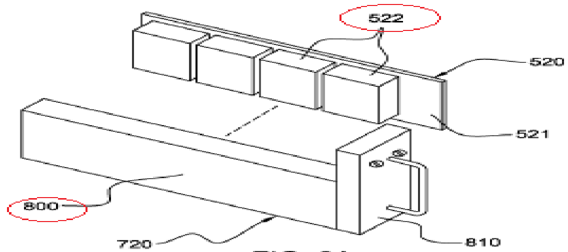


FIG. 8A

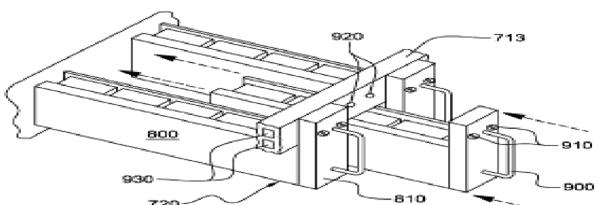


FIG. 9

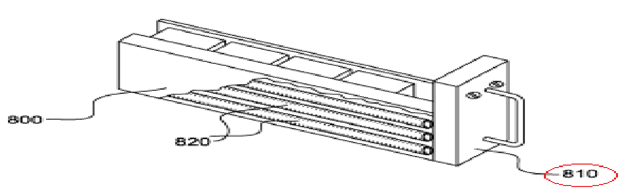


FIG. 8B

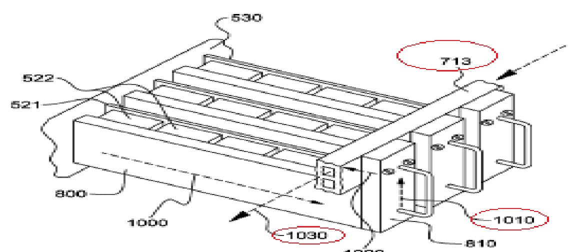


FIG. 10

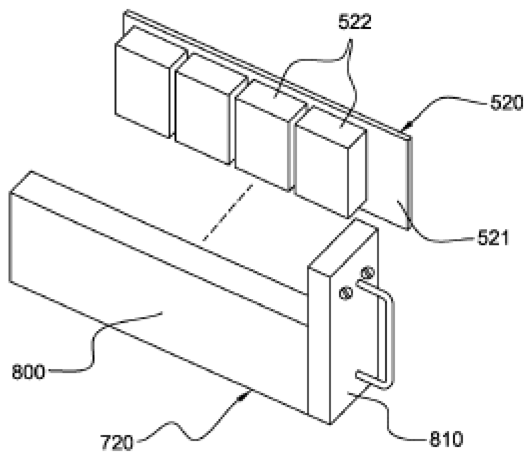


FIG. 8A

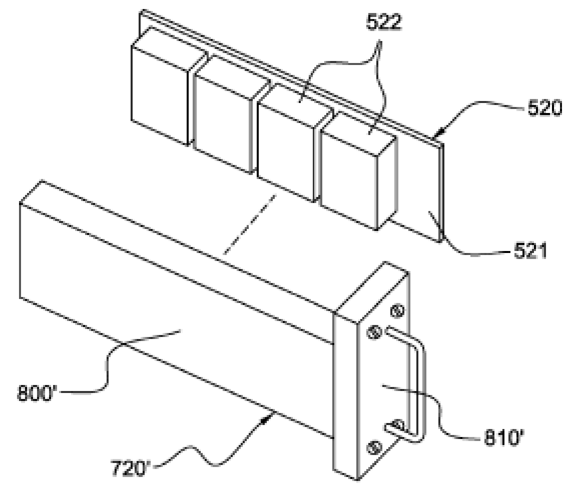


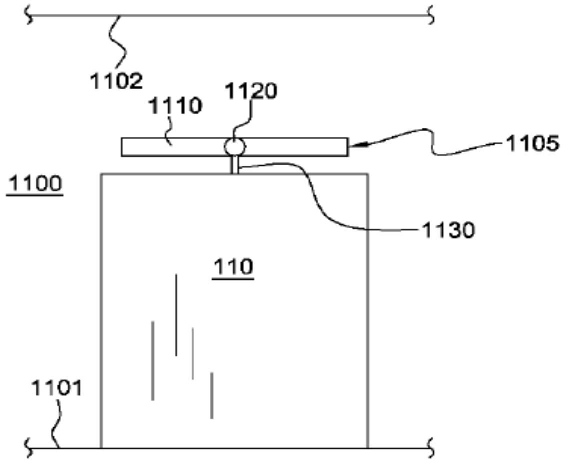
FIG. 11

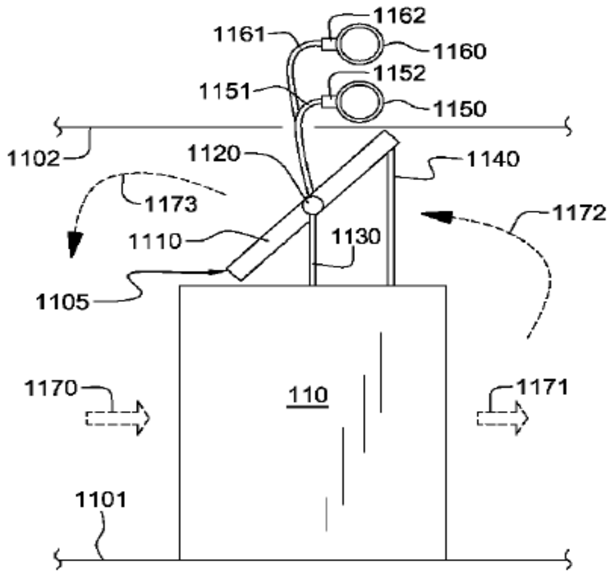
PATENT NO. US 7990709

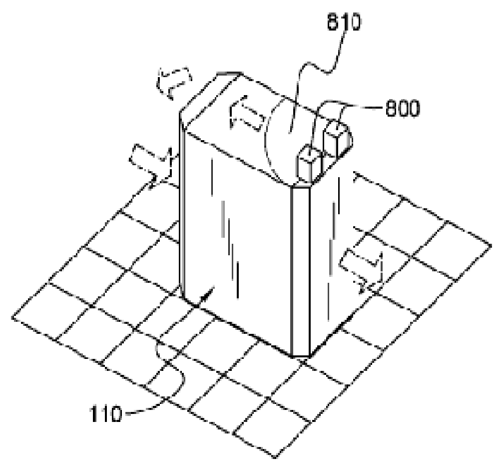
APPARATUS AND METHOD FOR FICILITATING COOLING OF AN ELECTRONICS RACK

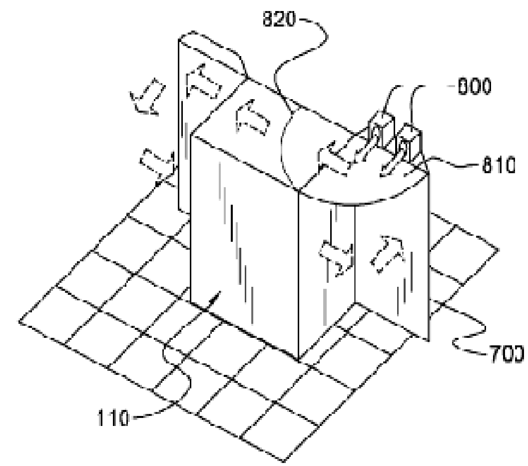
INTERNATIONAL BUSINESS MACHINES CORPORATION.2011

- The apparatus includes a heat exchange assembly hingedly mounted above and external to the rack, such that air passing above the rack from an air outlet side to an air inlet side thereof passes through the heat exchange assembly, and is cooled.






810
800
110


820
800
810
700
110

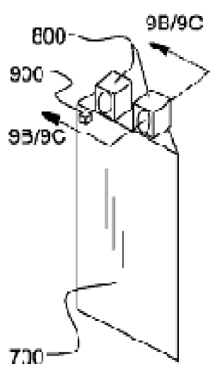
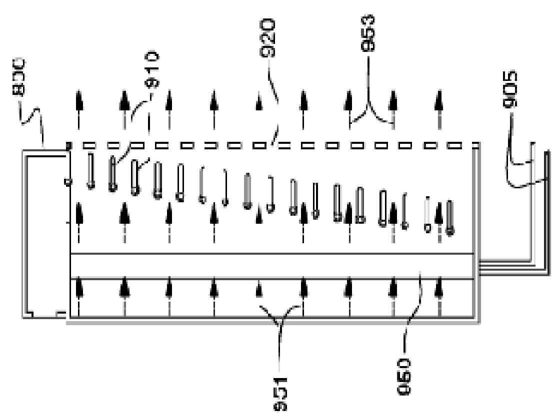
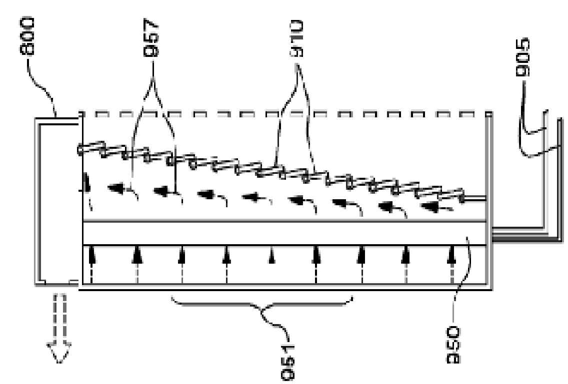

800
9B/9C
900
9B/9C
700

FIG. 9A


800
910
920
953
905
951
950

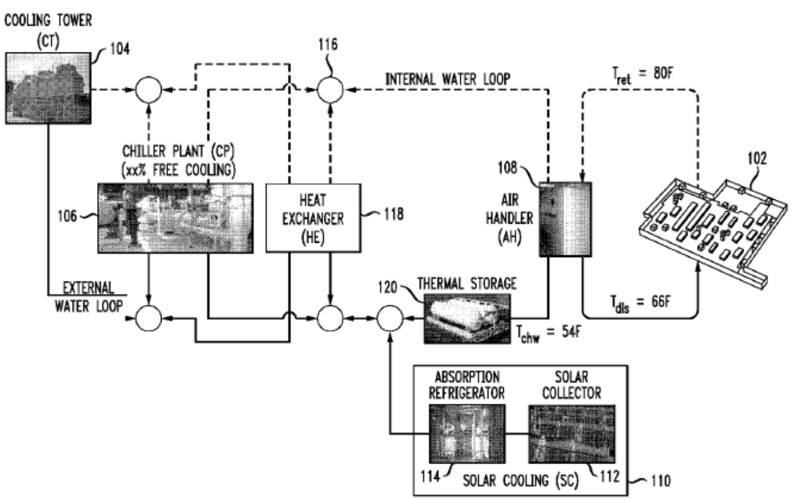

800
957
910
905
951
950

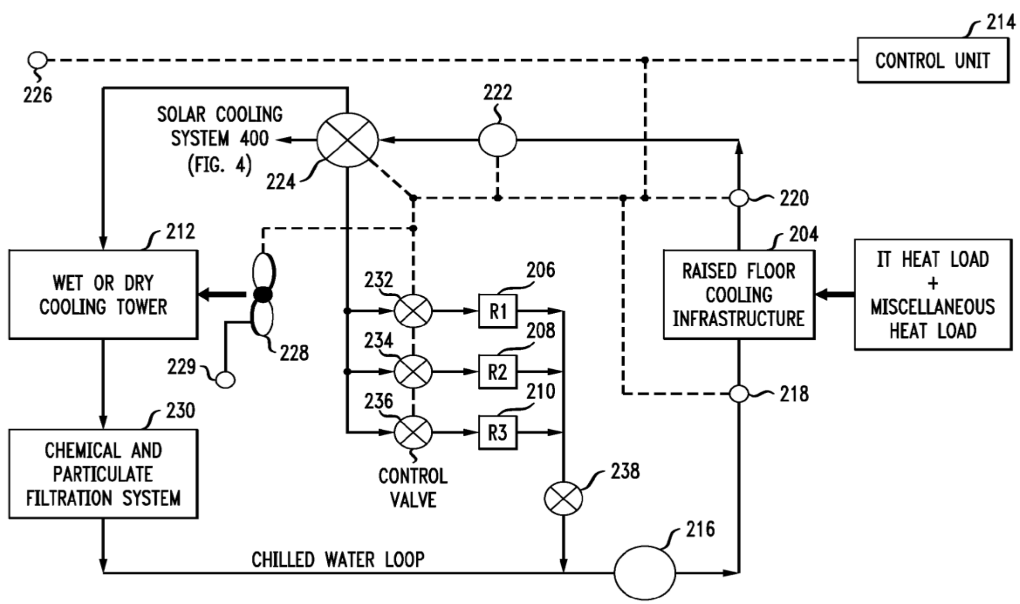
COOLING INFRASTRUCTURE LEVERAGING A COMBINATION OF FREE AND SOLAR COOLING

Patent No. US 8020390

IBM, 2011

- A free cooling loop with cooling tower (212).
  - a dry cooling tower
    - where the water does not contact with the air .
  - a wet cooling tower
    - where the water contact with the air which uses water evaporation to help heat transfer.





Variable Flow Computer Cooling System For a Datacenter and a Method for Operation

Patent No. US 7808780B2

IBM, 2010

- A direct liquid cooling system (can incorporated with “free cooling”)
- The liquid flow can be further arranged to … ” with variable flow control.

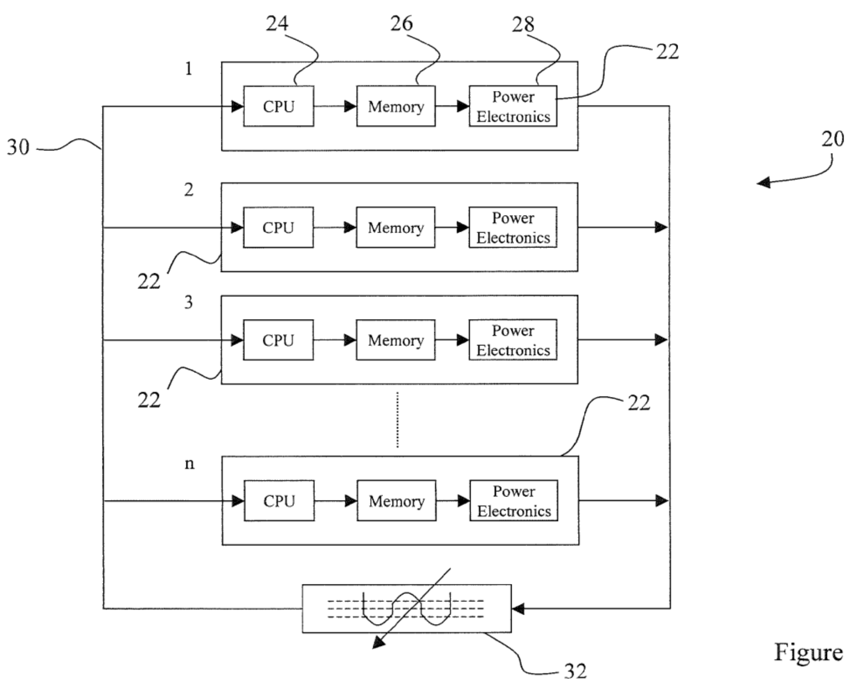
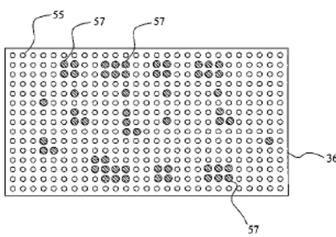
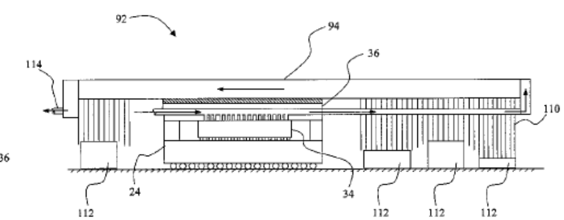


Figure 1





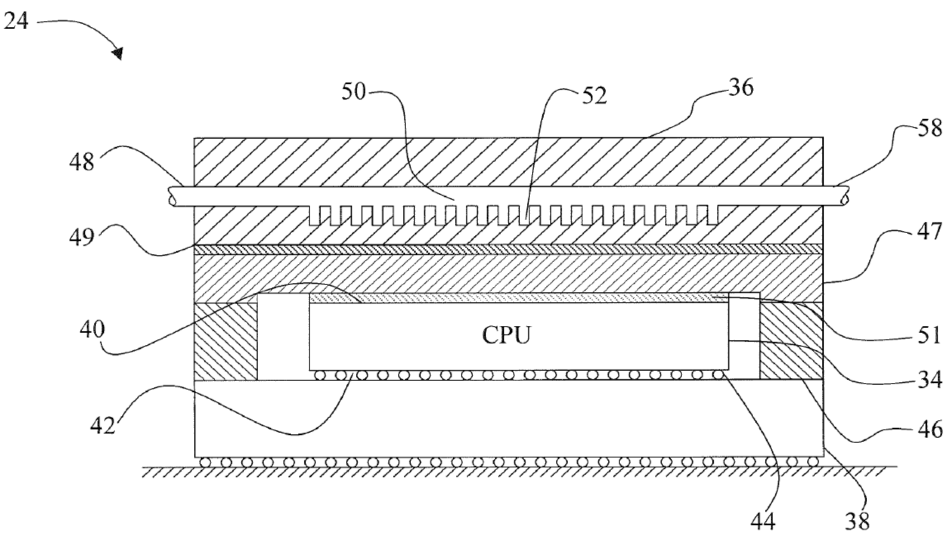


Figure 2B

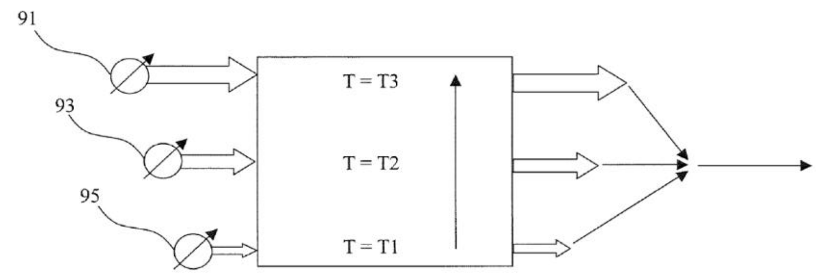


Figure 8

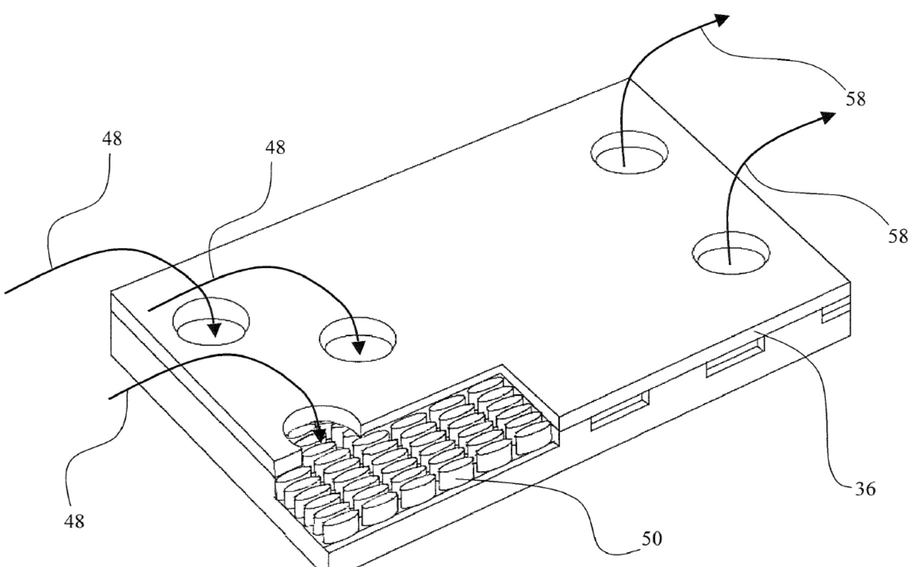


Figure 3

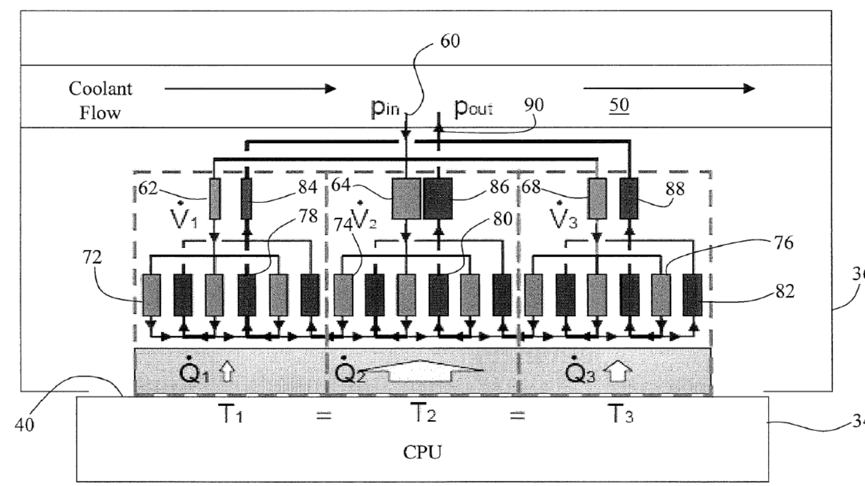


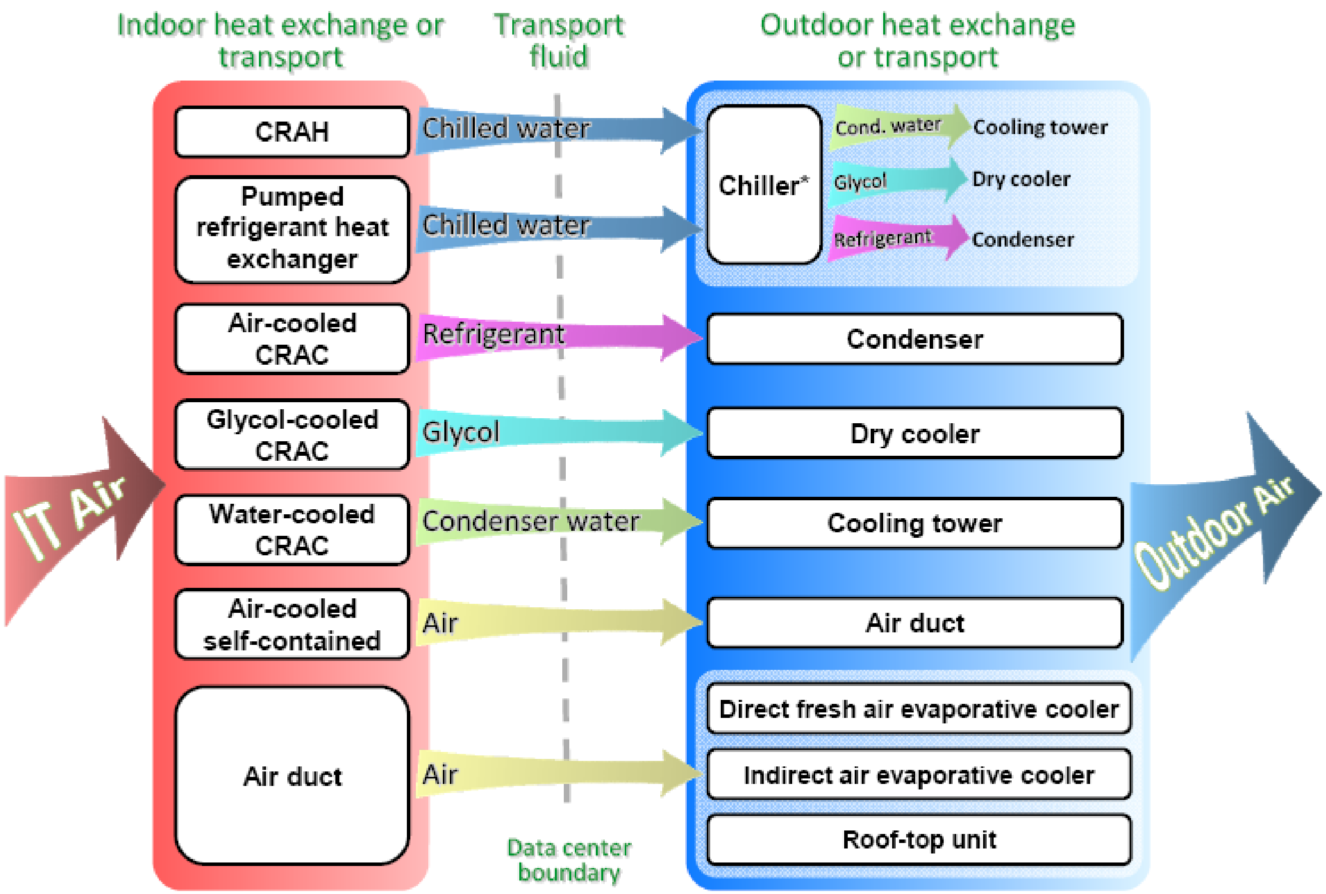
Figure 6

Appendix 2 : The Different Technologies for Cooling Data Centers

APC white paper #59

Figure 1

Simplified breakdown of the 13 fundamental heat removal methods



* Note that in some cases the chiller is physically located indoors.

Figure 2

Water-cooled chilled water system

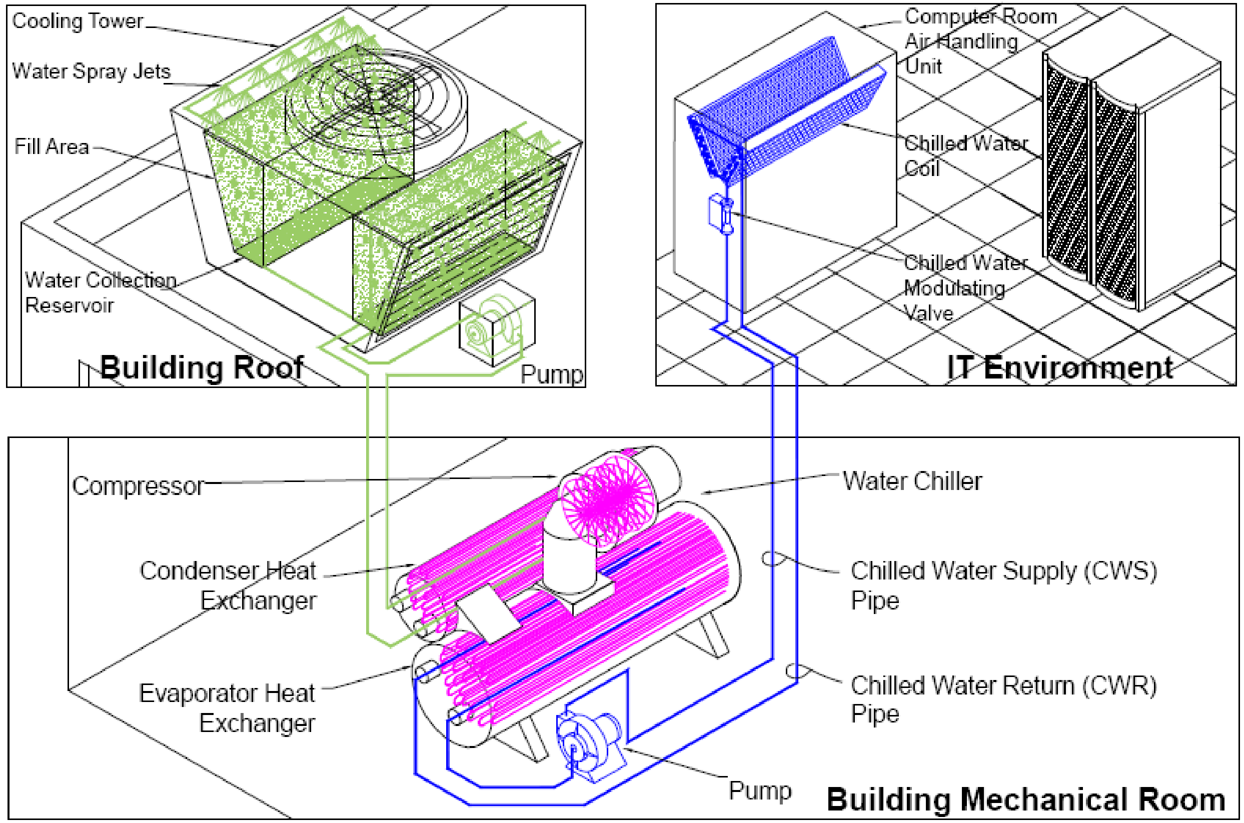


Figure 3

Example of a water-cooled chiller (left) and cooling tower (right)

Water-cooled Chiller

Cooling Tower

Advantages

- Chilled water CRAH units generally cost less, contain fewer parts, and have greater heat removal capacity than CRAC units with the same footprint.
- Chilled water system efficiency improves greatly with increased data center capacity
- Chilled water piping loops are easily run very long distances and can service many IT environments (or the whole building) from one chiller plant.
- Chilled water systems can be engineered to be extremely reliable.
- Can be combined with economizer modes of operation to increase efficiency. Designing the system to operate at higher water temperatures 12-15°C [54-59°F]) will increase the hours on economizer operation.

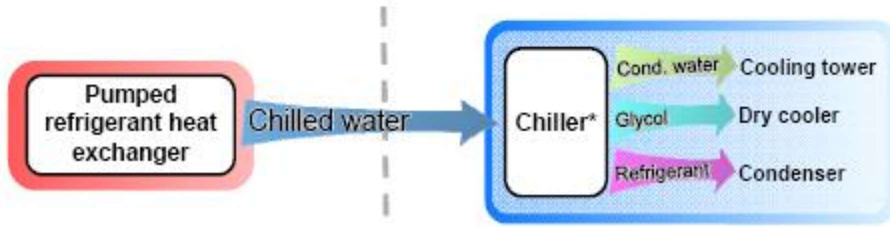
Disadvantages

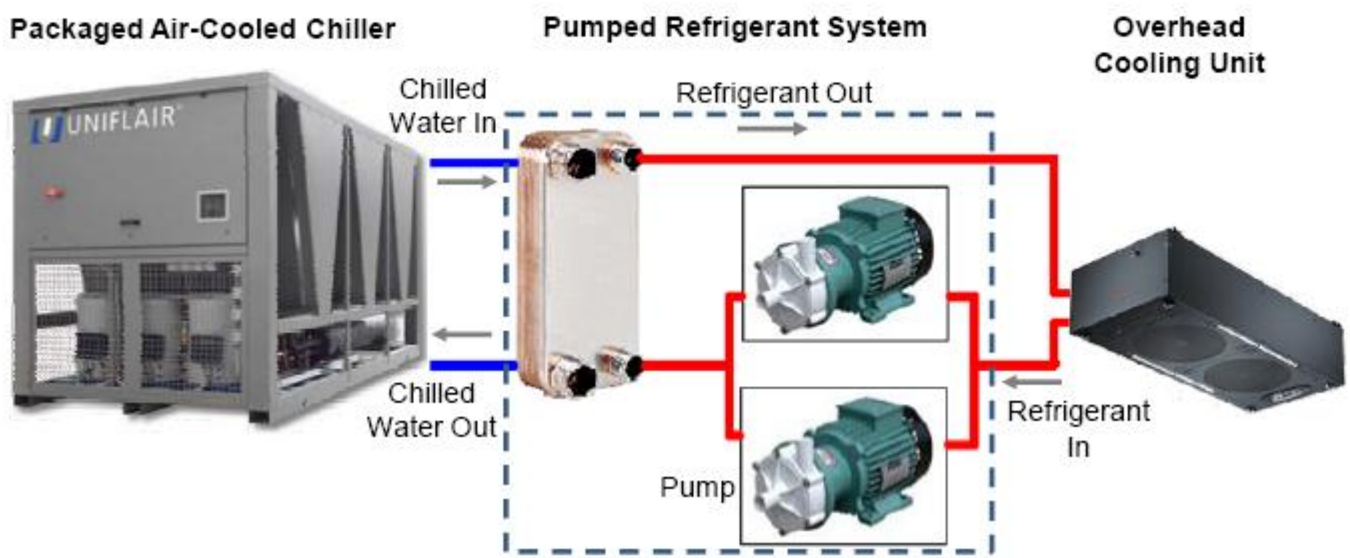
- Chilled water systems generally have the highest capital costs for installations below 100 kW of electrical IT loads.
- Introduces an additional source of liquid into the IT environment.

Usually used

- In data centers 200 kW and larger with moderate-to-high availability requirements or as a high availability dedicated solution. Water-cooled chilled water systems are often used to cool entire buildings where the data center may be only a small part of that building.

Pumped refrigerant for chilled water systems





Advantages

- Keeps water away from IT equipment in chilled water applications
- Oil-less refrigerants and non-conductive fluids eliminate risk of mess or damage to servers in the event of a leak.
- Efficiency of cooling system due to close proximity to servers or direct to chip level.

Disadvantages

- Higher first cost as a result of adding additional pumps and heat exchangers into the cooling system.

Usually Used

- These systems are usually used for cooling systems that are closely coupled to the IT equipment for applications like row and rack based high density cooling.
- Chip Level Cooling where coolant is piped directly to the server

Air-cooled system (2-piece)

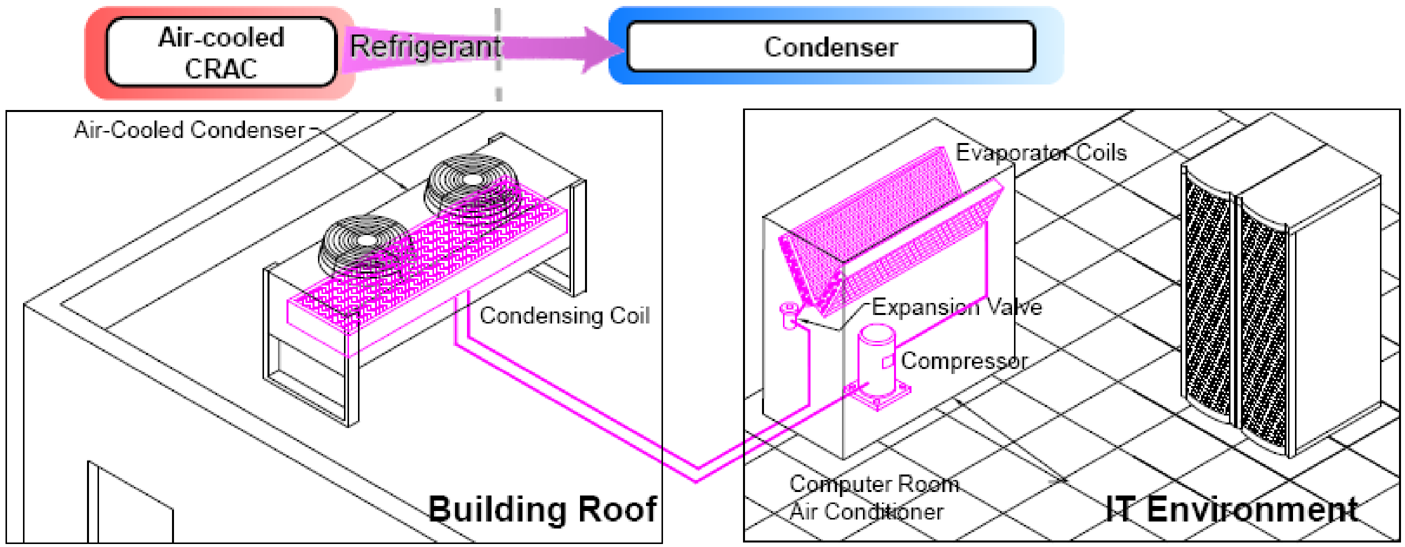


Figure 6

Air-cooled DX system (2-piece)

Advantages

- Lowest overall cost
- Easiest to maintain

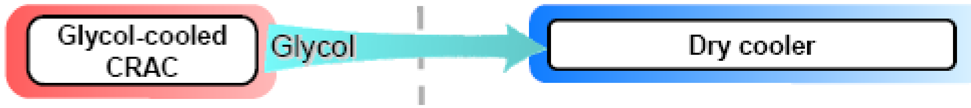
Disadvantages

- Refrigerant piping must be installed in the field. Only properly engineered piping systems that carefully consider the distance and change in height between the IT and outdoor environments will deliver reliable performance.
- Refrigerant piping cannot be run long distances reliably and economically.
- Multiple computer room air conditioners cannot be attached to a single air-cooled condenser.

Usually used

- In wiring closets, computer rooms and 7-200kW data centers with moderate availability requirements.

Glycol-cooled system



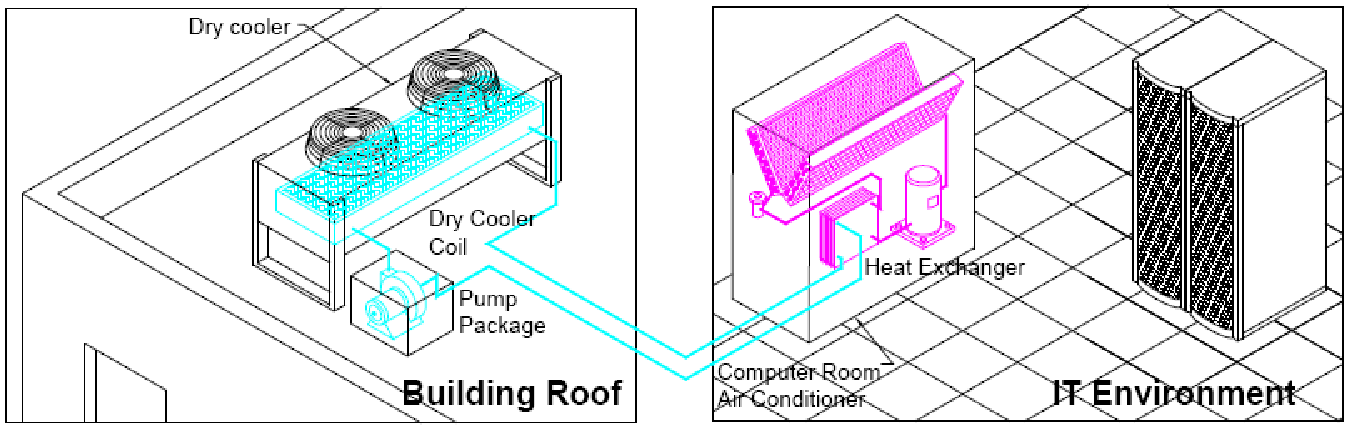


Figure 8

Glycol-cooled system

Advantages

- The entire refrigeration cycle is contained inside the CRAC unit as a factory-sealed and tested system for highest reliability with the same floor space requirement as a two piece air-cooled system.
- Glycol pipes can run much longer distances than refrigerant lines (air-cooled split system) and can service several CRAC units from one dry cooler and pump package.
- In cold locations, the glycol within the dry cooler can be cooled so much (below 10°C [50°F]) that it can bypass the heat exchanger in the CRAC unit and flow directly to a specially installed *economizer coil*. Under these conditions, the refrigeration cycle is turned off and the air that flows through the economizer coil, now filled with cold flowing glycol, cools the IT environment. This economizer mode, also known as "*free cooling*", provides excellent operating cost reductions when used.

Disadvantages

- Additional required components (pump package, valves) raise capital and installation costs when compared with air-cooled DX systems.
- Maintenance of glycol volume and quality within the system is required.
- Introduces an additional source of liquid into the IT environment.

Usually used

- In computer rooms and 30-1,000 kW data centers with moderate availability requirements.

Water-cooled system

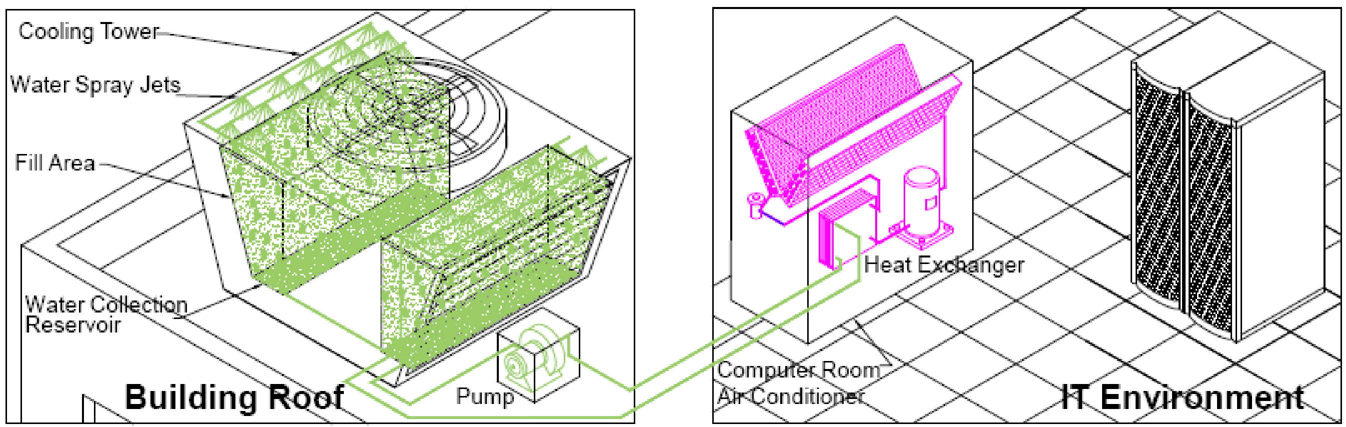


Figure 9

Water-cooled system

- A water (also called *condenser water*) loop is used instead of glycol to collect and transport heat away from the IT environment
- Heat is rejected to the outside atmosphere via a cooling tower instead of a dry cooler as seen in **Figure 9**.

Advantages

- All refrigeration cycle components are contained inside the computer room air conditioning unit as a factory-sealed and tested system for highest reliability.
- Condenser water piping loops are easily run long distances and almost always service many computer room air conditioning units and other devices from one cooling tower.
- In leased IT environments, usage of the building's condenser water is generally less expensive than chilled water (chilled water is explained in the next section).

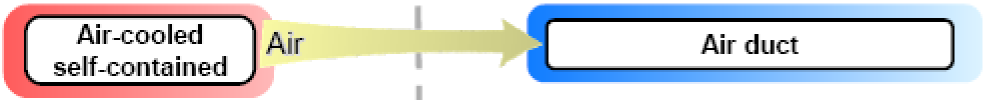
Disadvantages

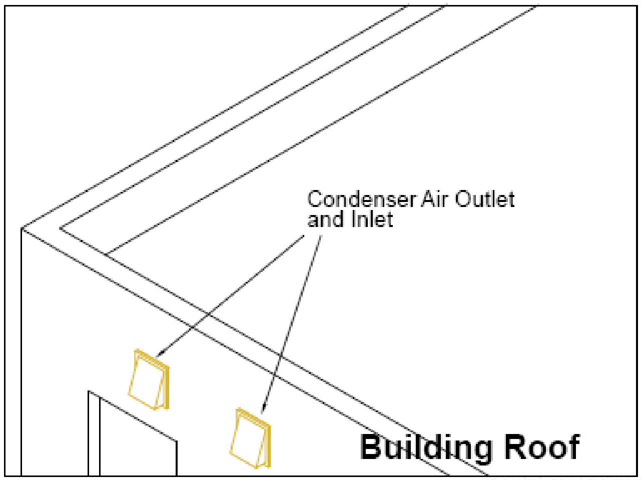
- High initial cost for cooling tower, pump, and piping systems.
- Very high maintenance costs due to frequent cleaning and water treatment requirements.
- Introduces an additional source of liquid into the IT environment.
- A non-dedicated cooling tower (one used to cool the entire building) may be less reliable then a cooling tower dedicated to the computer room air conditioner.

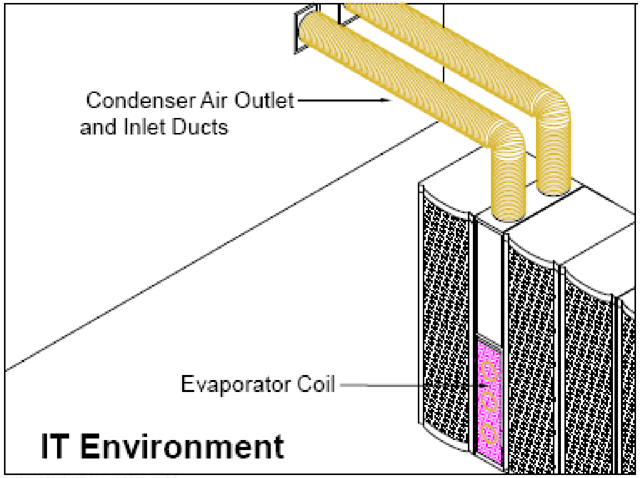
Usually used

- In conjunction with other building systems in data centers 30kW and larger with moderate-to-high availability requirements.

Air-cooled self-contained system (1-piece)







Air cooled self contained

Figure 10

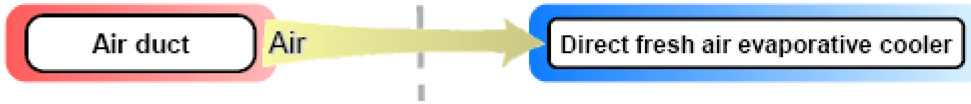
Indoor air-cooled self-contained system

Portable Self Contained Cooling Unit

Figure 11

Examples of indoor air-cooled self-contained system

Direct fresh air evaporative cooling system



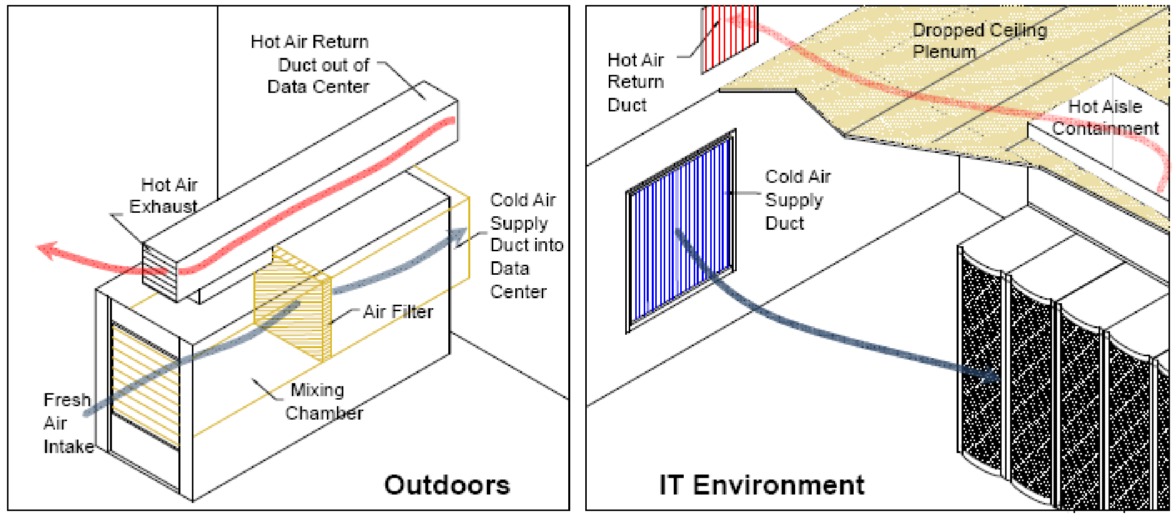


Figure 12

Example of an indirect air evaporative cooling system

Figure 13

Example of a direct fresh air evaporative cooling system

Advantages

- All cooling equipment is placed outside the data center, allowing for white space to be fully utilized for IT equipment.
- Significant cooling energy savings in dry climates (e.g. 75%) compared to systems with no economizer mode.

Disadvantages

- May be difficult to retrofit into an existing data center.
- Subject to frequent filter changes in locations with poor air quality.
- Evaporative cooling contributes to humidity in the data center.

Usually used

- In 1,000kW data centers and larger with high power density.

Indirect air evaporative cooling system

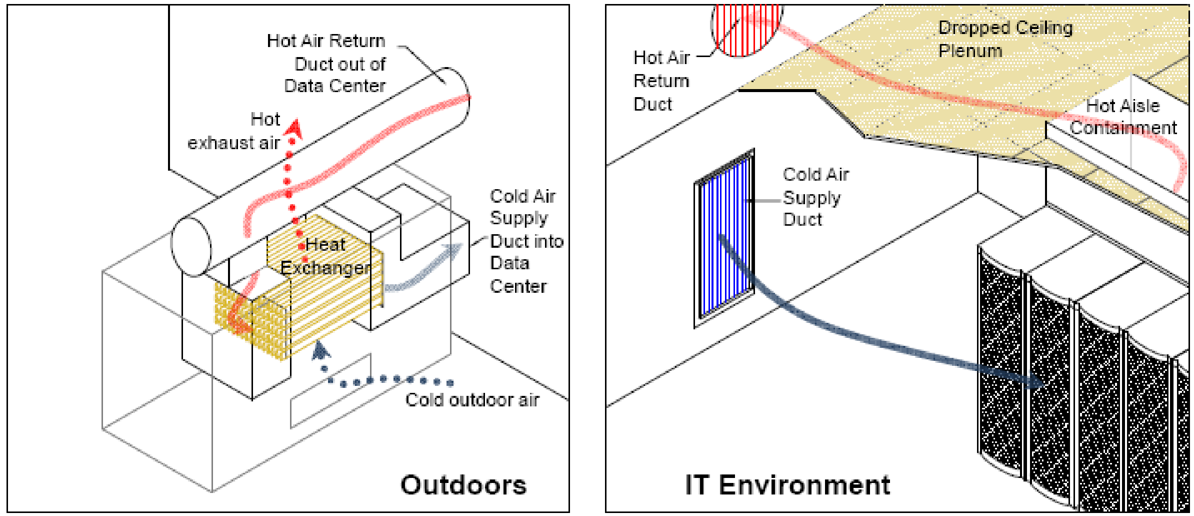


Figure 14

Indirect air economizer system

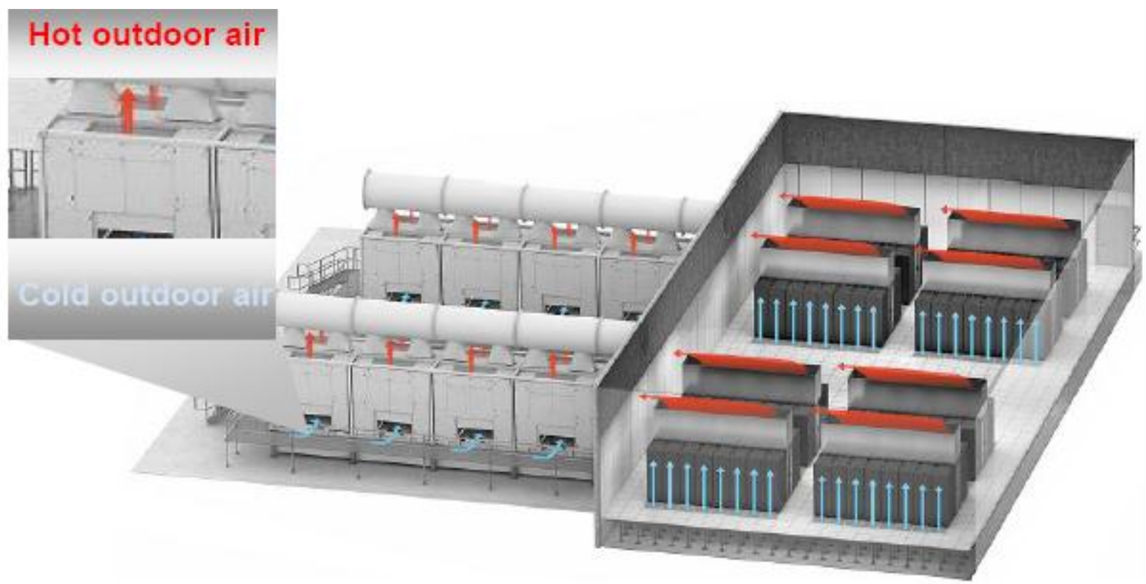


Figure 15

Example of an indirect air evaporative cooling system

Advantages

- All cooling equipment is placed outside the data center, allowing for white space to be fully utilized for IT equipment.
- Significant cooling energy savings in most climates (e.g. 75%) compared to systems with no economizer mode.

Disadvantages

- May be difficult to retrofit into an existing data center.

Usually used

- In 1,000kW data centers and larger with high power density.

Self-contained roof-top system

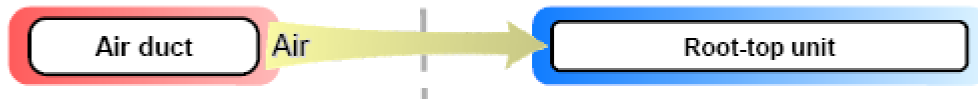


Figure 16

Self-contained roof-top system

Advantages

- All cooling equipment is placed outside the data center, allowing for white space to be fully utilized for IT equipment.
- Significant cooling energy savings in mild climates compared to systems with no economizer mode.

Disadvantages

- May be difficult to retrofit into an existing data center.

Usually used

- In data centers that are part of a mixed-use facility.

Advantages

- Indoor self-contained systems have the lowest installation cost. There is nothing to install on the roof or outside the building except for the condenser air outlet.
- All refrigeration cycle components are contained inside one unit as a factory-sealed and tested system for highest reliability.

Disadvantages

- Less heat removal capacity per unit compared to other configurations.
- Air routed into and out of the IT environment for the condensing coil usually requires ductwork and/or dropped ceiling.
- Some systems can rely on the building HVAC system to reject heat. Issues can arise when the building HVAC system shuts down in the evening or over the weekend.

Usually used

- In wiring closets, laboratory environments and computer rooms with moderate availability requirements.
- Sometimes used to fix hot spots in data centers.

Two fundamental physical arrangements of precision cooling equipment

- **Ceiling mounted systems**

Figure 6 – *Typical ceiling mounted computer room air conditioner*

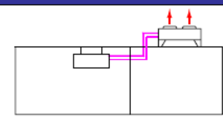
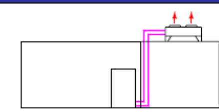
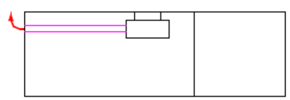
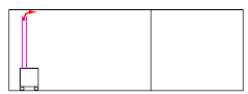
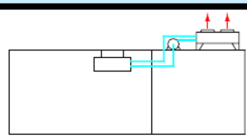
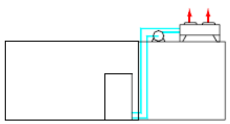
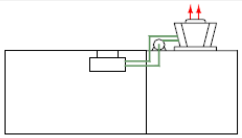
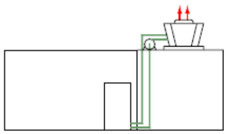
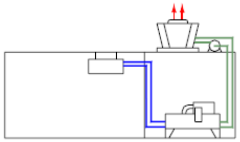
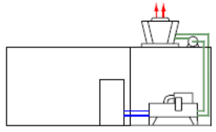
Figure 7 – *Typical floor mounted portable computer room air conditioner*

Figure 8 – *Typical floor mounted computer room air conditioner*

- **Floor mounted system**

The 10 combinations of heat removal methods and equipment arrangements

***Table 1** – The 10 basic cooling system configurations*

	Ceiling Mounted	Floor Mounted
Air Cooled System (2Piece)	 Requires roof access and a 10' (3m) floor to structural ceiling height. Roof should be within 2 stories of IT environment. Air cooled condenser and refrigerant piping required.	 Requires roof access. Roof should be within two stories of IT environment. Requires air cooled condenser and refrigerant piping. Portable systems usually don't use outdoor components.
Air Cooled Self Contained System (1Piece)	 IT environment must have dropped ceiling or ducts should be installed for condenser air. Ensure 10' (3m) floor to structural ceiling height.	 IT environment must have dropped ceiling for condenser air tubes. Large floor mounted systems require outdoor heat rejection components
Glycol Cooled Systems	 Building must have roof access and a 10' (3m) floor to structural ceiling height. Fluid cooler, pump package and glycol piping required.	 Requires roof access. Fluid cooler, pump package and glycol piping required. Portable systems usually don't use outdoor components.
Water Cooled Systems	 Building must have 10' (3m) floor to structural ceiling height. Hookup to building condenser water required	 Building must have condenser water system with adequate capacity. Hookup required. Portable systems don't use condenser water.
Chilled Water Systems	 Building has 10' (3m) floor to structural ceiling height and reliable chilled water system. Chilled water hookup required.	 Building must have reliable chilled water system with adequate capacity. Chilled water hookup required. Portable systems usually don't use chilled water.