Thermal managements in datacenter – An overview and Outlook

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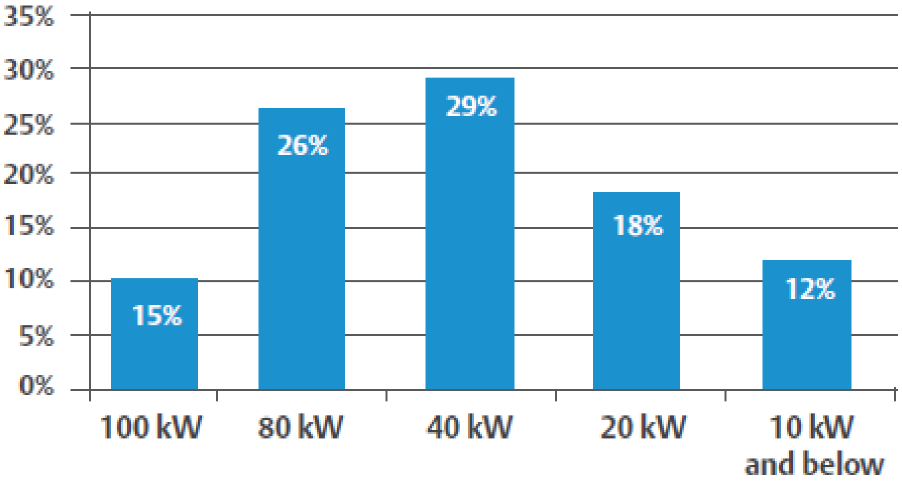
Outline

- General Background
- Thermal management in Datacenter
- Free cooling in datacenter
- Waste heat management
- Airside management
- Some on-going airside work in NCTU
- Concluding Remarks



Participants in Data Center 2025 expected data center power density to rise to 50 kW per rack in the next ten years.

Data Center 2025: In 2025, what will the average power density of a data center be?

General Background

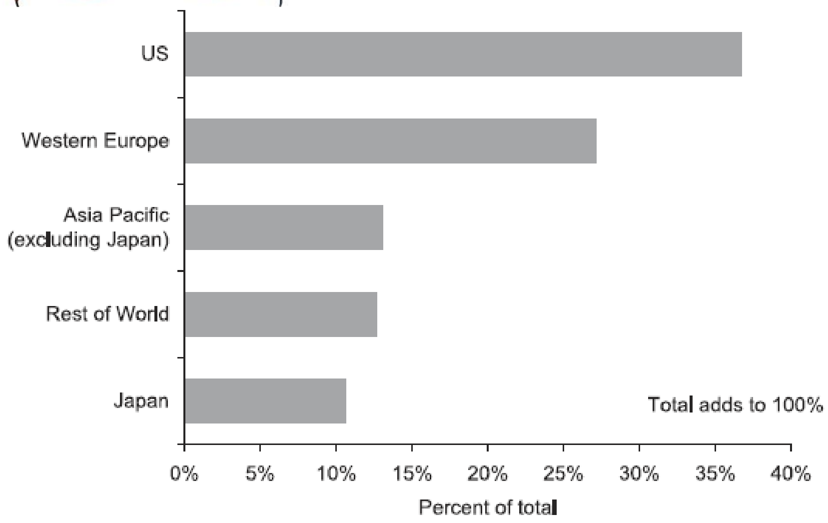
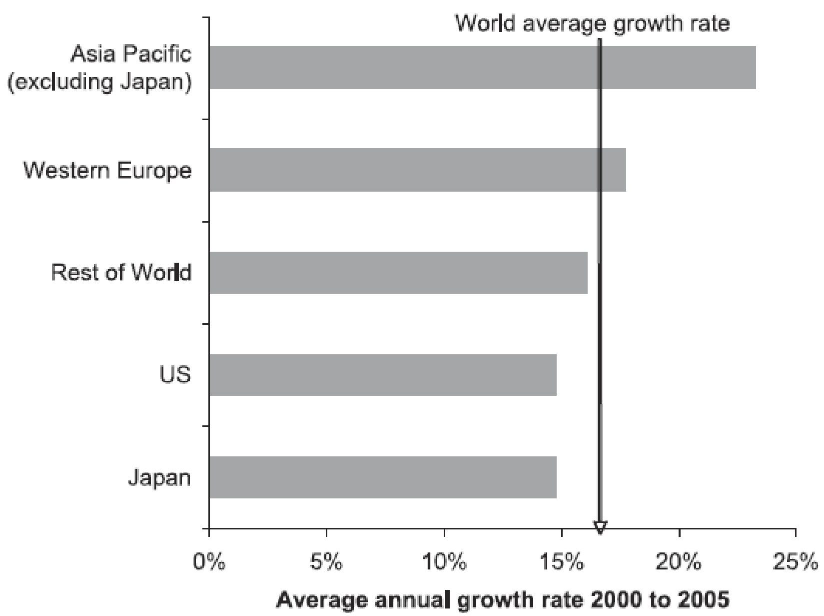


Figure 2. Regional distribution of electricity use for data centers in 2005.



. 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

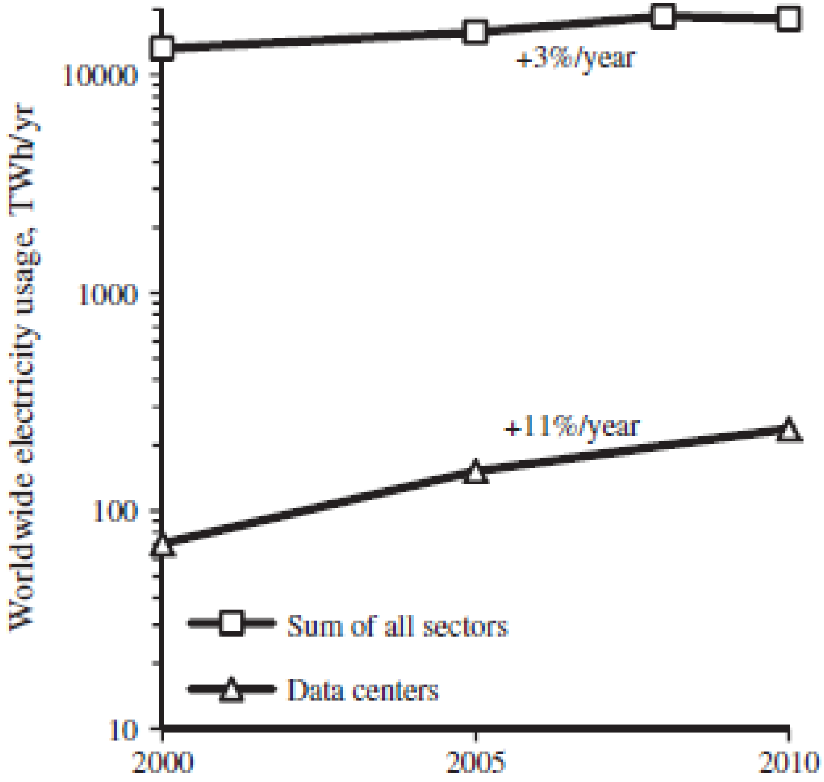
Note: (1) Installed base for US and World taken from Koomey (2007b). Non-US installed base by region was not available from IDC, so it was approximated using IDC shipments data by region and multipliers characterizing the relationship between installed base and shipments for all non-US regions in the 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).

Environmental Research Letters. vol. 3, no. 034008.

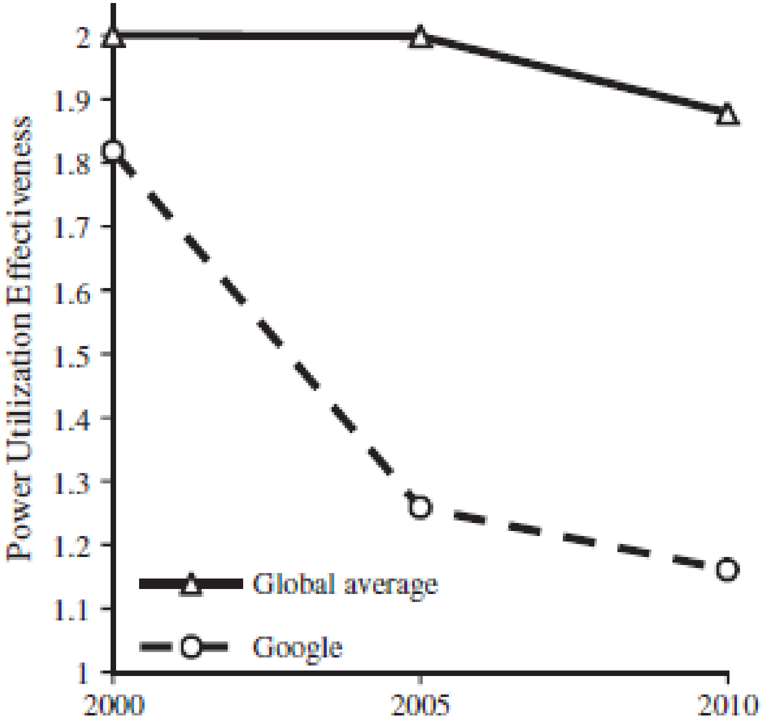
General Background

PUE = datacenter power consumption/IT power consumption

Evolution of the worldwide electricity usage from 2000 until 2010: contribution of data centers compared to the sum of all sectors

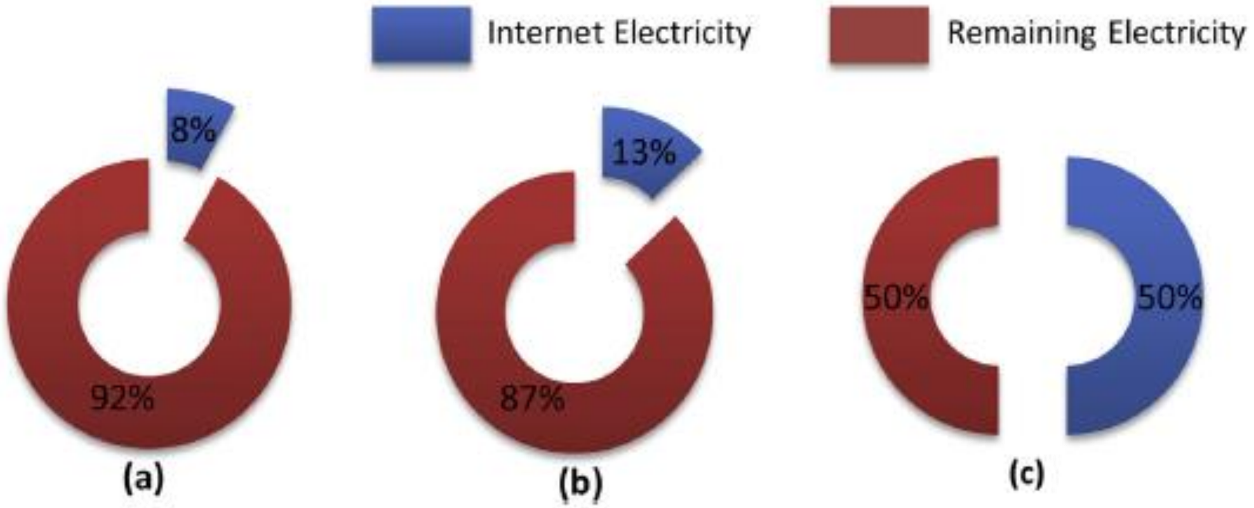


Evolution of the average power usage effectiveness (PUE) of data centers from 2000 until 2010: Worldwide average (4) and company-average for Google



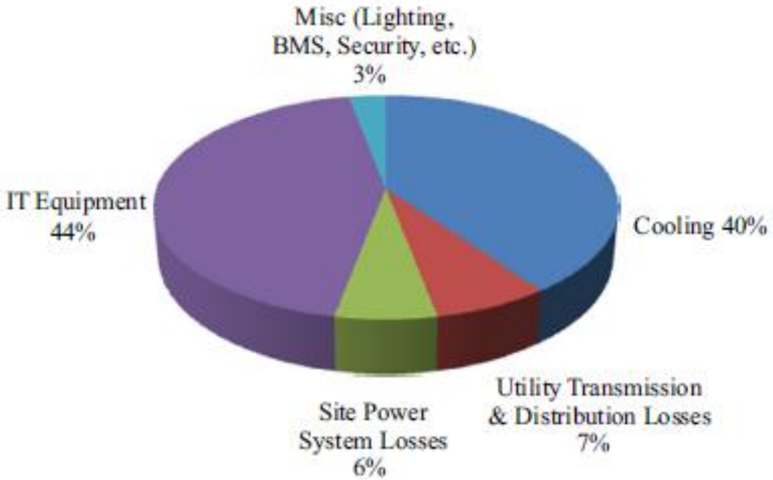
Applied Energy, Volume 107, July 2013, Pages 66–8

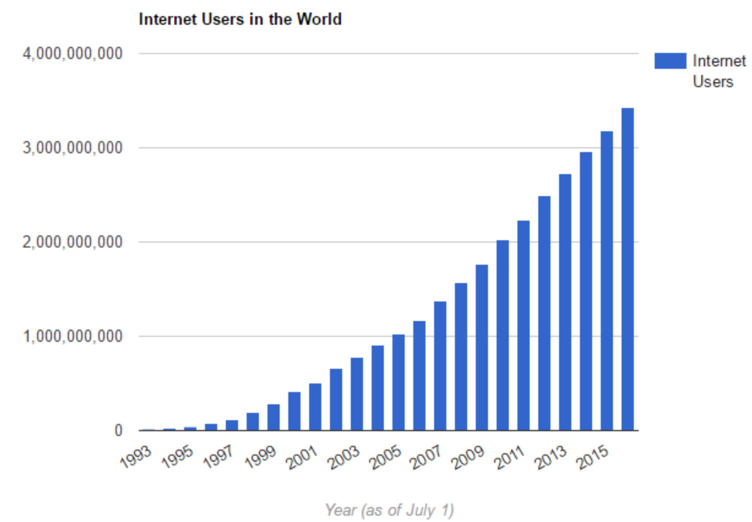
Building and Environment
Volume 82, December 2014, Pages 151–159



Proportion of US electricity used for the internet (a), including embodied and operational impacts (b), and projected over next one to two decades (c).

Typical breakdown of datacenter energy consumption





Internet users in the world
http://www.internetlivestats.com/internet-users/.

Applied Energy

Volume 107, 2013, Pages 66–80

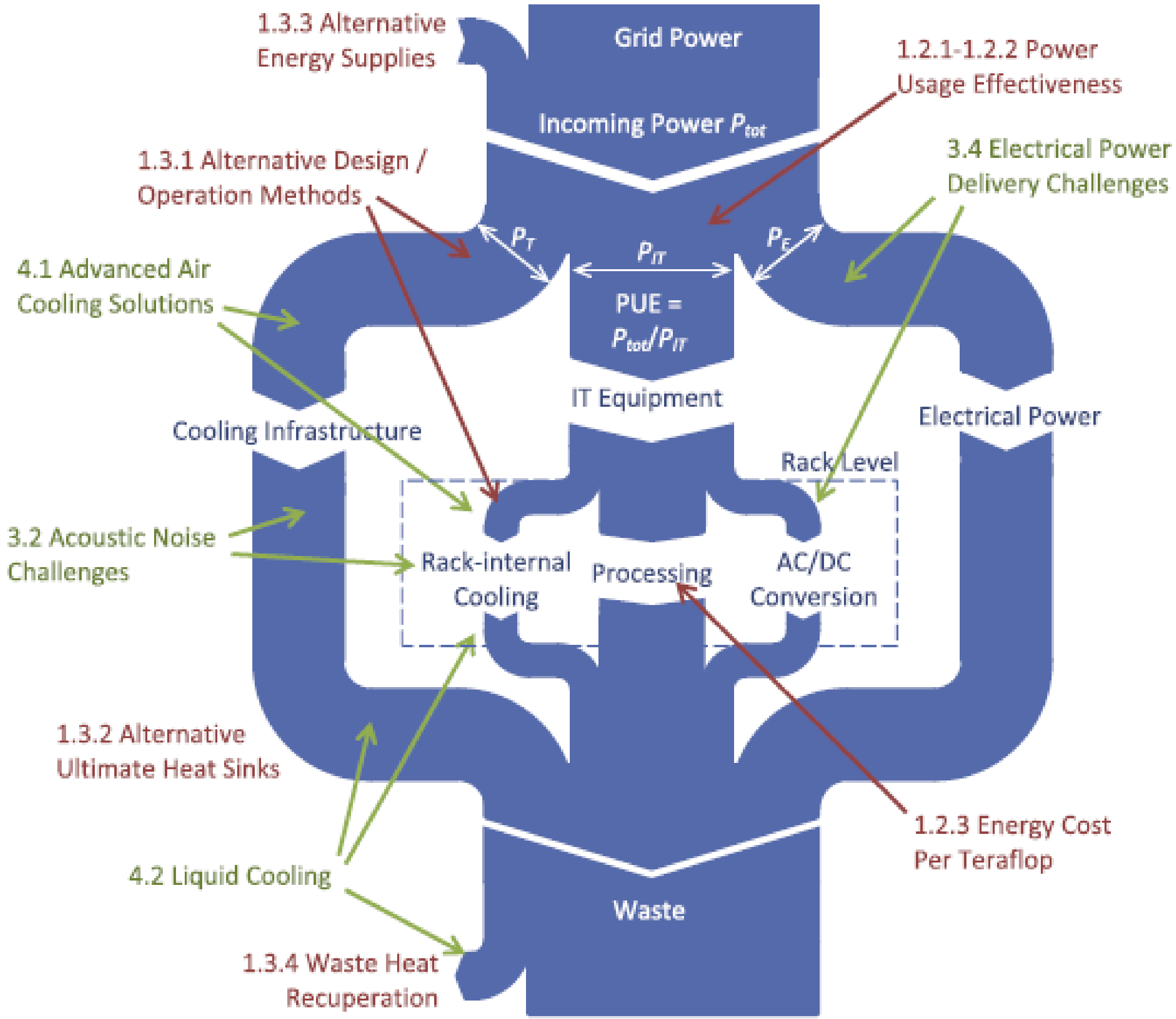
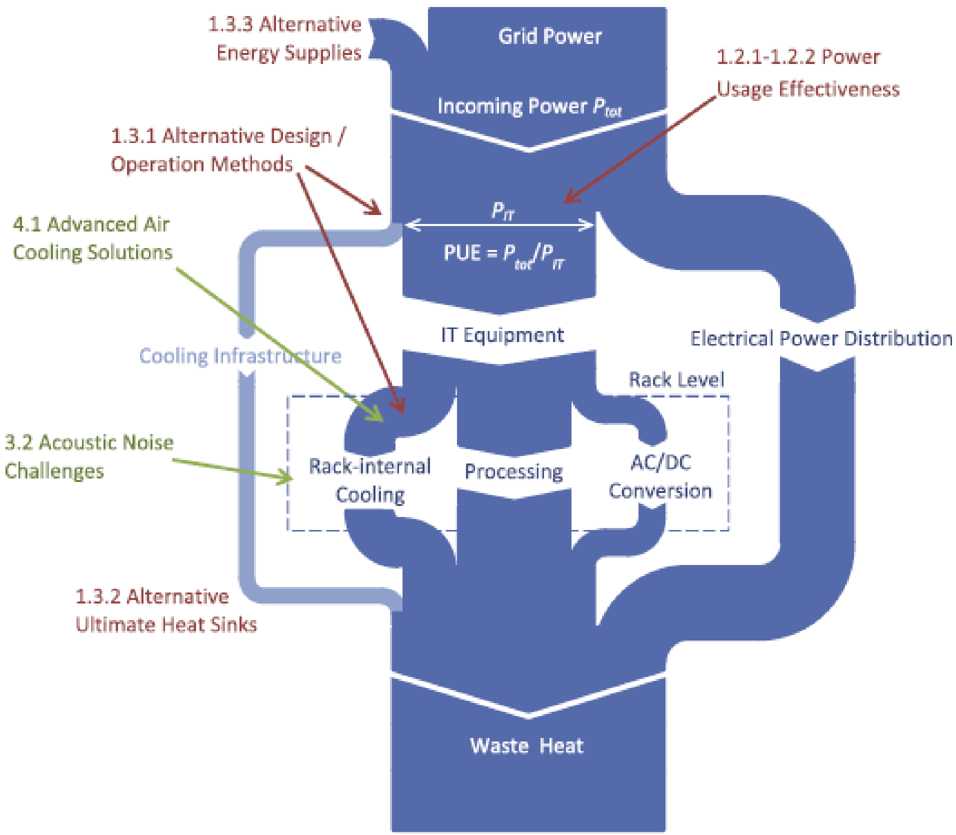
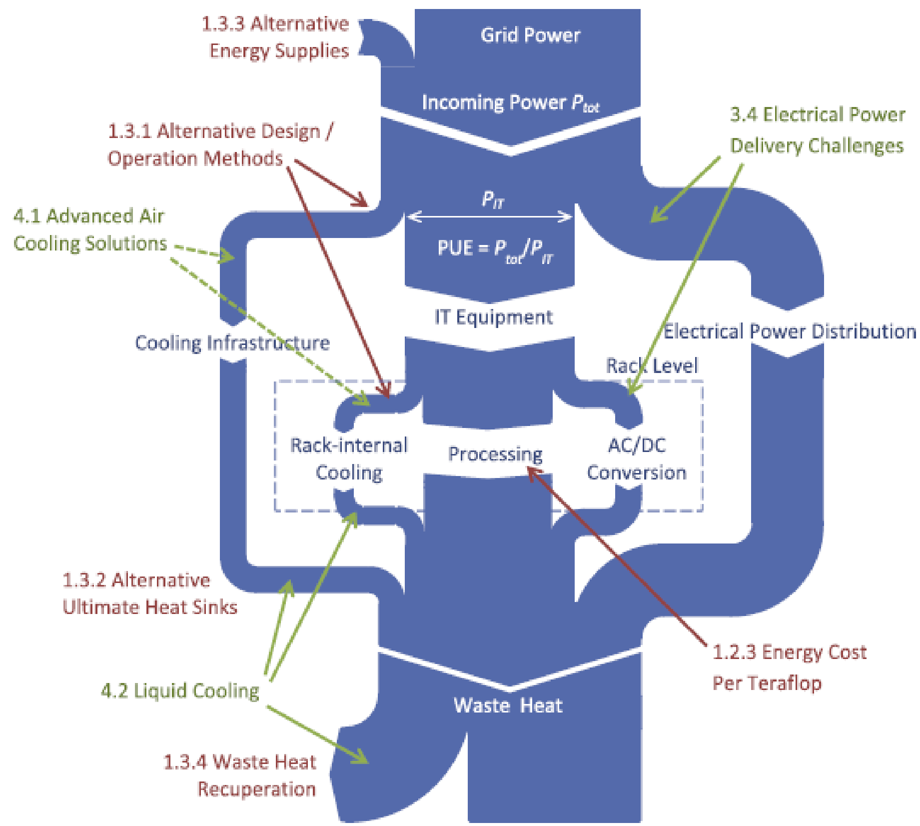


Fig. 2. Sankey diagram for a typical present-day data center facility, representing the distribution of power through three main system components (system and rack level IT equipment, cooling infrastructure, electrical power storage and delivery), partly based on data from [1,2].

Sankey diagram for a ‘cloud-optimized’ data center using air cooling at an elevated room temperature to maximize the use of free cooling. Compared to a typical data center, more demanding rack-internal air cooling leads to acoustic noise challenges, which can be partly addressed with advanced air cooling solutions.

Sankey diagram for a fully liquid-cooled data center, with more efficient high-density rack-level cooling due to the superior heat carrier properties of water. Using water at an elevated temperature, this approach is most suitable for waste heat recuperation





More Facts…
Current status

- 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.

Background – General Trend

Datacom equipments power trends and cooling applications ASHRAE 2005

Table 1
Summary of 2011 ASHRAE thermal guidelines for data centres [7].

	Dry-bulb temperature	Humidity range	Maximum dew point
	Recommended		
Class A1 and A4	18 to 27 °C	5.5 °C DP to 60% RH and 15 °C DP	–
	Allowable		
Class A1	15 to 32 °C	20% to 80%	17 °C
Class A2	10 to 35 °C	20% to 80%	21 °C
Class A3	5 to 40 °C	8% to 85%	24 °C
Class A4	5 to 45 °C	8% to 90%	24 °C

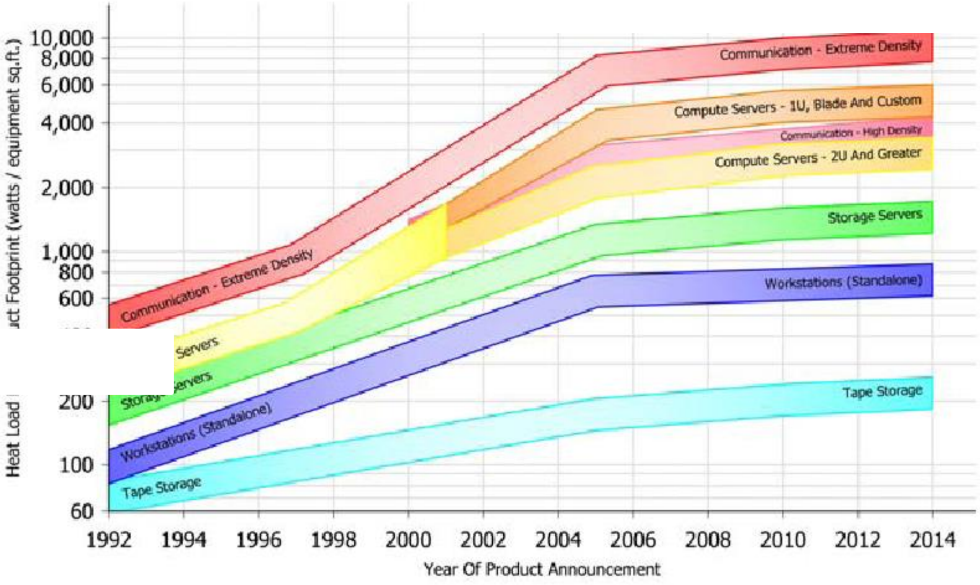


Figure 3-10 New ASHRAE updated and expanded power trend chart.

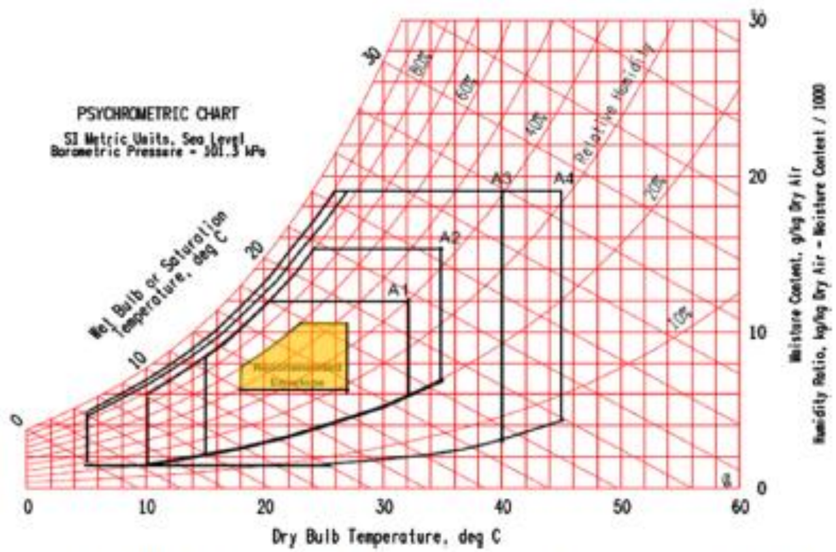


Fig. 1. ASHRAE thermal guides for data centre operating environments [7].

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National Chiao Tung University

Table 2.1 Datacom Computer Room Area Breakdown Example

Space Description	Facility Area (Percent of Total)
IT Space	
Storage Servers	19.0%
Compute Servers	11.0%
Telecommunications	5.0%
Command Area	4.0%
Printers	2.0%
Patch Panels	1.0%
IT Space Subtotal	**42.0%**
Non-IT Space	
Aisles	20.0%
Empty (Future Growth)	16.0%
Cooling Equipment	12.0%
Specialty Rooms	3.5%
Power Distribution	3.0%
Room Supplies	2.0%
Columns	1.0%
Doorways/Access Ramps	0.5%
Non-IT Space Subtotal	**58.0%**
GRAND TOTAL	**100.0%**

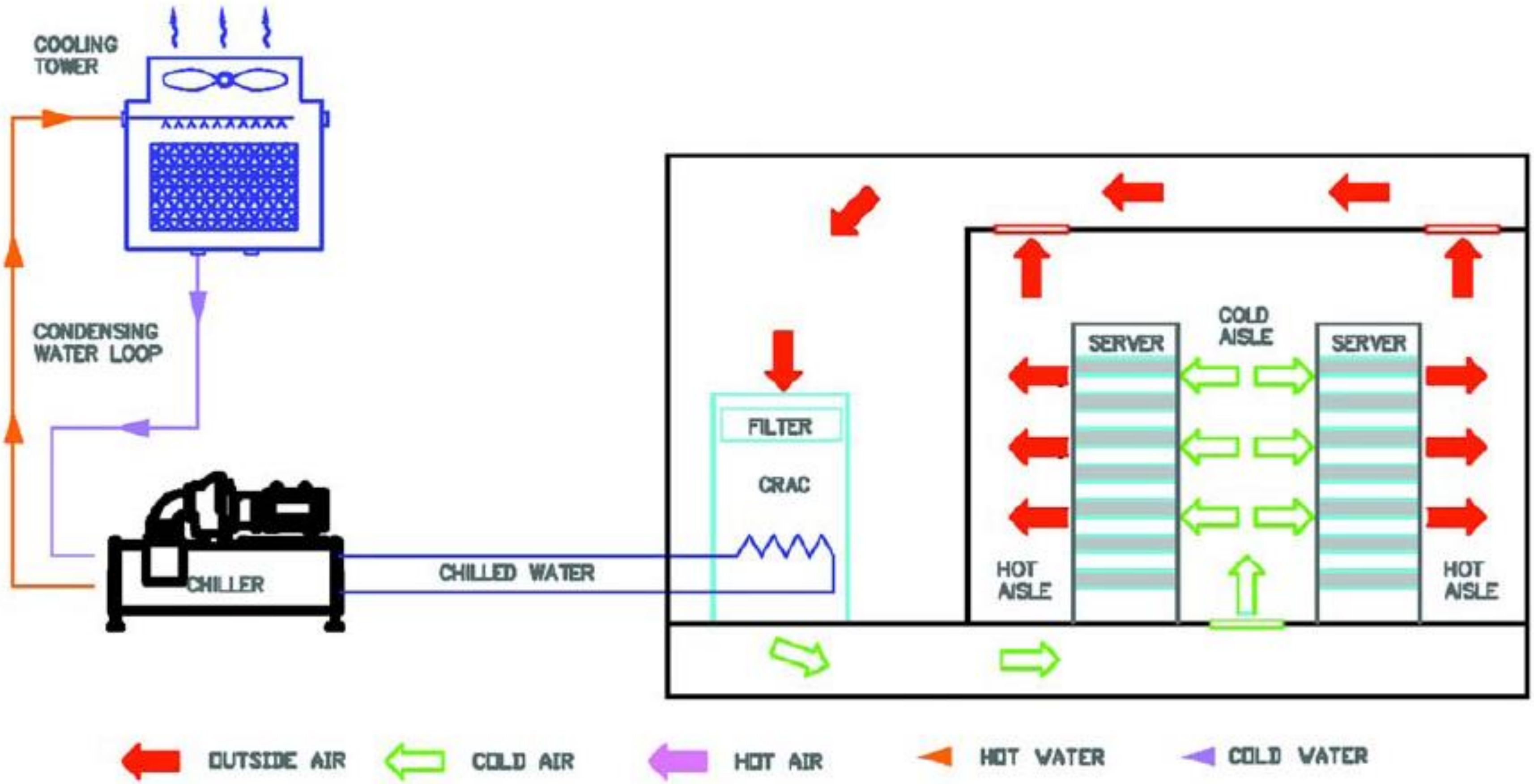
Datacom Equipment Power Trends and Cooling Applications 2nd Edition, 2012

Free Cooling..

-- Cooling without compressor or less compressor loading

Conventional data center air conditioning flow diagram

ASHRAE Transactions 2010, Vol. 116, Part 1.2010, 98-108



FACT: compressor consumes 85-90% electricity of a Chiller

Remove compressor, how?

- Use outside cold air or low humidity
  - Airside economizer
  - With Evaporative cooling
  - With Heat Pipe
- Use outside chilled water (from well, river, lake, sea..)
  - Waterside economizer
  - Cooling tower
- Use special HVAC&R system
  - Absorption chiller
  - Adsorption chiller

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Summary of 2011 ASHRAE thermal guidelines for data centres [7].

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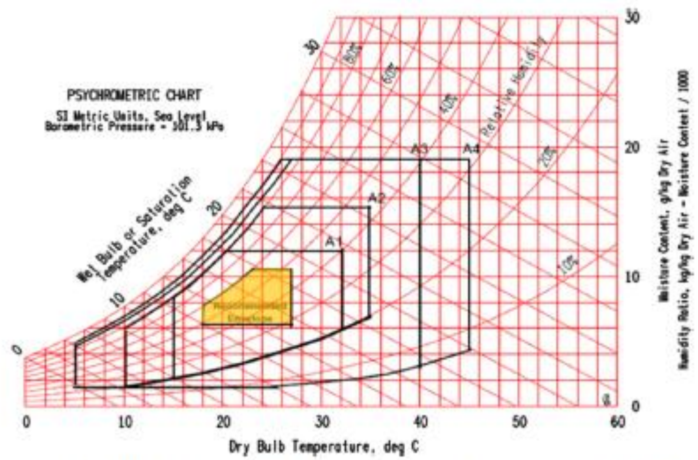


Fig. 1. ASHRAE thermal guides for data centre operating environments [7].

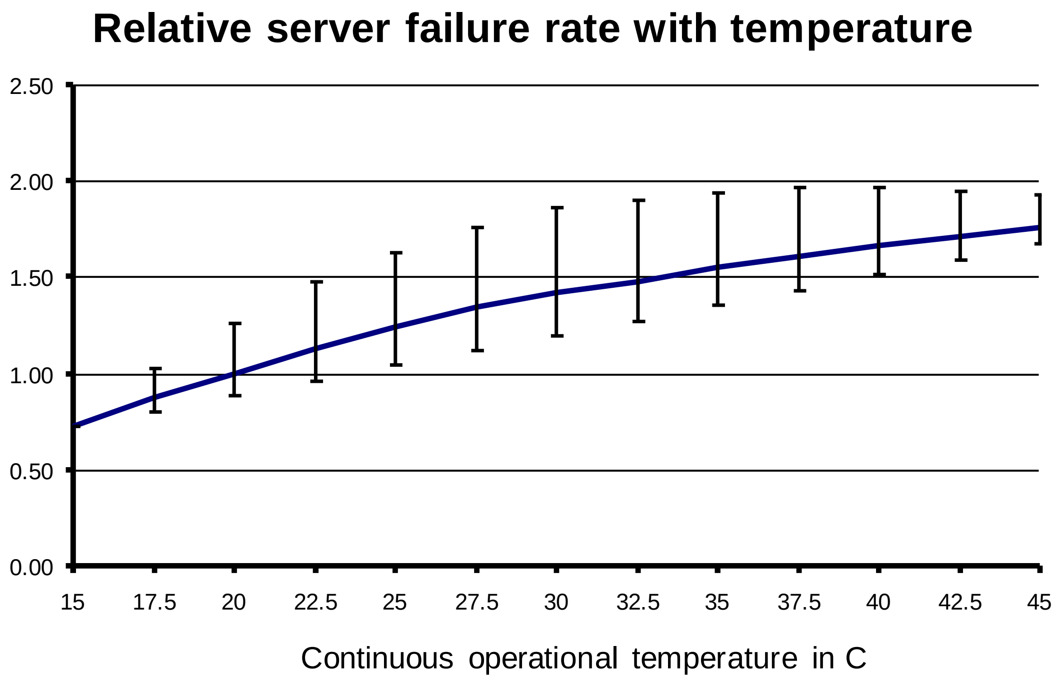
ASHRAE Expanded Data Center Classes

Equipment Environmental Specifications					
Classes	**Product Operation**				
	Dry-Bulb Temperature (°C)	**Humidity Range non-Condensing**	**Maximum Dew Point (°C)**	**Maximum Elevation (m)**	**Maximum Rate of Change (°C/hr)**
Recommended					
A1 to A4	**18 to 27**	**5.5C DP to 60% RH and 15C DP**			
Allowable					
A1	**15 to 32**	**20 to 80% RH**	**17**	**3040**	**5/36**
A2	**10 to 35**	**20 to 80% RH**	**21**	**3040**	**5/36**
A3	**5 to 40**	**8 to 85% RH**	**24**	**3040**	**5/36**
A4	**5 to 45**	**8 to 90% RH**	**24**	**3040**	**5/36**
B	**5 to 35**	**8 to 85% RH**	**28**	**3040**	**NA**
C	**5 to 40**	**8 to 85% RH**	**28**	**3040**	**NA**

Source: ASHRAE Whitepaper – 2011 Thermal Guidelines for Data Processing Environments (Reformatted)

IT Reliability and Temperature

Relative failure rate compared to 20 °C



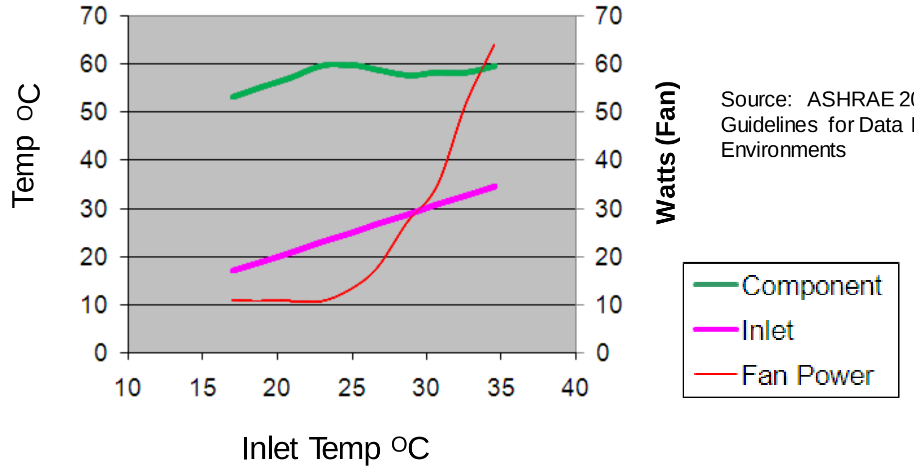
Source: ASHRAE Whitepaper – 2011 Thermal Guidelines for Data Processing Environments

- Manufacturer's data in ASHRAE 2011 guidance shows moderate increasing failure rate with temperature
  - Limited duration operation above 20 °C has marginal impact on overall failure rate
  - Operation below 20 °C reduces failure rate

From The Green Grid

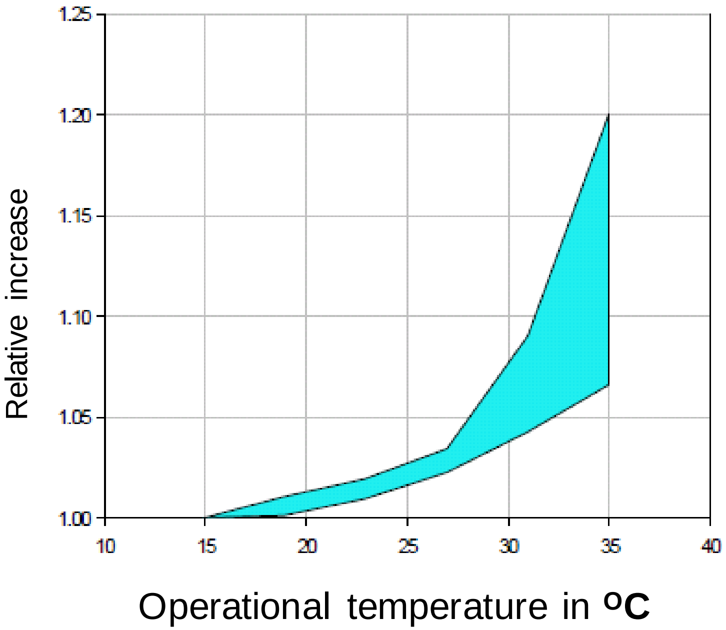
Power Consumption With Temperature

Fan power consumption and component temperature



Source: ASHRAE 2008 Thermal Guidelines for Data Processing Environments

Relative server power increase compared to 15°C inlet temperature



Source: ASHRAE Whitepaper – 2011 Thermal Guidelines for Data Processing Environments

- **Fan power consumption increases as a cube of the airflow rate**
- Large fans consume less energy and create less noise for the same airflow

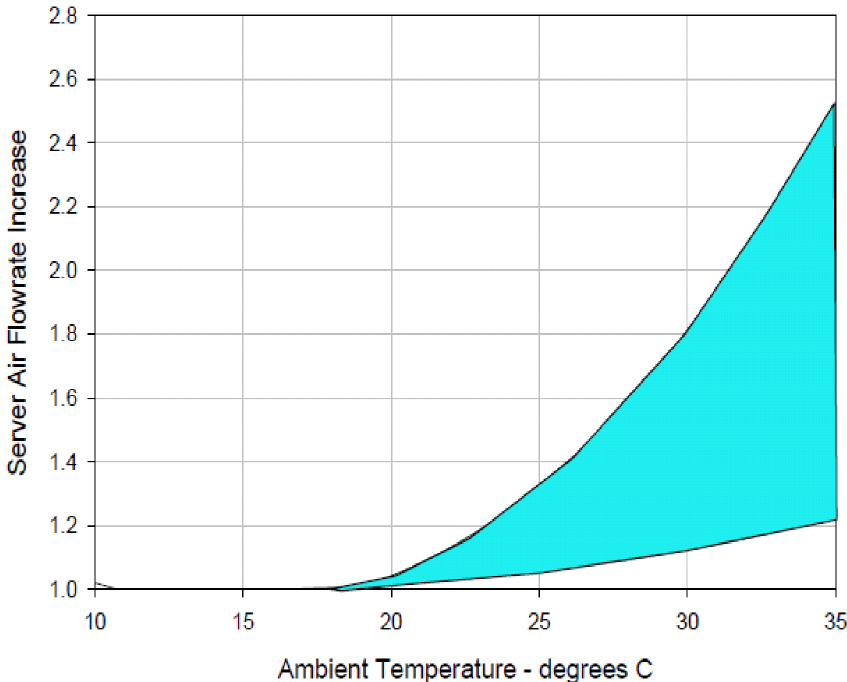
From The Green Grid

Higher Inlet Temperatures..

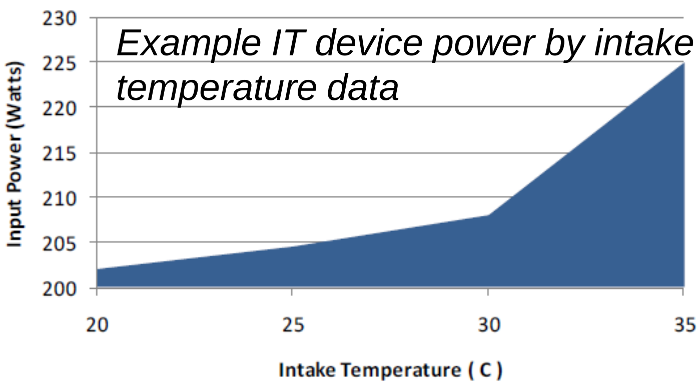
Source: ASHRAE Whitepaper – 2011 Thermal Guidelines for Data Processing Environments

- Power
  - **Increase by up to 20%**
- Airflow
  - **Can double by 35 °C**
  - Requires improved air flow design
  - Increased failure rate if starved
- Noise
  - **Increases as 5th power of rotational speed**
  - Exceed health and safety guidelines
- Exhaust temperature
  - **Can be 20 °C more than inlet**
  - Exceed health and safety guidelines

Air flow increase with ambient temperature

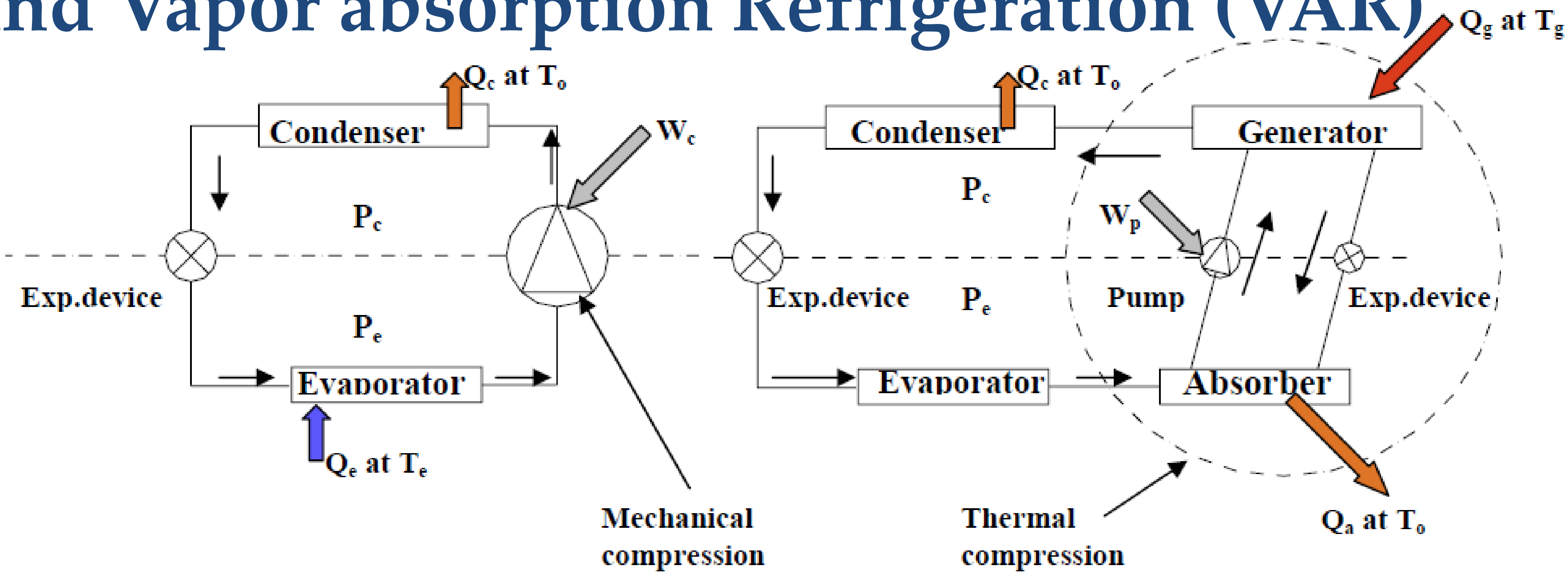


Total Device Power



From The Green Grid

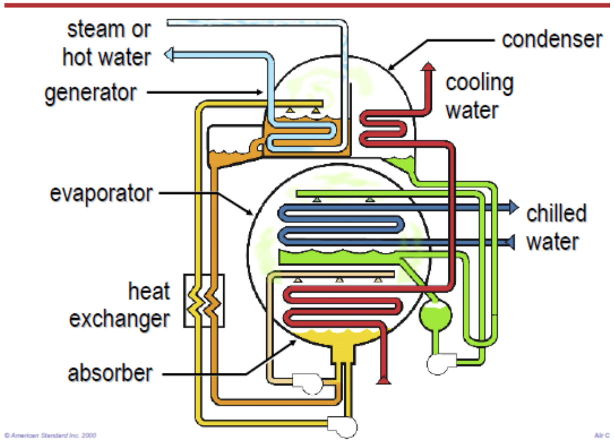
Comparison between Vapor compression (VCR) and Vapor absorption Refrigeration (VAR)

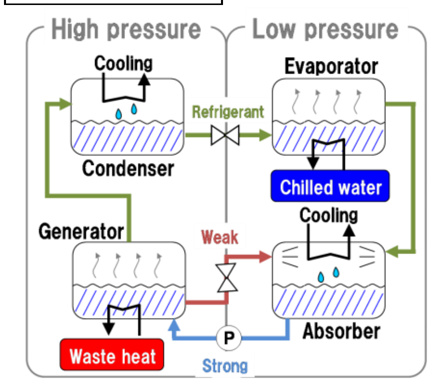


a) VCRS

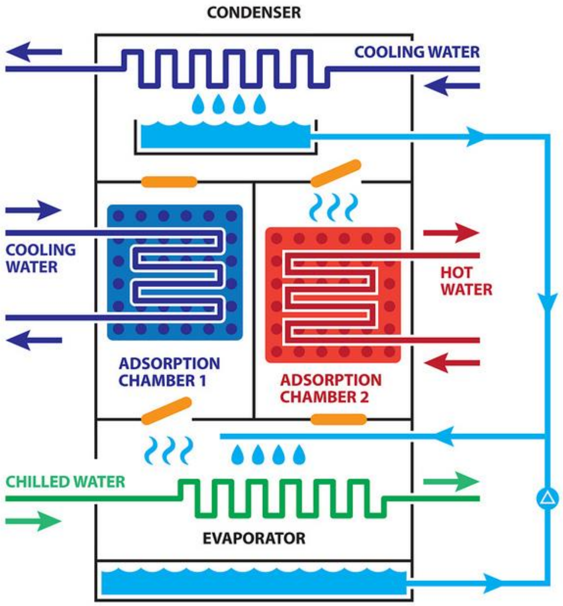
b) VARS

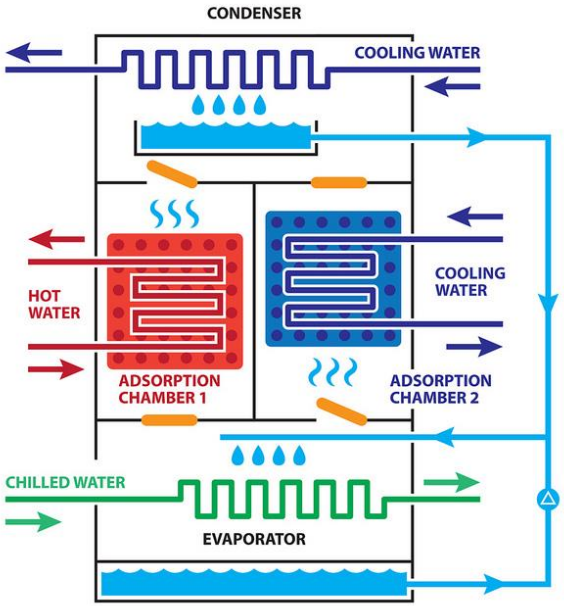
Absorption Refrigeration Cycle



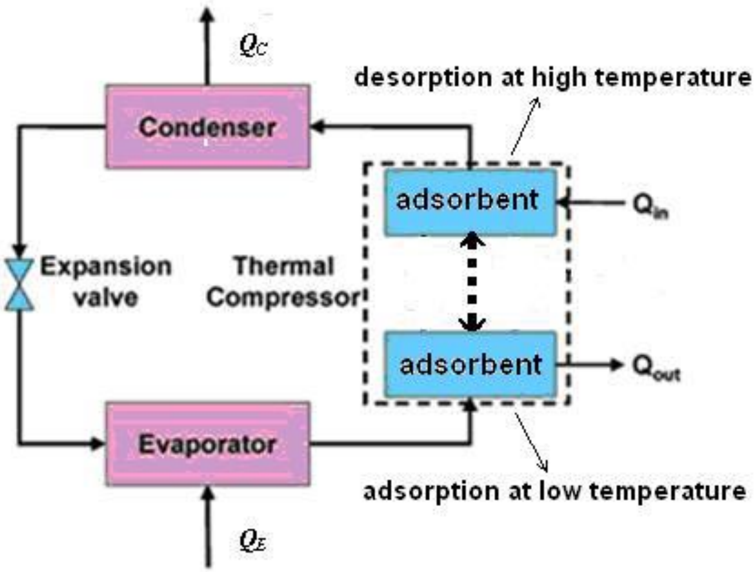


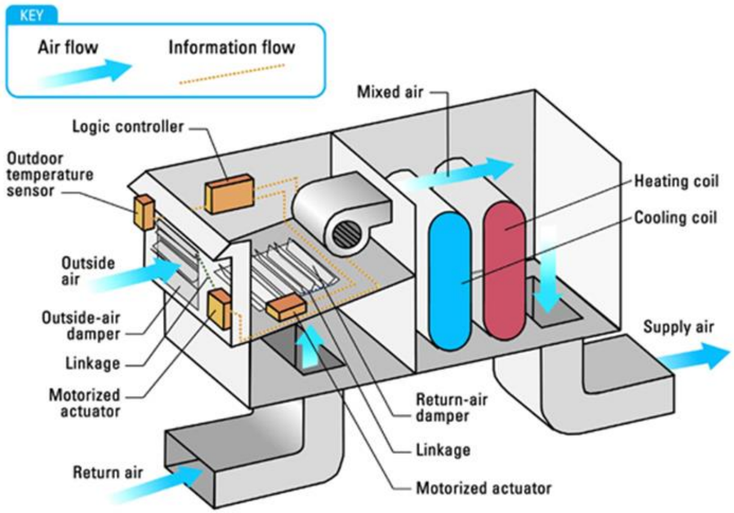
Adsorption refrigeration

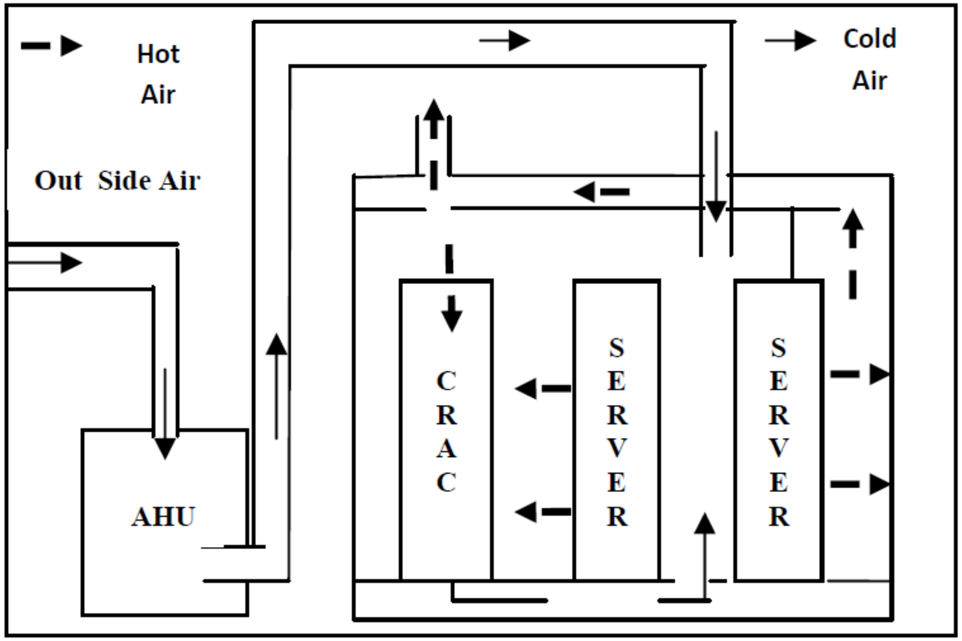




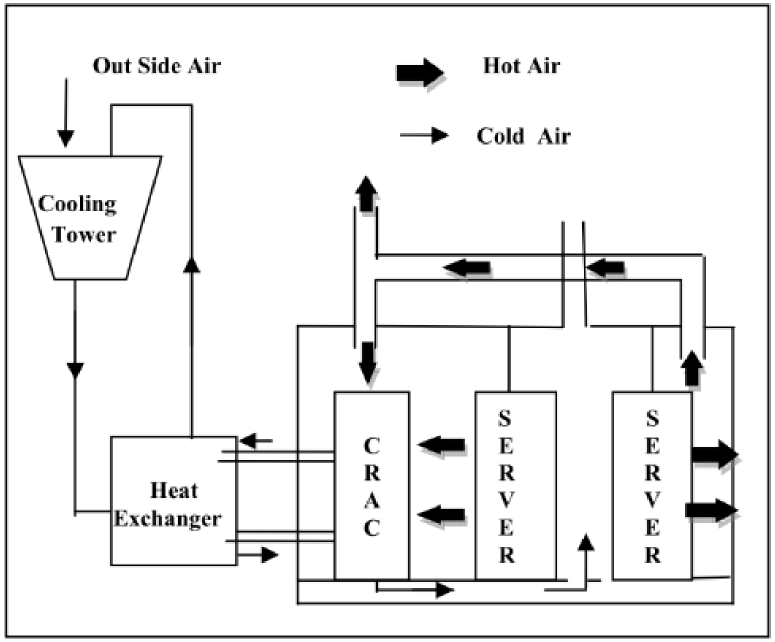
Essential components of the vapor absorption cycle







Air Economizer



Water Economizer

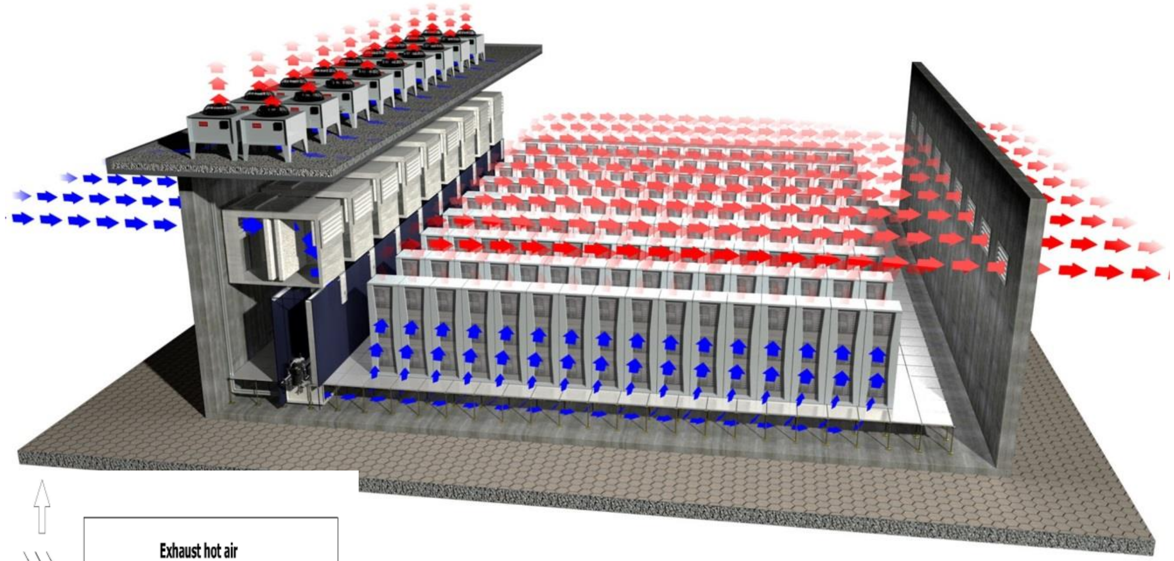
Ref : Christy Sujatha, D., & Abimannan, S., "Energy Efficient Free Cooling System for Data Centers", In Cloud Computing Technology and Science (CloudCom), 2011 IEEE Third International Conference on (pp. 646-651). IEEE, 2011.

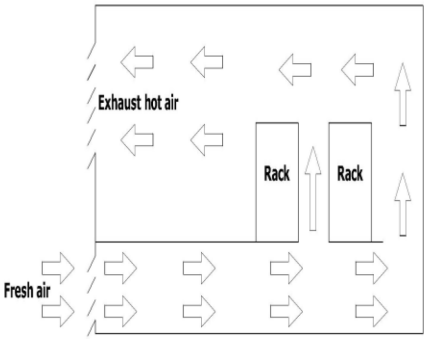
Green Energy

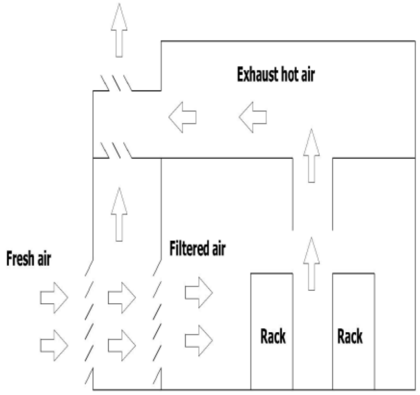
Data Center Free Cooling Economizers

Airside free cooling

Direct air cooling : outside air is brought into the data center directly through filters or indirectly through heat exchangers.







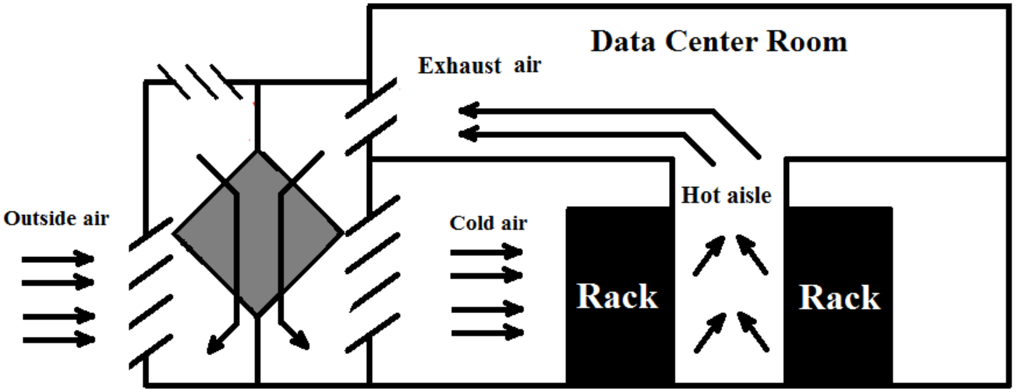
https://www.stulz.de/en/newsroom/professional-article/news/a-brief-history-of-precision-air-conditioning-technology/

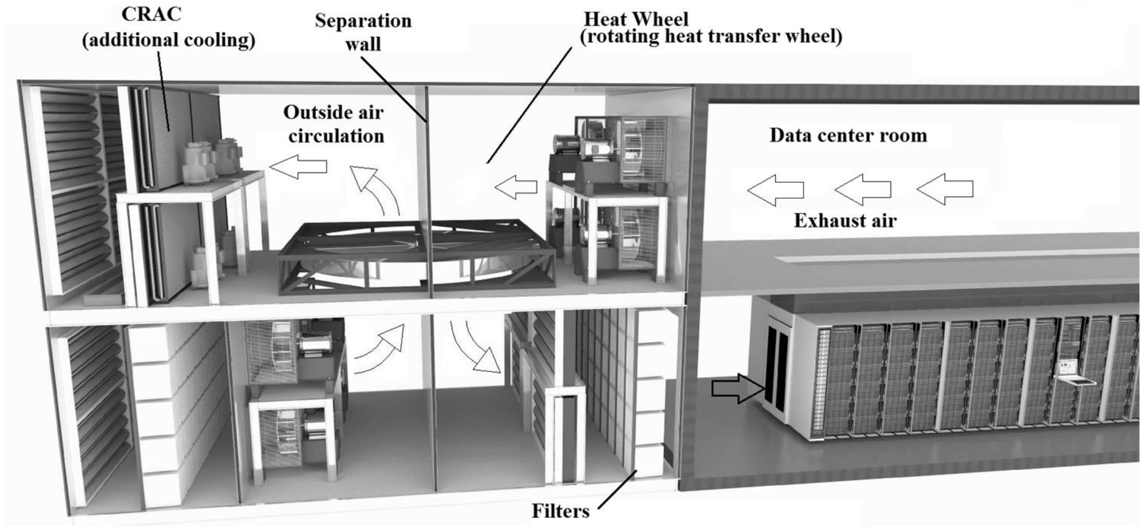
Data Center Free Cooling Economizers

- **Indirect air cooling**

Air side free Cooling

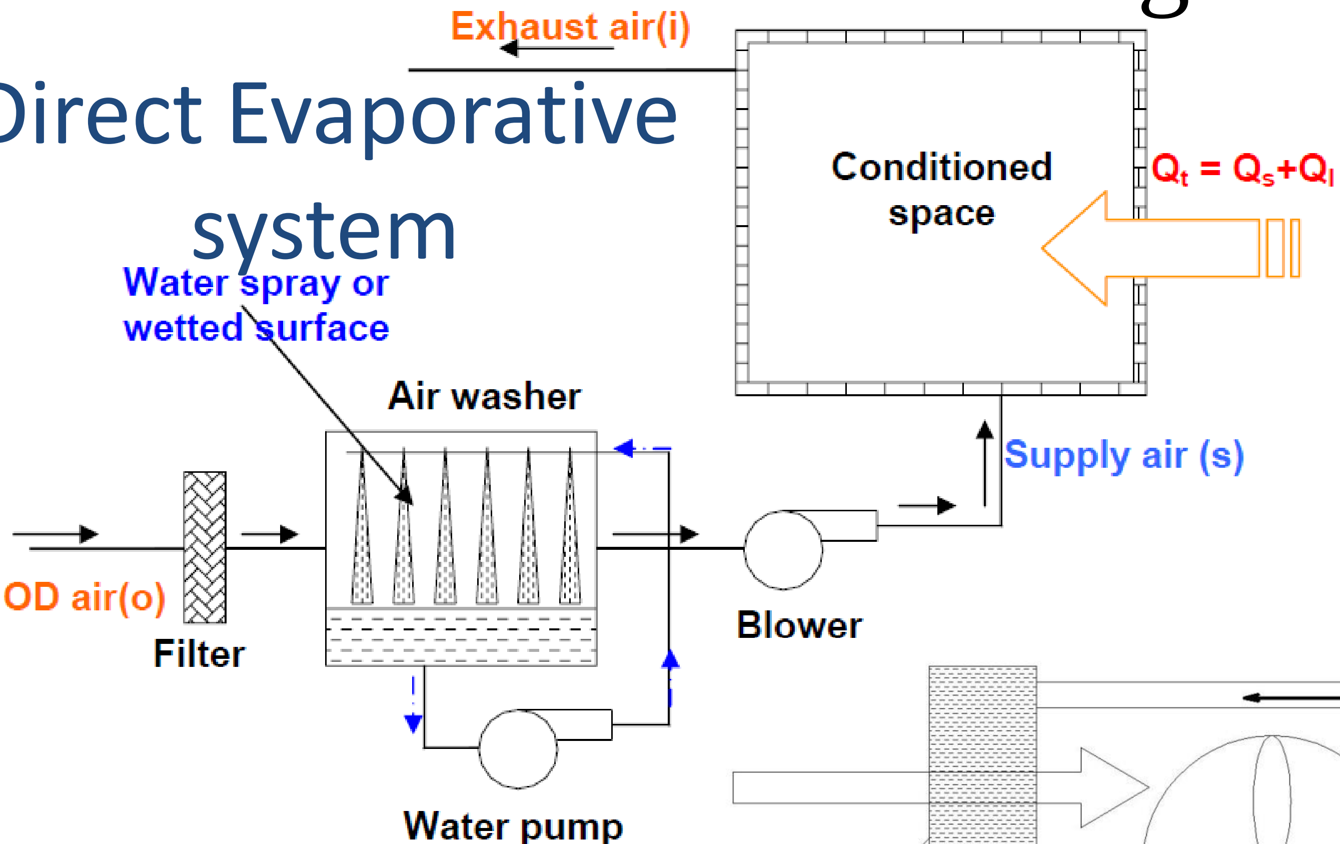
1. Air quality – need filtering- Air filtering → reduces the air flow
2. Require cleaning and replacement
3. High Humidity Case
4. Air Volume and Velocity needed is very large
5. Sizes Vs Costs

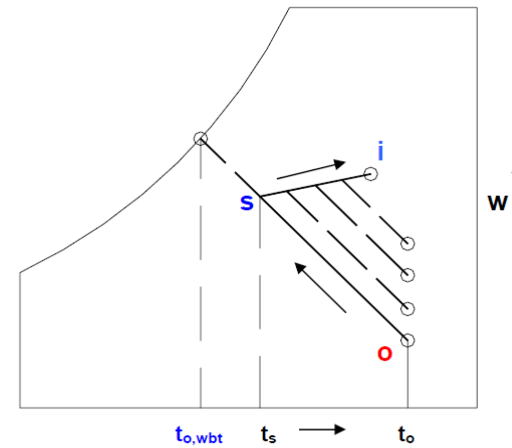


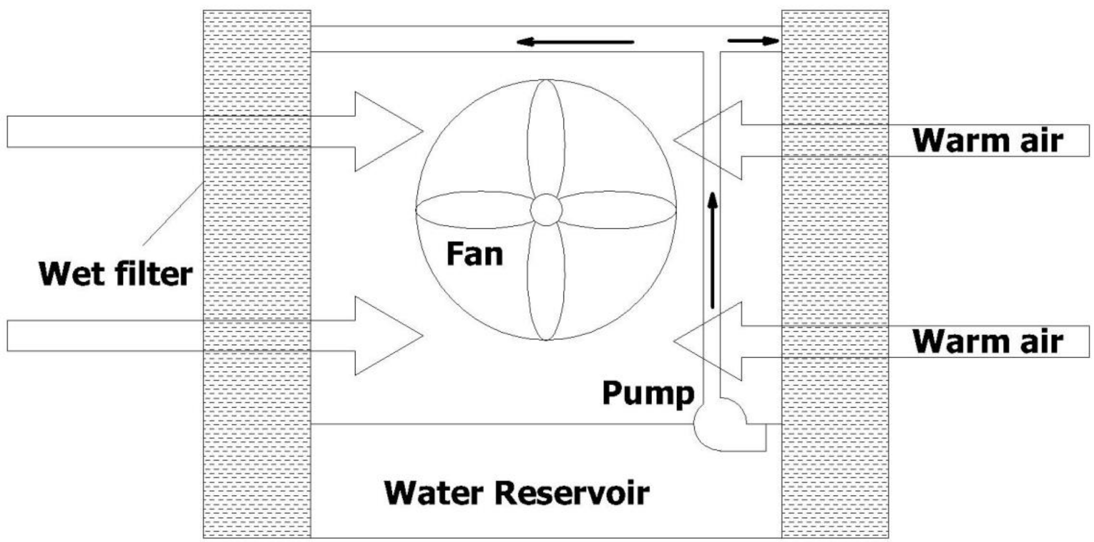


Data Center Free Cooling Economizers

Direct Evaporative system

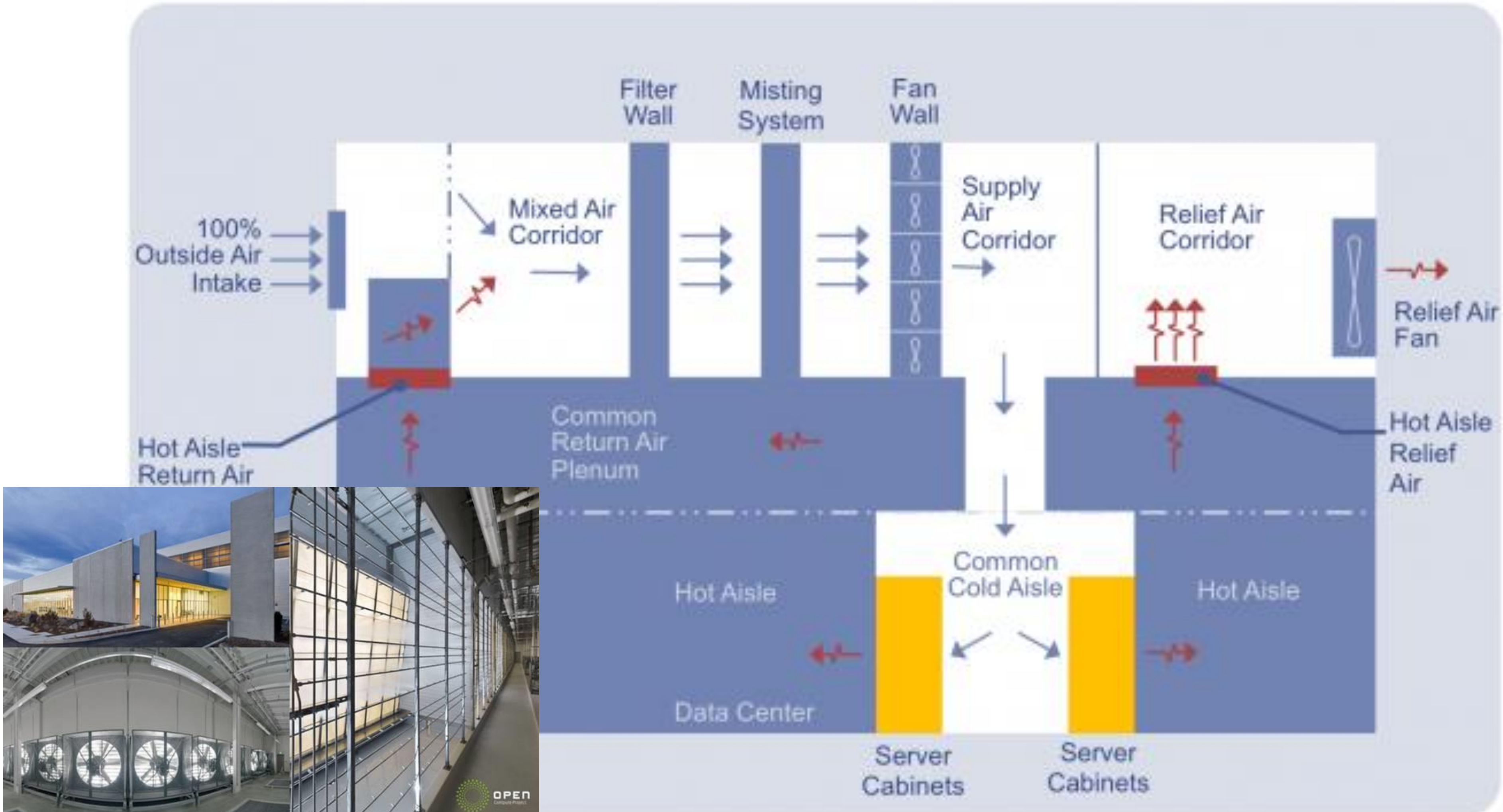




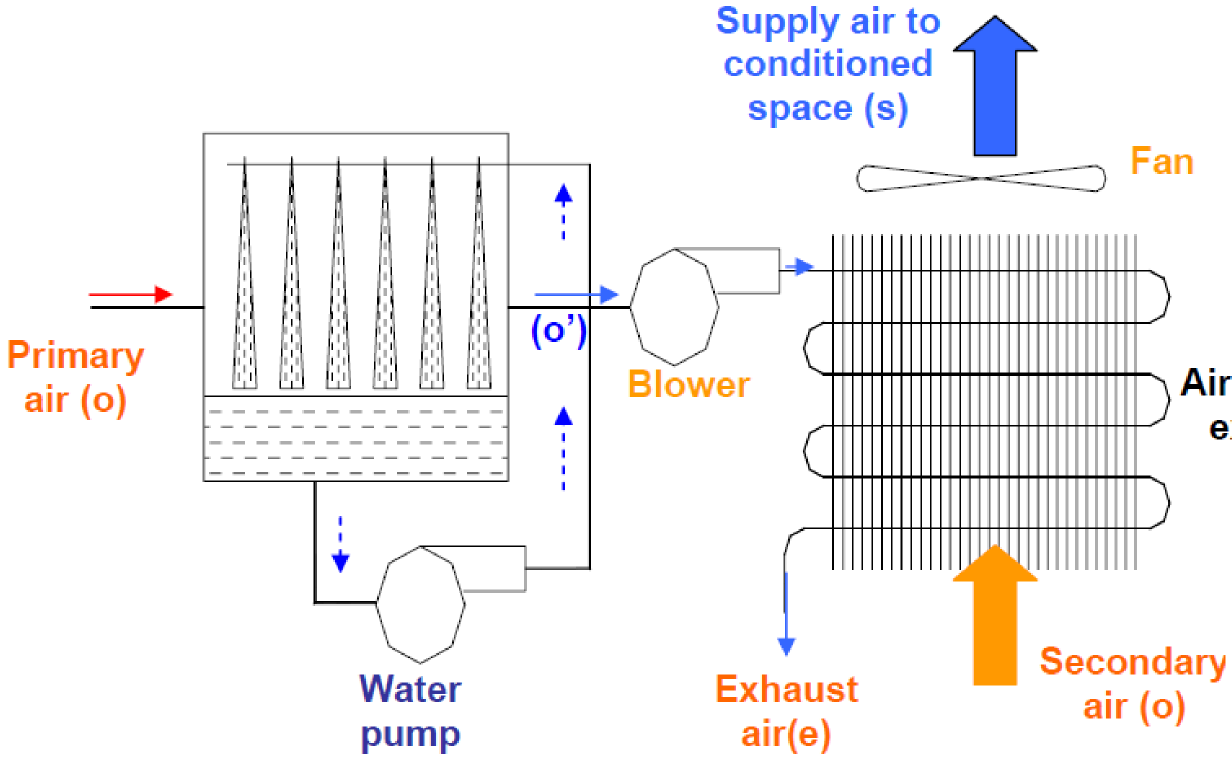


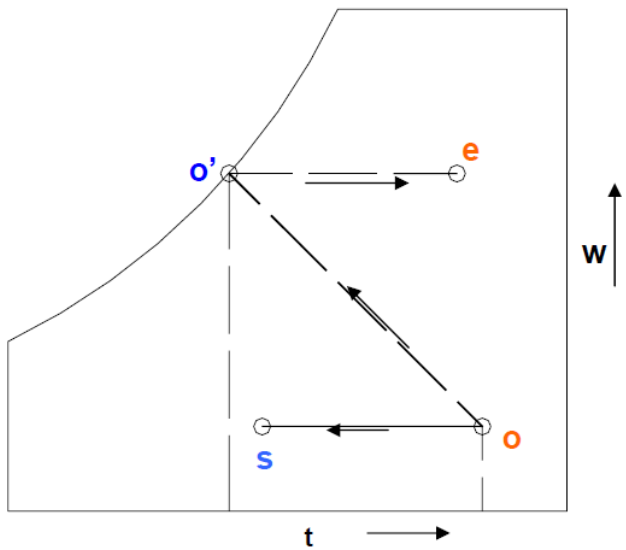
Facebook Prineville, Oregon, datacenter

No mechanical cooling & cooling tower

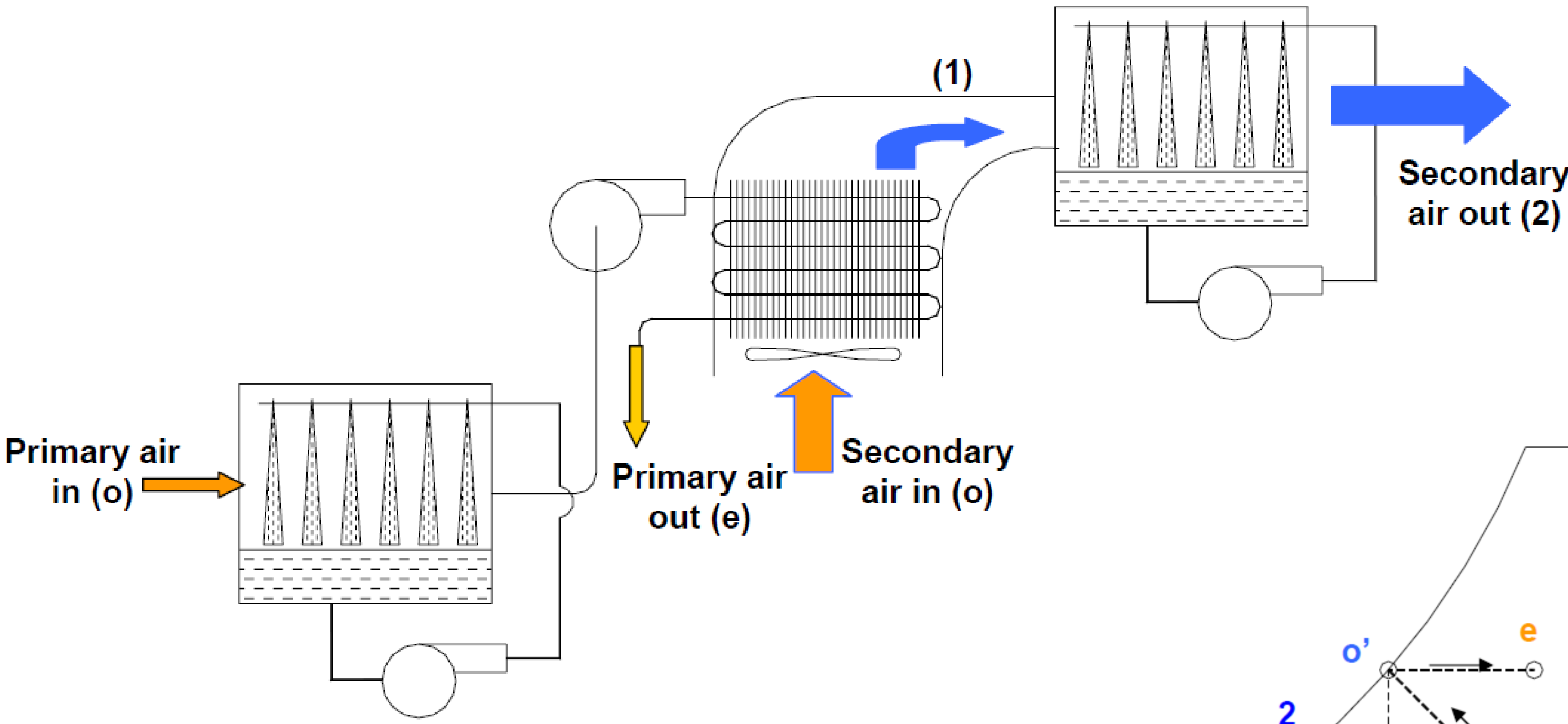


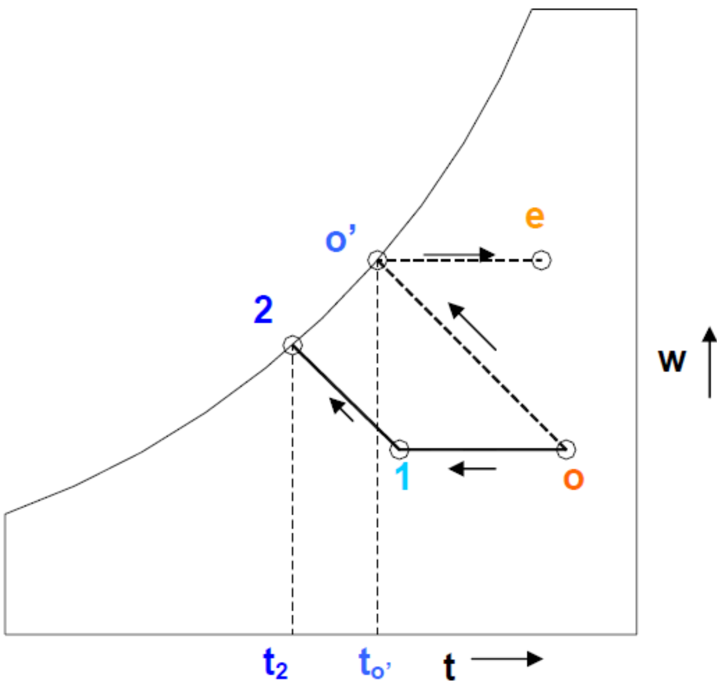
Indirect evaporative cooling system





Multi-stage evaporative cooling systems

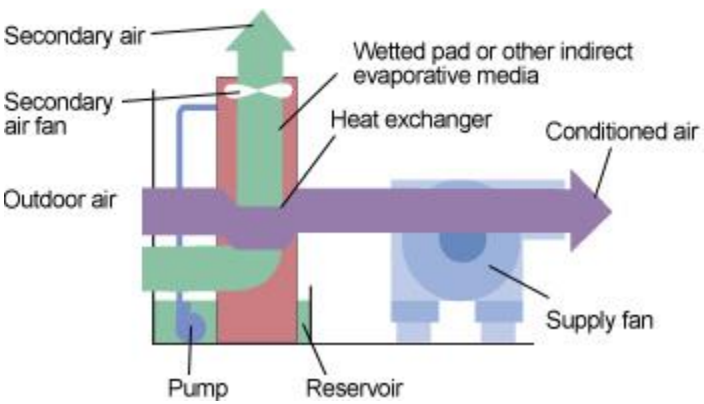




Data Center Free Cooling Economizers

- **Indirect Evaporative Cooling**

air is brought (indirectly) to some chamber and used along with water evaporation to cool the air



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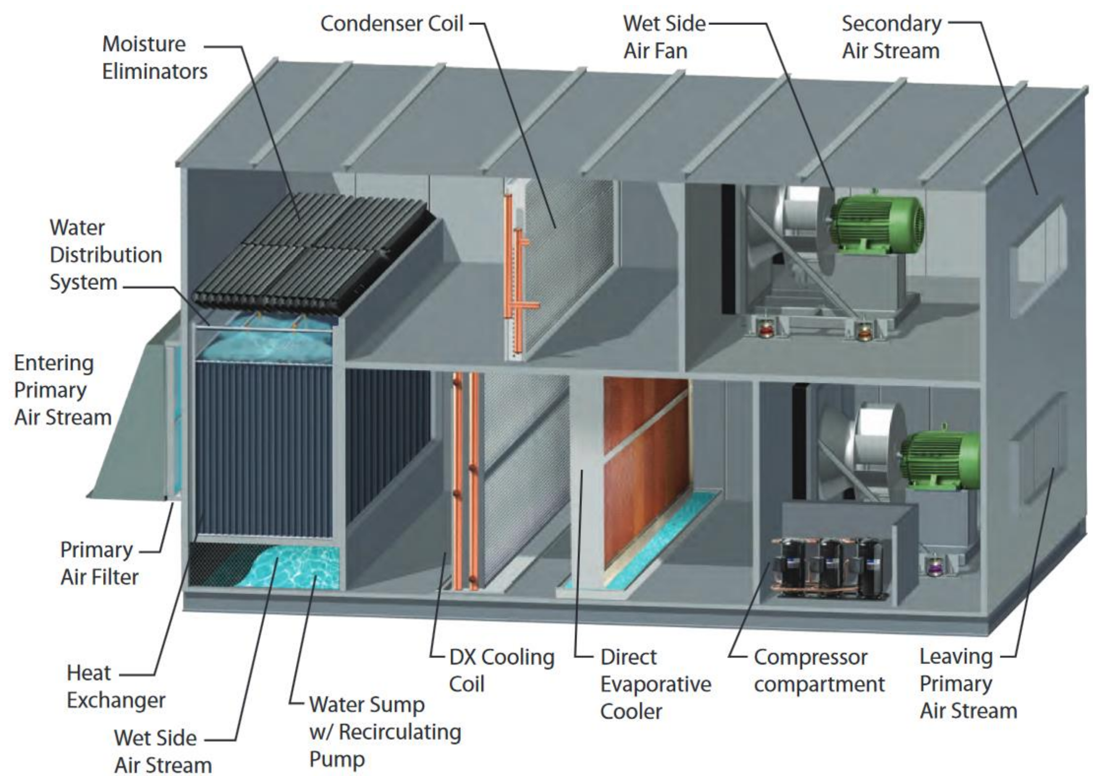
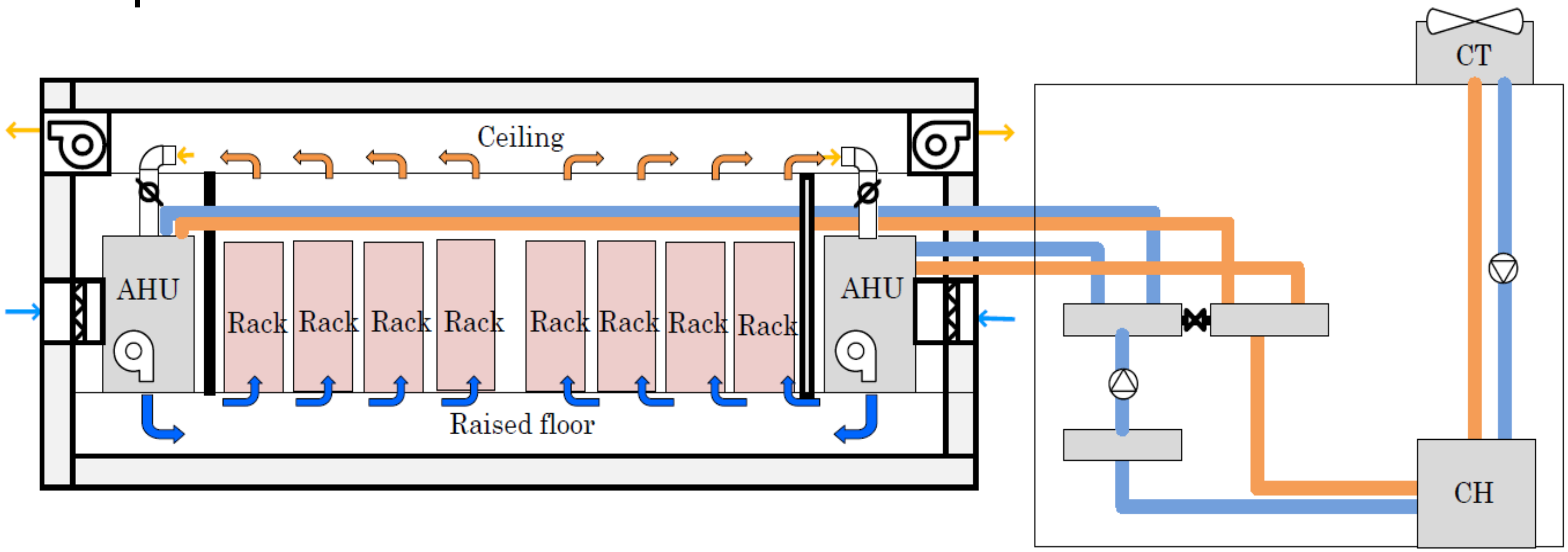


Data Center Free Cooling Economizers

- **Water-Side Free Cooling** where a cooling medium, such as water, circulates directly through cooling towers rather than the chillers or compressors.



Water side free Cooling

- Changeover from free to mechanical Refrigeration System
- Require cleaning and replacement

Using Heat pipe technology for datacenter

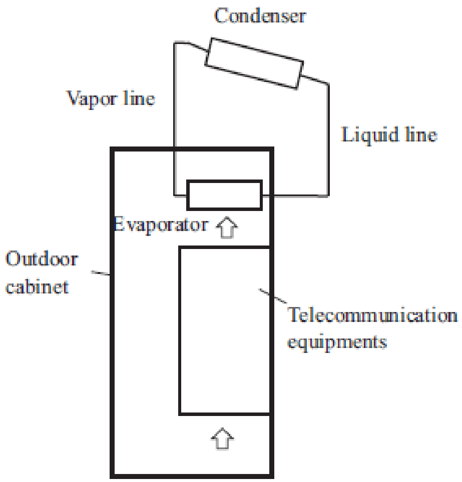
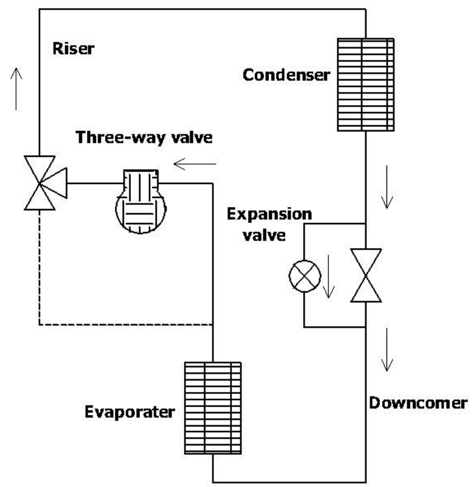
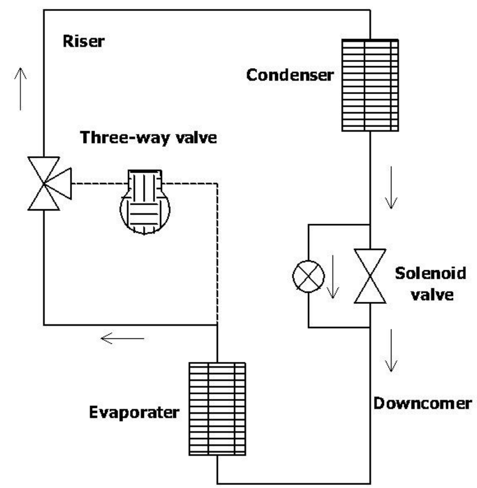


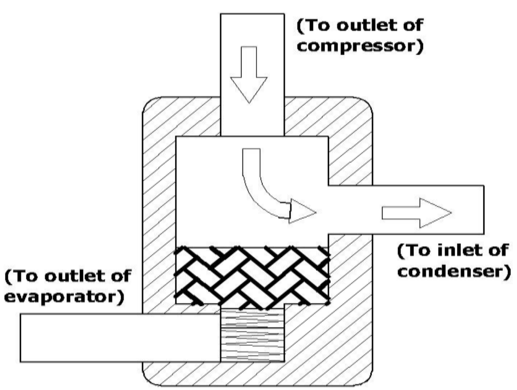
Fig. 17. Thermosyphon loop for cooling telecommunication equipments in the outdoor cabinet [86].



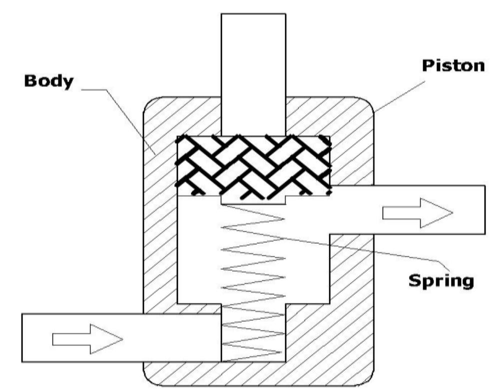
Vapor compression mode



Thermosiphon mode

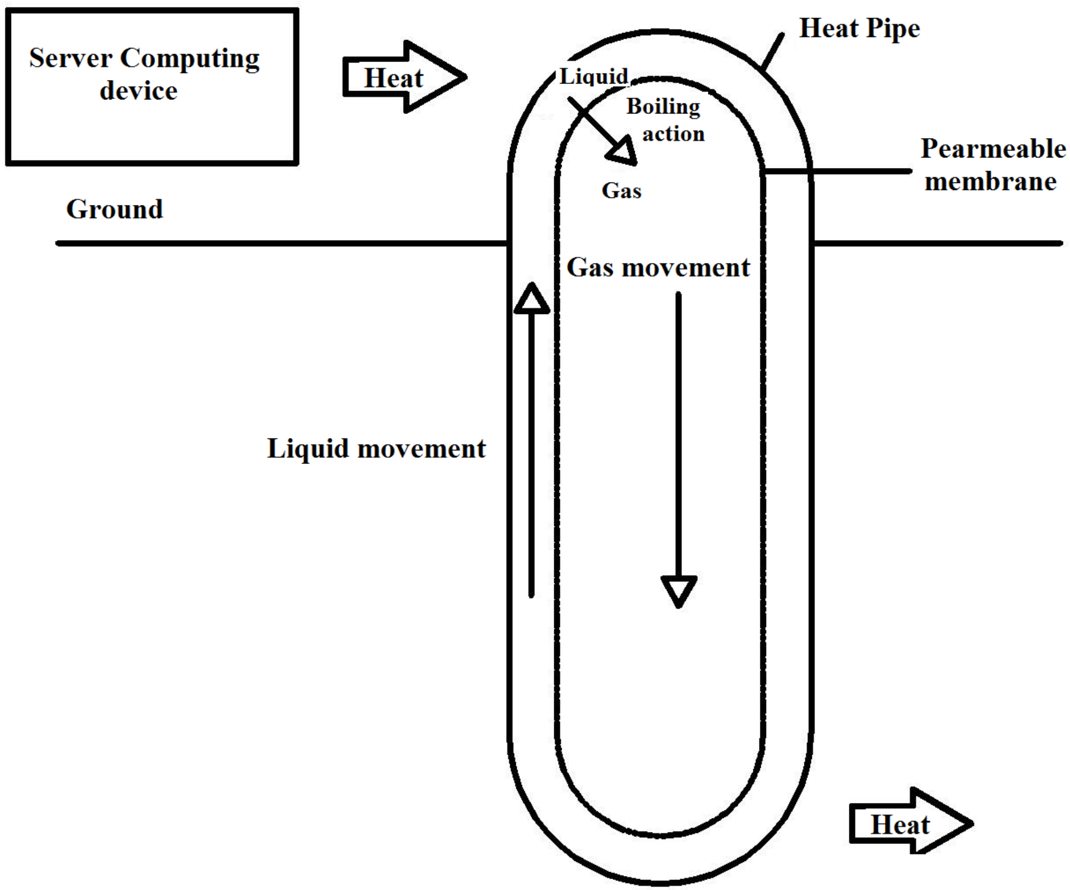


Vapor Compression mode



Thermosiphon mode

US Patent 20140368991 A1



Datacenter cooled by geothermal mechanism along with heat pipe.

US7525207B2; 2009. From Google

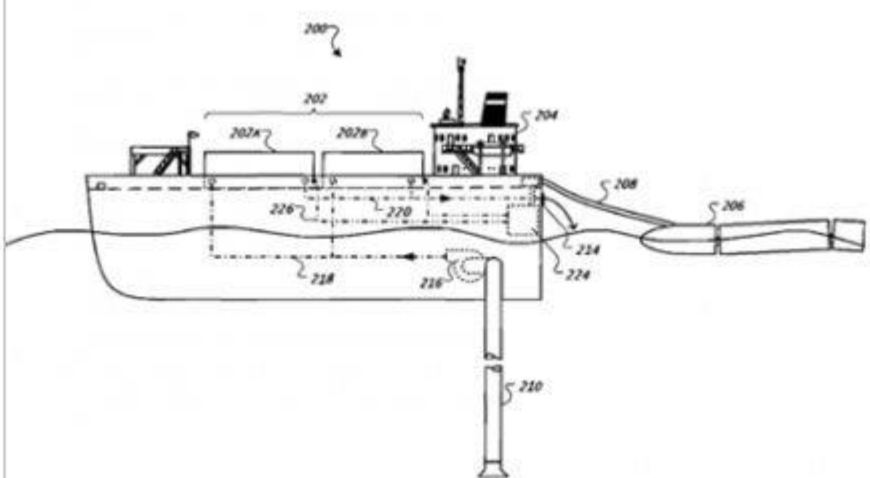
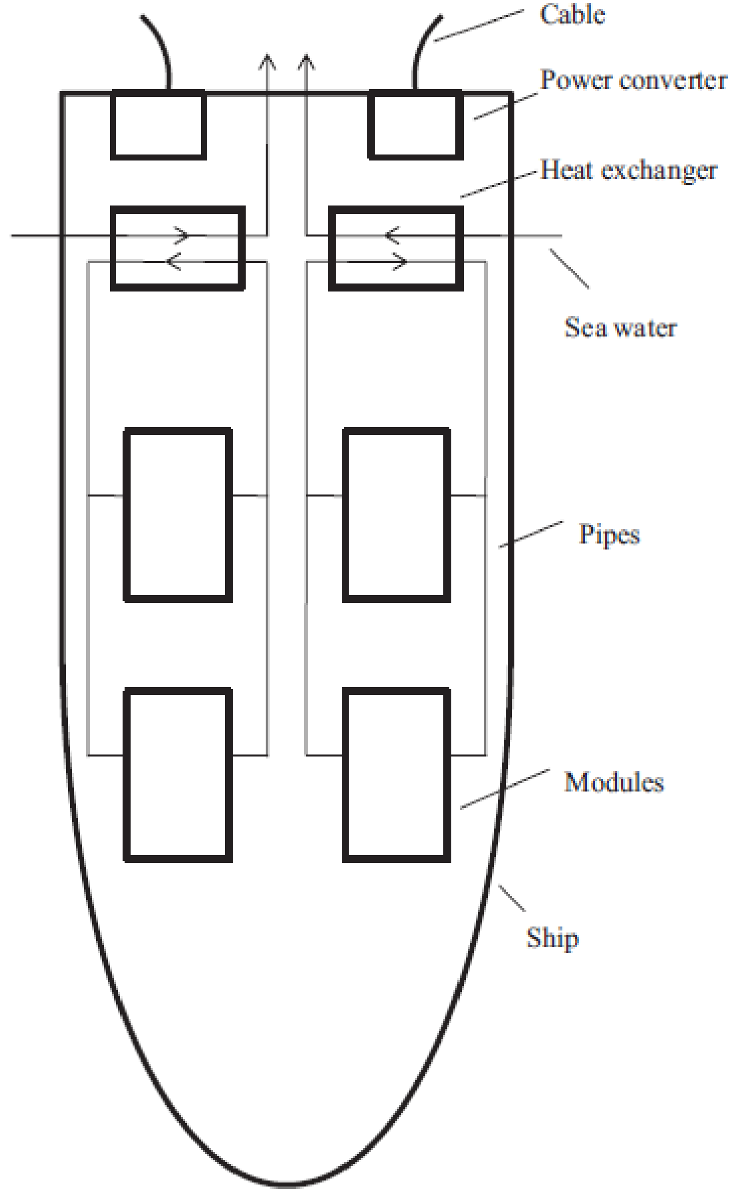
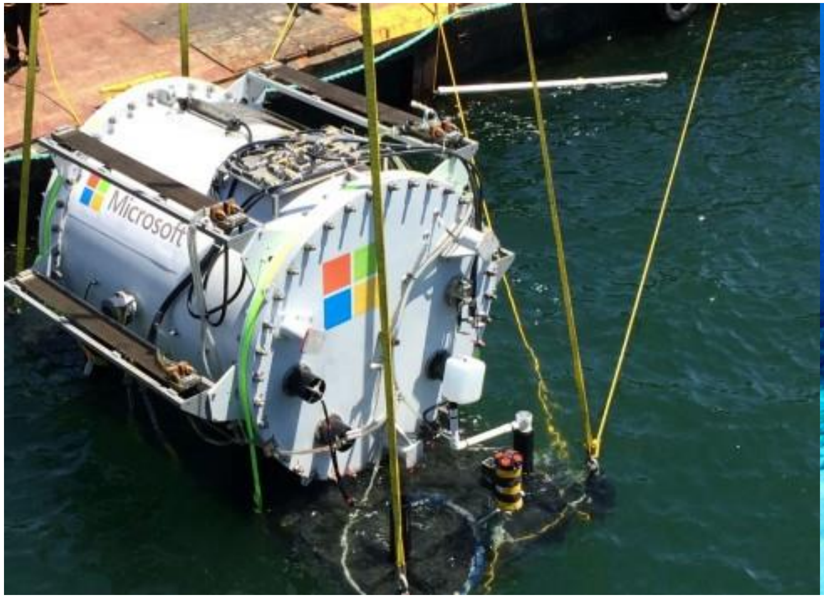


FIG. 2

This is the side view of the data center system.



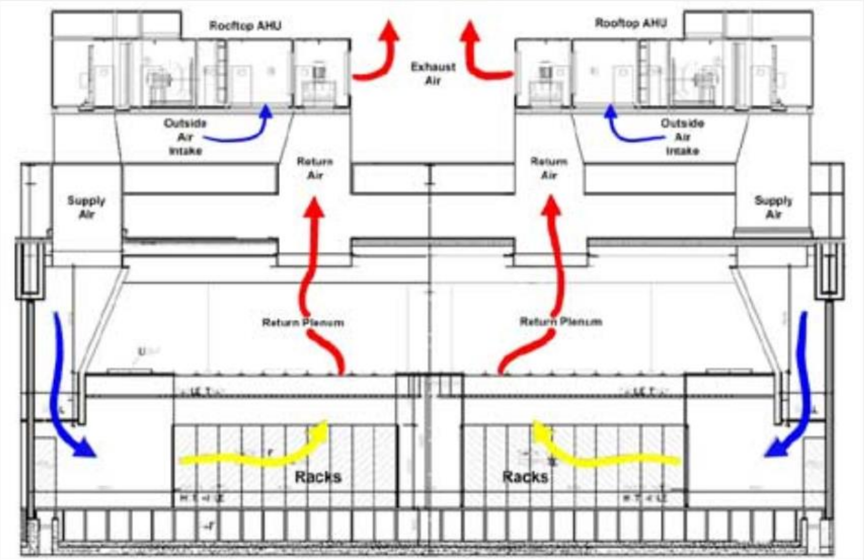
Microsoft testing underwater data centers



http://www.businessfinancenews.com/27526-microsoft-corporation-plans-to-store-your-data-10000-leagues-under-the-sea/

- **Microsoft** – the chiller-less data center. Microsoft announced that its huge facility in Dublin, Ireland is running without any chillers.

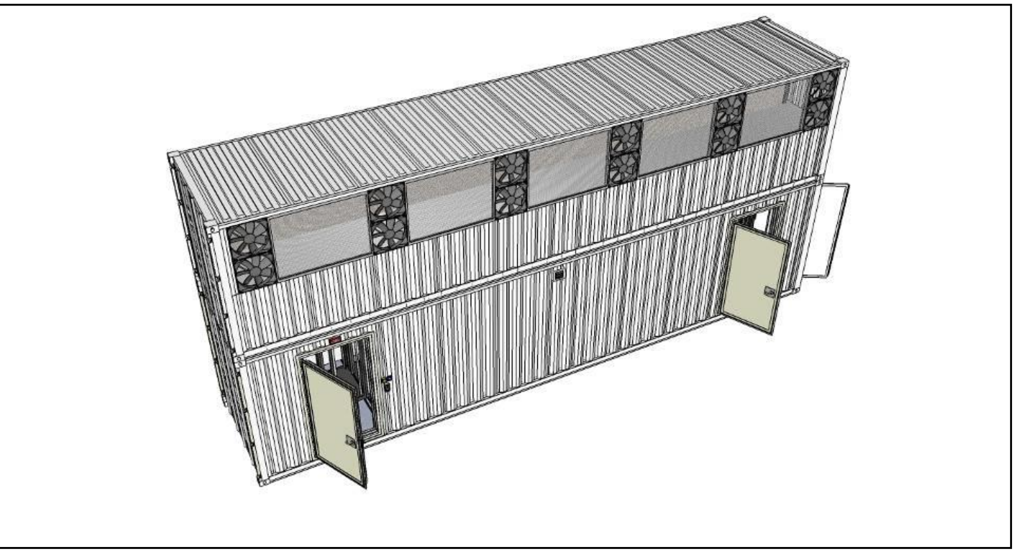
Dublin Data Center: Free Cooling Diagram

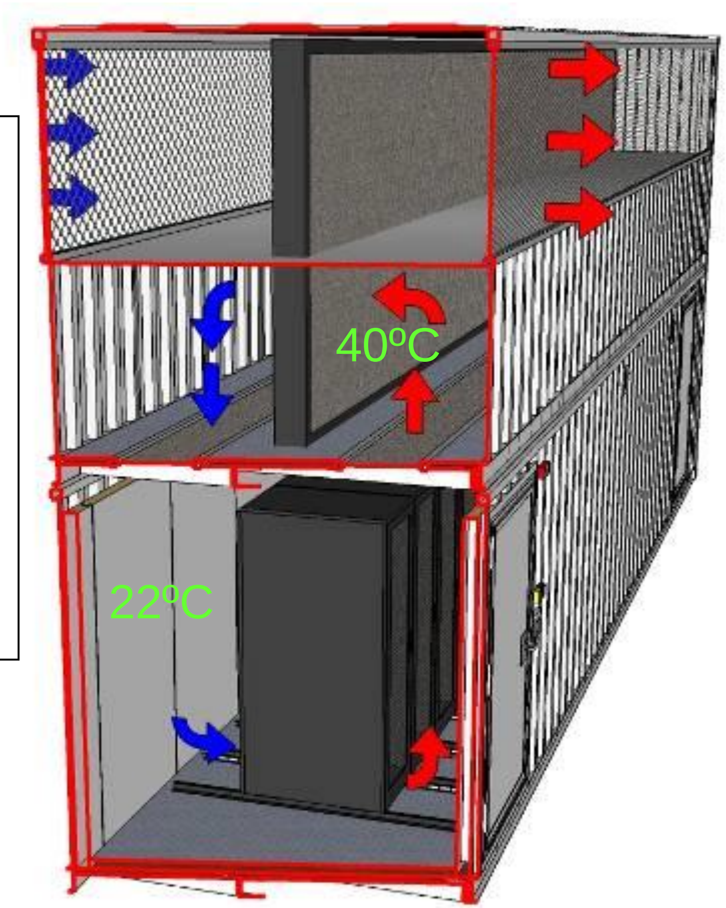


A diagram of the air economization (free cooling) system at the new Microsoft data center in Dublin, Ireland (click for larger version of image)

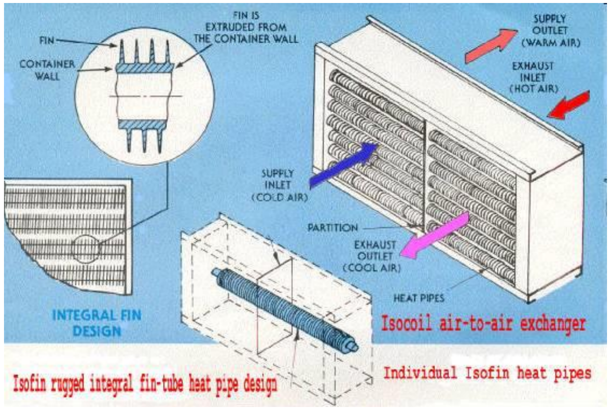
Cooling Operation

15ºC





31ºC



Claimed PUE 1.07

Using The ASHRAE Classes

Free cooling depends on the setting temperature

The Green Grid has identified that much of Europe can benefit from air side economizers while remaining within ASHRAE Class 2 **Recommended** upper guideline of 27 °C

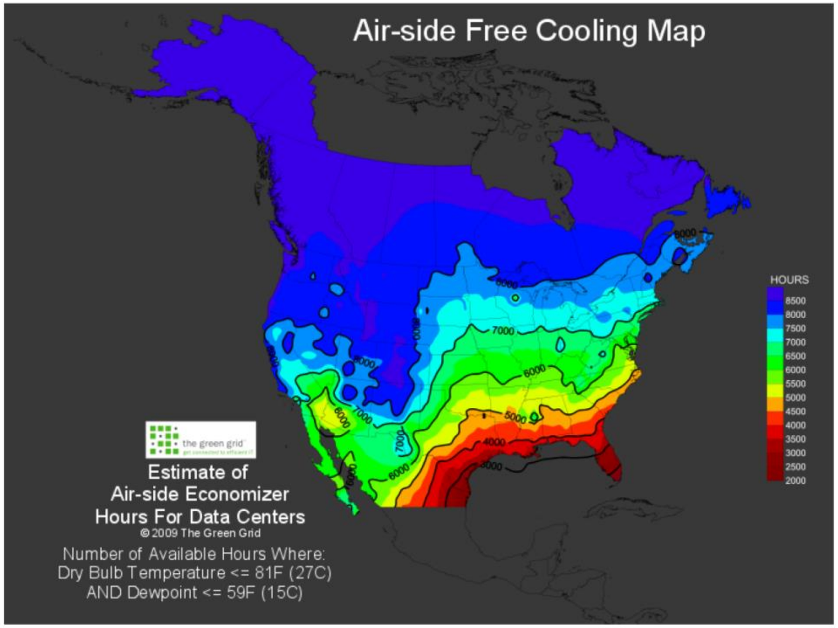


Figure 6. 2009 North America free cooling map 27°C

Hours per year when dry bulb temperature less than or equal 27 °C

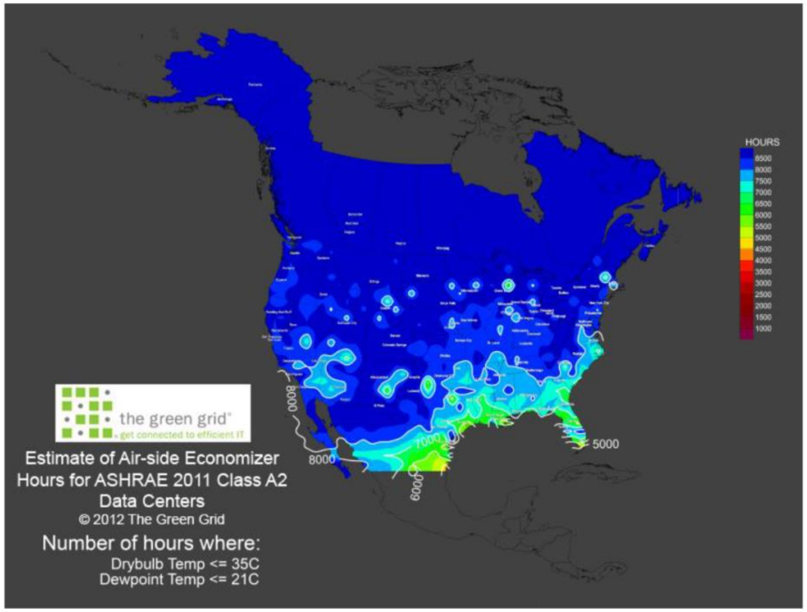


Figure 8. 2012 North America free cooling map 35°C

Hours per year when dry bulb temperature less than or equal 35 °C

From The Green Grid

From "IT environmental range and data center cooling analysis"

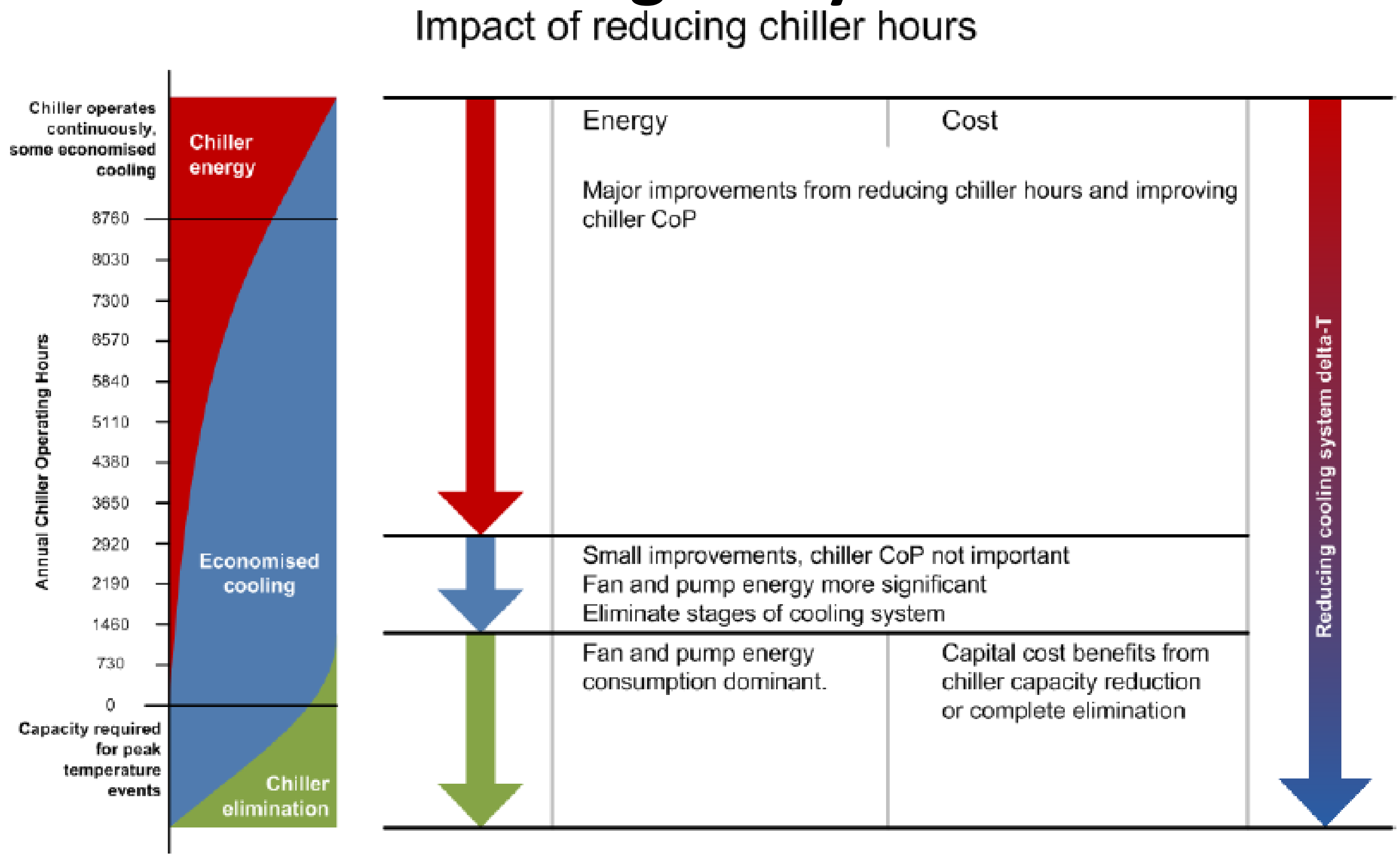


Figure 11 Impact of reducing chiller hours

The Different Technologies for Cooling Data Centers

APC white paper #59

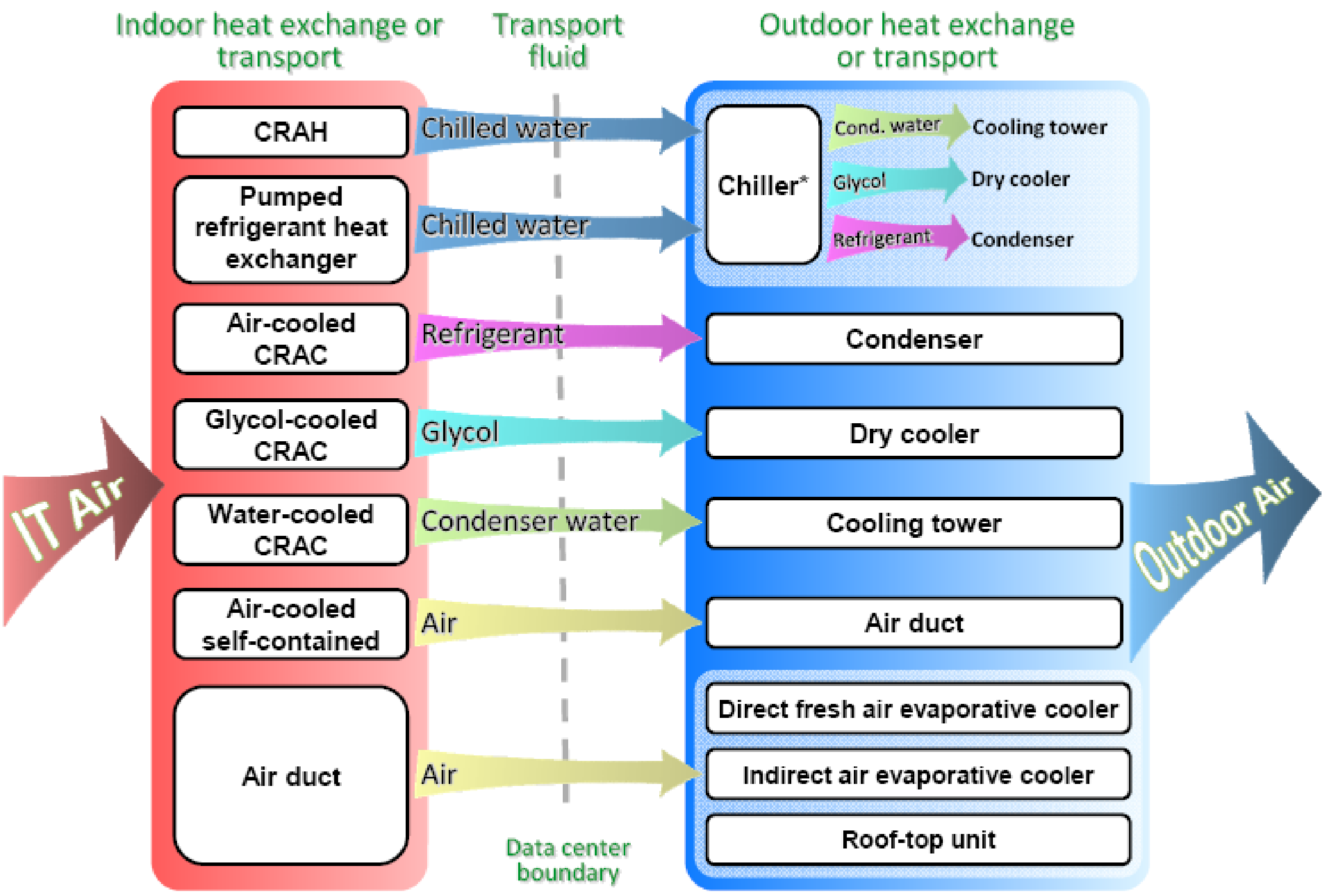


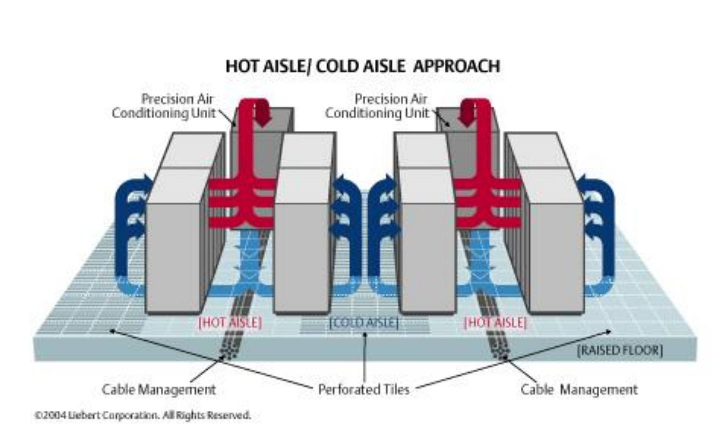
Figure 1

Simplified breakdown of the 13 fundamental heat removal methods

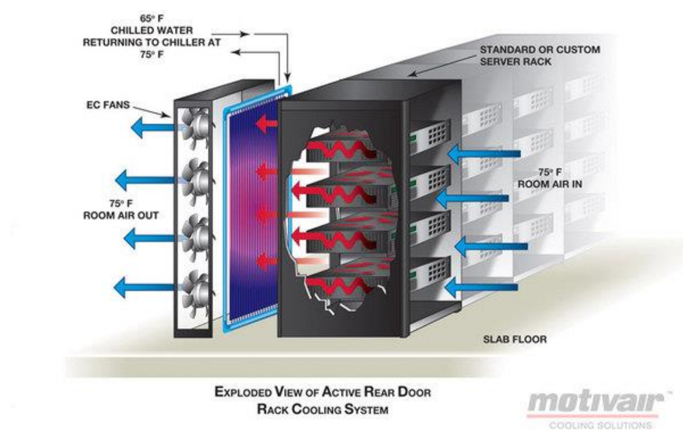
* Note that in some cases the chiller is physically located indoors.

Data center cooling

- Air cooling
- Liquid cooling
  - Direct cooling
  - Indirect cooling
- Hybrid cooling



Air cooling schematic



Liquid cooling schematic

Multi-scale Thermal Management

Renewable and Sustainable Energy Reviews 43, Pages 981–996

- Scale 1: Chip
- Scale 2: Server
- Scale 3: Chassis
- Scale 4: Cabinet (Rack)
- Scale 5: Room
- Scale 6: Plenum
- Scale 7: Building

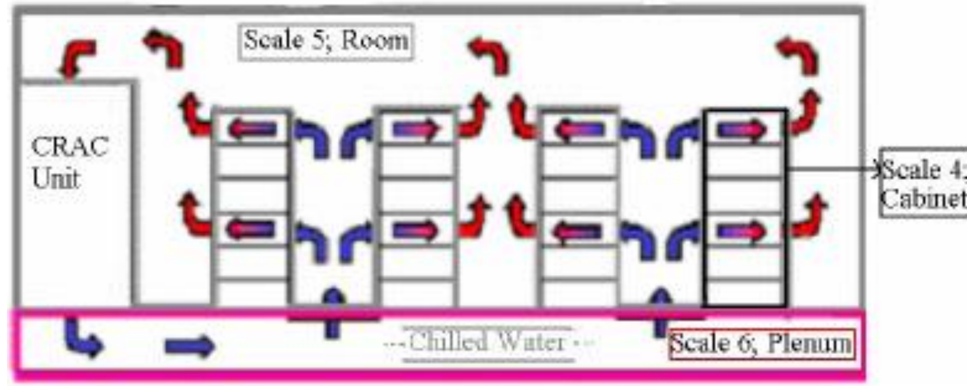
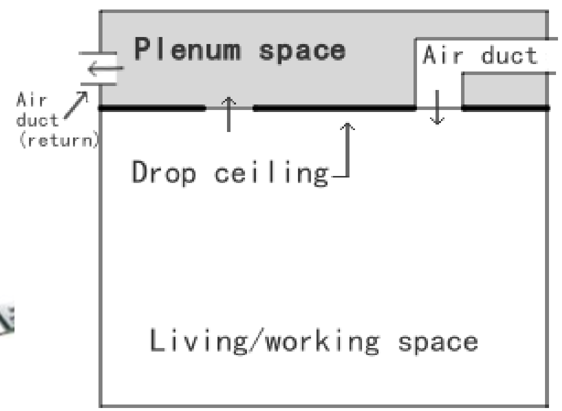


Figure 1. Air-cooled data center with involved scales



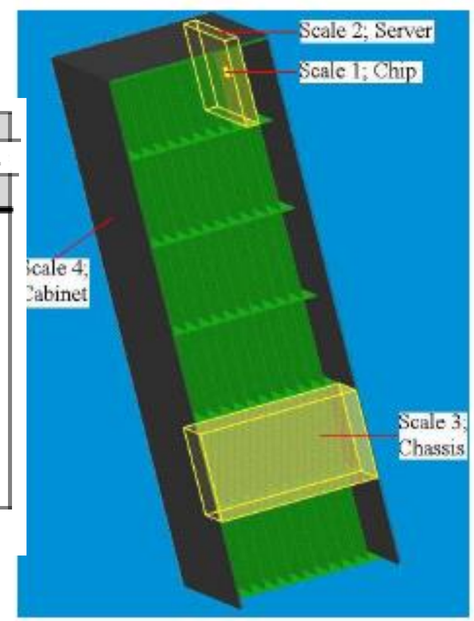


Figure 2. A blade server cabinet with involved

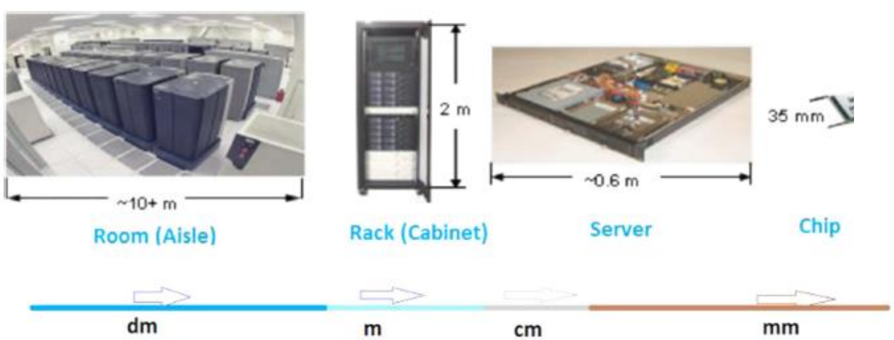


Fig. 5. Data center length scales (Adopted from [81]).

Data center air stream

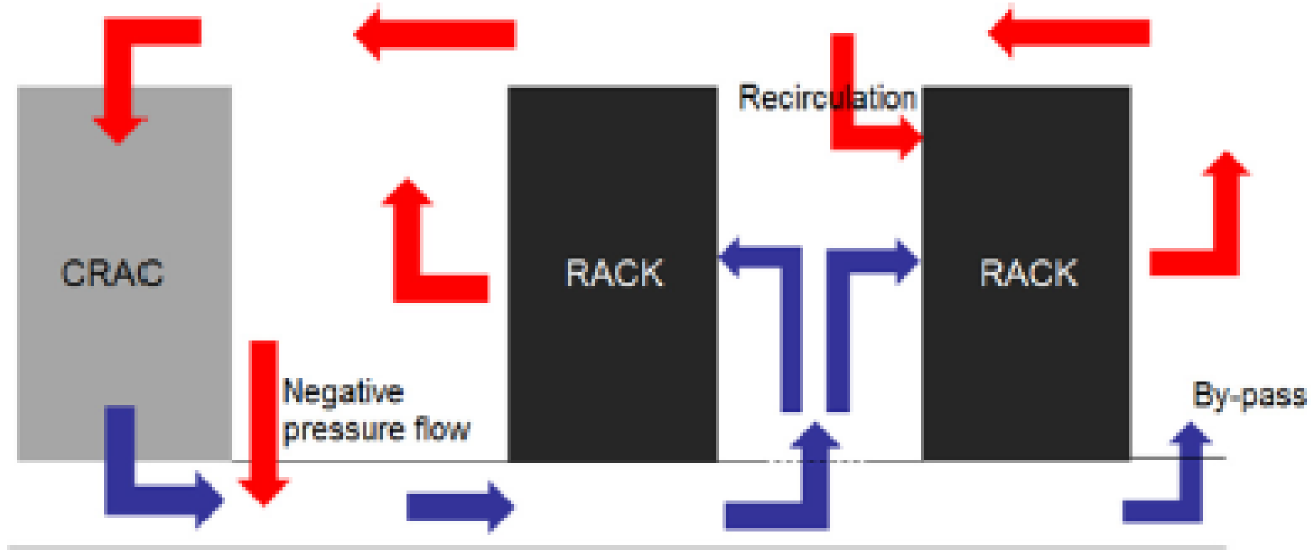
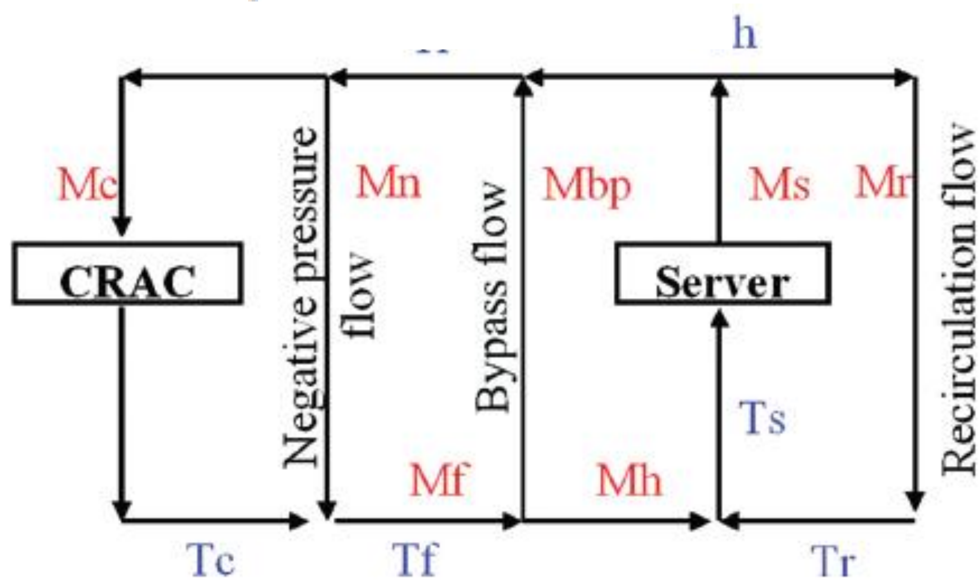


Fig. 6. Air flow circulation with standard problems (by-pass, recirculation, negative pressure flow) in an air cooled data centre. Blue lines represent cold air while red lines represent hot air.

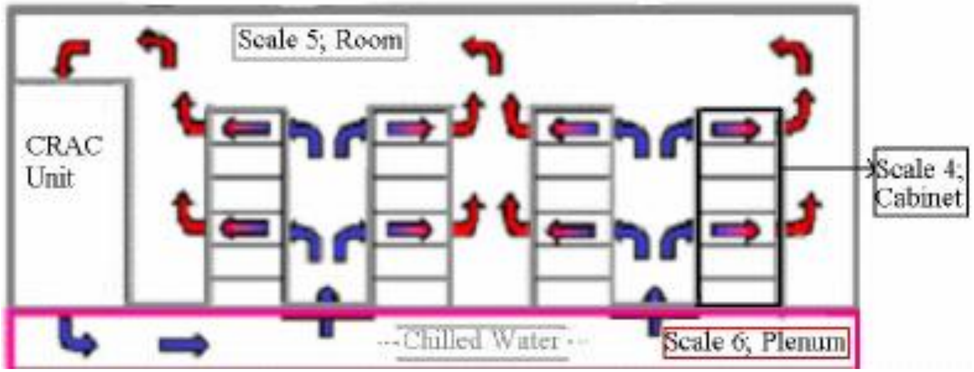
Data center air streams. (Note: CRAC: computer room air conditioning unit; Server: IT equipment server; bp: bypass; c:CRAC; f:floor; h:hall; M:mass flow rate; n: negative pressure; r: recirculation; s: server; T:temperature.)



Thermal challenges

- *Technological Challenges: Component Level*
  - *Thermal Effects on Transistor Operation*
    - For 45-nm down to 28-nm technology, **leakage amounts to 40–50% of the total power dissipation**.
    - **ITRS predicts the chip power dissipation continues to rise at a decreased rate**.
- *Spatial and Temporal Variations in Heat Load*
  - **Spatially nonuniform heat loads** are currently mitigated using effective heat spreading.
    - micro-structured liquid flow heat sinks or chip-integrated arrays of thermoelectric coolers.
  - **Transient response** (component) to varying heat loads is attenuated by effective heat capacity of packaging.

Technological Challenges: System Level



- *Multiple Heat Transfer Interfaces*
- *Standardization for IT Cooling Equipment (ASHRAE* 20–25 °C in 2004 to 18–27 °C in 2008)
- *Acoustic Noise Emission*
  - As a rule of thumb, the **energy consumption of an axial or centrifugal fan increases with the third power of rotational speed**, however its **acoustic noise emission increases with the fifth power**.

General Cooling System Design Challenges

- Interfaces: Improved contact conductance and heat spreading, novel high-conductivity materials, and embedded thermoelectric elements.
- Liquid cooling: Both passive (e.g., optimized transport in metal foams wicks and miniature heat pipes) and active approaches (e.g., electro-hydrodynamic liquid flow actuation and two-phase boiling in microchannels).
- Enhanced heat rejection to ambient air (e.g., ion-driven flows, piezoelectric fans and synthetic jets).
- Micro- and nano-scale sensing and control (e.g., electroactuated droplet cooling, micro-scale temperature measurements using laser-induced fluorescence, infrared micro-PIV in a silicon microchannel heat sink.

Implementing Liquid Cooling

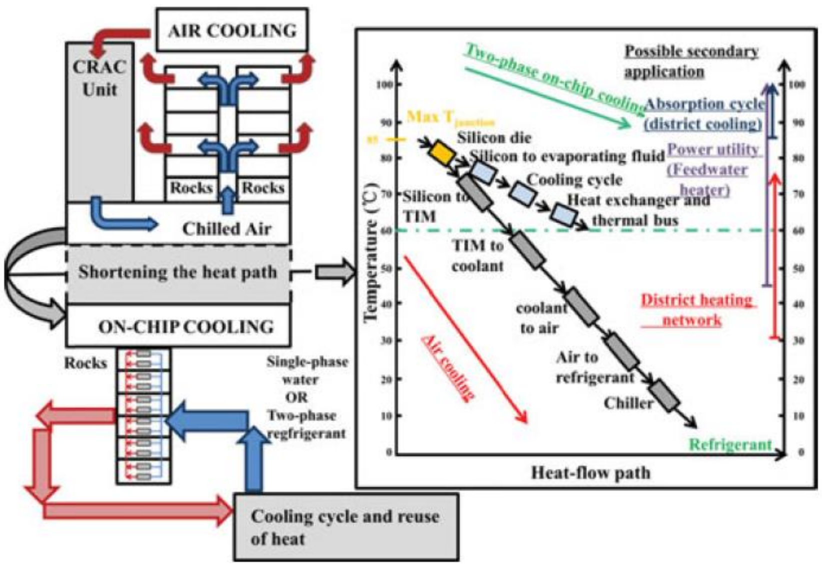
- *Thermal interconnects: fluidic*
- *Thermal interconnects: solid state*
- *Choice of liquid coolant*
- *Two-Phase Liquid Cooling*

Some advanced cooling methods..

Current Status and Future Trends in Data-Center Cooling Technologies

ZHEN LI and SATISH G. KANDLIKAR

Heat Transfer Engineering
(2015)

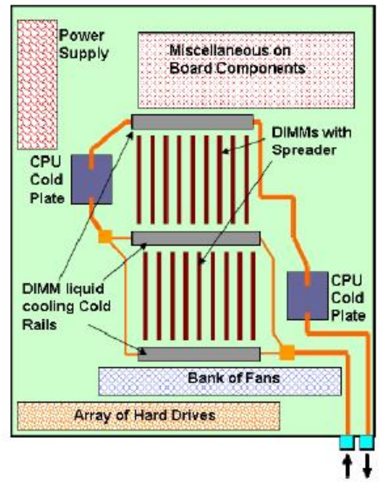


- **Cold plates** provide a platform for transferring heat from electronic components to the coolant. **Incorporation of microchannels and minichannels** leads to significant reduction in the thermal resistances between the coolant and the electronic components
- **Integration of heat pipes and thermosyphon systems** provides significant energy savings through a drastic reduction in the thermal resistances.
- The **waste heat** from the data center can be effectively utilized for other applications such as building heating, absorption refrigeration, feedwater heating.

28th IEEE SEMI-THERM Symposium, IBM

Energy, Vol. 43, 2012, Pages 237–245

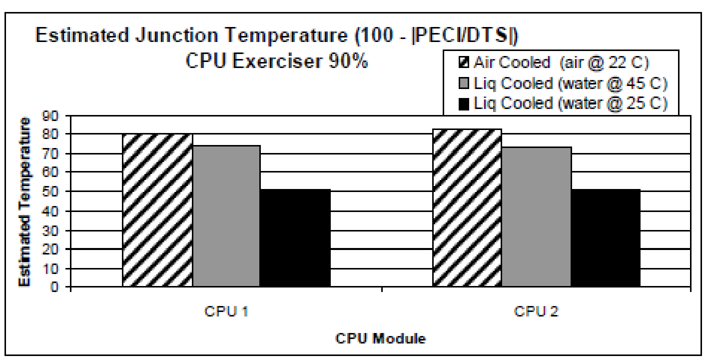
Fig. 1. (a) Hot water cooled first of a kind data center: Aquasar. (b) Water cooled IBM BladeCenter QS22.



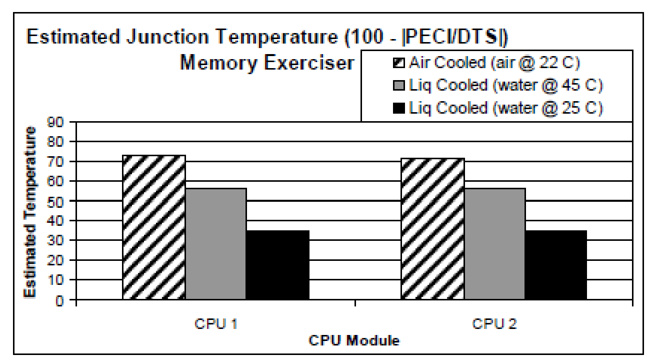
(a)

(b)

ure 1. (a) Schematic of the volume server with node liquid cooling loop and other server components. (b) Node liquid ling loop, having liquid cooling components for both the processors (CPU 1 and CPU 2) and the 12 DIMMs (numbered 2 through 18), installed in an IBM System X volume server.



(a)



(b)

Figure 6. Comparison of estimated junction temperature for a liquid cooled server with a typical air cooled server (a) when the CPUs are exercised at 90% and (b) when the memory modules are exercised.

3D IC with Microchannel

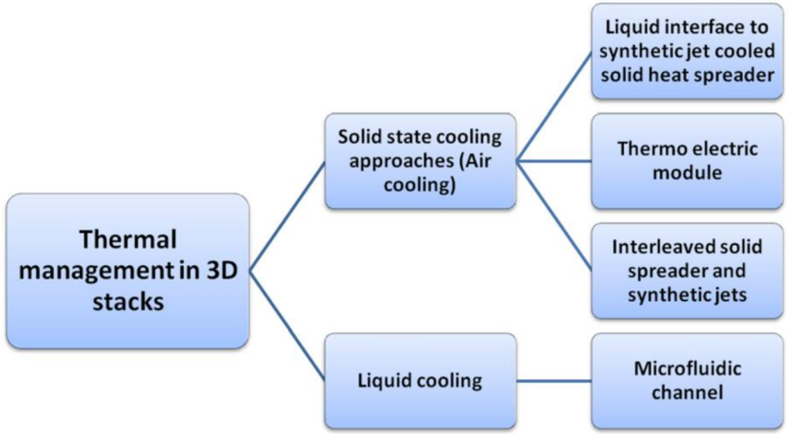
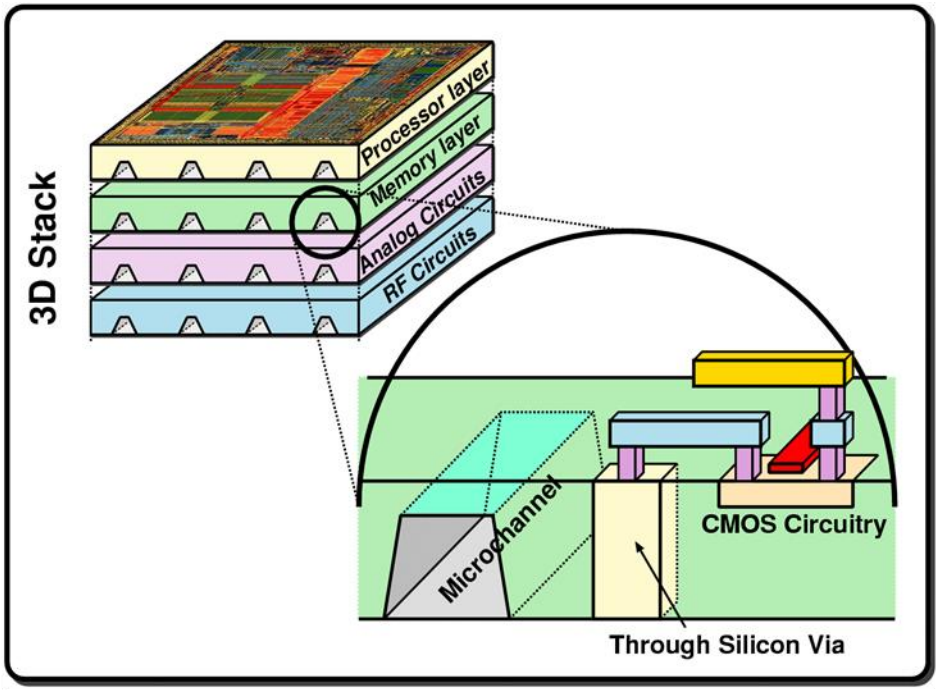
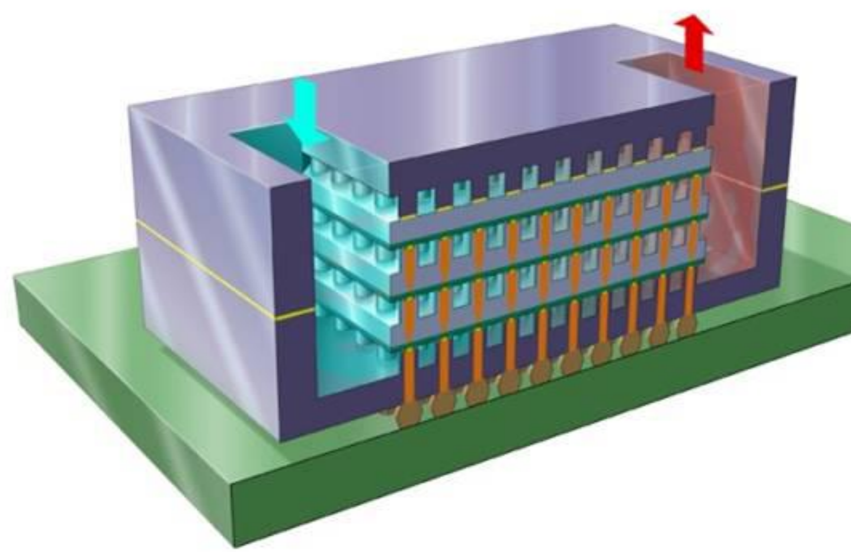


Fig. 13 Thermal management strategies in 3D stacks

Journal of Electronic Packaging, 2011, Vol. 133 / 041011-1



Thermal-Aware Design for 3D Multi-Processor



http://flashinformatique.epfl.ch/spip.php?article2260

IEEE ELECTRON DEVICE LETTERS

VOL. 27, 2006, pp.117-119

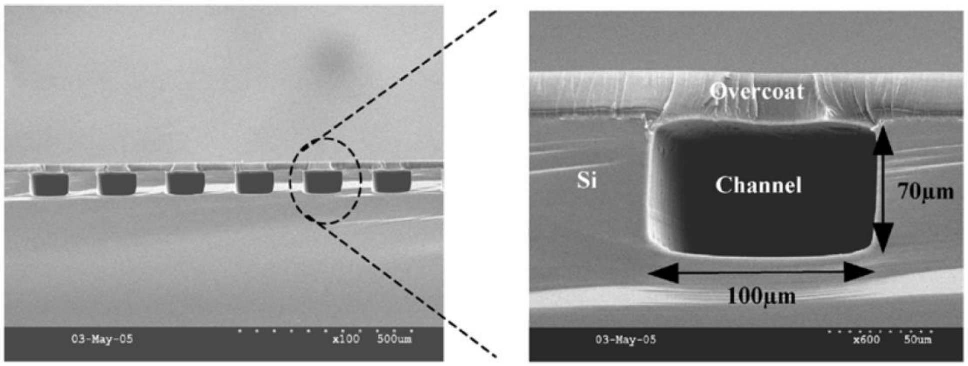
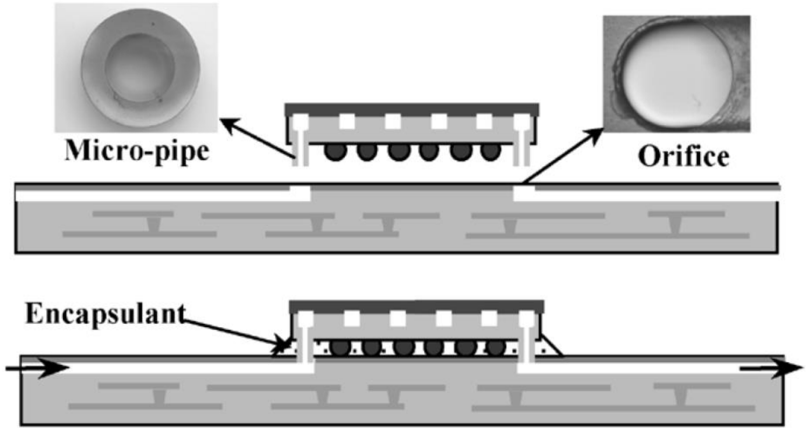
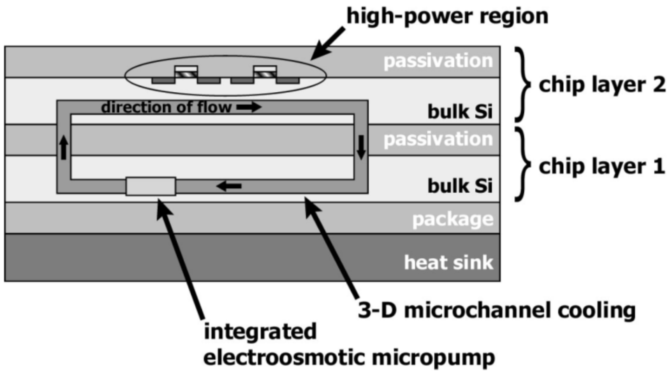


Fig. 2. Cross-sectional SEM image of monolithic microchannels enclosed with a polymer overcoat of ~30 μm.



(a)

The 12th International Conference on Solid State Sensors, Actuators and Microsystems, 2003



(a)

Journal of Electronic Packaging, 2011, Vol. 133 / 041011-1

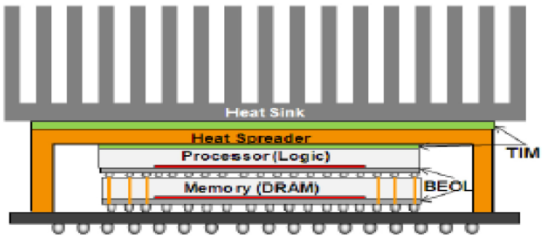


Fig. 12 Thermal management in 3D chip stacks using conventional air cooling [55]

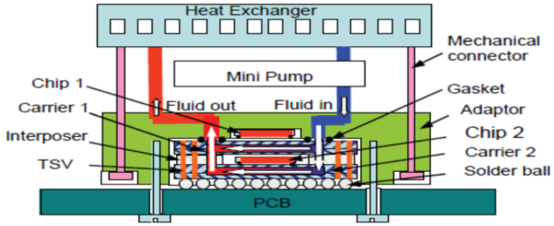


Fig. 14 Schematic of integrated liquid cooling system for 3D system using microfluidic channel [56]

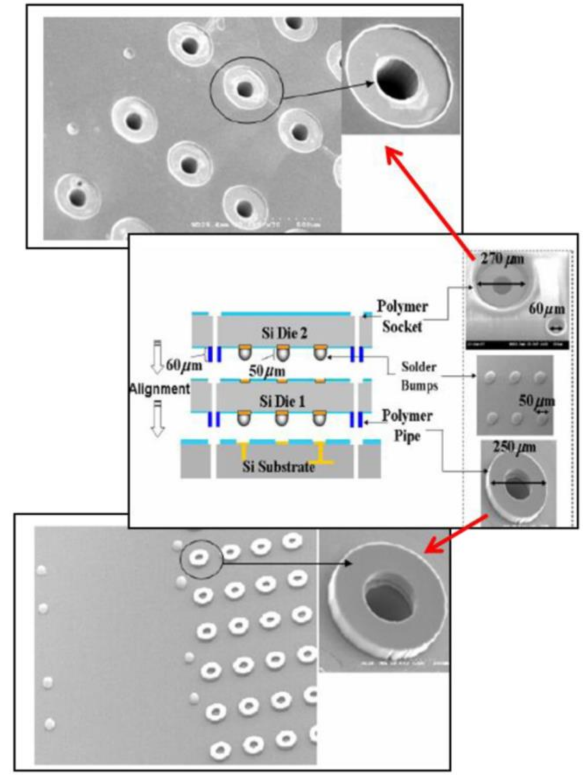


Fig. 15 Assembly of 3D prototype of integrated microfluidic channel cooling solution [58]

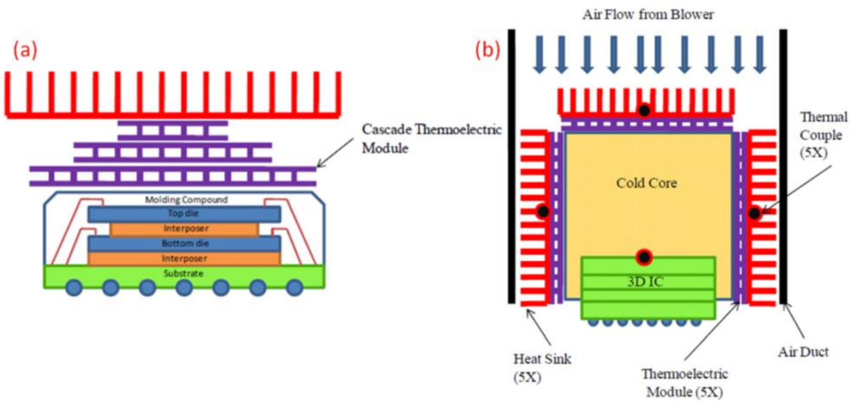


Fig. 18 (*a*) Unidirectional cascade TEM and (*b*) multidimensional heat transfer system (MHTS) using TEM [62]

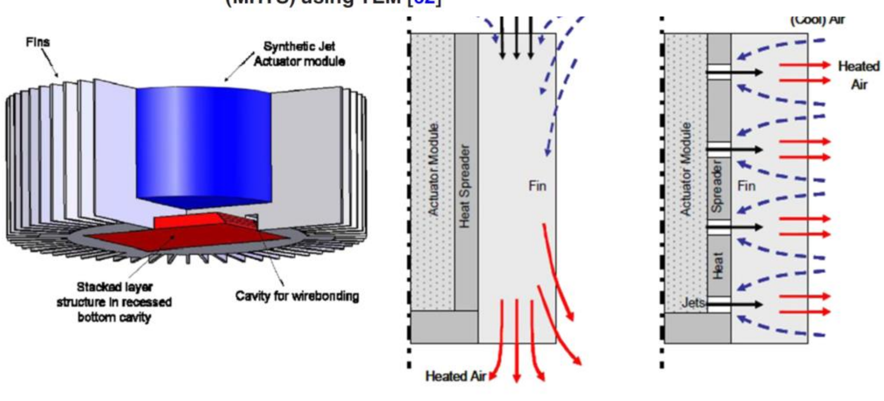


Fig. 16 (*a*) Heat sink assembly showing the synthetic jet module and the chip stack cavity, (*b*) original heat sink with longitudinal air flow, and (*c*) modified heat sink with lateral air flow [60]

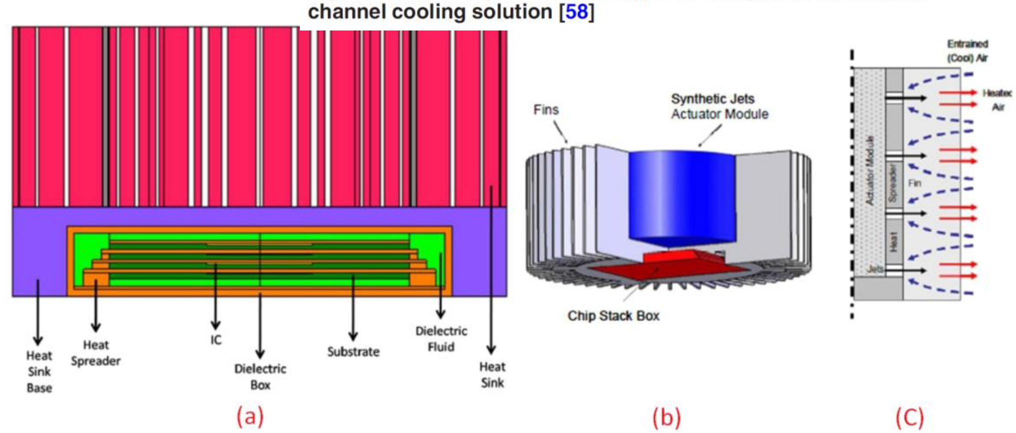
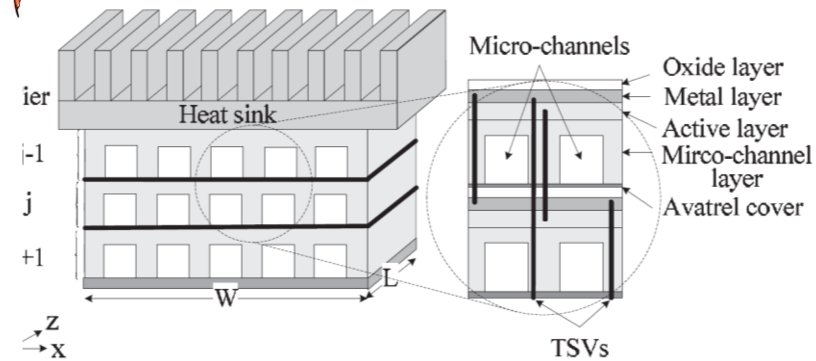


Fig. 17 (*a*) 3D stack enclosure connected to a cylindrical finned heat sink, (*b*) heat sink assembly showing the synthetic jet module and the chip stack cavity, and (*c*) jet induced flow between the fins [61]



Hybrid 3D-IC Cooling System Using Micro-Fluidic Cooling and Thermal TSVs (through-silicon-vias)

2012 IEEE Computer Society Annual Symposium on VLSI

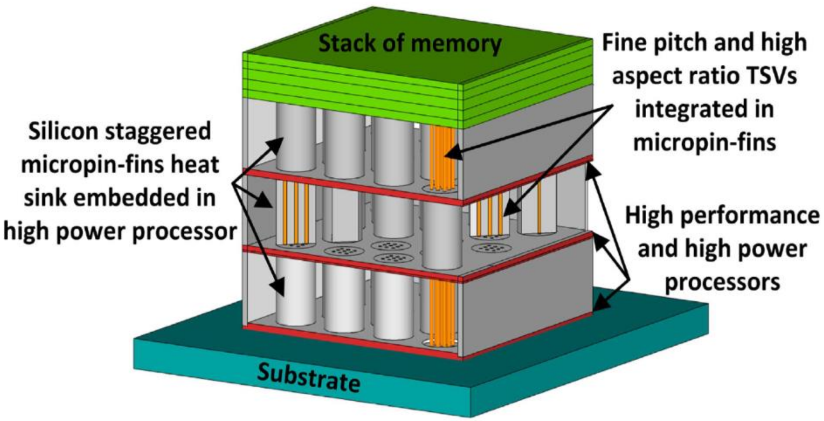


Fig. 1. Schematic of a three-microprocessor chip stack each with interlayer microfluidic cooling. A 3-D stack of memory chips resides above the microprocessors. High aspect ratio TSVs are integrated in the micropin-fin heat sink.

IEEE TRANSACTIONS ON COMPONENTS, PACKAGING AND MANUFACTURING TECHNOLOGY, VOL. 3, NO. 11, NOVEMBER 2013, pp. 1842-1850.

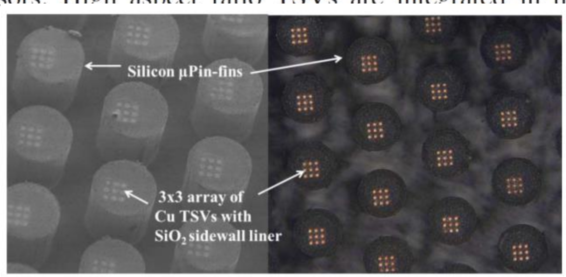


Fig. 13. SEM (left) and optical images (right) of high aspect ratio TSVs integrated in micropin-fins (10 μm diameter, 35 μm pitch, and 178 μm tall).

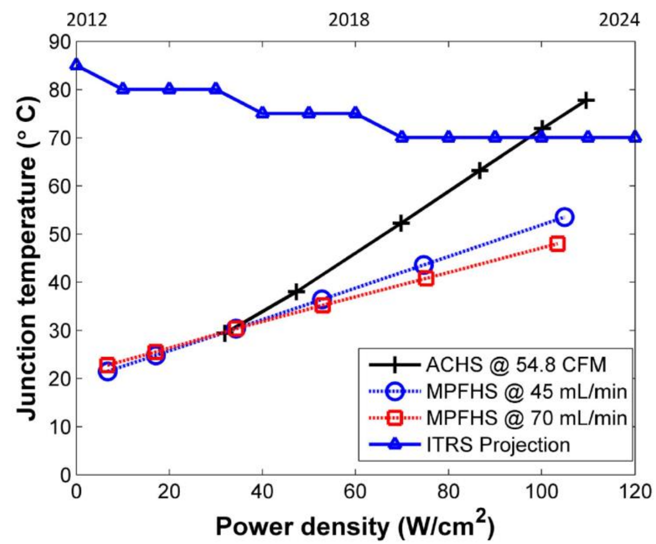
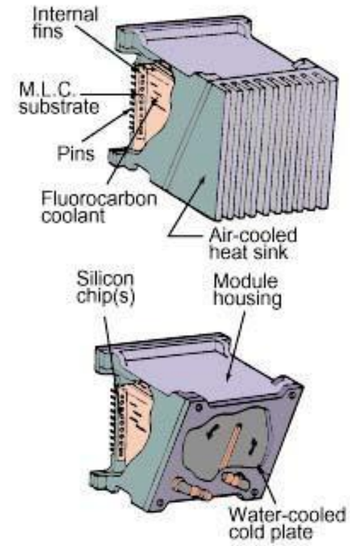
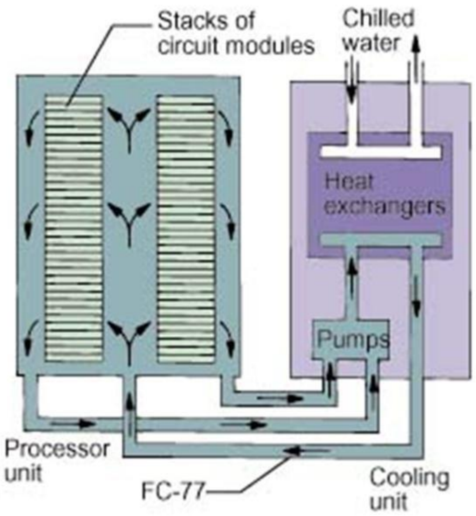


Fig. 17. Average junction temperature under air cooling and microfluidic cooling compared with ITRS projections.

Liquid Immersion Cooling

- Not a new concept!
  - Direct liquid immersion cooling has been used within IBM for over 20 years to cool high powered chips on multi-chip substrates during electrical testing prior to final module assembly.
  - Early supercomputers relied on liquid cooling technologies.
    - Cray 2 supercomputer





http://www.electronics-cooling.com/1996/05/direct-liquid-immersion-cooling-for-high-power-density-microelectronics/

Liquid Immersion Cooling Example

- Liquid Submersion Blade Server
  - LiquidCool Solutions (Hardcore Computer) Supports High Frequency Trading with Liquid Submersion Cooled Computers
    - Released in 2010
  - 2012: LSS is the world's first rack-mounted total liquid submerged server. The system's patented liquid submersion cooling technology promises improvements in speed, performance, reliability and latency, while reducing environmental impact.

http://www.liquidcoolsolutions.com/

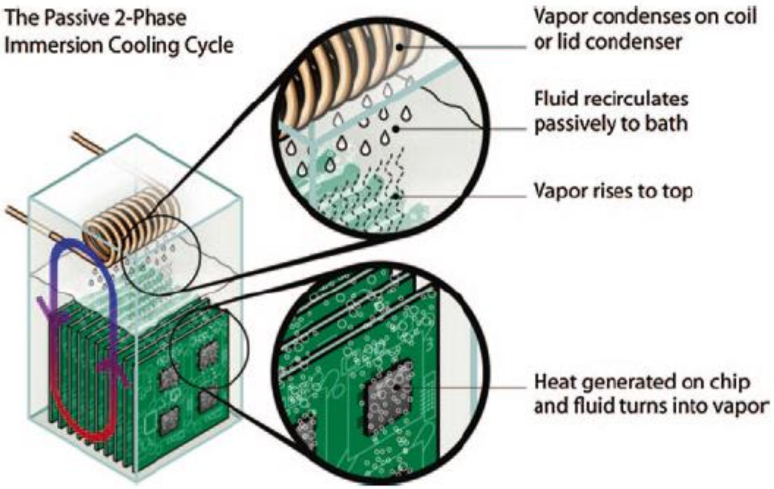
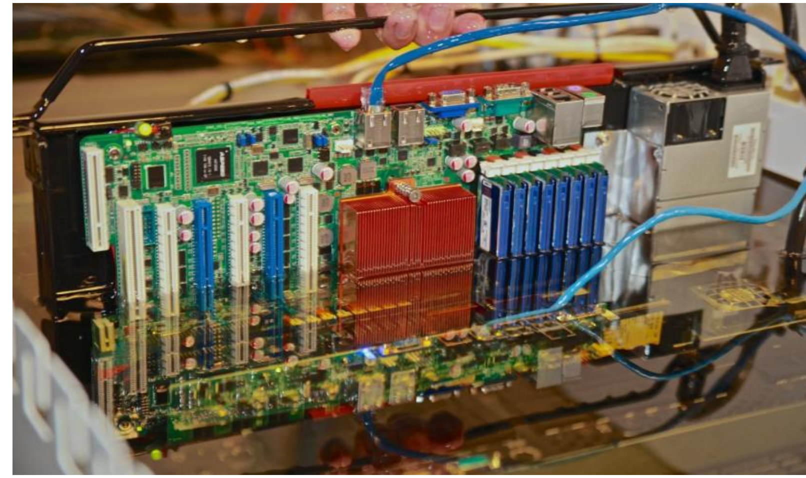
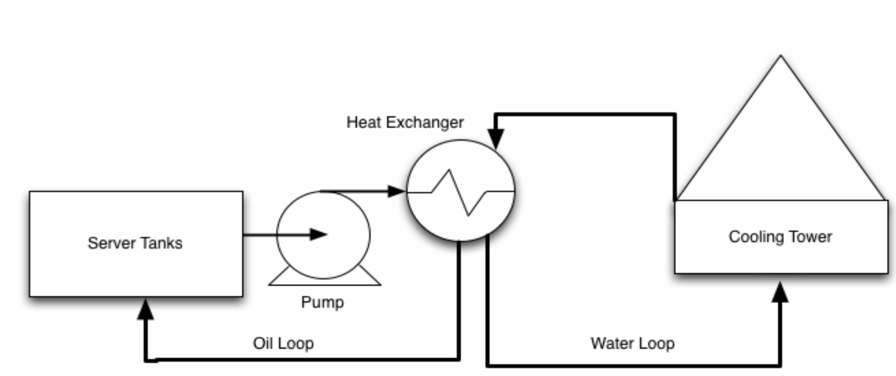


Fig. 4.2 Working principle of immersion cooling system (http://www.allied-control.com/immersion-cooling)

Cooling Using Dielectric Oil



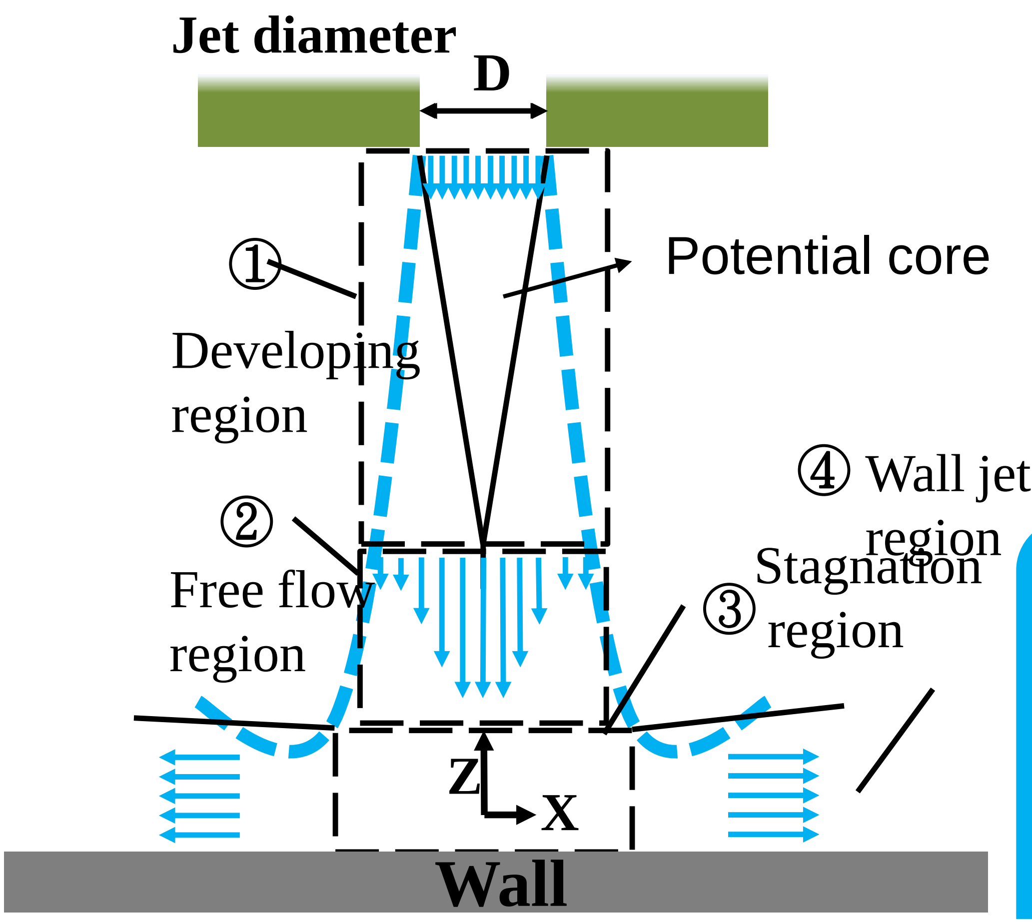


Tanks can dissipate 40kW of power or more

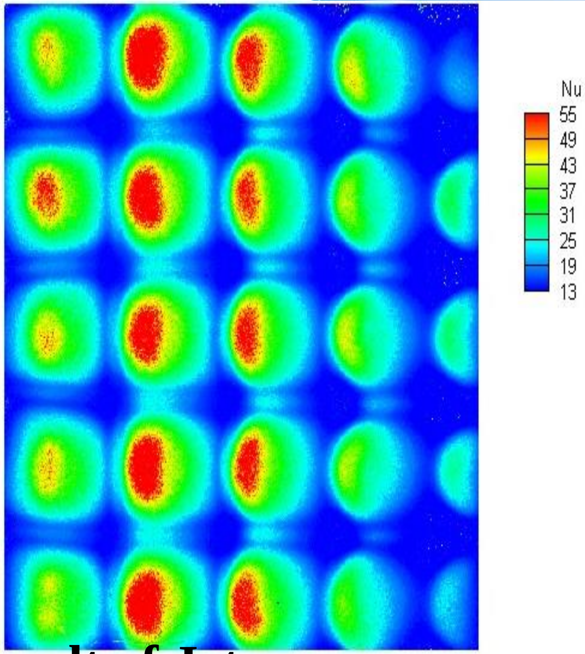
Implementing Alternative Cooling Techniques

- *Enhanced Heat Spreading:*
  - *High-conductivity materials*
  - *Two-phase heat spreading*
- *Thermoelectrics*
  - Characterized by incremental improvements in the thermoelectric figure-of merit *ZT* (= $S^2\sigma T/k$, where *S*, *σ*, *T,* and *k* are the Seebeck coefficient, electrical conductivity, absolute temperature, and thermal conductivity, respectively)
- *Advanced Air Cooling*

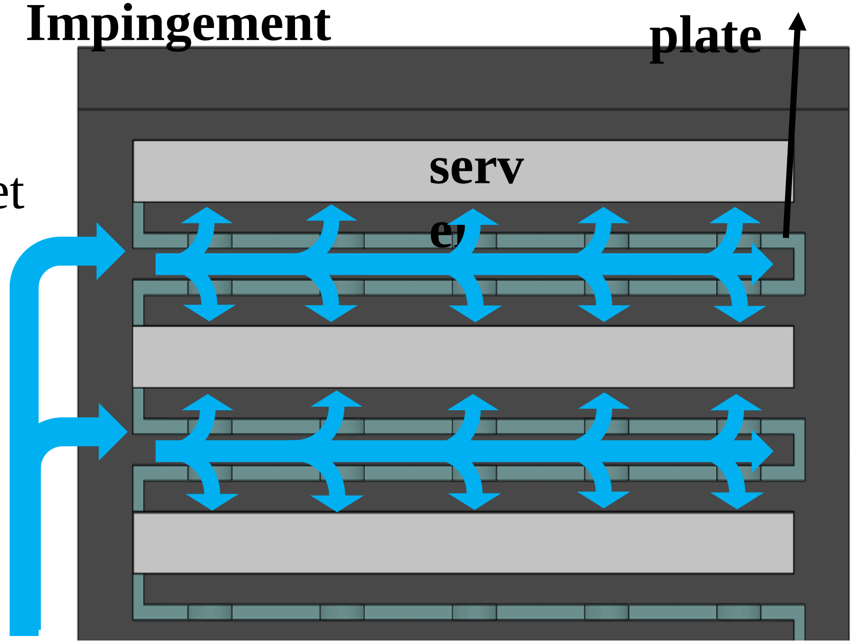
Jet Impingement



Jet Flow Structure

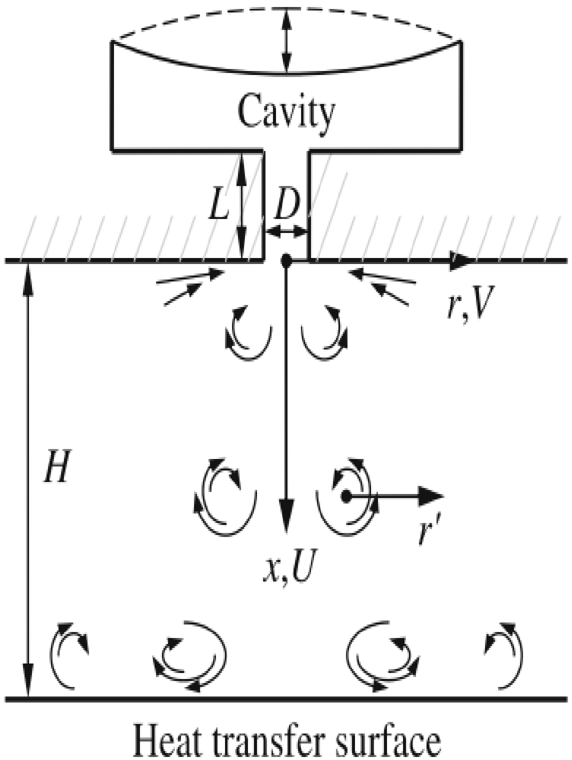


Result of Jet Impingement

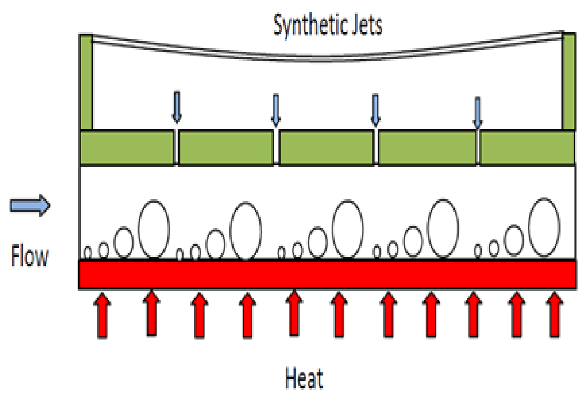


Jet Impingement in Data Center Rack

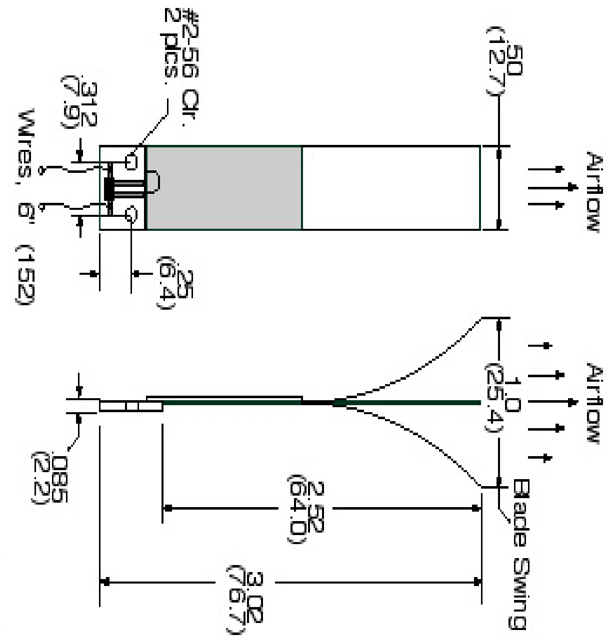
Synthetic Jet/Piezo Fan



Synthetic Jet



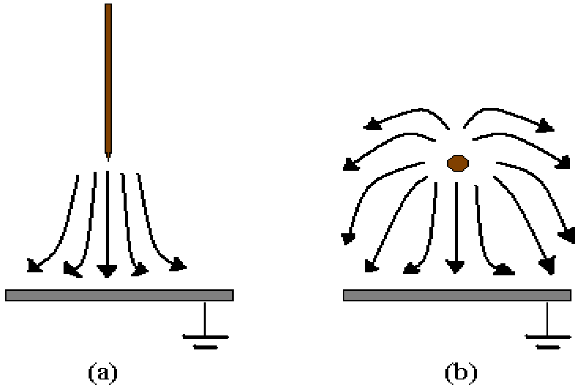
Synthetic Jets for Cooling



Piezo Fan

Corona wind

A fluid motion driven by an electric field is termed a corona wind or an ionic wind.



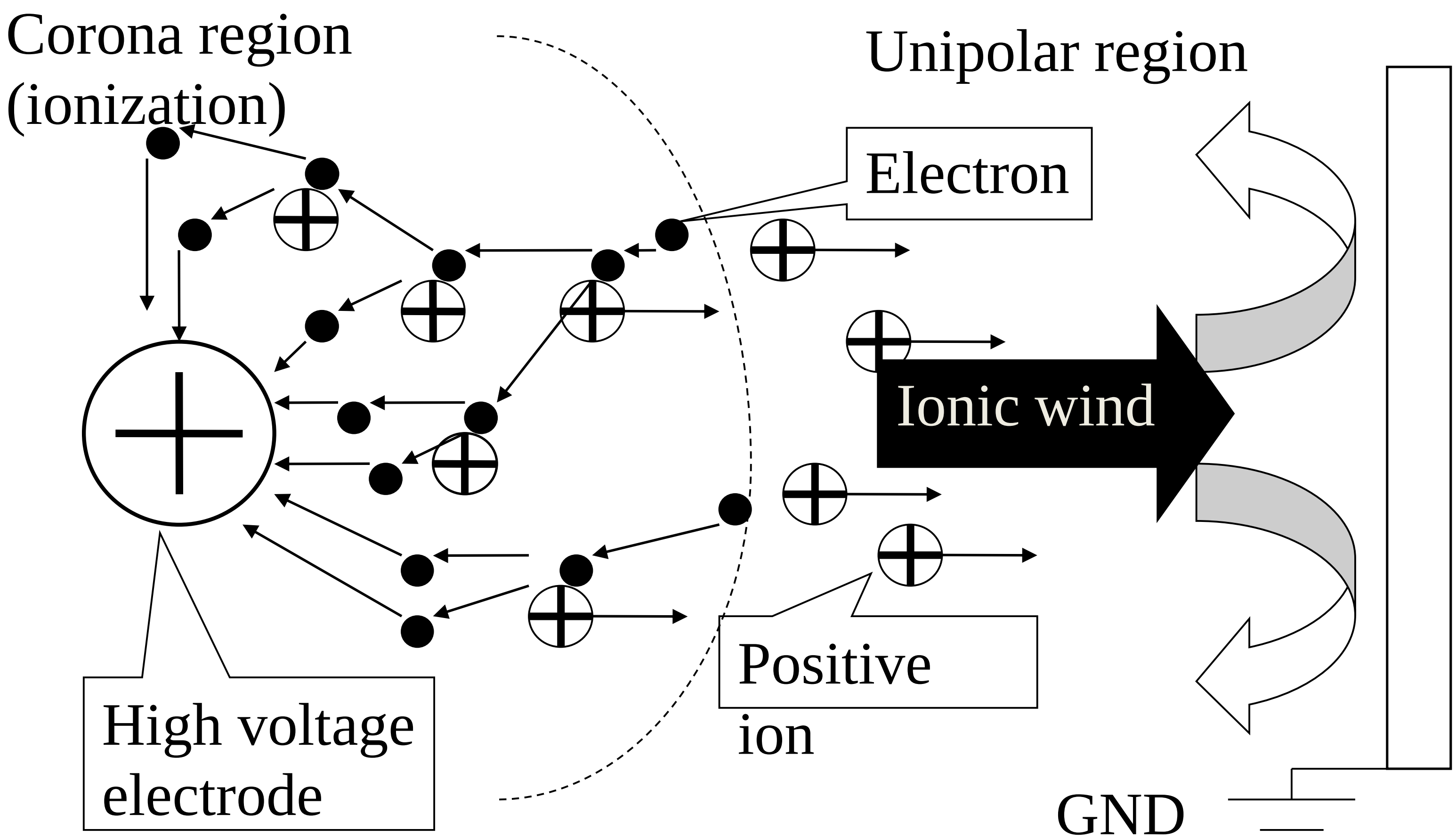
Corona region (Ionization region)

Near the charged electrode, ionization occurs and creates positive ions and free electrons in a process known as the electron avalanche. The positive ions are attracted toward or repelled away from the curved electrode (depending on the polarity). The electrons thus migrate in the opposite direction.

Unipolar region

The energized electrons, accelerated by the electric field, inelastically collide with the neutral atoms, entraining the stagnant fluid from the ambience to the grounded surface.

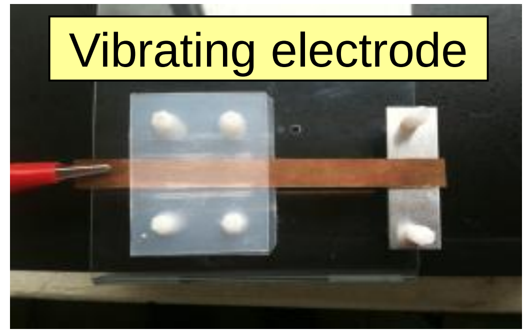
Positive Corona

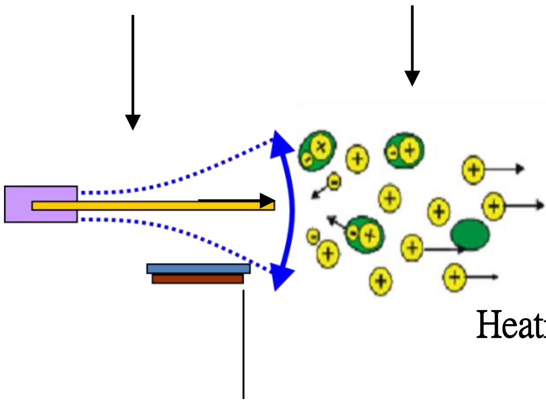


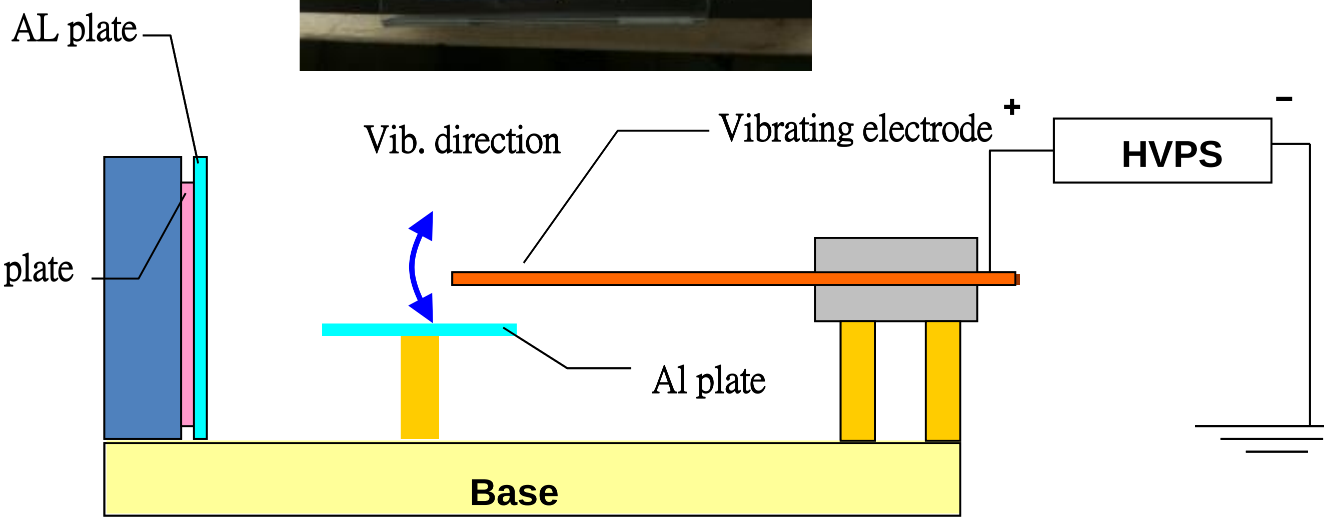
Positive corona generation and ionic wind.

Hybrid Design for Ionic Wind and Oscillation

Electrostatic cantilever beamSimplified cantilever beam model:





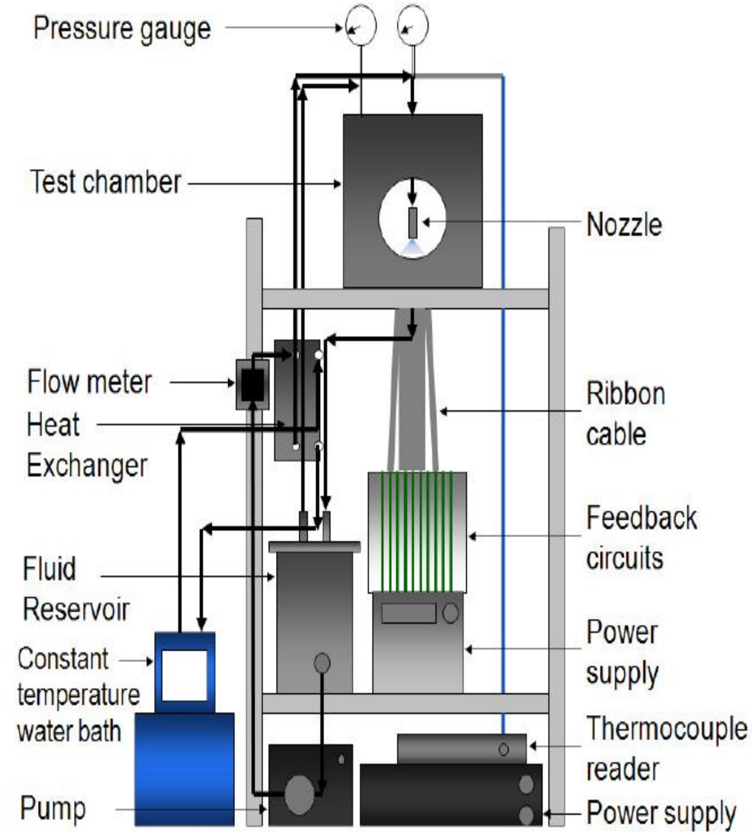


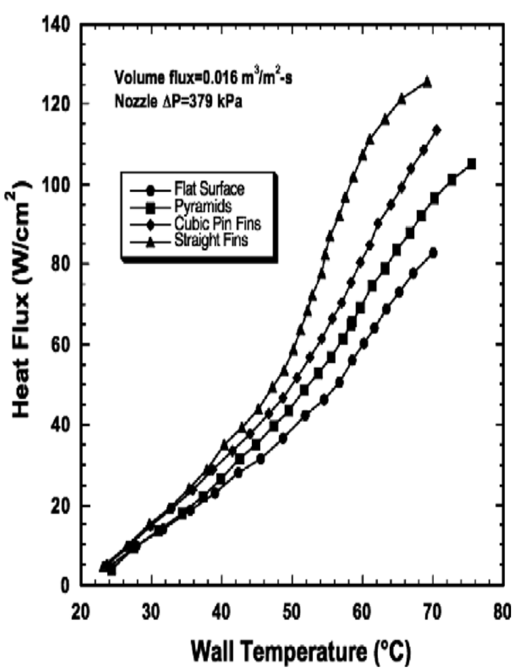
IMG_1871.MOV

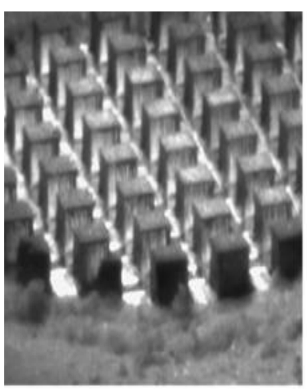
Vibrating electrode side view

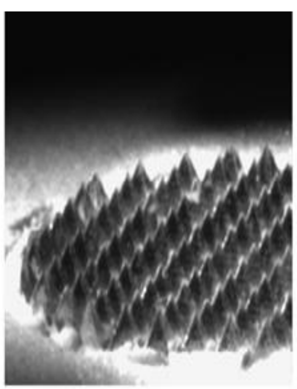
Spray cooling

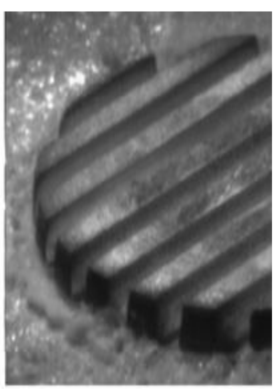
- Using in the small but high heat flux surface.
- Different surface structures cause the different heat transfer performance.






Cubic Pin Fins


Pyramids


Straight Fins

Waste Heat Management & Upgrade

Waste Heat Upgrade

Renewable and Sustainable Energy Reviews
Vol. 31, 2014, Pages 622–638

- Why Upgrade?
  - Theoretical limit of Carnot cycle : $\eta_{th} = 1 - T_L/T_H$
  - For T_L = 35 °C & T_H = 60 °C, η_{th} ~ 7.5%

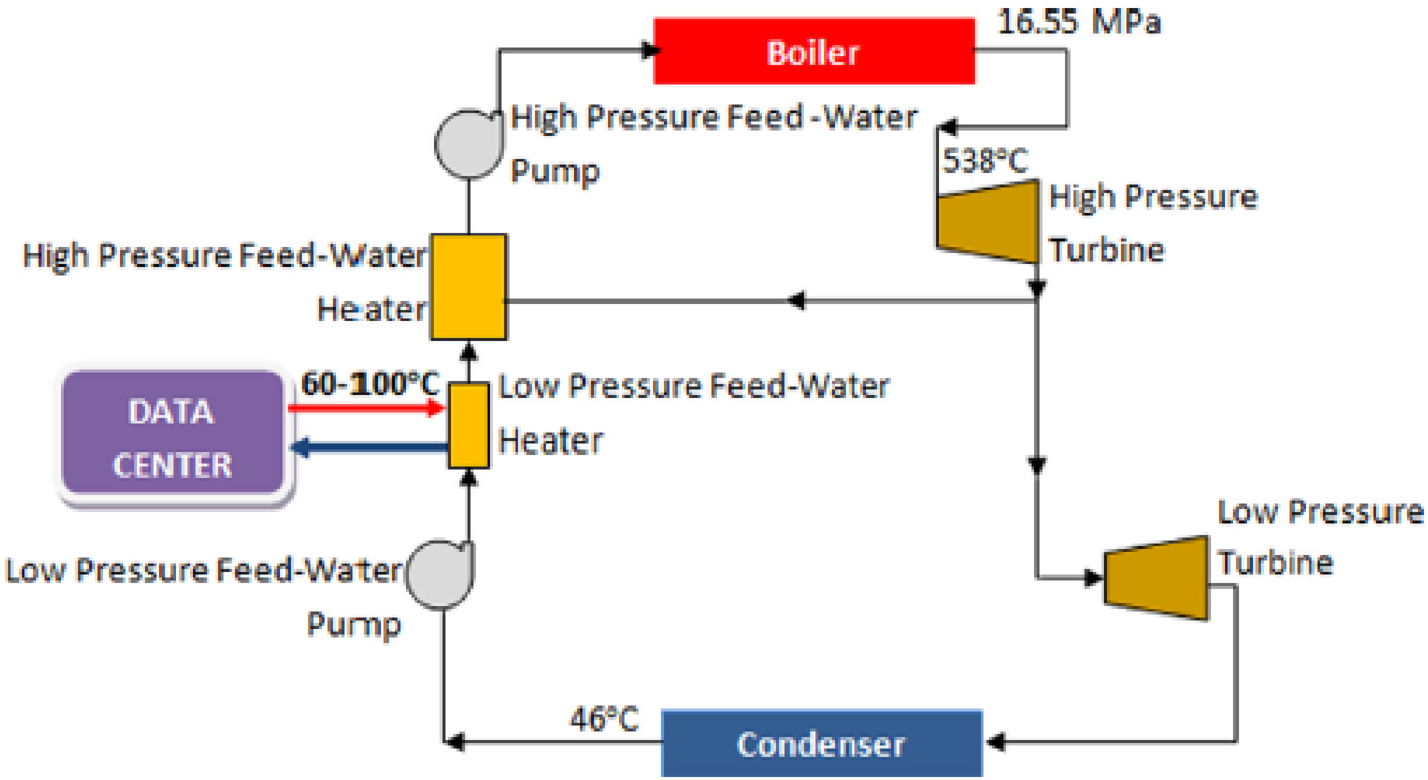


Fig. 1. A schematic of a system in which the data center waste heat is utilized in a coal power plant Rankine cycle.

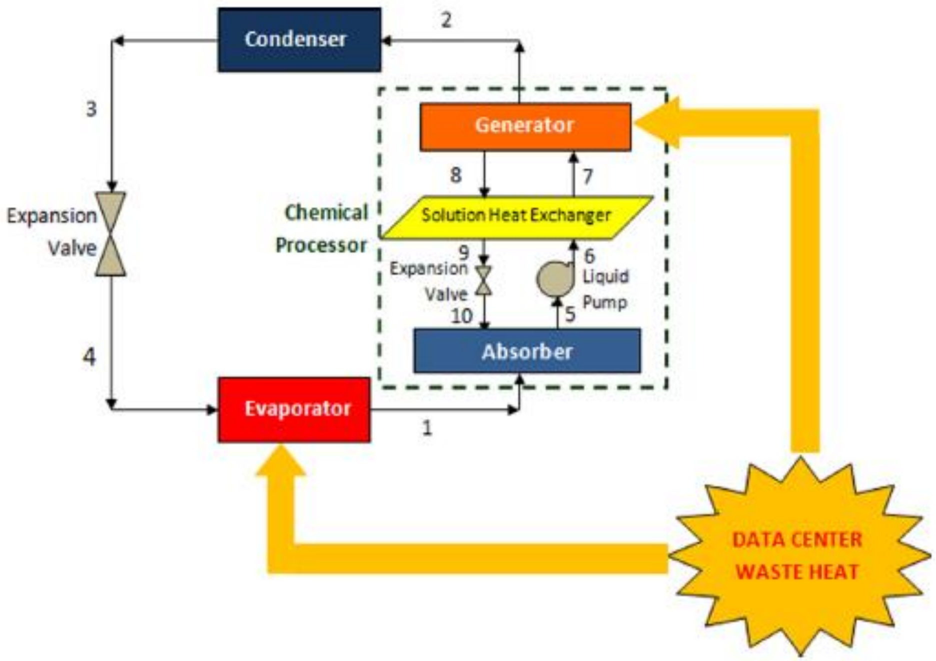


Fig. 2. A schematic of a simple absorption refrigeration system driven by data center waste heat.

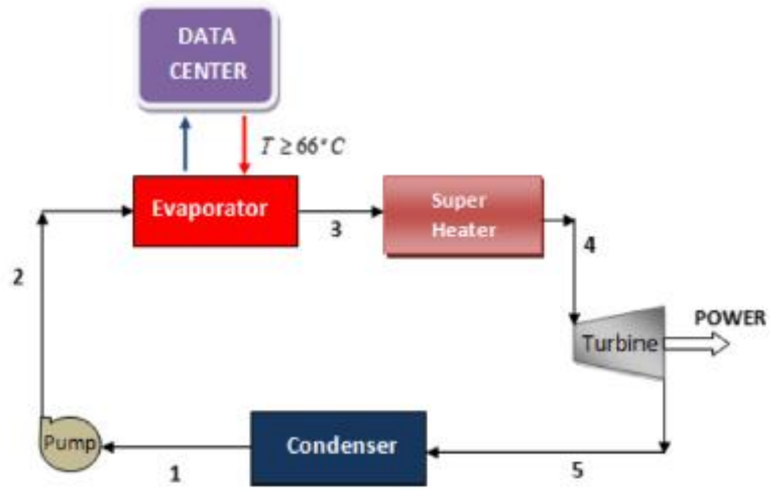
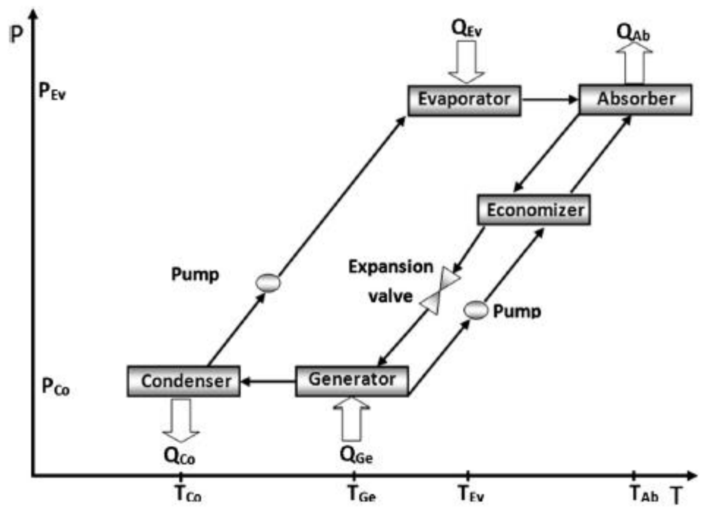


Fig. 3. Schematic diagram of organic Rankine cycle. The super heater is necessary only when the working fluid is wet.



- Main Drawbacks of AHT
  - Crystallization
  - Corrosion

- Absorption refrigeration systems can operate with generator temperatures of 70–90 °C which is consistent with available waste heat from water-cooled and two-phase cooled data centers. **This technology is not suitable for waste heat from air cooled data centers without an additional heat booster**.
- The benefit of using datacenter waste heat in absorption refrigeration systems is a direct reduction of the load on data center CRAC systems, through the generation of chilled water for cooling, which is of significant economic benefit to most data center operators.

Heat Transformer

Experimental Thermal and Fluid Science
Vol. 60, 2015, Pages 275–283

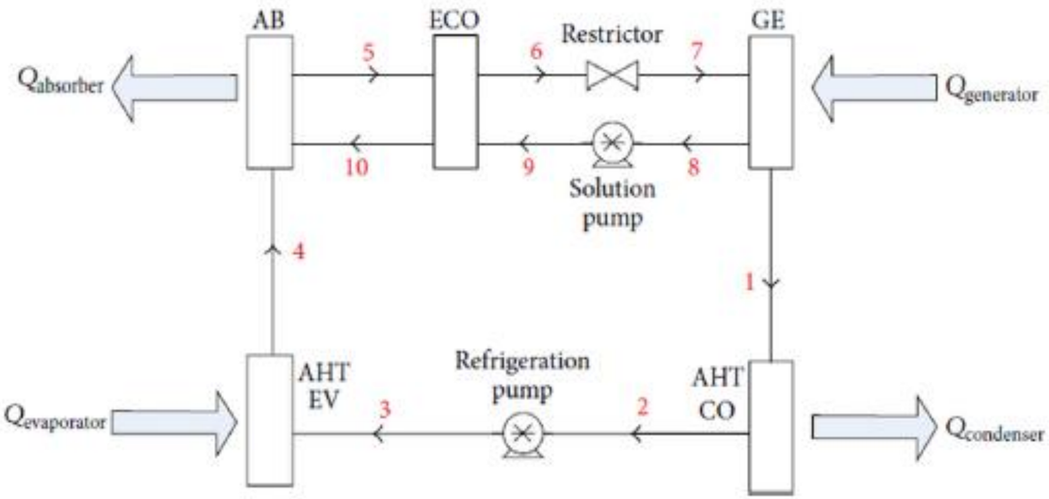
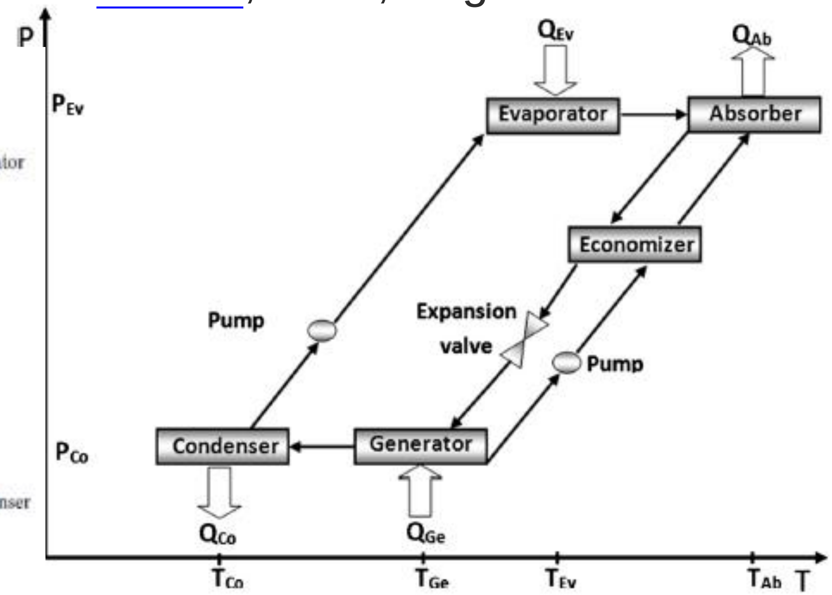


Fig. 1. Single stage absorption heat transformer [6].



ematic diagram a four temperature levels and two pressure levels Absorption Heat Transformer (*AHT*).

Renewable and Sustainable Energy Reviews
Vol. 34, 2014, Pages 430–452

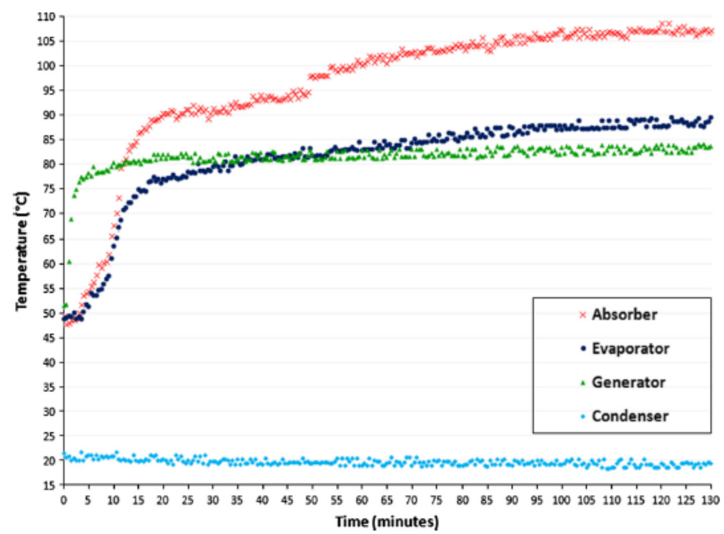


Fig. 3. Temperature records for run test 1.

Double/Triple Effect AHT

Renewable and Sustainable Energy Reviews

Vol.42, 2015, Pages 1290–1304

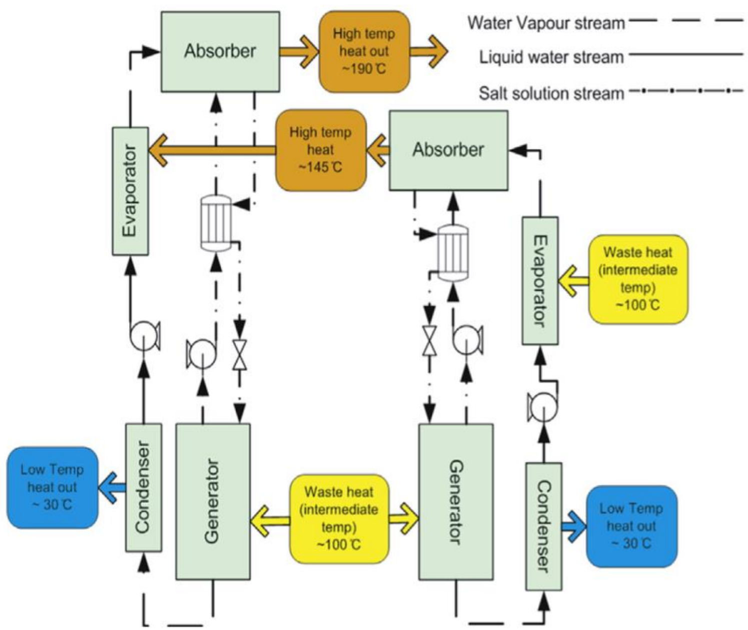


Fig. 7. Schematic of a double stage heat transformer (DSHT) in which the absorber in the low temperature cycle is coupled to the evaporator in the high temperature cycle.

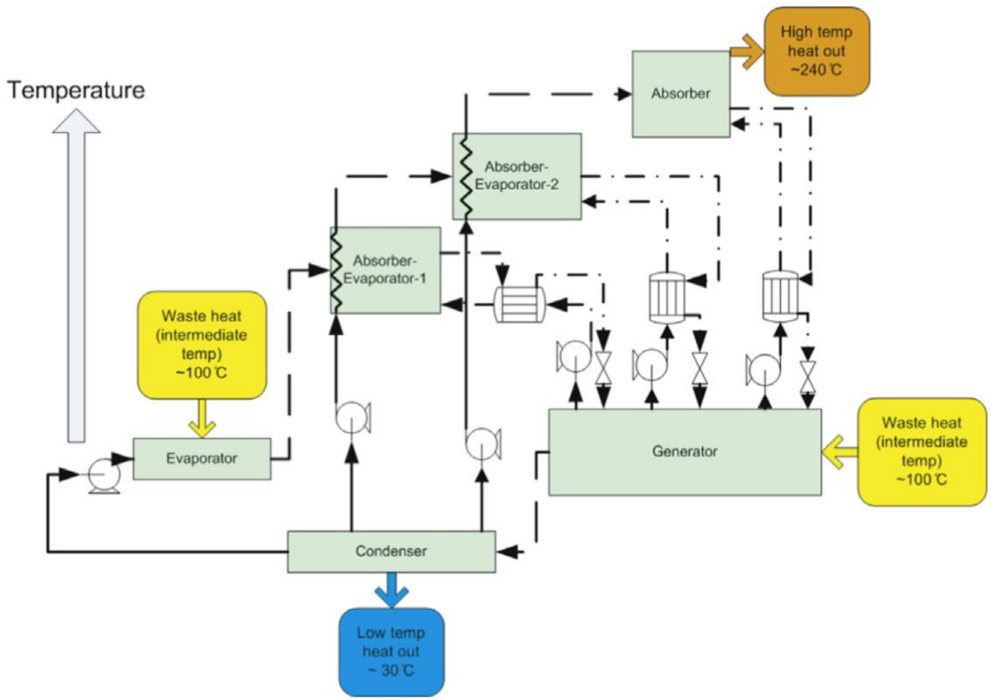


Fig. 11. Schematic of a triple absorption heat transformer (TAHT).

Adsorption Heat Transformer

AIChE Journal, 2013, Vol. 59, pp. 1355-1346

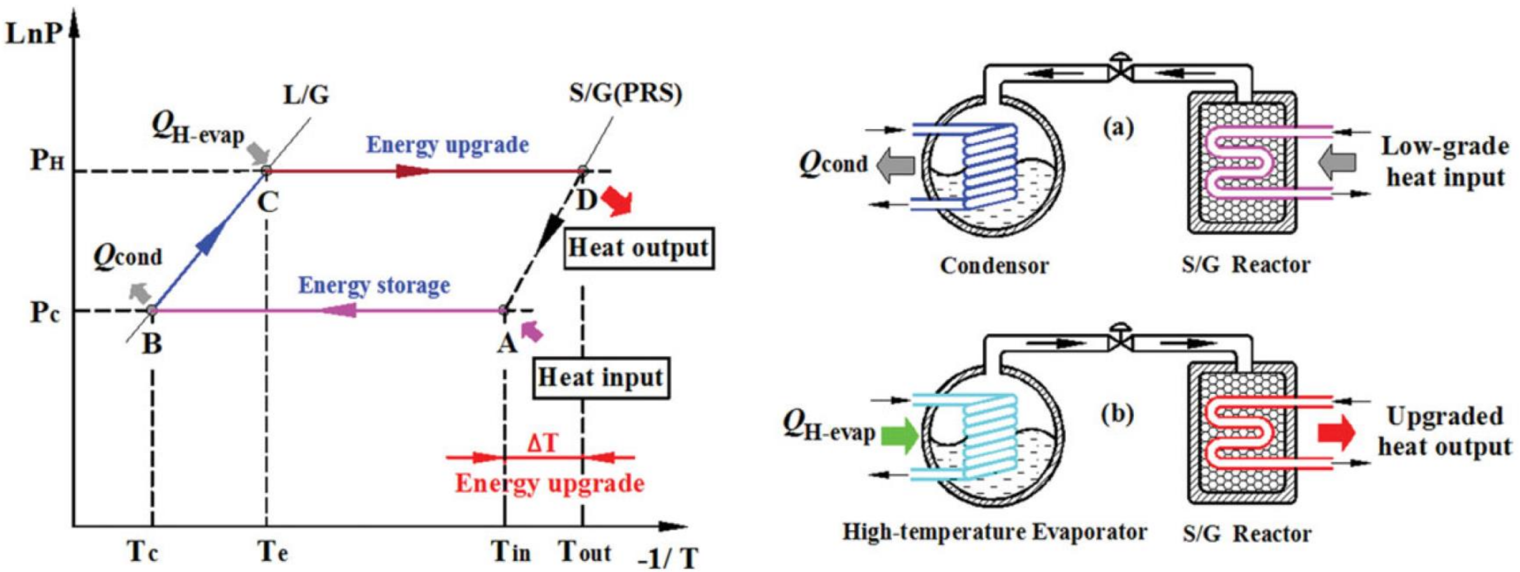


Figure 1. Schematic diagram of solid-gas thermochemical sorption heat transformer based on temperature-lift adsorption process.

(a) Energy storage process of low-grade thermal energy; (b) energy release process for energy upgrade using temperature-lift adsorption technique. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Temperature upgrade is achieved by lifting the operating pressure of working gas, and the temperature magnitude of energy upgrade is nearly proportional to the pressure-lift extent of the gas. The high-operating pressure is the common drawback and it may cause the safety problem when a high-heat output temperature is required during energy release process.

Solid-gas thermochemical sorption heat transformer based on pressure-reducing desorption process

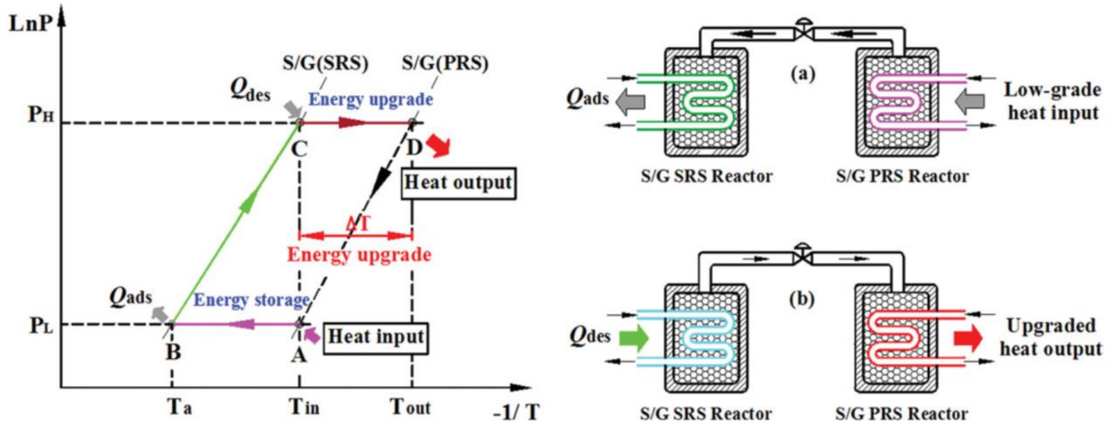


Figure 2. Schematic diagram of solid-gas thermochemical sorption heat transformer based on pressure-reducing desorption process.

(a) Energy storage process of low-grade thermal energy using pressure-reducing desorption technique; (b) energy release process of stored low-grade thermal energy. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

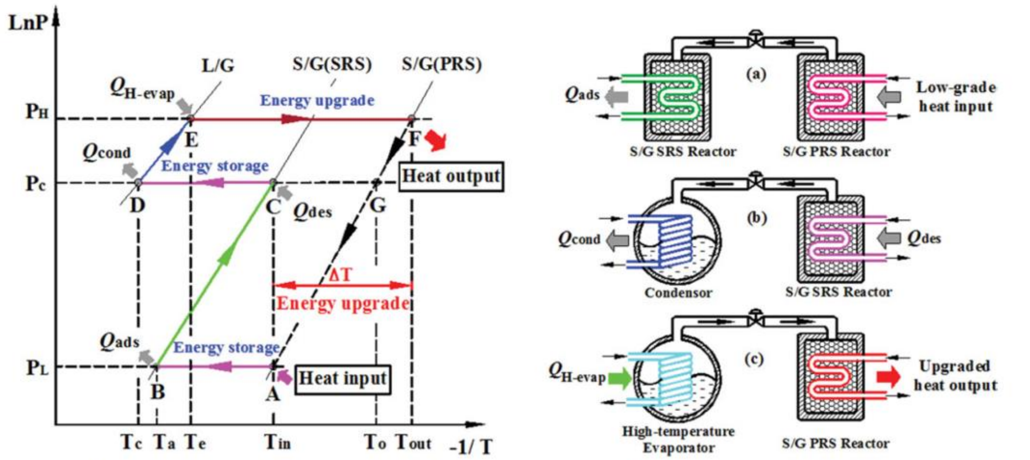


Figure 3. Schematic diagram of solid-gas thermochemical sorption heat transformer based on pressure-reducing desorption and temperature-lift adsorption processes.

(a) Energy storage process of PRS reactor using pressure-reducing desorption technique; (b) energy storage process of SRS reactor; (c) Energy release process for energy upgrade using temperature-lift adsorption technique. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

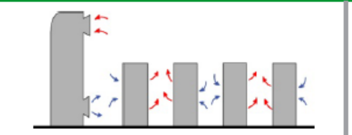
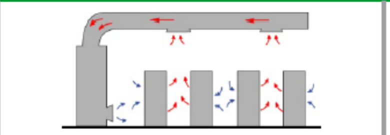
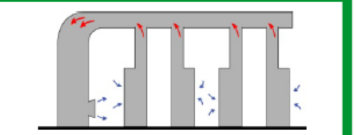
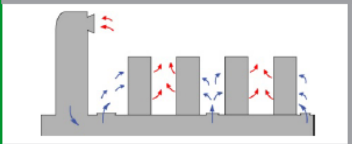
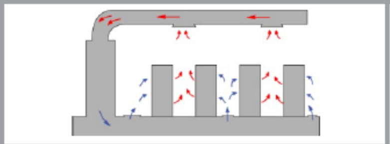
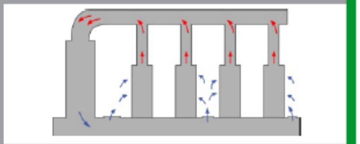
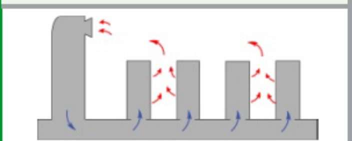
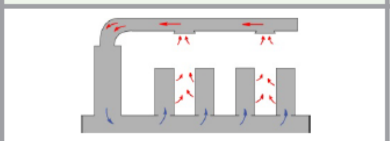
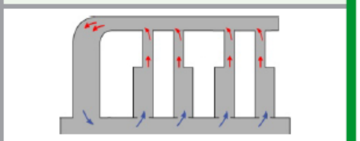
Short Summary

- Significant progress had been made for datacenter thermal managements during the past decades.
- Recirculation/bypass/negative pressure elimination is regarded as the most important issue for air flow management.
- Thermal management in datacenter requires multi-scale and multi-disciplinary efforts to tackle.
- Free cooling is becoming a must for effective PUE reduction.
- CFD is a viable tool in thermal management of datacenter.
- Waste heat management in datacenter is an essential subject that deserve further exploration.

Airflow Management

Table 1

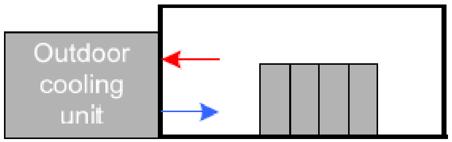
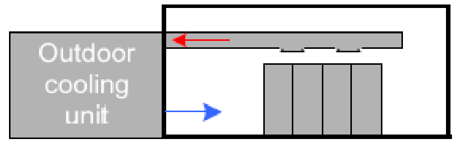
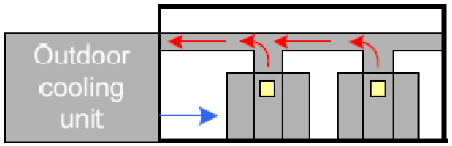
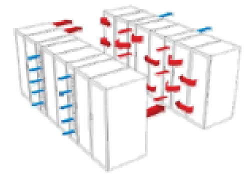
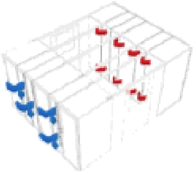
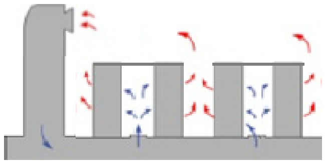
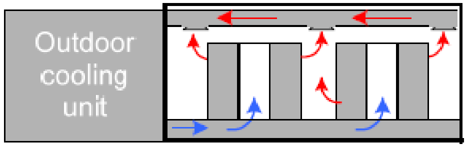
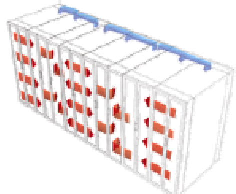
The 9 types of air distribution (traditional room-based cooling implementations)

	Flooded return	Targeted return	Contained return
Flooded supply	 **Small LAN rooms < 40kW** Not recommended for most data centers Low cost, simple installation Least energy efficient of all air distribution architectures because 100% of the cold supply air is allowed to mix with hot return air. Supply air temperature extremely unpredictable above. Distribution type can cool up to 3kW per rack	 **General use** Not recommended for most data centers Low cost, ease of install More energy efficient than flooded return since 40-70% of IT hot exhaust air is captured and delivered back to the cooling unit. Supply air more predictable than flooded supply since less hot air is allowed to mix with cold supply air. Distribution type can cool up to 6kW per rack	 **Large data center / colocation** Upgradeable (vendor specific) Most energy efficient of all air distribution architectures since it allows increased cooling unit supply temp resulting in increased economizer hours. 70-100% of IT equipment hot exhaust air is captured and delivered back to the cooling unit. Supply air is most predictable since no hot air is allowed to mix with cold supply air. Distribution type can cool up to 30kW per rack
Targeted supply	 **Data centers with static power densities** Not recommended for new designs – unable to keep up with power density projections More energy efficient than flooded supply since more IT equipment hot exhaust air is diverted back to the cooling unit. Distribution type can cool up to 6kW per rack	 **Small to medium data centers** More energy efficient than flooded return since 60-80% of IT equipment hot exhaust air is captured and delivered back to the cooling unit. Supply air more predictable since less hot air is allowed to mix with cold supply air. Distribution type can cool up to 8kW per rack	 **Hot spot problem solver** Upgradeable (vendor specific) More efficient than targeted supply and return since 70-100% of IT equipment hot exhaust air is captured and delivered back to the cooling unit. Supply air is most predictable since no hot air is allowed to mix with cold supply air. Allows increased cooling unit supply temp resulting in increased economizer hours. Distribution type can cool up to 30kW per rack
Contained supply	 **Mainframes / racks with vertical airflow** More energy efficient than targeted supply but less efficient than contained return. Containing the supply air, forces the rest of the room to become the hot aisle which limits the number of economizer hours. Supply air is more predictable since little hot air is allowed to mix with cold supply air. Distribution type can cool up to 30kW per rack	 **Mainframes / racks with vertical airflow** More energy efficient than targeted supply but less efficient than contained return. Containing the supply air, forces the rest of the room to become the hot aisle which limits the number of economizer hours. Supply air is most predictable since no hot air is allowed to mix with cold supply air. Distribution type can cool up to 30kW per rack	 **Harsh non-data center environments** Slightly less efficient than contained return with flooded or targeted supply - requires more fan energy. Allows increased cooling unit supply temp resulting in increased economizer hours. Distribution type can cool up to 30kW per rack

- APC white paper #55

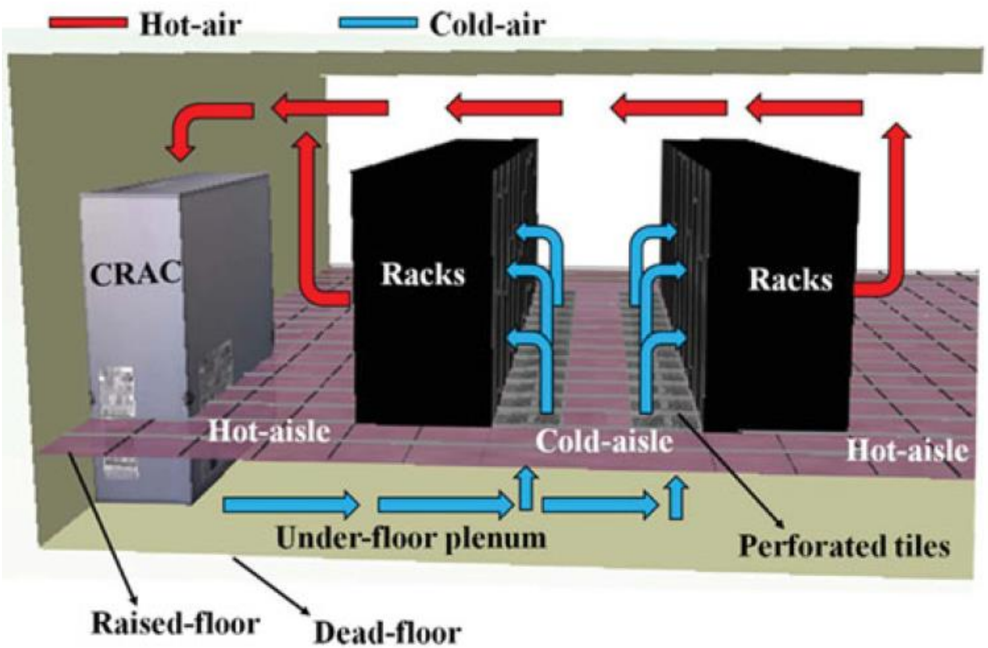
Table 2

Non-traditional implementations

	Flooded return	Targeted return	Contained return
Flooded supply	 **Hard floor, cooling unit located outdoors** Not recommended for most data centers. Not effective because air mixing prevents predictable IT inlet temperatures.	 **Hard floor, cooling unit located outdoors** Not recommended for most data centers. Not effective because air mixing prevents predictable IT inlet temperatures.	 **Hard floor, cooling unit located outdoors** Recommended for new data centers. Variable speed fans on cooling units controlled by IT temperature.
Targeted supply	**No non-traditional alternative**	 **Hard floor, row-based cooling units** Recommended for data centers below 1MW. Variable speed fans on cooling units controlled by IT temperature.	 **Hard floor, row-based cooling units** Recommended for data centers below 1MW. Variable speed fans on cooling units controlled IT temperature.
Contained supply	 **Raised floor, perimeter cooling units** Not recommended for new data centers. Good solution for existing data centers. Variable speed fans on cooling units controlled by pressure and active tiles controlled by IT temperature.	 **Raised floor, cooling unit located outdoors** Targeted return doesn't add much value since supply is contained therefore not recommended. Variable speed fans on cooling units controlled by pressure and active tiles controlled by IT temperature.	 **Hard floor, row-based cooling units** Only recommended for harsh environments or existing data centers where complete containment is required for a single row of racks (e.g. squeezing a row into an existing hot aisle). Variable speed fans on cooling units controlled by IT temperature.

Hot / Cold Aisle with Raised Floor configuration

- Hot / Cold Aisle
- Raised Floor
- Perforated Tiles
- Underfloor supply



Hot / Cold Aisle

Ref: Srinarayana, N., Fakhim, B., Behnia, M., & Armfield, S. W. "Thermal Performance of an Air-Cooled Data Center with Raised-Floor and Non-Raised-Floor Configurations", Heat Transfer Engineering, 35(4), 384-397, 2014.

Data center air stream

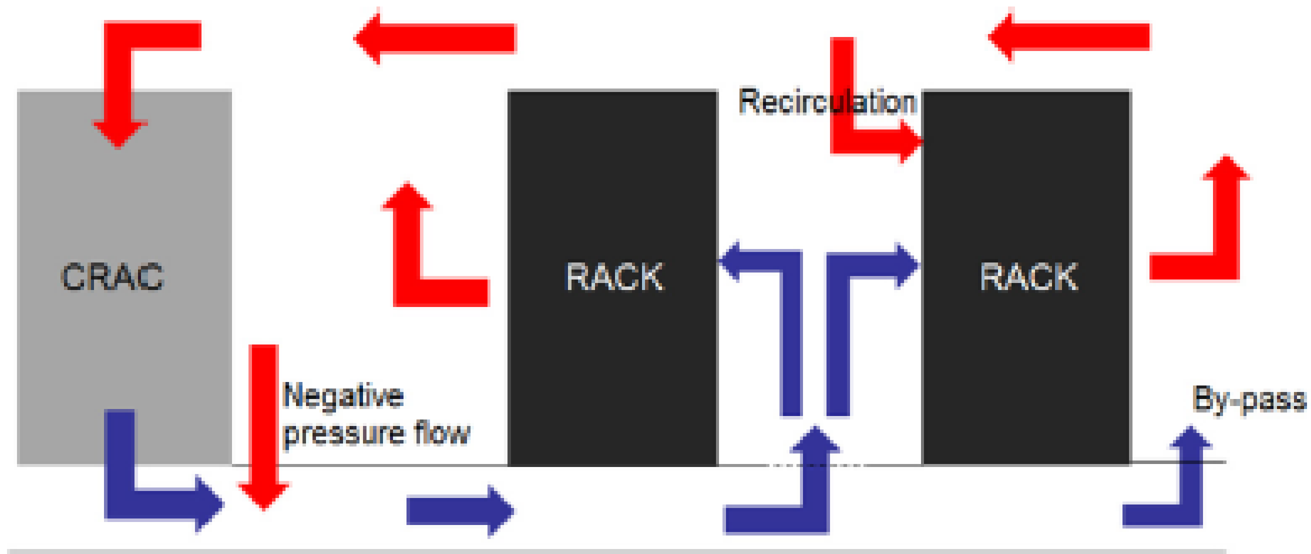
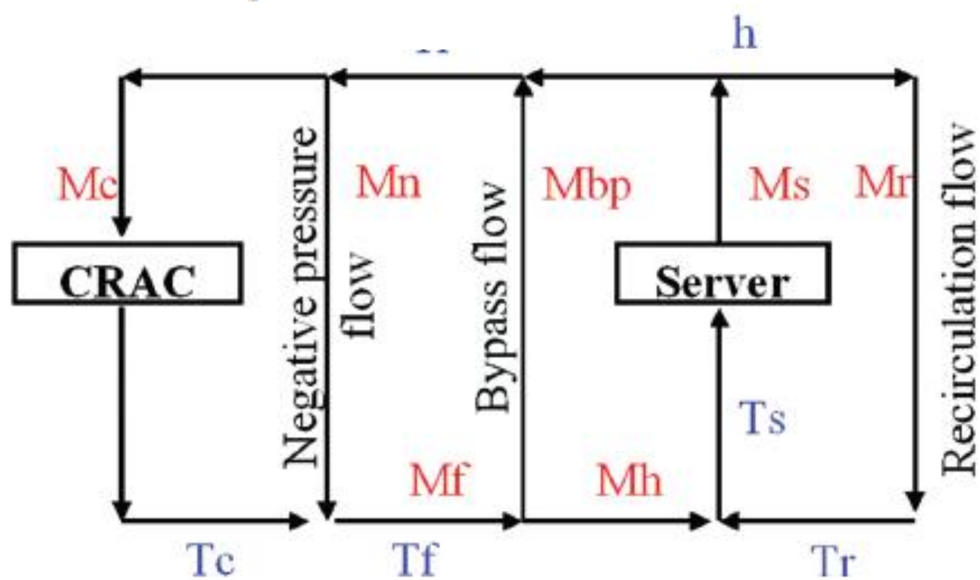


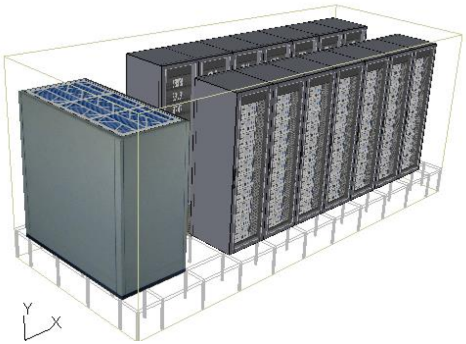
Fig. 6. Air flow circulation with standard problems (by-pass, recirculation, negative pressure flow) in an air cooled data centre. Blue lines represent cold air while red lines represent hot air.

Data center air streams. (Note: CRAC: computer room air conditioning unit; Server: IT equipment server; bp: bypass; c:CRAC; f:floor; h:hall; M:mass flow rate; n: negative pressure; r: recirculation; s: server; T:temperature.)

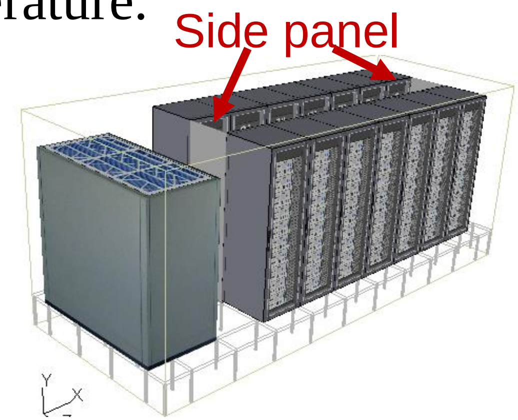


Panel cover

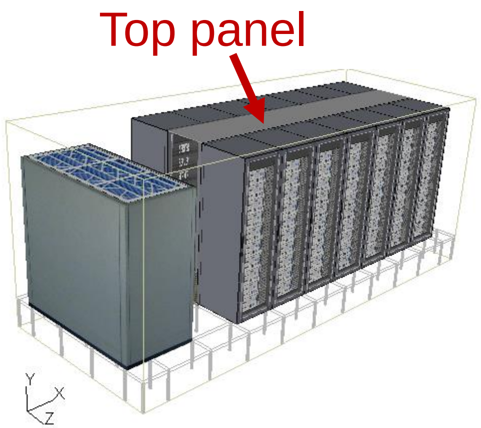
- The effect of adding panel depend on the design of data center, in this case the literal space is crowded so adding side panel can lower the server inlet temperature.



Without panel

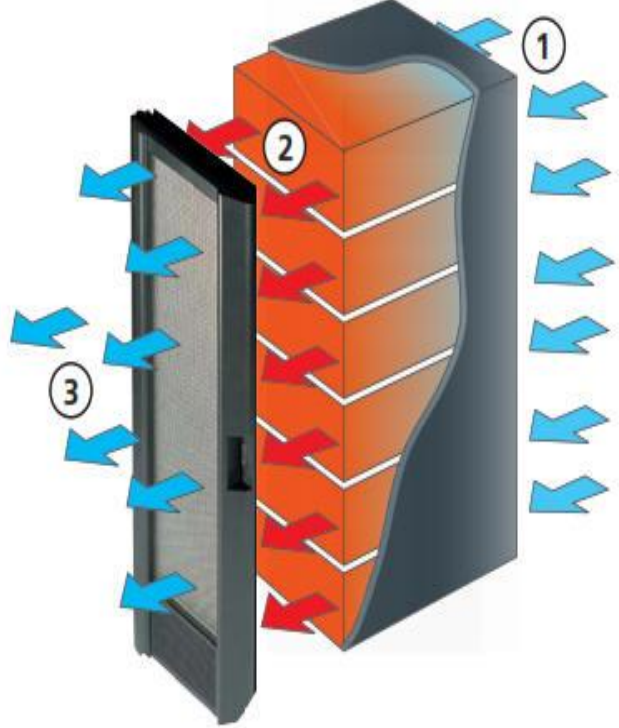


Side cover



Top cover

	Without Panel	Side Panel	Top Panel
Server Inlet maximum temperature (℃)	47.03	26.14	51.32
Server inlet mean temperature (℃)	19.18	15.78	18.9



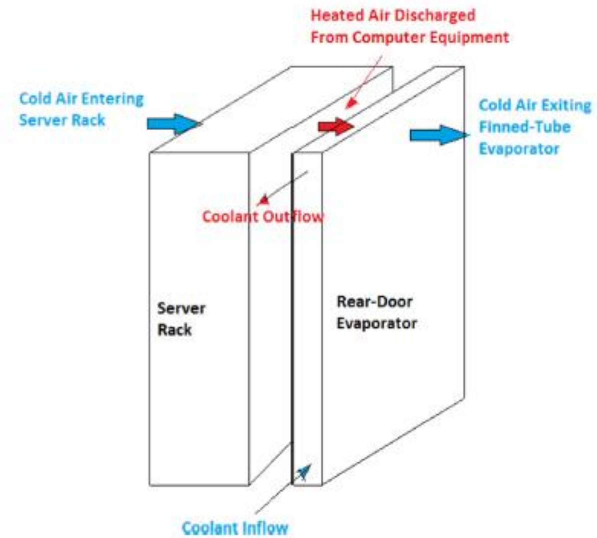


Fig. 3. Schematic diagram showing the use of the finned-tube evaporator for cooling the hot air discharged by a server rack in a data center environment (Adapted from [84]).

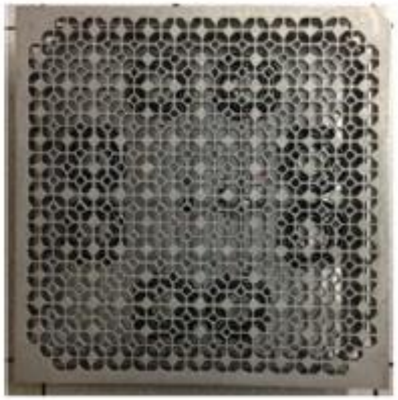
Active tiles

***Heat Transfer Engineering*, 37(3–4):246–256, 2016**

- Better temperature uniformity
- Better Chiller COP
- Better PUE

(a) Top view of passive tile

(b) Bottom view of passive tile



(c) Top view of active tile

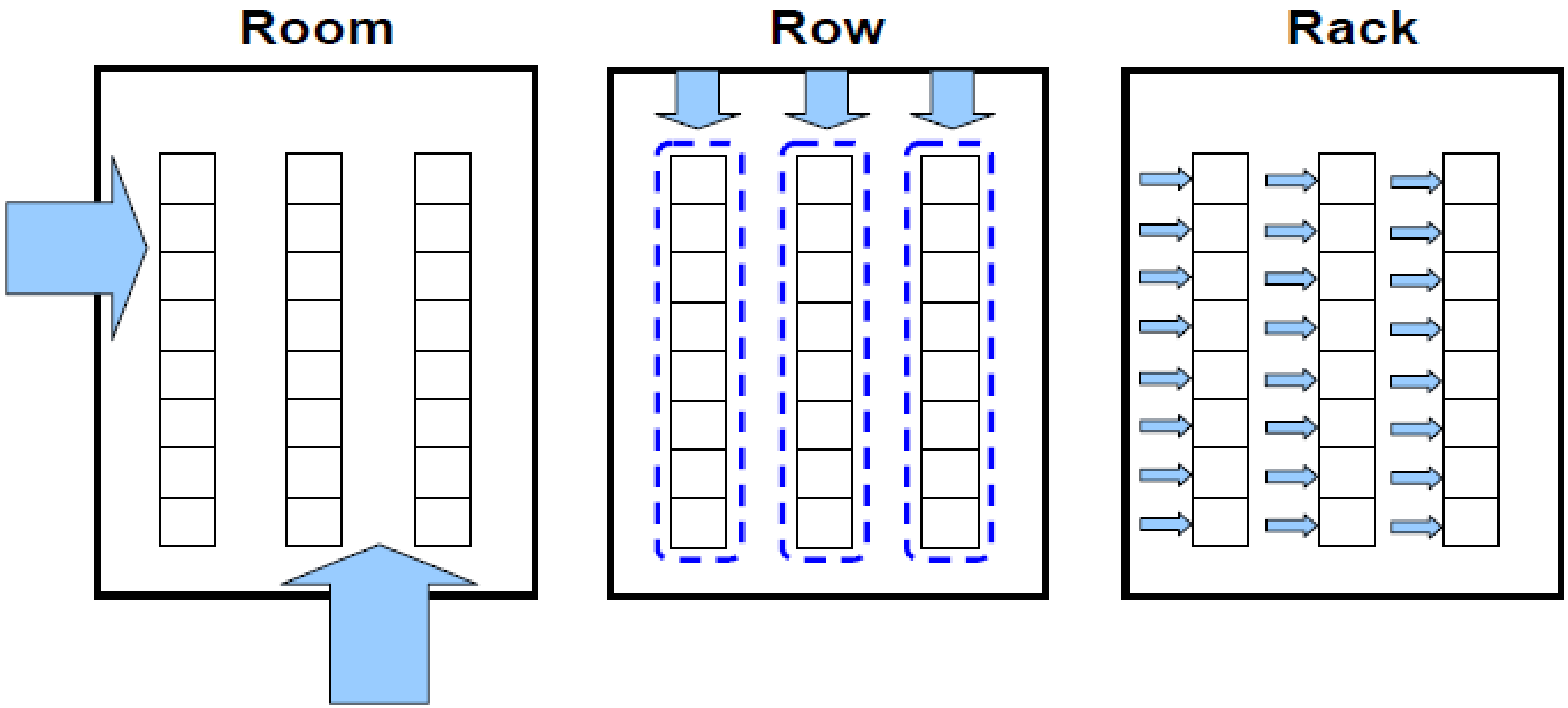
(d) Bottom view of active tile

Figure 2 Photographs of (a, b) passive and (c, d) active tiles.

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.*



Row-oriented architecture

- With a row-oriented architecture, the CRAC units are associated with a row and are assumed to be dedicated to a row for design purposes. The CRAC units may be mounted among the IT racks, they may be mounted overhead, or they may be mounted under the floor.

Figure 2a – *In-row cooling solution*

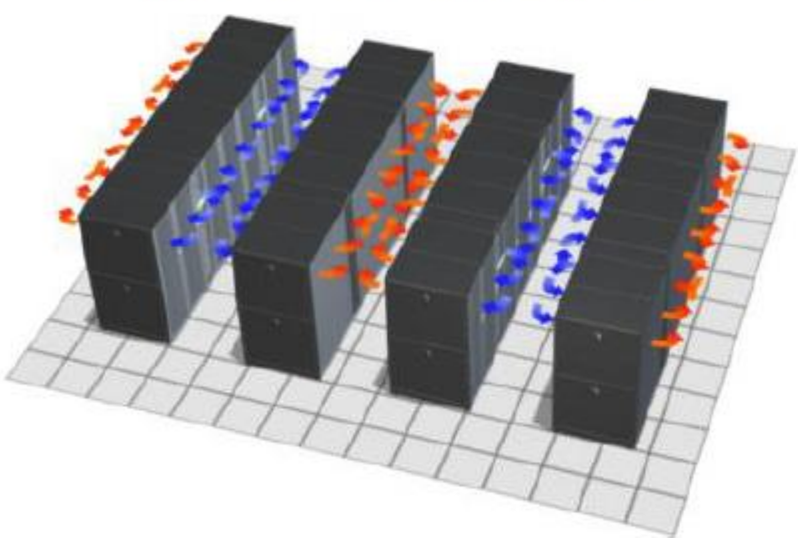


Figure 2b – *Overhead cooling solution*

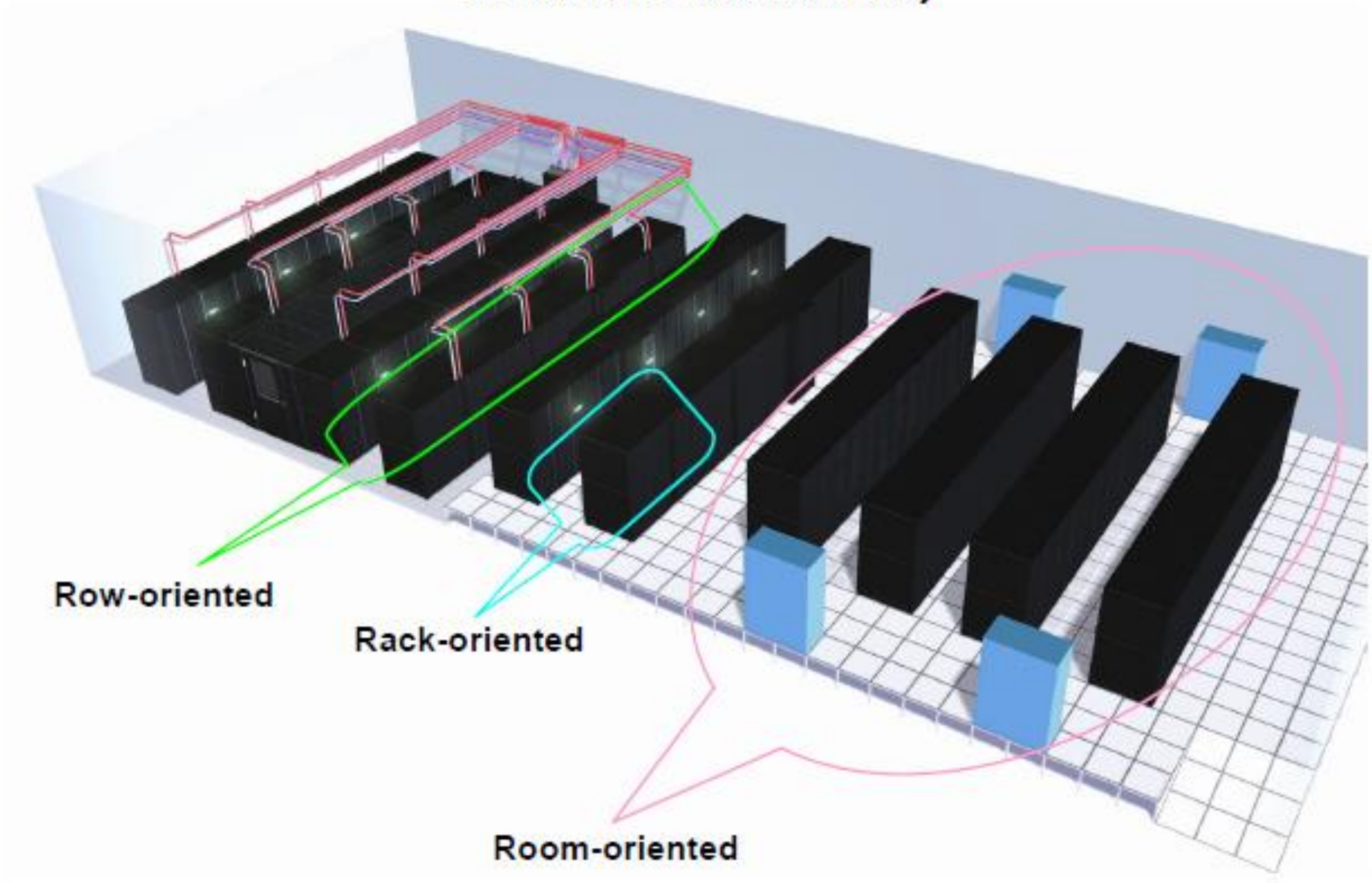
Rack-oriented architecture

- The CRAC units are directly mounted to or within the IT racks.
- Airflow paths are even shorter and exactly defined, so that airflows are totally immune to any installation variation or room constraints.
- Up to 50 kW per rack can be achieved.

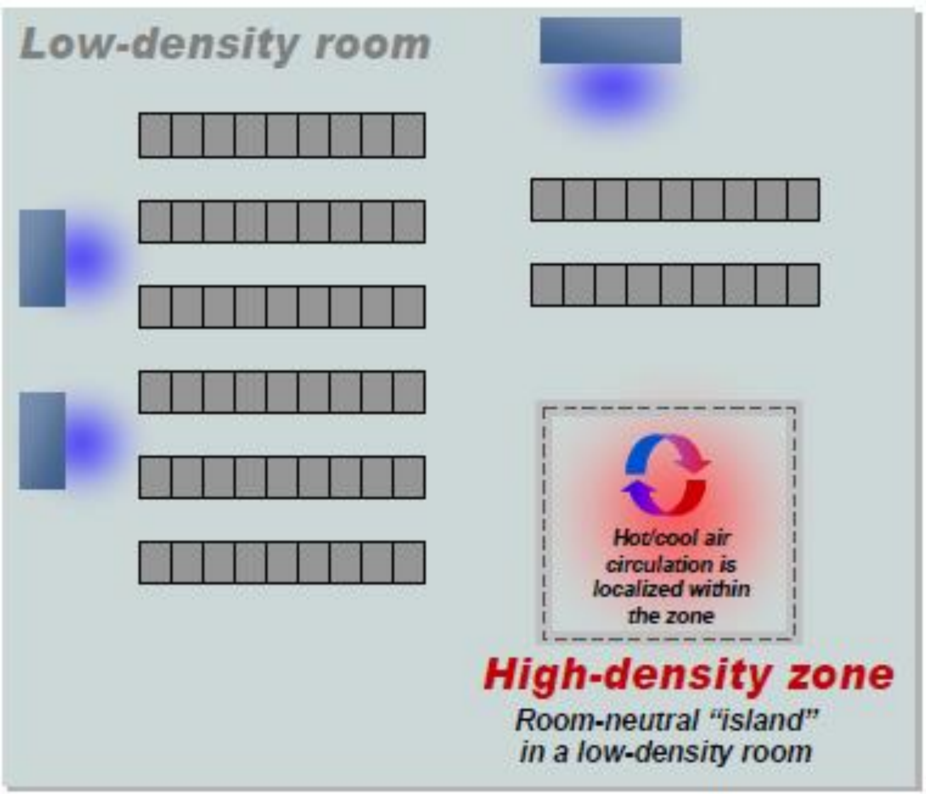
Figure 3 *– Rack cooling solution with cooling completely internal to rack*

Mixed architecture

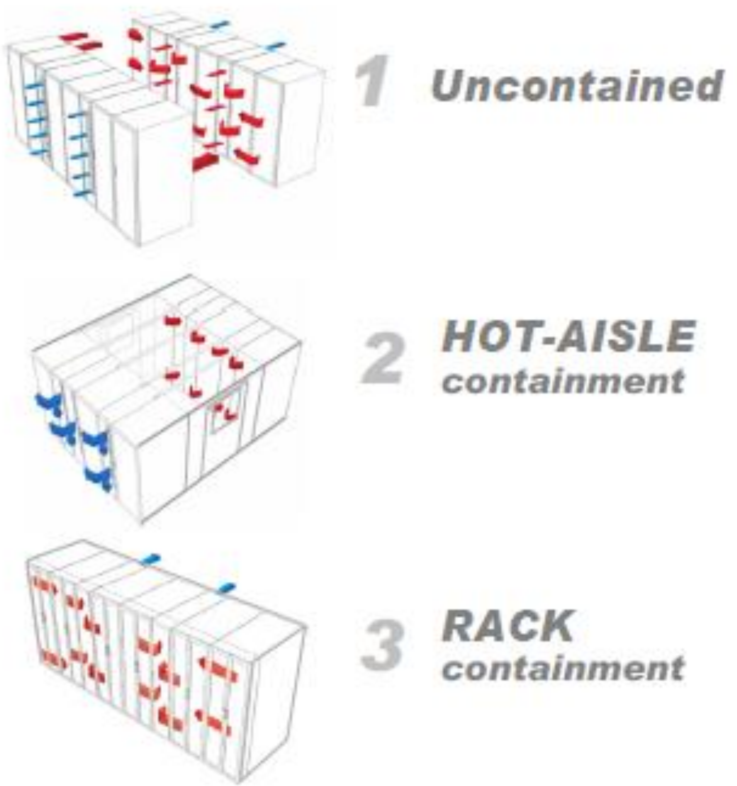
Figure 4 – Floor layout of a system utilizing room, row, and rack-oriented architectures simultaneously



High-density zone containment methods

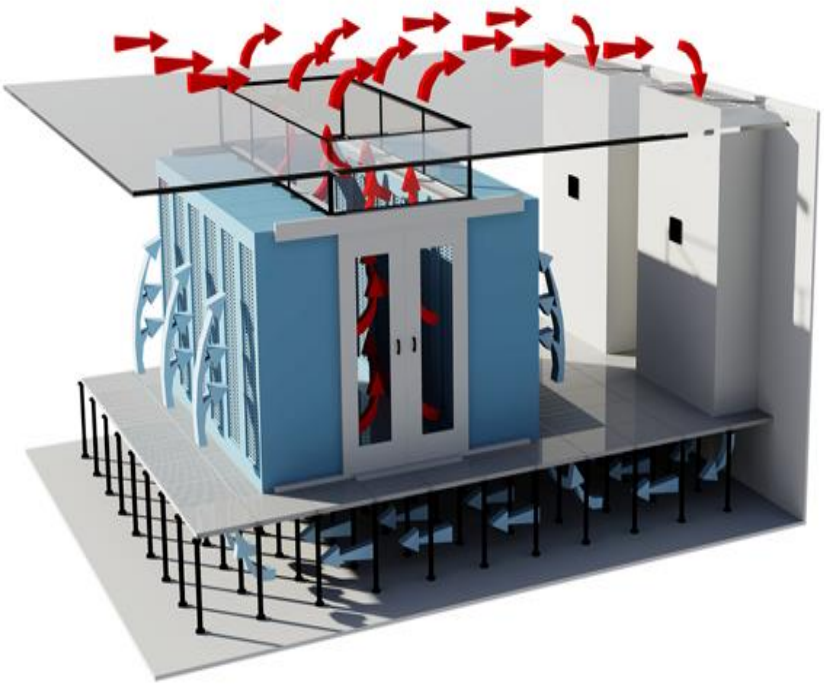


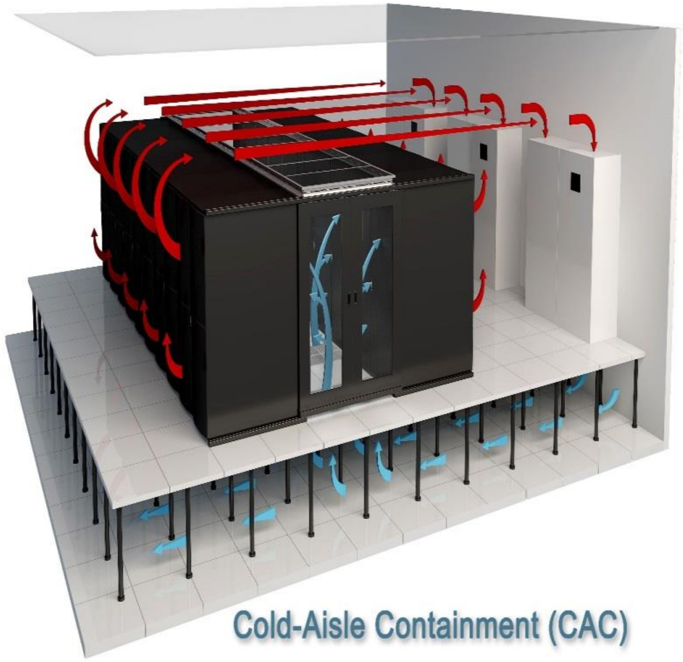
Three ways to create a room-neutral "island" in a low density room



Air Flow Management

- Hot Aisle Cold Aisle Separation





Hot Aisle Containment

Cold Aisle Containment

Rack containment

- Rack containment (also called rack air containment) is similar to hot aisle containment except that the hot exhaust air is contained using the back frame of the equipment racks and a series of panels to form a rear air channel.

Figure 8

*High-density zone with **rack containment***

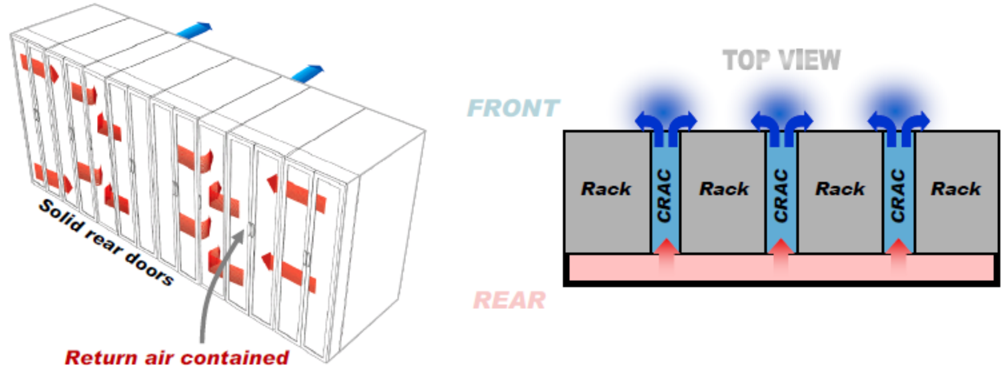
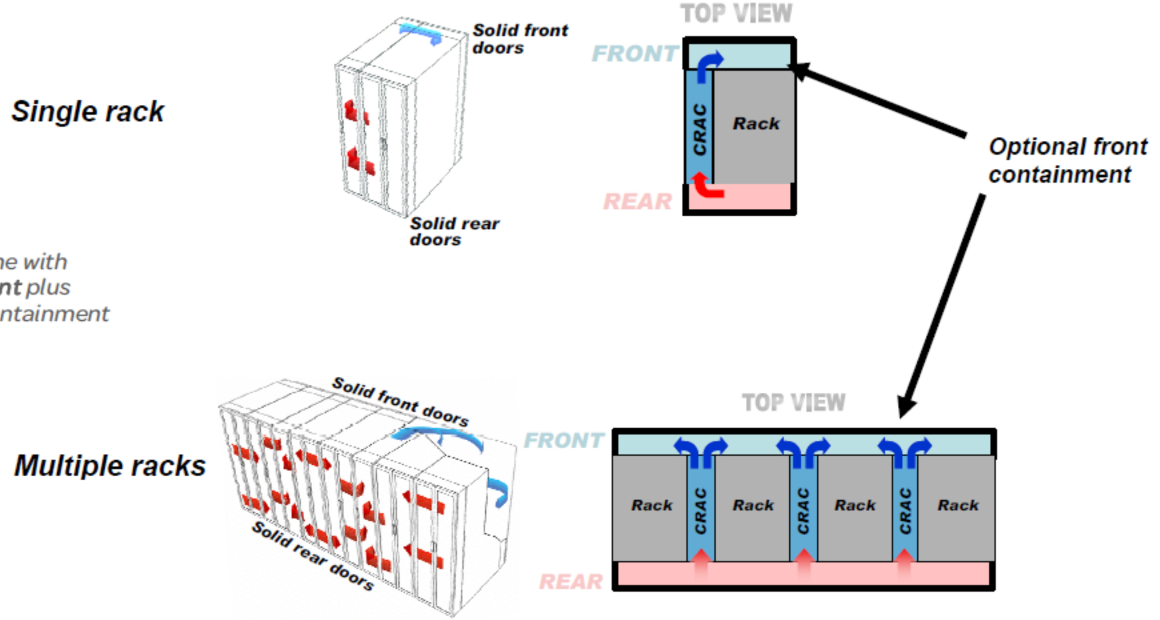


Figure 9

*High-density zone with **rack containment** plus optional front containment*



Some recent efforts for airside management in small datacenter

@NCTU

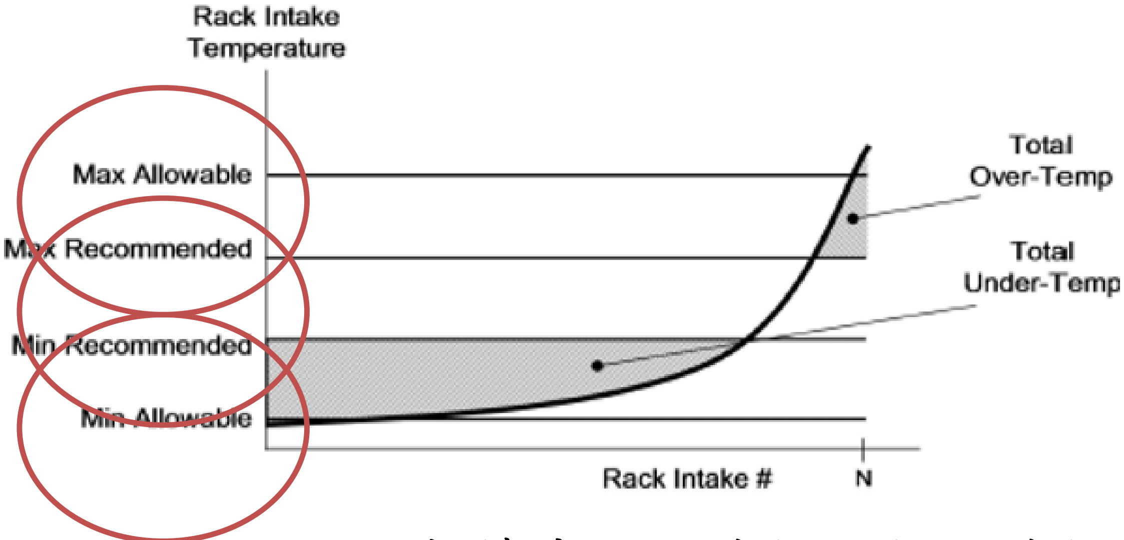
實驗量測案例探討

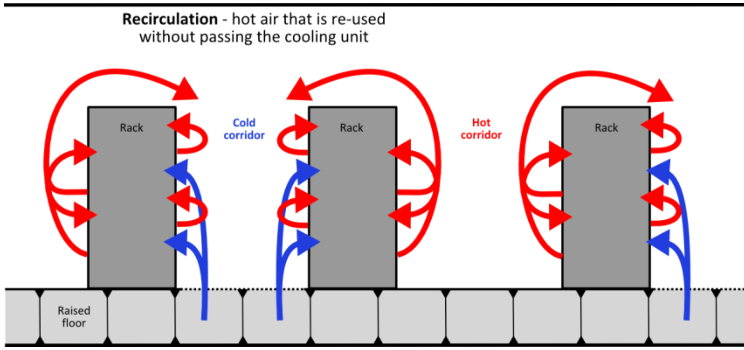
- 機房之指標參數
- 機房量測及設備
- 機櫃不均勻發熱之

全尺寸機房探討

- 機櫃加裝擋板之影響
- 機櫃距離回風口位置
- 供風口位置
- 針對供風口開1-6，4不開進行探討
- 改變熱通道大小
- 改變供風量大小
- 改變冷通道封閉方式
- 影響-半尺寸

機房之指標參數





- Herrlin 針對數據中心的機櫃，提供機櫃冷卻效率的程度指標，分別為機櫃過熱的程度RCI_{HI}與機櫃過冷程度RCI_{LO}:

$$RCI_{HI} = \left[1 - \frac{\sum(T_x - T_{max-rec})_{T_x > T_{max-rec}}}{(T_{max-all} - T_{max-rec})n}\right] 100\%$$

$$RCI_{LO} = \left[1 - \frac{\sum(T_{min-rec} - T_x)_{T_{min-rec} > T_x}}{(T_{min-rec} - T_{min-all})n}\right] 100\%$$

其中，T_x=進入伺服機之平均溫度、n =機櫃進氣總個數、 $T_{max-rec}$ =建議之溫度上限、 $T_{max-all}$ =允許之溫度上限、 $T_{min-rec}$=建議之溫度下限、 $T_{min-all}$ =允許之溫度下限。

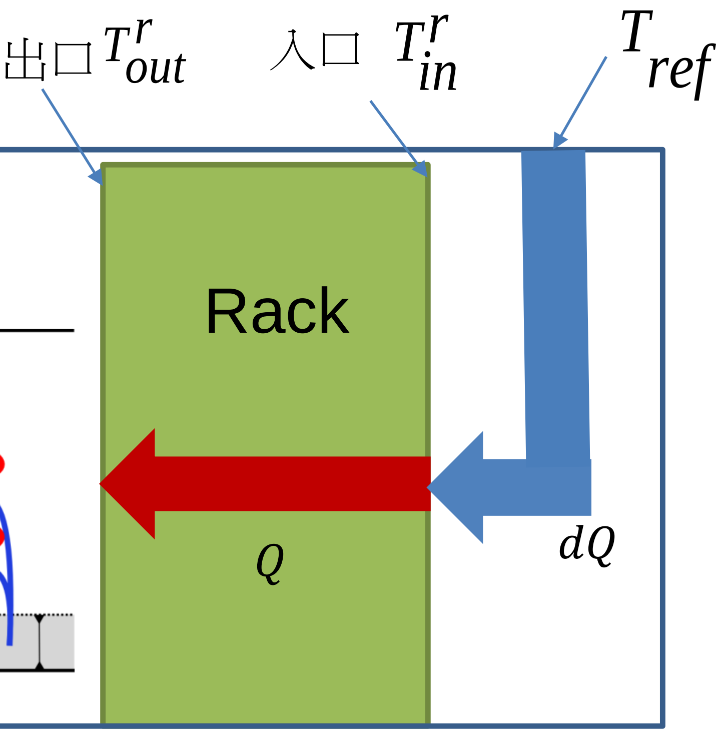
M. K. Herrlin, "Rack cooling effectiveness in data centers and telecom central offices: The rack cooling index (RCI)", American Society of Heating Refrigerating and Air conditioning Engineers, 111(2), 2005.

資料中心規範

- Sharma 等人提供熱空氣回流至冷通道的現象，作為熱回流程度的具體指標，稱為供熱指數SHI(Supply Heat Index):

$$SHI = \frac{dQ}{Q + dQ} = \frac{\text{空氣由供風口至機櫃入口所得到之發熱量}}{\text{空氣由供風口至機櫃出口所得到之發熱量}}$$

$$SHI = \frac{\sum_j \sum_i \left[\left(T_{in}^{r} \right)_{i,j} - T_{ref} \right]}{\sum_j \sum_i \left[\left(T_{out}^{r} \right)_{i,j} - T_{ref} \right]}$$



其中，此值介於0~1間，越小代表熱回有程度越低

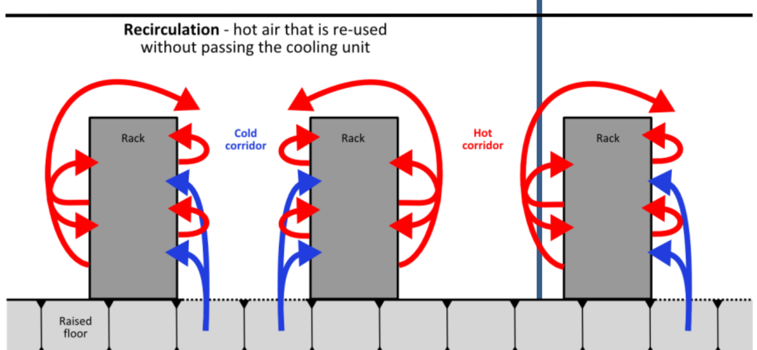
j 為機櫃之列

i 為機櫃之排

T_{in}^{r} 為機櫃入口溫度

T_{ref} 為供風口溫度

T_{out}^{r} 為機櫃出口溫度



R. K. Sharma, C. E. Bash, C. D. Patel, “Dimensionless parameters for evaluation of thermal design and performance of large-scale data centers”, 8th ASME/AIAA Joint Thermophysics and Heat Transfer Conference, 2002.

資料中心規範

- 如果RCI_{HI}值越小代表機櫃過熱越嚴重，RCI_{LO}值越小代表機櫃過冷越嚴重。

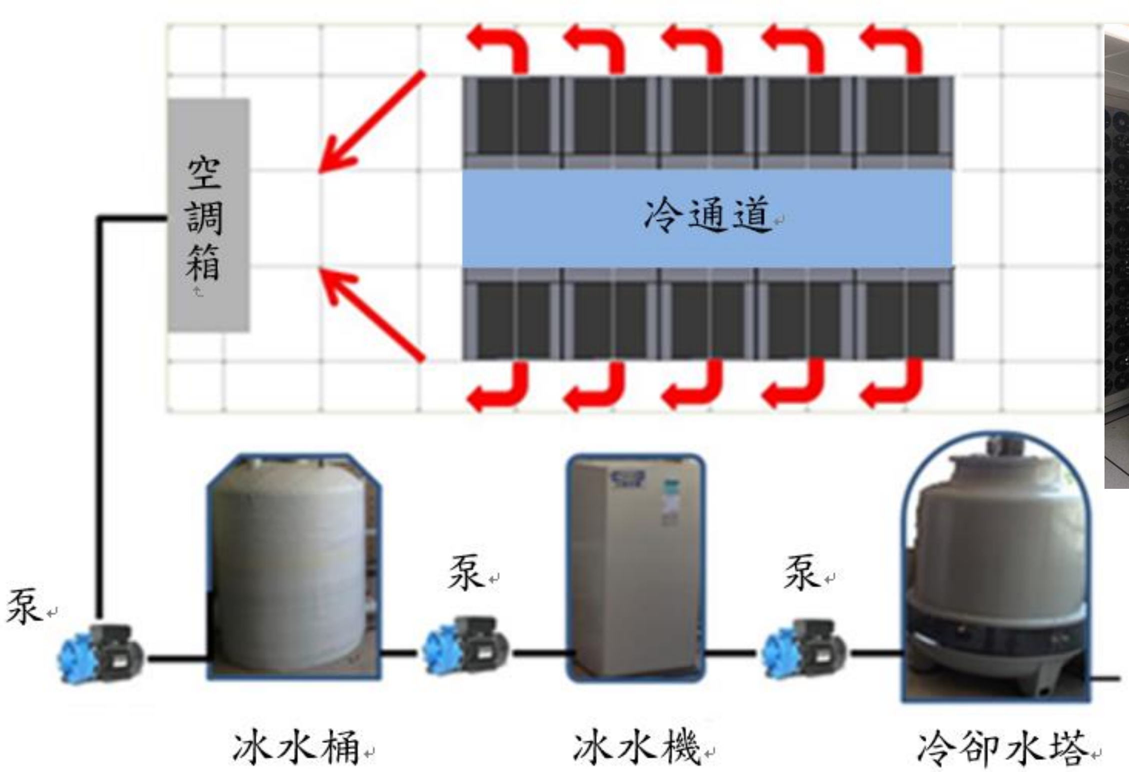
等級	RCI
理想	100%
良好	≥96%
可接受	91~95%
糟糕	≤90%

ASHRAE 2008 RCI指標

M. K. Herrlin, “Rack cooling effectiveness in data centers and telecom central offices: The rack cooling index (RCI)”, American Society of Heating Refrigerating and Air conditioning Engineers, 111(2), 2005.

機房量測及設備

冷房能力:30 RT

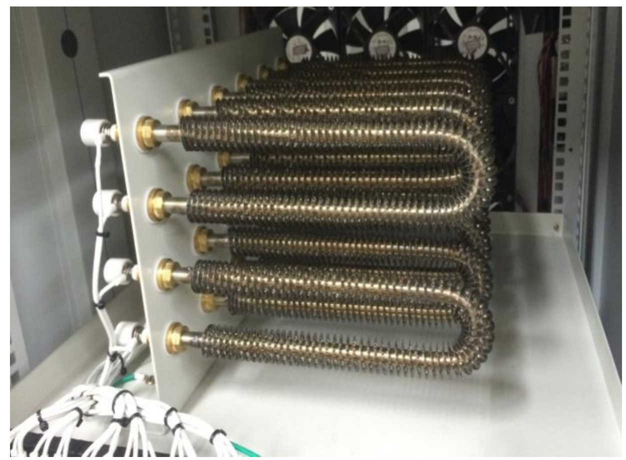


機櫃

天花板供風口

實驗設備

- 機櫃寬度為0.6m、深度為0.615m、高度為1.95m，總發熱量15.5 kW*4 、 10 kW*2台、7.5 kW*4台
- 42個風扇，每個最大流量192 m^3/hr



實驗設備

F900感測器
0.15 m/s-10 m/s
0.15 m/s-5 m/s
誤差:±5 %

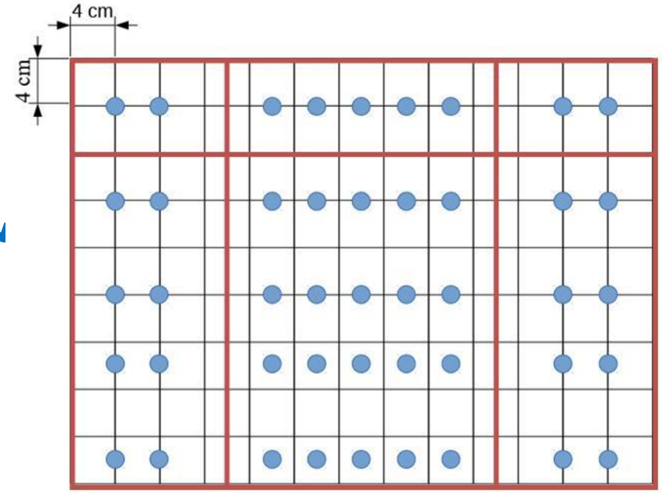
風罩流量計
50 m^3/h ~3,500 m^3/h
誤差:±5 %

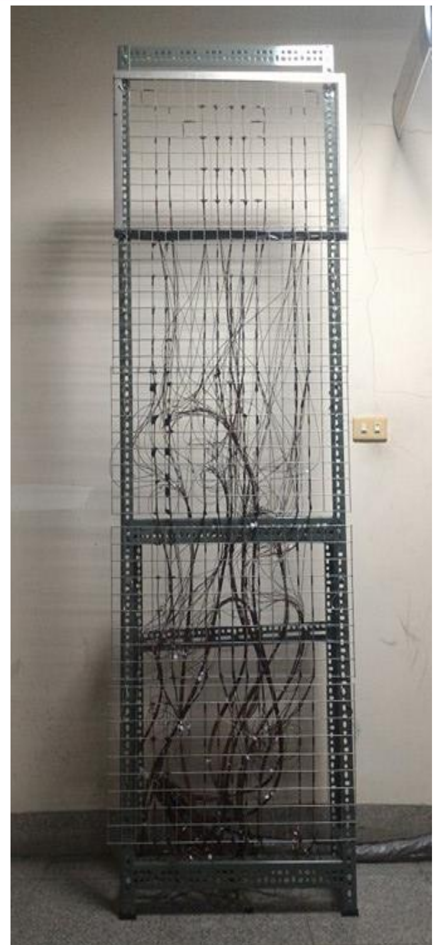
熱電偶
溫度範圍為0 °C～370 °C
校正誤差:±0.1 °C

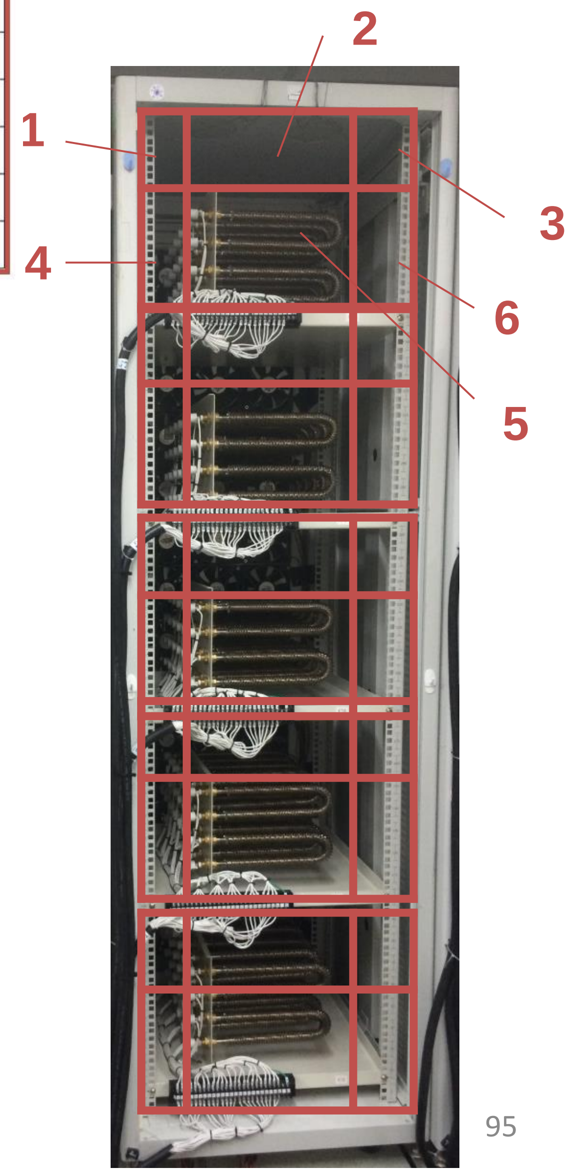
資料擷取器
(MX100)
速度:0.01 s

資料擷取器
(LR8400)
速度:0.01 s

溫度量測與布點方式







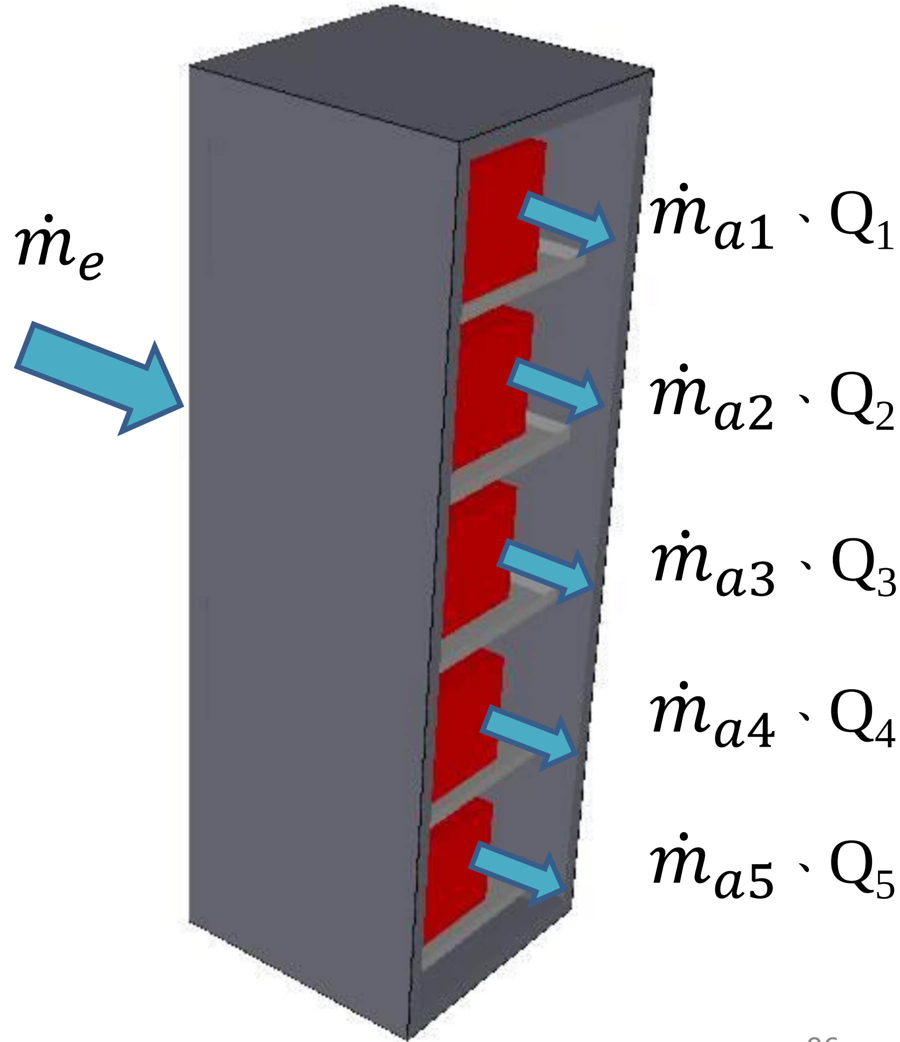
實驗驗證

機櫃風扇之風量	小流量	大流量
入　口	0.74 kg/s	1.82 kg/s
出　口	0.65 kg/s	1.74 kg/s
誤　差	12 %	4 %

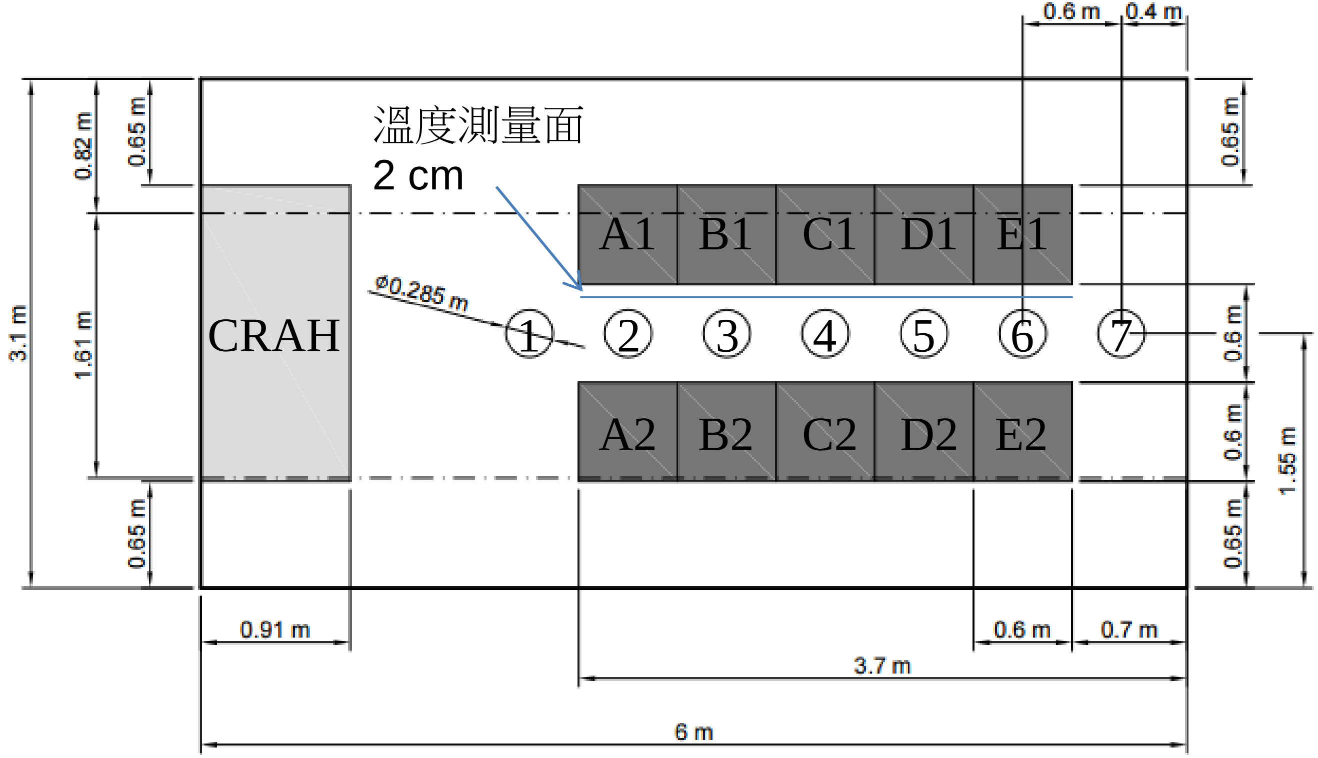
入出口質量流率比較

機櫃風扇之風量	小流量 ($0.65\ m^3/s$)	大流量 ($1.74\ m^3/s$)
電熱管之電功率	7.8 kW	
進出口之能量差	8.2 kW	8.1 kW
誤　差	5 %	4 %

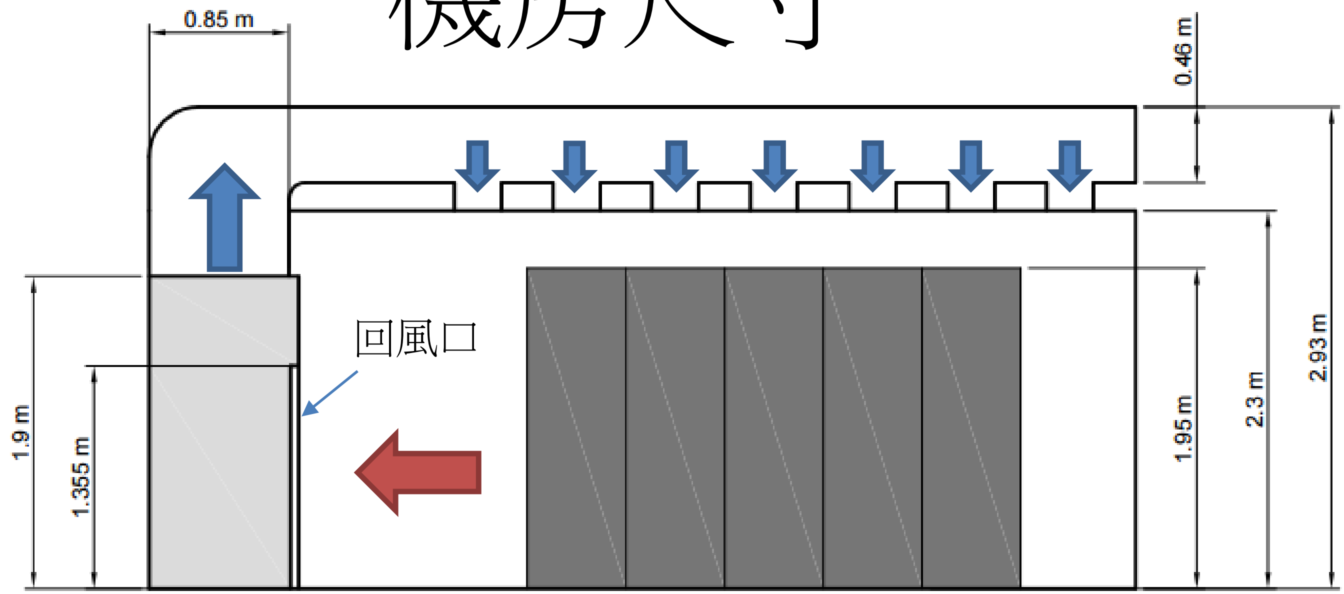
能量守恆比較



全尺寸container機房探討


0.6 m
0.4 m
溫度測量面
2 cm
0.82 m
0.65 m
3.1 m
1.61 m
CRAH
ø0.285 m
A1
B1
C1
D1
E1
①
②
③
④
⑤
⑥
⑦
A2
B2
C2
D2
E2
0.65 m
0.6 m
0.6 m
0.65 m
1.55 m
0.91 m
0.6 m
0.7 m
3.7 m
6 m

機房尺寸

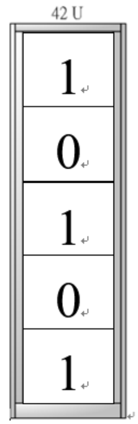

0.85 m
0.46 m
回風口
1.9 m
1.355 m
1.95 m
2.3 m
2.93 m

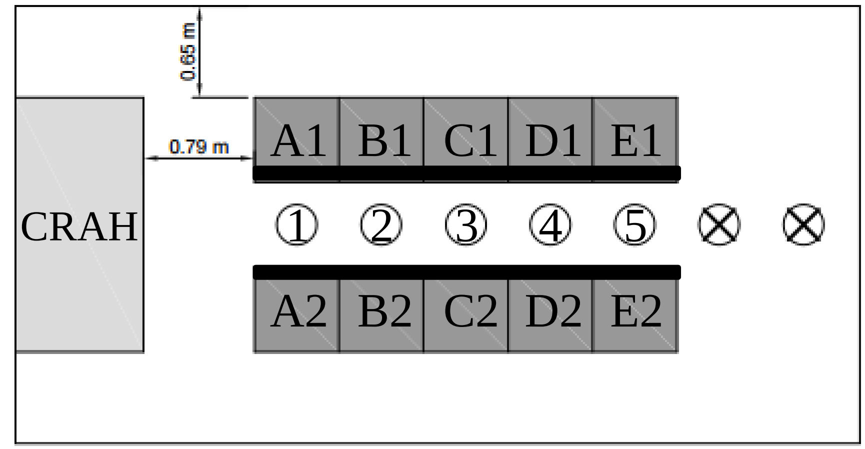
探討機櫃加裝擋板之影響

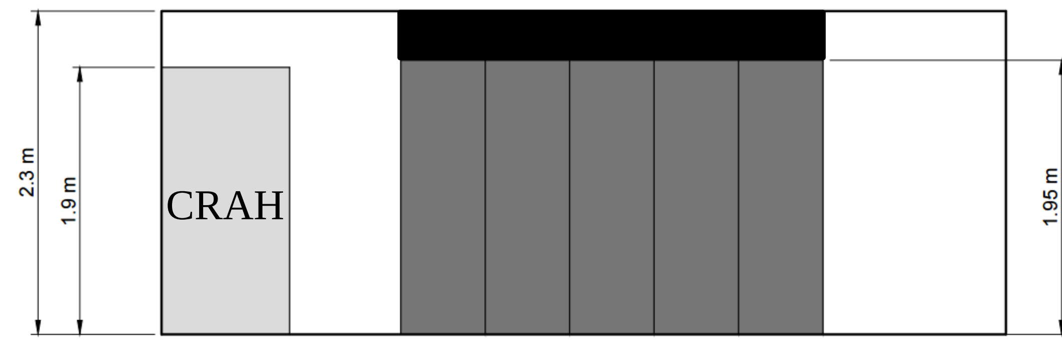
機房設定

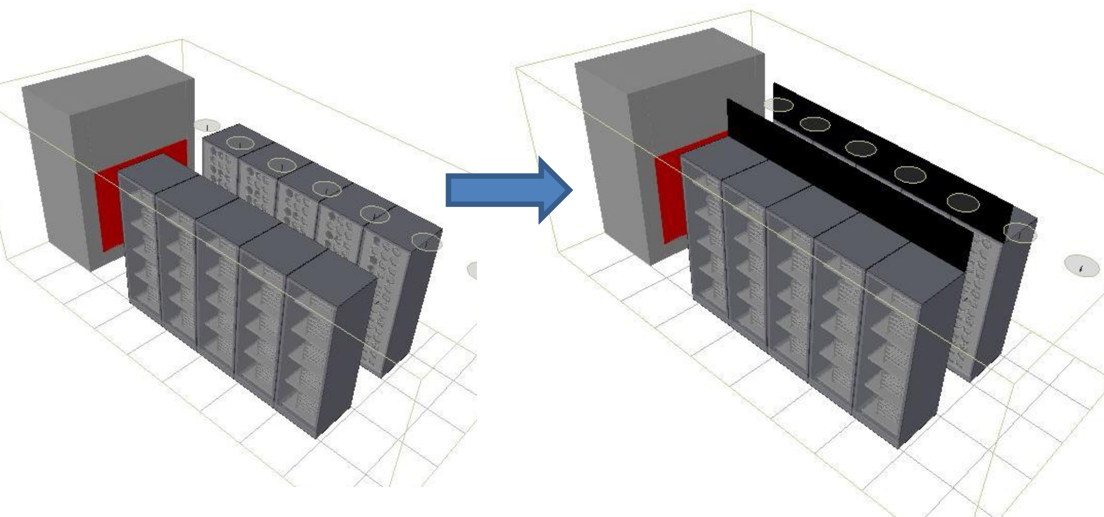
機房發熱量:30kW
供風溫度:21℃
供風風量:3.52 m^3/s
機櫃抽風量:3.53 m^3/s

機櫃設定



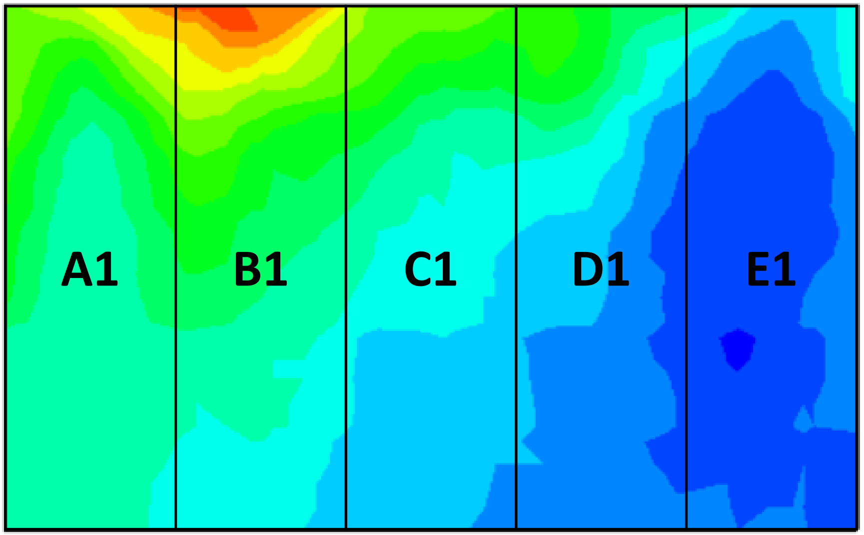




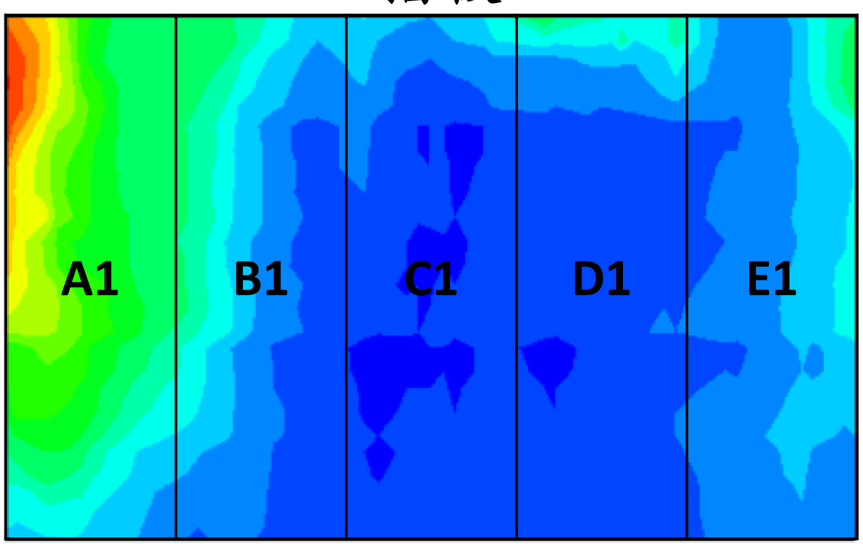


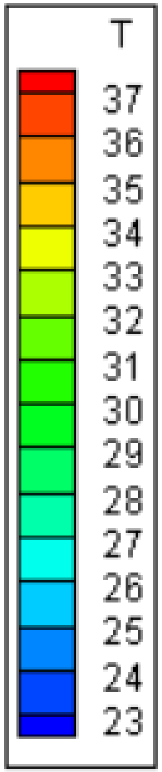
入口溫度分布及機房指標

無擋板



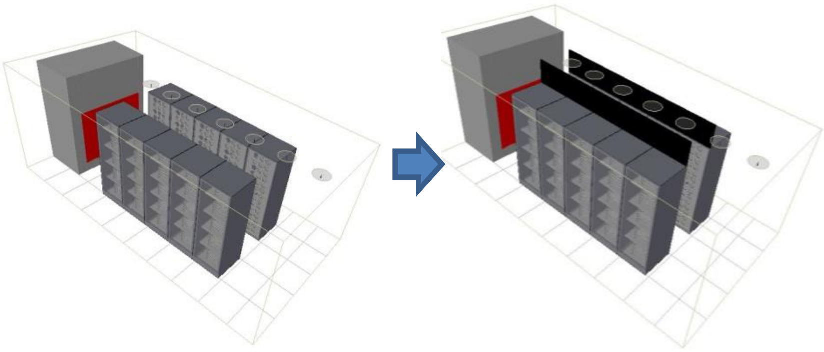
擋板

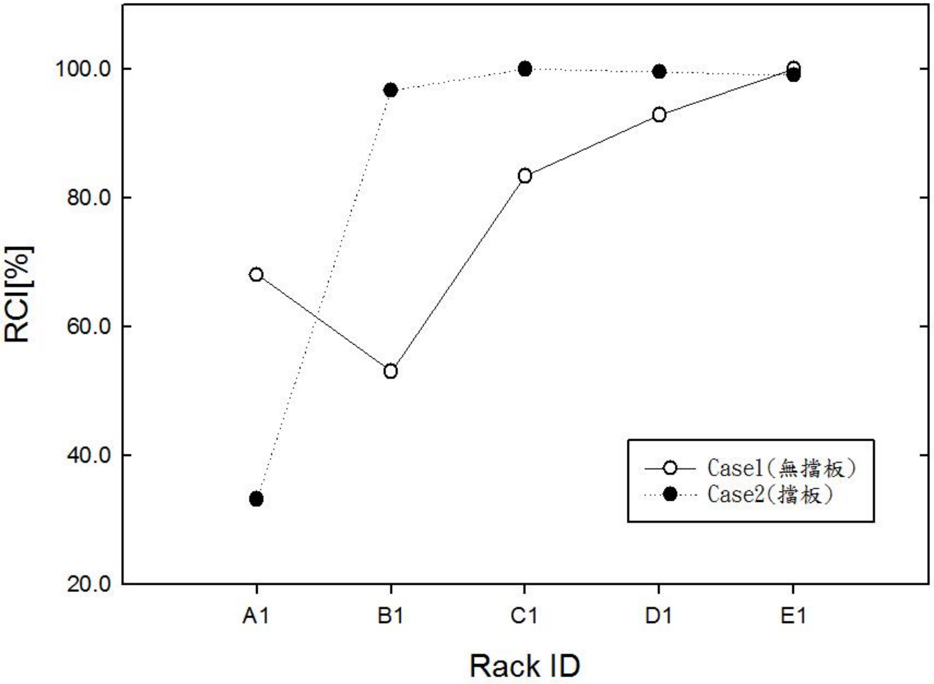


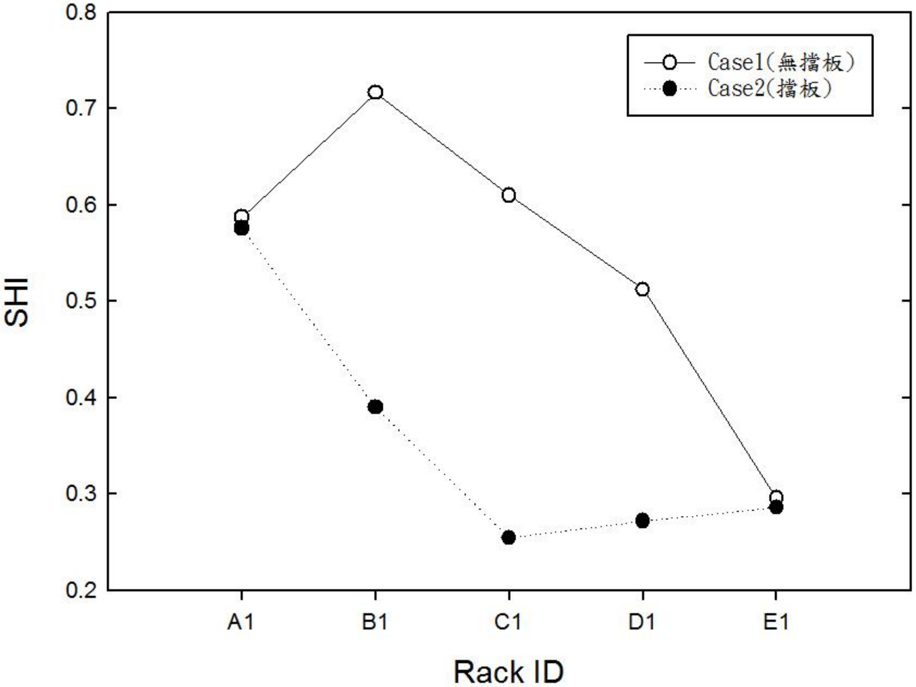


	無擋板	擋板
RCI	84%	86%
SHI	0.51	0.37
T_{max}	36.5	37.4
T_{avg}	26.7	25.8

在無擋板時，熱空氣由機櫃上半部回流情形相當嚴重，在機櫃上方加裝擋板後，可看到SHI明顯下降，有效改善熱回流情形，入口平均溫度明顯下降。







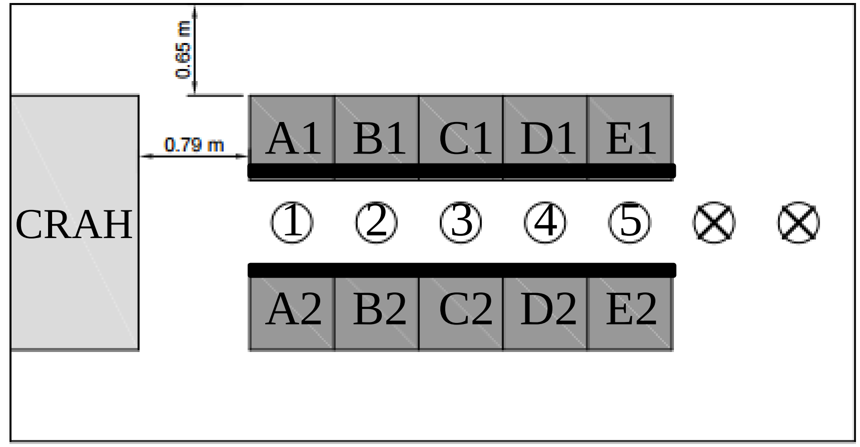
RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重
SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

探討機櫃距離回風口位置之影響

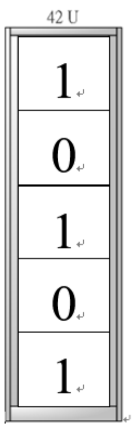
機房設定

機房發熱量:30 kW
供風溫度:21℃
供風風量:3.52 m^3/s
機櫃抽風量:3.53 m^3/s

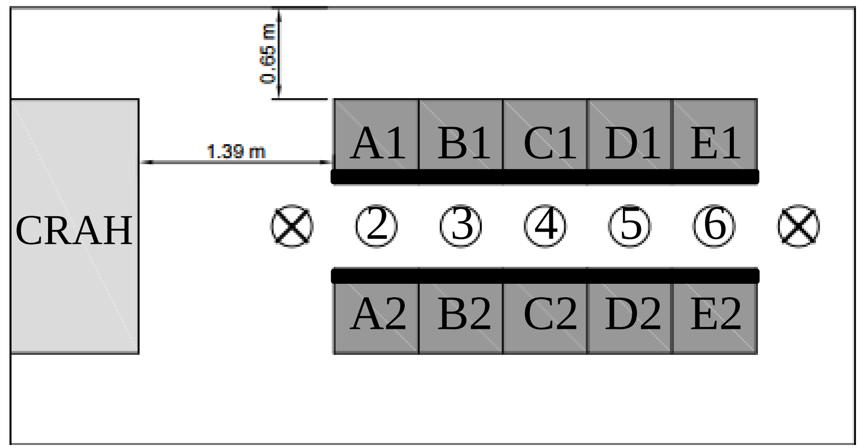
位置一



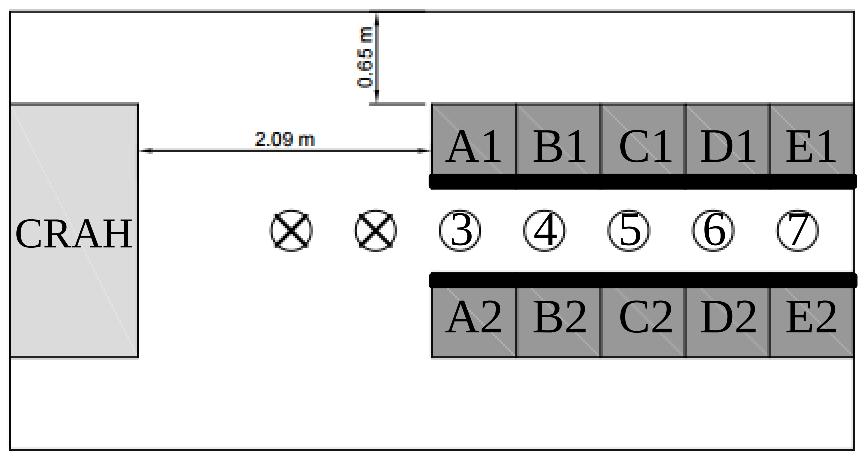
機櫃設定



位置二

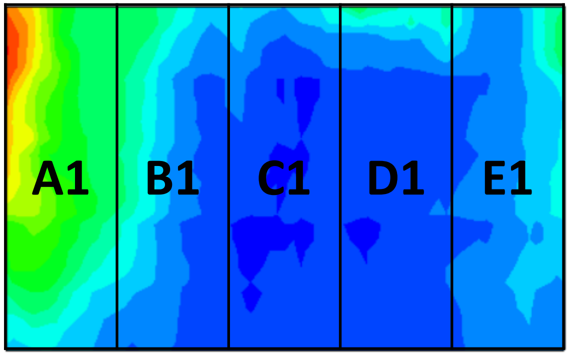


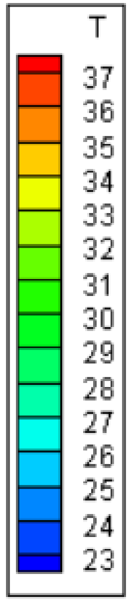
位置三



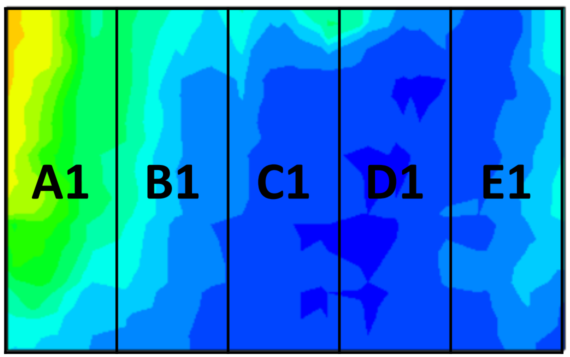
入口溫度分布及機房指標

位置一

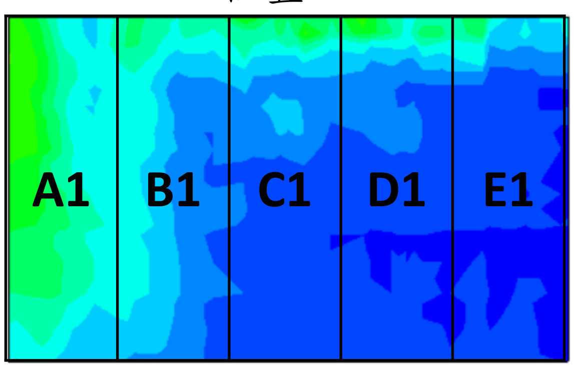




位置二

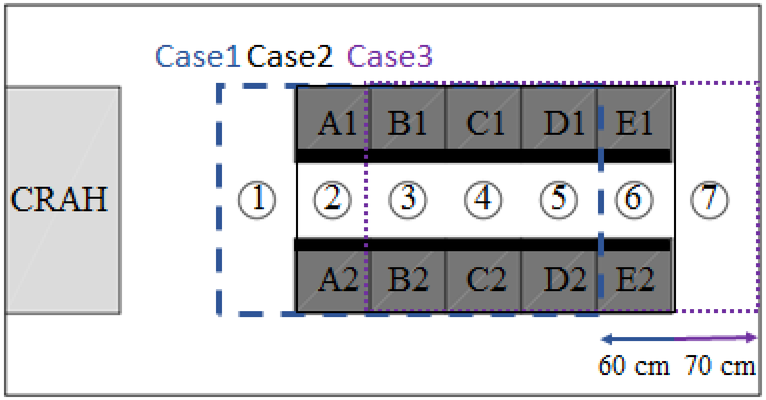


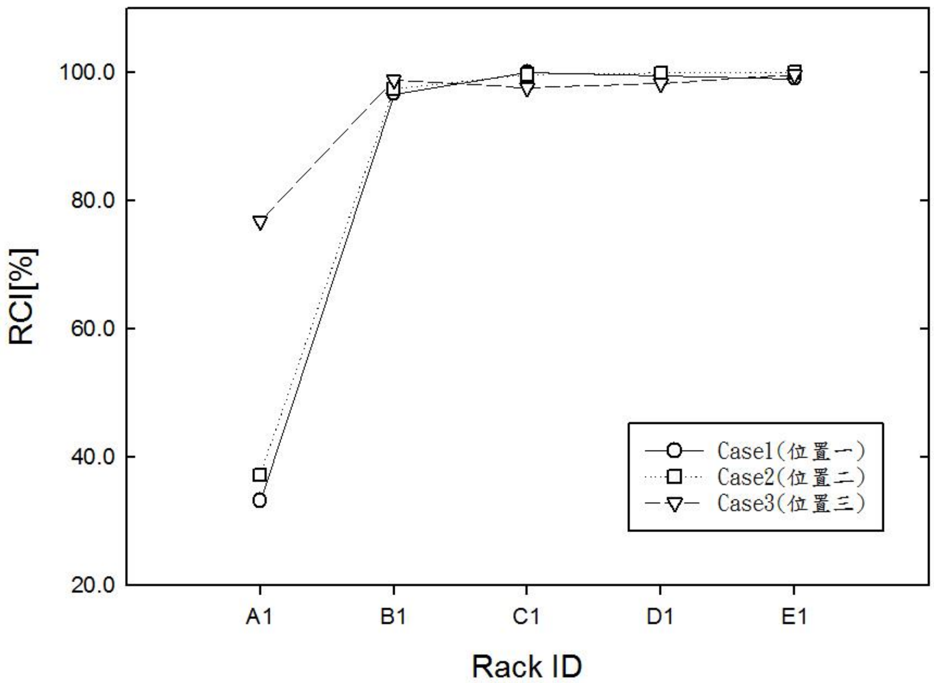
位置三

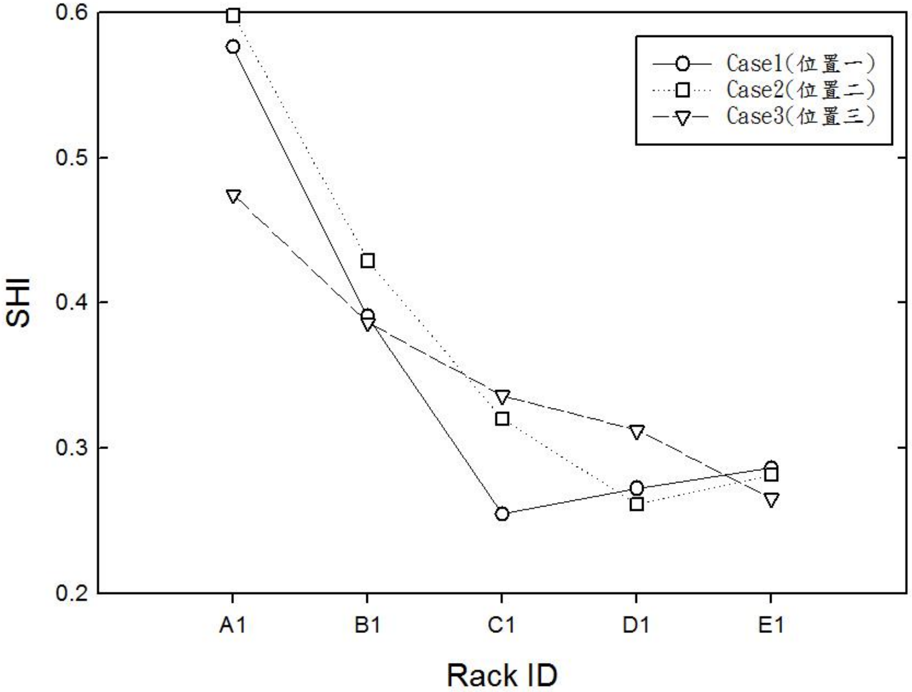


	位置一	位置二	位置三
RCI	86%	87%	92%
SHI	0.37	0.37	0.38
T_{max}	37.4	35.1	34.8
T_{avg}	25.8	25.6	25.4

當機櫃靠近空調箱的回風口時，冷空氣容易產生旁通現象，加上回風口位置關係，導致機櫃A1、A2過熱情形嚴重，當移動至位置三時，可改善機櫃E1、 E2熱回流現象和機櫃A1、A2之局部熱點。







RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重

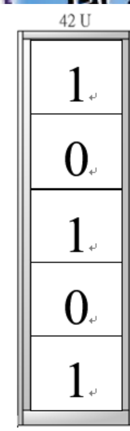
SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

探討供風口位置之影響

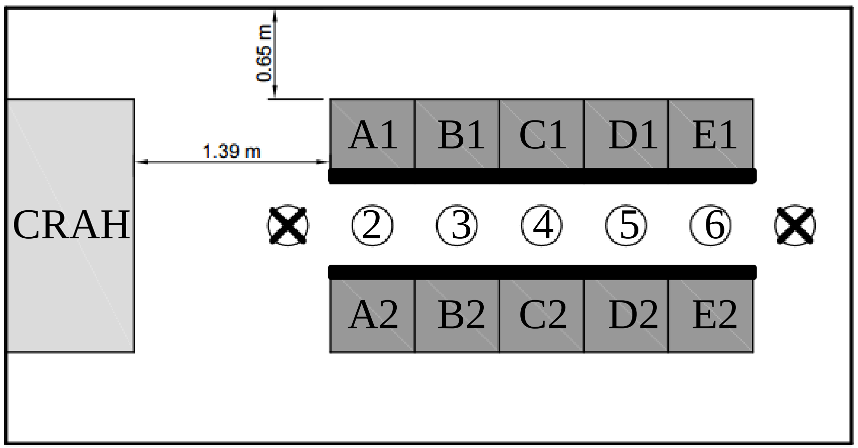
機房設定

機房發熱量:30 kW
供風溫度:21℃
供風風量:3.52 m³/s
機櫃抽風量:3.53 m³/s

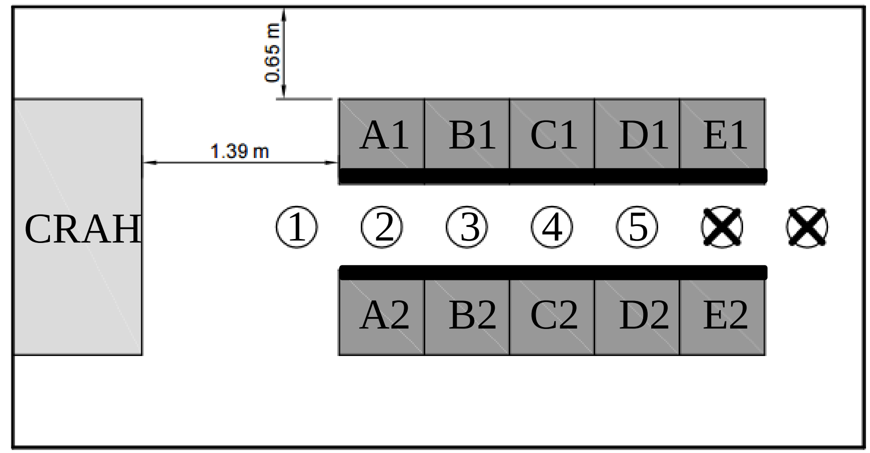
機櫃設定



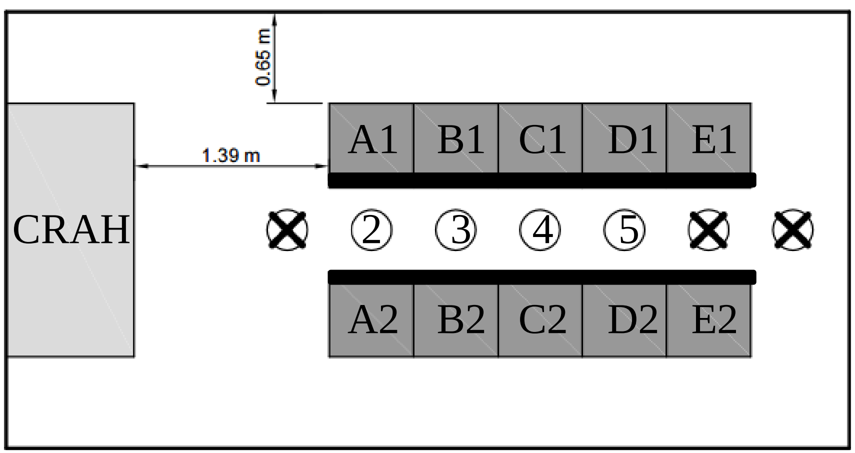
出風口2-6



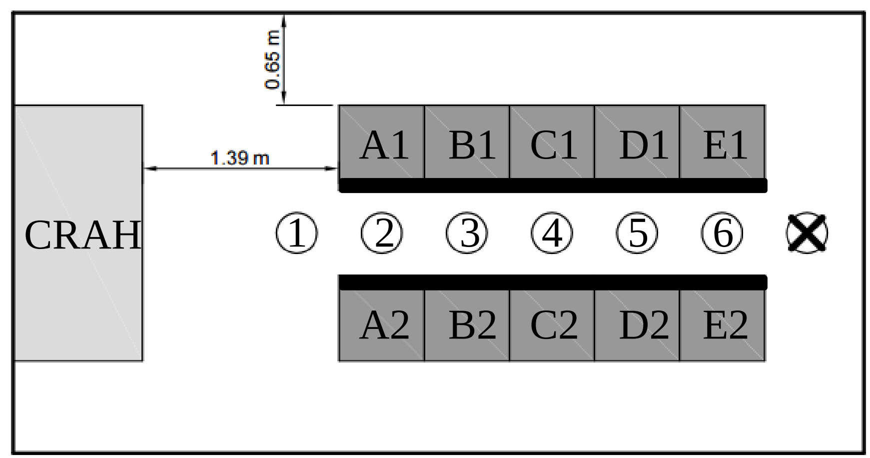
出風口1-5



出風口2-5

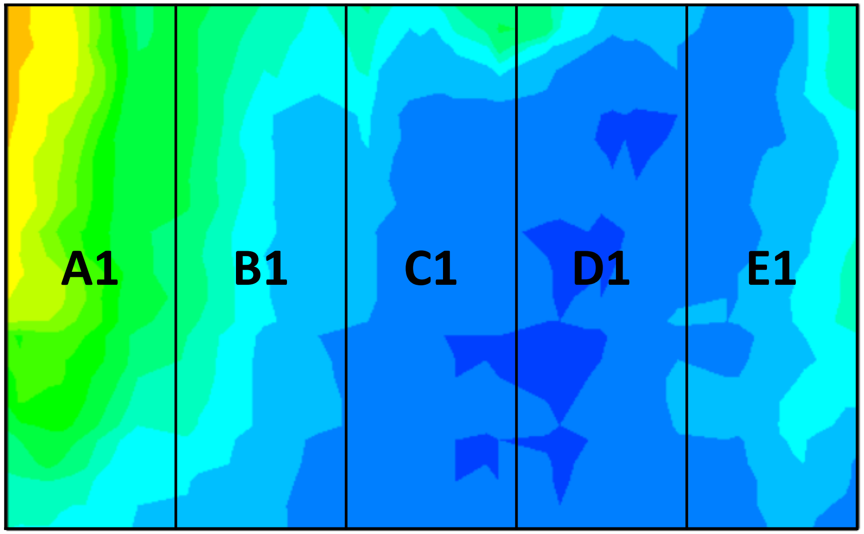


出風口1-6

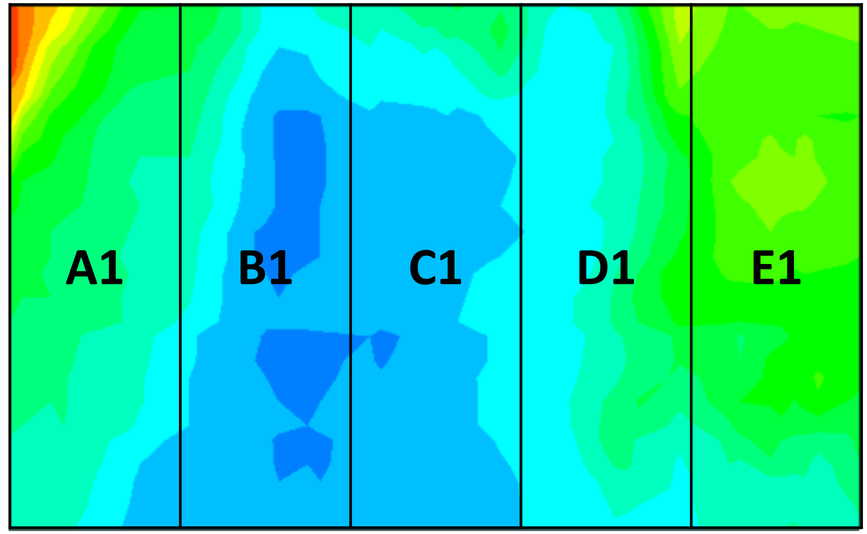


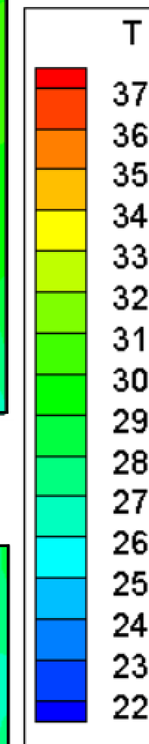
入口溫度分布

開孔2 -6

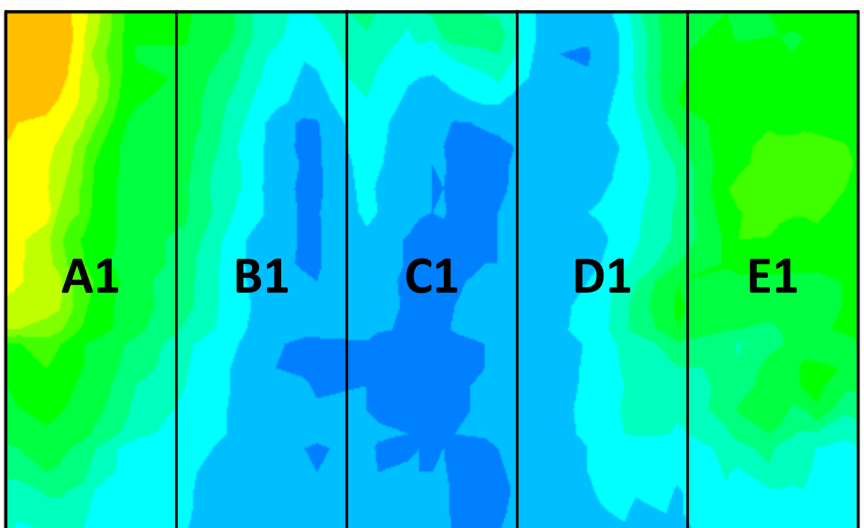


開孔1-5

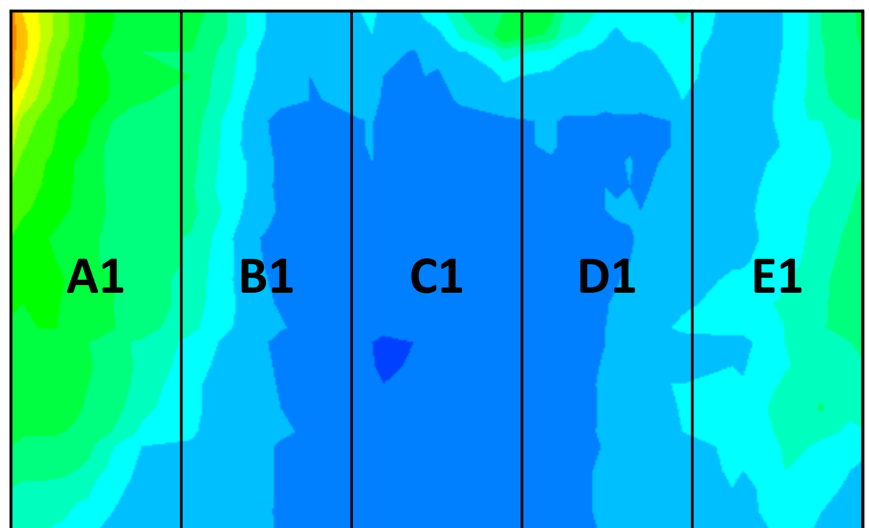


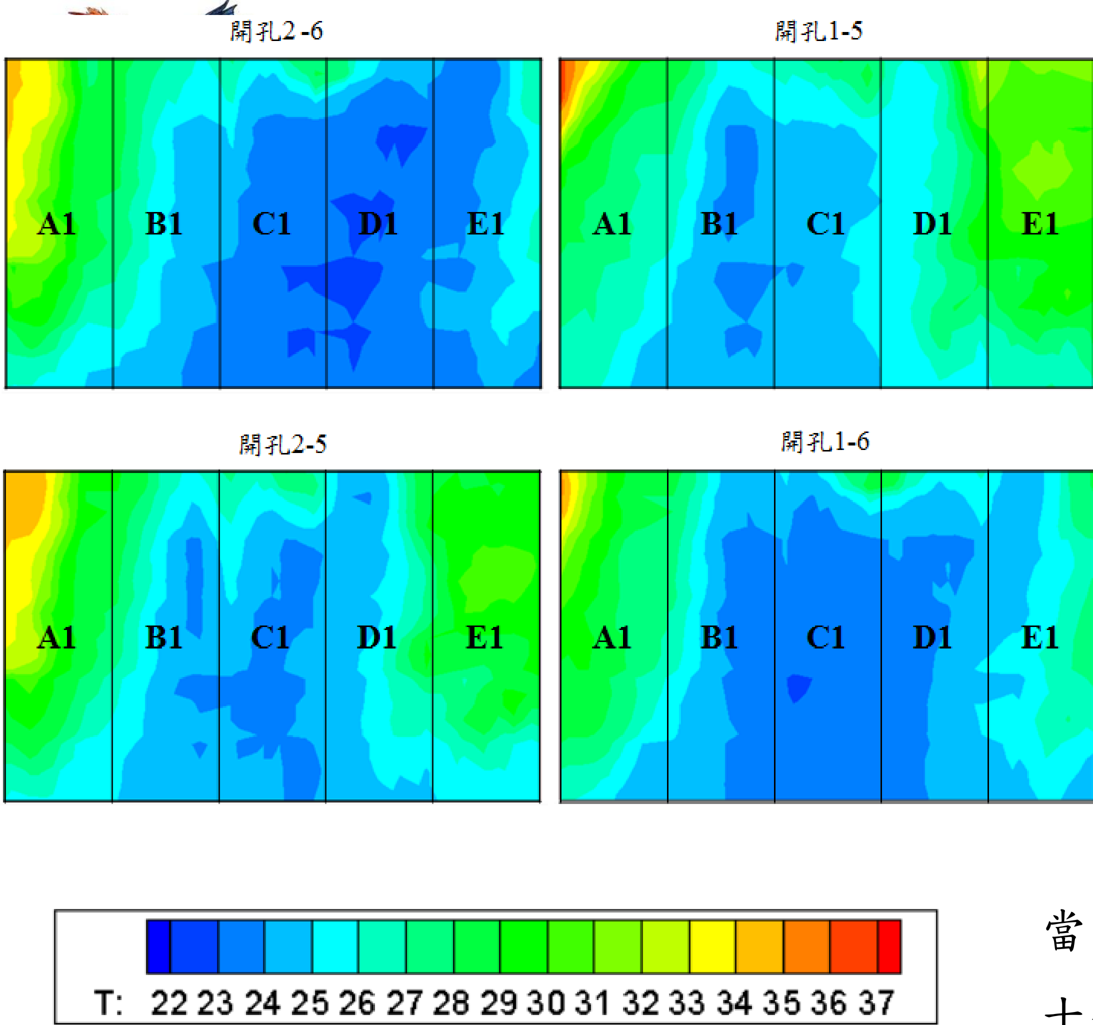


開孔2-5



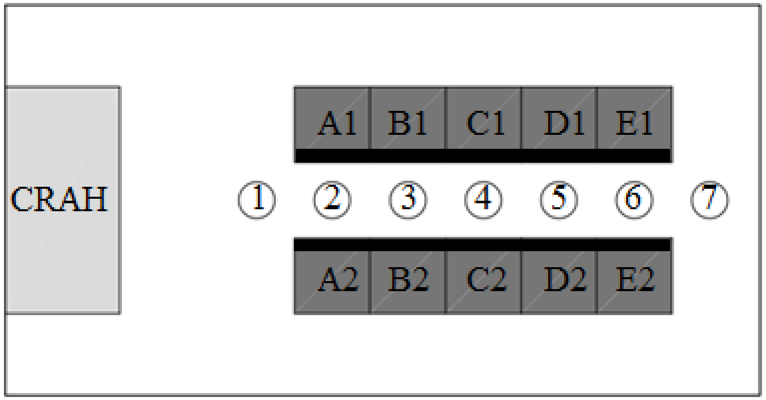
開孔1-6

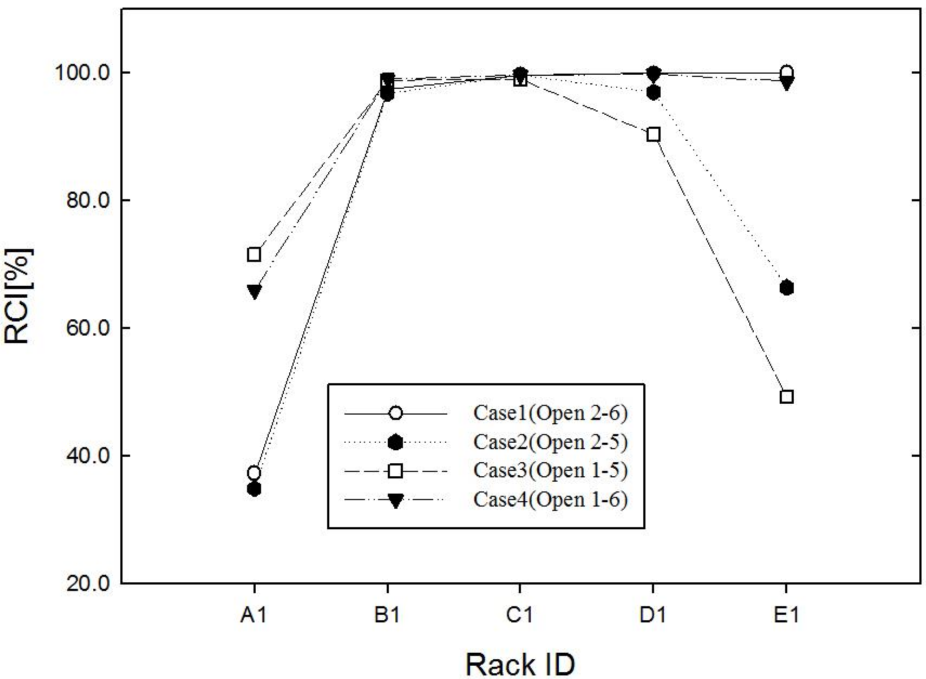


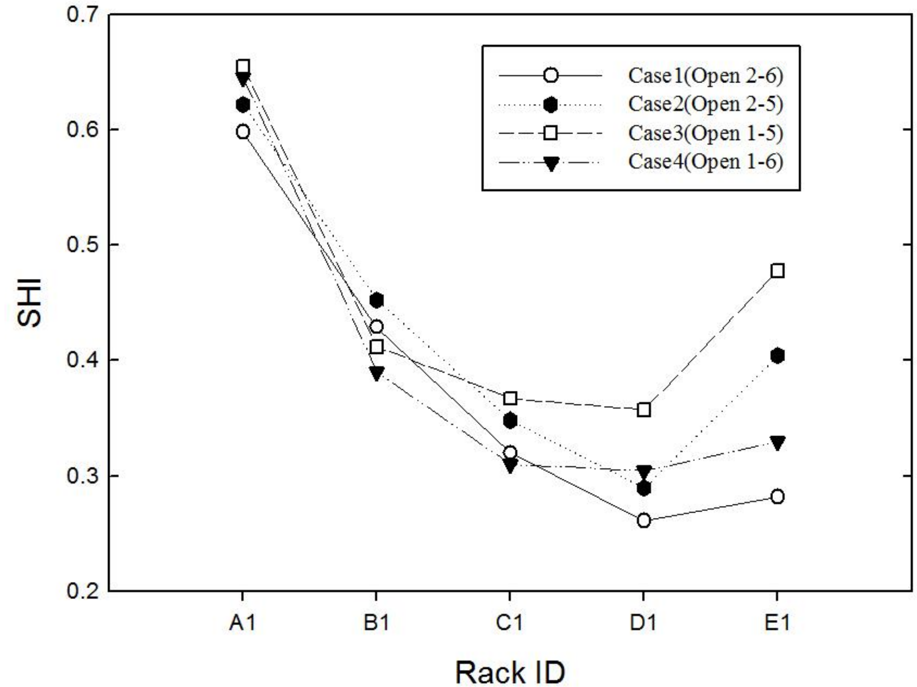


風口位置	2-6	2-5	1-5	1-6
RCI	87%	79%	81%	94%
SHI	0.37	0.42	0.43	0.39
T_{max}	35.1	35.7	37.0	35.9
T_{avg}	25.6	26.9	27.0	25.5

當開孔1~5和2~5之情況下，機櫃I、J過熱十分嚴重，由此看出每個機櫃入口處必須安裝供風口。比較開孔1~6和2~6可看出，雖然在機櫃E1、E2的溫度，因開孔6風量減少而些許上升，但是對於機櫃A1、A2有明顯的改善。





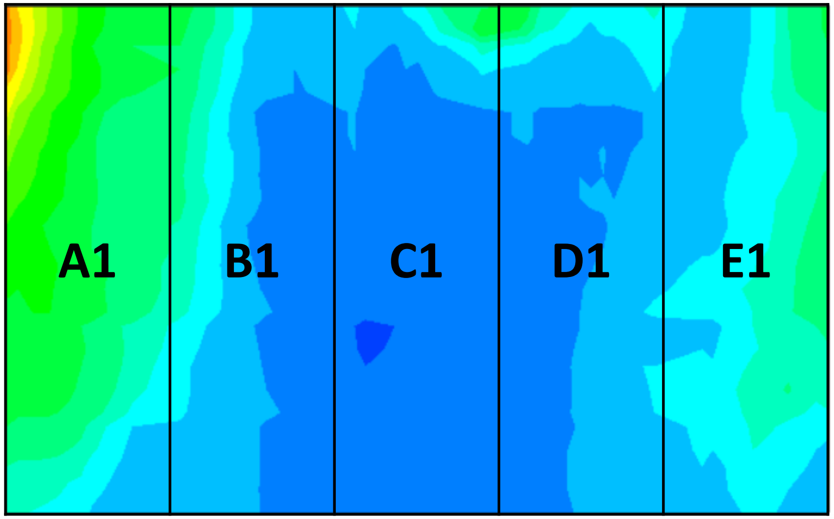


RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重

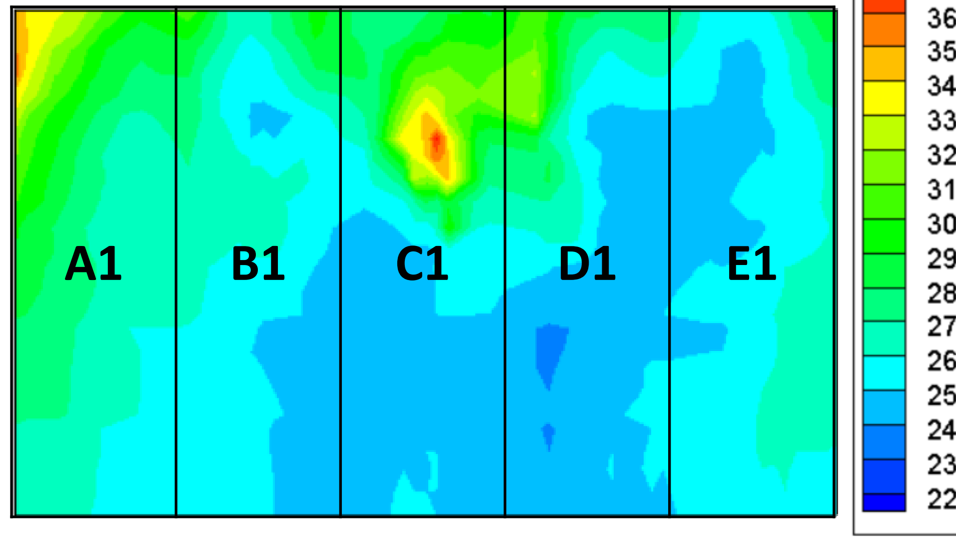
SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

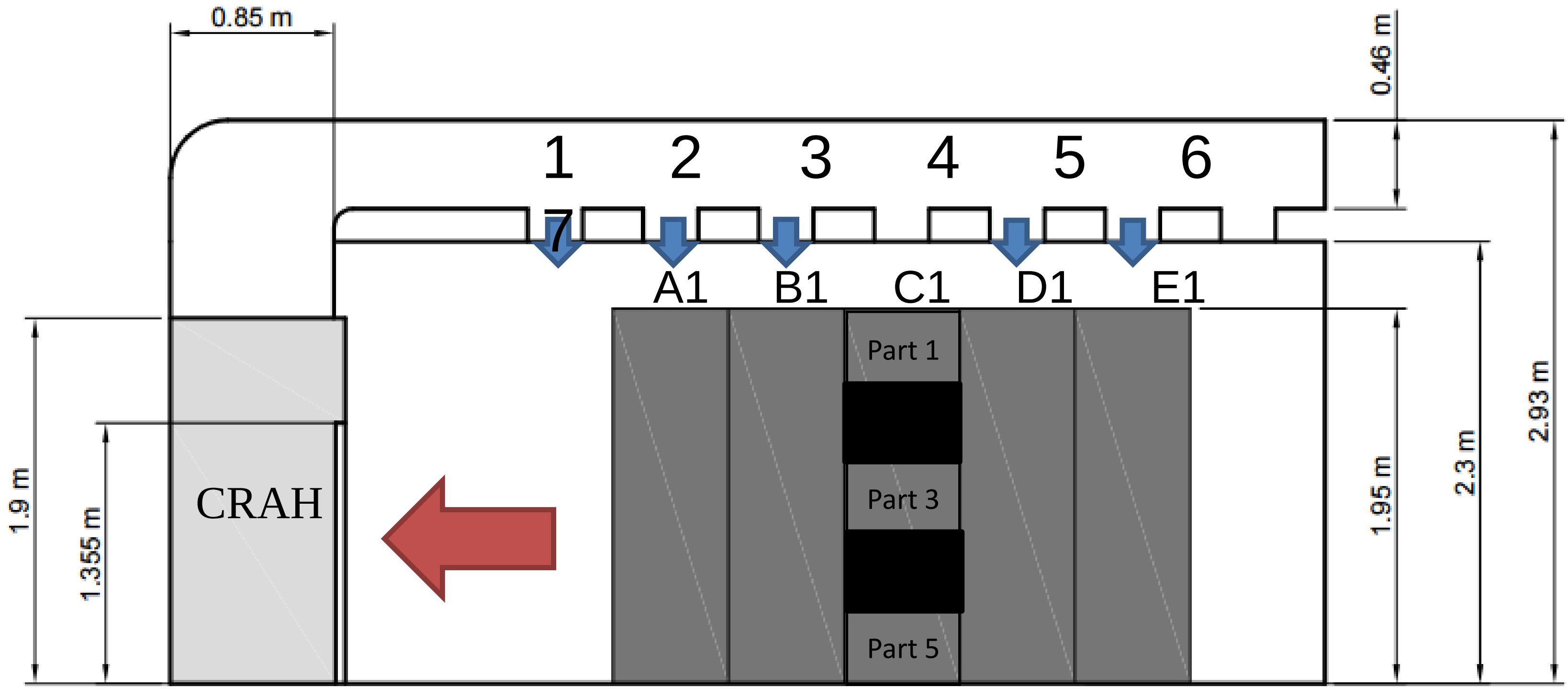
針對供風口開1-6，4不開進行探討

開孔1-6

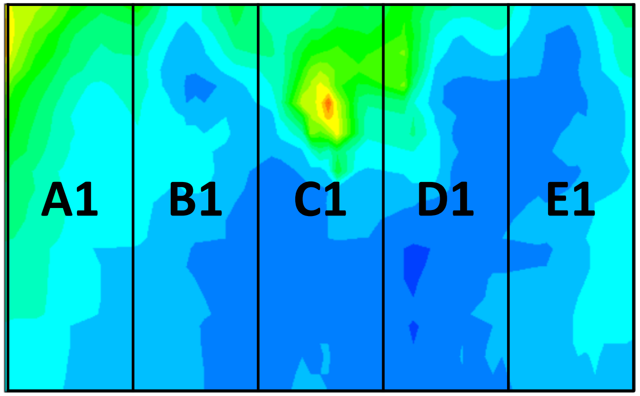


開孔1-6(4不開)

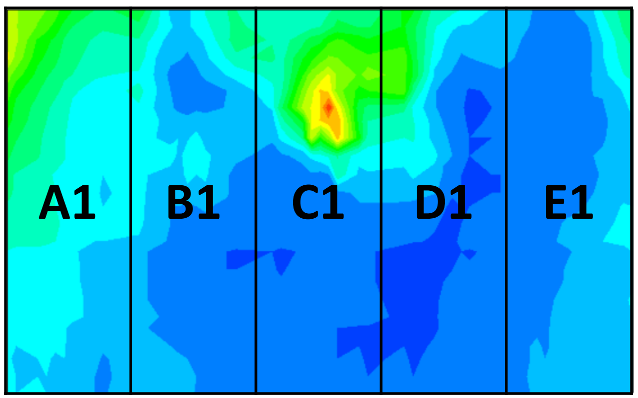




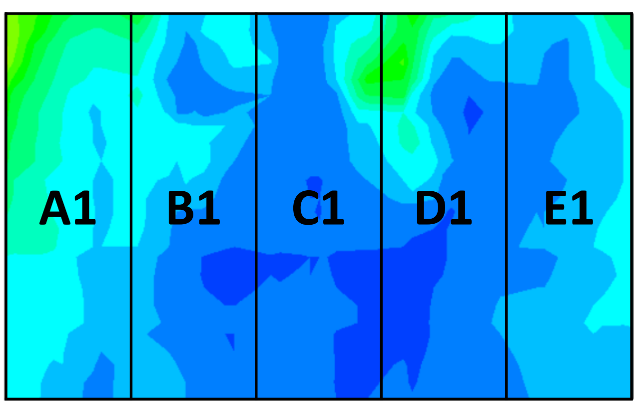
Case1:開孔1-6,4不開

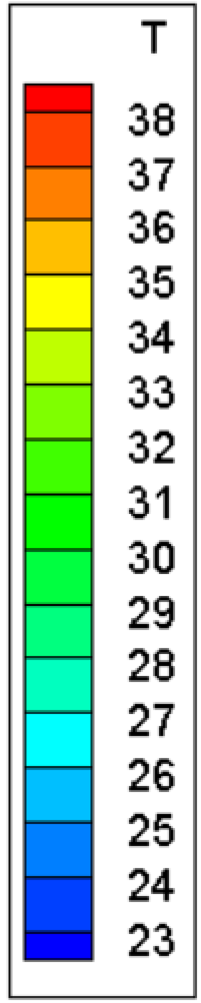


Case2:開孔1-6,4不開(封機櫃C1、C2之part4)

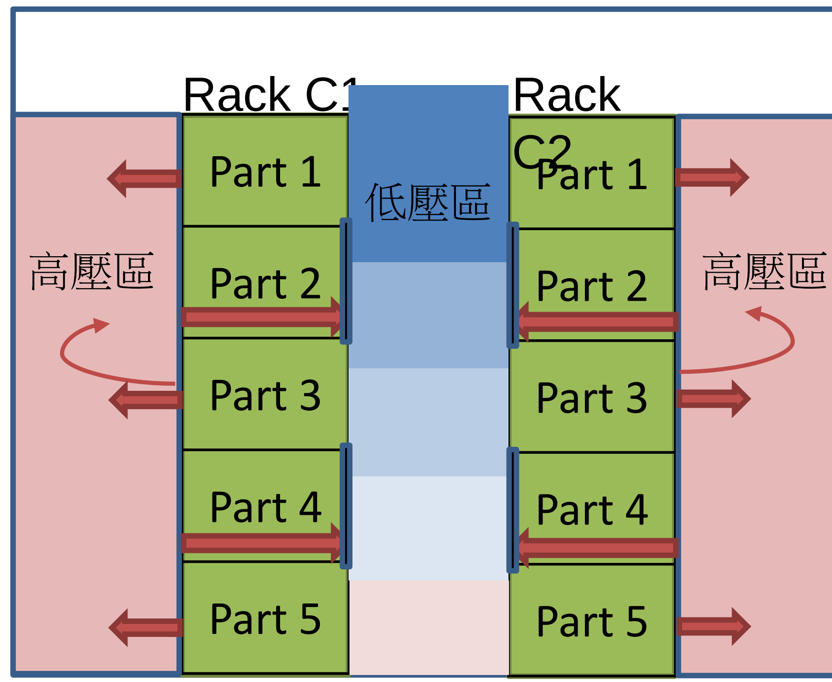


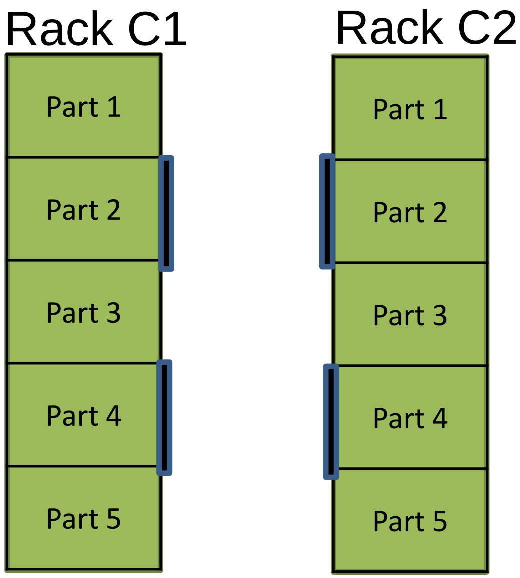
Case3:開孔1-6,4不開(封機櫃C1、C2之part2)

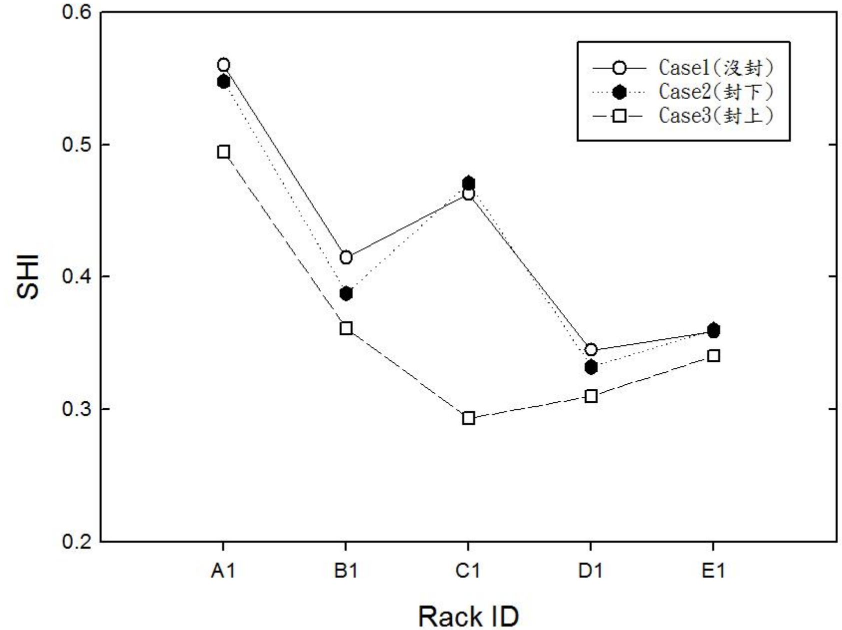


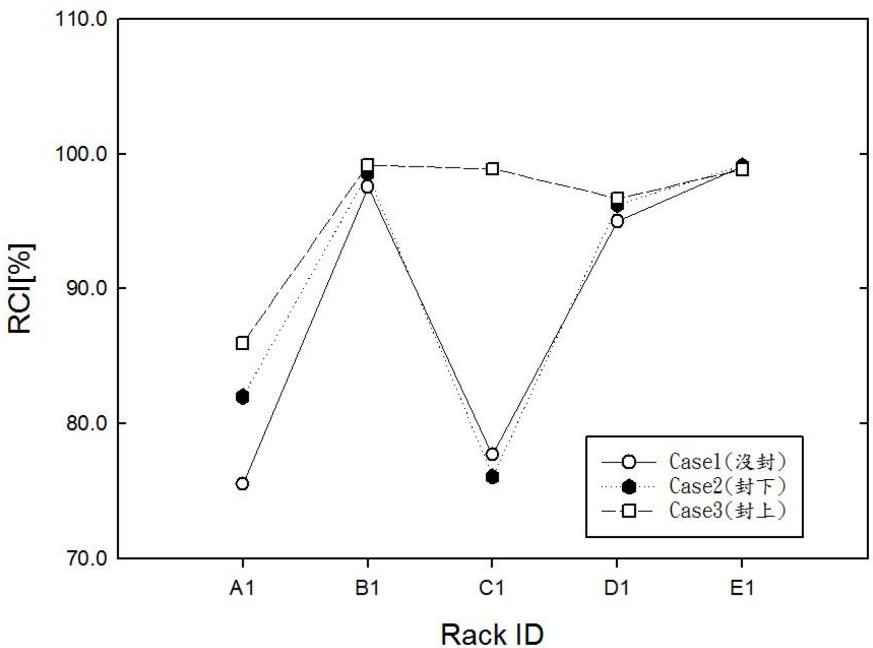


	Case1	Case2	Case3
RCI	89%	90%	97%
SHI	0.41	0.40	0.34
T_{max}	38.3	37.9	33.5
T_{avg}	26.4	26.1	25.5









RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重

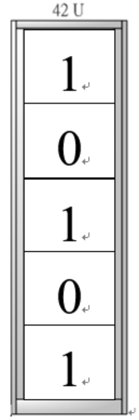
SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

探討改變熱通道大小之影響

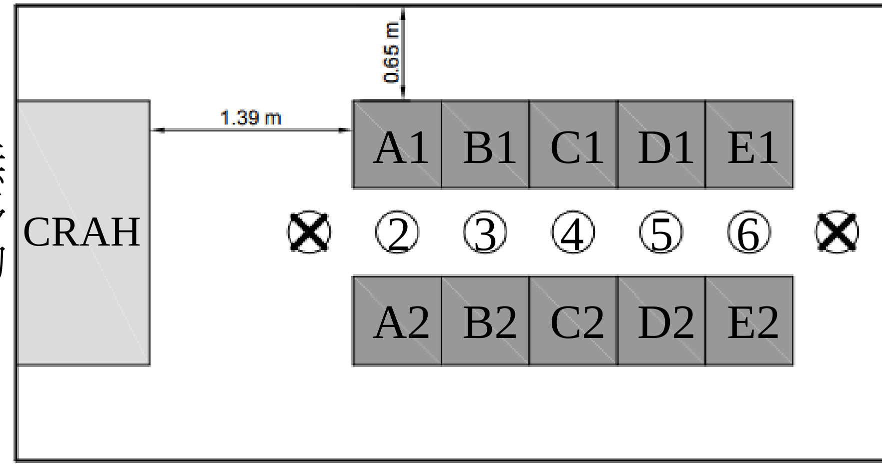
機房設定

機房發熱量:30kW
供風溫度:21℃
供風風量:3.52 m^3/s
機櫃抽風量:3.53 m^3/s

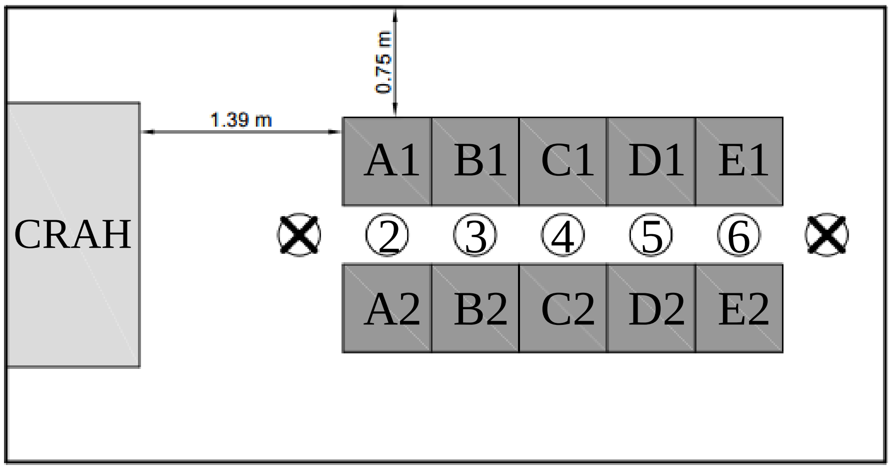
機櫃設定



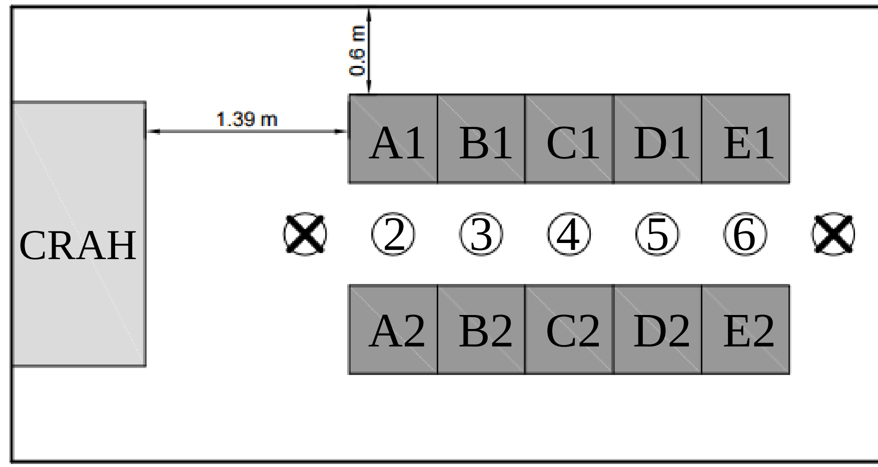
無移動



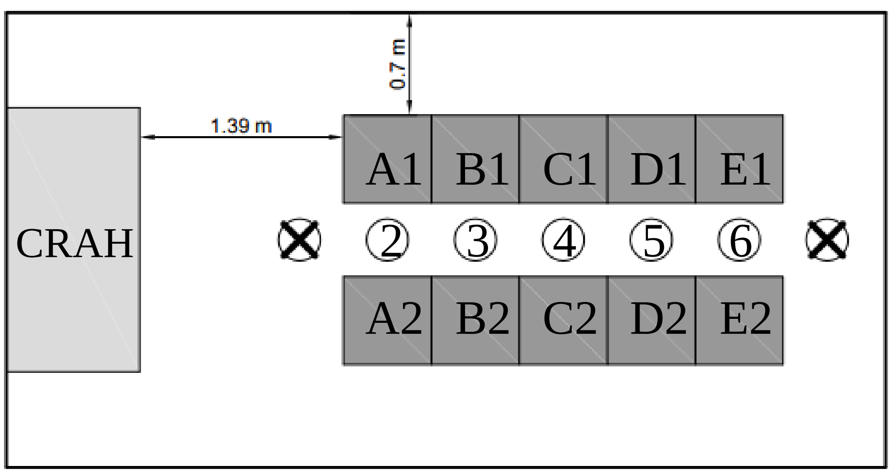
內移10 cm



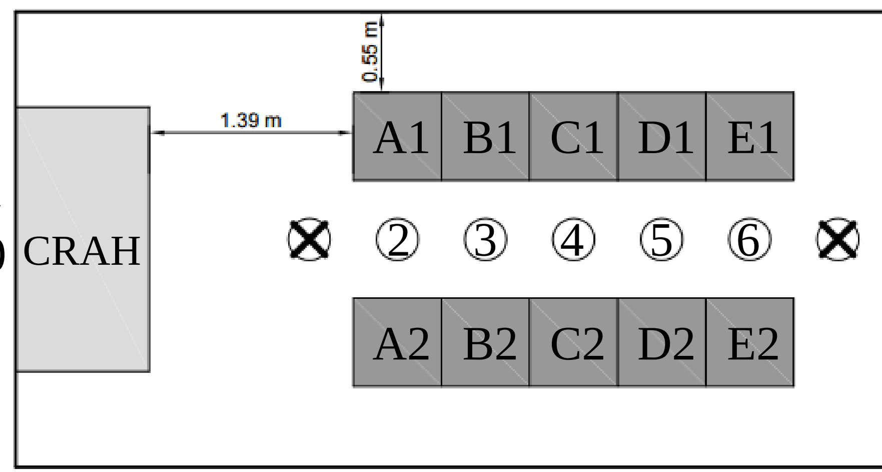
外移5 cm



內移5 cm

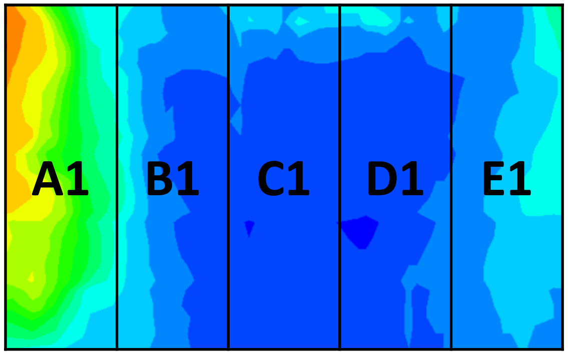


外移10 cm

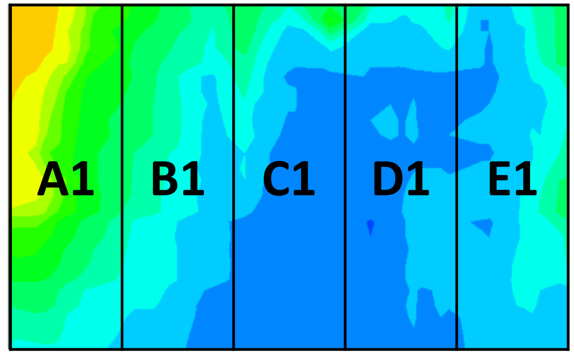


入口溫度分布

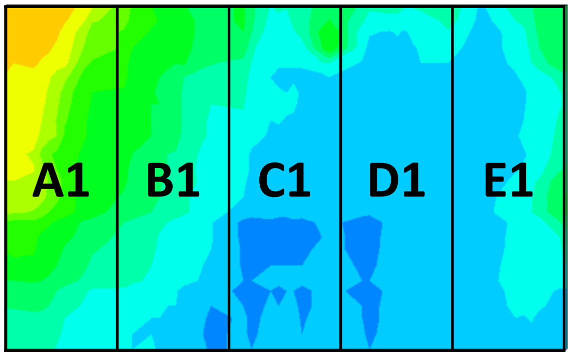
內移10 cm



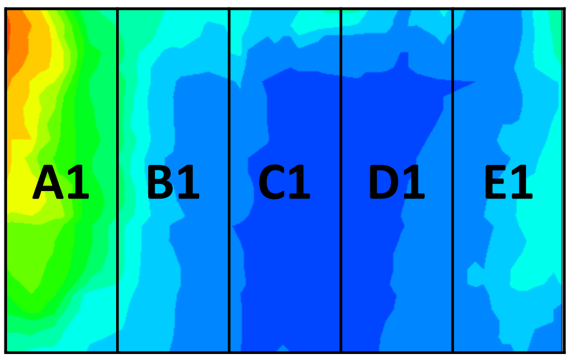
外移5 cm



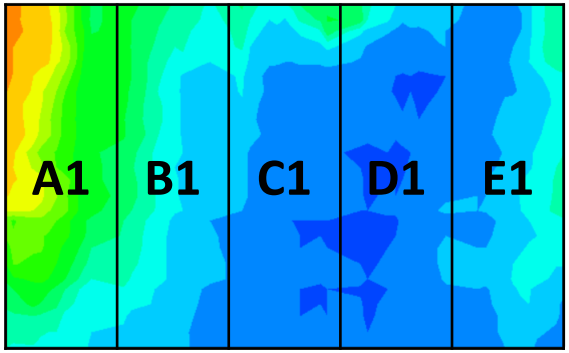
外移10 cm

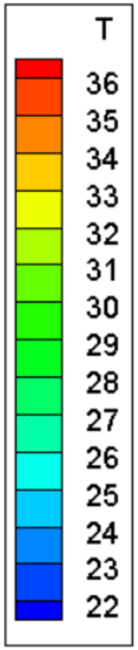


內移5 cm



無移動

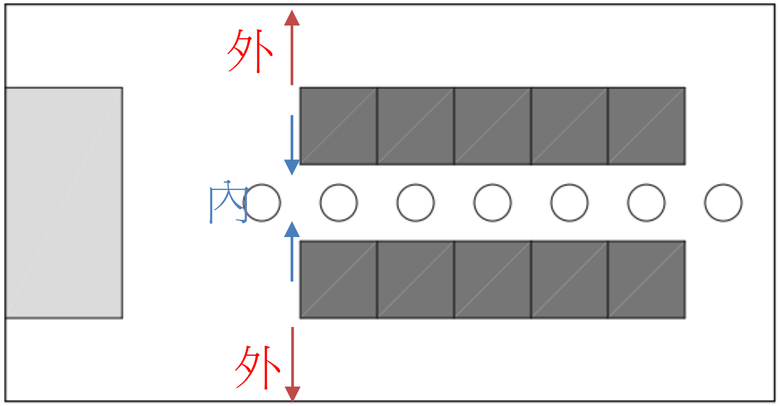


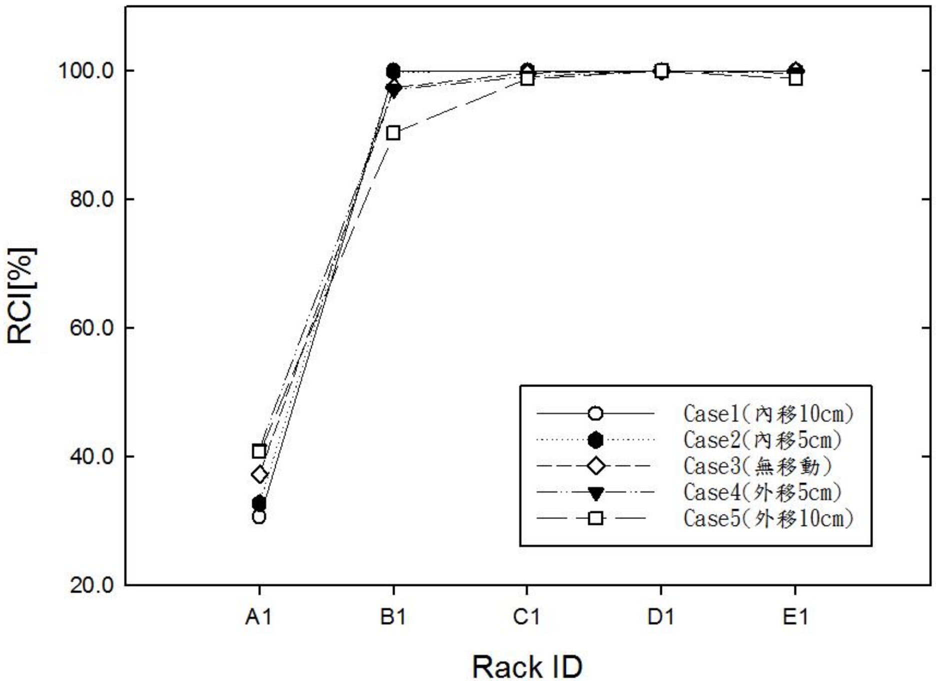


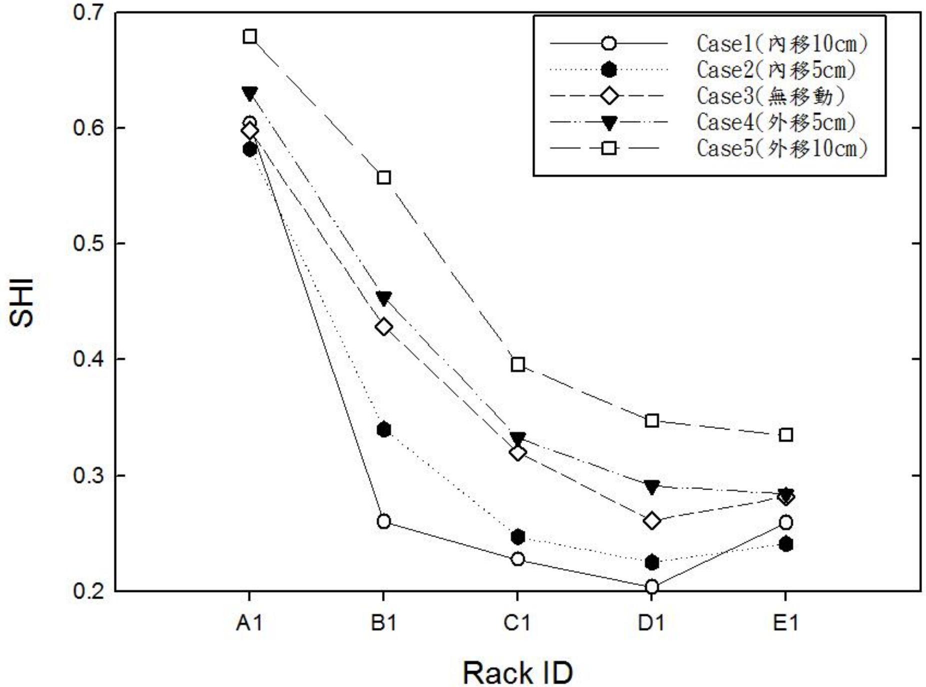
風口位置	內移 10 cm	內移 5 cm	無移動	外移 5 cm	外移 10 cm
RCI	87%	86%	87%	89%	86%
SHI	0.318	0.337	0.366	0.390	0.432
T_{max}	35.2	35.6	35.1	34.2	34.3
T_{avg}	24.9	25.3	25.6	25.8	26.3

風口位置	內移 10 cm	內移 5 cm	無移動	外移 5 cm	外移 10 cm
RCI	87%	86%	87%	89%	86%
SHI	0.318	0.337	0.366	0.390	0.432
T_{max}	35.2	35.6	35.1	34.2	34.3
T_{avg}	24.9	25.3	25.6	25.8	26.3

機櫃平均入口溫度與SHI會隨著冷通道體積大小而改變，但在冷通道大小減少時，速度上升，導致入口靜壓下降，使機櫃A1、A2過熱較為嚴重。







RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重

SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

探討改變供風量大小之影響

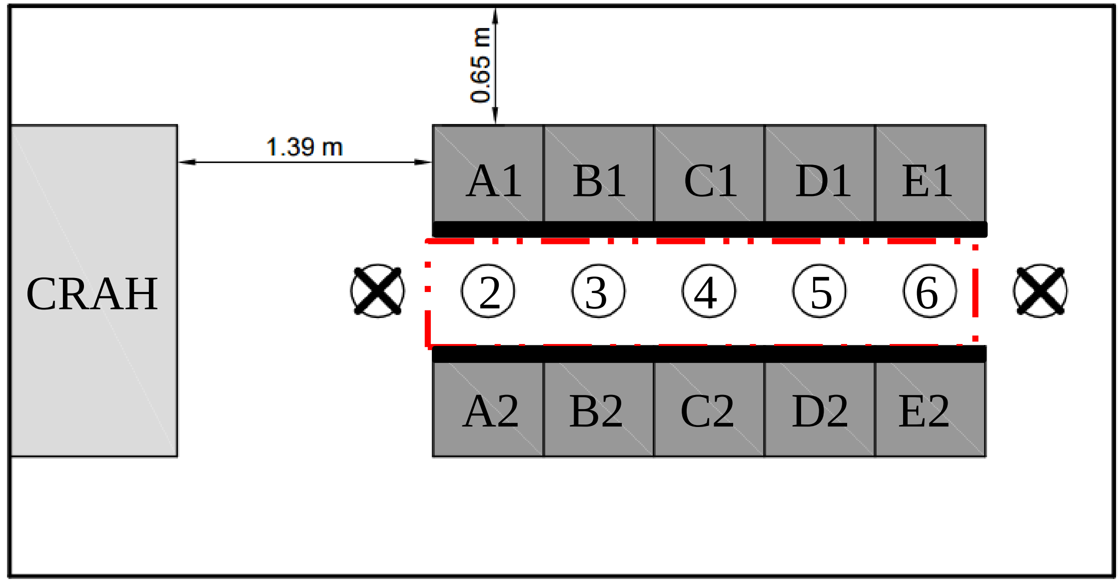
機房設定

機房發熱量:30kW

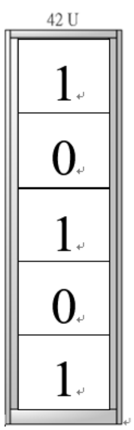
供風溫度: 21℃

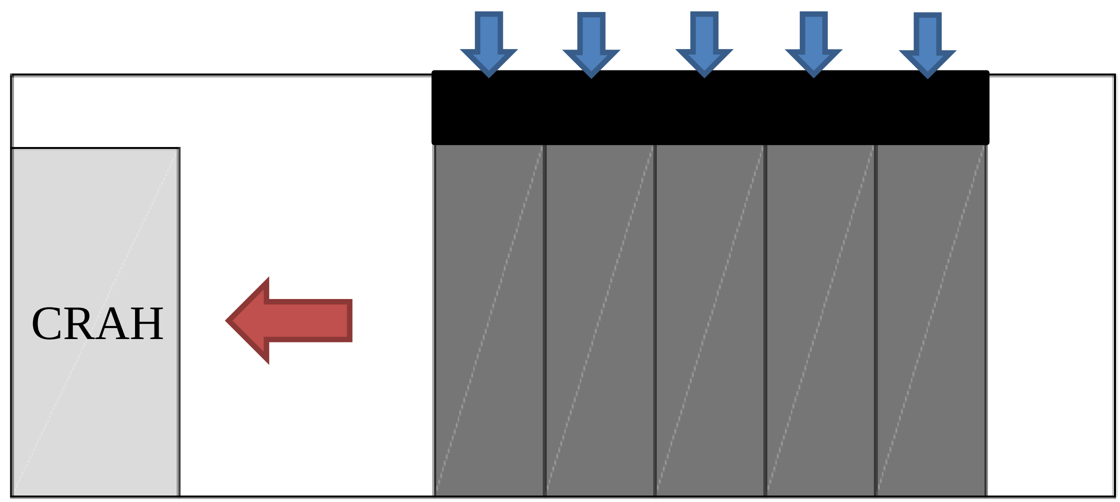
供風風量:2.83、3.52 、 3.64、 3.93 m^3/s

機櫃抽風量:3.53 m^3/s



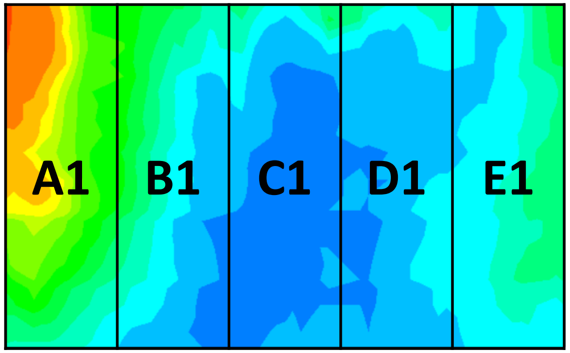
機櫃設定



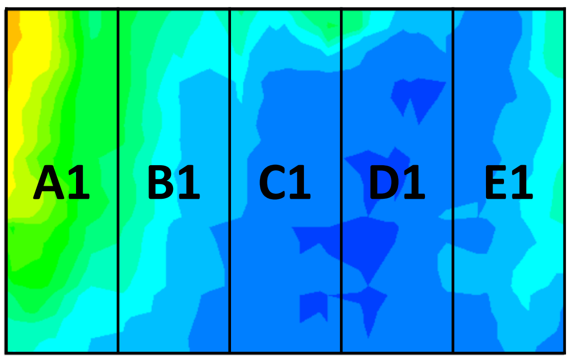


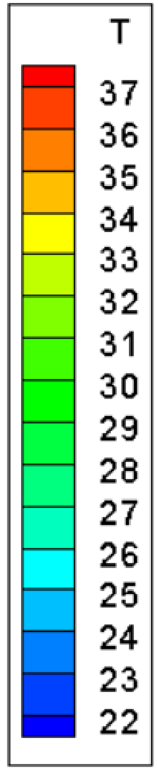
入口溫度分布

小流量



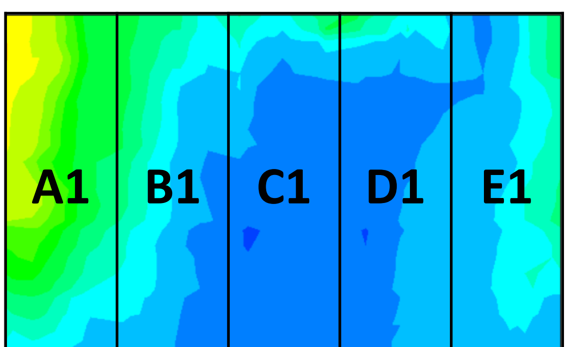
中流量



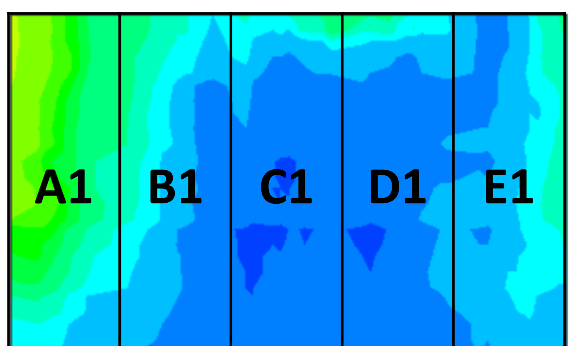


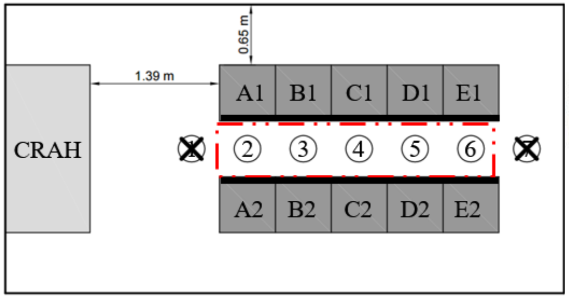
風口流量 (m^3/s)	小 (2.83)	中 (3.52)	大 (3.64)	最大 (3.93)
RCI	77%	87%	89%	93%
SHI	0.43	0.37	0.37	0.36
T_{max}	36.9	35.1	34.4	32.9
T_{avg}	26.8	25.6	25.7	25.2

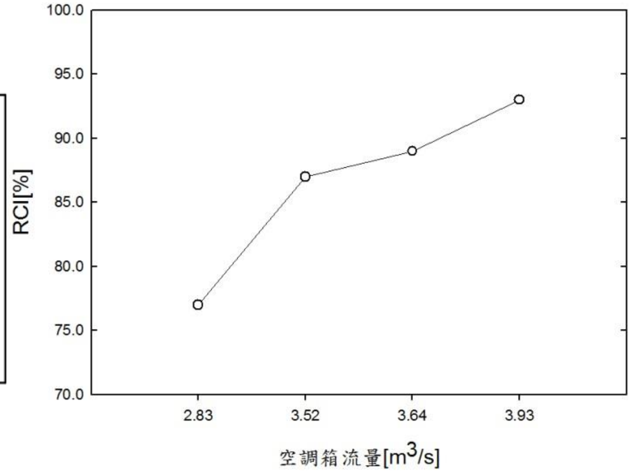
大流量

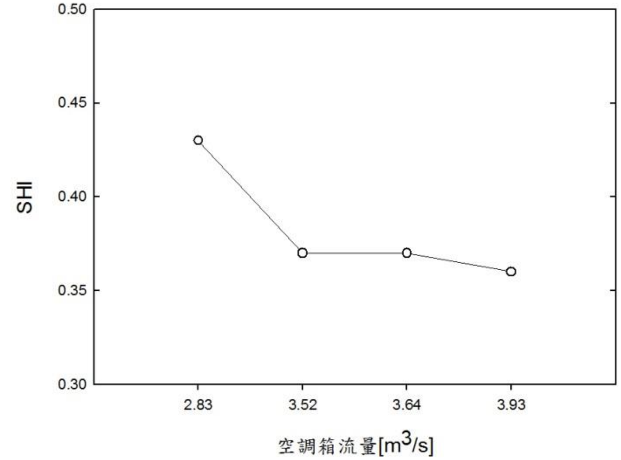


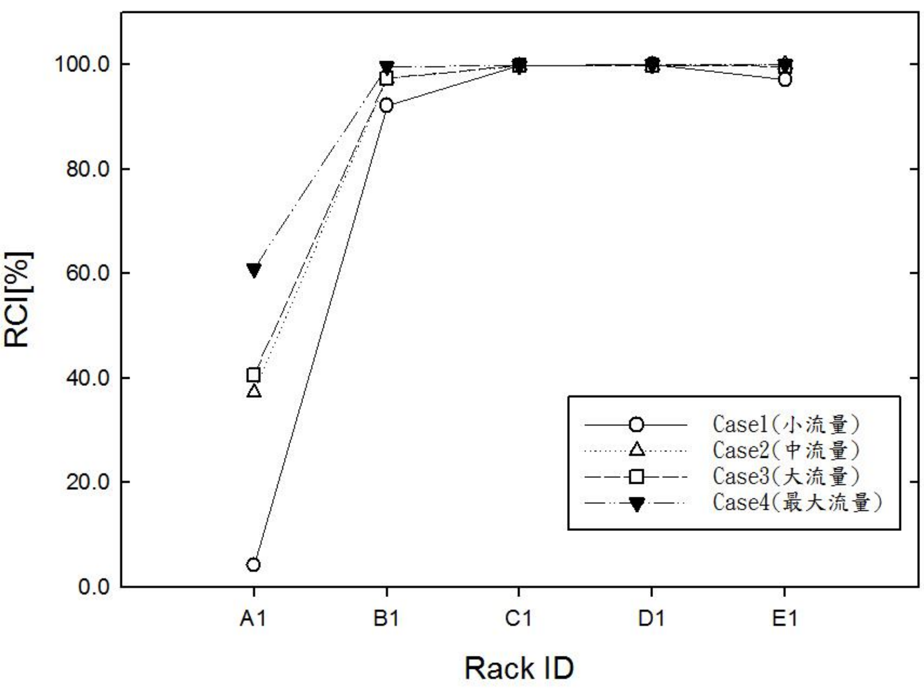
最大流量

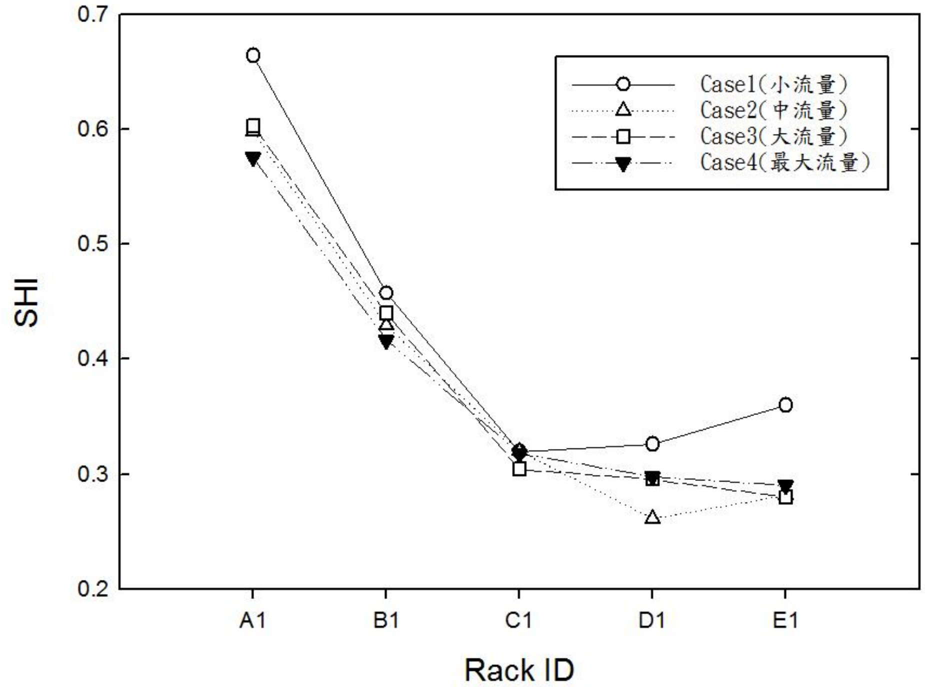












RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重

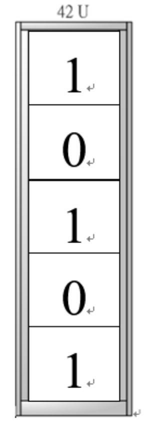
SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

將冷通道封閉之探討

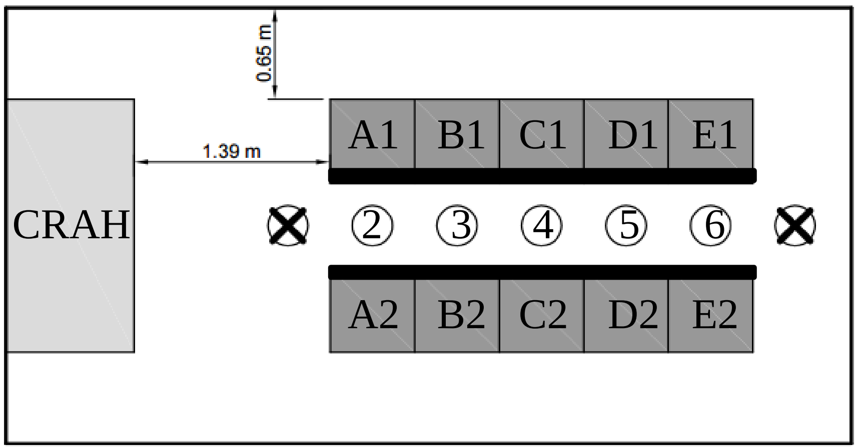
機房設定

機房發熱量:30kW
供風溫度:21℃
供風風量:3.52 m^3/s
機櫃抽風量:3.53 m^3/s

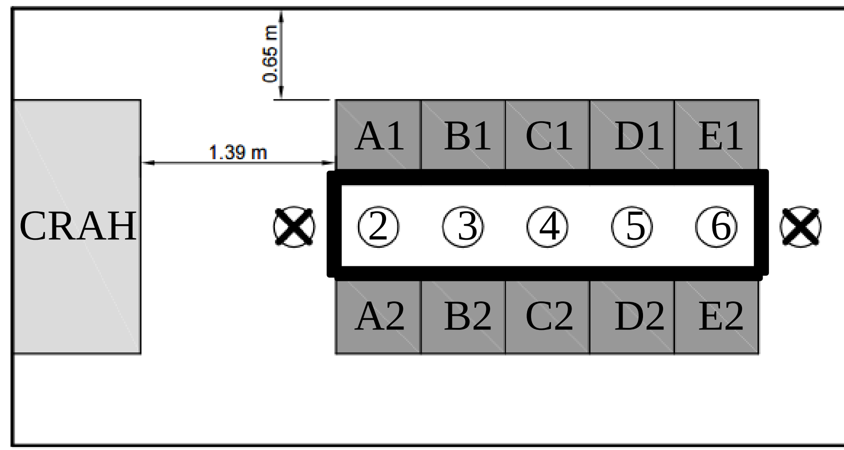
機櫃設定



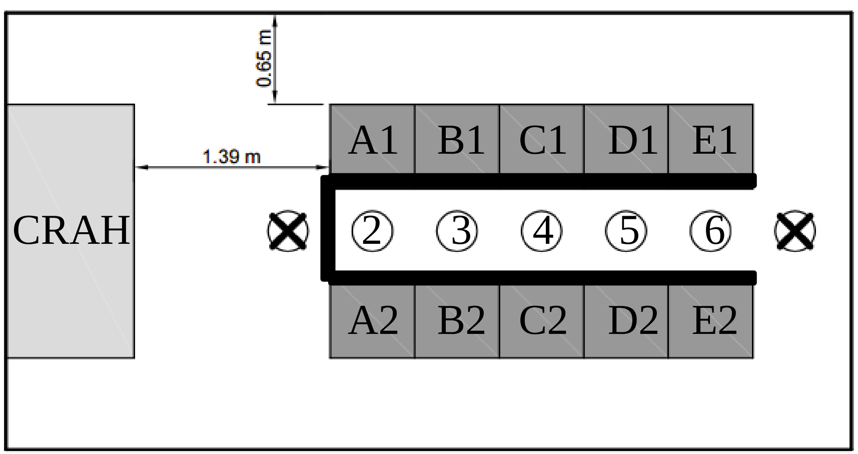
無擋板



擋板-機櫃A、E

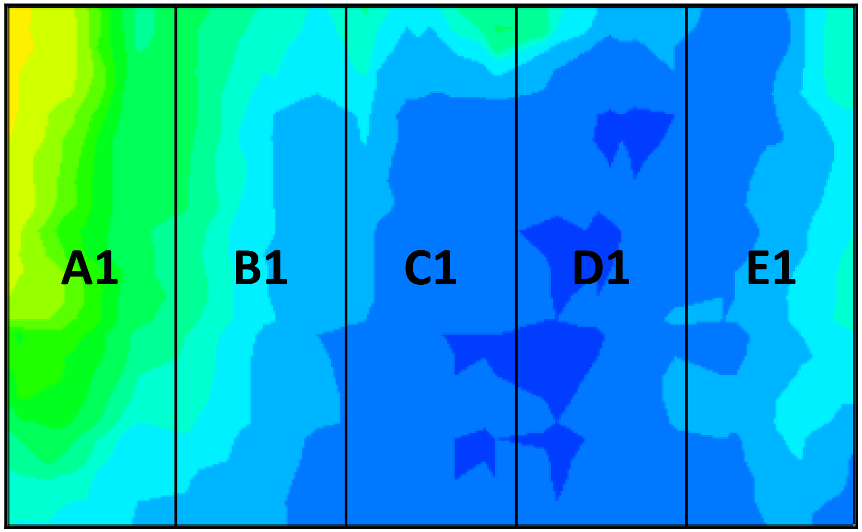


擋板-機櫃A

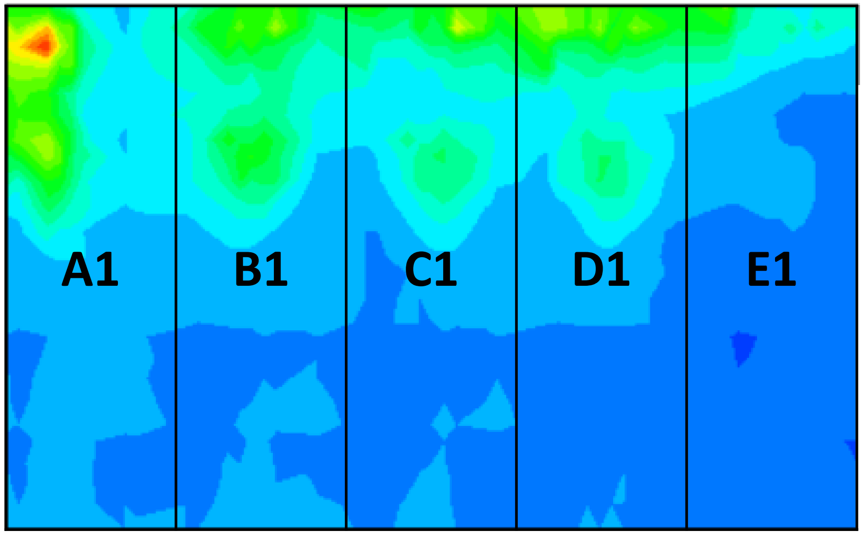


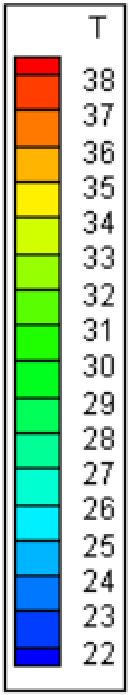
入口溫度分布

無擋板

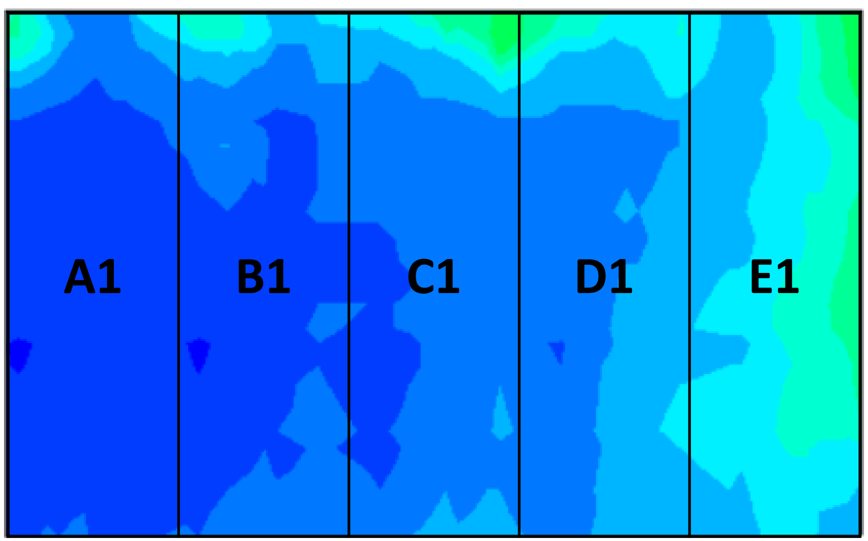


擋板-機櫃A、E

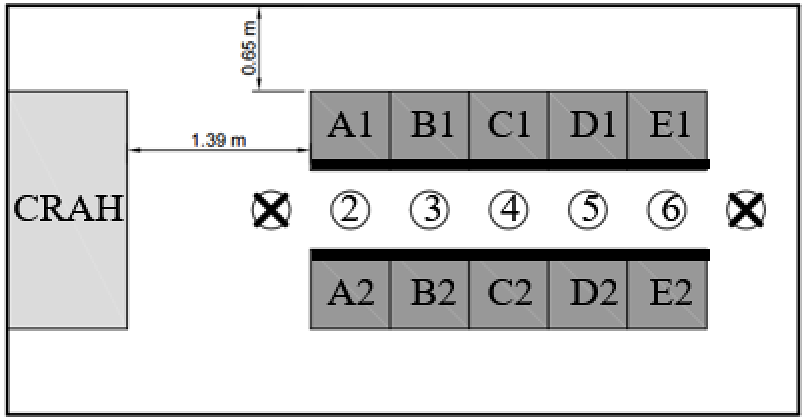


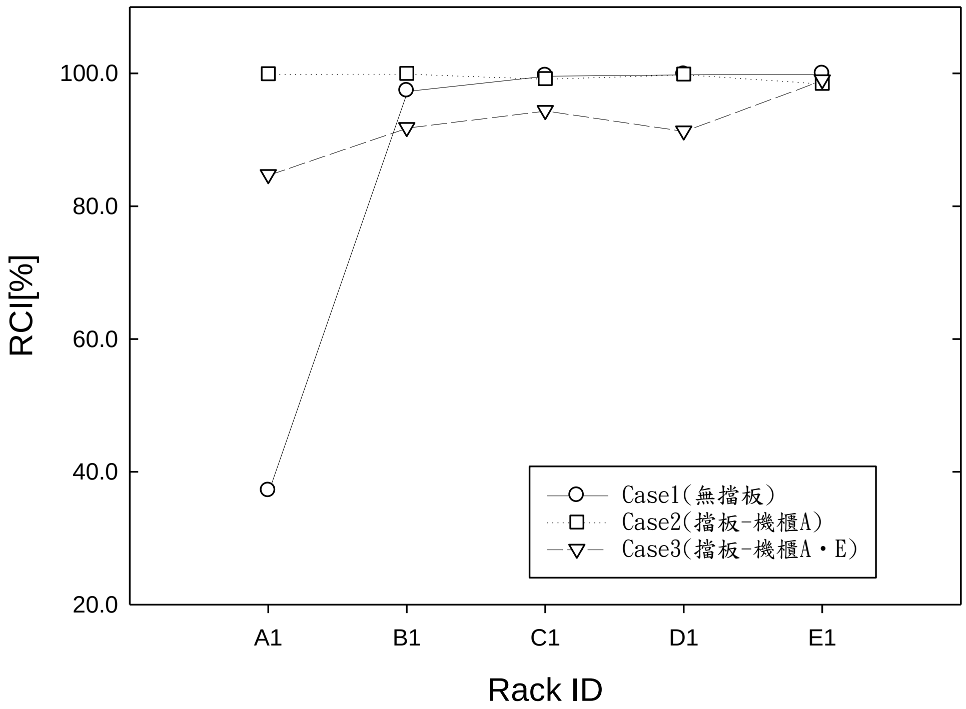


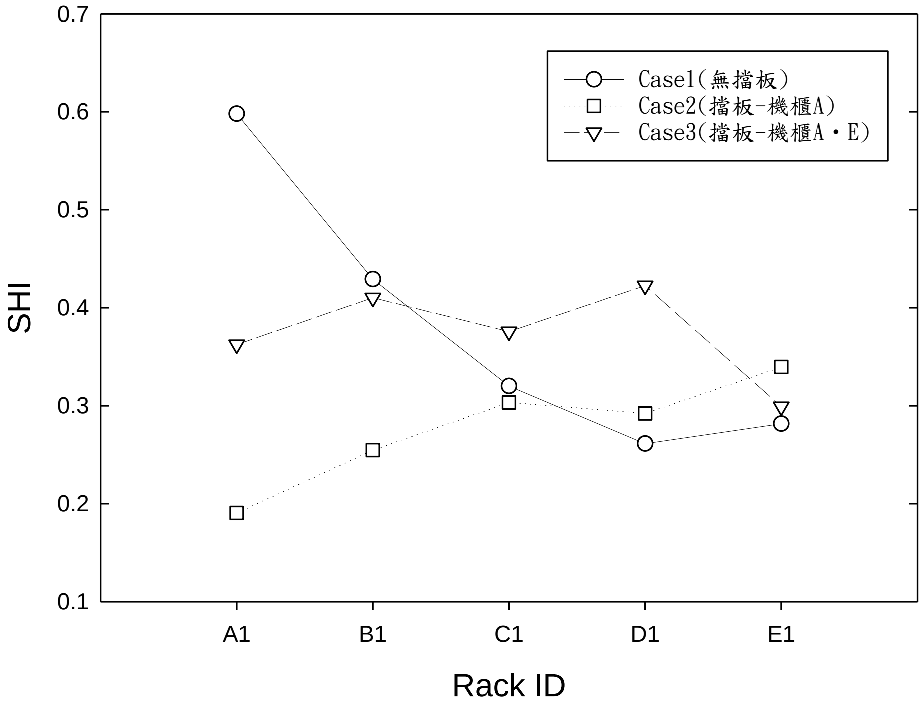
擋板-機櫃A



	無擋板	擋板-機櫃A	擋板-機櫃A、E
RCI	87%	99%	91%
SHI	0.37	0.27	0.39
T_{max}	35.1	28.9	38.3
T_{avg}	25.6	24.2	25.3







RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重

SHI:判斷機櫃熱回流程度，0~1，越大代表熱回流程度越嚴重

結論

- 機櫃上方加裝擋板，可有效改善機櫃入口溫度分布。
- 增加機櫃和回風口距離，可改善機櫃A1和A2過熱情形，且使最高溫度由37.4 ℃降至34.8 ℃。
- 由供風口2-6可以看出機櫃A1和A2過熱嚴重，在不變總供風量情況下，增加供風口(1-6)，可有效改善機櫃A1和A2過熱情形，RCI由87 %上升至94 %。
- 機櫃內部上方空隙之熱回流情況遠比下方嚴重，將內部上方加裝擋板可有效改善過入口過熱和平均溫度。
- 增加熱通道空間可降地入口平均溫度，SHI和熱通道空間成負相關。
- 在流量不足情況下，導致熱回流非常嚴重。RCI和供風量成正相關、SHI和供風量成負相關。

模擬

研究方法

- 商用套裝軟體(6SigmaDC)

本研究使用資料中心熱流管理軟體(6SigmaDC)，此軟體已將大部份機房內的構造以及設備模組化，方便使用者快速建立模型，並完成後續的分析。

- 數值方法

本研究針對資料中心內的空氣流動情況進行模擬,利用有限體積法(Finite Volume Method)分析並使用卡式座標、交錯網格以及SIMPLE演算法來計算流場，流場的部份假設為紊流並以Standard k-ε model模擬。

數學模型

- 這套軟體(6SigmaDC)為了節省計算時間但又要保持模擬結果的正確性，所以做了以下幾點假設。

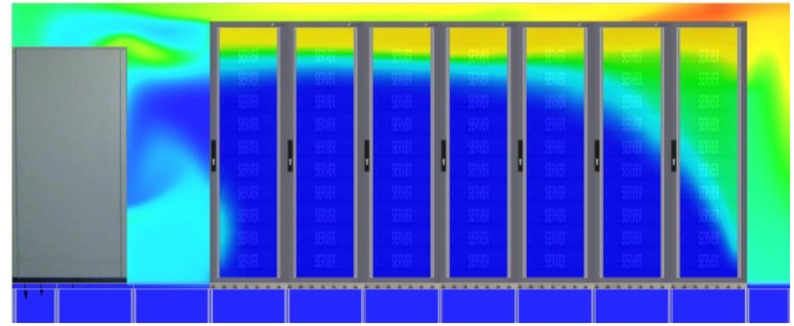
1. 流體為三維不可壓縮流。
2. 流體在機房內流動的狀態為紊流。
3. 流體之物理性質皆為常數。
4. 熱傳假設滿足Boussinesq approximation。

邊界條件

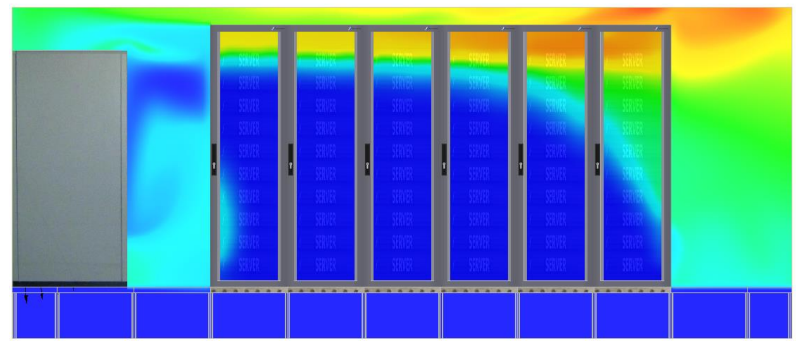
- 入口邊界條件(Inlet):假設進口有固定的流量，在本研究中出風設定為均勻流速。
- 出口邊界條件(Outlet):假設在垂直出口方向的各個物理性質梯度皆為零。
- 壁面邊界條件(Wall):天花板以及四周的壁面設定為絕熱。

Examples of how you can improve the cooling system (56 kW in total)

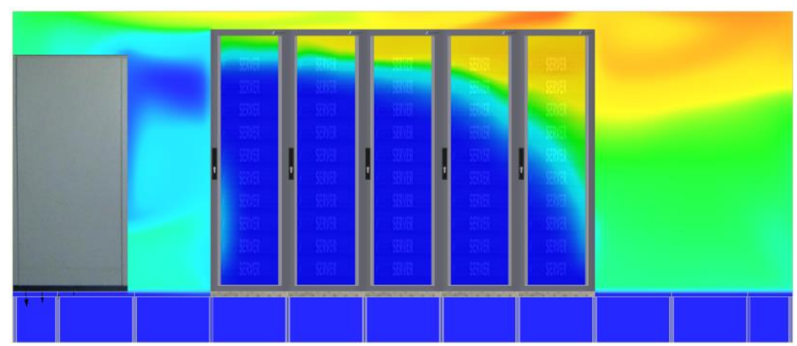
Max Inlet Temperature	RCI	Overheated servers	Percentage of overheating
47°C	75%	21	15%
47°C	79%	20	17%
42°C	79%	18	18%



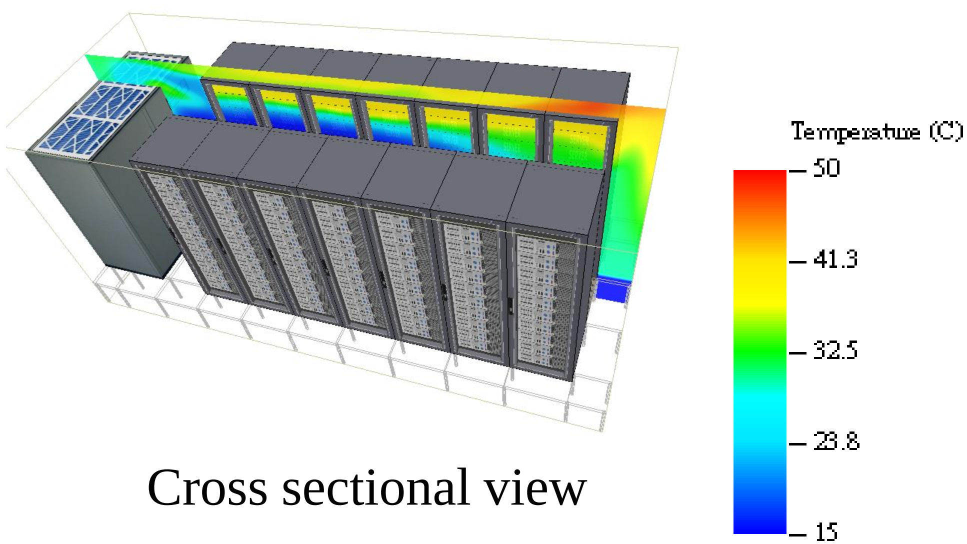
14 Rack 4 kW



8 Rack 4 kW 4 Rack 6 kW

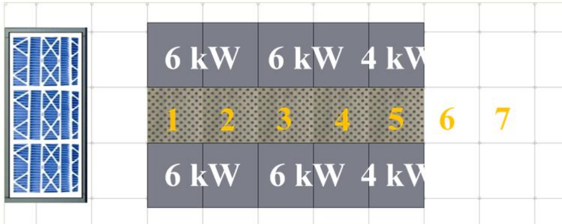


2 Rack 4 kW 8 Rack 6 kW

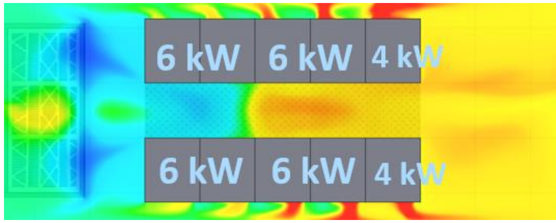


Cross sectional view

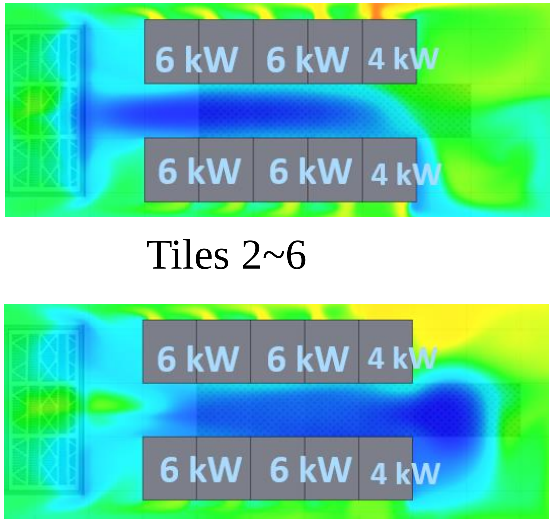
Change the Grille..



Tile number

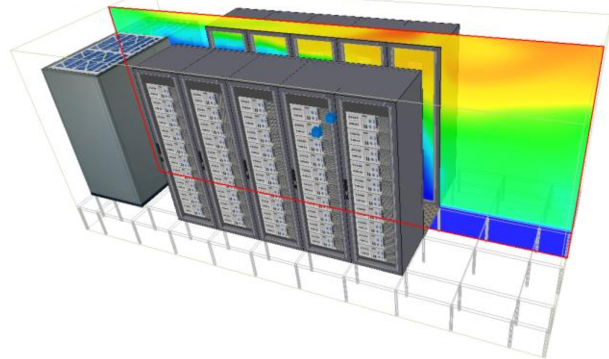


Tiles 1~5



Tiles 2~6

Tiles 2~7

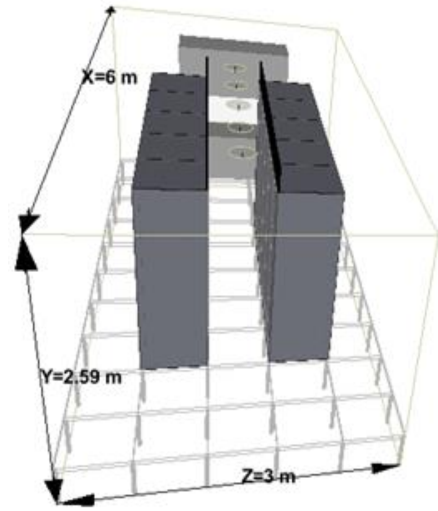


Cross sectional view in the container

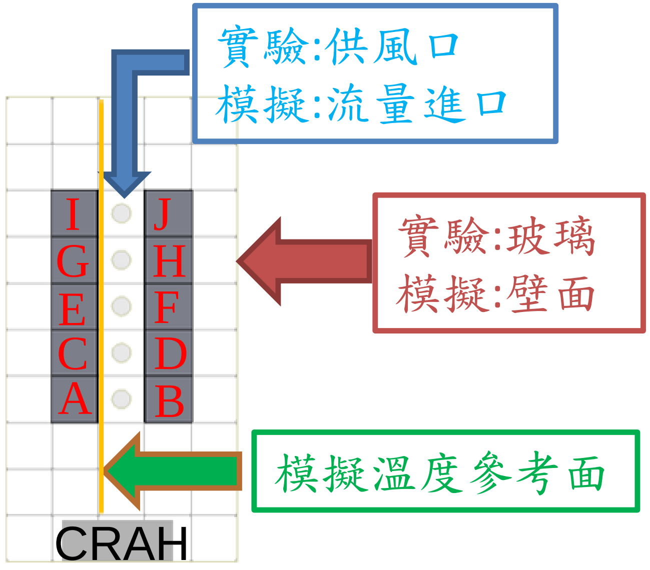
Max Inlet Temperature	RCI	Overheated servers	Percentage of overheated servers
42°C	79%	18	18%
33°C	99%	2	2%
29°C	100%	0	0%

機房物理模型

幾何參數	
機房長寬高	6m × 3m × 2.59m
機櫃長寬高	0.615m × 0.6m × 1.95m
地板長寬	0.6m × 0.6m
回風口長寬	1.42m × 0.6m
黑色擋板長寬高	3m × 0.02m × 0.24m
供風口半徑	0.24m
供風口溫度	16℃
供風口總流量	$1m^3/s$
單一供風口流量	$0.2m^3/s$
機櫃總抽風量	$3m^3/s$
單一機櫃抽風量	$0.3m^3/s$
(A~J)機櫃發熱量	2.5kW



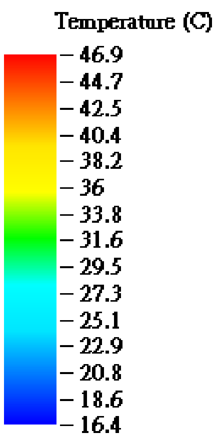
機房示意圖

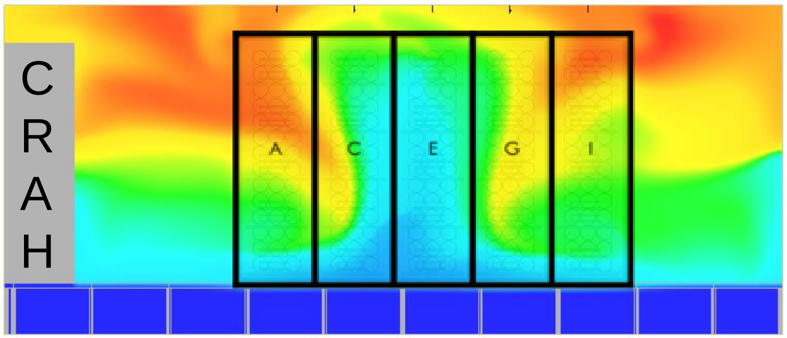


機房上視圖

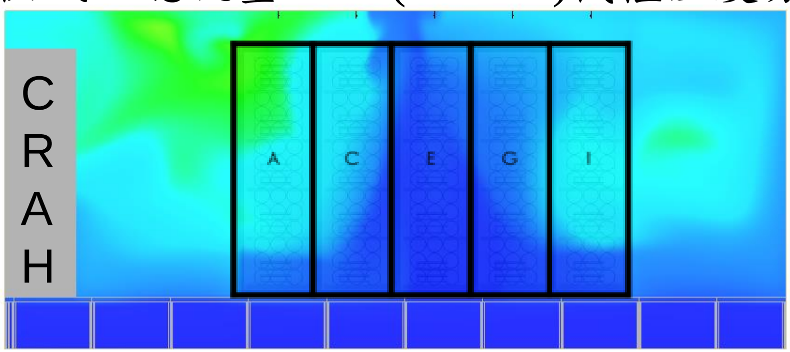
結果與討論

- 改變供風口總流量

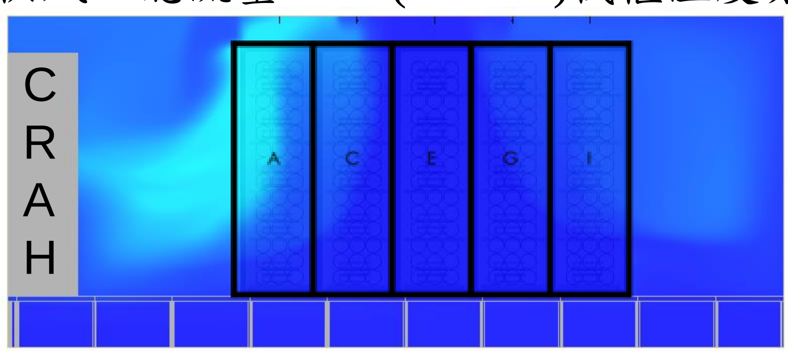




供風口總流量1m³/s(ACEGI)機櫃溫度分佈圖



供風口總流量2m³/s(ACEGI)機櫃溫度分佈圖



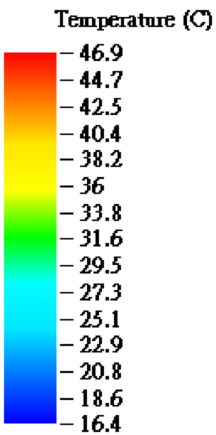
供風口總流量4m³/s(ACEGI)機櫃溫度分佈圖

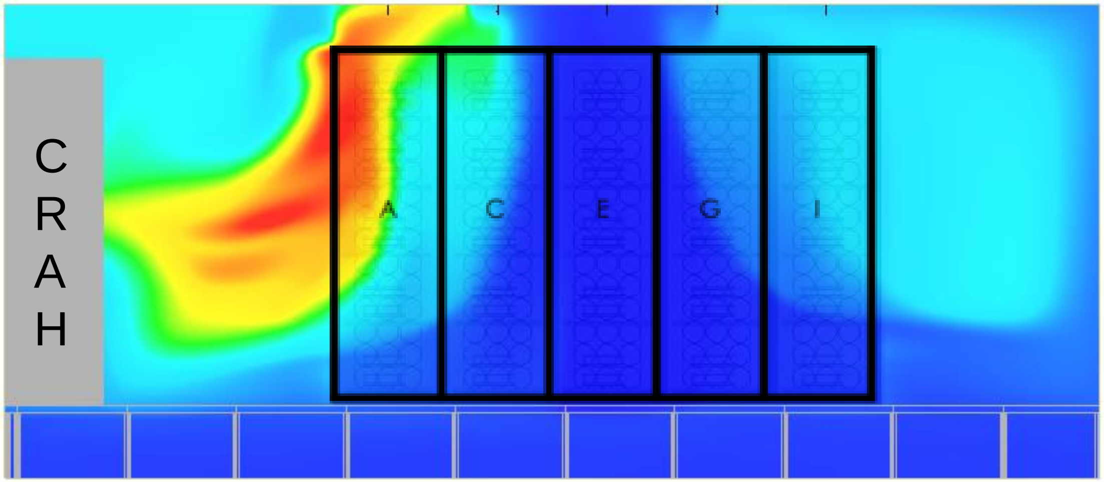
供風口總流量(m^3/s)	SHI
1	0.73
2	0.51
3	0.35
4	0.25

不同供風口總流量對應之SHI

結果與討論

- 改變供風口溫度

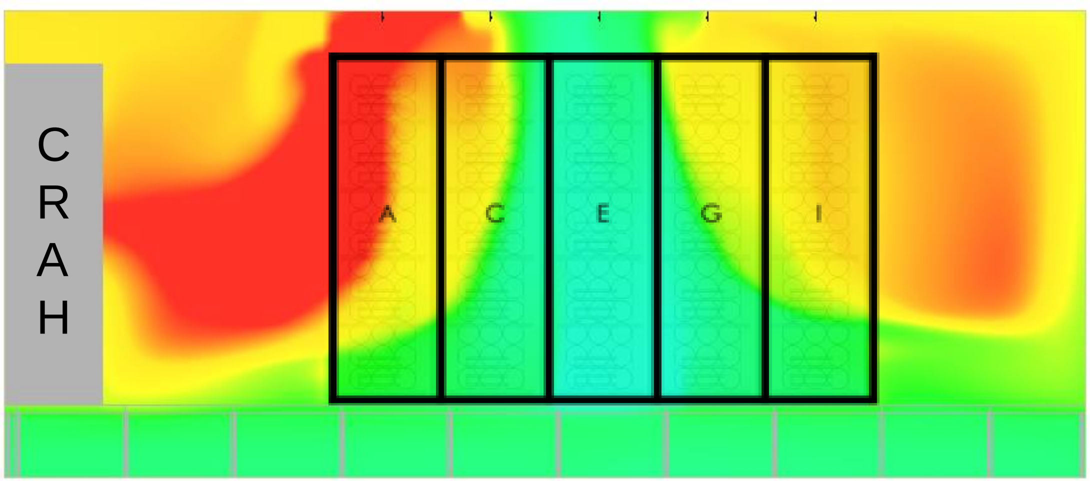




供風口溫度16℃(ACEGI)機櫃溫度分佈圖

供風口溫度(℃)	SHI
16	0.253
17	0.252
18	0.256
19	0.253
20	0.256

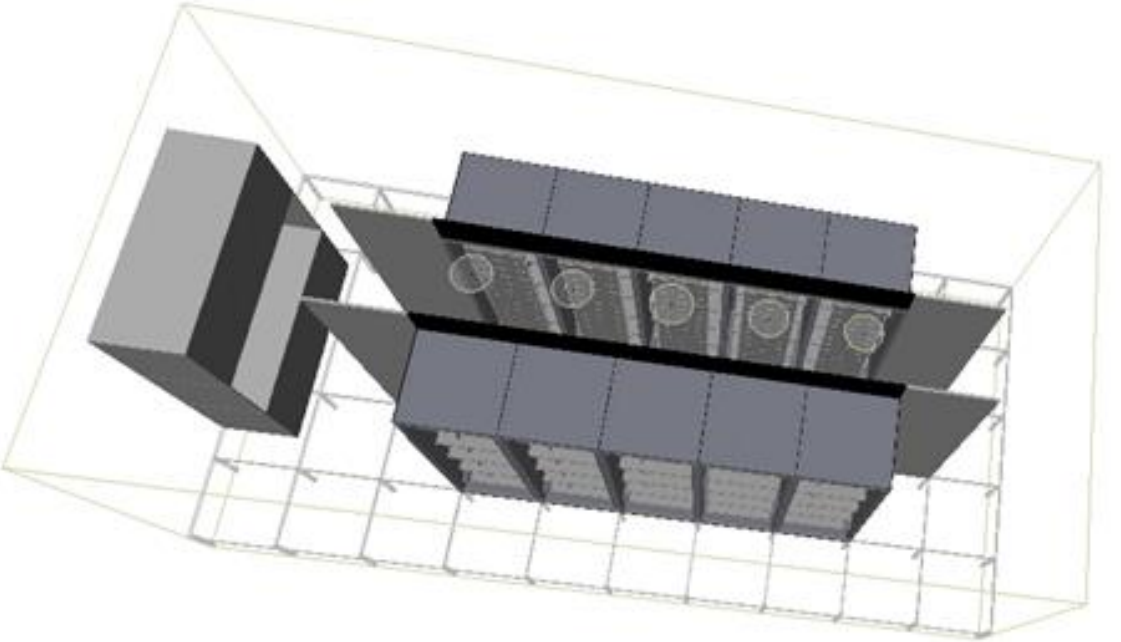
不同供風口溫度對應之SHI



供風口溫度20℃(ACEGI)機櫃溫度分佈圖

結果與討論

- 機櫃兩側加裝有角度的擋版



機櫃兩側加裝90° 擋版

結果與討論

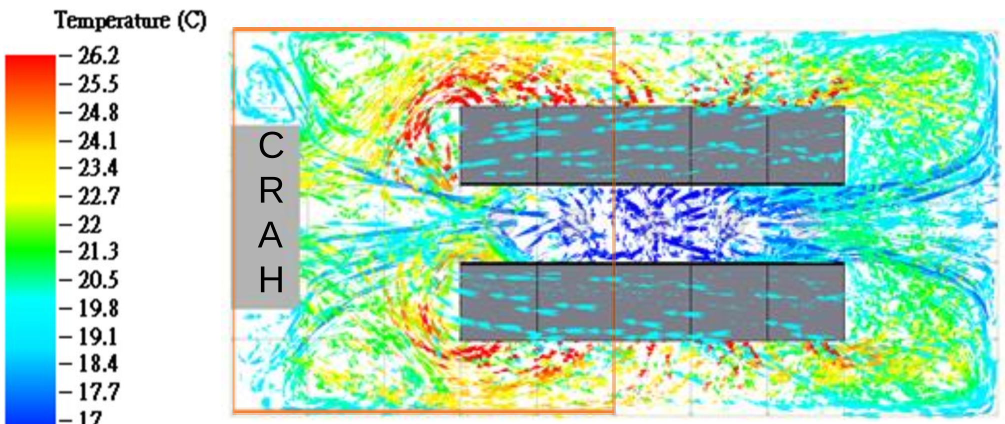
- 機櫃兩側增加有角度擋板

擋板角度 \ 機櫃入風面平均溫度	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)
0°	20.1	19.9	17.9	17.8	16.4	16.5
90°	19.4	19.1	17.7	17.2	16.7	16.7

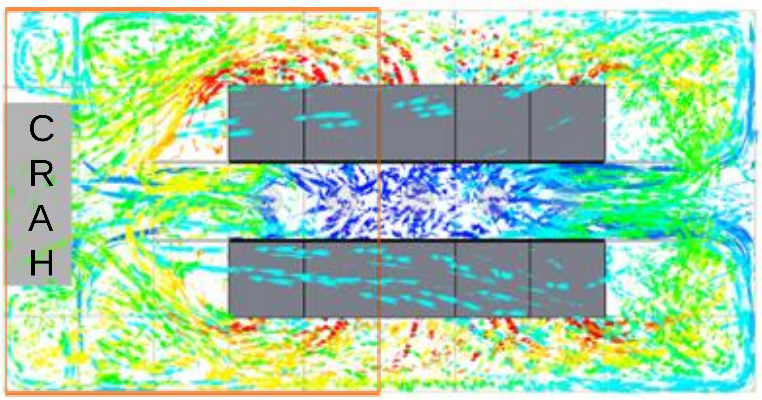
不同角度擋版之(A~F)機櫃入風面平均溫度

擋板角度	SHI
0°	0.255
90°	0.252

不同角度擋版對應之SHI



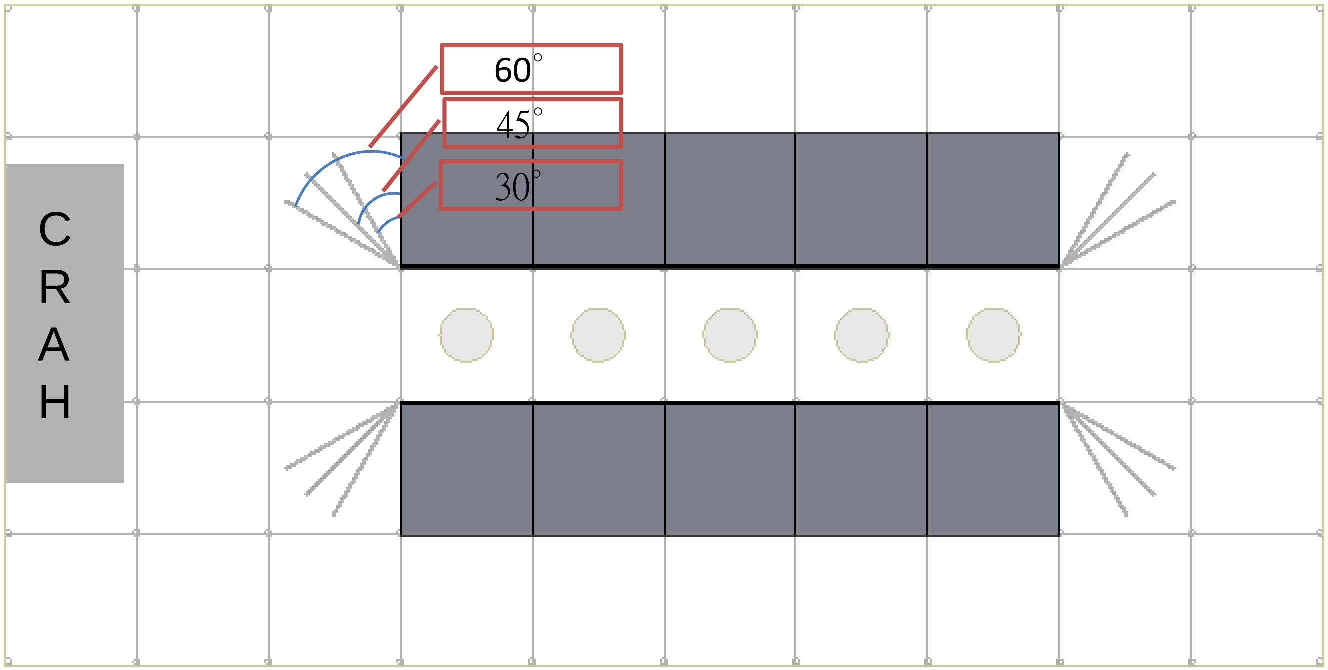
未加裝擋板空氣在機房內流動情形



加裝90° 擋板空氣在機房內流動情形

結果與討論

- 機櫃兩側增加有角度擋板



機櫃兩側加裝30°、45°、60°擋板之機房上視圖

結果與討論

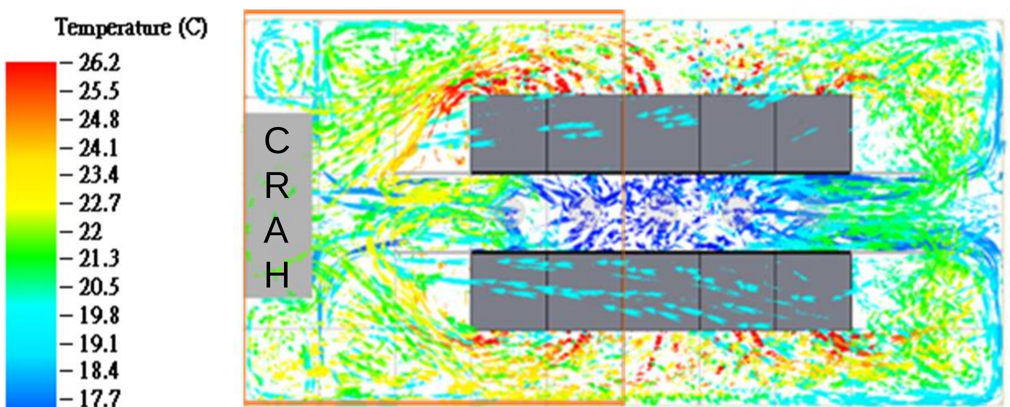
- 機櫃兩側增加有角度擋板

機櫃入風面 平均溫度 擋板角度	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)
90°	19.4	19.1	17.7	17.2	16.7	16.7
30°	18.1	18.3	17.2	16.6	16.4	16.4
45°	18.2	18.6	17.2	17.5	16.5	16.6
60°	18.3	18.7	17.1	17.4	16.6	16.6

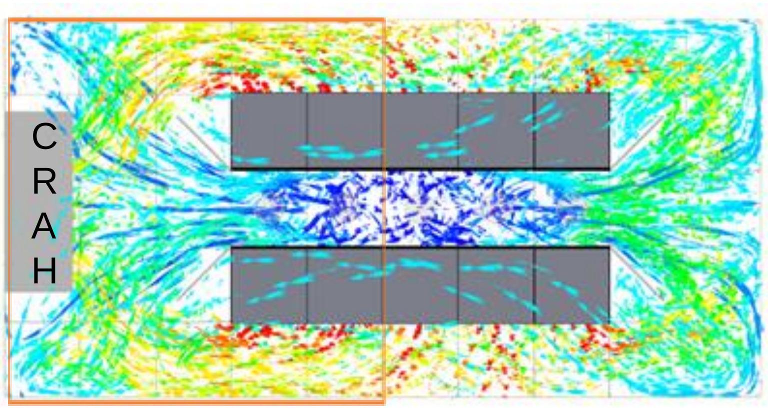
不同角度擋版之(A~F)機櫃入風面平均溫度

擋板角度	SHI
90°	0.252
30°	0.228
45°	0.227
60°	0.223

不同角度擋版對應之SHI



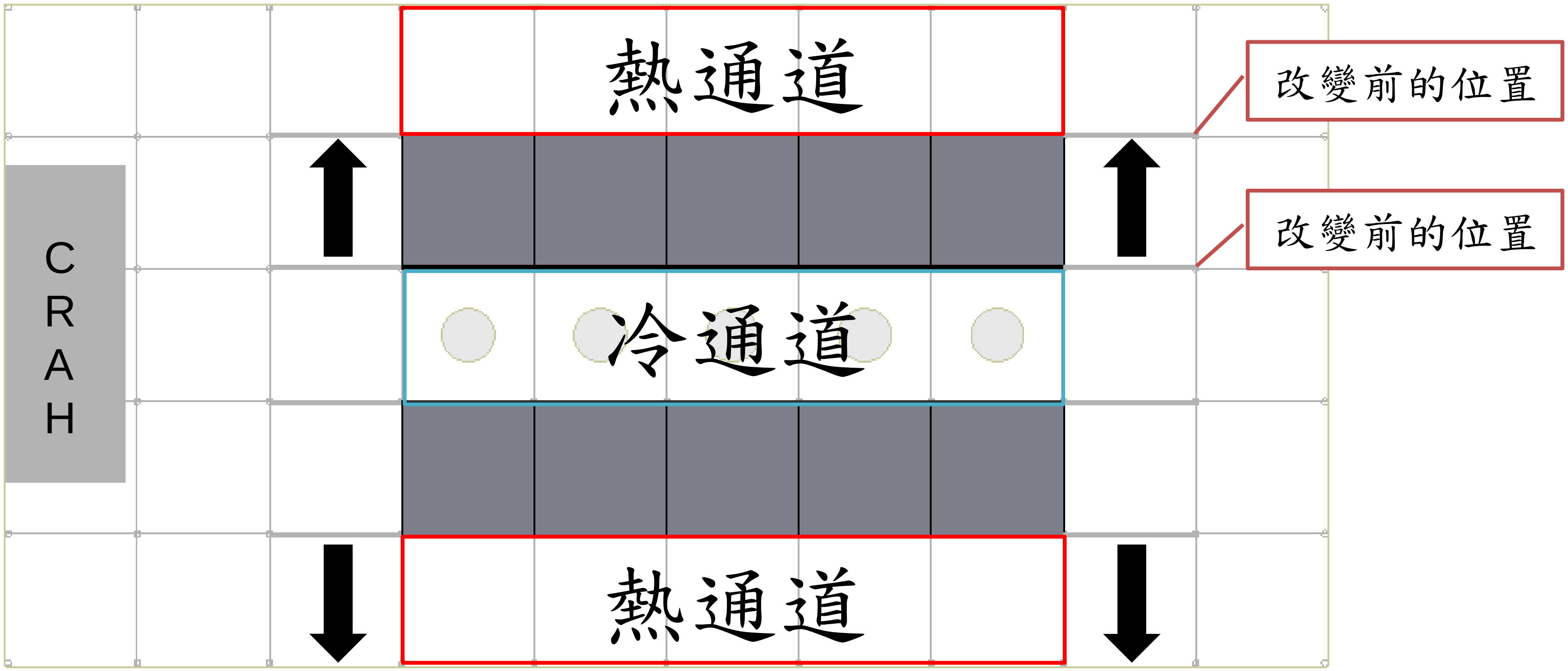
加裝90° 擋板空氣在機房內流動情形



加裝45° 擋板空氣在機房內流動情形

結果與討論

- 機櫃兩側加裝有角度擋板-改變擋板位置



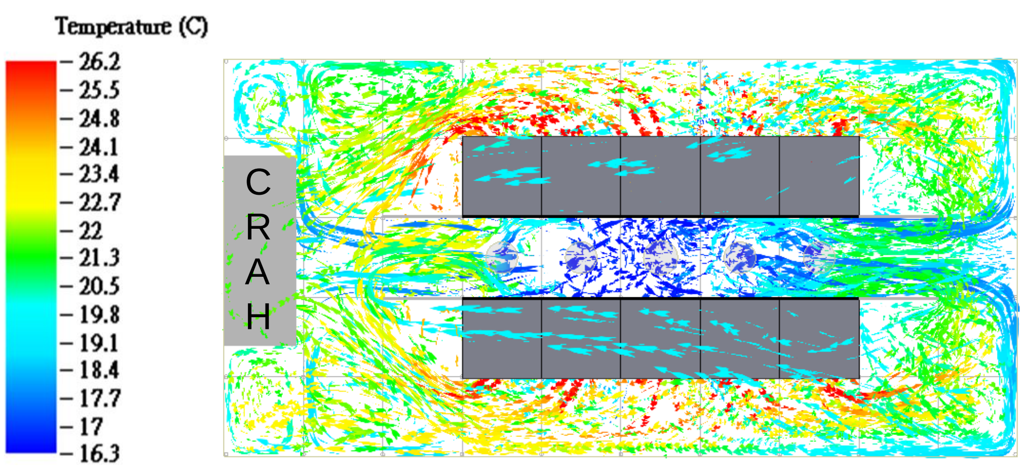
機櫃兩側加裝檔板-改變擋板位置示意圖

結果與討論

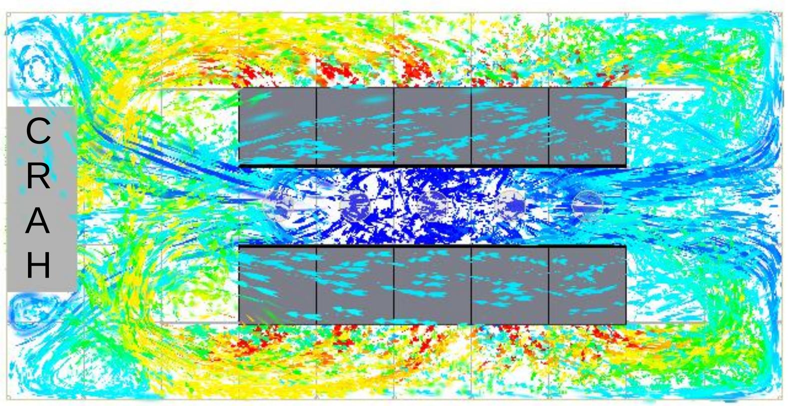
- 機櫃兩側加裝有角度擋板-改變擋板位置

機櫃入風面平均溫度 / 擋板位置	A(in)	B(in)	C(in)	D(in)	E(in)	F(in)	G(in)	H(in)	I(in)	J(in)	SHI
靠近冷通道	19.3	19.1	17.6	17.1	16.7	16.7	17.7	17.6	19.2	19.1	0.252
靠近熱通道	18.1	18.3	17.2	16.6	16.4	16.4	17.2	17.2	18.4	18.5	0.189

不同擋板位置之機櫃入風面平均溫度及SHI



擋板位置靠近冷通道之空氣流動情形



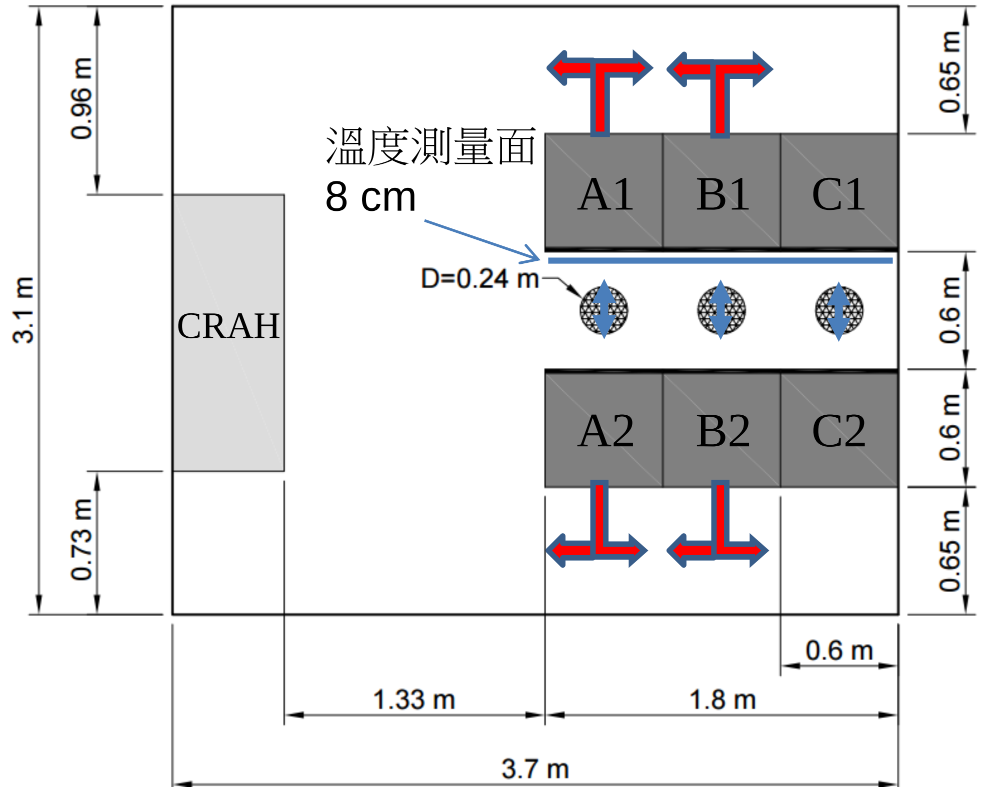
擋板位置靠近熱通道之空氣流動情形

結果與討論

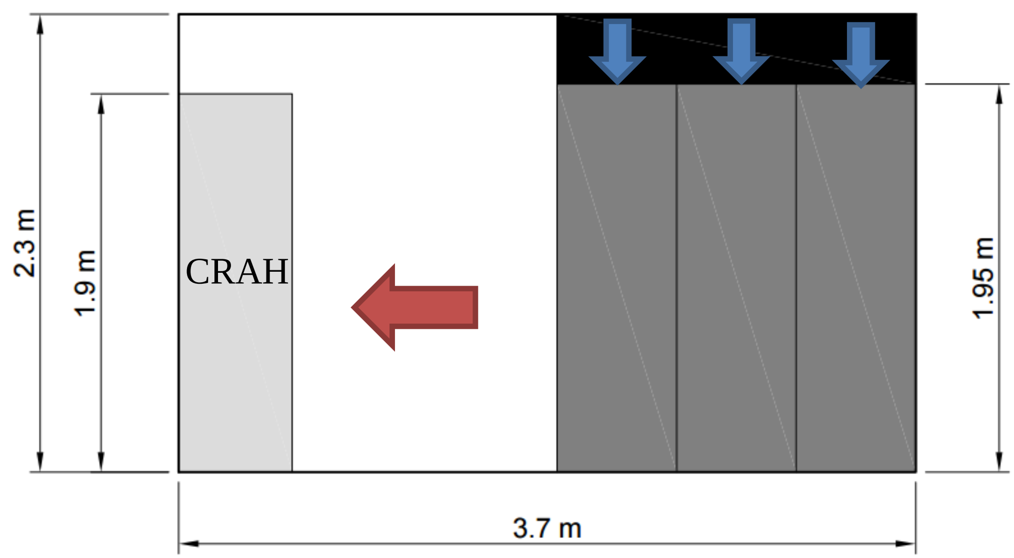
- 在改變供風口流量的設計中，流量配置正確與否，對於減低機房內熱空氣回流的情形以及機房內的溫度有很大的影響。
- 在改變供風口溫度的設計中，發現供風口溫度的高低，對於降低機房內熱空氣回流的情形只有很微小的影響，因此改變供風口溫度對於機房設計而言，並不是一個有效的方法。
- 在機櫃兩側增加有角度擋板的設計中，能有效降低機房內熱空氣回流的現象，此外，有角度擋板的擺放位置也將影響上述現象的效果，放置的位置越靠近熱通道時，減少的效果越顯著。

探討機櫃不均勻發熱之影響-半尺寸

機房尺寸



0.96 m
3.1 m
0.73 m
溫度測量面
8 cm
D=0.24 m
A1
B1
C1
A2
B2
C2
CRAH
0.65 m
0.6 m
0.6 m
0.65 m
0.6 m
1.33 m
1.8 m
3.7 m

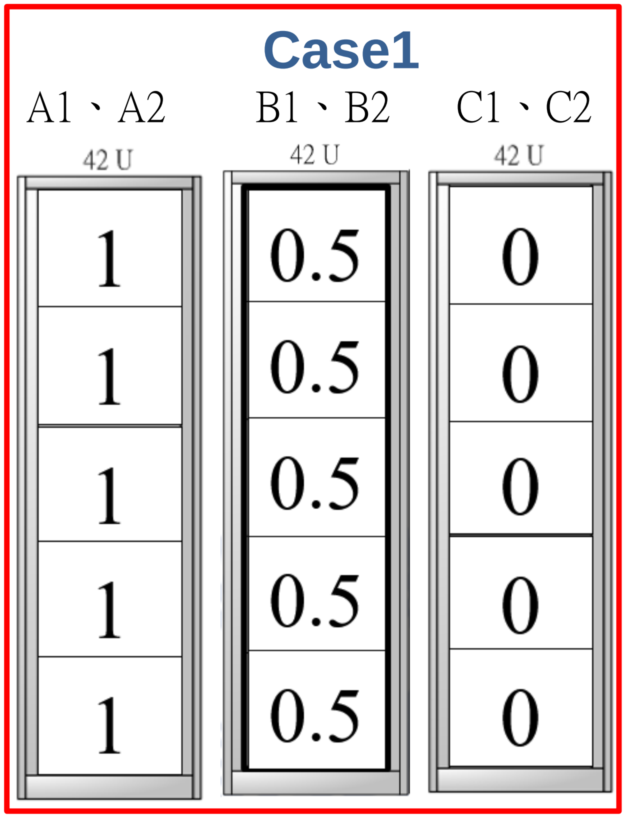


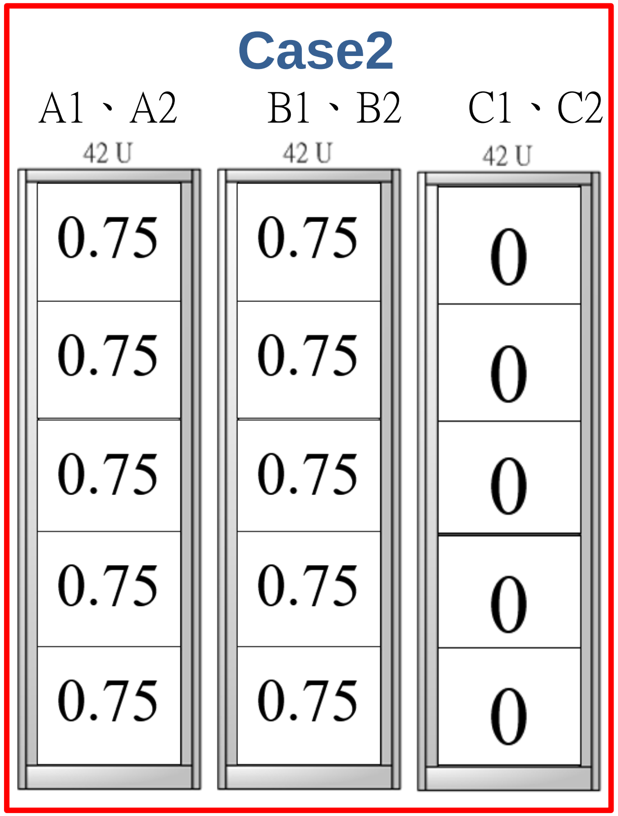
2.3 m
1.9 m
CRAH
1.95 m
3.7 m

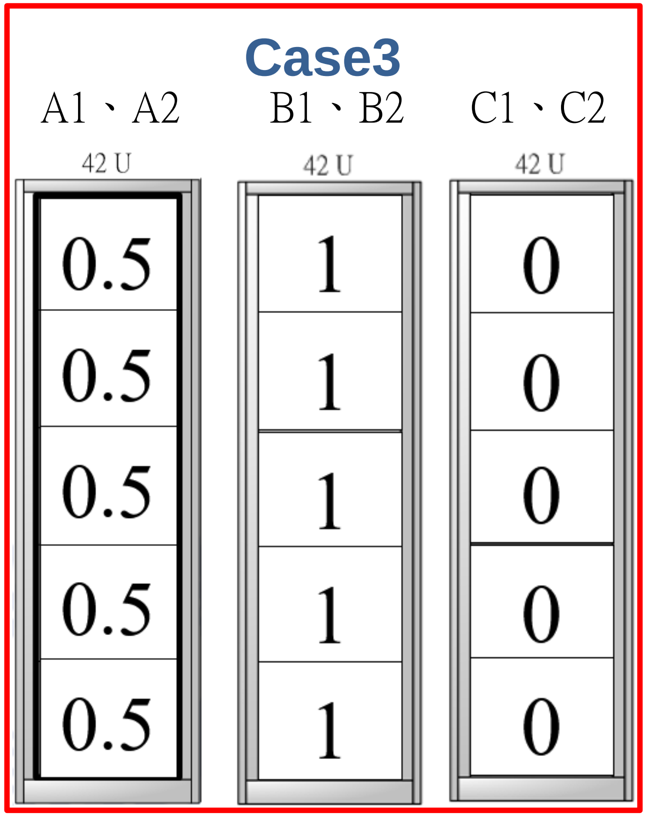
機房設定

機房發熱量:15kW
供風溫度:19.8℃
供風風量:0.77 m^3/s
機櫃抽風量:3.52 m^3/s

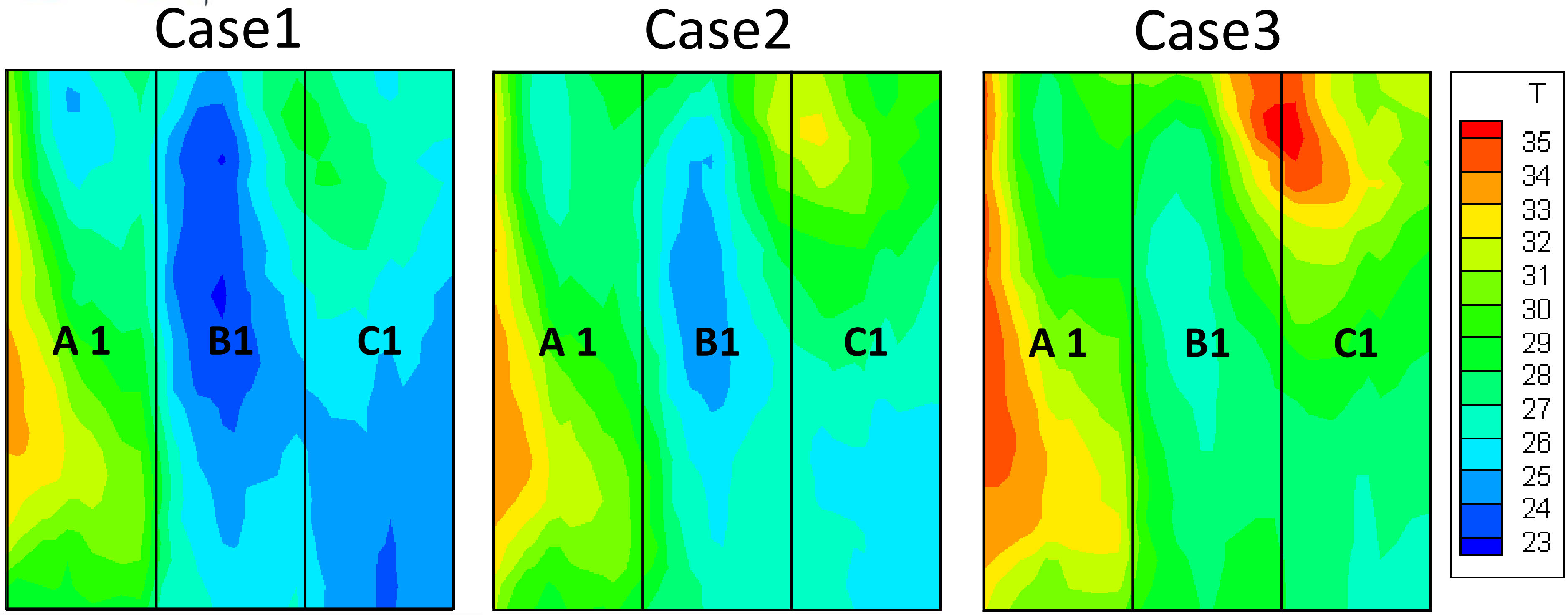
	A1與A2機櫃	B1與B2機櫃
Case1	5kW	2.5 kW
Case2	3.75 kW	3.75 kW
Case3	2.5 kW	5kW
在C1與C2機櫃加入擋板		
Case4	5kW	2.5 kW
Case5	3.75 kW	3.75 kW
Case6	2.5 kW	5kW

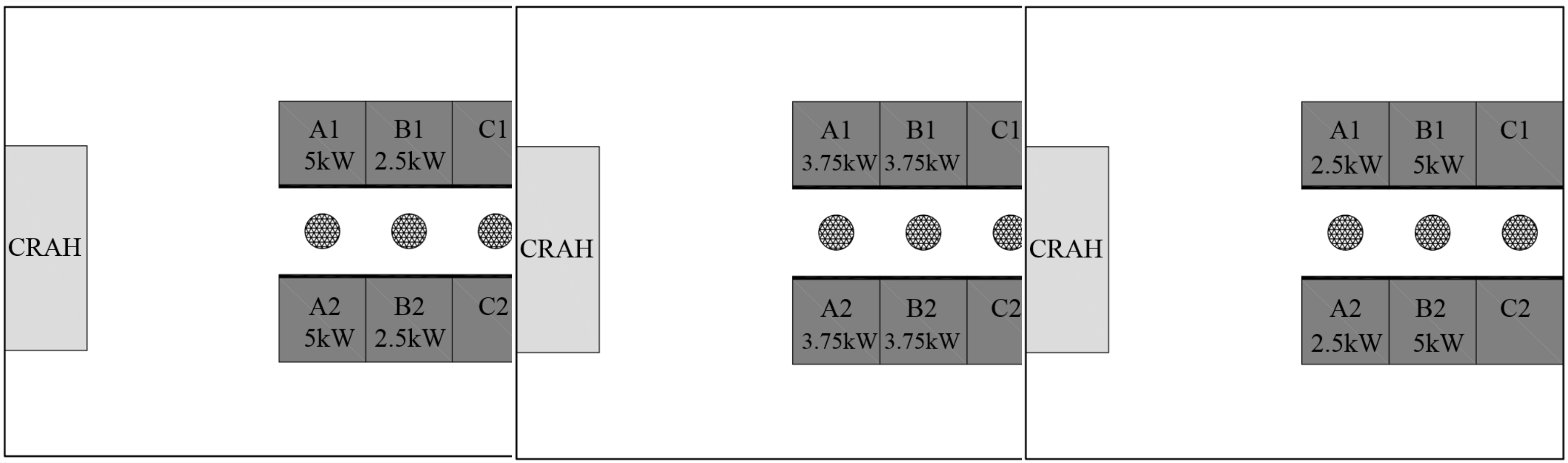






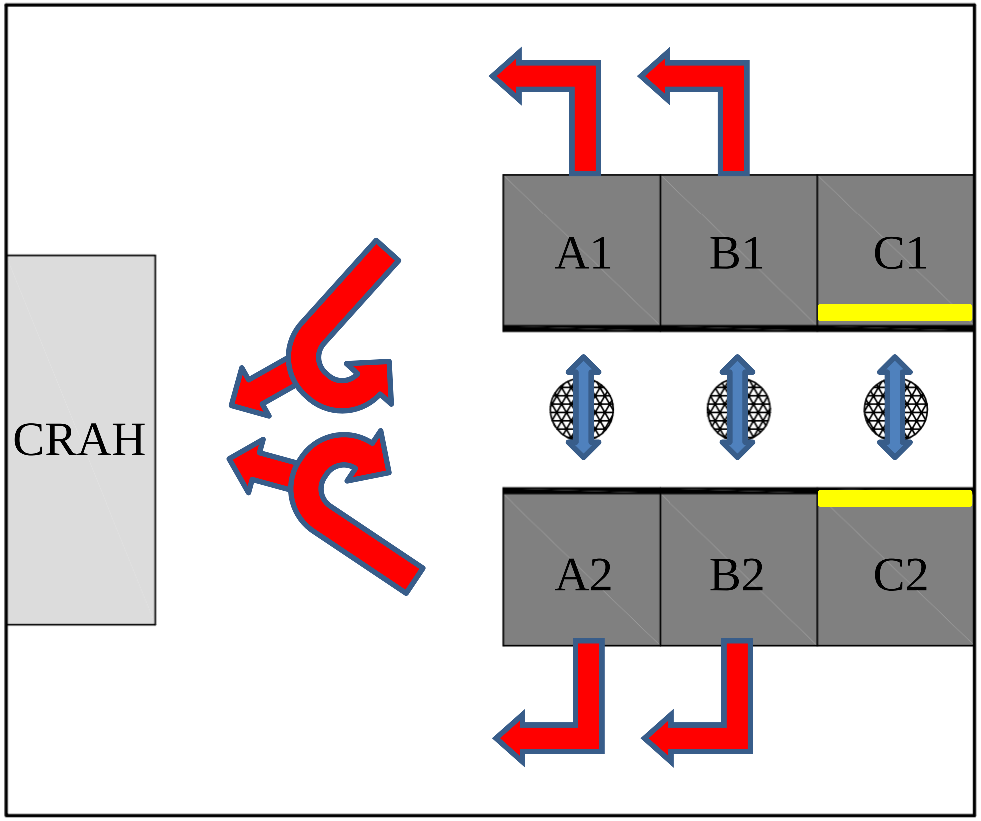
入口溫度分布及機房指標



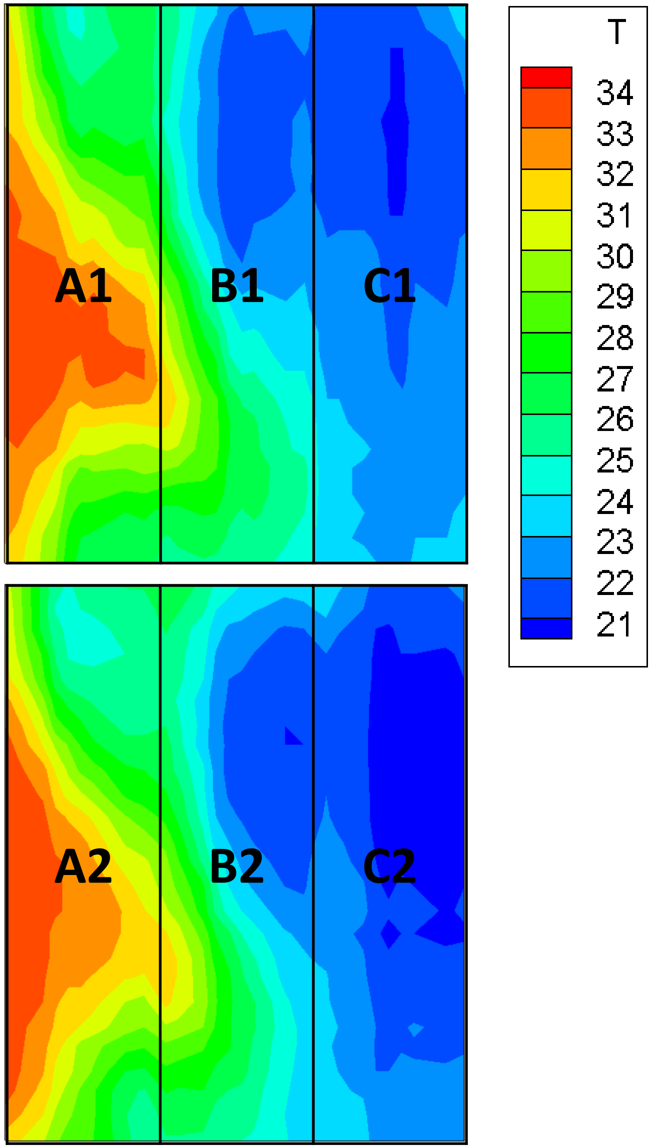


機櫃C1、C2加入擋板

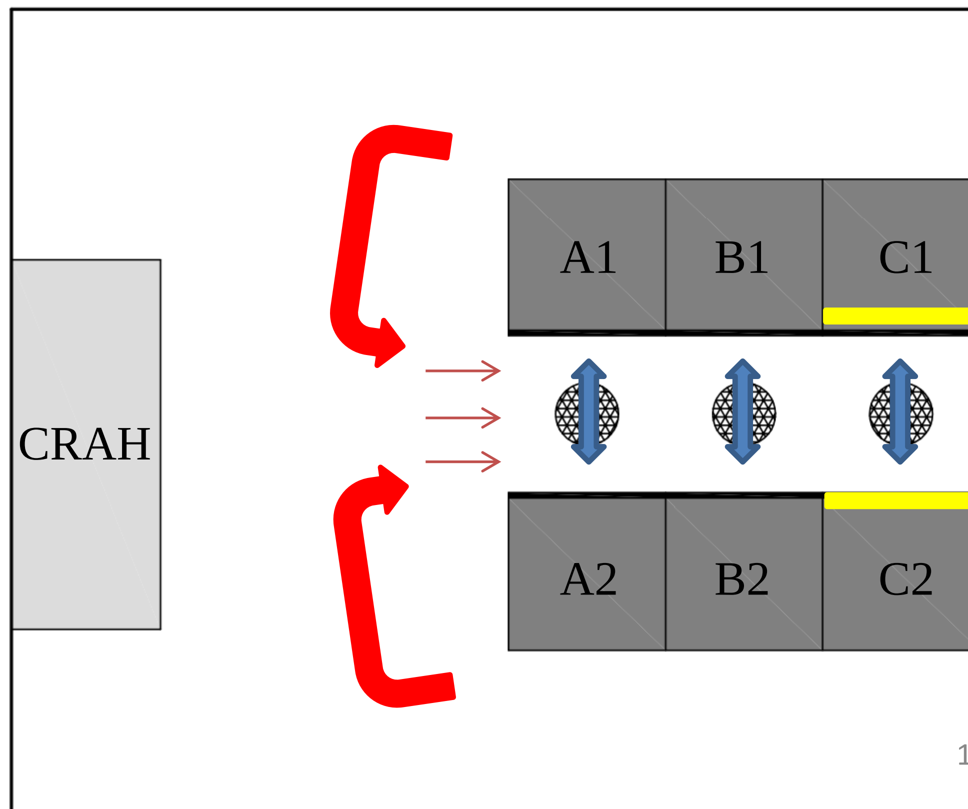
	A1與A2機櫃	B1與B2機櫃
在C1與C2機櫃加入擋板		
Case4	5kW	2.5 kW
Case5	3.75 kW	3.75 kW
Case6	2.5 kW	5kW



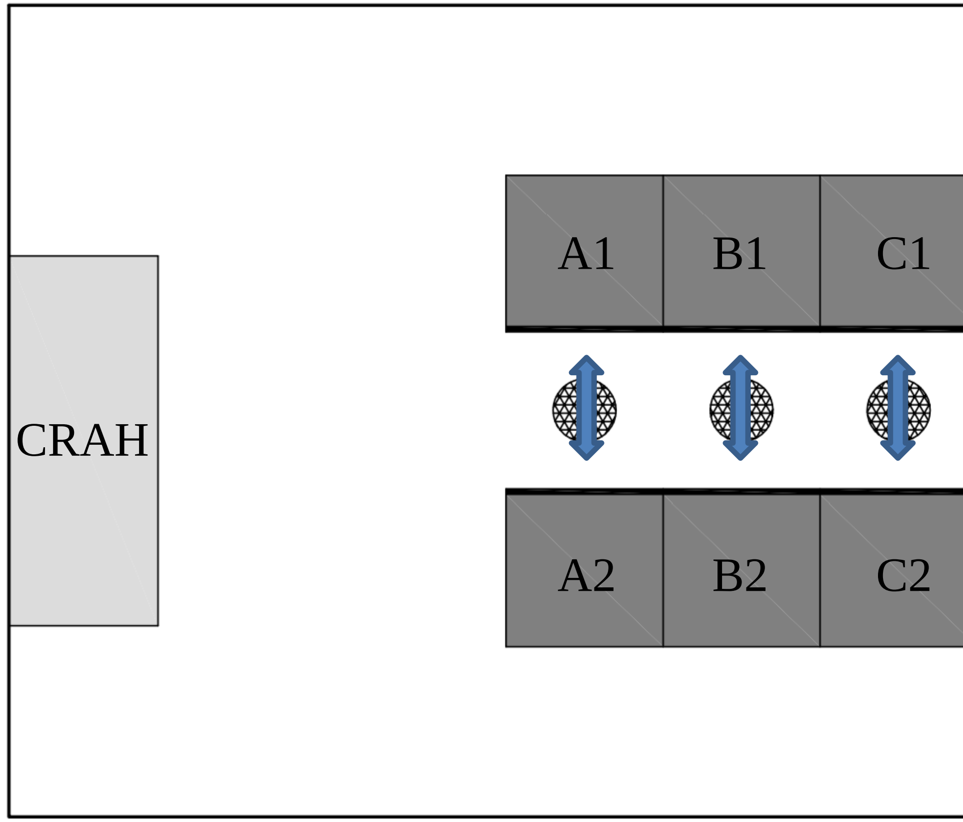
Case4



	A1與A2機櫃	B1與B2機櫃
在C1與C2機櫃加入擋板		
Case4	5kW	2.5 kW
Case5	3.75 kW	3.75 kW
Case6	2.5 kW	5kW

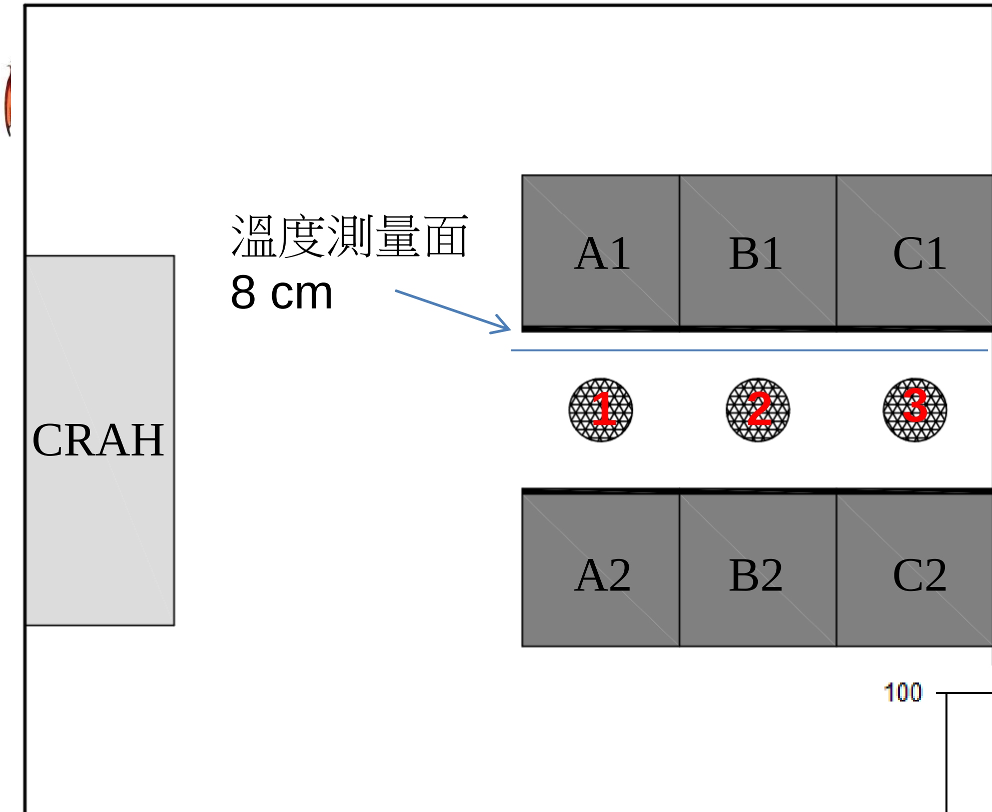


	A1與A2機櫃	B1與B2機櫃
Case1	5kW	2.5 kW
Case2	3.75 kW	3.75 kW
Case3	2.5 kW	5kW
在C1與C2機櫃加入擋板		
Case4	5kW	2.5 kW
Case5	3.75 kW	3.75 kW
Case6	2.5 kW	5kW



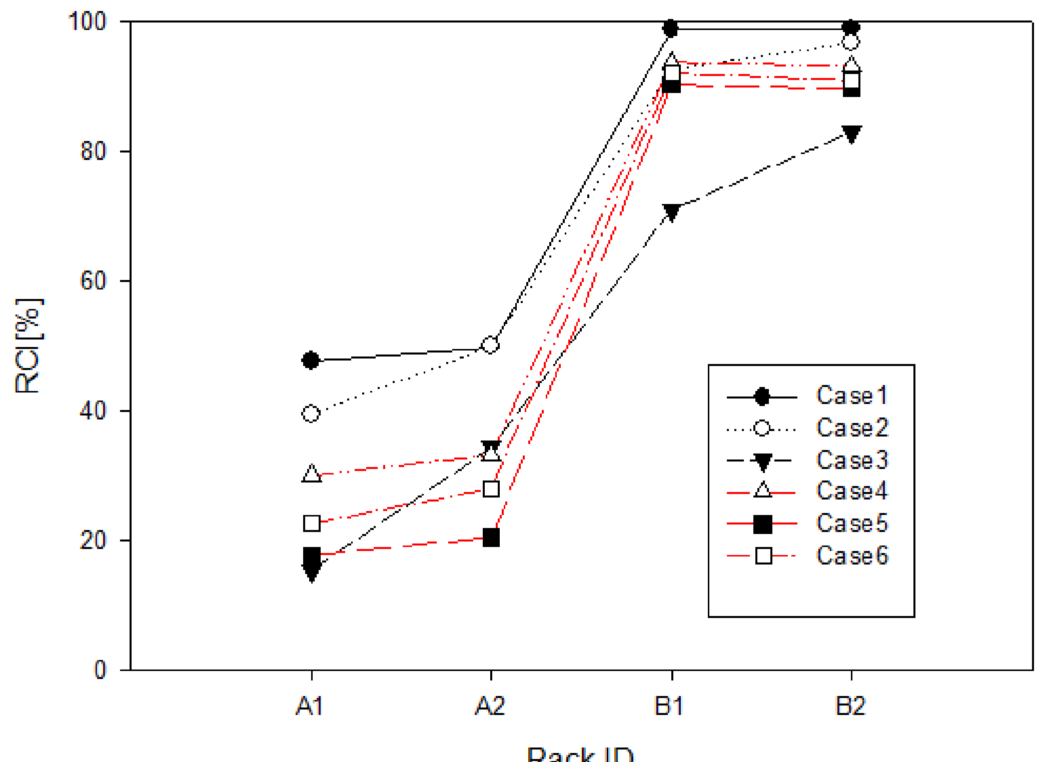
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
T_{max}	34 ℃	33.8 ℃	35.6 ℃	33.9 ℃	34.9 ℃	34.1 ℃
T_{mean}	26.4 ℃	27.5 ℃	29.2 ℃	25.6 ℃	26.2 ℃	26.1 ℃
RCI(all)	82.3 %	75.5 %	53.6 %	75.2 %	69.7 %	72.3 %
RCI(A-B)	74 %	70 %	51 %	62.8 %	54.6 %	58.5 %

RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重



	A1與A2機櫃	B1與B2機櫃
Case1	5kW	2.5 kW
Case2	3.75 kW	3.75 kW
Case3	2.5 kW	5kW
在C1與C2機櫃加入擋板		
Case4	5kW	2.5 kW
Case5	3.75 kW	3.75 kW
Case6	2.5 kW	5kW

RCI:判斷機櫃過熱程度，0~100%，越小代表過熱程度越嚴重



結論

- 將發熱量較大之機櫃擺置於空調箱附近，可提高機櫃之RCI，並且降低機櫃平均入口溫度。
- 將機櫃C1、C2入口以擋板阻隔空氣後，因冷通道流量供氣不足，使機櫃A1、A2熱回流問題嚴重。

Thank you

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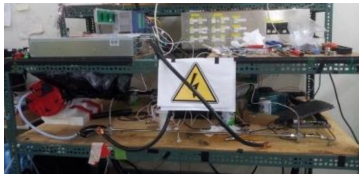
科技部能源國家型計劃: 雲端熱管理技術研究(3/3) , under contract 105-3113-E-009 -003 – ； 台達電子 & 工業技術研究院

熱與能源管理實驗室主要設備與人力

高溫熱交換器測試設備

冷媒沸騰對流熱傳



微通道熱沉蒸發測試設備

微通道熱沉冷凝測試設備

直接冷卻壓電式散熱系統

擁有約40名研究生

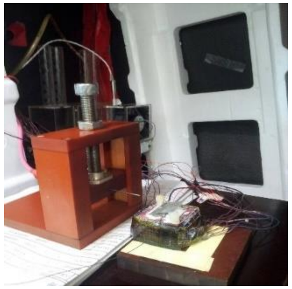
電子散熱用小型熱沉風洞測試設備

雲端熱管理測試設備

高功率冷板液冷式散熱測試設備

膨脹裝置測試設備

LED散熱測試設備



環境控制室與鰭管式
熱交換器測試設備

多種CFD模擬軟體