Airflow Management on the Efficiency Index of Data Centers – An Overview

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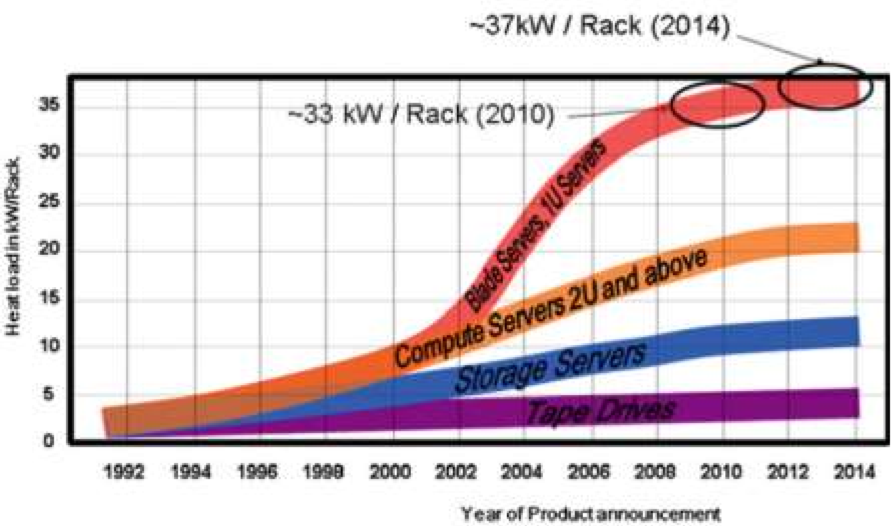
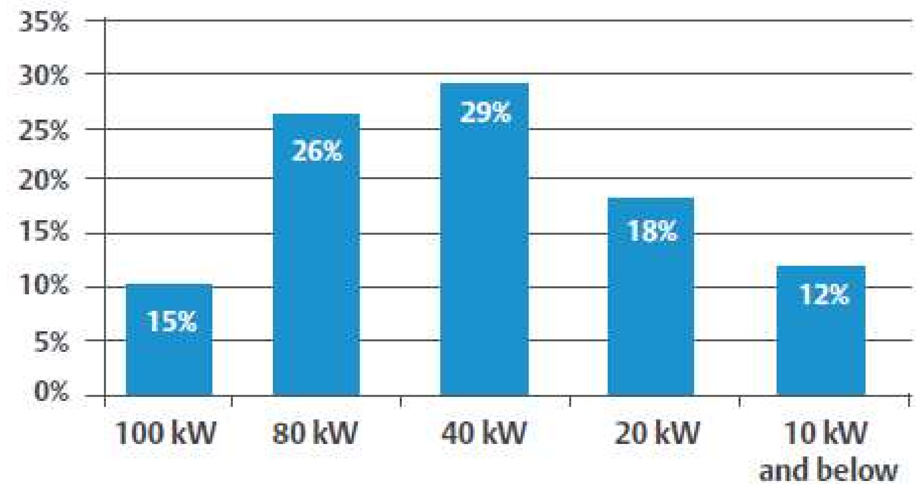
Plenary lecture presented for the 12th International Green Energy Conference （IGEC- XII）
July 31 – August 3, 2017, Xi'an, Shaanxi, China

Outline

- General Background
- Thermal management in data center
- Airside Management
  - Raised floor
  - Overhead design
- Concluding Remarks



Datacom Equipment Power Trends and Cooling Applications (2005) American Society of Heating Refrigeratingand Air-Conditioning Engineers (ASHRAE), TC 9.9 Committee, Atlanta, GA



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

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

Data center (From Wikipedia)

- A **data center** is a facility used to house computer systems and associated components, such as telecommunications and storage systems. It generally includes redundant or backup power supplies, redundant data communications connections, environmental controls (e.g. air conditioning, fire suppression) and various security devices.
- A large data center is an industrial-scale operation using as much electricity as a small town.

General Background

National Chiao Tung University

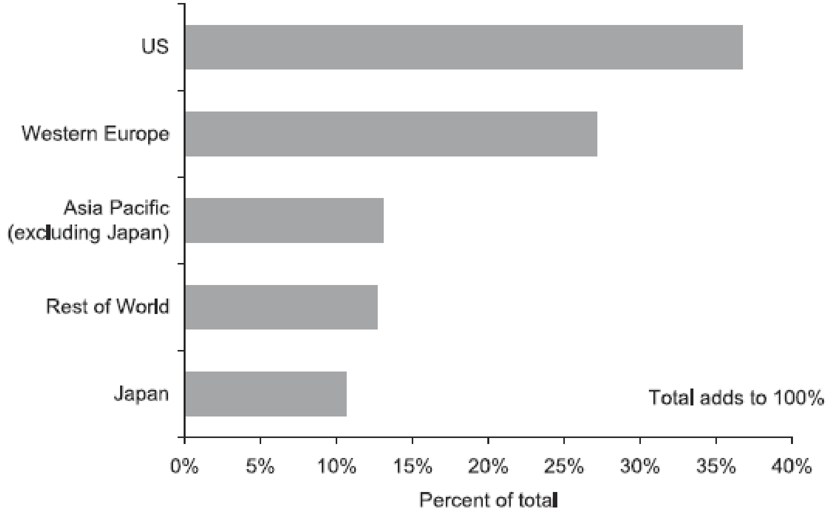
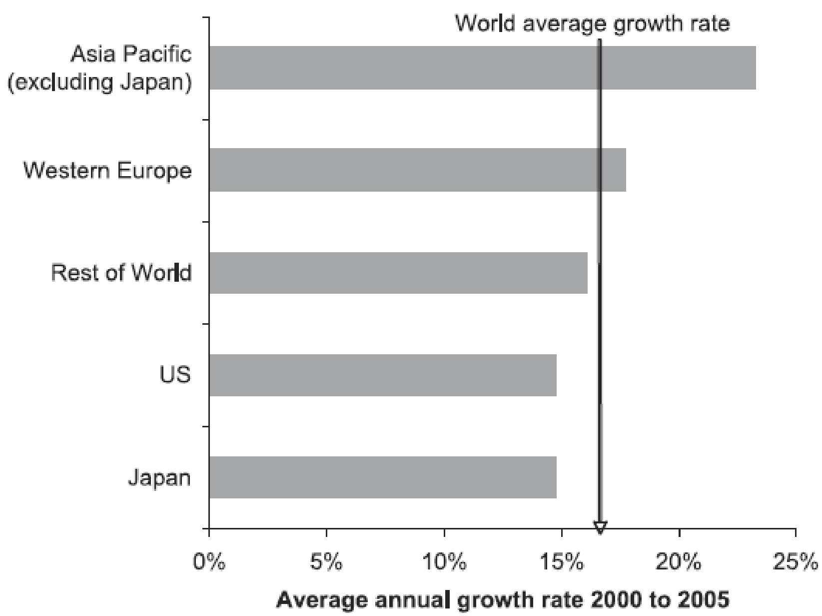


Figure 2. Regional distribution of electricity use for data centers in 2005.



. 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.

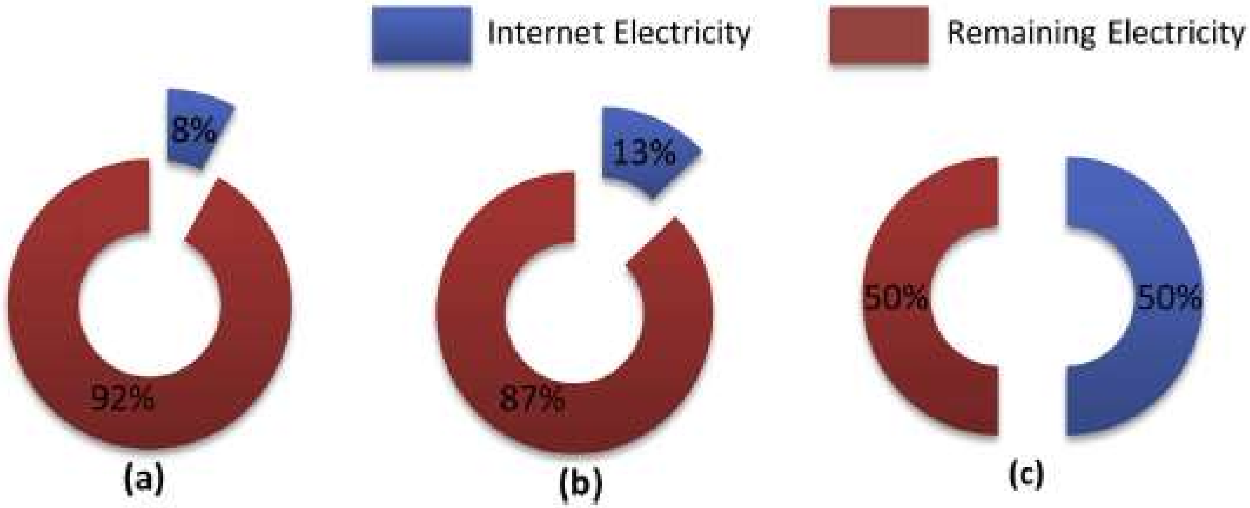
Installed base	Units	Volume	Mid-range	High-end	Total/avg
2000					
US	Thousands	4 927	663	23	5 613
Western Europe	Thousands	3 332	447	15	3 794
Japan	Thousands	1 140	250	15	1 405
Asia Pacific (ex. Japan)	Thousands	1 416	132	4	1 552
Rest of World	Thousands	1 425	317	8	1 750
Total	Thousands	12 240	1808	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.

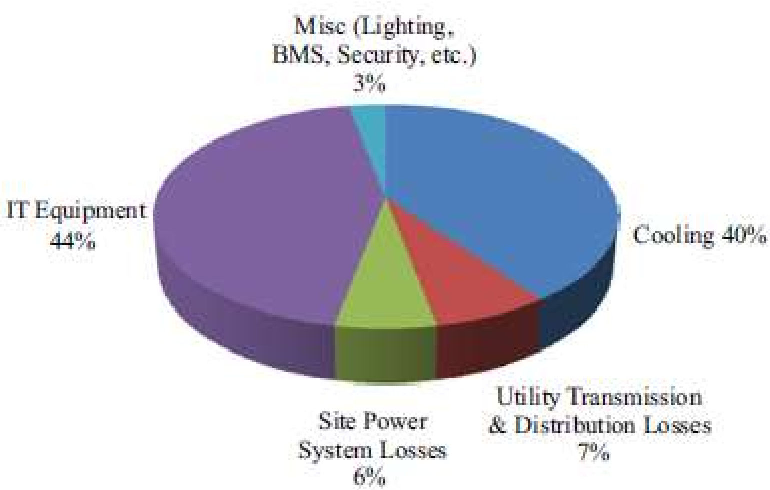
General Background

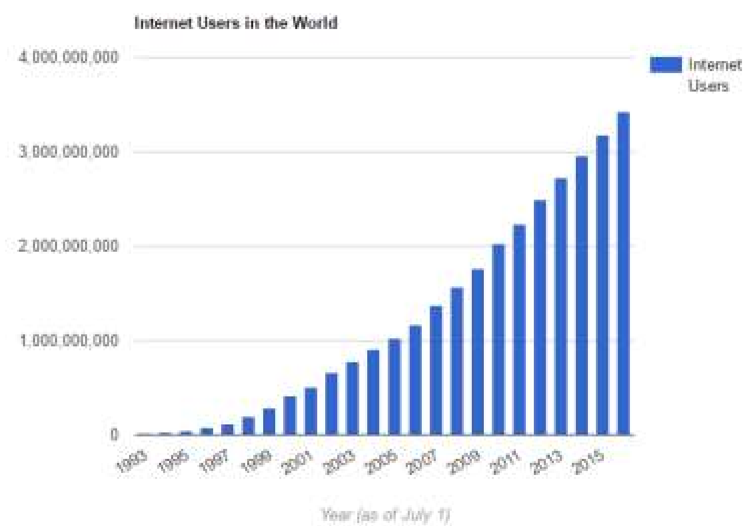
Building and Environment, Volume 82, December 2014, Pages 151–159



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



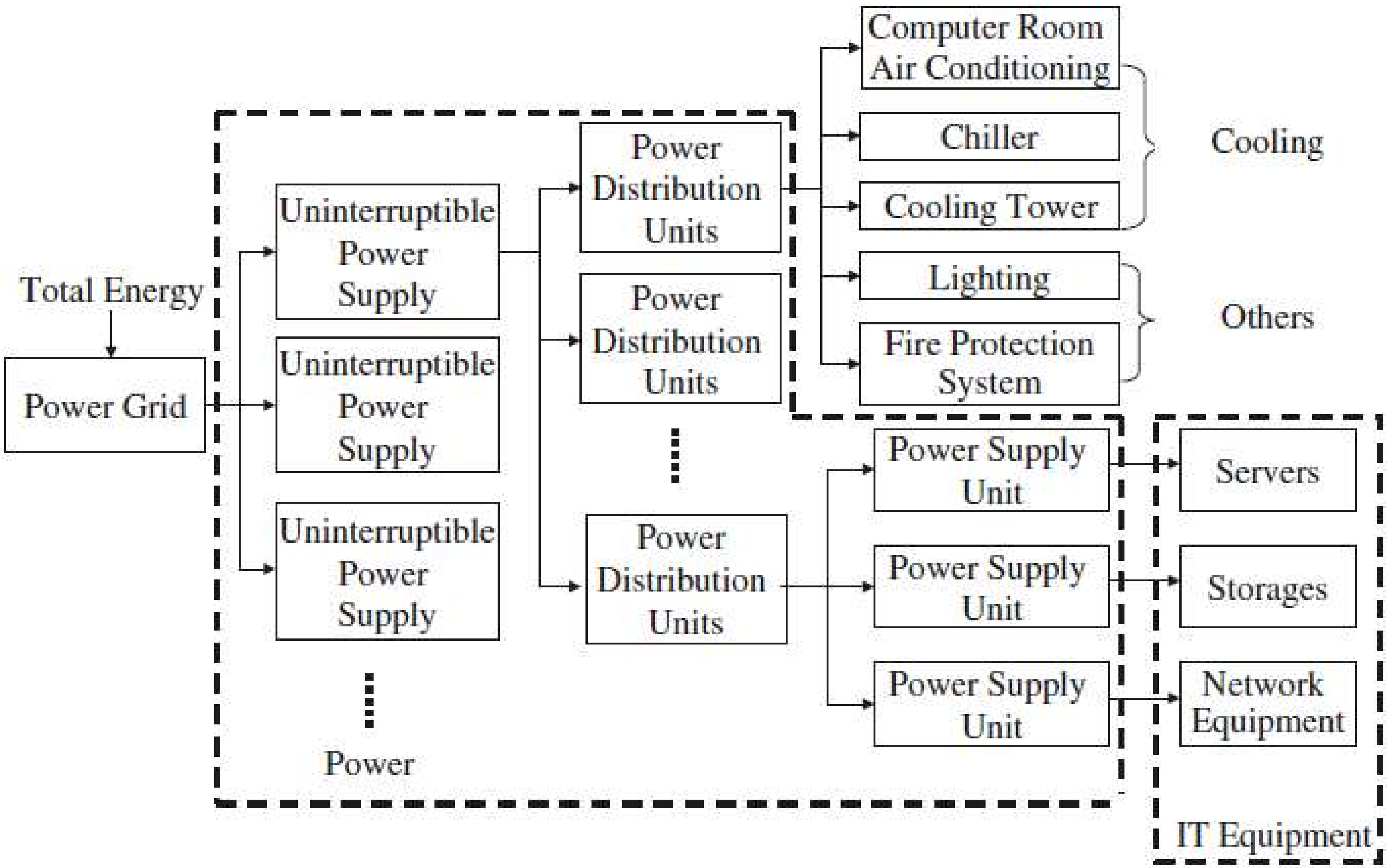


Internet users in the world
http://www.internetlivestats.com/internet-users/.

Equipment in Data Center

- Power equipment
  - power distribution units (PDUs), uninterruptible power supply systems (UPSs), switchgears, generators, and batteries.
- Cooling equipment
  - chillers, computer room air-conditioning (CRAC) units, cooling towers, and automation devices.
- **IT equipment**
  - servers, network, and storage nodes (network-attached storage, and external hard disk drive (HDD) arrays), telecom equipment (e.g., routers and switches), and supplemental equipment such as keyboards, monitors, workstations, and laptops used to monitor or other control..
- Miscellaneous component
  - lighting and fire protection systems…

A typical power delivery procedure in data centers



"Optimum Cooling of Data Centers," Springer 2016

Energy Efficiency Metrics

- Power Usage Effectiveness $\text{PUE} = \dfrac{\text{Total facility power}}{\text{IT facility power}}$

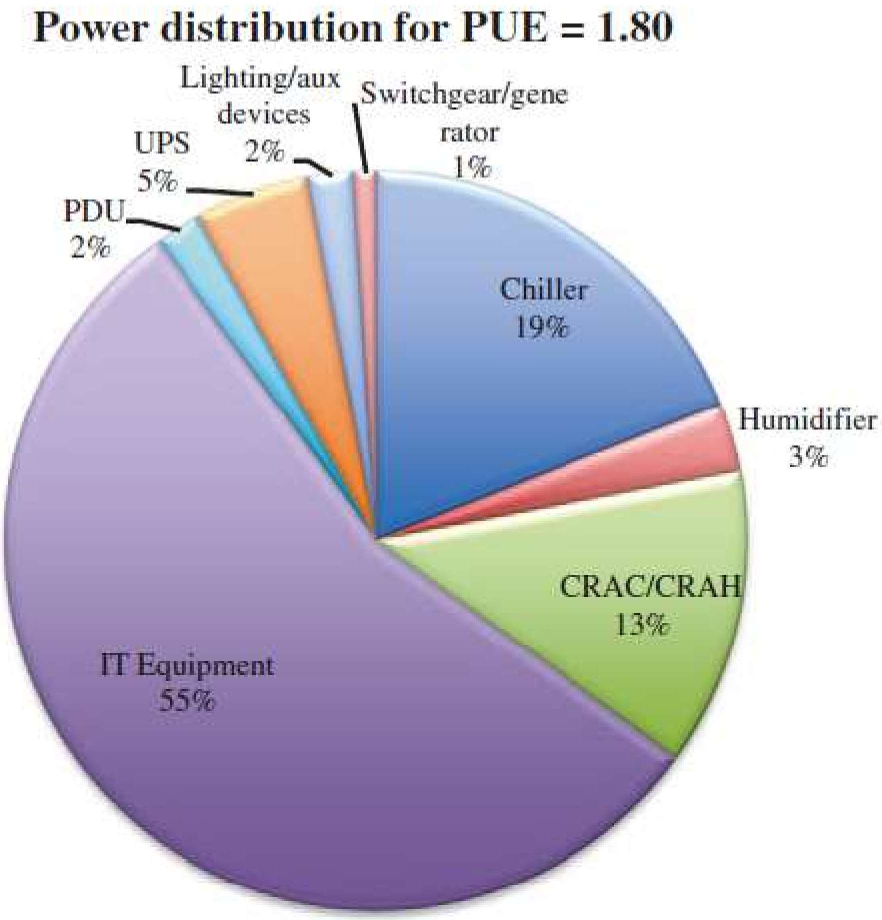
	Category 0	Category 1	Category 2	Category 3
IT energy measurement location	UPS output	UPS output	PDU output	Server input
Definition of IT energy	Peak IT electric demand	IT annual energy	IT annual energy	IT annual energy
Definition of total energy	Peak total electric demand	Total annual energy	Total annual energy	Total annual energy

- Data center infrastructure efficiency (DCiE)

$$\text{DCiE} = \frac{\text{IT facility power}}{\text{Total facility power}}$$

$$\text{DCiE} = \frac{1}{\text{PUE}}$$

Energy consumption in a typical data center



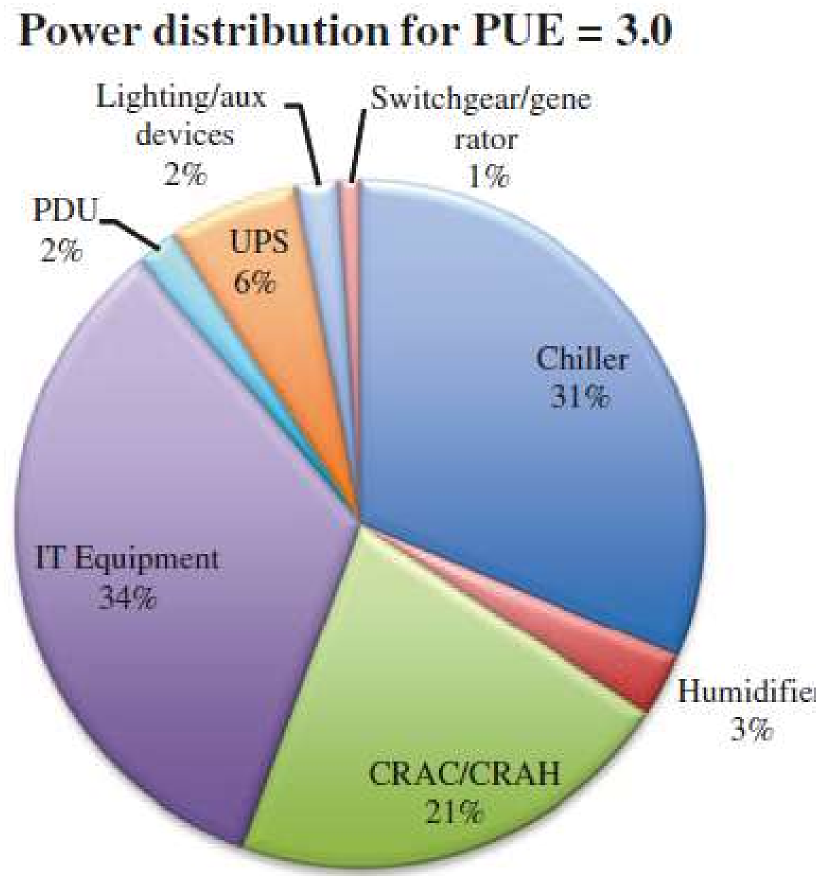


Figure represents the average value reported in a survey of more than 500 data centers as reported by Uptime Institute in 2011. Graphs from "Optimum Cooling of Data Centers," Springer 2016.

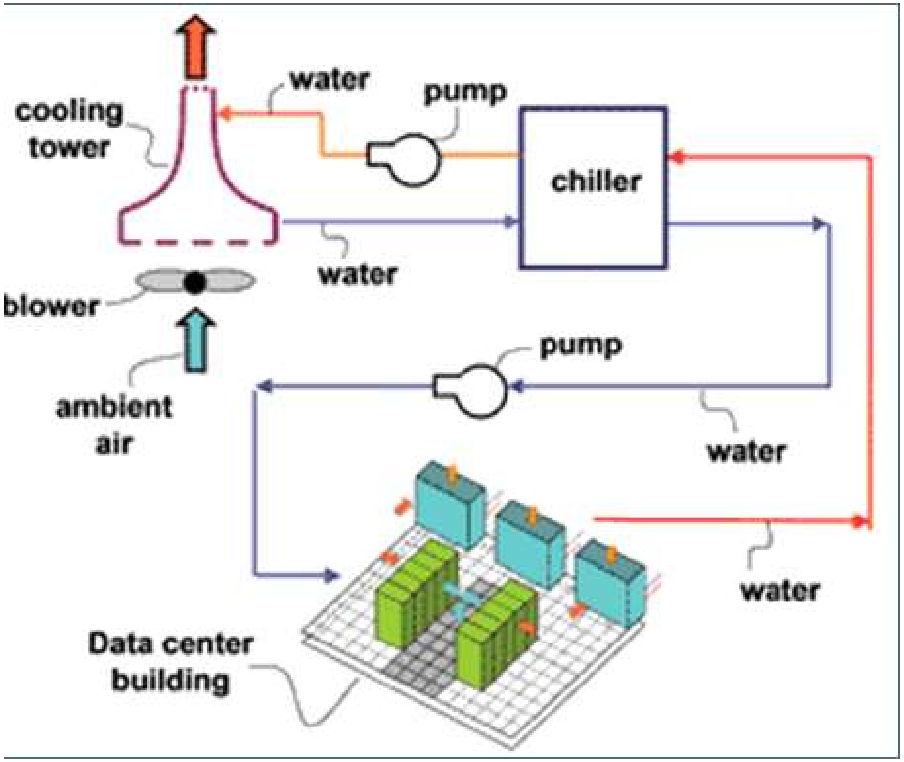
Methods to Improve Energy Efficiency

- ***Efficient Electronics***
- ***Efficient Software Applications***
- ***Efficient Power Supply and Distributions***
- ***Efficient Cooling Systems***
  - ***Typical cooling Technologies***
    - ***Air-cooling***
    - ***Liquid Cooling***
    - ***Hybrid cooling, free cooling, heat pipe/thermosphion, conduction, heat spreading system..***

Thermal management

Data center cooling infrastructure

- ASHRAE guidelines for IT equipment:
  - The previous 2004 guidelines recommended air temperatures from **20˚C low end to 25˚C high end** temperature
  - The updated 2008 guidelines expanded the envelope for recommended air temperatures from **18˚C low end to 27˚C high end** temperature.



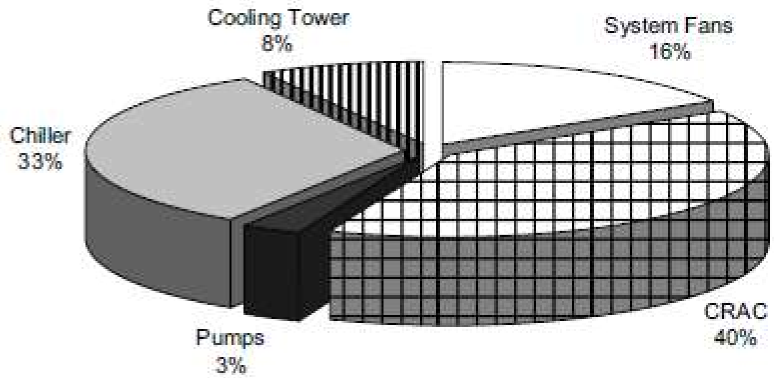
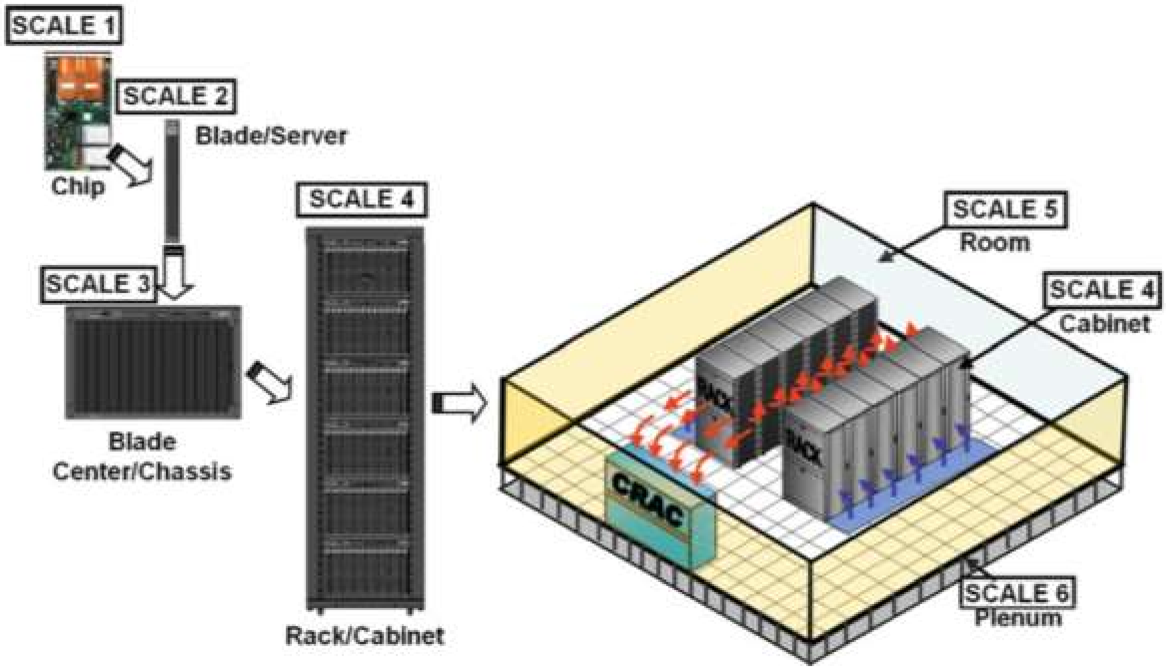


Fig. 5. Estimated cooling energy consumption in the ensemble

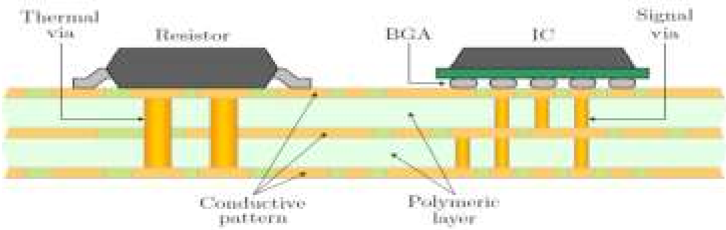
Multi-scale Thermal Management

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

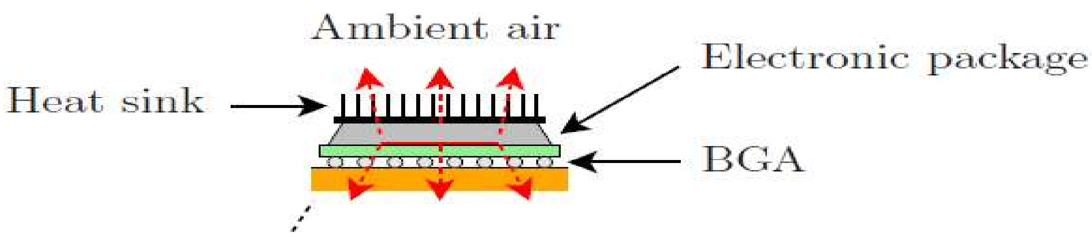


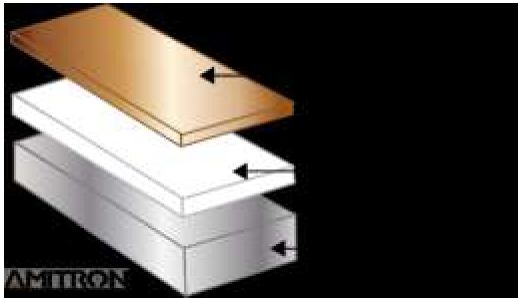
Heat generated in Chip/Substrate/PCB level is focused on heat spreading

Heat Removal @ chip or substrate PCB Level



- Heat Transfer Path
  - From Top: Use effective heat sinks and micro heat exchangers attached to the chip for single- or two-phase heat transfer
  - From Bottom: Improve conduction Path
    - **A short heat conduction path** to a heat sink perpendicular through the PCB (e.g. thermal vias)
    - **A conductor layer acting as a lateral heat spreader** (extended thermal pads) or a combination of both.
    - **IMS (Insulated Metallic Substrates)** are also state of the art and widely spread for thermal issues in electronic systems.





Conduction path

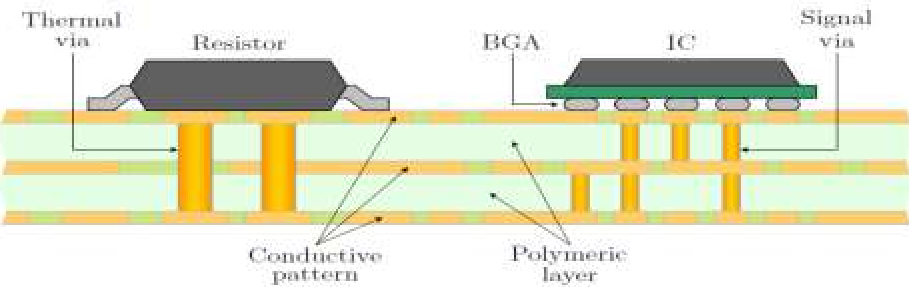


Figure 2.1: *Schematic cross section of a Circuit Card Assembly (CCA).*

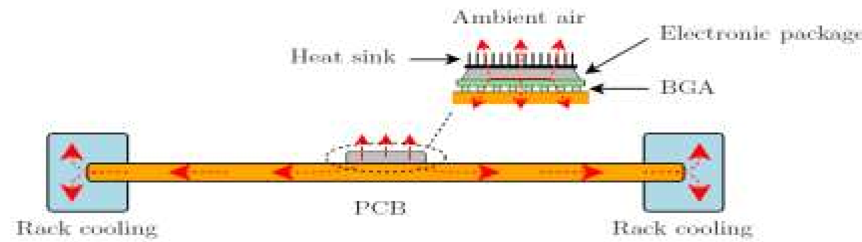


Figure 2.4: *General cooling trajectories for electronic packages.*

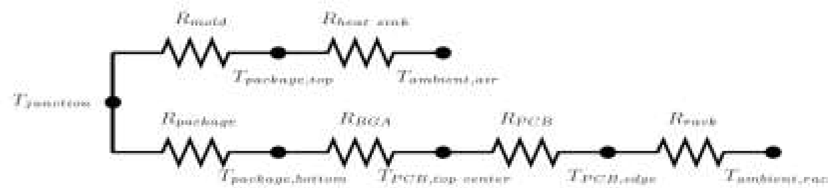


Figure 2.5: *Compact thermal model of Figure 2.4.*

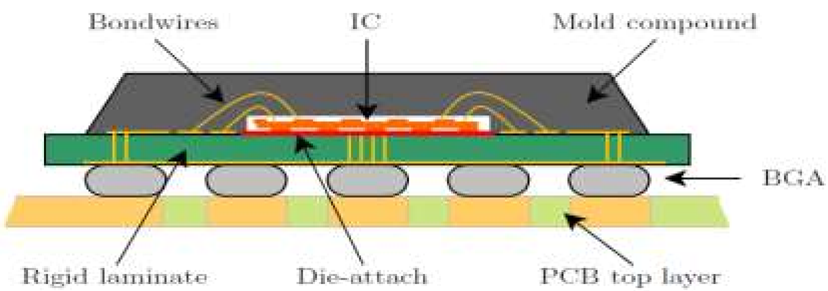


Figure 2.3: *Schematic of a Ball Grid Array (BGA) package.*

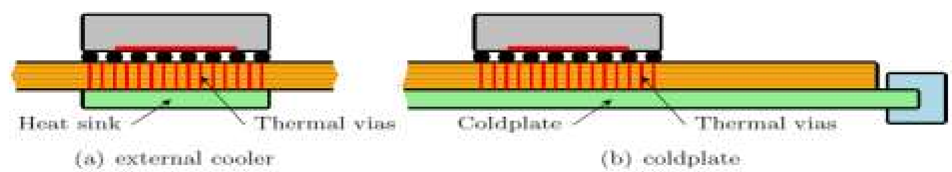


Figure 2.6: *Concept illustration with a cooling device on the opposite side.*

Integrated cooling concepts for Printed circuit boards, PhD Thesis, W. W. Wits, the University of Twente, Enschede, the Netherlands, 2008

Effective Heat Spreading @ chip/substrate

PCB Level

Lateral spreading + Open Thermal Via

To avoid the well-known problem of solder soaking, it is not possible to place open thermal vias directly underneath a component. Due to this fact, the thermal path is elongated.

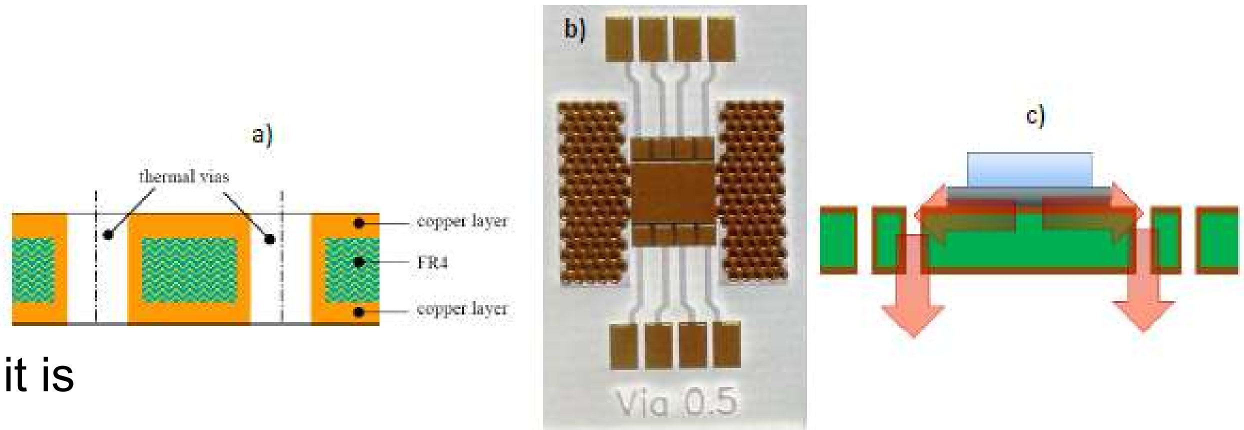


Figure 2. PCB with open thermal vias: a) Scheme; b) design; c) thermal path

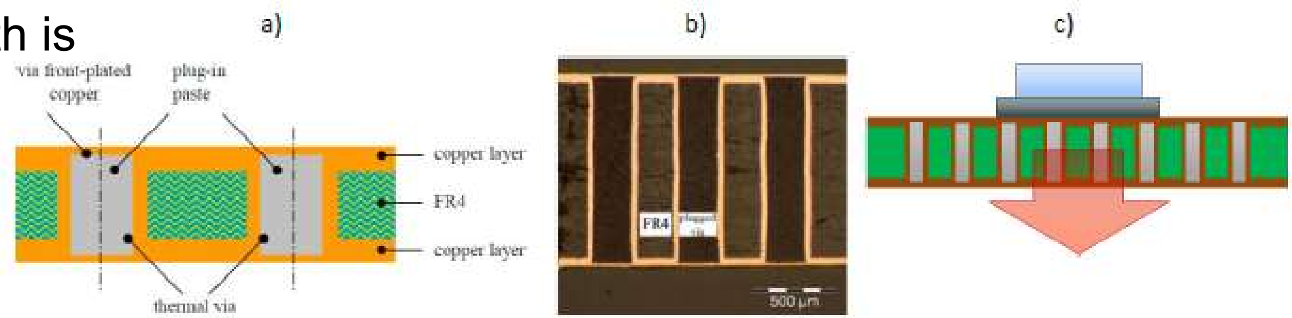
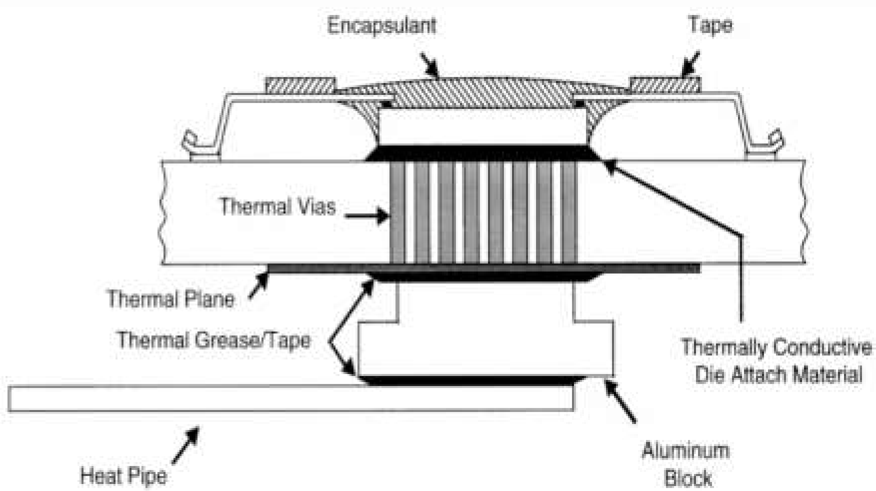


Figure 3. PCB with plugged thermal vias: a) Scheme; b) cross section; c) thermal path

Lateral spreading + Thermal Via

Advanced Thermal Management Solutions on PCBs for High Power Applications. Journal of Microelectronics and Electronic Packaging: 2014, Vol. 11, No. 3, pp. 104-114.

In-board Cooling



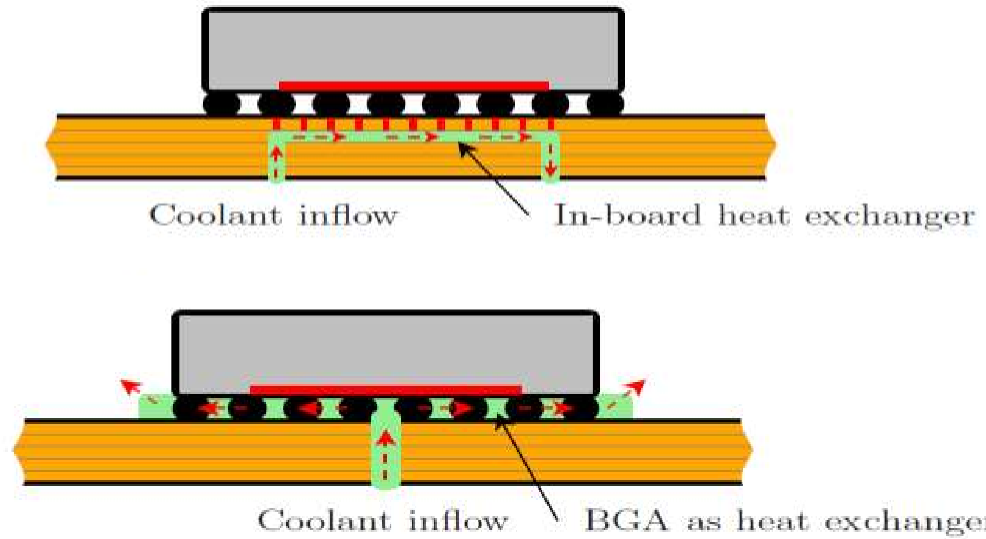


Figure 2.8: *Concept illustration of directly injected cooling.*

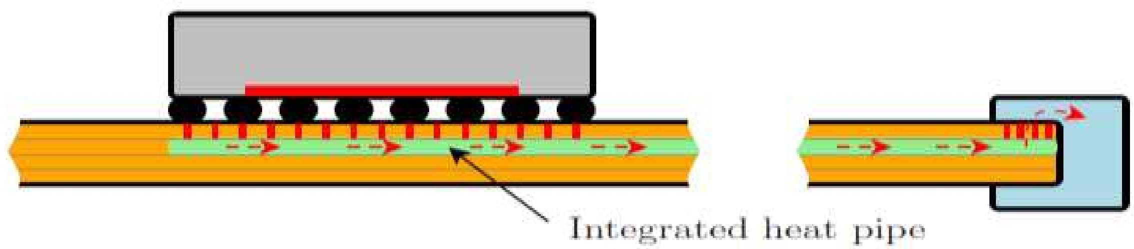


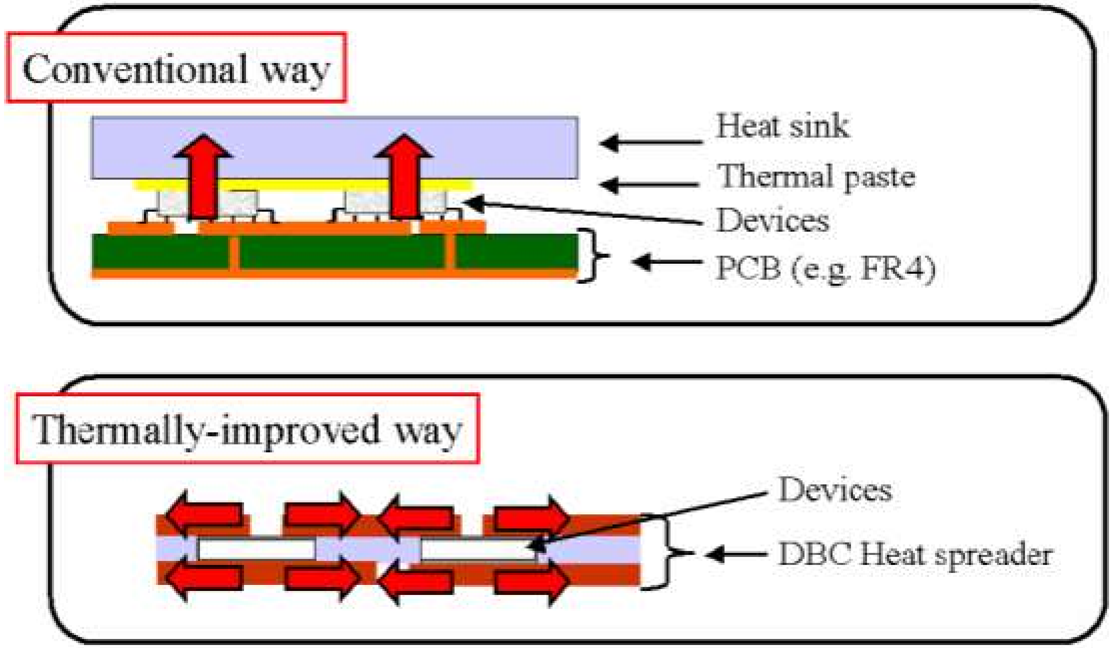
Figure 2.9: *Concept illustration of integrated heat pipe cooling.*

Integrated cooling concepts for Printed circuit boards, PhD Thesis, W. W. Wits, the University of Twente, Enschede, the Netherlands, 2008

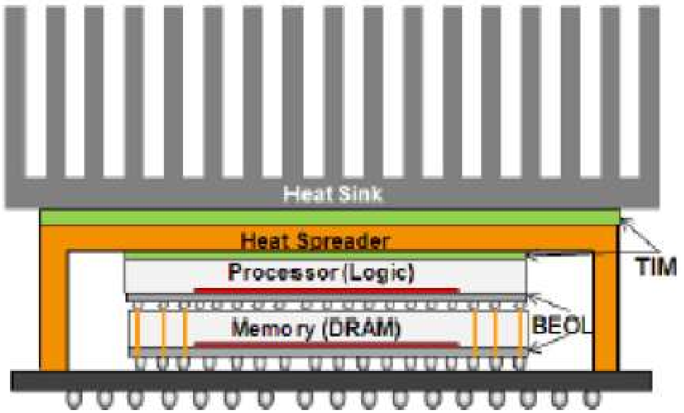
Use Ceramic Substrate

Thermal and Electrical Considerations for the Design of Highly-Integrated Point-of-Load Converters
A.H. Ball, phD thesis, 2008, Blacksburg, Virginia, USA

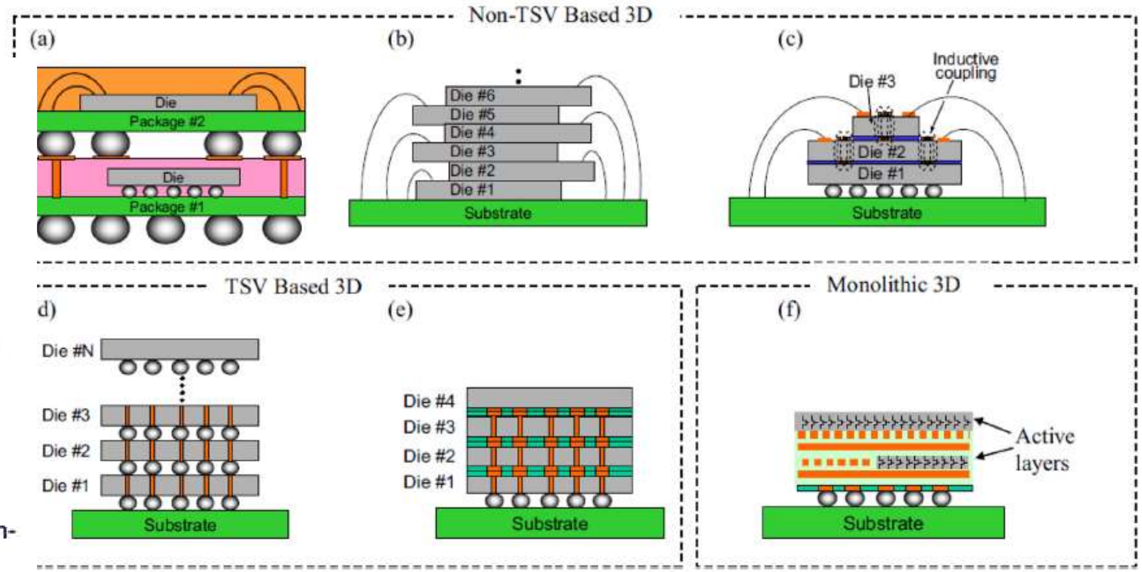
When using a substrate with a low thermal conductivity, such as FR4, heat spread poorly, creating hotspots in the main power dissipation devices – typically the MOSFETs. These hotspots not only limit the potential current output but they also reduce the package effectiveness. By going to a ceramic substrate, the hotspot is effectively spread over the entire package. The hotspot-to-package-area ratio has thus gone from about 20% to 85%.



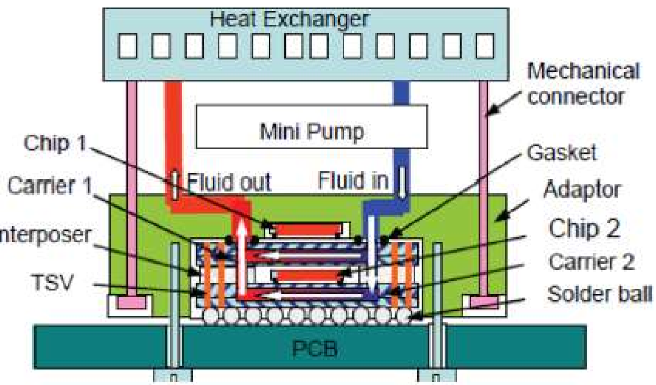
Advanced Designs..



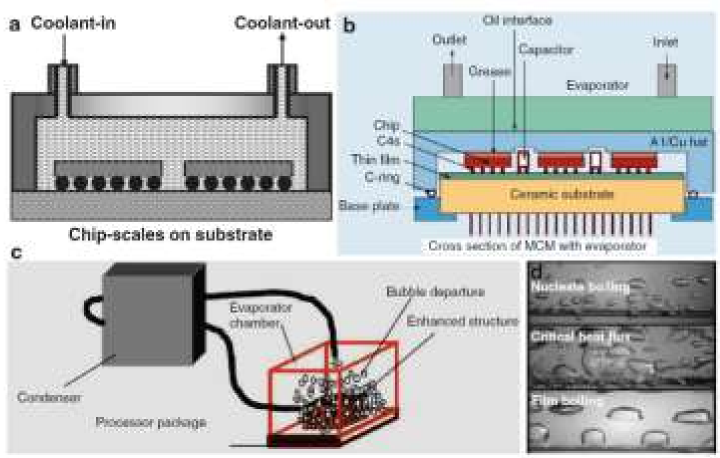
ig. 12 Thermal management in 3D chip stacks using conven-
ional air cooling [55]



.g. 2 Existing packaging and 3D integration technologies: (*a*) stacking of fully packaged die (*b*) die stacking based on wire
onding, (*c*) die stacking using wireless interconnection, (*d*) die stacking using controlled collapse chip connection (C4)
umps and TSVs, (*e*) die stacking based on thin-film bonding, and (*f*) monolithic 3I



g. 14 Schematic of integrated liquid cooling system for 3I
ystem using microfluidic channel [56]



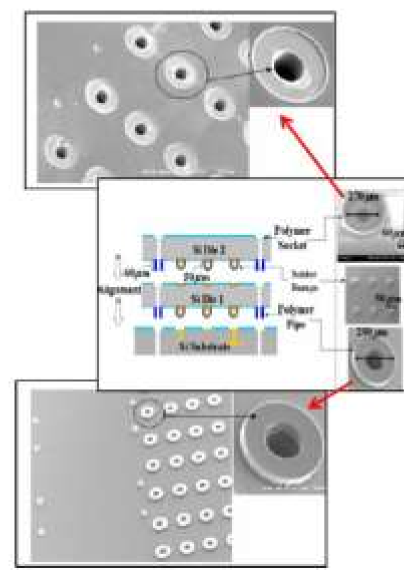


Fig. 15 Assembly of 3D prototype of integrated microfluidic channel cooling solution [58]

3D IC, A Review of Recent Advances in Thermal Management in Three Dimensional Chip Stacks in Electronic Systems. Journal of Electronic Packaging, ASME, 2011, Vol. 133 / 041011-1

Advanced Thermal Management Solutions in Planar 2D Circuits

- Compact Thermosyphon

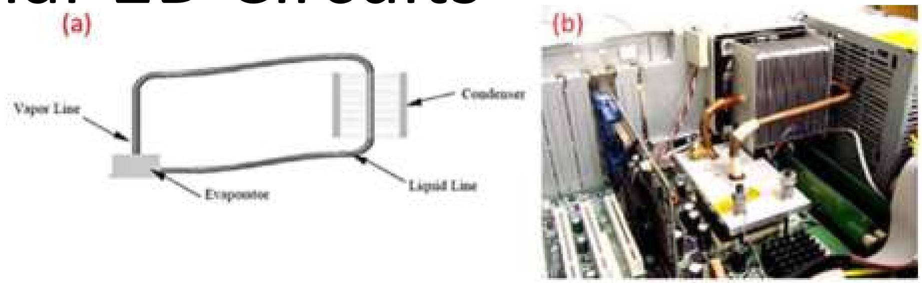


Fig. 6 (*a*) Loop thermosyphon and (*b*) HP Vectra PC with the thermosyphon assembly [26]

- Mirco CPL (capillary pump Loops)

- Miniature Loop Heat Pipe

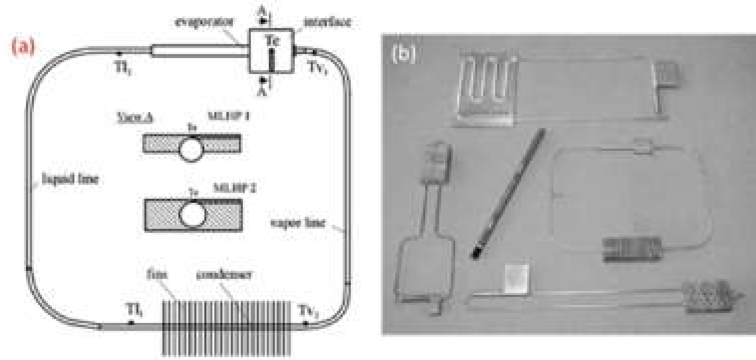


Fig. 7 (*a*) Miniature loop heat pipe principle and (*b*) general view of miniature loop heat pipe [2

- Electro-Osmotic Pump

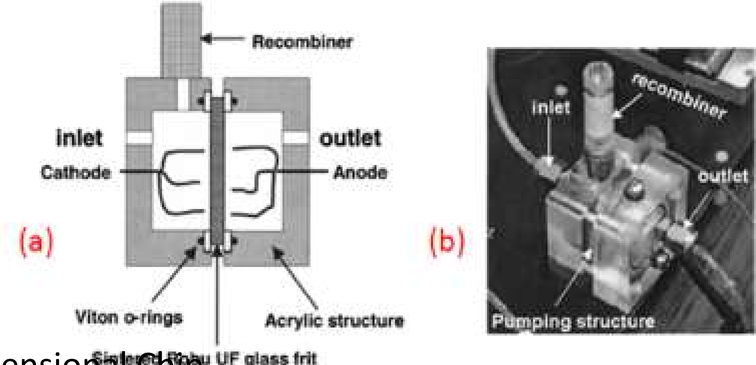


Fig. 8 (*a*) Schematic and (*b*) image of an electro-osmotic pump [28]

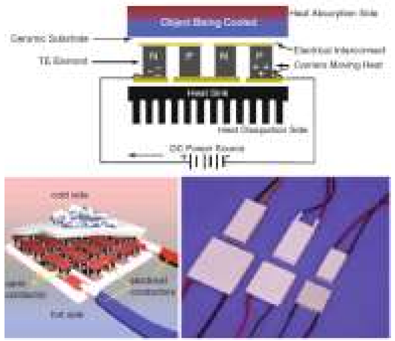
- Stacked Micro-Channel

DESIGN AND FABRICATION OF A MICRO-CPL FOR CHIP-LEVEL COOLING, Dorian Liepmann, 2001

3D IC, A Review of Recent Advances in Thermal Management in Three Dimensional Chip Stacks in Electronic Systems. Journal of Electronic Packaging, ASME, 2011, Vol. 133 / 041011-1

Advanced Thermal Management Solutions

- Impinging Jet
- Thermoelectric Micro-Cooler
- Miniature Vapor Compression Heat Pump
- Miniature Absorption Heat Pump



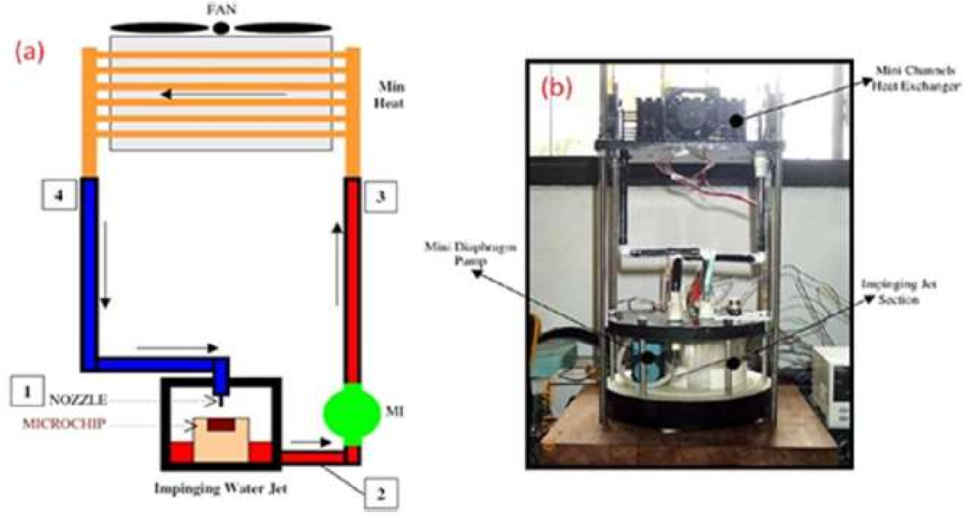


Fig. 9 (*a*) Schematic and (*b*) close-up picture of the impinging jet cooling system [30]

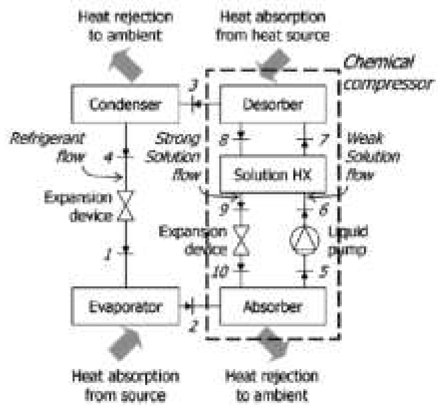


Fig. 11 Schematic of miniature absorption heat pump micro-electronics cooling solution [34]

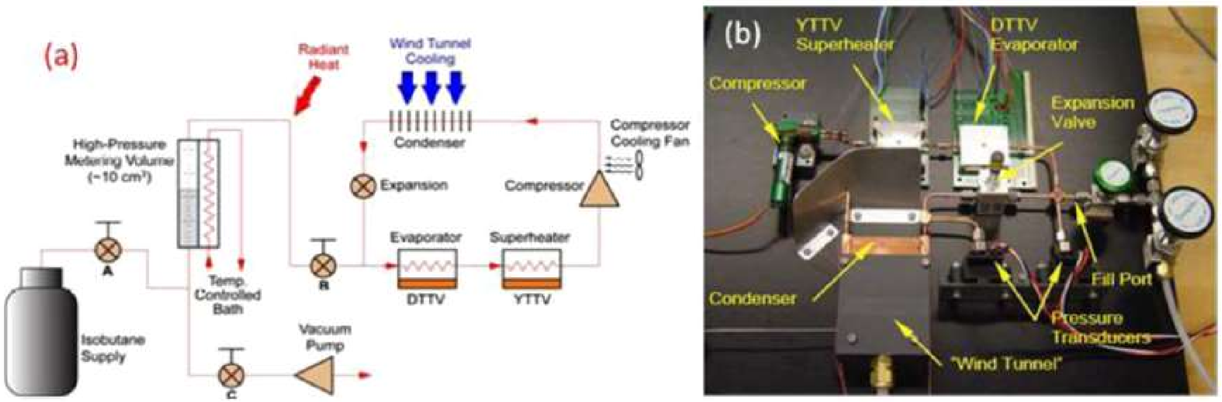


Fig. 10 (*a*) Schematic and (*b*) actual setup of a miniature vapor compression heat pump microelectronics cooling solution [33]

DESIGN AND FABRICATION OF A MICRO-CPL FOR CHIP-LEVEL COOLING, Dorian Liepmann, 2001

3D IC, A Review of Recent Advances in Thermal Management in Three Dimensional Chip Stacks in Electronic Systems. Journal of Electronic Packaging, ASME, 2011, Vol. 133 / 041011-1

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

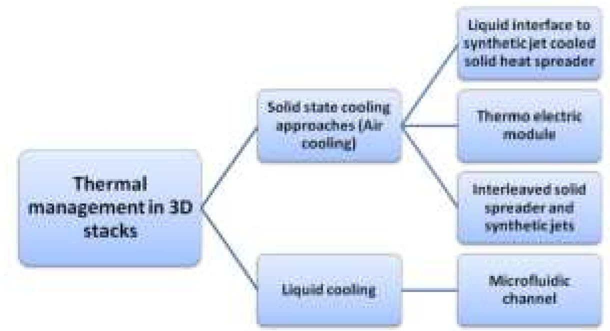
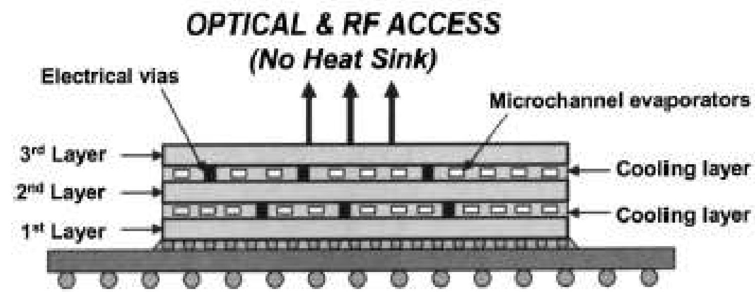
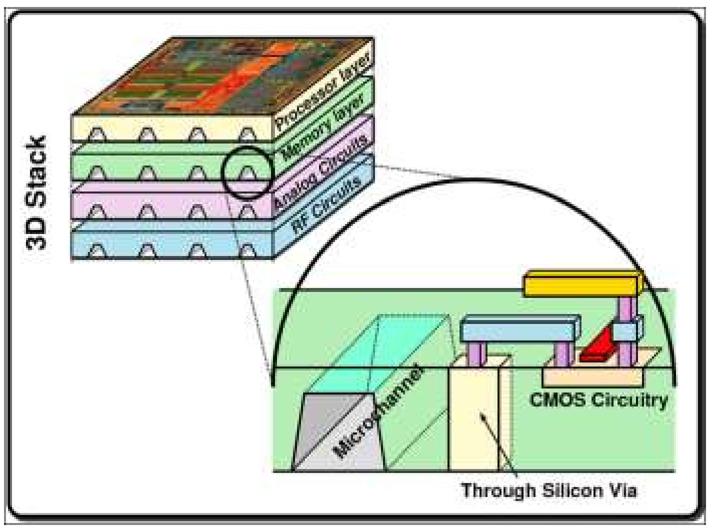


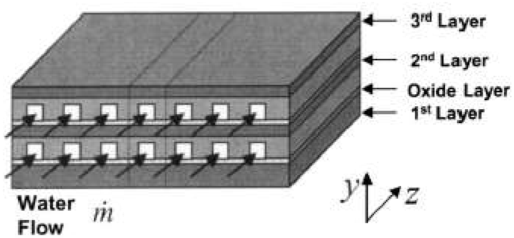
Fig. 13 Thermal management strategies in 3D stacks



(a) 3D circuit with a microchannel cooling system

3D IC with Microchannel





(a) Schematic of microchannel cooling for a 3D circuit

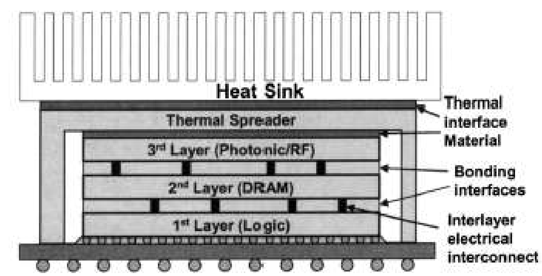
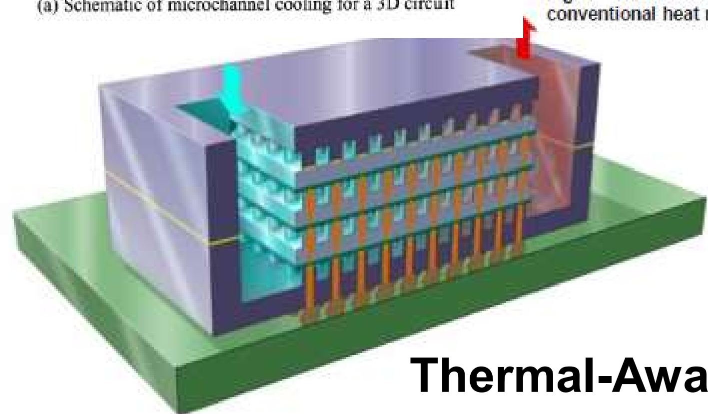


Fig. 1 Three-dimensional circuit architecture connected to a conventional heat removal device

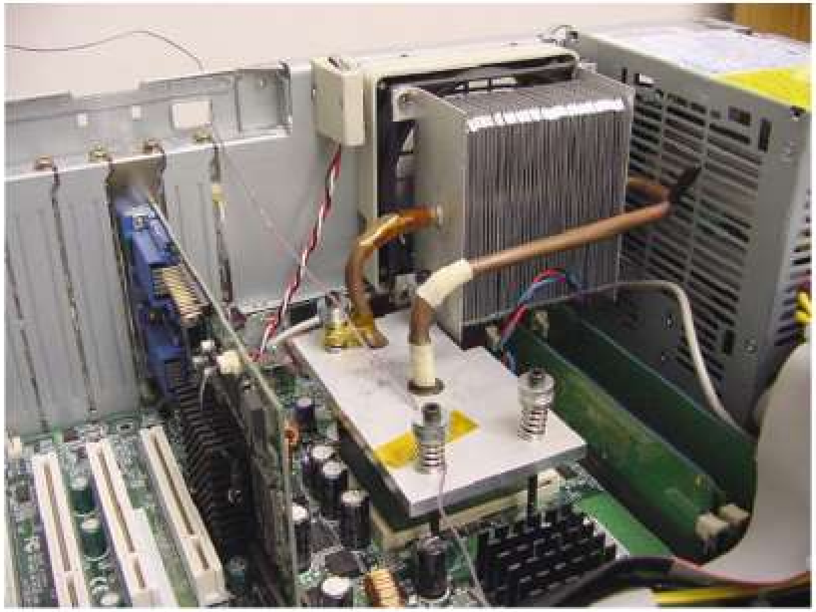


http://flashinformatique.epfl.ch/spip.php?article2260

Thermal-Aware Design for 3D Multi-Processor

Thermal Management in Server Level

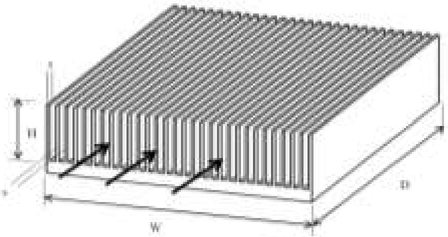
Aircooled Heat Sinks



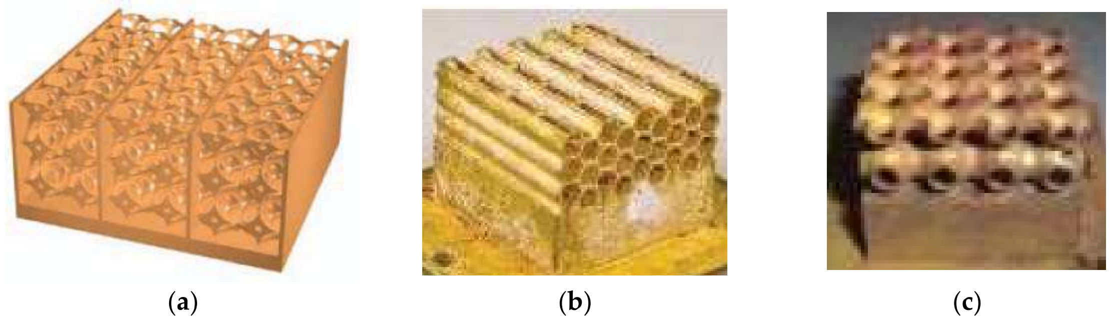
Server level indirect cooling using a two-phase thermosyphon.

Novel Heat Sink

__Wang, C.C.__, (2017), **"A Quick Overview of Compact Air-cooled Heat Sinks Applicable for Electronic Cooling – Recent Progress,"** ***Inventions***, Vol. 2, issue 1, article no. 5. Abstract: http://www.mdpi.com/2411-5134/2/1/5/. doi:10.3390/inventions2010005.



- Porous fins



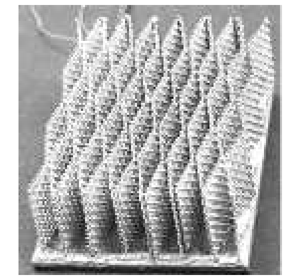
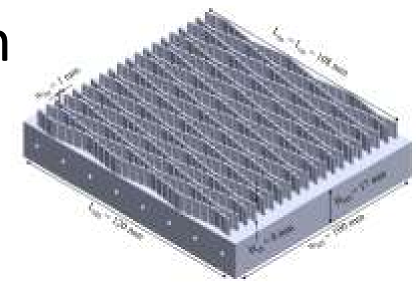
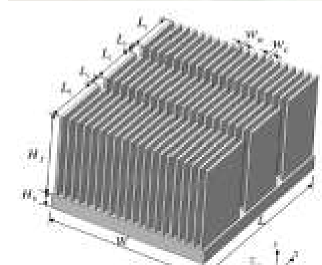


Figure 5. Fin structure tested by Krishnan et al. Reprinted with permission from [24].. (**a**) Fin metal foam heat sink; (**b**) slotted hexagon heat sink; (**c**) Schwartz type heat sink.

- VG, cannelure, Louver, partial bypass, slit, … Design

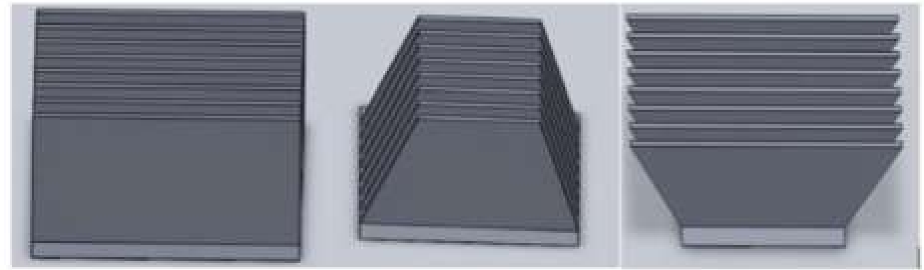
Heat Sink	Side View	Photos of Test Sample
(a) Plate		
(b) Oblique dimple gap 4–12 fin		
(c) Oblique dimple gap 6–12 fin		
(d) Cannelure fin I		
(e) Cannelure fin II		
(f) Oblique dimple gap 4–12 cannelure fin		
(g) Oblique dimple gap 6–12 cannelure fin I		
(h) Oblique dimple gap 6–12 cannelure fin II		



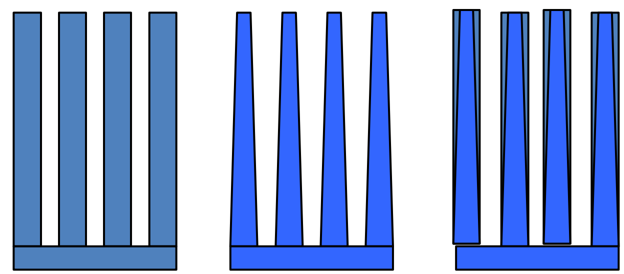


Historical studies related to fin design

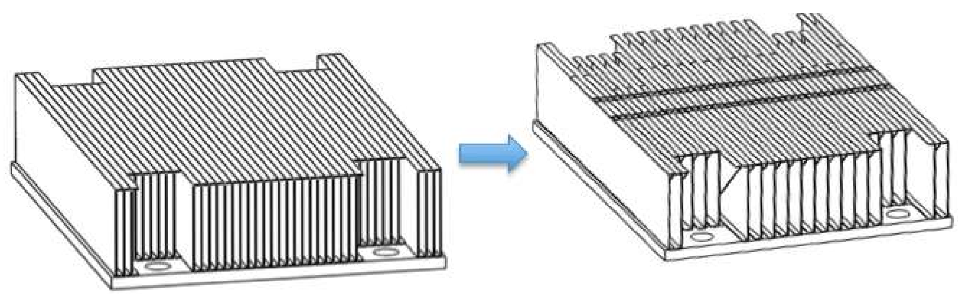
Authors	Year	Geometry	Orientation	Experimental/numerical
Bar-Cohen et al. [1]	2003	Rectangular fins	Vertical	Numerically
Mokheimer [2]	2003	Straight and pin fin with rectangular, convex parabolic, triangular and concave parabolic, and radial fins	Horizontal	Experimentally
Khan et al. [3]	2006	Circular, elliptical, square and rectangular fins	Horizontal	Numerically
Huang et al. [4]	2008	Flat and square pin fin heat sinks	Upward, sideward and downward	Experimentally
Goshayeshi and Ampofo [5]	2009	Rectangular fins	Vertical & horizontal	Numerically
Suryawanshi and Sane [6]	2009	Rectangular fins	Horizontal	Experimentally & numerically
Zhang and Liu [7]	2010	Rectangular fins	Vertical	Numerically & analytically
Fahiminia et al. [8]	2011	Rectangular fins	Vertical	Numerically
Goshayeshi et al. [9]	2011	Rectangular fins	Vertical	Experimentally
Torabi et al. [10]	2013	Rectangular, trapezoidal and concave parabolic	Horizontal	Numerically & analytically
Tari and mehrtash [11]	2013	Rectangular fins	Inclined $\pm 4^\circ \le \theta \le \pm 90^\circ$	Numerically & experimentally
Mehrtash and Tari [12]	2013	Rectangular fins	Inclined $\pm 4^\circ \le \theta \le \pm 90^\circ$	Numerically & experimentally
Tari and Mehrtash [13]	2013	Rectangular fins	Slightly inclined: $\theta = \pm 60^\circ$ to $\pm 90^\circ$	Experimentally & numerically
Kim et al. [14]	2013	Cylindrical heat sink	Horizontal	Experimentally



(a) Rectangular fin (b) Trapezoidal fin (c) Inverted trapezoidal fin



Approach I & II

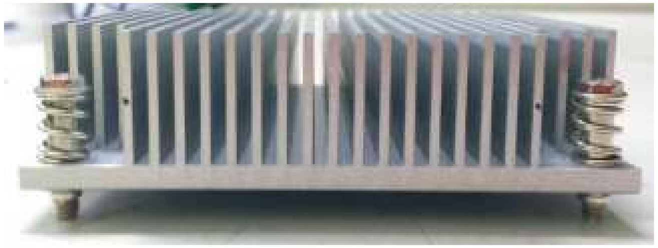


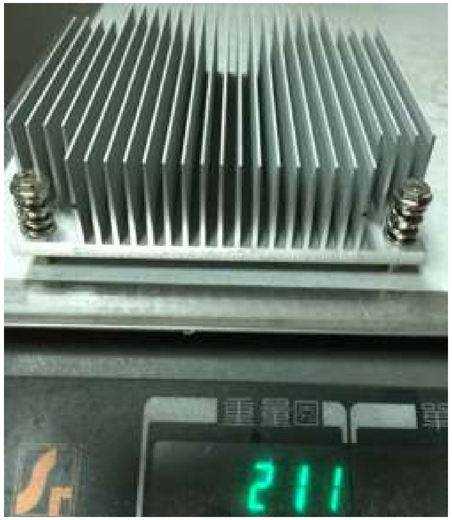
Approach III

Chen, H.L., and Wang, C.C., (2016), "Analytical Analysis and Experimental Verification of Trapezoidal Fin for Assessment of Heat Sink Performance and Material Saving," *Applied Thermal Engineering*, Vol. 98, pp. 203-212.

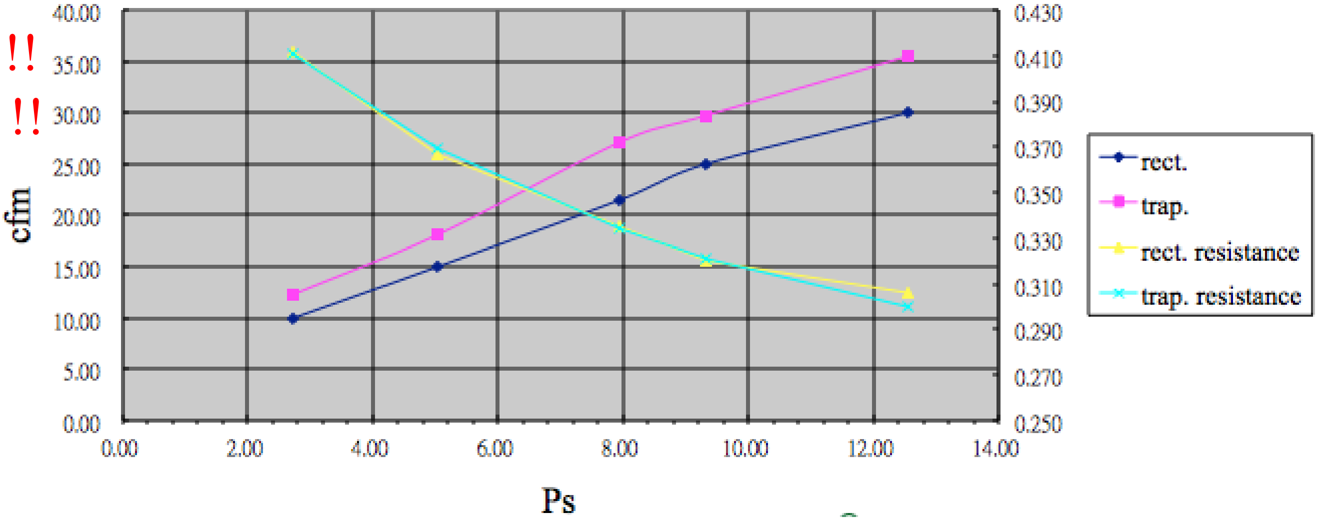
APPLICATION CASE

r_t =0.5, weight 25%↓↓ , performance 2.7%↓



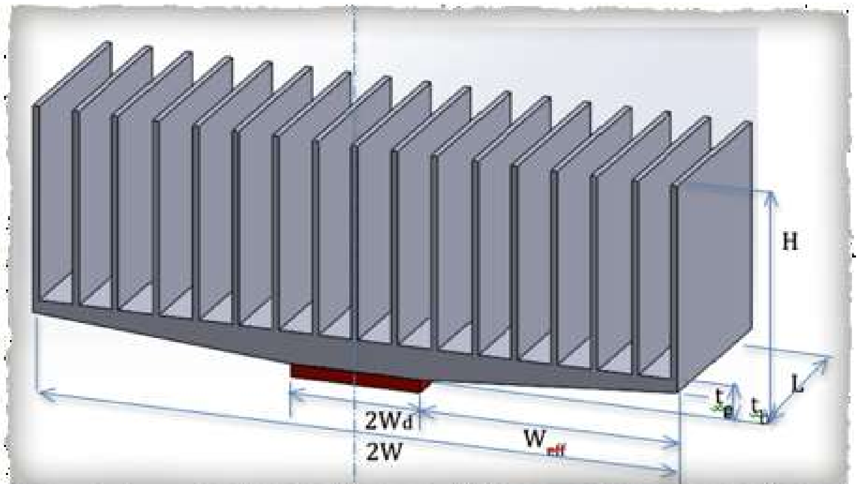


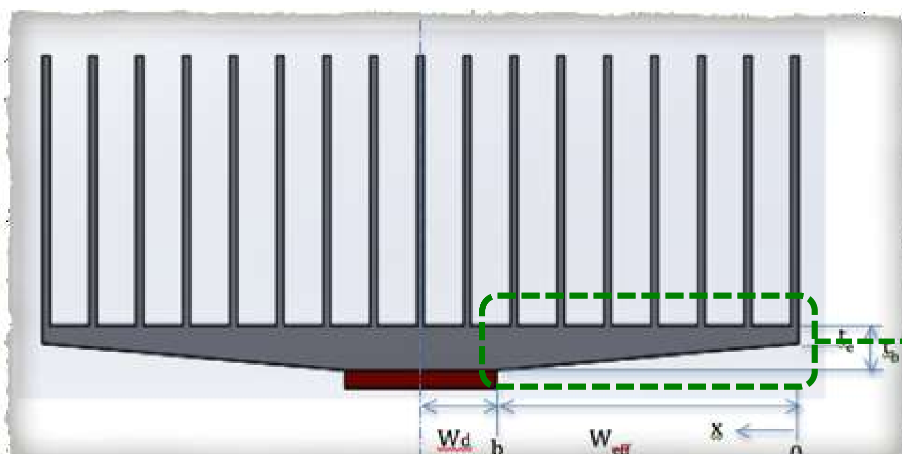
- Weight down 22%↓ !!
- Performance down 0% !!
- CFM gains 18-20%!!



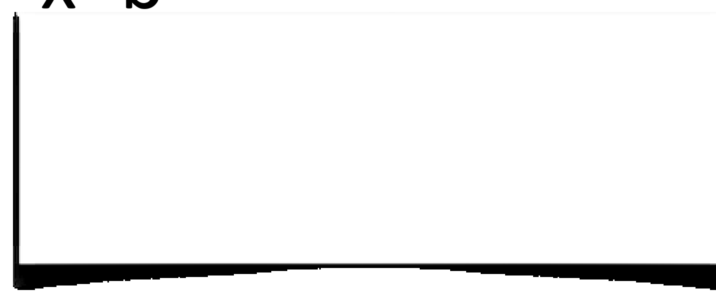
Chen, H.L., and Wang, C.C., (2016), "Analytical Analysis and Experimental Verification of Trapezoidal Fin for Assessment of Heat Sink Performance and Material Saving," *Applied Thermal Engineering*, Vol. 98, pp. 203-212.

Schematics of heat sink – saving of base area



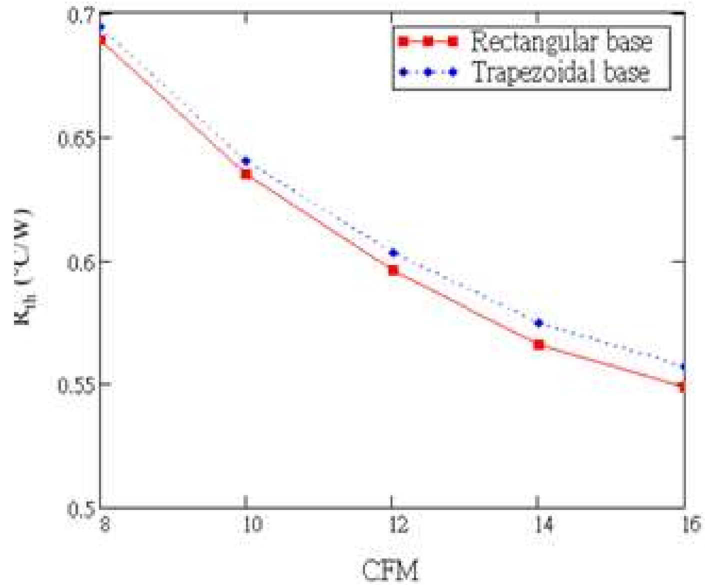


- Base edge is x=0 position
- Chip edge is x=b



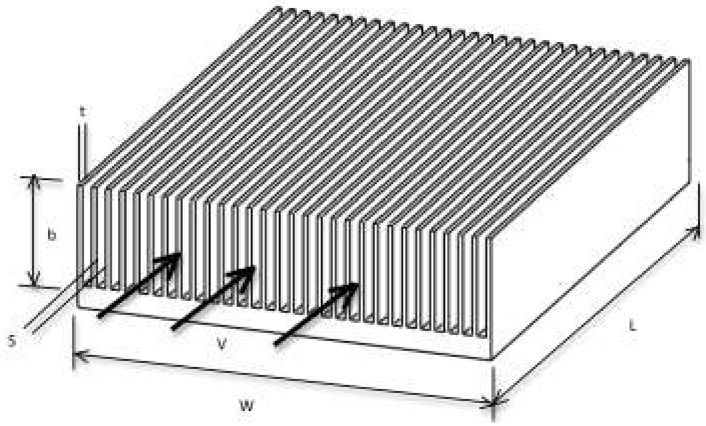
length for material saving study

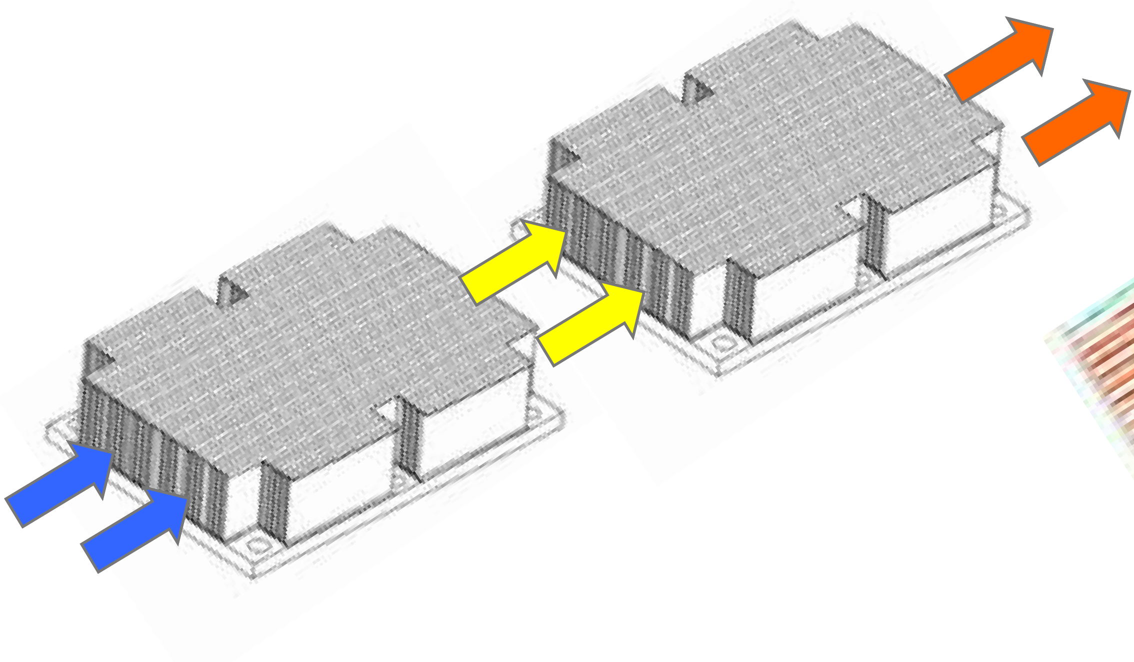
Base weight reductions

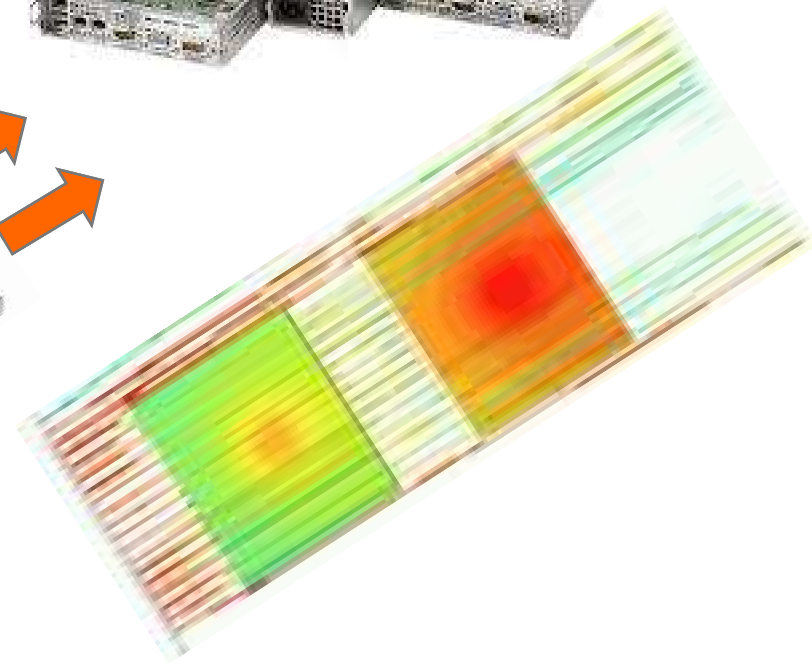


Chen, H.L., and Wang, C.C., (2017), "Analytical analysis and experimental verification of weight saving with heat sink having trapezoidal base," *Applied Thermal Engineering*, in reveiew.

Plate fin heat sink used for data center server

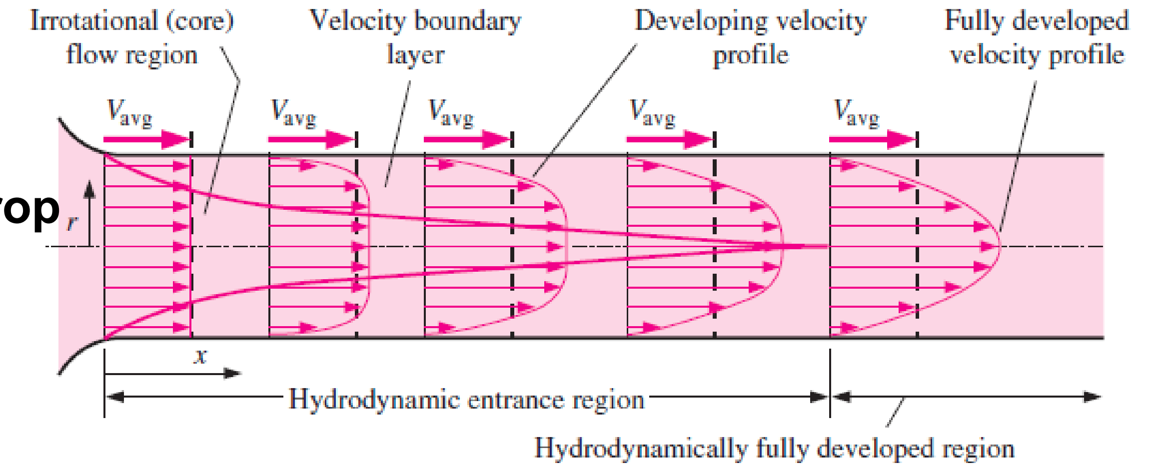


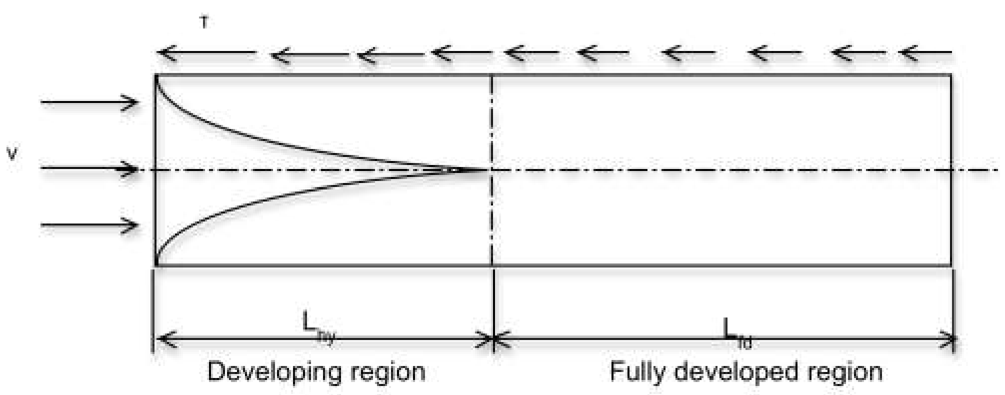


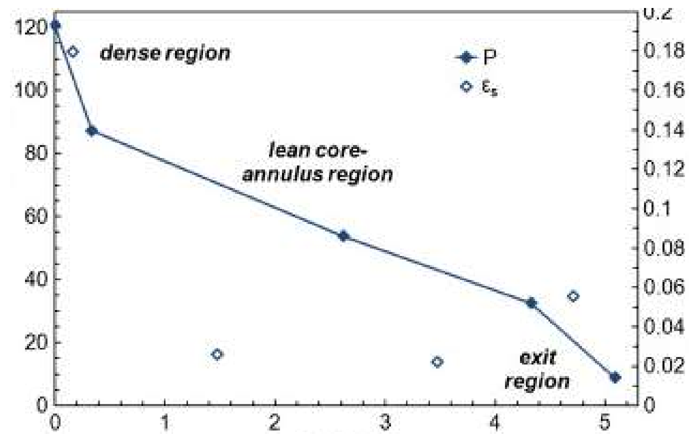


Pressure Drops of fin module

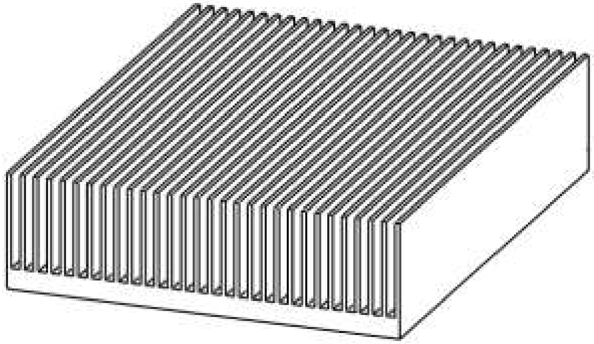
- **Contraction pressure drop**
- **Developing pressure drop**
- **Fully developed pressure drop**
- **Expansion pressure drop**
- **Acceleration pressure drop**

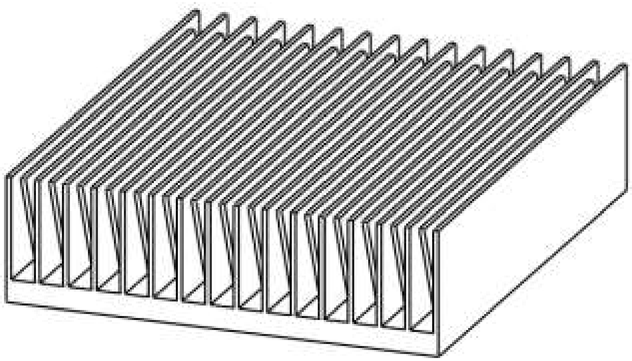




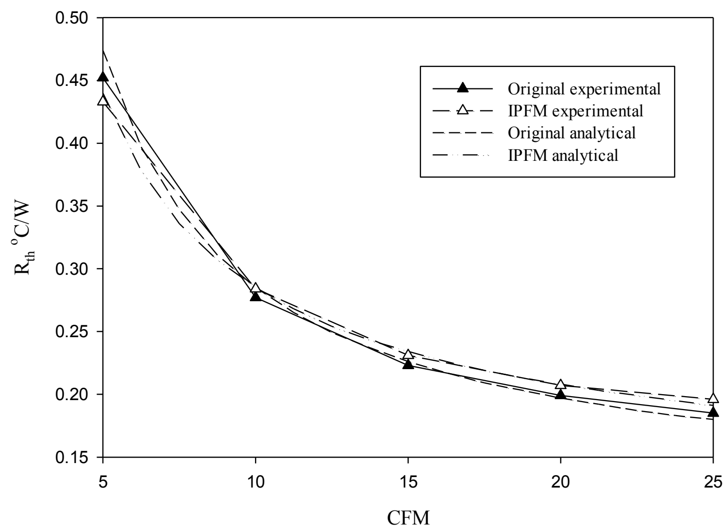


Original vs. IPFM design

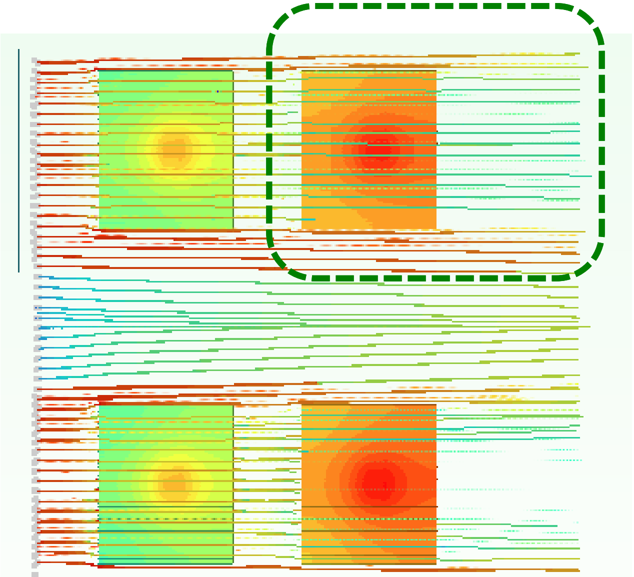




Comparison of analytical and experimental results



Less ΔP drop, More airflow, Better performance!



Uniform gap

Non-uniform gap

Chen, H.L., and Wang, C.C., (2017), "Analytical analysis and Experimental Verification of Interleaved Parallelogram Heat Sink," Applied Thermal Engineering, Vol. 112, pp. 739-749.

Some Typical Cabinets Designs

ASHRAE Transactions, 2005, Vol. 111, pt. 2, pp. 715-724

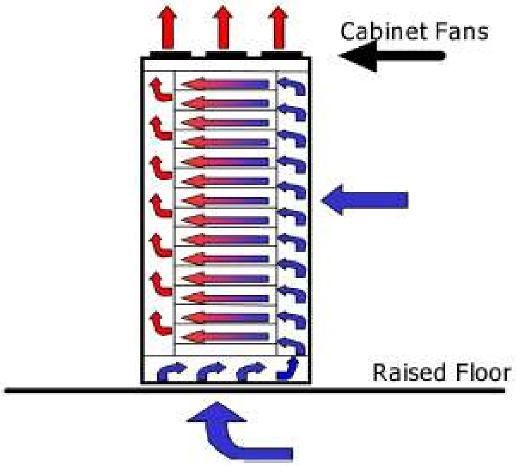


Figure 2 *Fans on top.*

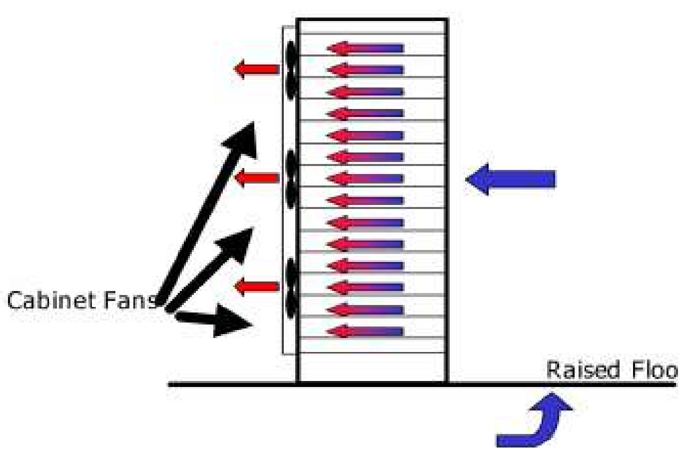


Figure 4 *Fans on rear (horizontal discharge).*

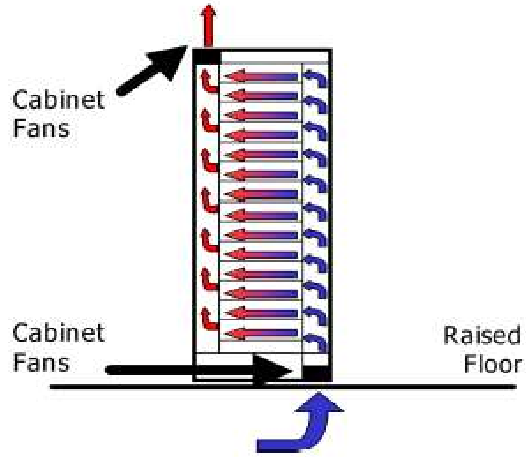


Figure 6 *Fans on bottom and top.*

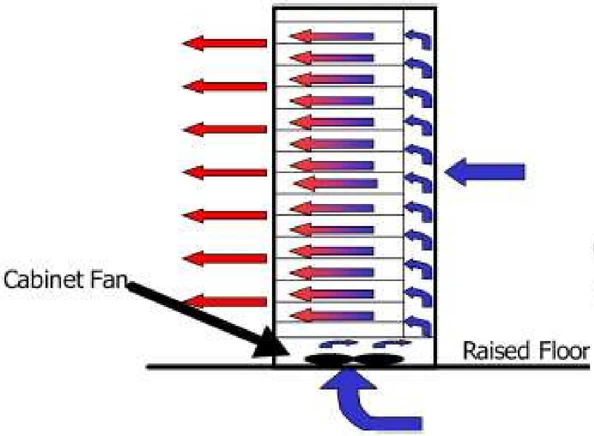


Figure 3 *Fans on bottom.*

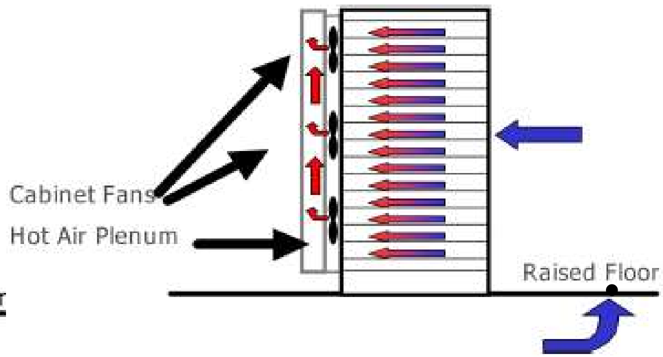


Figure 5 *Fans on rear (vertical discharge).*

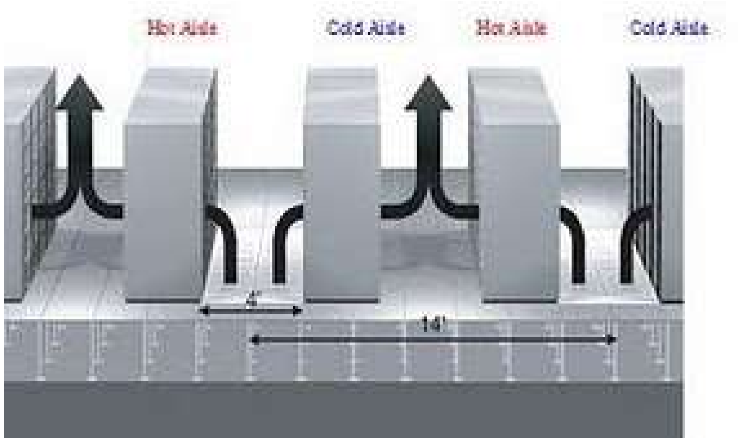
- Cabinet fan in Figures 3 and 4 lend themselves to the “hot aisle/cold aisle” solution and were designed with that concept in mind.

  Cabinet arrangements in Figures 2, 5, and 6 lend themselves to the use of the ceiling plenum space as a return air plenum.

Physical design of data center systems

(IBM J. RES. & DEV. VOL. 49, 2005, pp. 709-723)

- Layout of computer rack equipment
  - Data centers are typically arranged into hot and cold aisles.
- Air distribution configurations
  - Hot rack exhaust air recirculation—A major cooling problem.



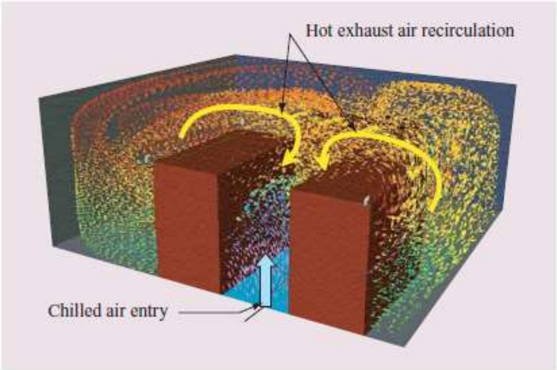
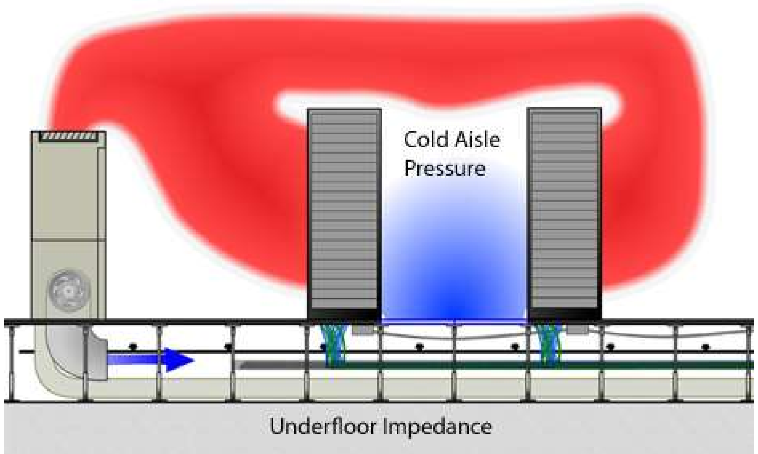


Figure 5

Computer-based simulation of hot-air recirculation in a raised-floor data center.

Airflow Management



Typically, the coolant temperature is maintained in the range of 12–14 °C, the cool air leaving the CRACs is in the range of 16–20 °C, and the cold aisle is about 18–22 °C.

Classes (a)	Equipment Environmental Specifications							
	Product Operations (b)(c)					Product Power Off (c) (d)		
	Dry-Bulb Temperature (°C) (e) (g)	Humidity Range, non-Condensing (h) (i)	Maximum Dew Point (°C)	Maximum Elevation (m)	Maximum Rate of Change(°C/hr) (f)	Dry-Bulb Temperature (°C)	Relative Humidity (%)	Maximum Dew Point (°C)
Recommended (Applies to all A classes; individual data centers can choose to expand this range based upon the analysis described in this document)								
A1 to A4	18 to 27	5.5ºC DP to 60% RH and 15ºC DP						
Allowable								
A1	15 to 32	20% to 80% RH	17	3050	5/20	5 to 45	8 to 80	27
A2	10 to 35	20% to 80% RH	21	3050	5/20	5 to 45	8 to 80	27
A3	5 to 40	-12°C DP & 8% RH to 85% RH	24	3050	5/20	5 to 45	8 to 85	27
A4	5 to 45	-12°C DP & 8% RH to 90% RH	24	3050	5/20	5 to 45	8 to 90	27
B	5 to 35	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29
C	5 to 40	8% RH to 80% RH	28	3050	NA	5 to 45	8 to 80	29

Arguments for increased air temperatures:

Journal of Electronic Packaging, MARCH 2011, Vol. 133 / 011004-1

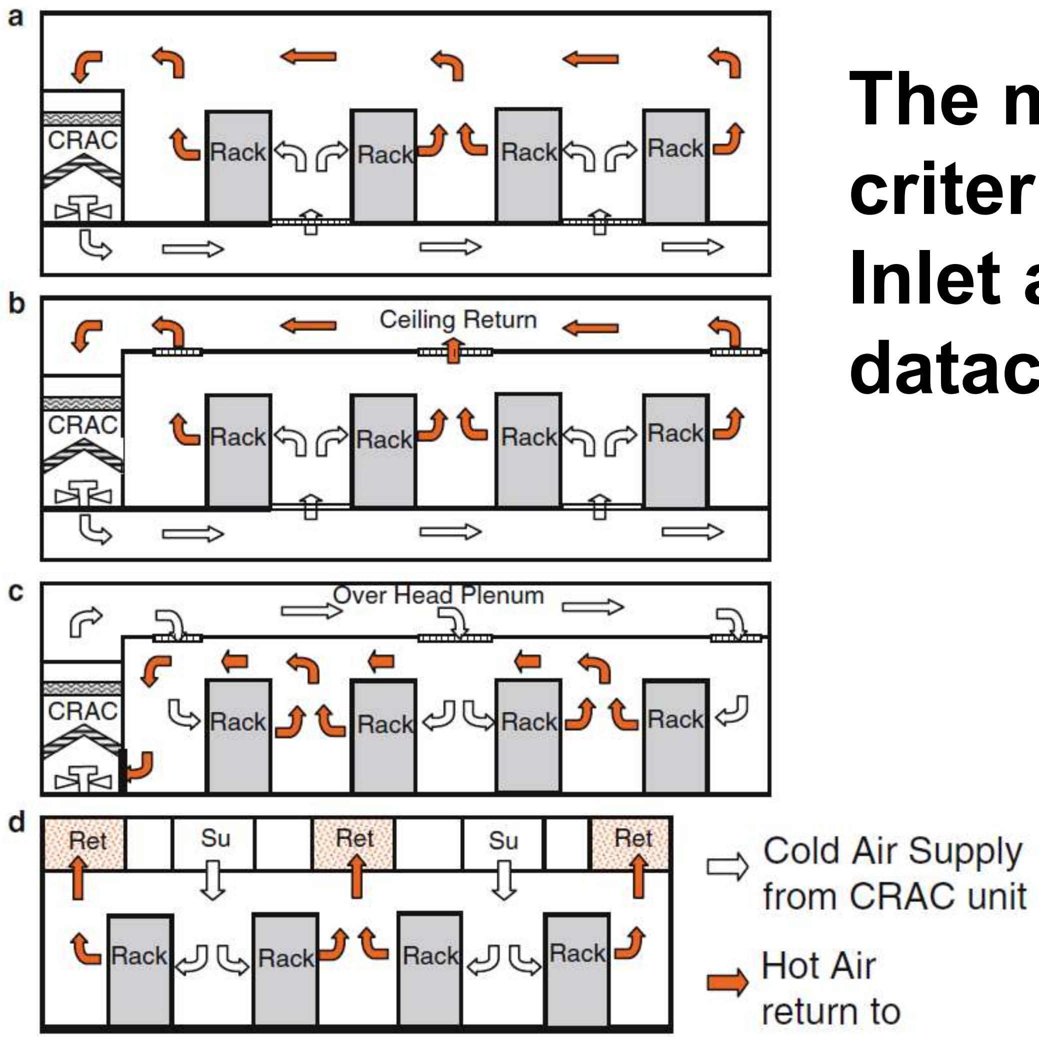
- **estimates predict that 4–5% of data center energy costs could be saved for every 1°C increase** in server inlet temperature
- **higher temperature settings could allow more free-cooling**
- servers have previously been deployed in high temperature environments with no failures.

Arguments against increased air temperatures

Journal of Electronic Packaging MARCH 2011, Vol. 133 / 011004-1

– Side effects of Raising inlet temperature
  - **additional energy consumption in other components.**
  - **costs of thermal-related equipment failures**
  - **impact server performance and service life.**
  - **require more frequent server shutdown where cooling system failure occurs.**

Raised floor or overhead with cooling in Plenum Level

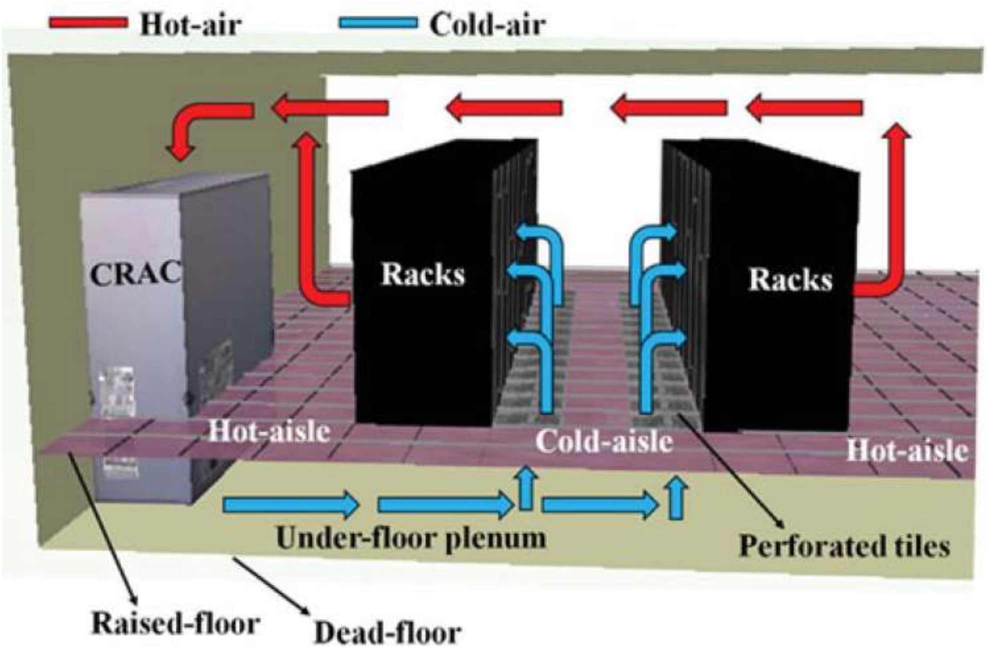


The most important design criterion in a data center: Inlet air condition to the datacom equipment,

Classes (a)		
	Product	
	Dry-Bulb Temperature (°C) (e) (g)	Humidity Range, non-Condensing (h) (i)
Recommended (Applies to all A cl		
A1 to A4	18 to 27	5.5ºC DP to 60% RH and 15ºC DP

Typical Hot/Cold Aisle with Raised Floor configuration

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

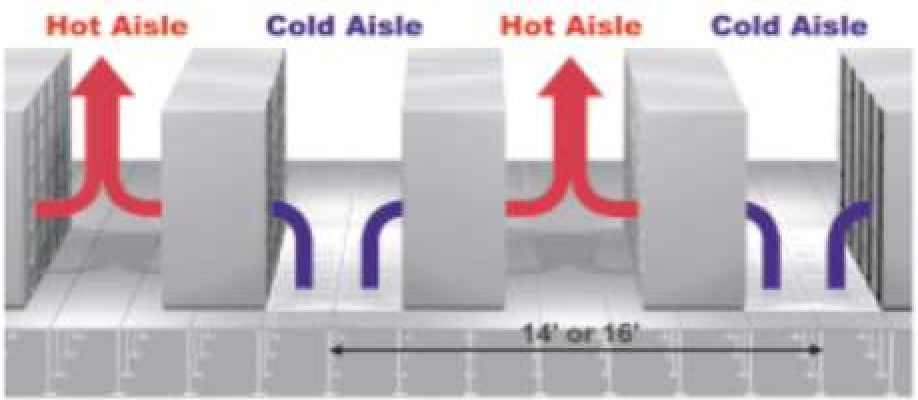


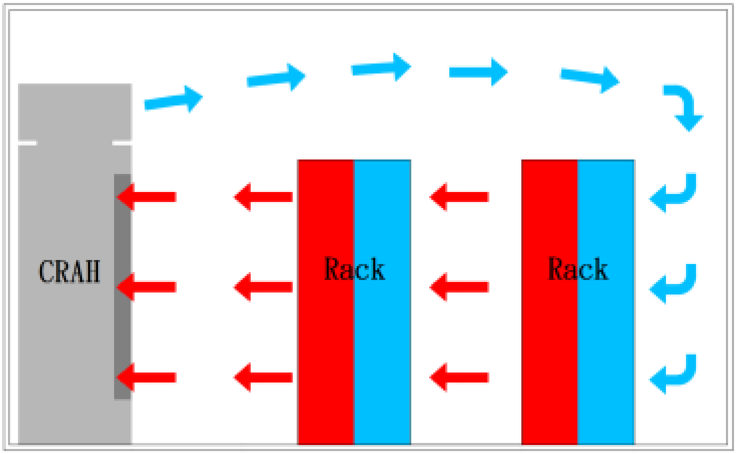
Hot / Cold Aisle

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.

Raised Floor & Modified Design

- A cold aisle is defined as having perforated floor tiles that allow cooling air to come up from the plenum under the raised floor, and a hot aisle has no perforated tiles.





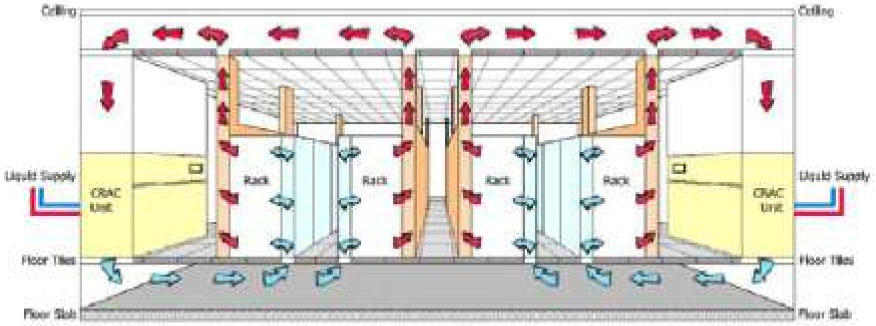


Figure 4-8 Raised floor implementation using inlet and outlet plenums/ducts integral to the rack.

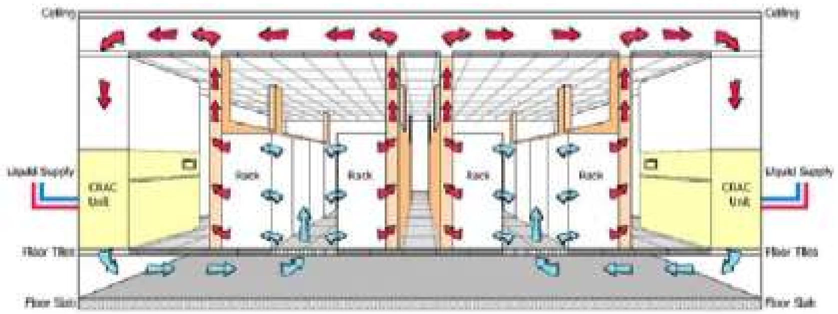


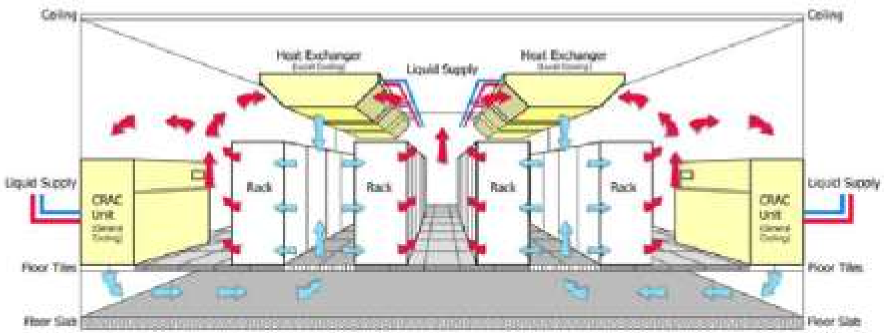
Figure 4-9 Raised floor implementation using outlet plenums/ducts integral to the rack.

R. F. Sullivan, "Alternating cold and hot aisles provides more reliable cooling for server farms," The Uptime Institute, 2000.

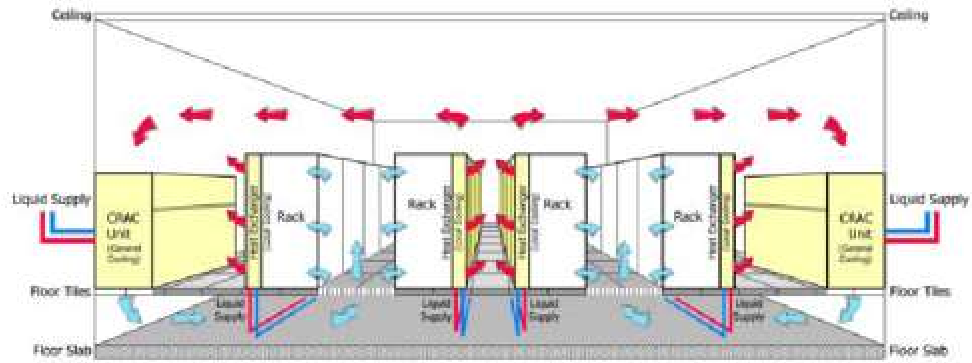
Local Distribution Design

Datacom Equipment Power Trends and Cooling Applications, 2nd ed. ASHRAE, 2012

- Introduce cold air to the rack as close as possible

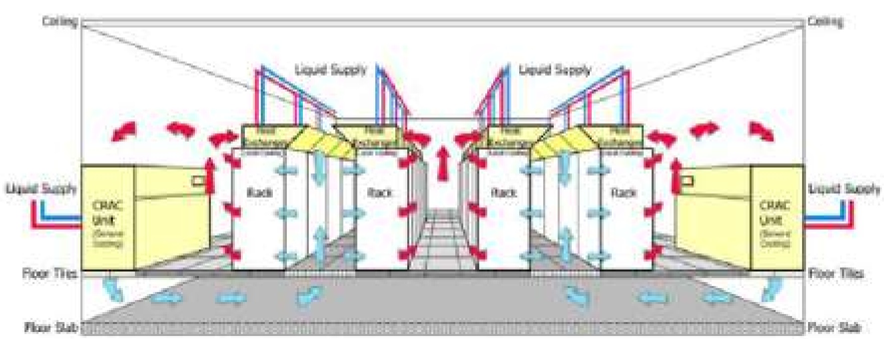


Local cooling distribution using overhead cooling units mounted to the ceiling.

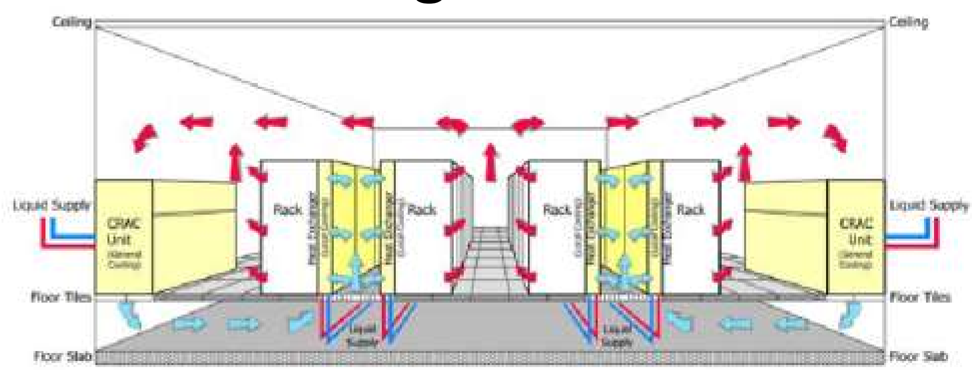


Local cooling via integral rack cooling units on the exhaust side of the rack.

- Reduce poor air distribution and mixing



Local cooling distribution using overhead cooling units mounted to the rack.

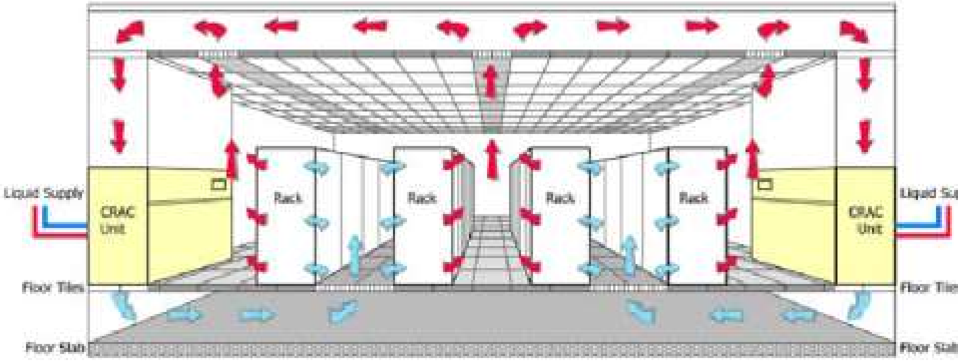


Local cooling via integral rack cooling units on the inlet side of the rack.

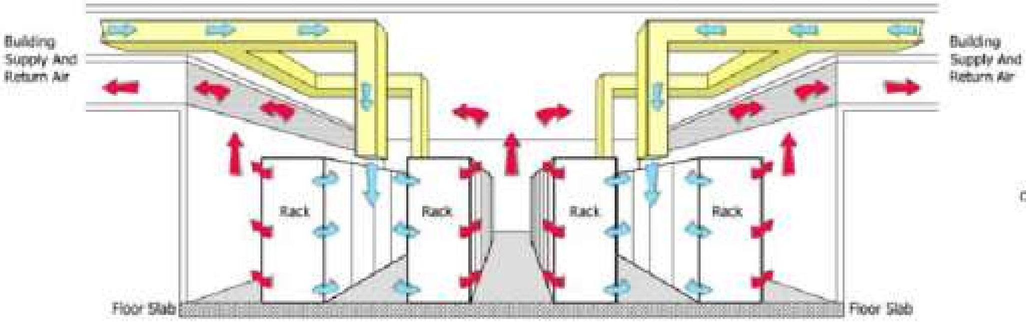
- Cooling @ exhaust is preferred to eliminate condensate carryover

Overhead Design

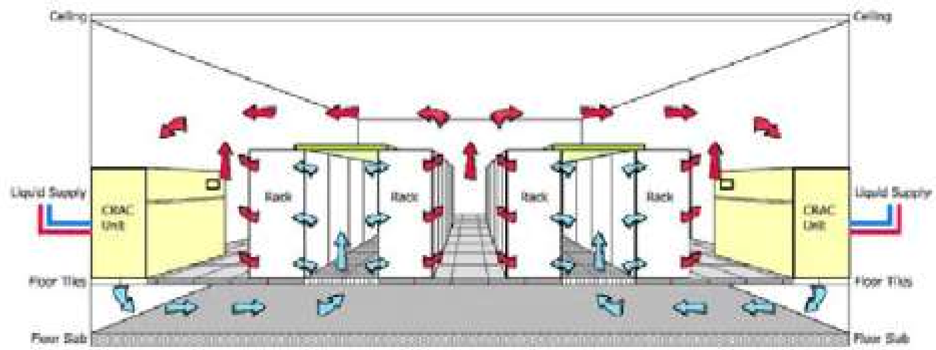
- Overhead design provide a higher static pressure which normally give rise to a better air flow distribution.



Raised floor implementation using a dropped ceiling as a hot air return plenum.



Overhead cooling distribution commonly found in central environments.



Raised floor implementation using baffles to limit hot-aisle/cold-aisle "mixing."

Datacom Equipment Power Trends and Cooling Applications, 2nd ed.
ASHRAE, 2012

Some results concerning the raised floor design..

Hot air recirculation, cold air bypass, negative pressure, flow distribution, geometric influence..

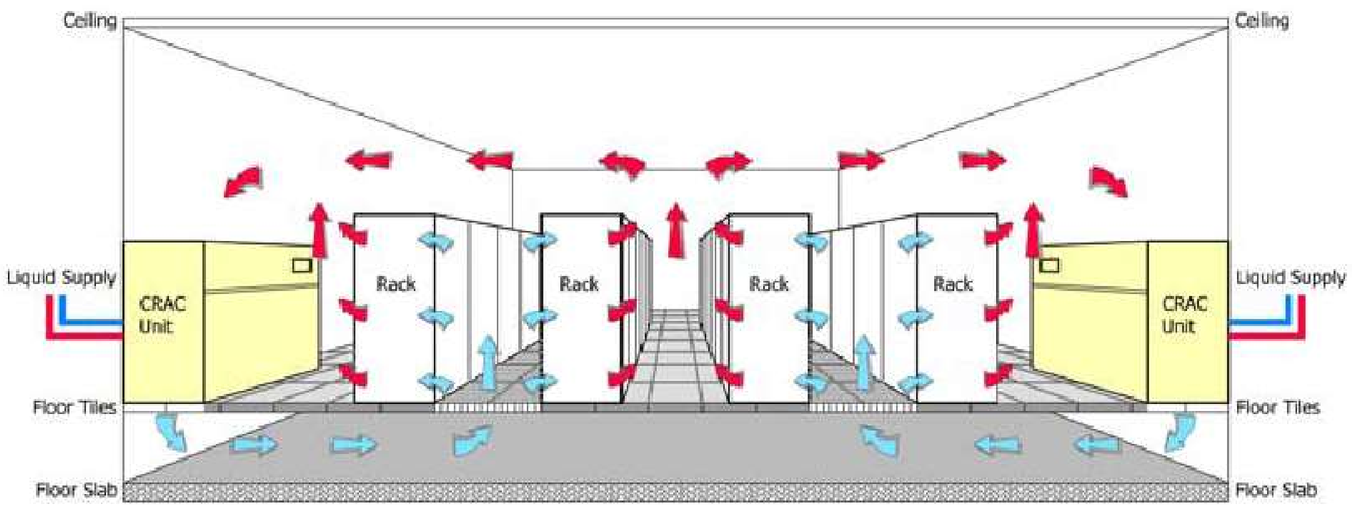


Figure 4-2 Raised floor implementation most commonly found in data centers today using CRAC units.

Data center air stream

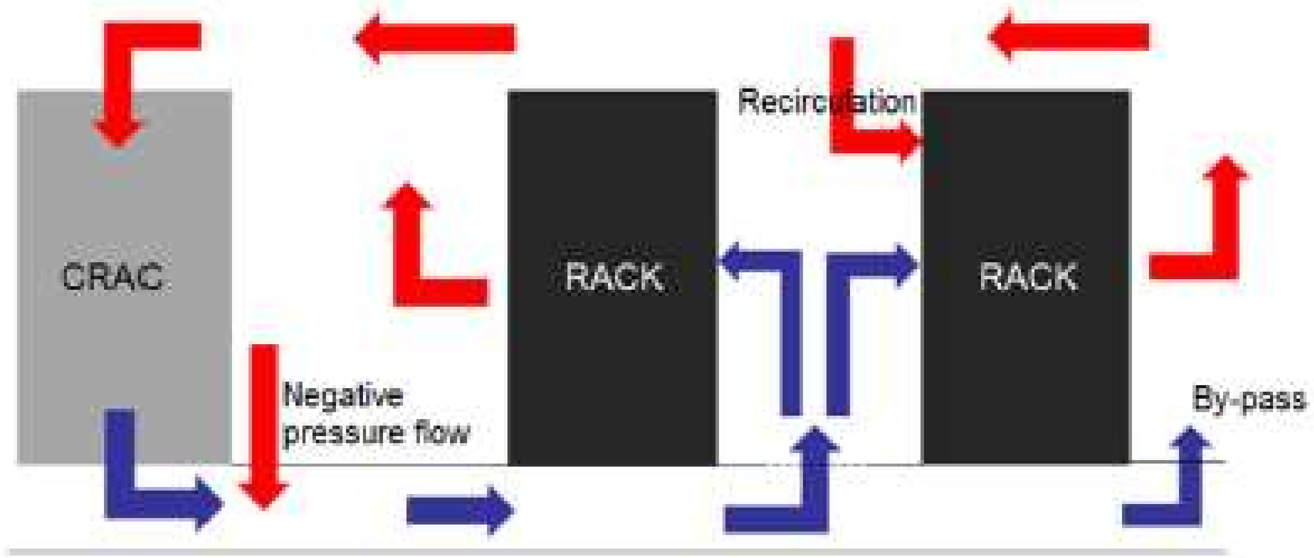
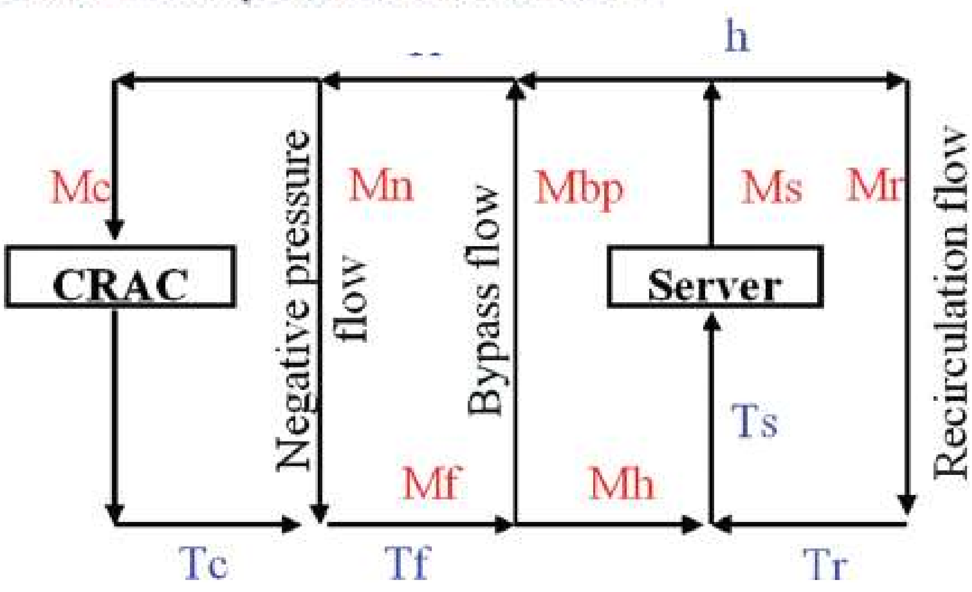


Fig. 6. Air flow circulation with standard problems (by-pass, recirculation, negative pressure flow) in an air cooled data centre. Blue lines represent cold air while red lines represent hot air.

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.)



Hot air recirculation

Journal of Electronic Packaging, MARCH 2011, Vol. 133 / 011004-1

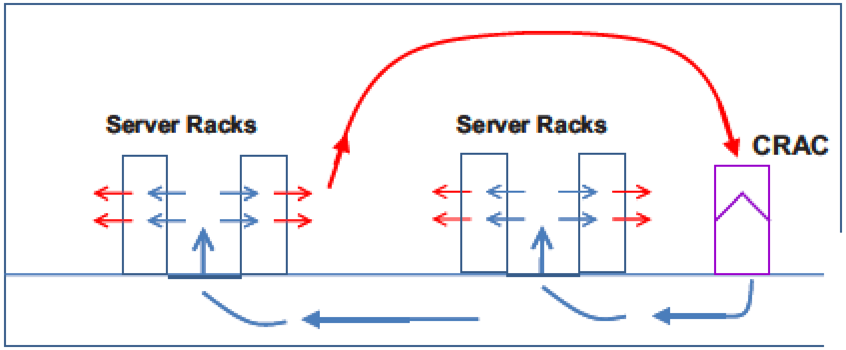


Fig. 1 A raised-floor data center

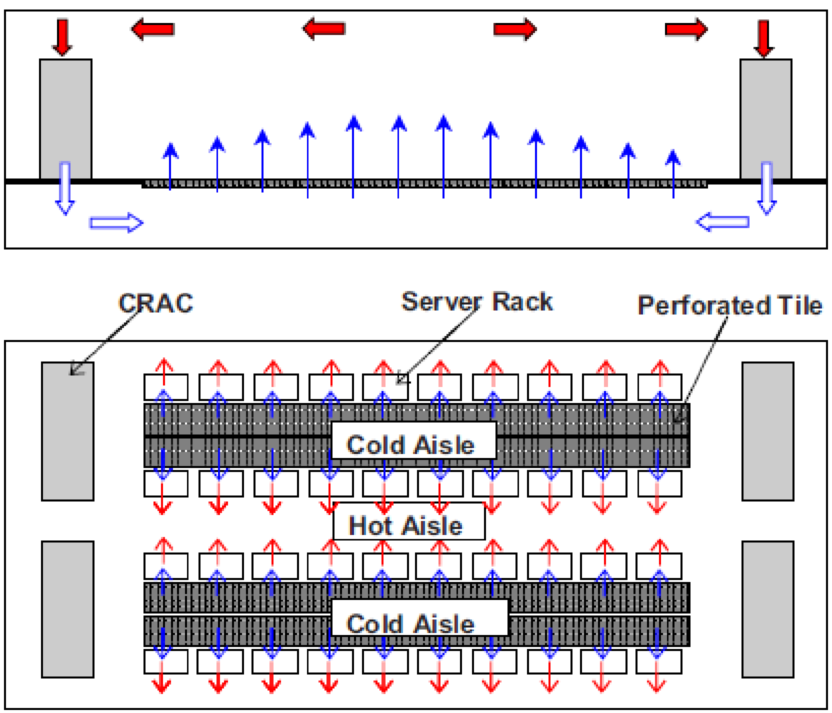


Fig. 2 The hot aisle/cold aisle arrangement

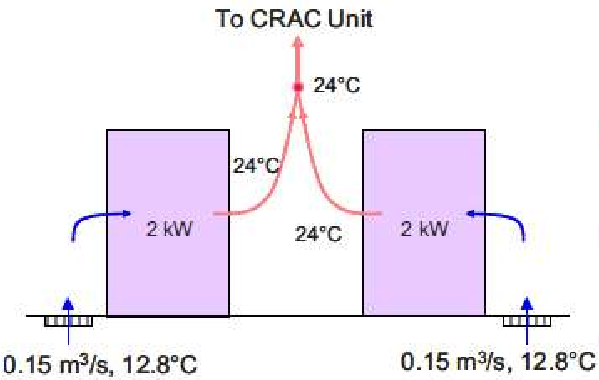


Fig. 4 Required airflow supplied

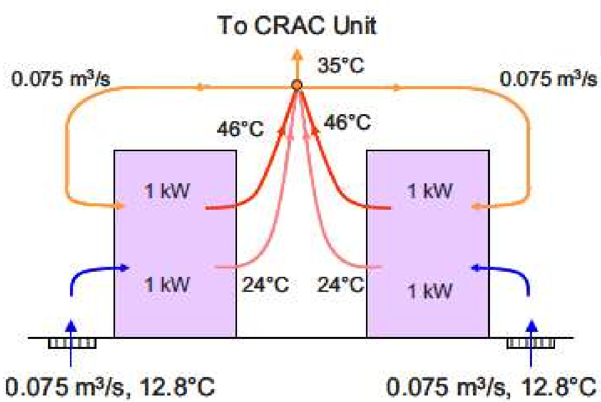
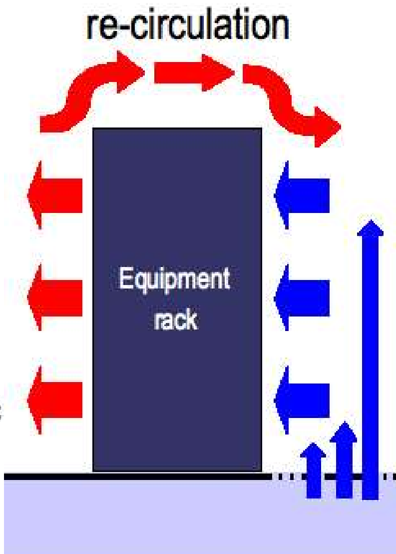


Fig. 5 Insufficient airflow



End Effects

- Insufficient cooling occurs near and far away from the CRAC.

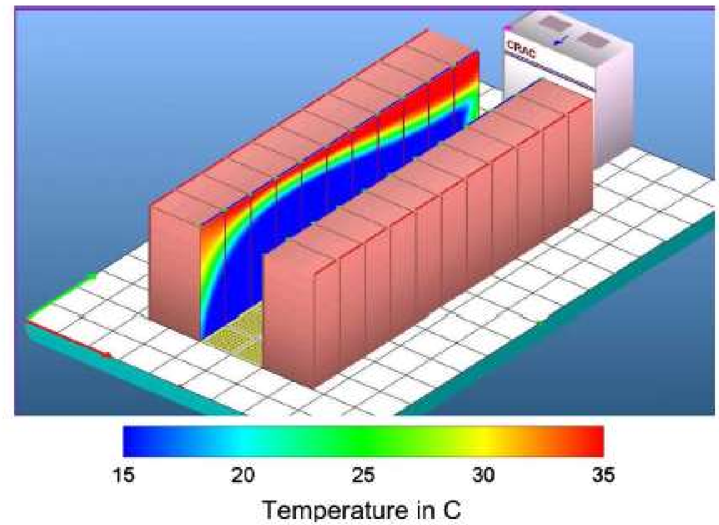


Fig. 29 Temperature distribution on the inlet faces of the racks (insufficient cooling airflow)

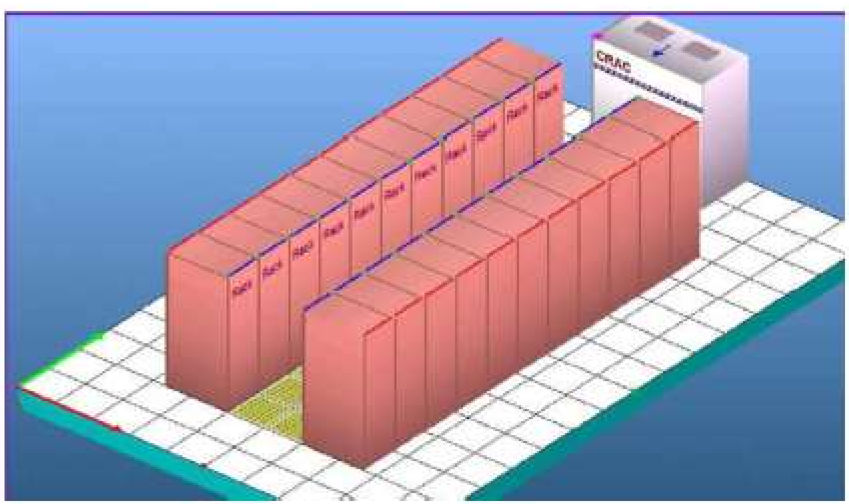


Fig. 28 A simple data center model with one CRAC, several racks, and perforated tiles (insufficient cooling airflow)

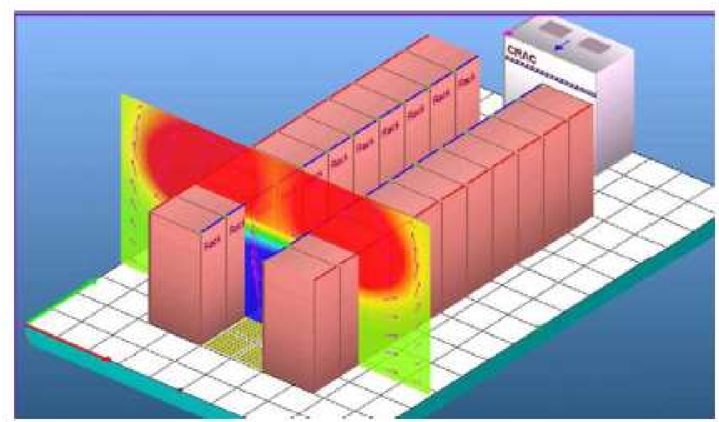


Fig. 30 Temperature distribution and velocity vectors on a plane (insufficient cooling airflow)

IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS, VOL. 19, pp. 1458-1472, 2008

End effects (Conti..)

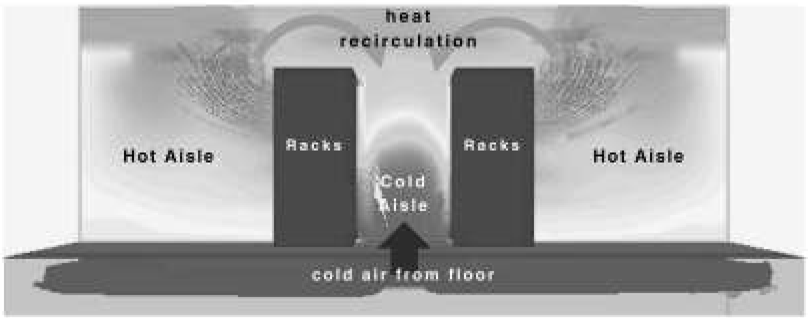


Fig. 1. Demonstration of heat recirculation: heated air in the hot aisle loops around the equipment to enter the air inlets.

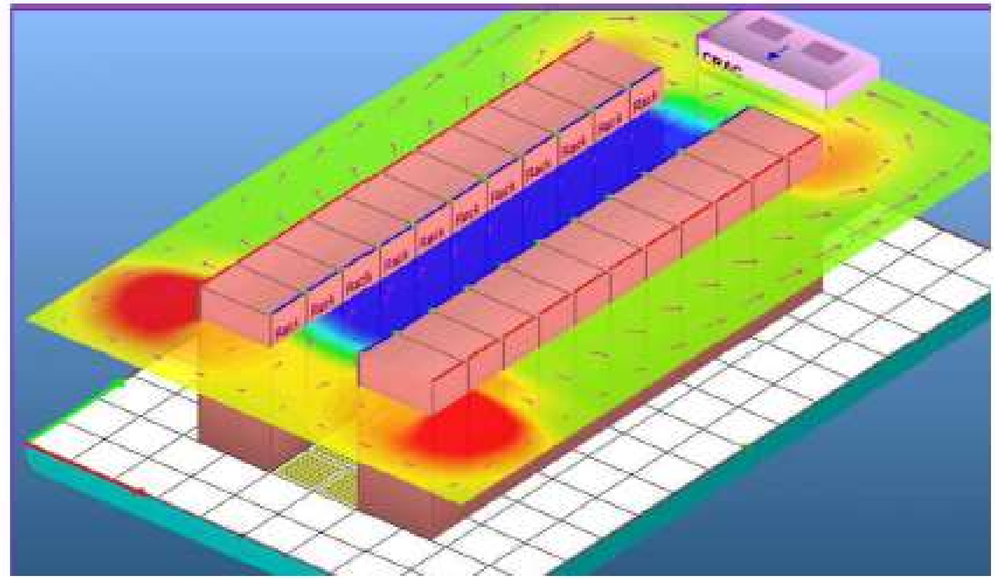
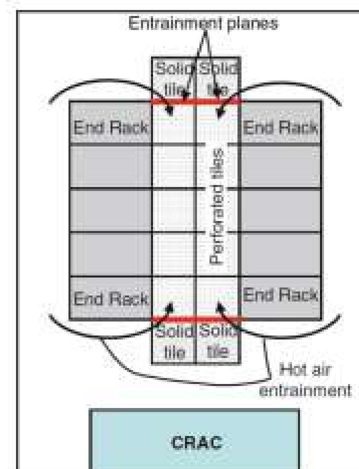


Fig. 32 Temperature distribution and velocity vectors on a horizontal plane



- The former is due to mal-distribution near the CRAC location.
- The latter is due to the hot exhaust circulation (heat recirculation).

IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS, VOL. 19, pp. 1458-1472, 2008

Base Case

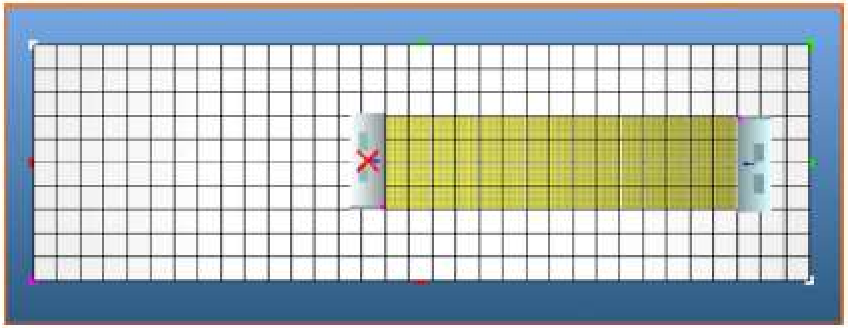


Fig. 8 Layout for a small test data center

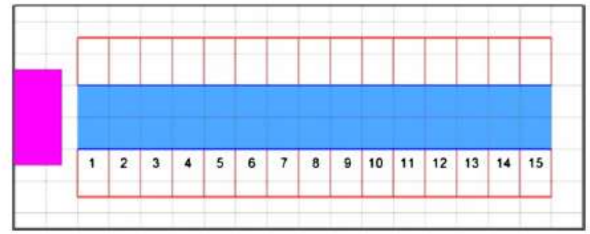


Fig. 12 The base case

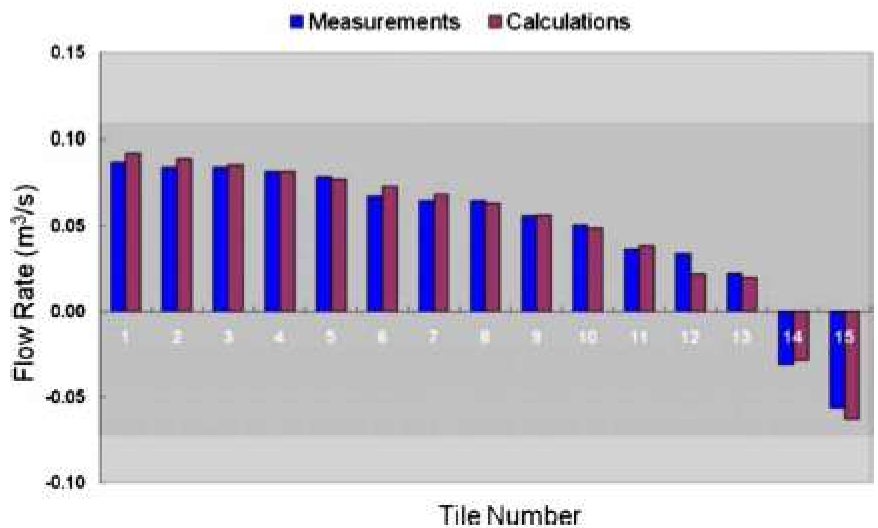


Fig. 9 Comparison of measured and calculated airflow rates (the tiles are numbered from left to right)

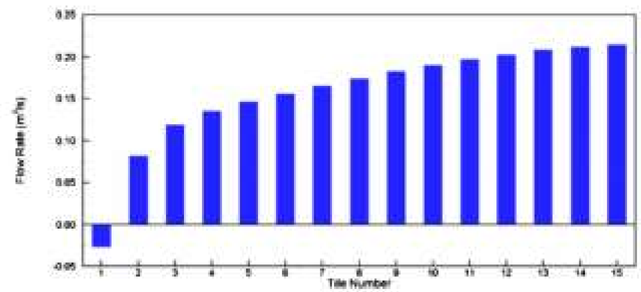


Fig. 13 Flow rates through perforated tiles for the base case

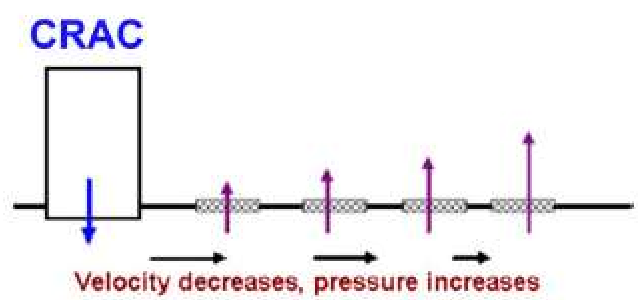


Fig. 7 Maldistribution of airflow and its cause

Effect of the Plenum Height

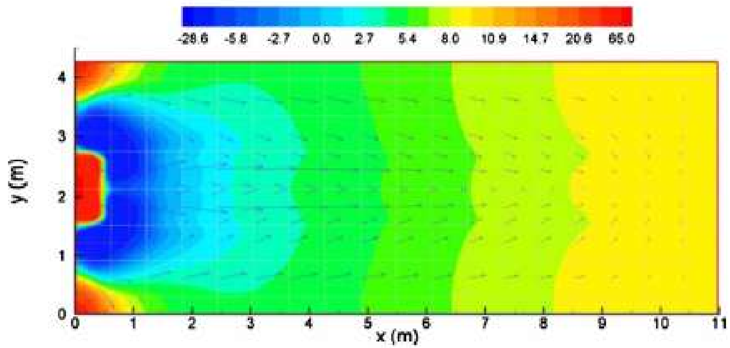


Fig. 14 Pressure distribution and velocity vectors under the raised floor for the base case (plenum height=12 in. (0.3048 m); the pressure values are in Pa)

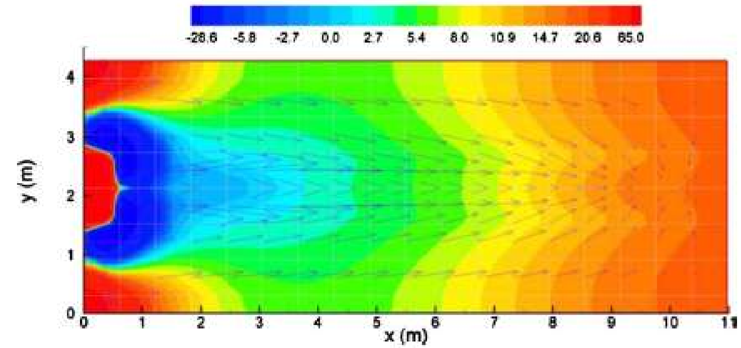


Fig. 16 Pressure distribution and velocity vectors under the raised floor for plenum height=6 in. (0.1524 m) (the pressure values are in Pa)

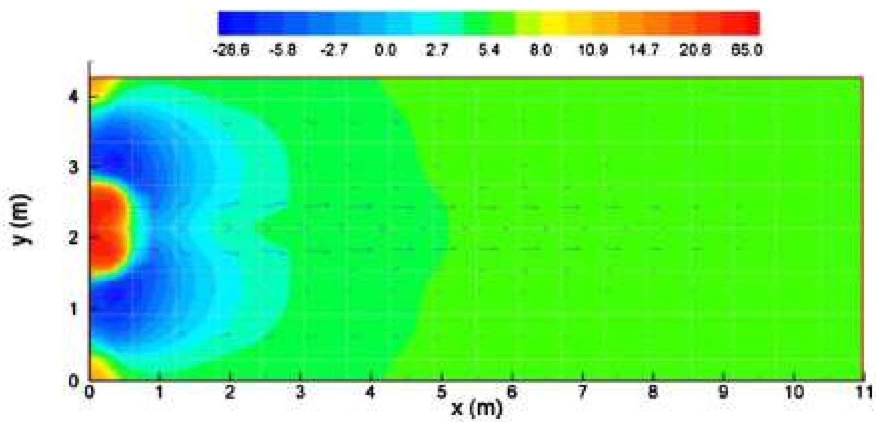


Fig. 17 Pressure distribution and velocity vectors under the raised floor for plenum height=24 in. (0.6096 m) (the pressure values are in Pa)

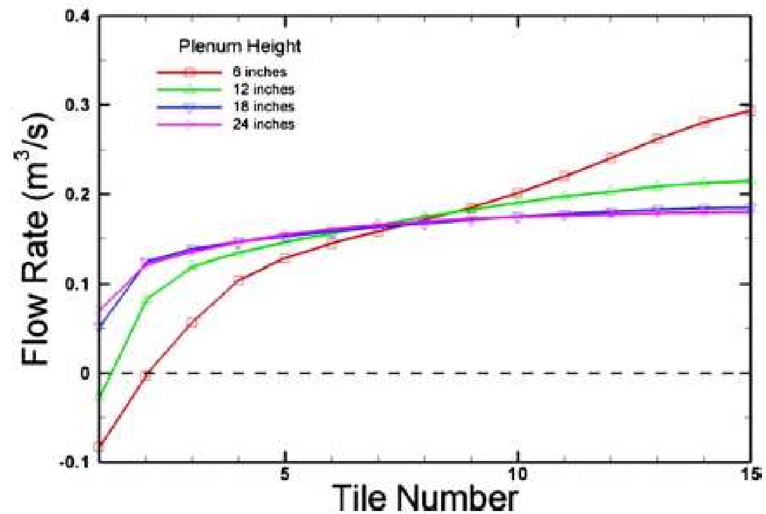


Fig. 15 Effect of plenum height on the airflow distribution

Raised Floor Plenum Height

Suhas V. Patankar , Airflow and Cooling in a Data Center
Journal of Heat Transfer, JULY 2010, Vol. 132 / 073001-1

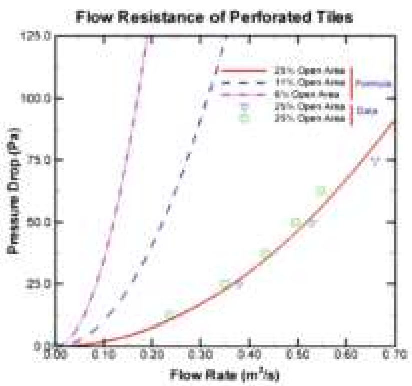
- For low raised floors (6-12 in. [0.15-0.3 m]), **do not place datacom equipment close to CRAC units since low airflow or reverse flow can occur from the perforated tiles**.
- **Airflow uniformity can be made available by varying percent openings of perforated floor.**
- Partitions can be placed underneath the raised floor to direct air into the desired areas.
- It is suggested that raised floors should allow a free flow height of at least 24 in. (0.61 m); that is, if piping and cabling take up 6 in. (0.152 m) then the raised floor height should be 30 in, (0,76 m). A large underfloor depth of 24 in. (0.61 m) was also recommended.

Factors Affecting the Airflow Distribution

Journal of Electronic Packaging, MARCH 2011, Vol. 133 / 011004-1

- Relationship Between the Flow Field in the Plenum and Flow Rates Through Perforated Tiles.
  - **the flow rate through a perforated tile depends on**
    - **the pressure drop across the tile**, that is, the difference between the plenum pressure just below the tile and the ambient pressure above the raised floor.
    - **plenum height**
    - **open area of perforated tiles**

Patankar SV (2010) Airflow and cooling in a data center. J Heat Transfer 132:073001



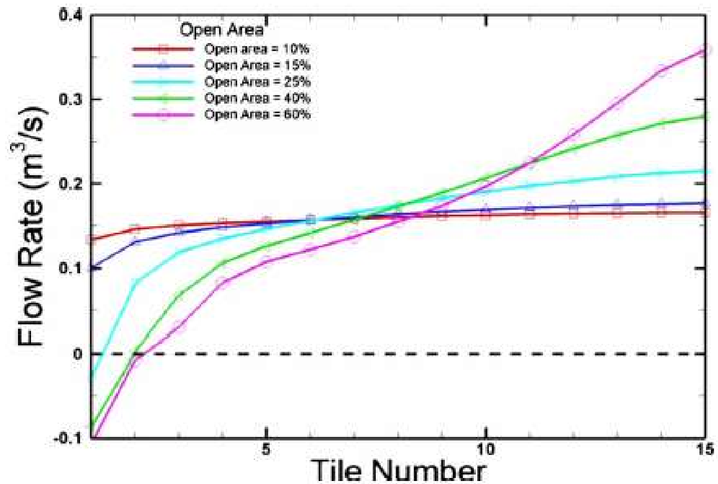


Fig. 18 Effect of open area of perforated tiles on the airflow distribution

Variable opening vs. uniform opening

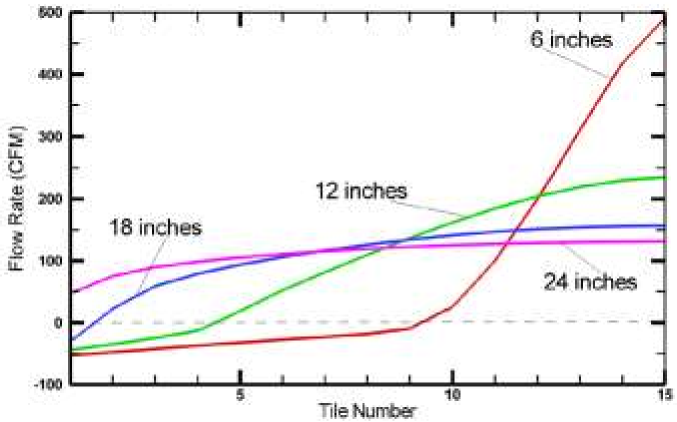
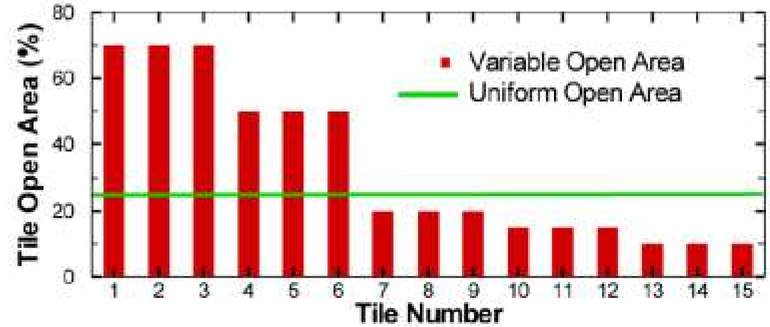
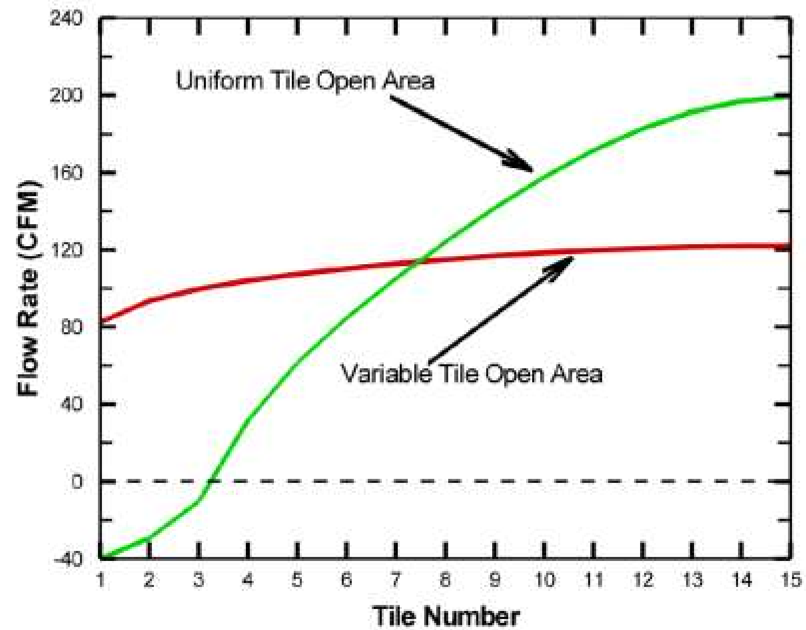


Figure 4 Effect of raised-floor height on airflow rates.





Patankar SV, Karki KC (2004) “Distribution of cooling airflow in a raised-floor data center,” ASHRAE Transaction 2004,110(2):599–603

Raised Floor Design

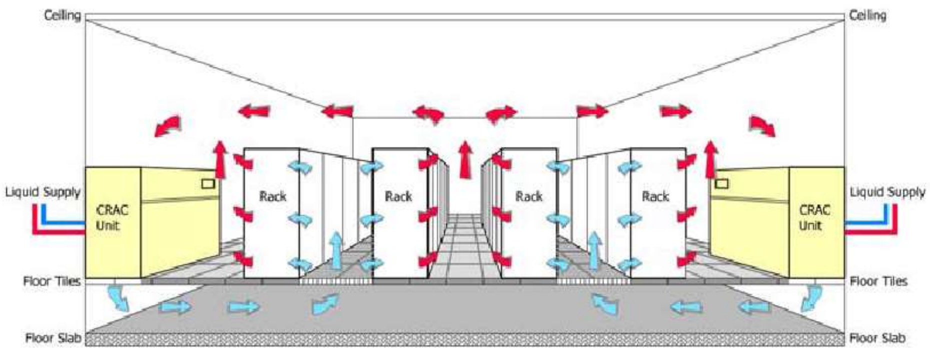


Figure 4-2 Raised floor implementation most commonly found in data centers today using CRAC units.

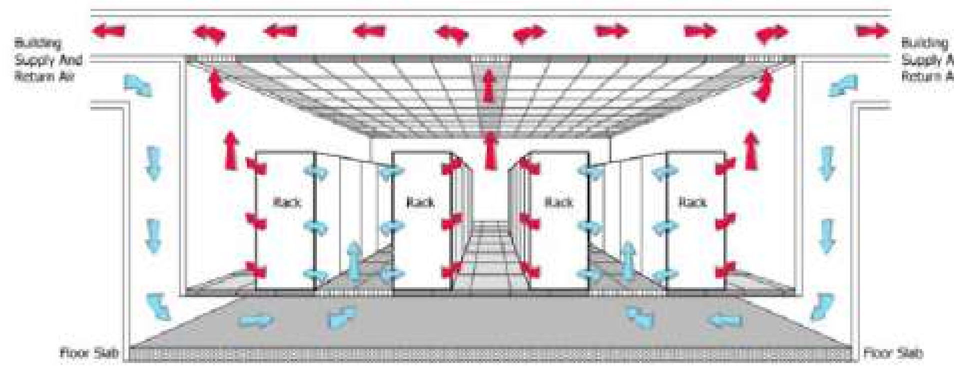


Figure 4-3 Raised floor implementation using building air from a central plant

High Ceiling

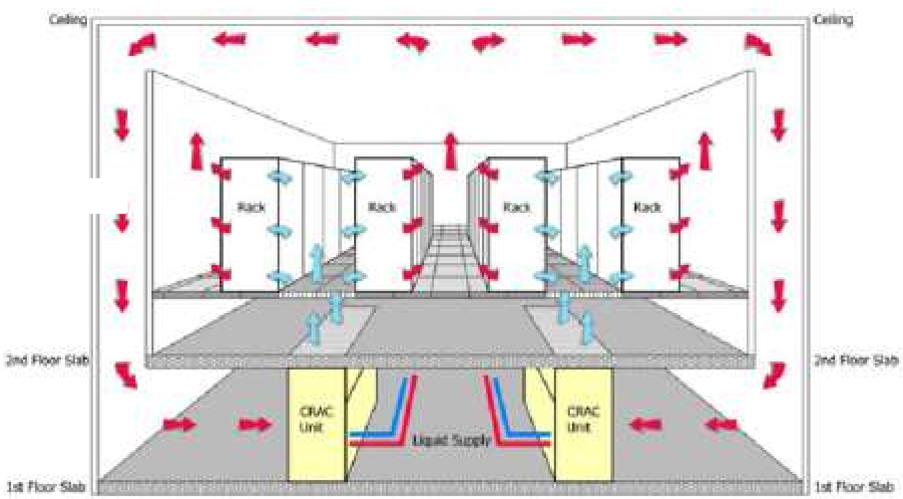


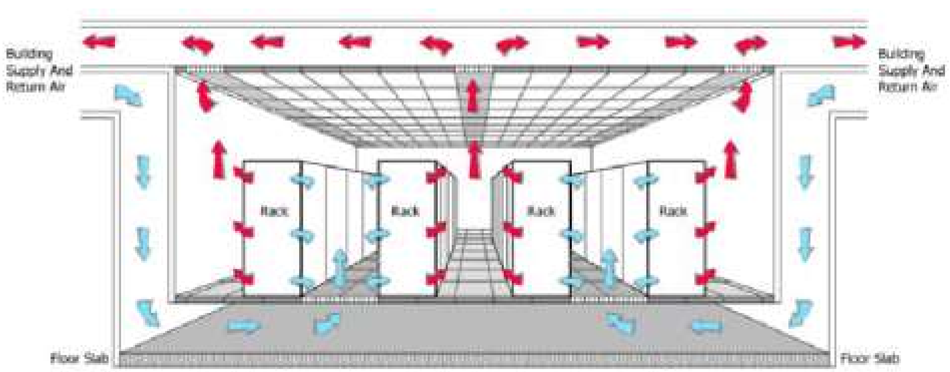
Figure 4-4 Raised floor implementation using two-story configuration with CRAC units on the lower floor.

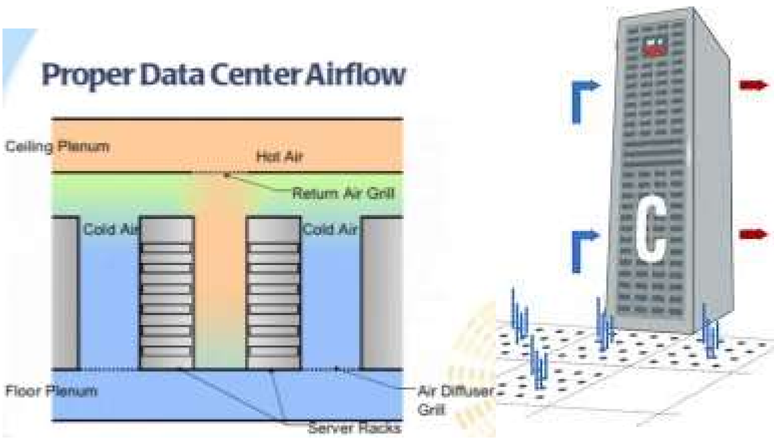
Ceiling with Plenum Better in avoid Mixing

Datacom Equipment Power Trends and Cooling Applications, 2nd ed.
ASHRAE, 2012

Room Ceiling Height

- **The ceiling height will depend on the type of ventilation system.**
- **When Supply air is greater than rack flow rates, increasing the ceiling height reduces the datacom equipment intake temperatures.**
- **When flow equal to or less than equipment flow rates, increasing the ceiling height can result in increased inlet temperatures for underfloor air distribution without a ceiling**. A hot recirculation cell intensifies over the datacom equipment with increased height.





"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

Room Ceiling Height (Conti..)

- **Increasing the ceiling height from 9 to 12 ft (2.74 to 3.66 m) reduces the rack inlet temperature by as much as 6 to 12°C.**
- **Increasing the ceiling height beyond 12 ft (3.66 m) for 6 ft (1.83 m) racks does not seem to have any impact on rack inlet temperatures.**

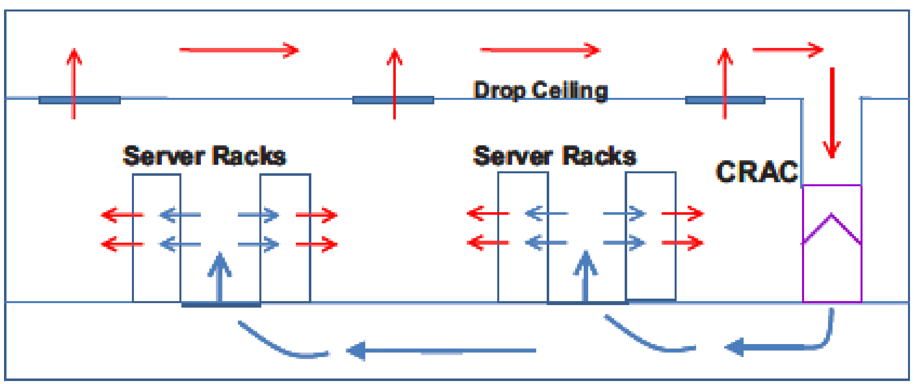


Fig. 36 A schematic of the drop-ceiling arrangement

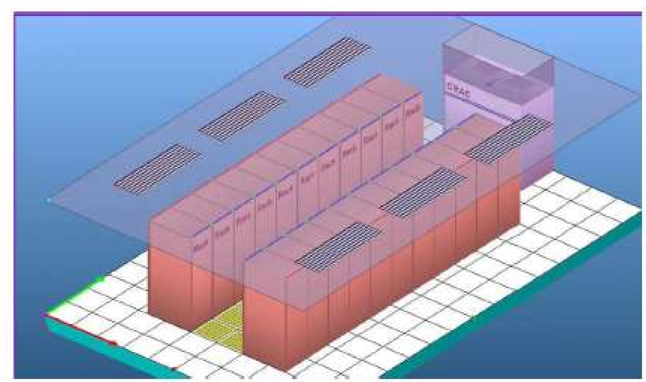


Fig. 37 Use of the drop ceiling

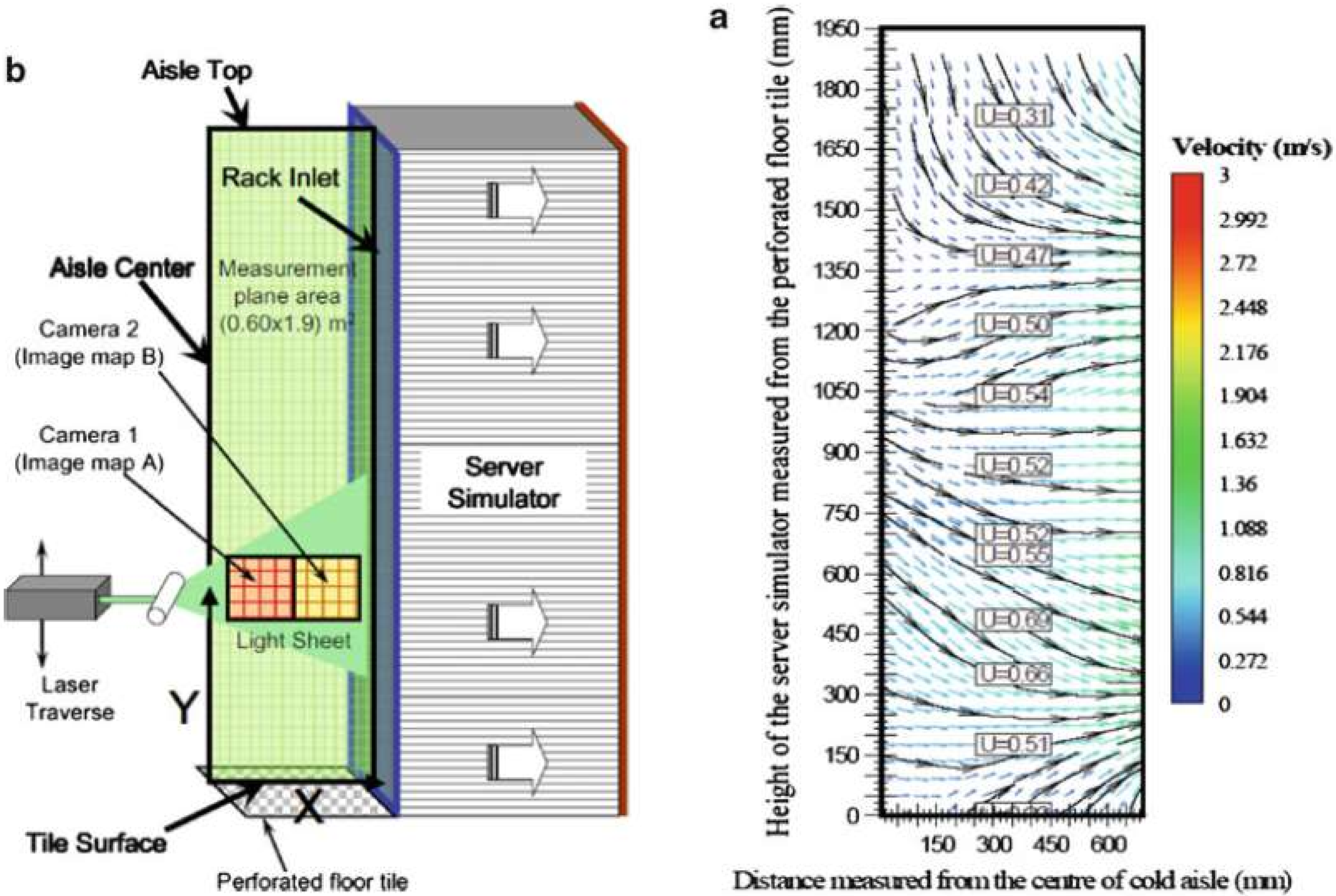
Journal of Heat Transfer, 2010, Vol. 132, 073001-1

“Best Practices for Data Center Thermal and Energy Management—Review of Literature,” ASHRAE Transactions, 2007, pp. 206-218.

Rack Placement..

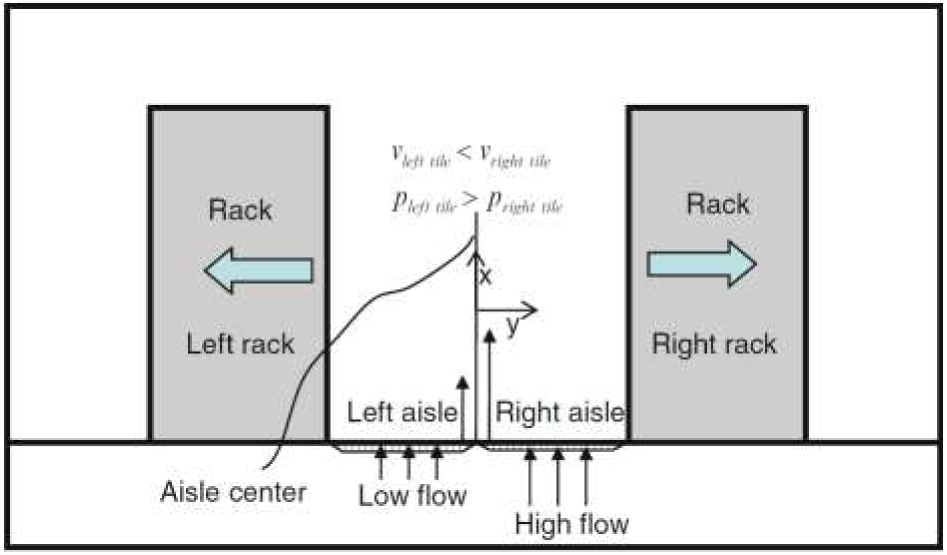
- Placement of high-density datacom equipment at floor locations that have high static pressure allows the highest possible airflow in the cold aisle adjacent to the equipment. **Typically, the highest static pressures are farther away from the CRAC units or where the flows from two or more CRAC units are in collision with each other.**
- The recirculation of the hot air can be reduced by load spreading. **By placing lower-powered equipment near high-powered equipment, the effect of the hot air recirculation can be reduced.**
- Flow near the end of an aisle should be considered in detail, as recirculation can occur both around the sides and over the top of the cabinet.

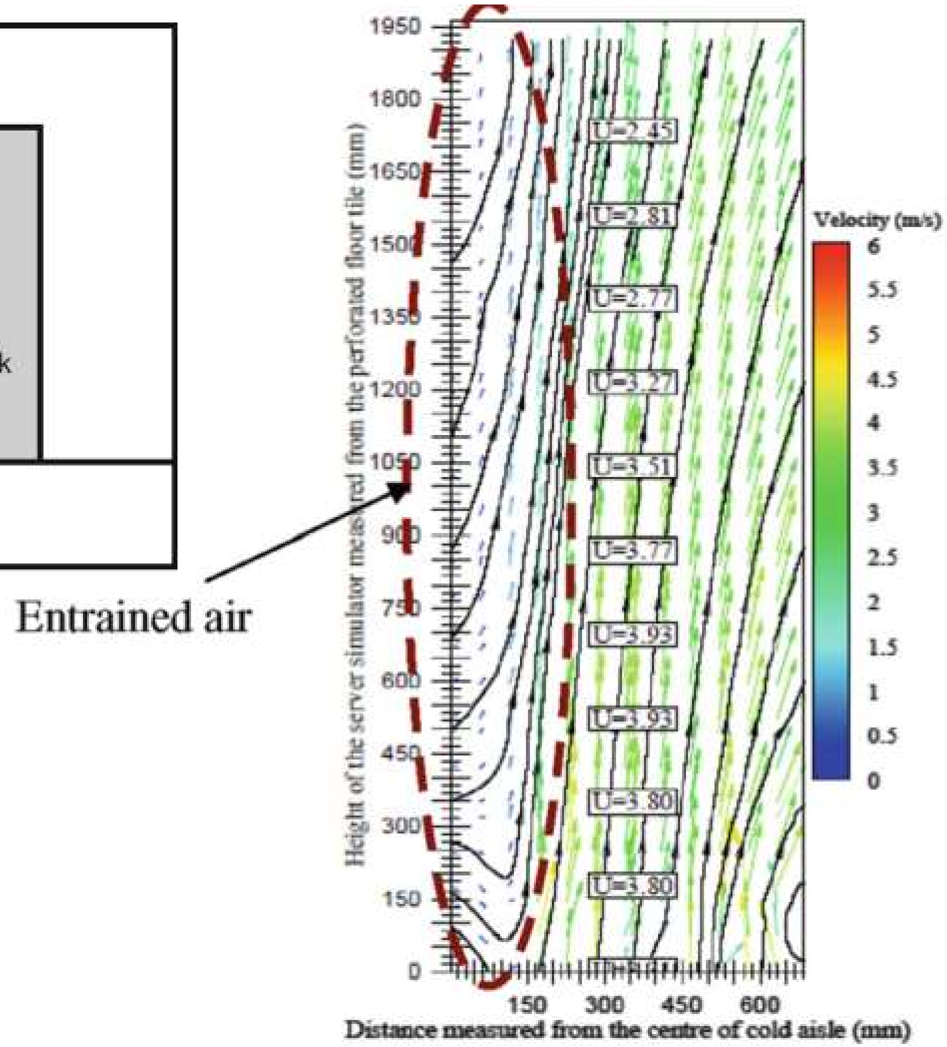
"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.



Kumar P et al. (2010) "Dynamics of cold aisle air distribution in a raised floor data center," in 2010 3rd international conference on thermal issues in emerging technologies, theory and applications, ThETA3 2010, 19–22 December 2010, Cairo, p 95–102.

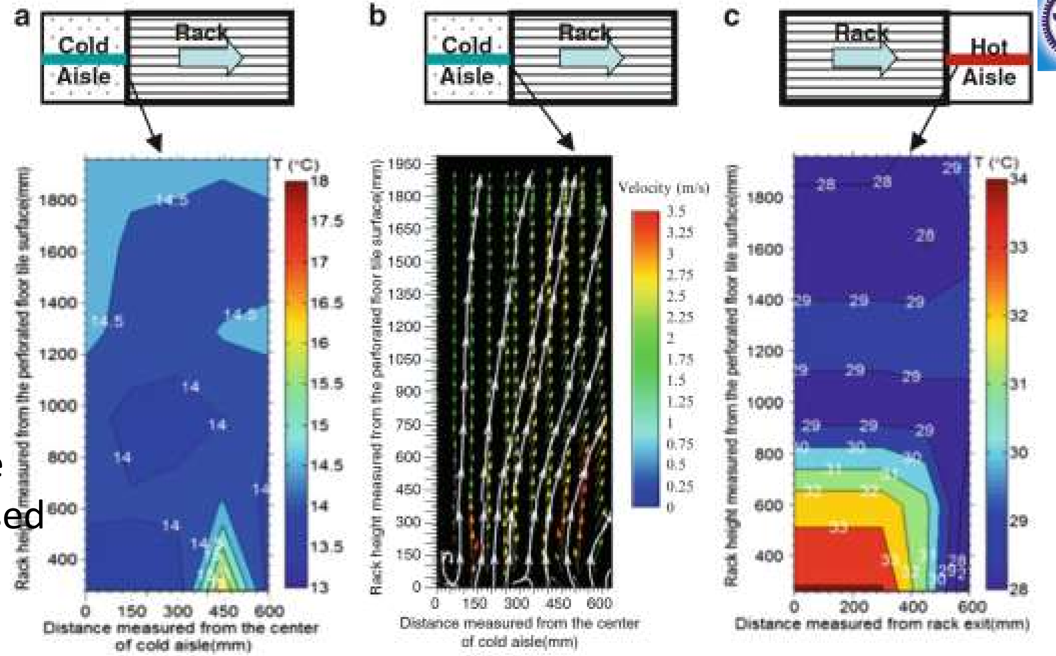
Imbalance of the airflow at right & Left Tiles



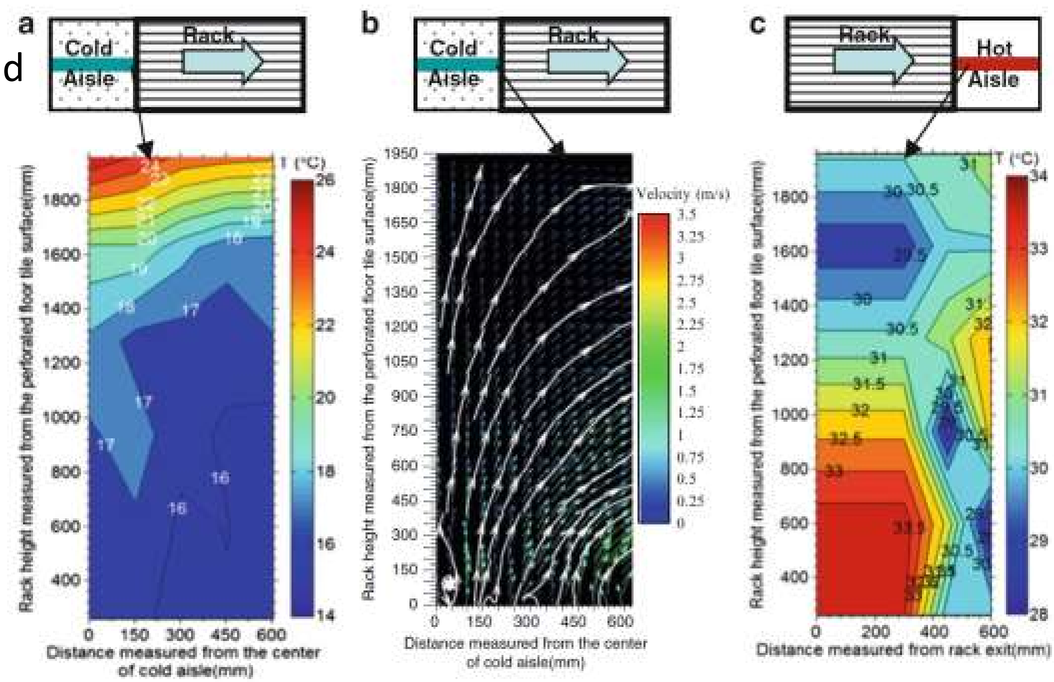


Kumar P et al. (2010) “Dynamics of cold aisle air distribution in a raised floor data center,” in 2010 3rd international conference on thermal issues in emerging technologies, theory and applications, ThETA3 2010, 19–22 December 2010, Cairo, p 95–102.

Kumar P et al. (2010) “Dynamics of cold aisle air distribution in a raised floor data center,” in 2010 3rd international conference on thermal issues in emerging technologies, theory and applications, ThETA3 2010, 19–22 December 2010, Cairo, p 95–102.



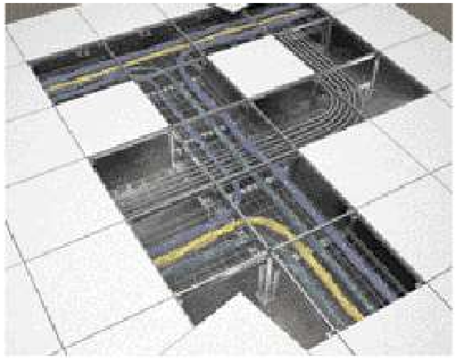
High flowrate from the perforated tile 0.667 m³/s



Low flowrate from the perforated tile 0.523 m³/s

Detrimental Underfloor Blockages

- **Chilled water pipes and cabling should be kept away from the exhaust of the CRAC units**.
- **Underfloor blockages have the biggest influence** on flow rate uniformity through the perforated tiles.
- **Blockages that are parallel to the hot and cold aisles have much lower impact than those that run perpendicular to the aisle**. This conclusion was found when the CRAC units are located parallel to the computer rack equipment aisles.
- **Blockages occurring under the cold aisle have the effect of reducing tile flow**.



"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

Effect of Under-Floor Obstructions

Effect of a Circular Pipe as an Obstruction
– 6 in. pipe @ 12 in. plenum

Fig. 19 A circular pipe as an under-floor obstruction (only the centerline of the pipe is shown)

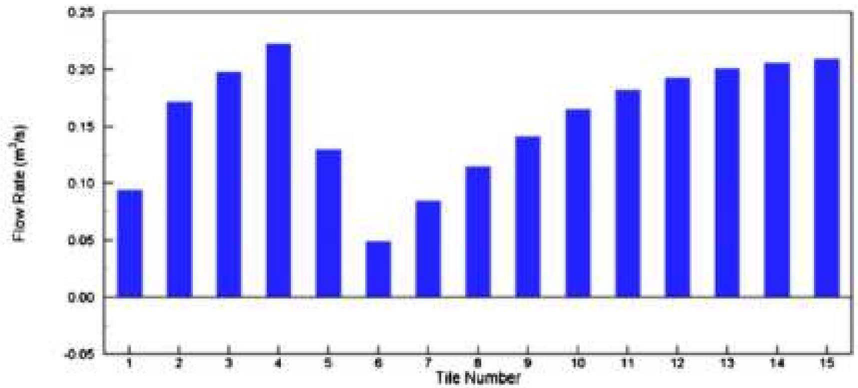


Fig. 20 Flow rates through perforated tiles as affected by the circular-pipe obstruction

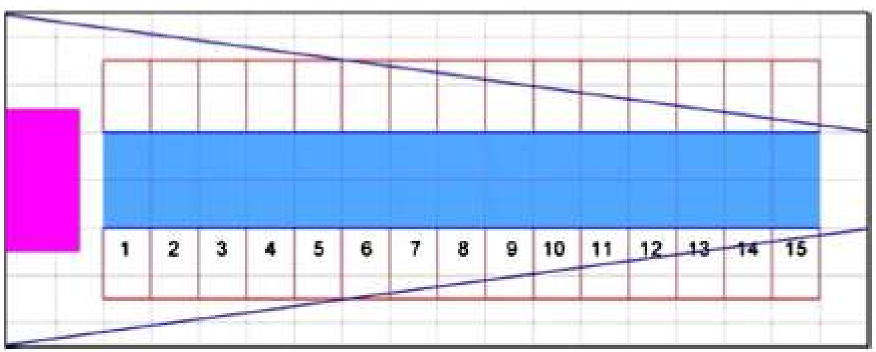
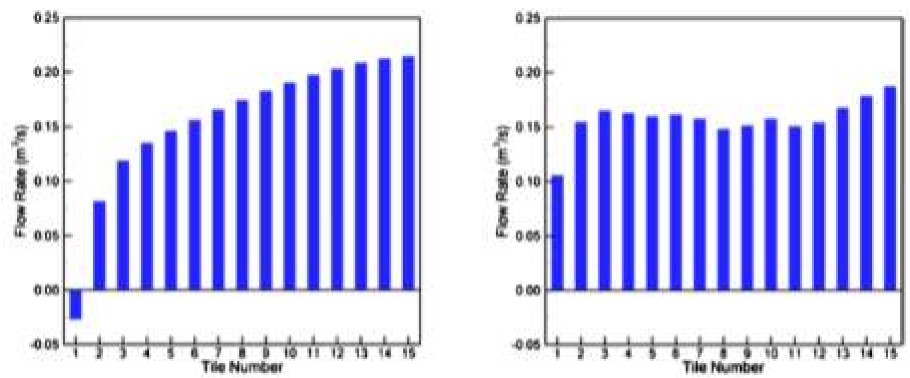


Fig. 22 Use of inclined partitions in the under-floor space



No partitions With inclined partitions

Fig. 23 Airflow distribution with and without inclined partitions

Patankar SV (2010) Airflow and cooling in a data center. J Heat Transfer 132:073001

Reduce blockage effect

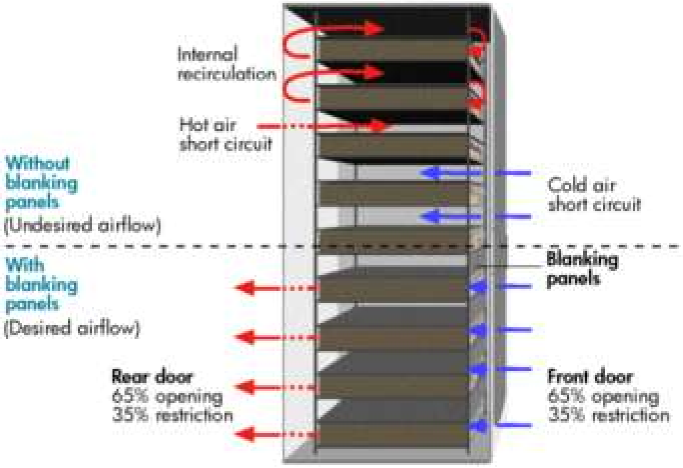
Seal cable cutouts

Integral – for new installations

Surface mount for existing installations

Cable management

Figure 5. Airflow in rack without blanking panels (top) and with blanking panels (bottom)

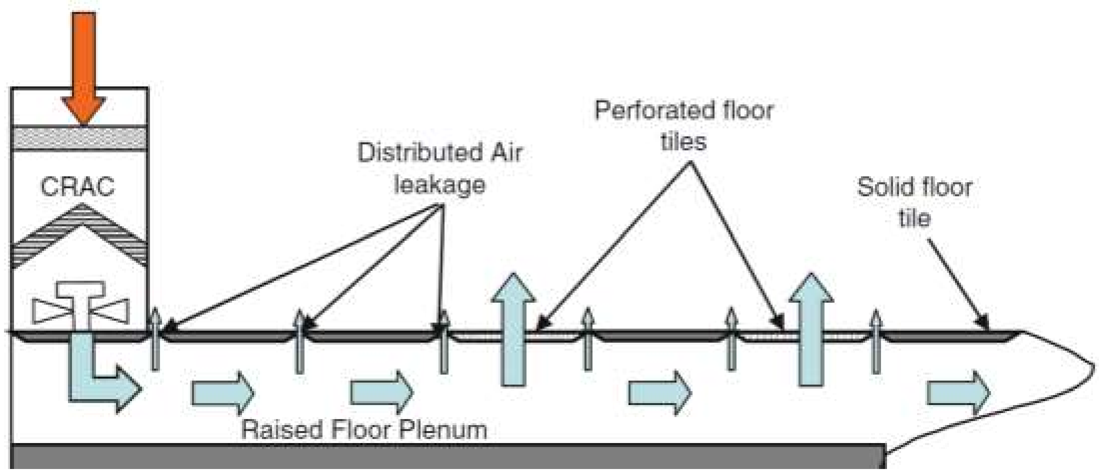


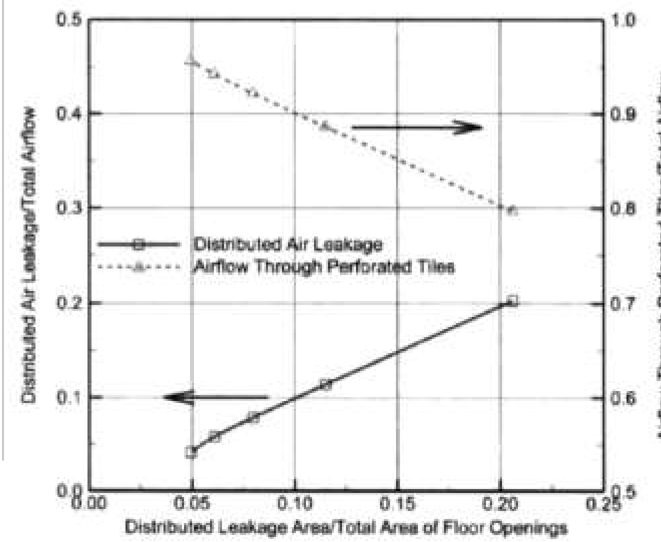
Wrong

Correct

Effect of Distributed Leakage

- Sealing the intentional openings in the plenum not only increase the plenum pressure (which leads to an increase in the distribution losses) but also reduce the total open area available for airflow.

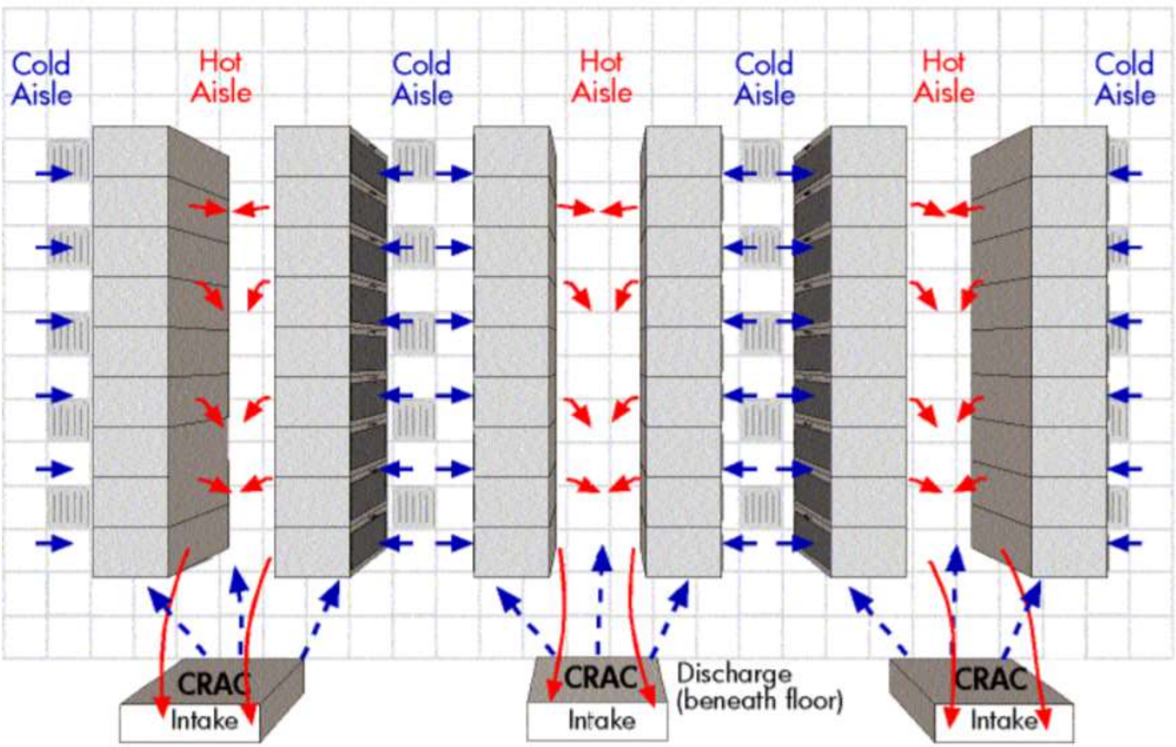




K.C. Karki, A. Radmehr, S.V. Patanka, Prediction of Distributed Air Leakage in Raised-Fioor Data Centers, ASHRAE Transactions, 2007, pp. 219-226.

Placement of CRAC units

Figure 16. CRAC units should be placed perpendicular to hot aisles so that they discharge cool air beneath the floor in the same direction.



Place CRAC facing hot aisles rather than cold aisles, as the underfloor velocity pressure should be minimized in cold aisles.

If CRAC units are aligned in parallel rows on a raised floor, then each row of CRACs should exhaust air in a direction that increases the static pressure across the floor rather than CRACs exhausting such that their plumes collide, causing decreased static pressure in these regions and overall loss of chilled air to the raised floor.

HP technology brief – “Optimizing facility operation in high density data center environments,”

CRAC Unit Placement and Configuration (Conti..)

- Airflow rate distribution in the perforated tiles is uniform when all the CRAC units are discharging in the same direction and this distribution is poor (non-uniform) when the CRACs discharge air in collision with each other.
- **Turning vanes and baffles appeared to reduce the CRAC airflow rate by about 15%**. It is, thus, preferable that turning vanes (scoops) not be used in CRAC units. However, when turning vanes are used in CRAC units facing each other, their orientation should be such that the airflow from the CRAC is in the same direction.

“Best Practices for Data Center Thermal and Energy Management—Review of Literature,” ASHRAE Transactions, 2007, pp. 206-218.

CRAC with/wo Turning Vane

Optimization of Enclosed Aisle Data Centers Using Bypass Recirculation, Journal of Electronic Packaging, 2012, Vol. 134, 020904-1

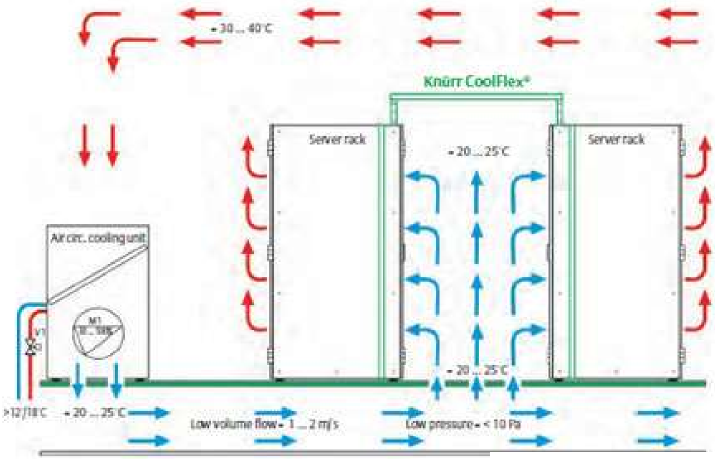
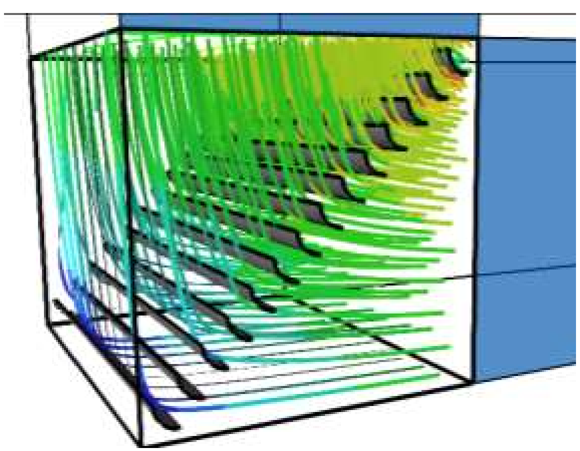


Table 2 Comparison of cold aisle rack inlet temperatures

	Configuration 1: Bypass near CRAC		Configuration 2: Bypass in hot aisle
Temperatures in Kelvin	With turning vane	Without turning vane	With turning vane
Maximum Temperature	300.55	302.55	307.25
Minimum Temperature	298.95	295.05	293.45



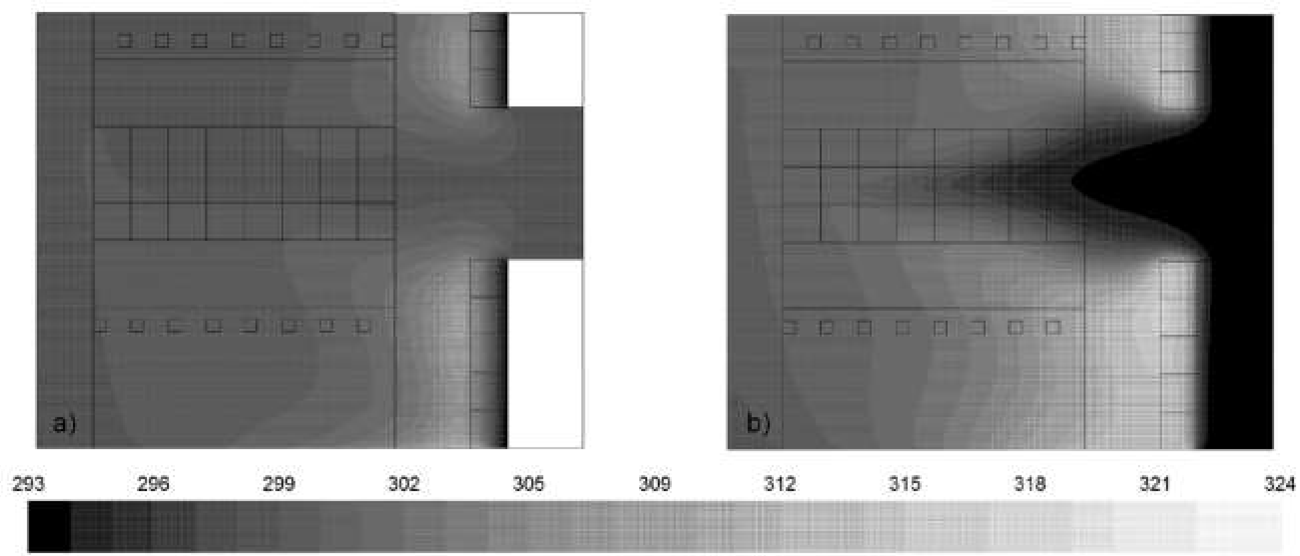


Fig. 7 Temperature (in K) contours 8 in. below the raised floor with bypass tiles placed near CRAC for (*a*) installed CRAC turning vane and (*b*) no CRAC turning vane

CRAC Unit Placement and Configuration

- Racks that have a clear path of hot air back to the intakes of the CRAC units generally show low rack air temperatures.
- Integrating sophisticated thermal instrumentation and control of a data center environment with the operational parameters of CRAC units e.g., volumetric airflow rate or chilled-air set point temperature, can result in significant energy savings of around 50%. **Variable-frequency drives can be used to change fan speeds** and, thus, CRAC airflow rates, and the chilled air setpoint temperatures can be changed via controlling the condenser conditions of the CRAC unit.

"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

Effect of Aisle Spacing

- The most commonly found **aisle spacings are 4 ft (1.22 m)** aisles that are consistent with two floor tiles for the hot aisle and cold aisle.
- **With the increased server rack powers, Beaty and Davidson (2005) suggest that the aisle widths be increased to allow for more air in the vicinity of the IT equipment and at a possible reduced velocity**.

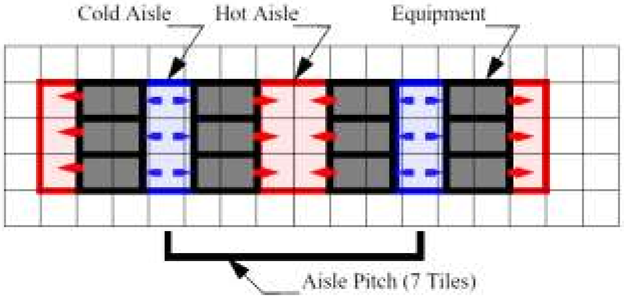


Figure 4.7 Seven-tile aisle pitch, equipment aligned on hot aisle.

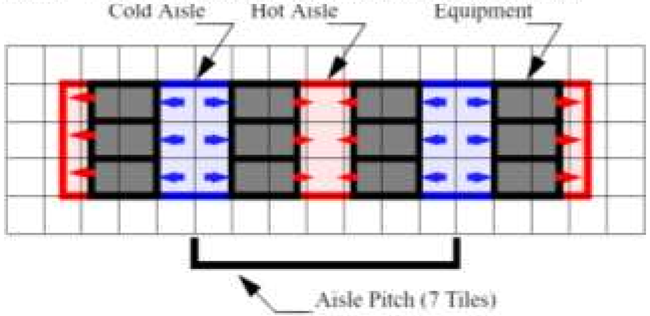


Figure 4.6 Seven-tile aisle pitch, equipment aligned on cold aisle.

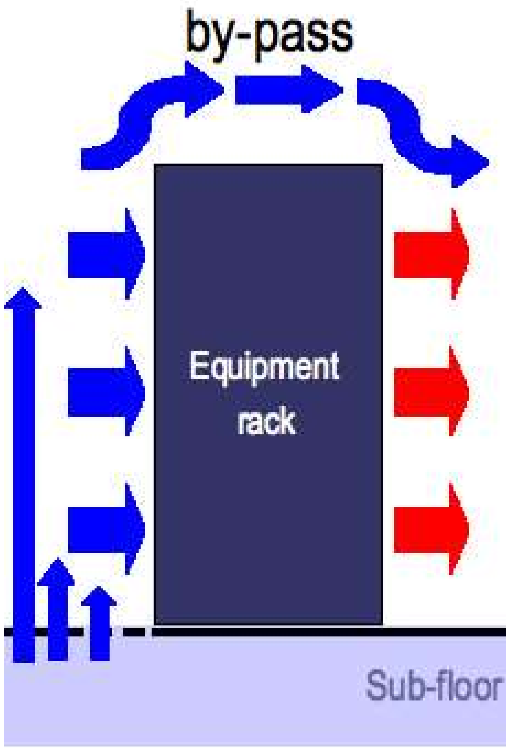
Table 4.1 Aisle Pitch Allocation

	Tile Size	Aisle Pitch (cold aisle to cold aisle)[a]	Nominal Cold Aisle Size[b]	Maximum Space Allocated for Equipment with No Overhang[c]	Hot Aisle Size
U.S.	2 ft (610 mm)	14 ft (4267 mm)	4 ft (1220 mm)	42 in. (1067 mm)	3 ft (914 mm)
Global	600 mm (23.6 in.)	4200 mm (13.78 ft)	1200 mm (3.94 ft)	1043 mm (41 in.)	914 mm (3 ft)

a. If considering a pitch other than seven floor tiles, it is advised to increase or decrease the pitch in whole tile increments. Any overhang into the cold aisle should take into account the specific design of the front of the rack and how it affects access to the tile and flow through the tile.
b. Nominal dimension assumes no overhang; less if front door overhang exists.
c. Typically a one meter rack is 1070 mm deep with the door and would overhang the front tile 3 mm for a U.S. configuration and 27 mm for global configuration.

Effect of Aisle Spacing

- **Limiting the velocity** of the air supply by the perforated tiles has two benefits
  - high-velocity air tends to blow by the inlet grilles of the servers.
  - high-velocity air near the center of the aisle tends to blow by the intake of the servers and out the top of the aisle, not serving any cooling benefit.
- **Wider cold aisles** will increase chilled air to the servers and lower the velocity exiting the tiles, thereby eliminating a potential "blow by" of the high-velocity chilled air.



"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

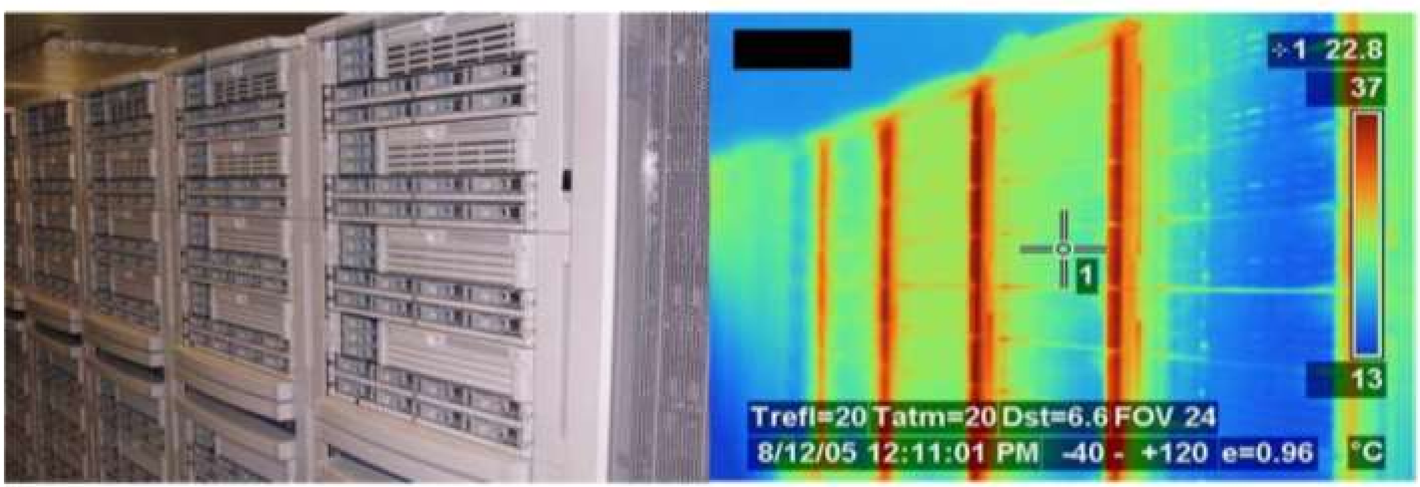
Partitions: At the End of Aisles, Above Racks, Within Racks, and Between Racks

- **Placed ceiling partitions may help prevent recirculation** (just be careful about the safety).
- **Install blanking panels for those areas of the rack that do not have servers.**
- Gap partitioning between the different units in a rack is helpful in reducing rack inlet temperature.
- **Gaps between low-powered racks may be acceptable.**
- **Gaps between high-powered racks that are arranged in a hot aisle/cold aisle fashion need to be eliminated**. They can cause significant infiltration of hot exhaust air from the racks directly into the neighboring cold aisles. **This can lead to higher rack inlet temperatures by as much as 6°C**.

"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

Gaps Between the Racks

- It is easy to see that **the gaps provide additional places where the "end effects" can be observed.** Hot air from the back of the racks can enter the cold aisle through the gaps and influence the inlet temperatures of the racks.
- An obvious remedy is to **close the gaps by using impermeable plates or partitions**.

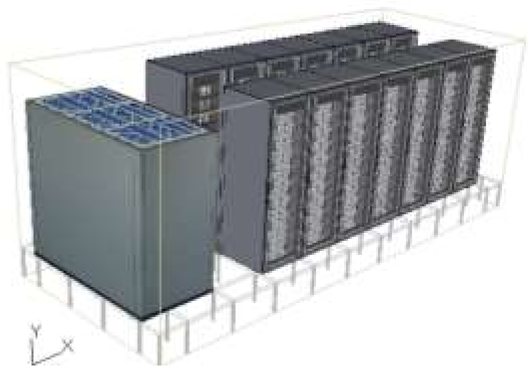


Normal and IR images of the inlet of a worst-case air-cooled rack.

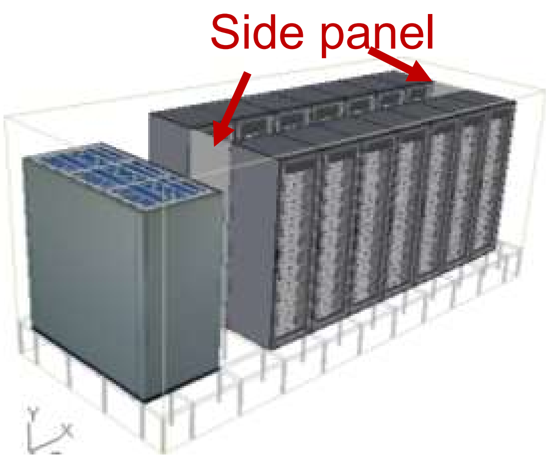
ASHRAE Transactions, Volume 112, Part 2, pp. 220-230.

Blockage Design
Panel cover

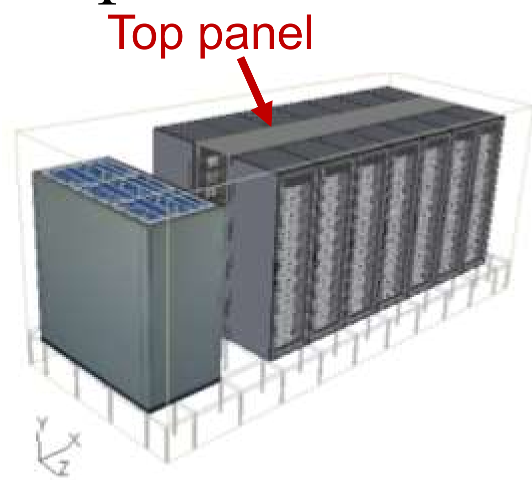
- The effect of adding panel depend on the design of data center, in this case the literal space is crowded so adding side panel can lower the server inlet temperature.



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

Partitions: At the End of Aisles, Above Racks, Within Racks, and Between Racks

Journal of Heat Transfer, 2010, Vol. 132, 073001-1

keeping the hot air away from the inlets of the server racks.

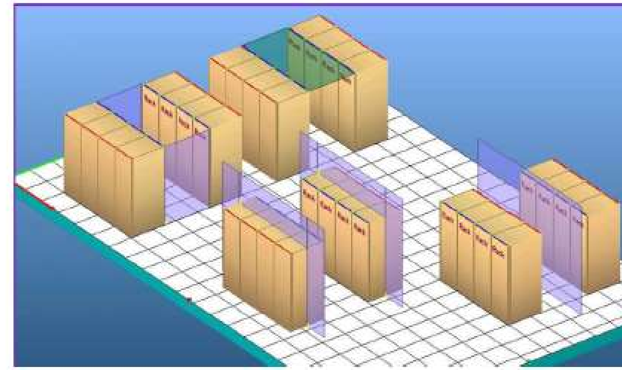
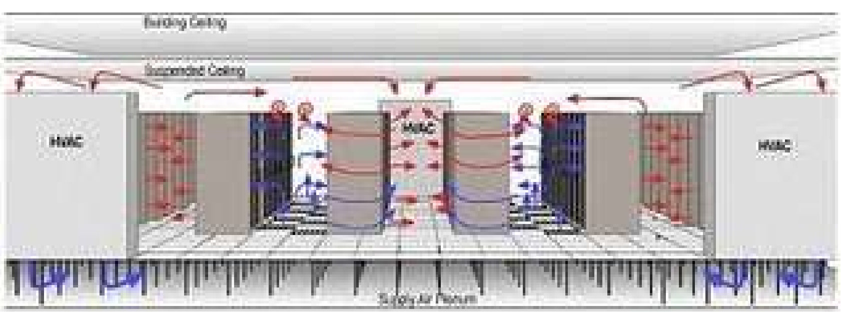
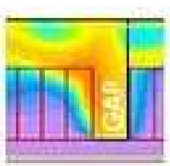
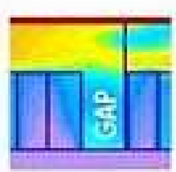


Fig. 35 Use of partitions to prevent hot air from entering the inlets of the racks

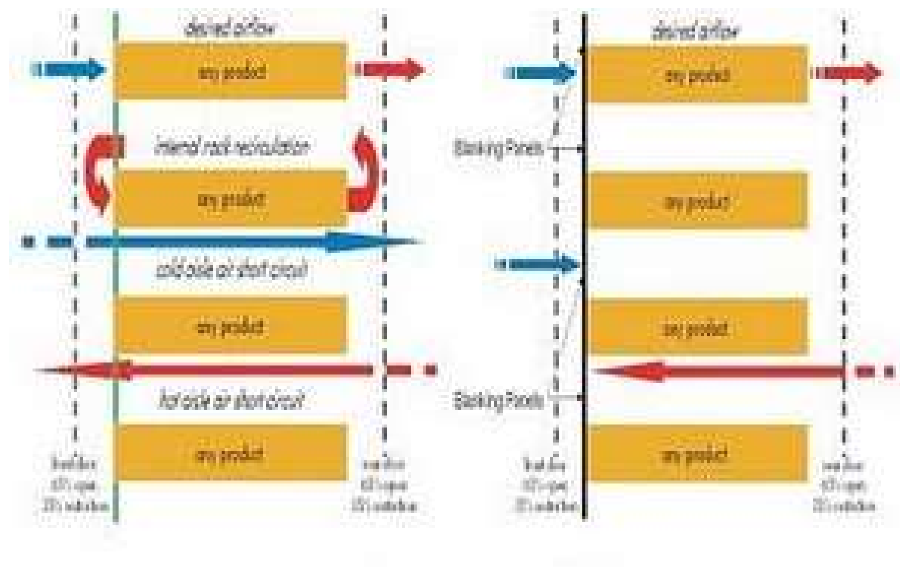




Gap in Row



Vent Tile in Gap



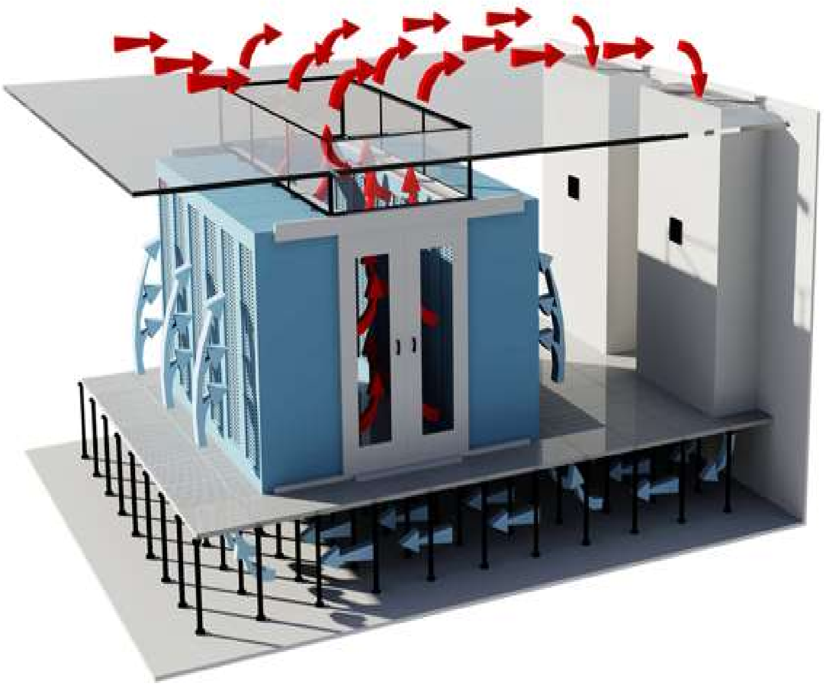
Without blanking panels

With blanking panels installed

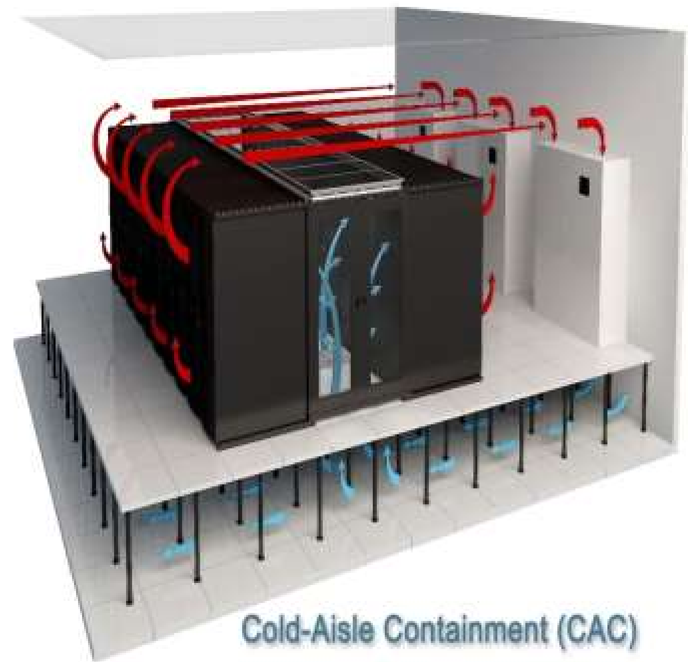
Schematic of the effects of gaps and blanking panels

Air Flow Management Containment

- Hot Aisle Cold Aisle Separation



Hot Aisle Containment



Cold Aisle Containment

Experimental Characterization of Various Cold Aisle Containment Configurations for Data Centers, Journal of Electronic Packaging ,2015, Vol. 137 / 011007-1

three cold-aisle containment configurations are experimentally compared against the open aisle conditions for underprovisioned (UP) and over-provisioned (OP) air flow rates. There are fundamentally three main systems for air flow management: hot aisle containment, cold aisle containment, and exhaust chimney containment

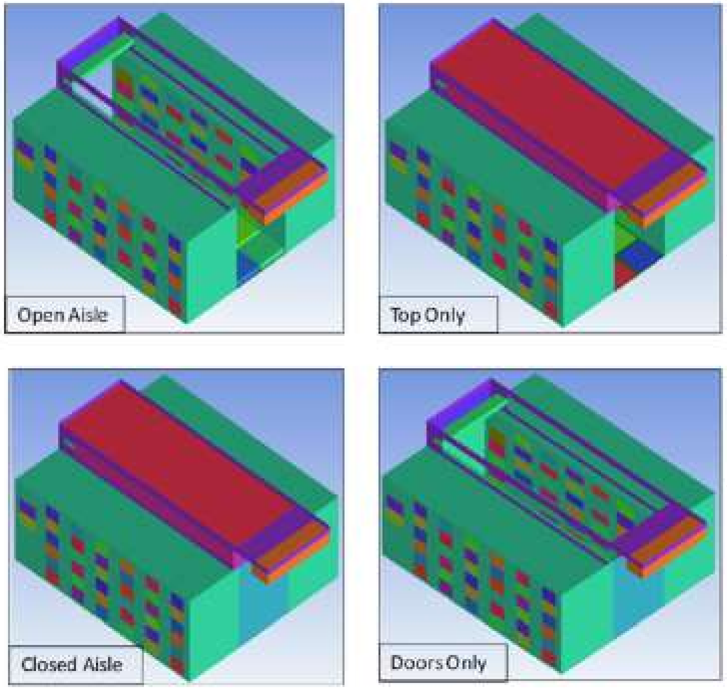


Fig. 6 Cold aisle configurations tested

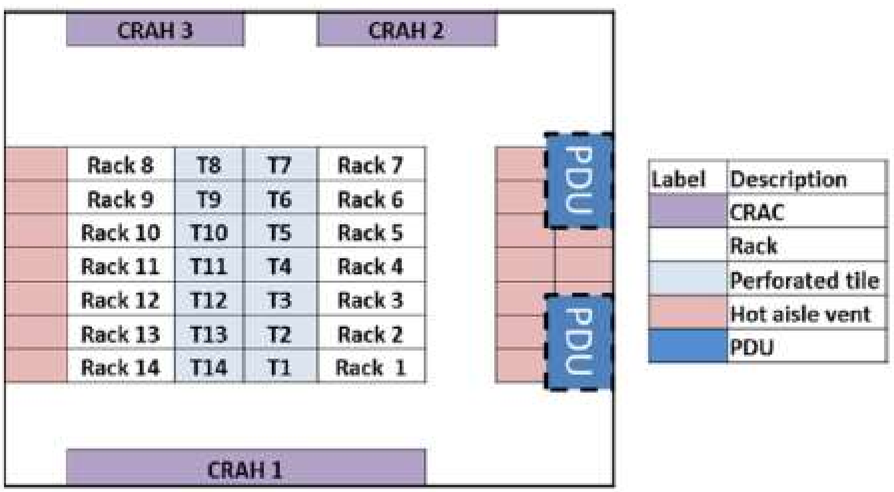


Fig. 1 DCL layout schematic

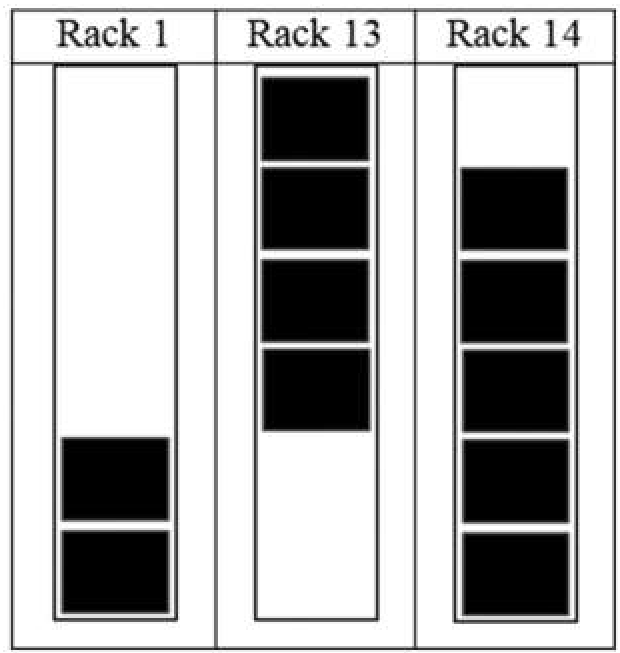


Fig. 4 Regions occupied by active servers for partially filled racks

For under supplied airflow arrangement, flow reversal may occurs even for full contained. The best method is to use blockage plate to block the empty server portion.

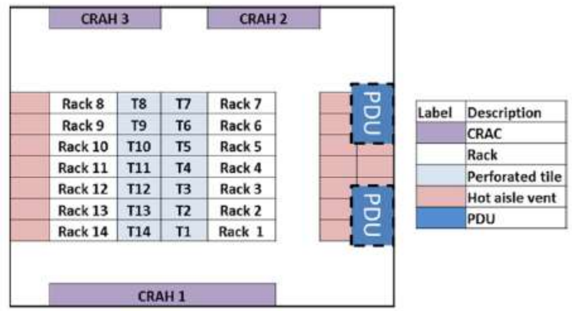
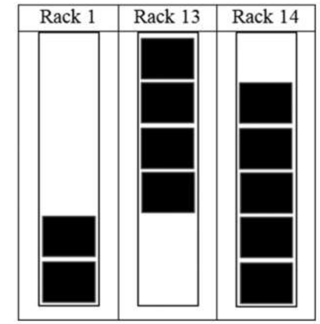
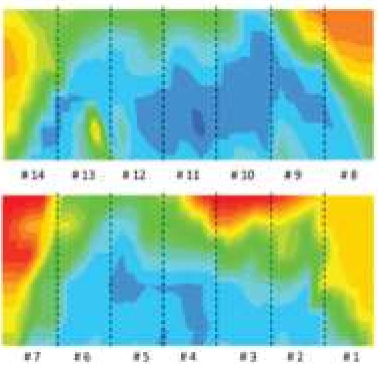


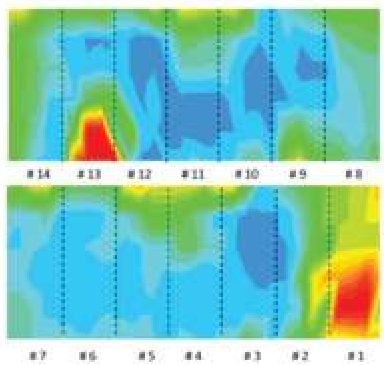
Fig. 1 DCL layout schematic



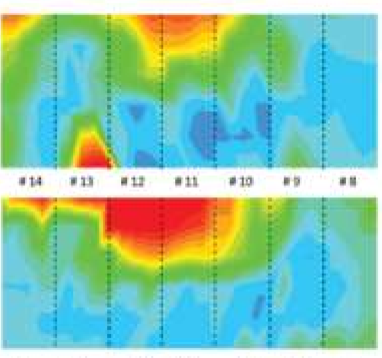
4 Regions occupied by active servers for partially filled racks



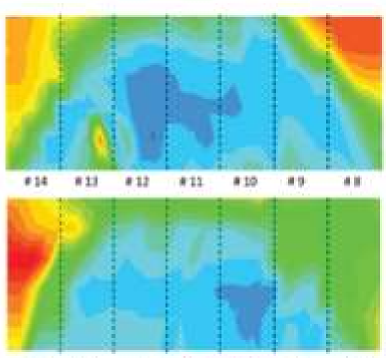
(a) Run 1: UP open aisle



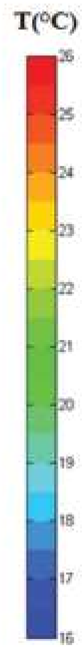
(b) Run 2: UP fully contained

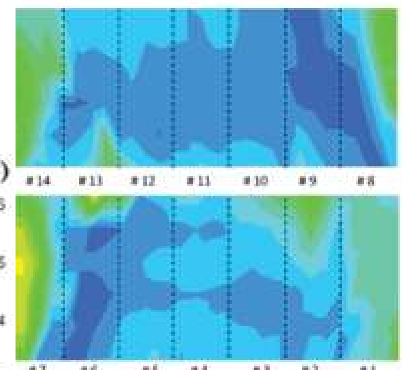


(c) Run 3: UP doors only

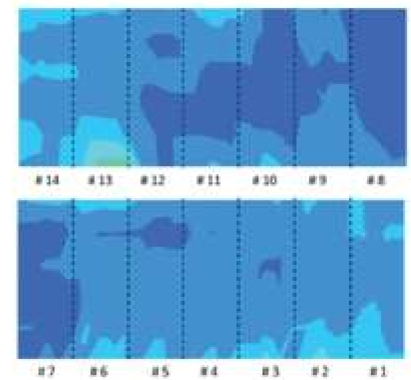


(d) Run 4: UP top only

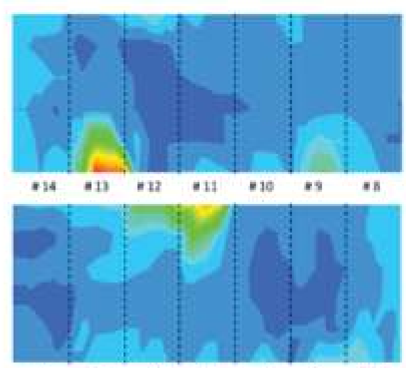




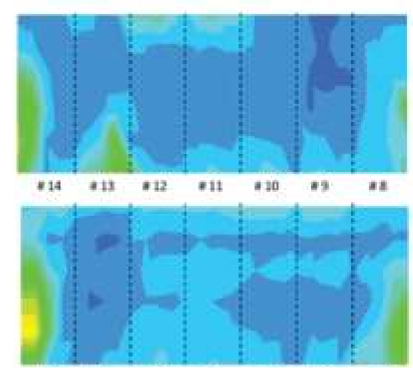
(a) Run 5: OP open aisle



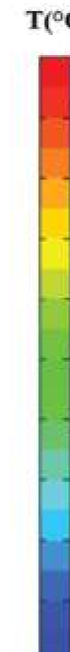
(b) Run 6: OP fully contained



(c) Run 7: OP doors only



(d) Run 8: OP top only



High-Velocity Flow Through the Perforated Tiles

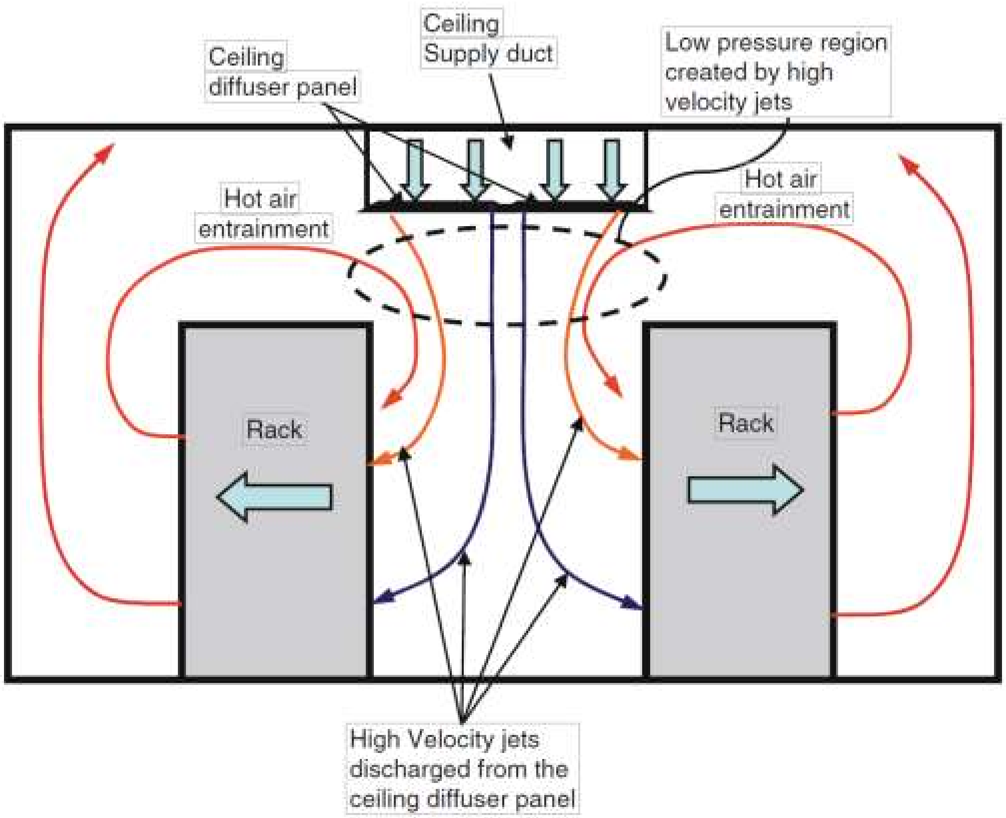
- The heat loads of modern server racks can be very high 10–20 kW
  - Corresponding airflow demand may be of the order of **1.0 m^3/s.**
  - Air emerges from the perforated tile at a velocity of **3 m/s**.
  - With this high-velocity stream flows over the inlet face of the rack, would the cooling air enter the rack or simply flow past it?
  - **The high-velocity airflow does create a low-pressure region at the bottom of the rack. The server fans in the bottom region deliver a lower flow rate compared with the uniform-pressure environment.**
  - Fortunately, this flow reduction is not large. For realistic values of the flow resistance inside a server rack and for common fan curves, **the flow reduction at the bottom of the rack is less than 15%.**

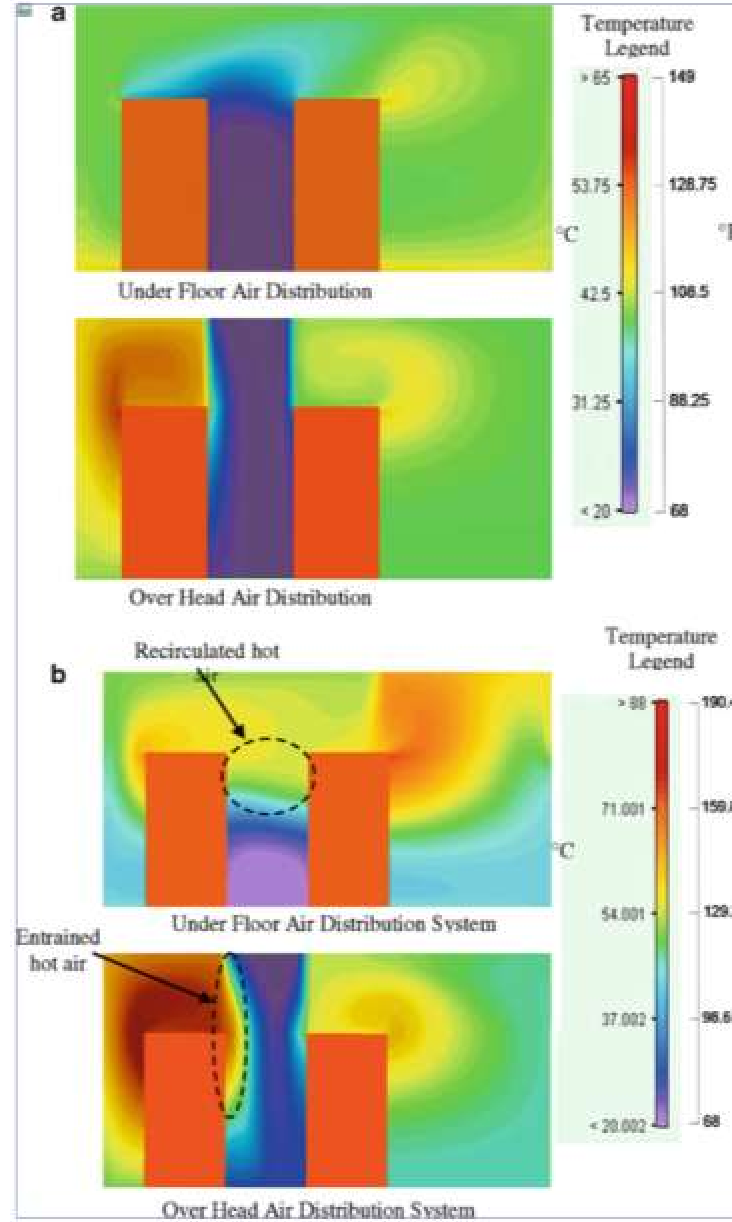
"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

Airflow for Overhead System

Stressed on the data tested in a container simulation lab. (confined space, small data center)

Underfloor vs. overhead





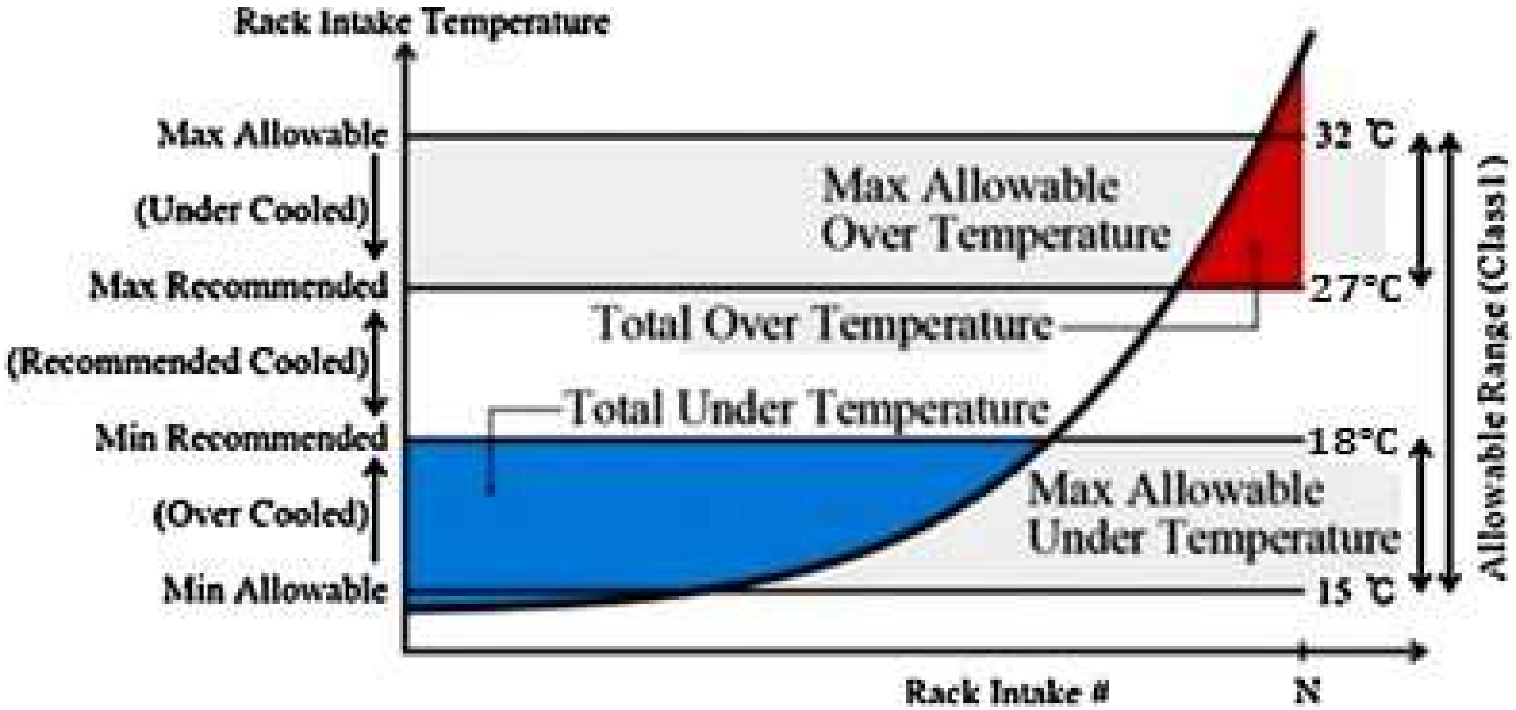
Schmidt RR, Iyengar M (2007) Comparison between underfloor supply and overhead supply ventilation designs for data center high-density clusters. In: 2007 Winter meeting of the American Society of heating, refrigerating and air-conditioning engineers, 27–31 January 2007, Dallas, p 115–125

Raised floor vs. OHAD

- The higher pressure drop in the ducts makes **balancing an OHAD system relatively simple**.
- OHAD system the entire process has to be repeated with addition or removal of IT equipment.
- Due to lower plenum pressure drop in a raised floor, small changes in plenum pressures cause large fluctuations in flow. **This makes it nearly impossible to completely balance an UFAD system.**

ASHRAE TC9.9, 2011

- Maximum allowable temperature = 32℃
- Maximum allowable temperature = 15℃
- Maximum recommended temperature = 27℃
- Minimum recommended temperature = 18℃



RCI

- Herrlin proposed Rack Cooling Index (RCI) to measure the healthy extent of the thermal environment for the equipment in data centers. The RCI includes two sibling indices: RCI_{HI} and RCI_{LO}.
- Compliance with a given intake temperature specification is the ultimate cooling performance metric; the RCI is such a metric. RCI = 100% mean ideal conditions; no over-or under-temperatures, all temperatures are within the recommended temperature range.

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

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

T_x = the mean temperature at intake x

n = total number of intakes

$T_{max-rec}$ = maximum recommended temperature

$T_{max-all}$ = maximum allowable temperature

$T_{min-rec}$ = maximum recommended temperature

$T_{min-all}$ = minimum allowable temperature

Level	*RCI*
Ideal	100%
Good	≥ 96%
Acceptable	91~95%
Poor	≤ 90%

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.

Evaluation metrics

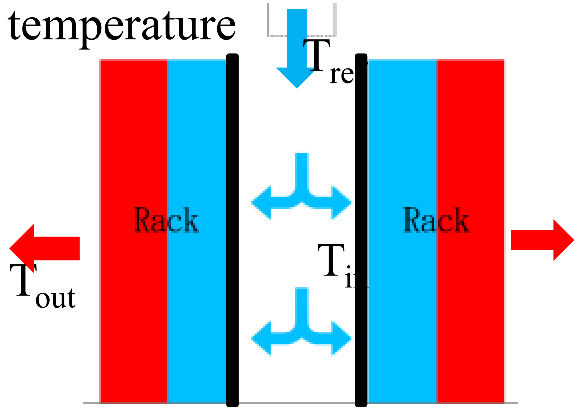
- The SHI is a dimensionless indicator of the recirculation of hot air into the cold aisles.

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

$$= \frac{dQ}{Q+dQ}$$

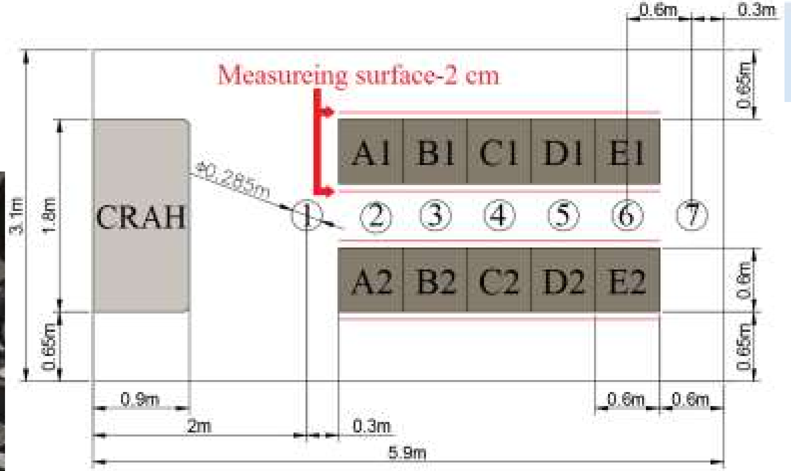
$$= \frac{\text{Enthalpy rise due to infiltration in cold aisle}}{\text{Total Enthalpy rise at the rack exhaust}}$$

T_{in} = average inlet temperature
T_{out} = average outlet temperature
T_{ref} = vent tile inlet air temperature

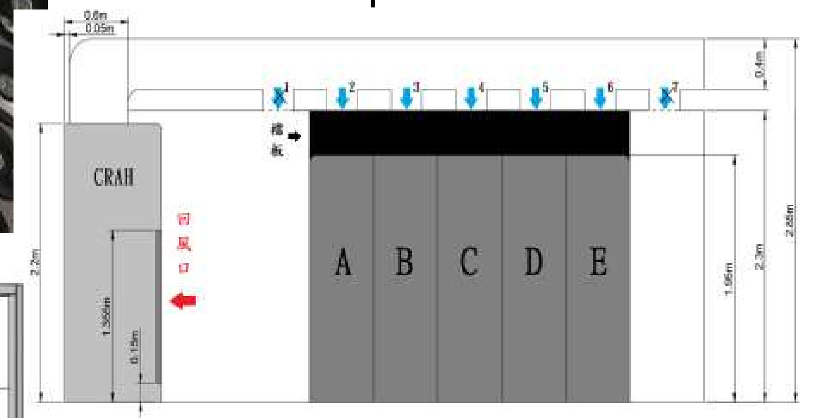


R. K. Sharma, C. E. Bash, C. D. Patel, “Dimensionless parameters for evaluation of thermal design and performance of large-scale data centers”, 8th ASME/AIAA Joint Thermophysics and Heat Transfer Conference, 2002.

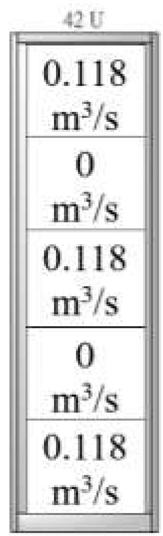
Test system in NCTU – 20ft Container



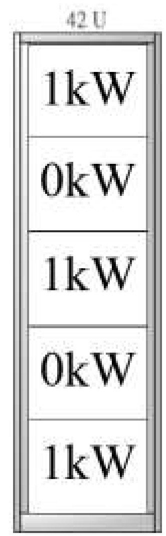
Top view



Side View



Airflow in 1 Rack

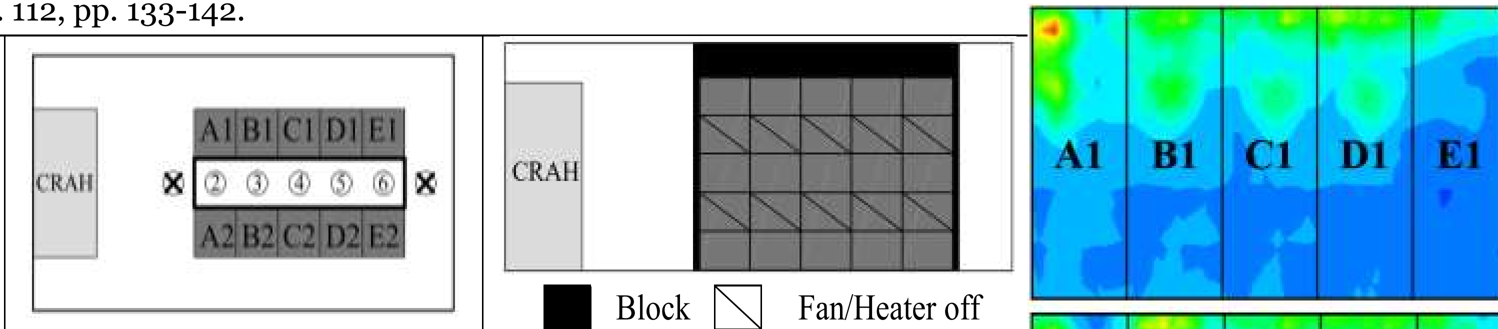
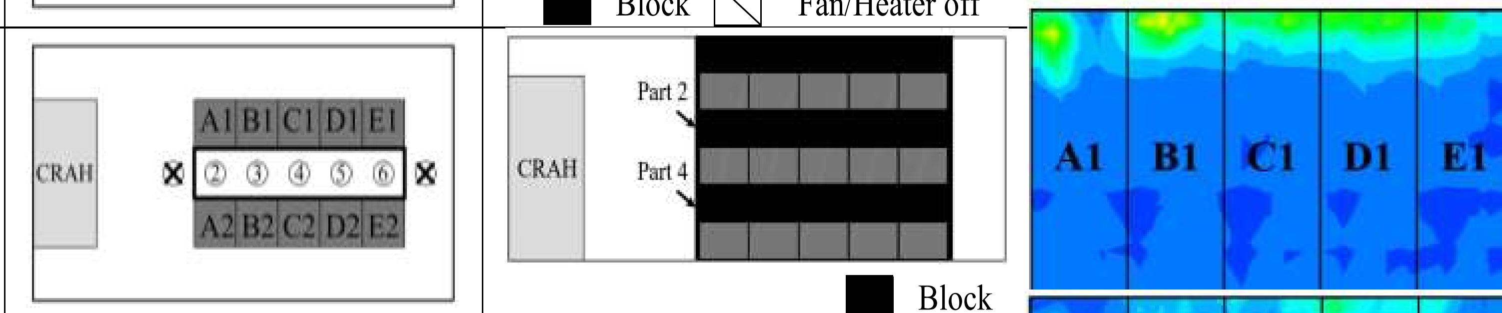
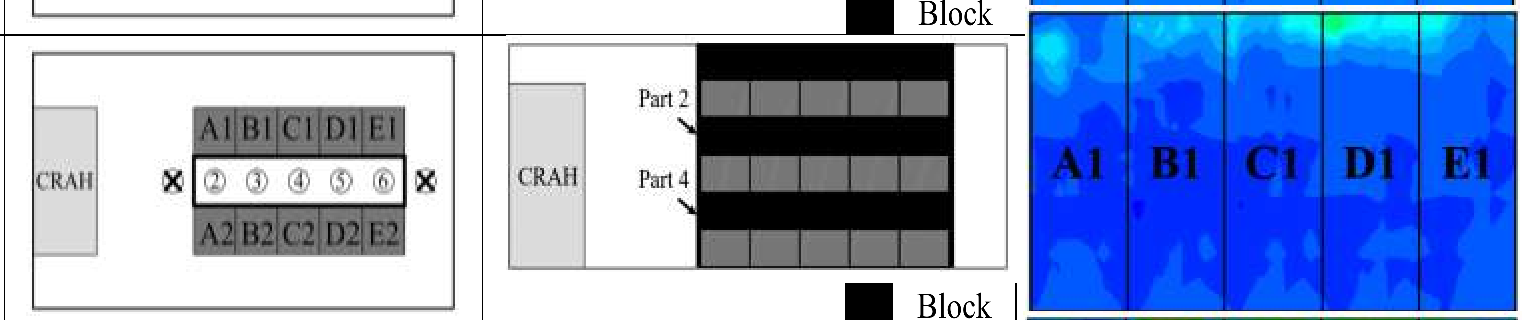
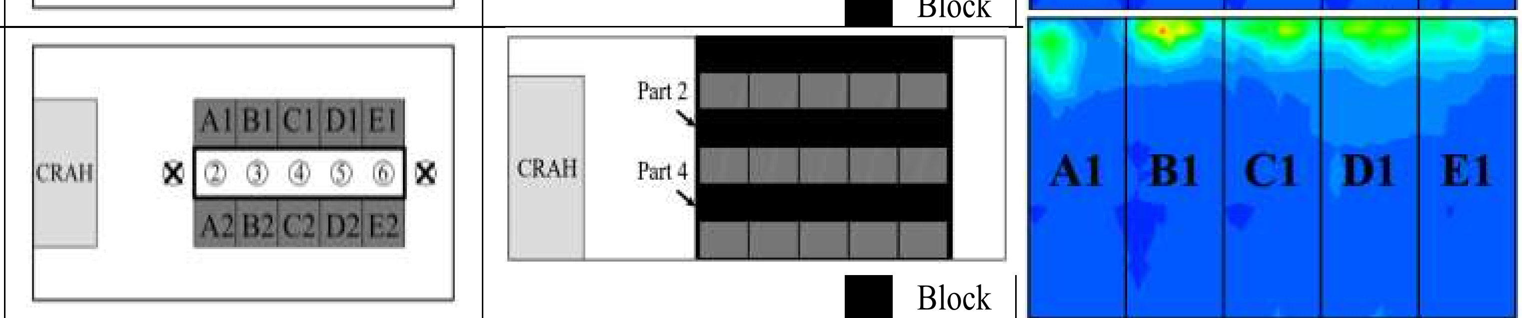


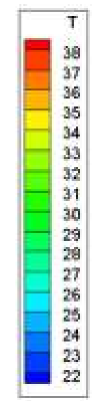
Power in 1 Rack

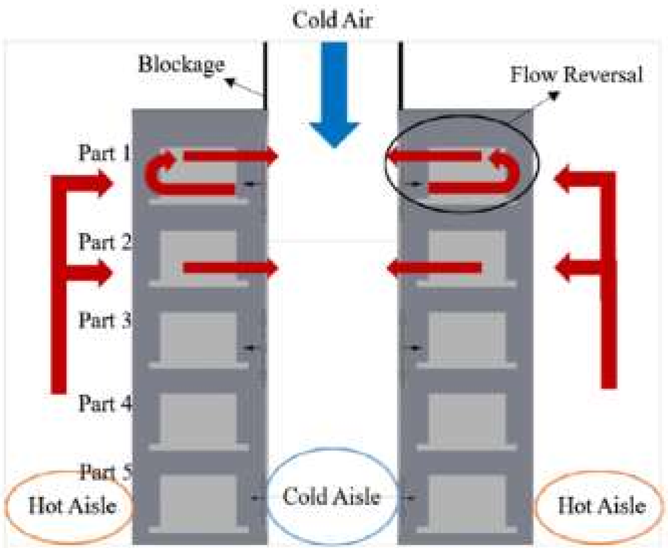
- Air from CRAH = $3.54 m^3/s$
- Air by RACK $3.54 m^3/s$
- Total capacity 30 kW
- Air supply T = 21℃

Effect of Cold-Aisle Containment

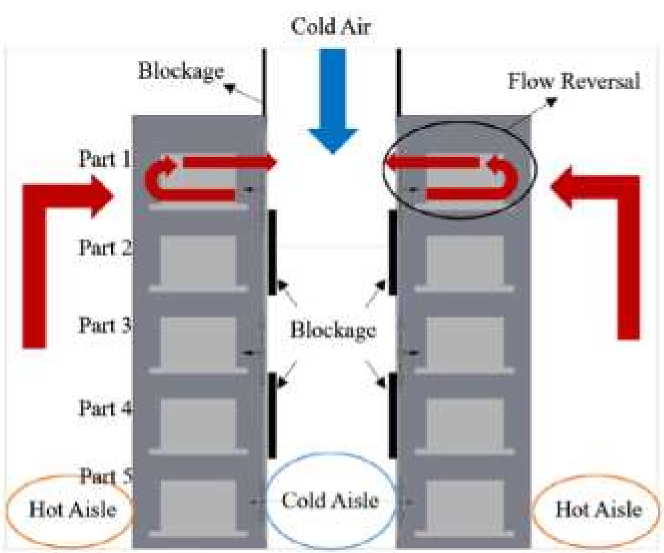
Wang, T.H., Tsui, Y.Y., and Wang, C.C., (2017), "On Cold-aisle Containment of a Container Datacenter," Applied Thermal Engineering, Vol. 112, pp. 133-142.

Case 5 Full containment but part 2, part 4 is not blocked Air flowrate of CRAH=3.52 m^3s^{-1}	
Case 6 Full containment, parts 2 and part 4 are blocked Air flowrate of CRAH=3.52 m^3s^{-1}	
Case 7 Full containment, parts 2 and part 4 are blocked Small flow rate=2.83 m^3s^{-1}	
Case 8 Full containment, parts 2 and part 4 are blocked Large flow rate=3.93 m^3s^{-1}	





(a) Without blockage plate in part 2 and part 4.



(b) With blockage plate being placed in part 2 and part 4.

Fig. 7. Schematic showing the flow reversal between cold and hot aisle.

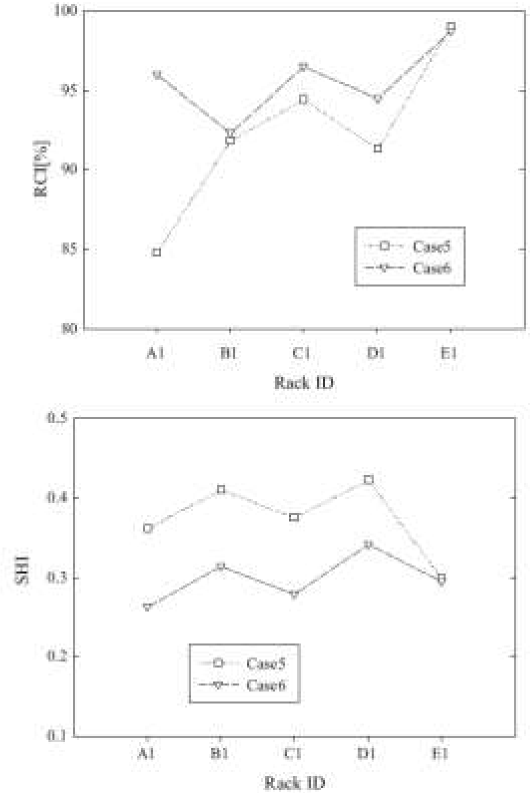
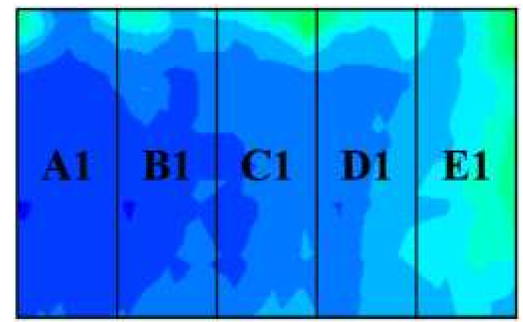
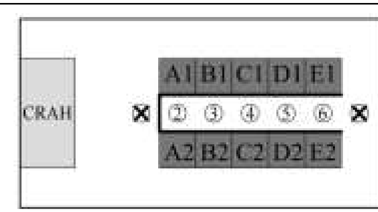
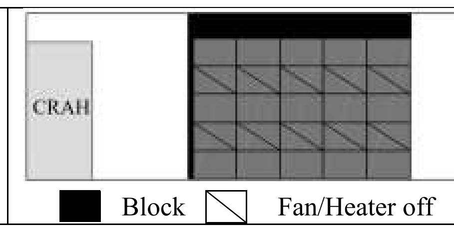
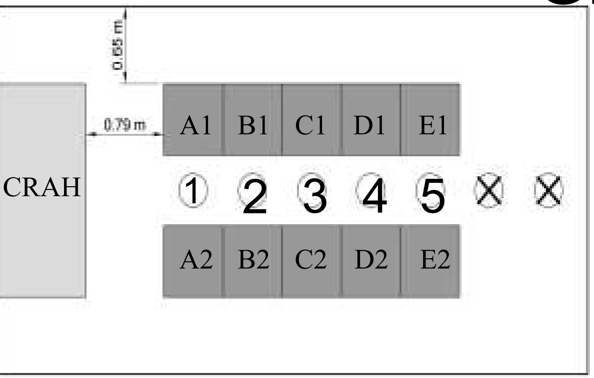


Fig. 6. Measured RCI and SHI for cases 5 and 6.

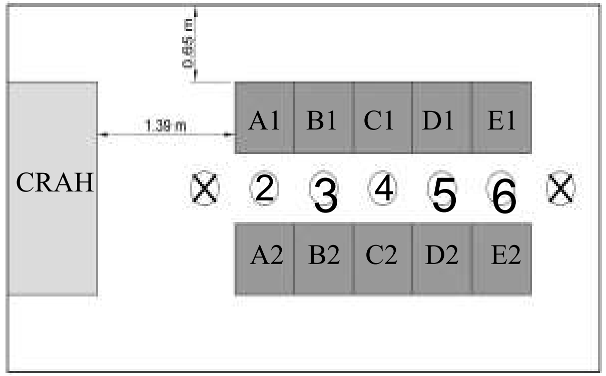


Case 4 Blockage plate at the entrance of aisle but leave open at the end Air flowrate of CRAH=3.52 m^3s^{-1}		

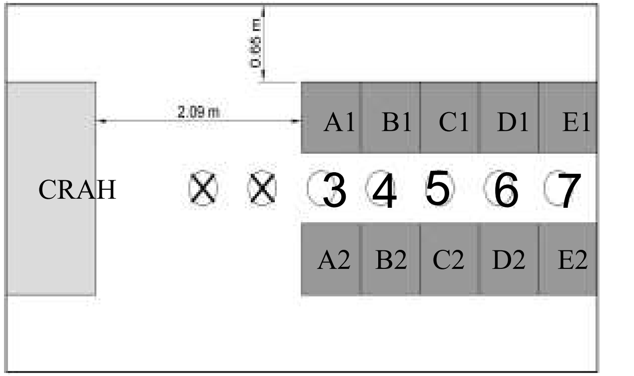
Effect of Distance between CRAH & Racks



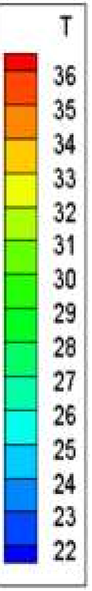
L = 0.79 m

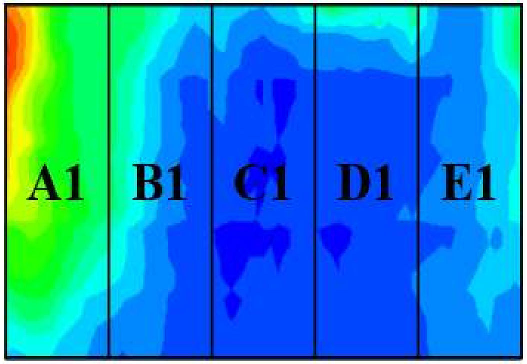


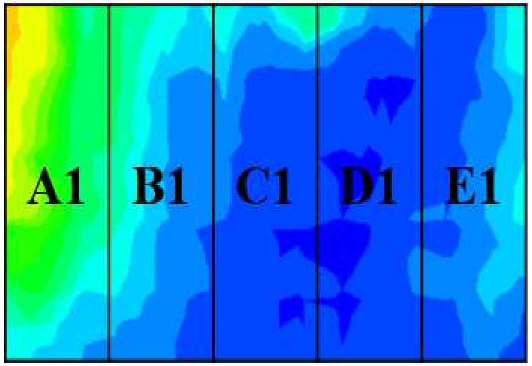
L = 1.39m

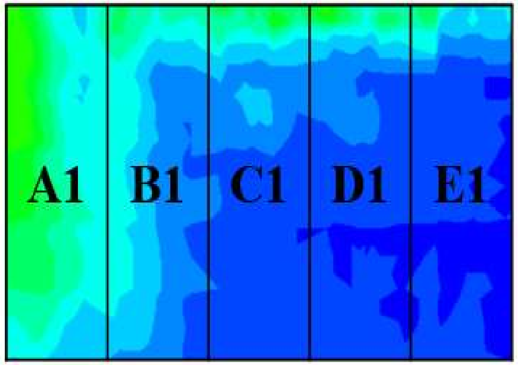


L = 2.09 m



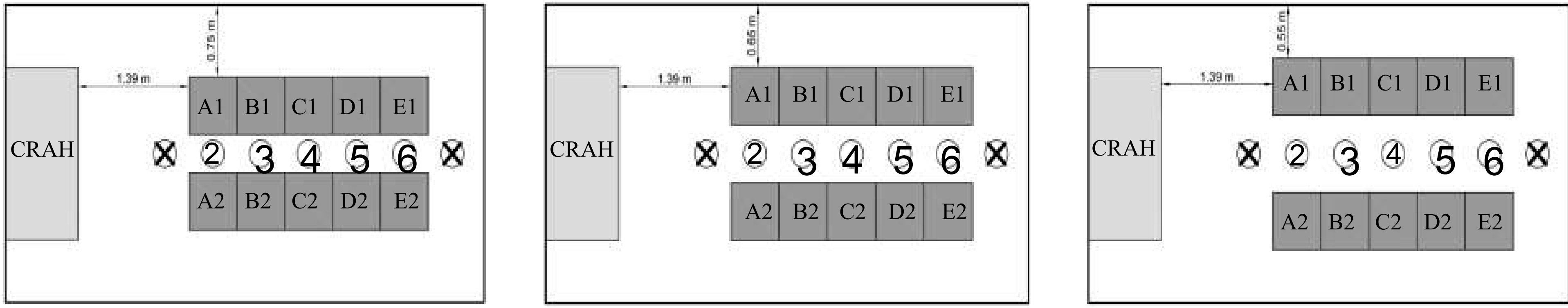




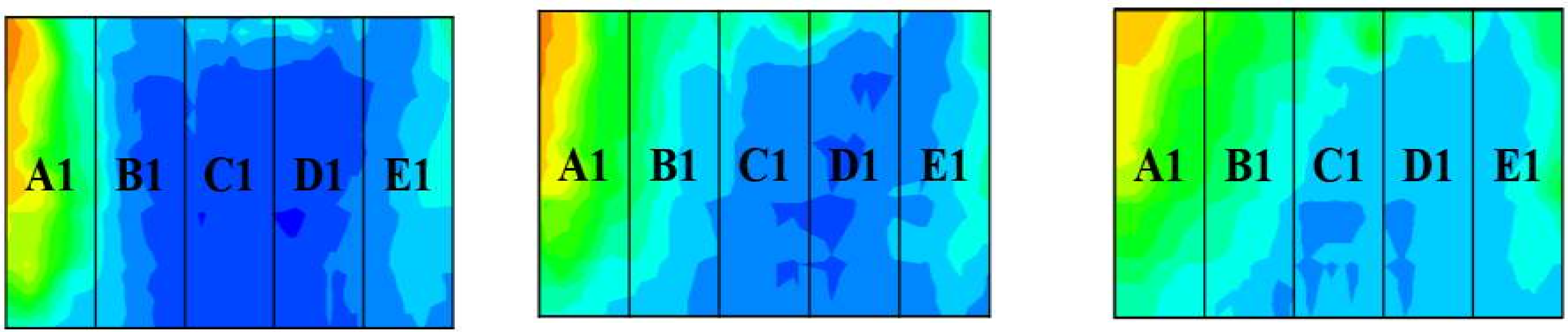


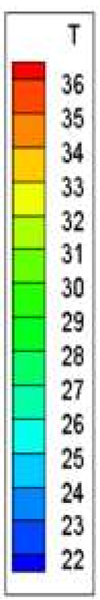
	L_1	L_2	L_3
RCI (%)	86	87	92
SHI	0.371	0.366	0.38
T_{max} (℃)	37.4	35.1	34.8
T_{avg} (℃)	25.8	25.6	25.4

Effect of Cold Aisle Spacing

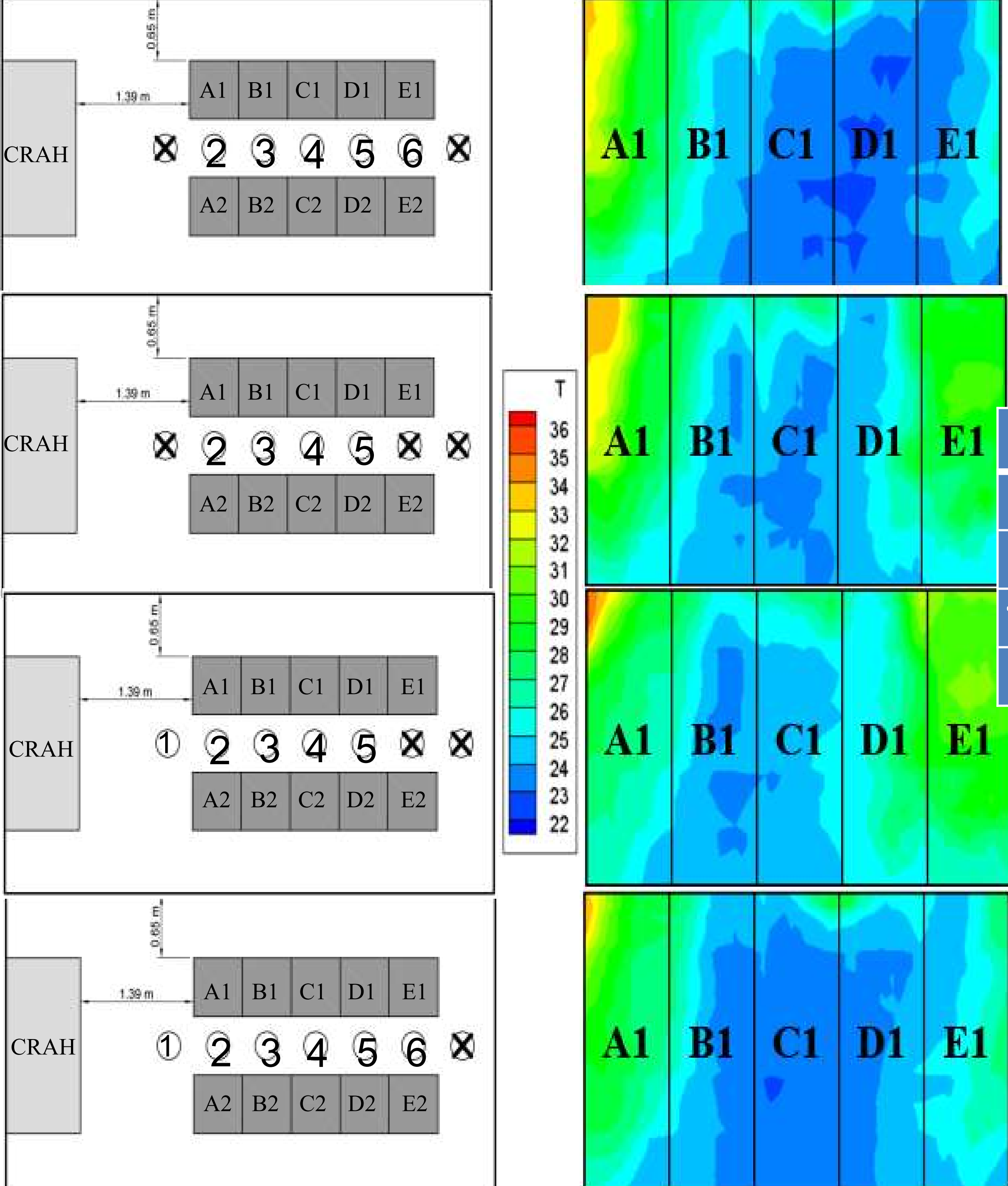


normal Normal +10cm Normal +20 cm





	Normal	5cm	10cm	15cm	20cm
RCI (%)	87	86	87	89	86
SHI	0.32	0.34	0.37	0.39	0.43
T_{max} (℃)	35.2	35.6	35.1	34.2	34.3
T_{avg} (℃)	24.9	25.3	25.6	25.8	26.3

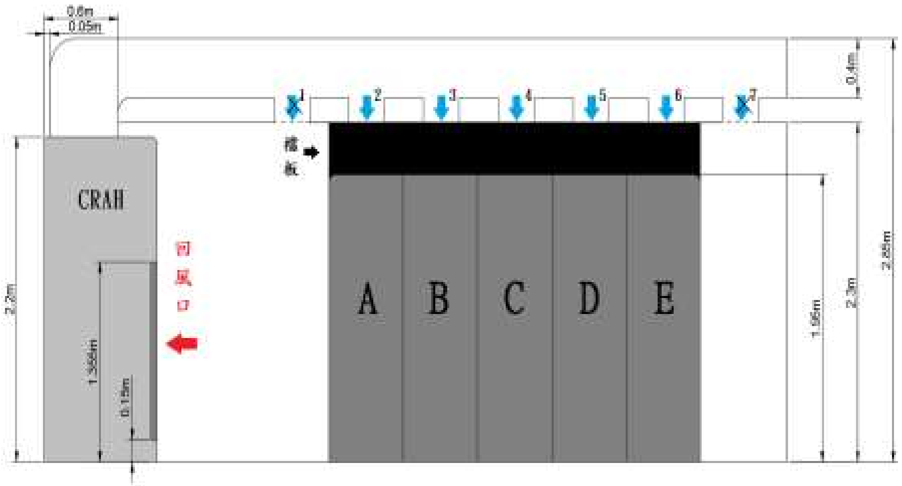


Effect of Vent Opening

opening	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

Experimental configuration

- Open the number 2-6 air supply vent
- Total heat load = 50kW(5 $kW/Rack$)
- CRAH unit temperature = 22℃

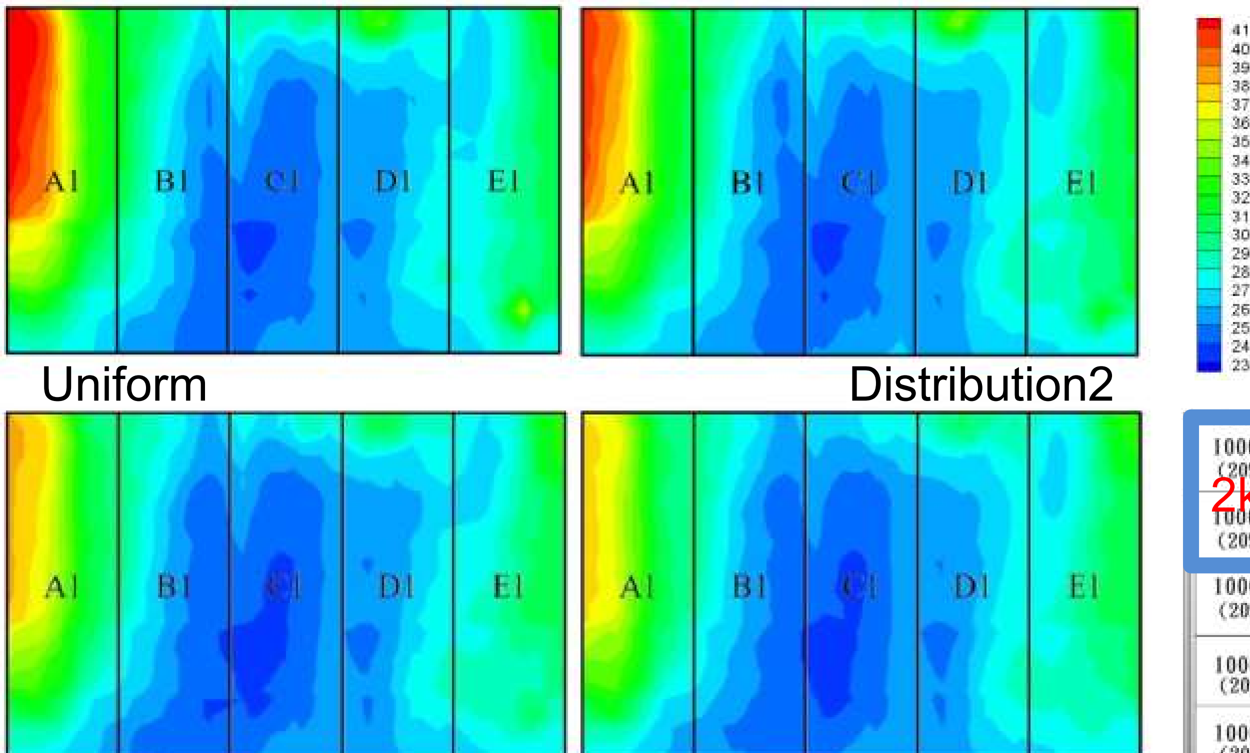


$$\text{Total racks flow rate} = 6\ m^3/s\ (0.6m^3/s \cdot \text{Rack})$$

$$\text{Total racks flow rate} > \text{Total CRAH unit flow rate}$$

Effect of non-uniform heat loading in racks

5 kW for each rack, total 10 racks, 50 kW

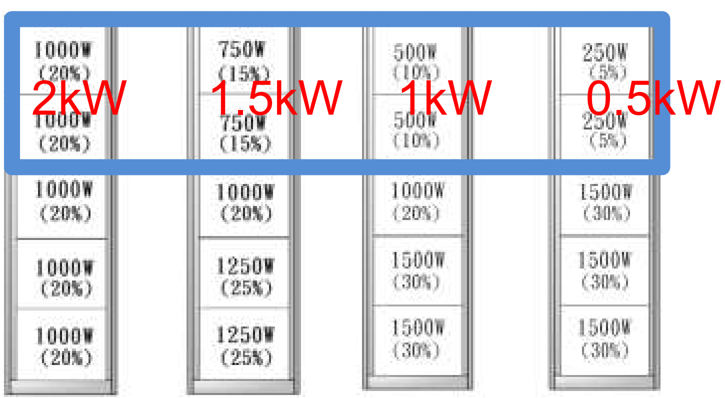


Uniform
Distribution2
Distribution5
Distribution6

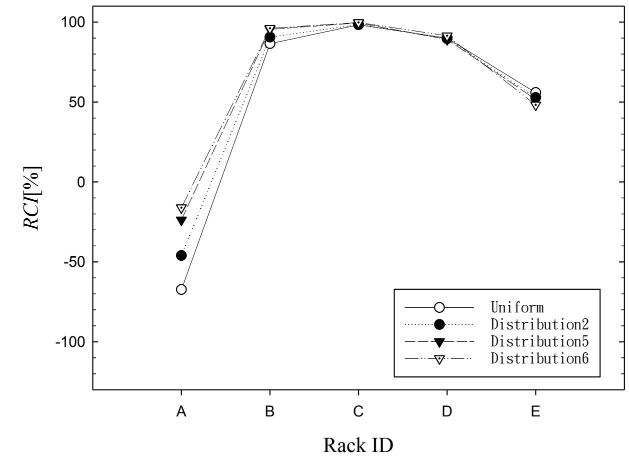
Uniform 2 5 6

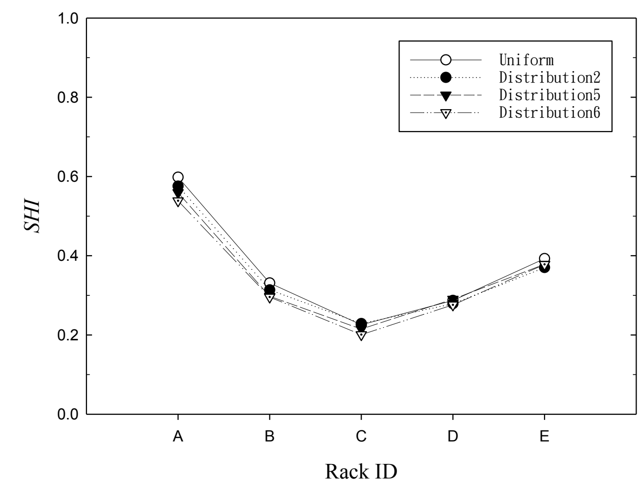
Higher power servers are suggested to placed far from the entrance

	Uniform	Distribution2	Distribution5	Distribution6
RCI (%)	53	57	62	64
SHI	0.367	0.354	0.348	0.338
T_{avg}(℃)	28.7	28.5	28.1	27.9
T_{max}(℃)	42.6	41	38.5	37.9
Rack A RCI(%)	-67	-47	-24	-16
Rack E RCI(%)	56	53	52	48



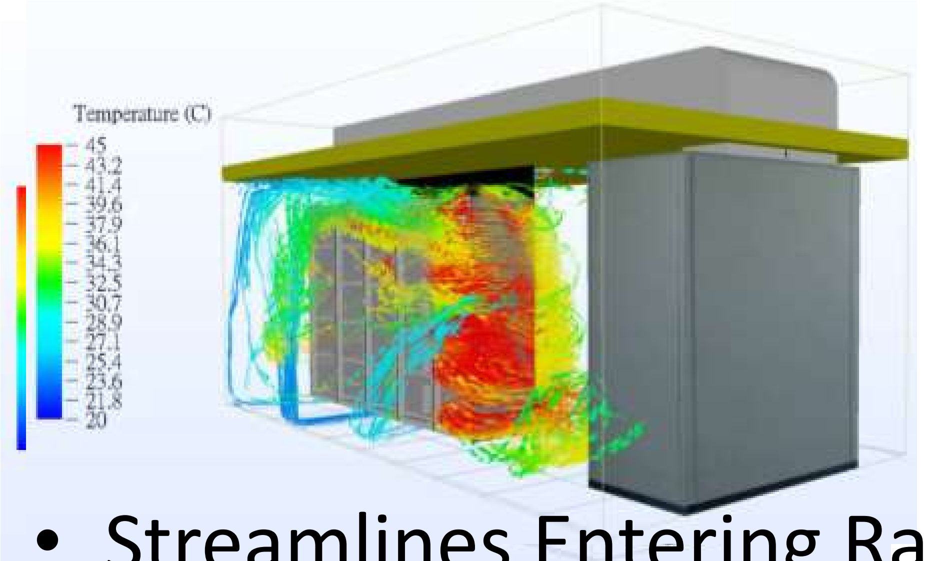
Uniform 2 5 6



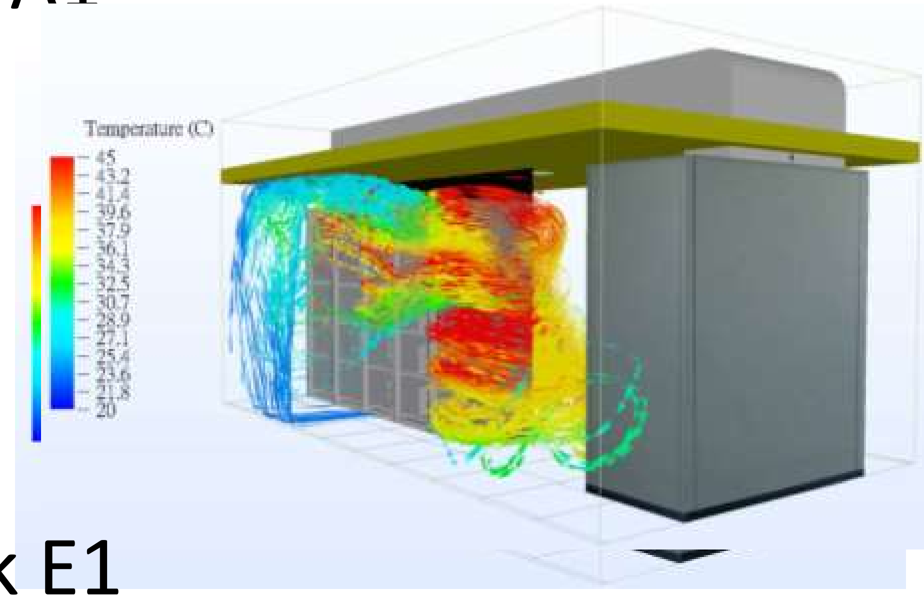


Effect of heat load distribution
(Numerical Simulation)

- Streamlines Entering Rack A1

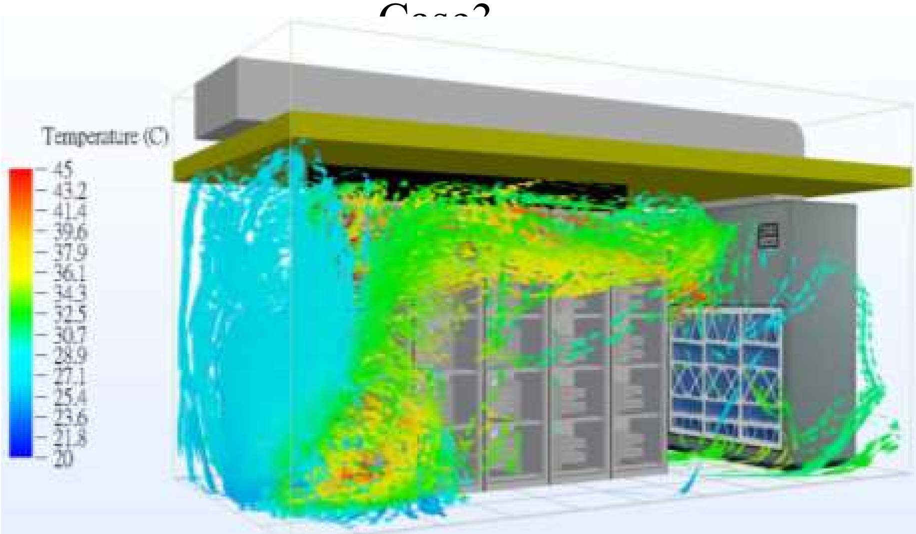


Case2

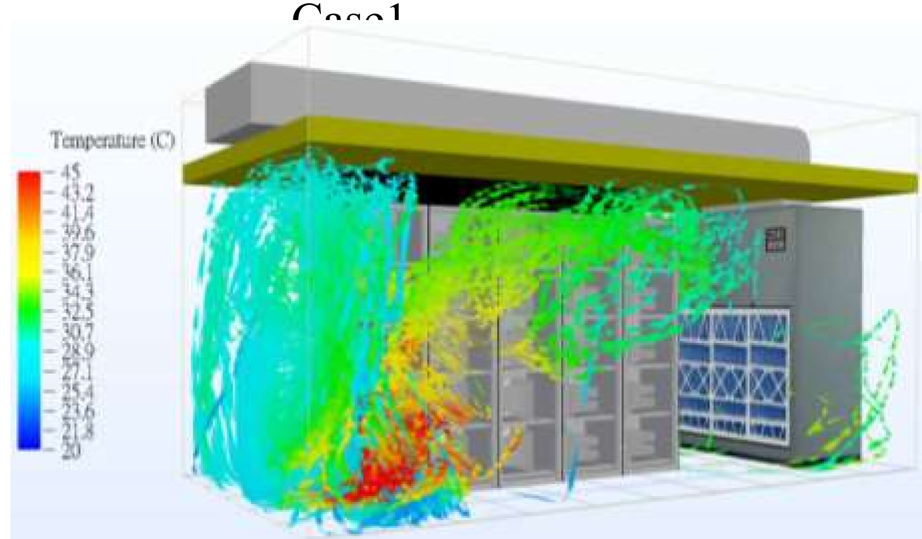


Case1

- Streamlines Entering Rack E1



Case3



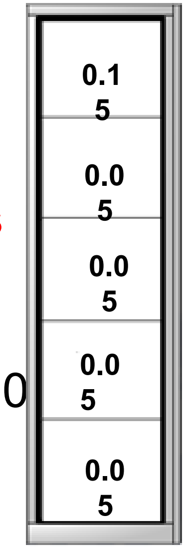
Case5

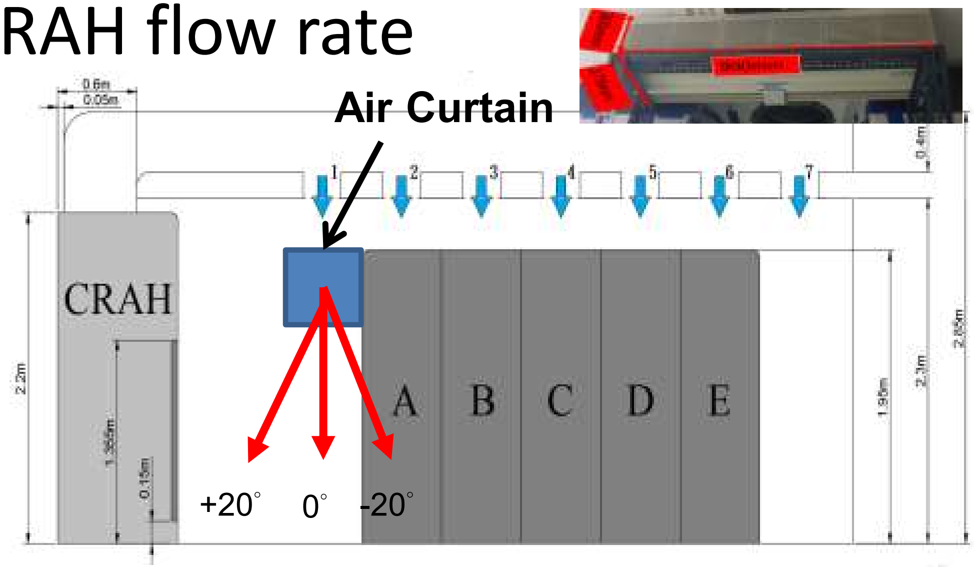
Air Curtain

Racks flow rate = CRAH flow rate

Working conditions:

Total heat load :50 kW
CRAH unit temperature :22 ℃
Total CRAH flow rate: 3.39 m^3/s
Each rack flow rate:0.34 m^3/s
Speed of air curtain：12m/s
Angle of air curtain：-20˚,0˚,+20



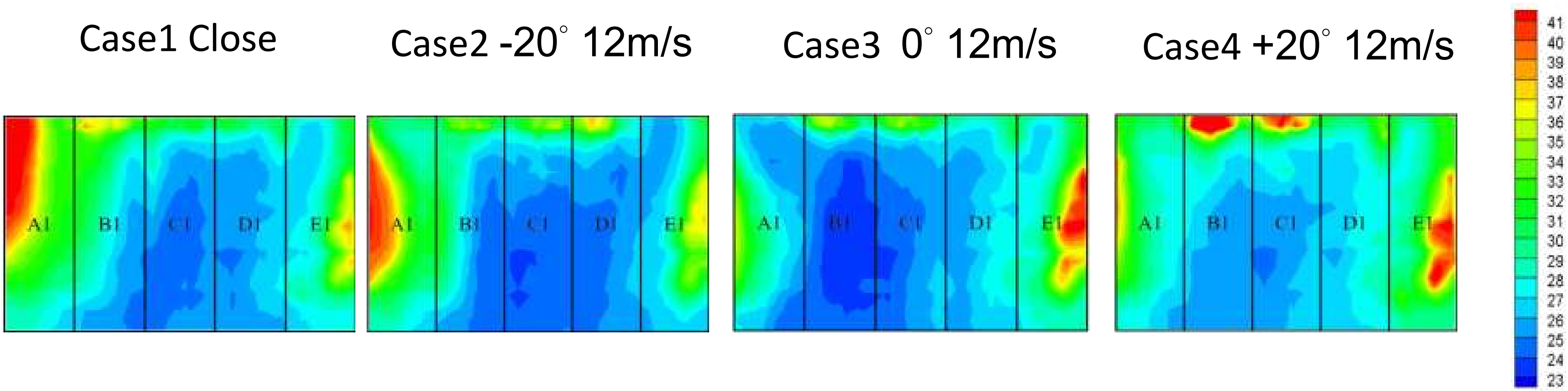


Case1 Close

Case2 -20˚ 12m/s

Case3 0˚ 12m/s

Case4 +20˚ 12m/s



Conclusions..

- Reduce airflow mixing between cold and hot air is a key issue to improve efficiency of data centers. Airflow management, either in server, rack, plenum, or room level requires elaborate considerations.
- Multi-scale thermal management is needed for accurate control of thermal environment of a data center.
- Containment, blockage, partition, flow distribution plays pivotal role in airflow management. Information from numerical, experimental, and field tests are quite essential in more detailing the airflow management/control within data center. Novel designs for effective airflow management is recommended in future research efforts.

Thank you for your attention.

ccwang@mail.nctu.edu.tw

Major funding support

Ministry of Science and Technology, Taiwan, under contract 105-3113-E-009-003–

Appendix

Air cooling for datacenter cooling - common questions

- Which one is the best ventilation scheme for air cooling the datacom equipment?
- What underfloor plenum height should one provide to allow proper distribution?
- What ceiling height is the most optimtim for both raised floor (underfloor supply) and non-raised floor (overhead supply)?
- Where should one place the cabling trays and piping under a raised floor so as to minimize airflow distribution problems?
- How should one design for future growth, which accommodates increases in datacom equipment power and, therefore, increased cooling needs?
- Where should the computer room air-conditioning (CRAC) units be placed for the most efficient use?

Conclusions

1. Increasing the CRAC unit flow rate from $3.4m^3/s$ to $4m^3/s$ will improve RCI by 20%.
2. By reconfiguring the permutations of high heat-density servers in the bottom of racks will improve RCI by 19%. Thereby, we recommend to configure the high heat-density servers in the bottom of the rack.
3. Increasing the flow rate amount of rack part1 to 45% will drastically decrease the hot air recirculation through the interior of the rack

Conclusions

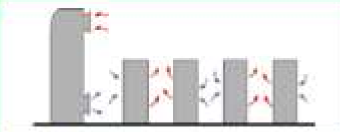
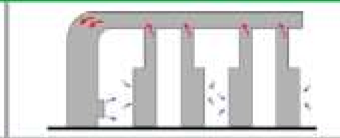
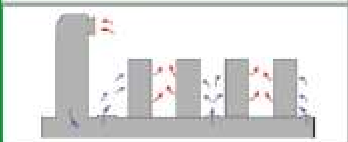
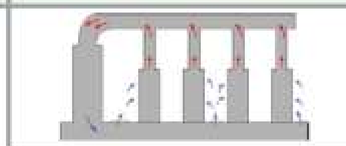
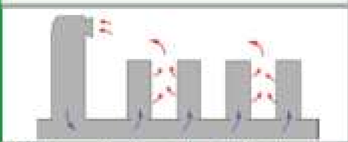
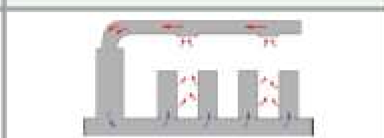
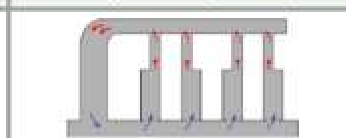
4. When opening the supply air vent 1 from the ceiling, decreasing the intake temperature of Rack A and increase RCI greatly; on the other hand, when opening the supply air vent 7 can increase RCI slightly.
5. Adding partitions on hot aisle will increase the pressure which leads to less cold-airflow into racks and causes temperature rise. After the temperature increase of rack BCD , most of the intake temperatures are below the max

Conclusions

6. Adding partitions on hot aisle will increase impedance, which can prevent the airflow from recirculating to rack A, reducing the over-temperature conditions. However, the hot airflow will recirculate to rack DE, decreasing the RCI of rack DE. Nevertheless, the overall RCI will increase.
7. The placement effects of adding one partition or a few partitions at the return air plenum are fairly equal.
8. Adding partitions on rack A will increase the

Table 1

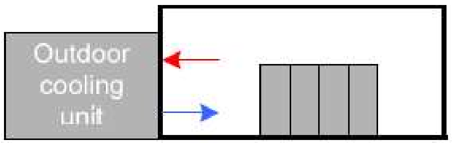
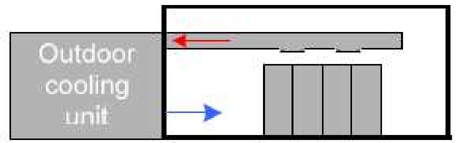
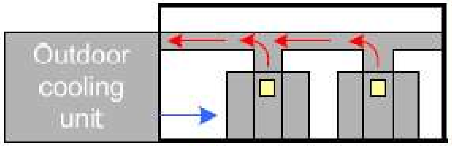
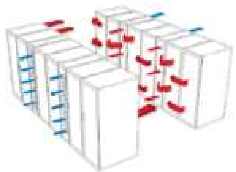
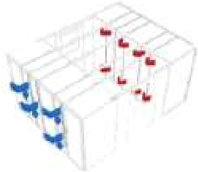
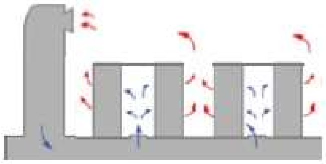
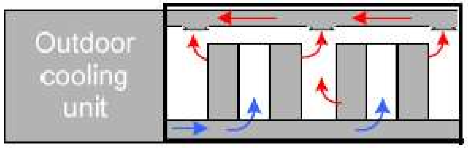
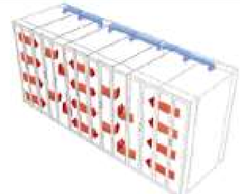
The 9 types of air distribution (traditional room-based cooling implementations)

	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

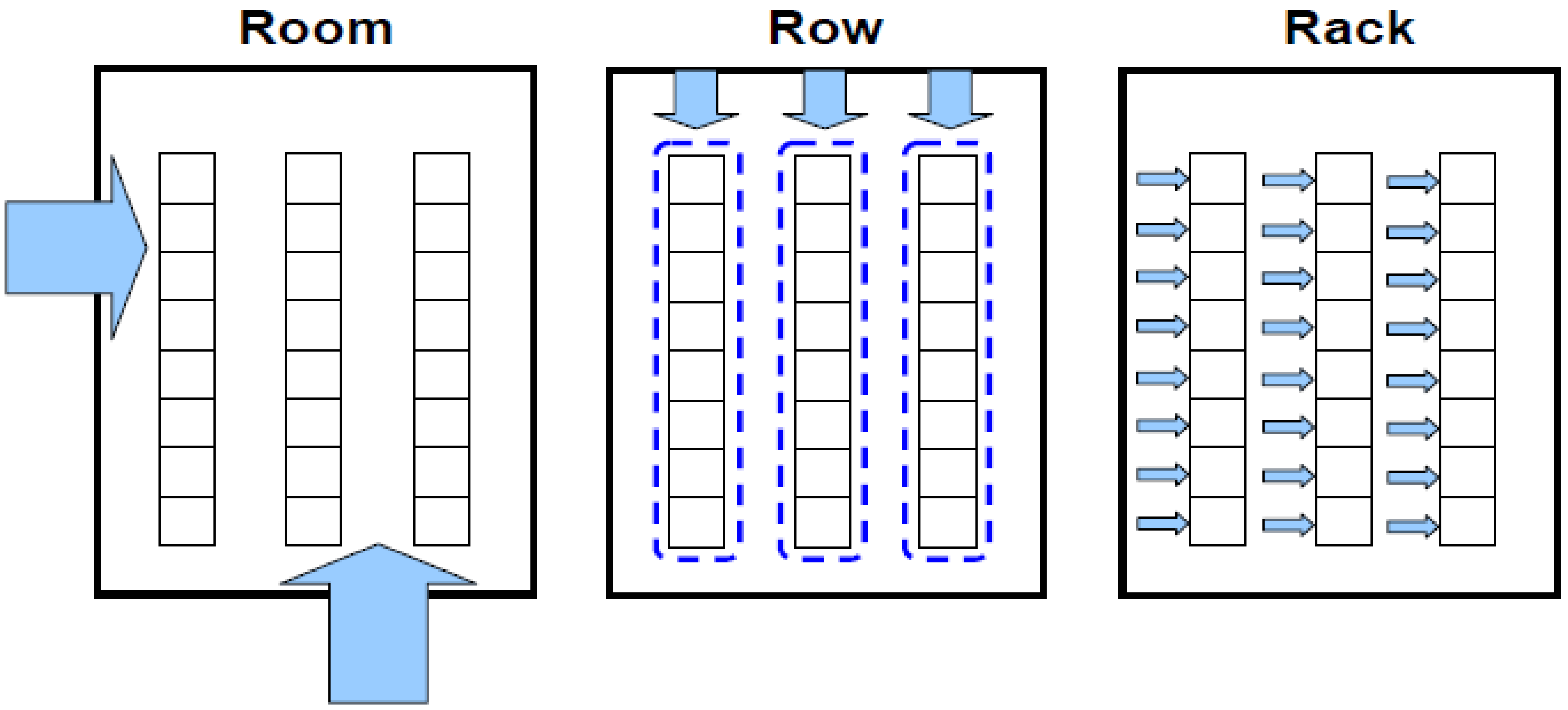
Non-traditional implementations

	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.

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.*



Cold Aisle Containment Benefits:

- Easier to implement; does not require additional architecture to contain exhaust air and return it to the cooling units (drop ceiling, air plenum etc.).
- Only requires doors at ends and cap at top.
- Generally less expensive.
- Cold aisle containment is typically going to be easier to retrofit in an existing data center, particularly when there are overhead obstructions to circumnavigate, such as power and network distribution, ducts, lighting.
- Cold aisle containment doesn't absolutely need to be on a raised floor, but it typically is because of challenges associated with delivering supply air to the contained space(s).
- Enables more surface area for "cold sinks" (with or without a raised floor) ride through in the event of power failure and engine generators not starting.

http://www.upsite.com/blog/hot-aisle-containment-vs-cold-aisle-containment-better-data-center/

Cold Aisle Containment Challenges:

- In cold aisle containment, the overall data center becomes the hot aisle and that space could be dramatically hot if the theoretical advantages of containment are fully pursued, i.e., higher supply temperatures resulting in possibly extreme exhaust temperatures.
- There may not be any space with a suitable temperature profile for equipment that for whatever reason is not compatible with living in the containment arrangement. This could mean lowering the supply temperature and losing some of those economic benefits to provide a suitable environment for some of these non-contained electronics.
- Increases mixing of return air and lowers delta T.
- Conditioned air leaking from the raised floor and openings under equipment such as PDUs enters the exhaust air paths returning to cooling units. This reduces the efficiency of the system.
- Full cold aisle containment creates what the NFPA codes call a “separate volume”, so there needs to be fire suppression for the overall data center space and then either additional fire suppression for the contained cold aisle, or the containment must be connected to the smoke detection system and remove itself as an obstruction on a smoke alarm.

Hot Aisle Containment Benefits:

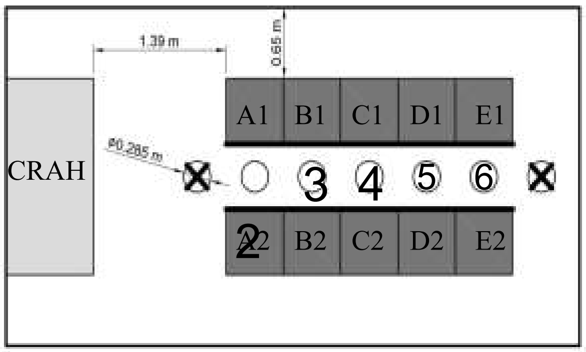
- Open area of room is a cold environment.
- Leakage from raised floor openings in the larger area of the room goes into the cold space.
- Generally more effective.
- Hot aisle containment will be more forgiving for network racks and stand-alone equipment such as storage cabinets that might have to live outside the containment architecture, i.e., they will live in the lower temperature area of the computer room.
- Hot aisle containment can perform well in a slab environment by merely flooding the data center with an adequate volume of supply air and containing the exhaust air.
- Hot aisle containment, by virtue of the containment structures typically abutting the ceiling where fire suppression is installed, is not creating separate volumes, but merely creating obstructions which need to meet clearance requirements from sprinkler heads. With a well-designed space, it is conceivable that a standard grid fire suppression system could be installed around a hot aisle containment array of barriers and meet code.

Hot Aisle Containment Challenges:

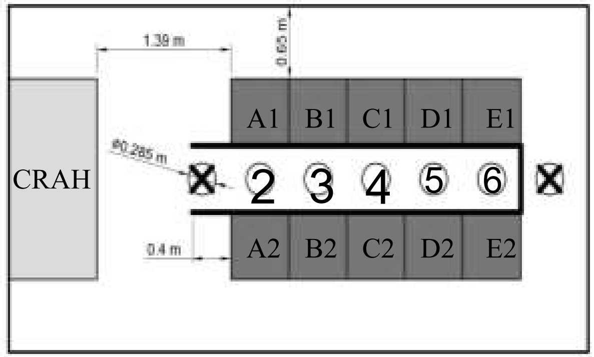
- Requires a contained path for air to flow from the hot aisle all the way to cooling units. Often a drop ceiling is used as return air plenum.
- Generally more expensive.
- Higher temperatures in the hot aisle create uncomfortable conditions for technicians working on IT gear. Note that some server manufacturers are developing and supplying front-serviceable servers, which means that the hot aisle, whether contained or not, would hardly ever need to be entered.

- In brief, cold aisle containment is a structure used to separate the hot and cold aisle. This minimizes the mixing of hot and cold air.
- One can expect energy savings from aisle containment for more uniform rack inlet temperatures to allow data center operators to supply air at a higher temperature and possibly also at a lower flow rate.

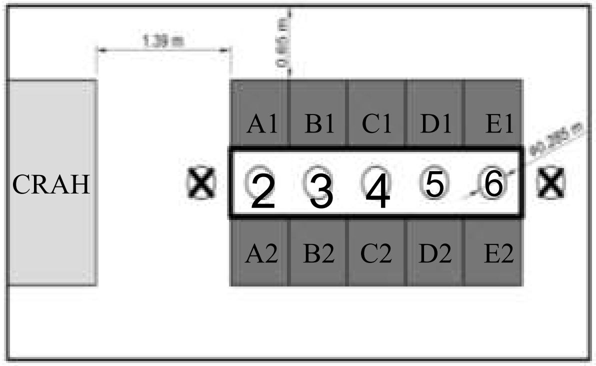
Effect of Blocking



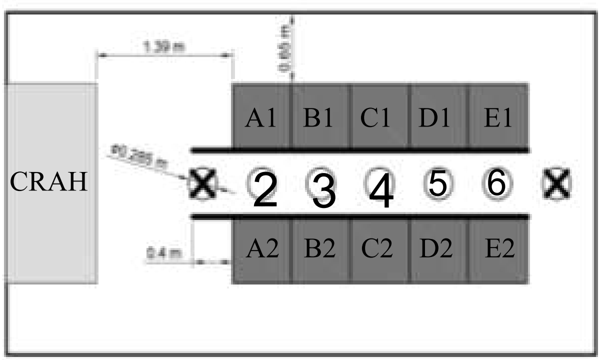
標準配置



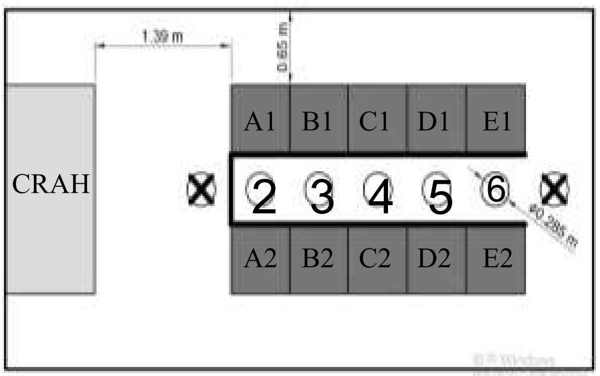
水平擋板於機櫃A和垂直擋板於機櫃E



垂直擋板於機櫃A和機櫃E

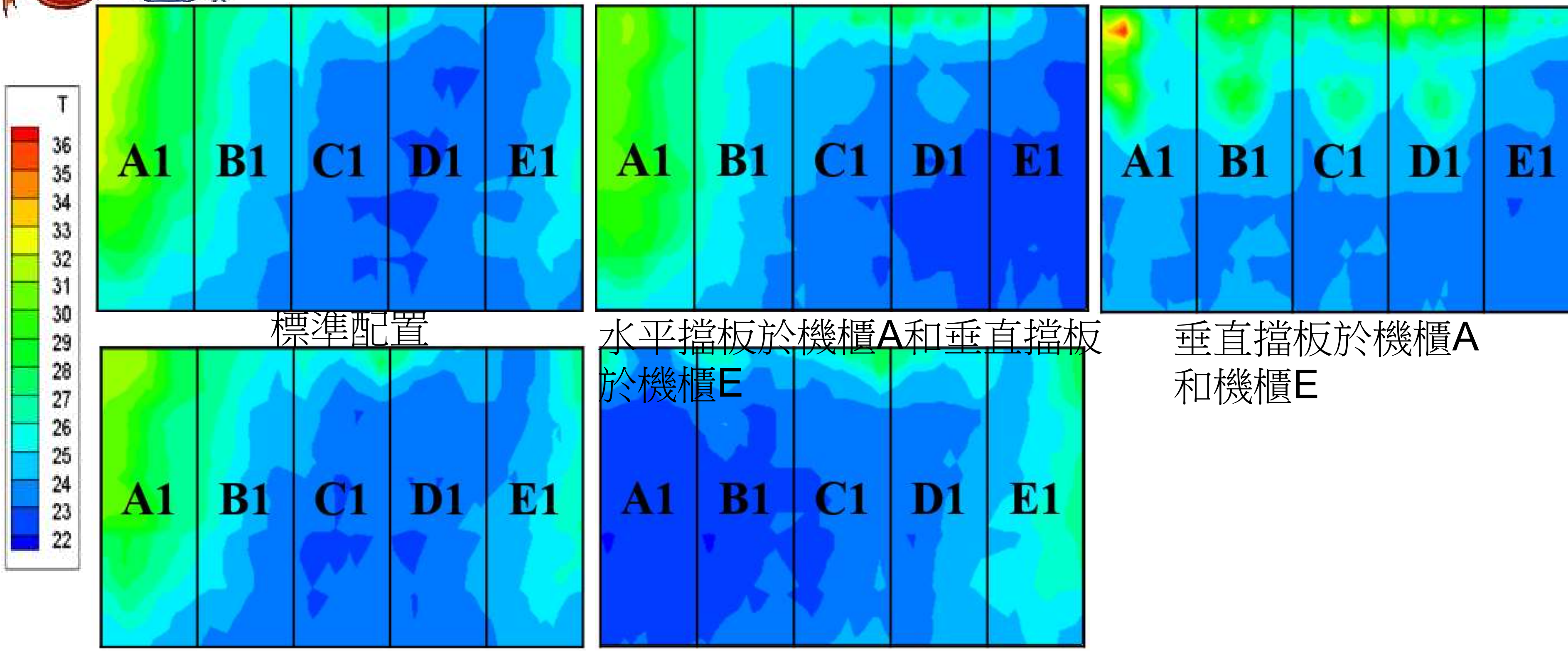


水平擋板於機櫃A



垂直擋板於機櫃A

Results



標準配置

水平擋板於機櫃A和垂直擋板於機櫃E

垂直擋板於機櫃A和機櫃E

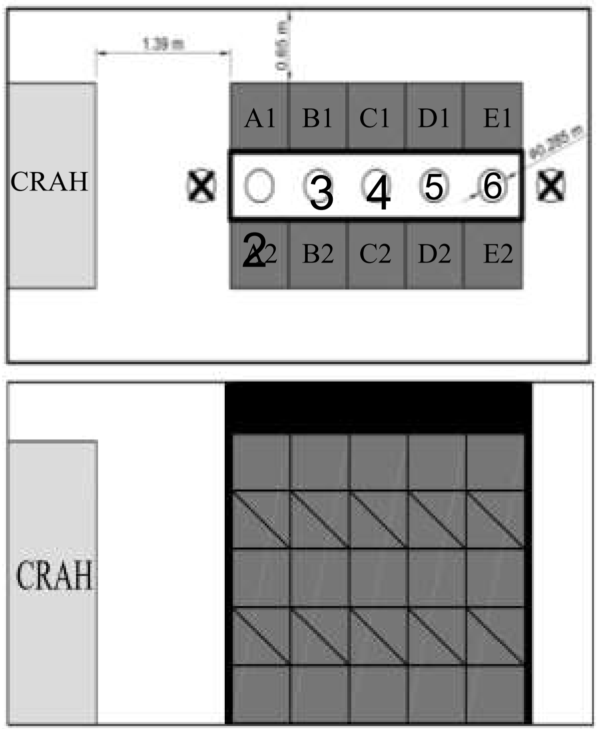
水平擋板於機櫃A

垂直擋板於機櫃A

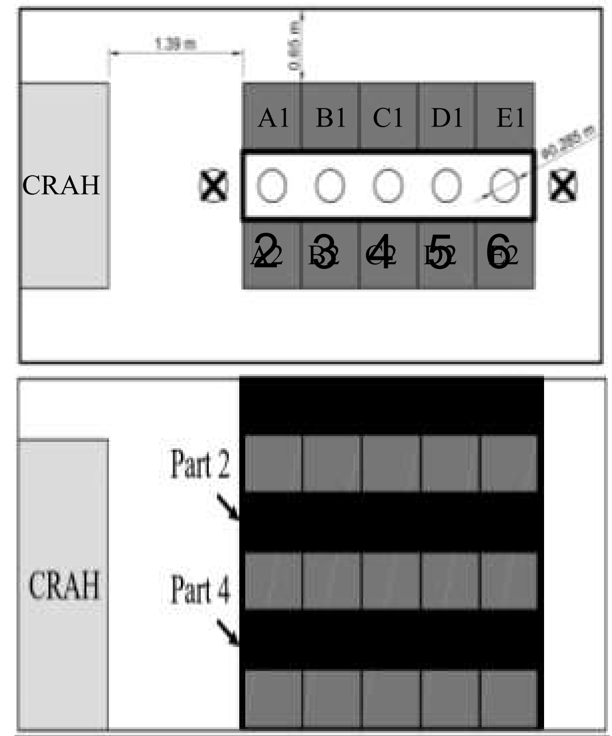
	標準配置	機櫃A 水平擋板	機櫃A 水平擋板-機櫃E 垂直擋板	機櫃A 垂直擋板	機櫃A、E垂直擋板
RCI (%)	87	91%	89%	99%	91%
SHI	0.37	0.35	0.36	0.27	0.39
T_{max} (℃)	35.1	33.6	33.6	28.9	38.3
T_{avg} (℃)	25.6	25.4	25.3	24.2	25.3

結果與討論

- 冷通道封閉之機櫃空隙探討



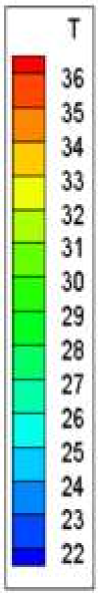
無入口
擋板

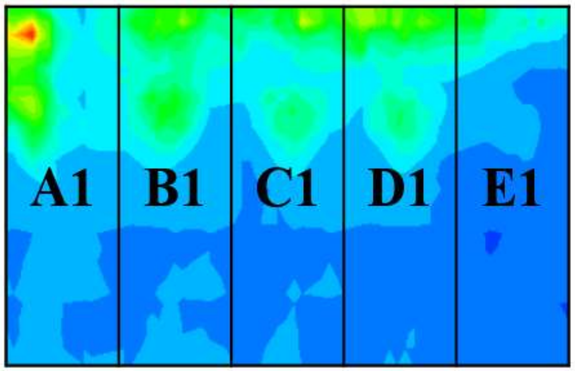


安裝入口
擋板

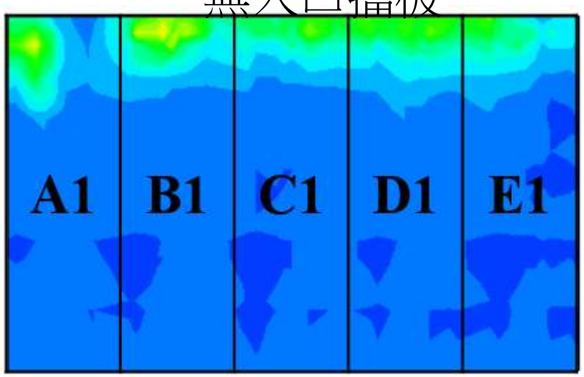
結果與討論

- 冷通道封閉之機櫃空隙探討

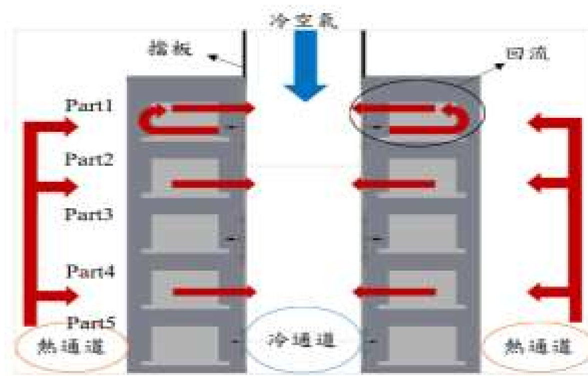




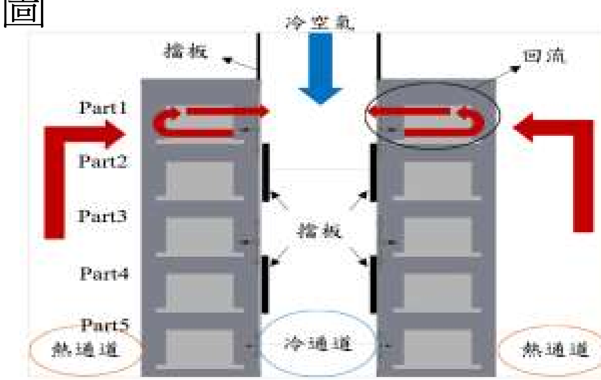
無入口擋板



安裝入口擋板



無入口擋板之熱空氣回流示意圖

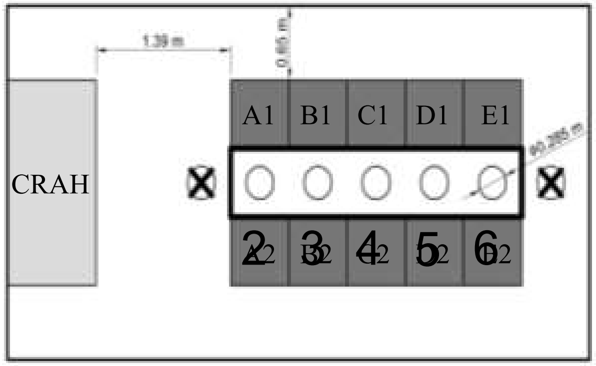


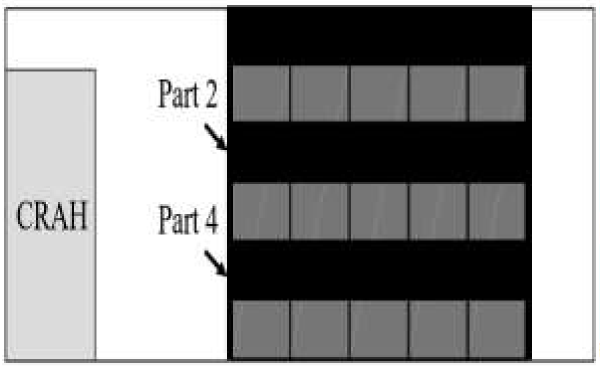
安裝入口擋板之熱空氣回流示意圖

機櫃Part2和Part4擋板	無	有
RCI (%)	91%	95%
SHI	0.39	0.3
T_{max} (℃)	38.3	35.9
T_{avg} (℃)	25.3	24.1

安裝擋板於入口之實驗結果

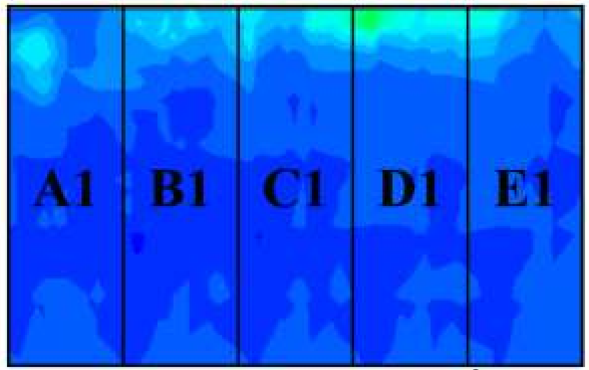
Effect of Air flowrate in Full Cold Aisle Containment



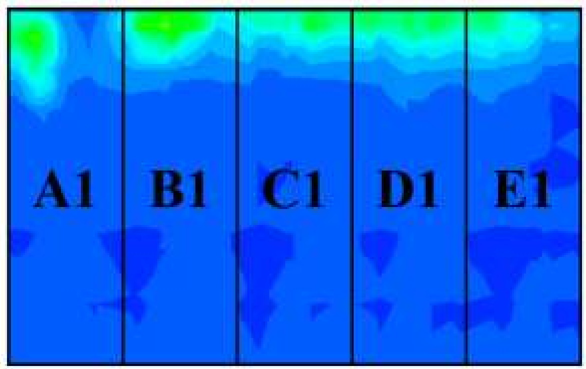


調整供風量之機房配置圖

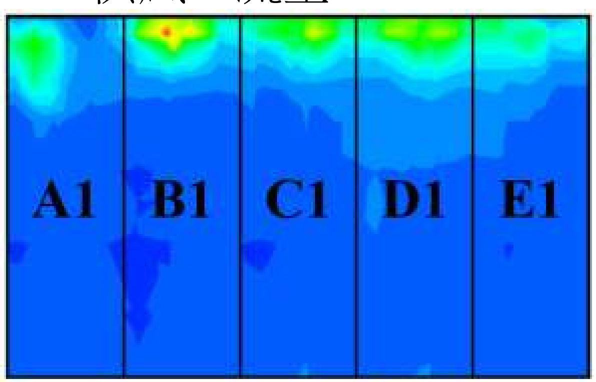
供風口流量2.83m³/s

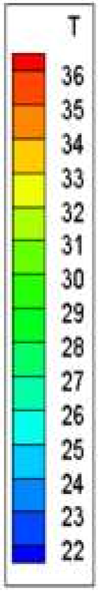


供風口流量3.52m³/s

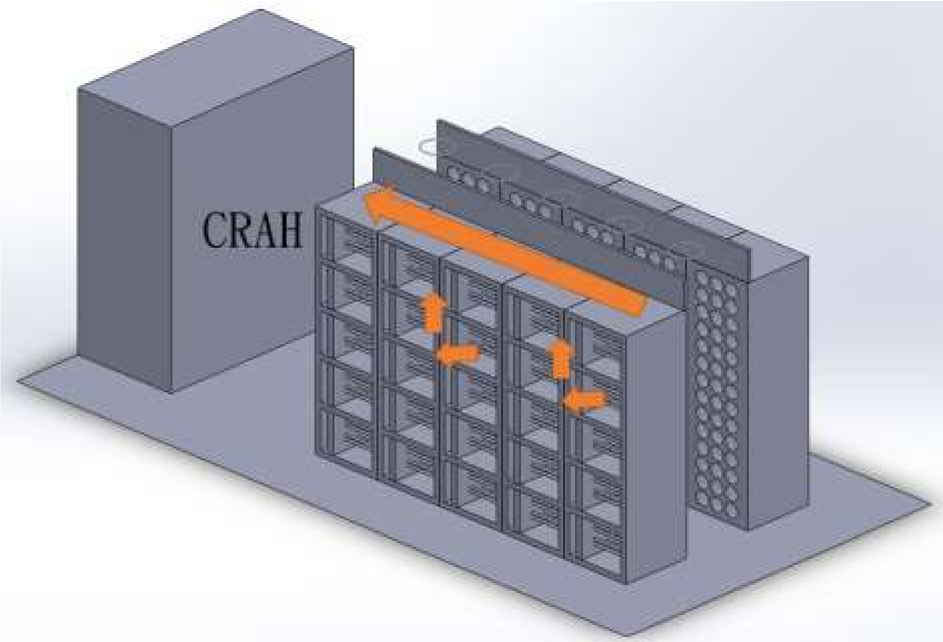


供風口流量3.93m³/s



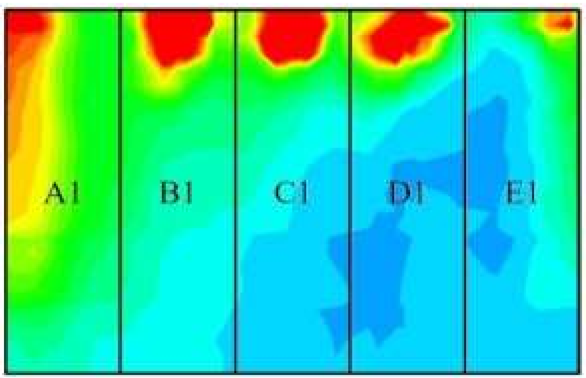


風口流量 (m^3/s)	小 (2.83)	中 (3.52)	大 (3.93)
RCI (%)	99%	95%	90%
SHI	0.23	0.3	0.37
T_{max} (℃)	33.7	35.9	43.3
T_{avg} (℃)	23.6	24.1	24.8

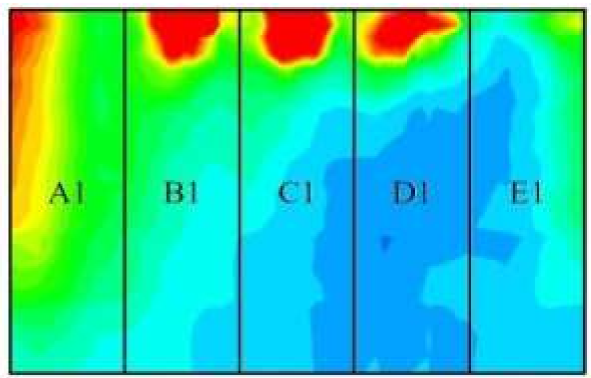

CRAH

Total racks flow rate > Total CRAH unit flow rate

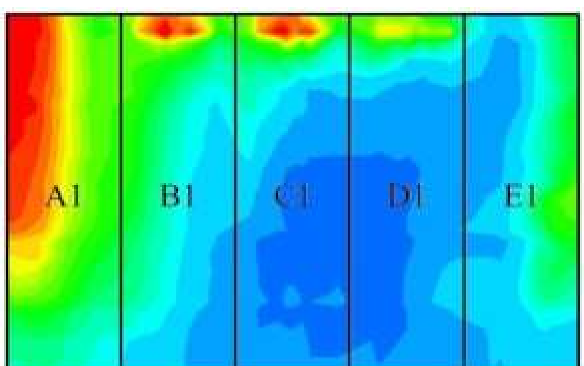
Total racks flow rate 3.4 m^3/s ($0.34 m^3/s \cdot$ Rack)



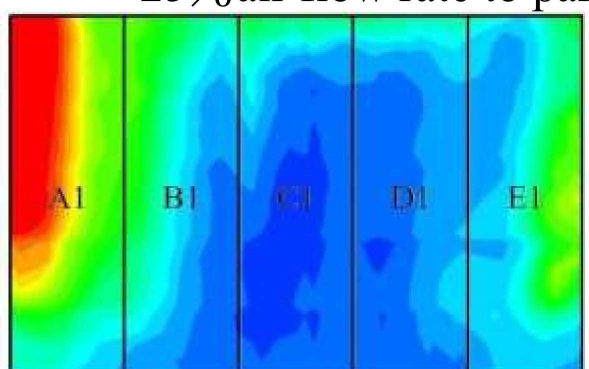
Uniform distribution



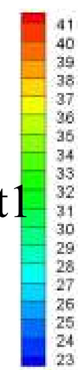
25%air flow rate to part1

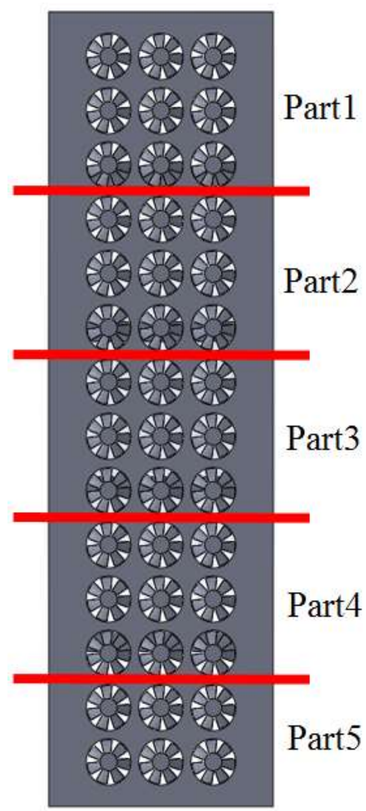


35%air flow rate to part1

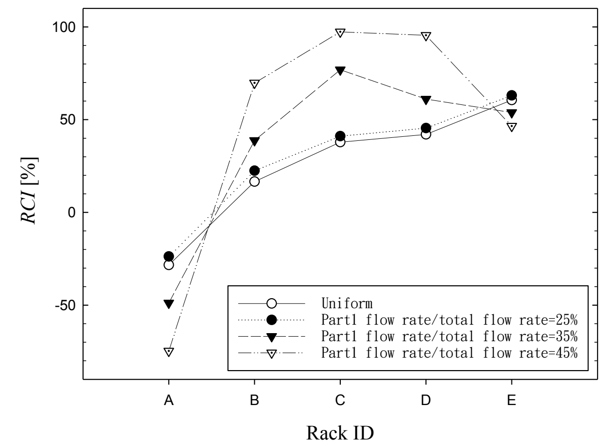


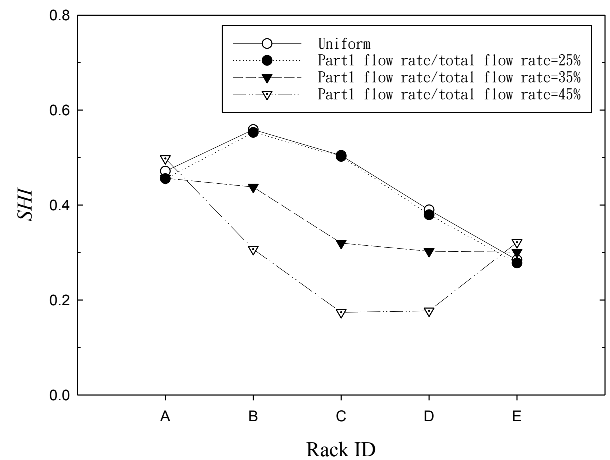
45%air flow rate to part1



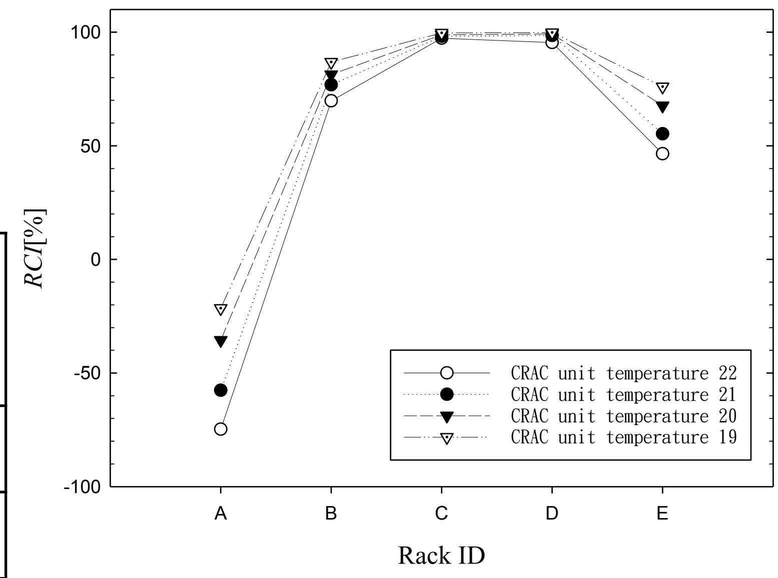


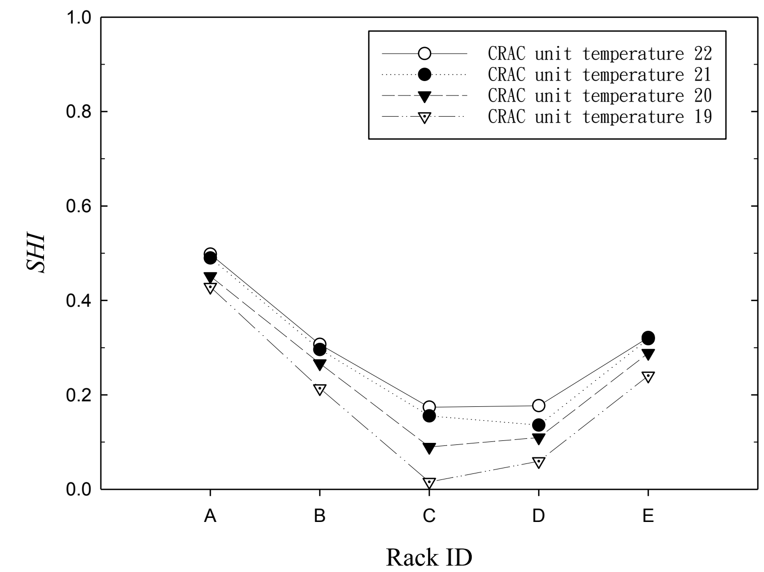
Part1flow rate/total flow rate (%)	Uniform	25%	35%	45%
RCI (%)	26	30	36	47
SHI	0.442	0.434	0.364	0.295
T_{max} (℃)	72.0	68.1	62.2	43.9
T_{avg} (℃)	30.6	30.3	29.7	28.6
Rack A *RCI*(%)	-28	-24	-49	-75
Rack E RCI(%)	61	63	54	46



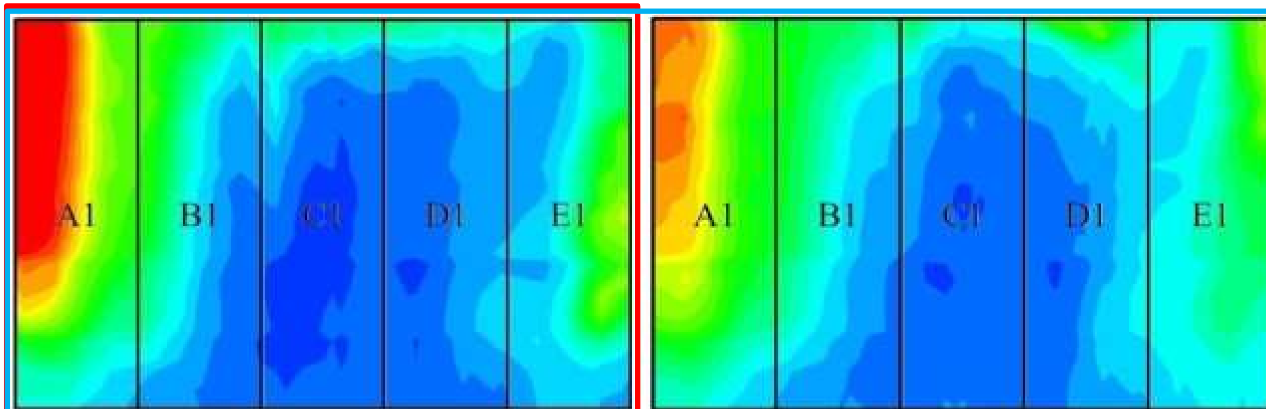


CRAC unit temperature(℃)	22 ℃	21 ℃	20 ℃	19 ℃
RCI (%)	47	54	62	68
SHI	0.295	0.282	0.241	0.192
T_{max} (℃)	43.9	43.6	42.1	42.0
T_{avg} (℃)	28.6	27.9	27.0	26.0
Rack A RCI(%)	-75	-58	-36	-21
Rack E RCI(%)	46	55	68	76

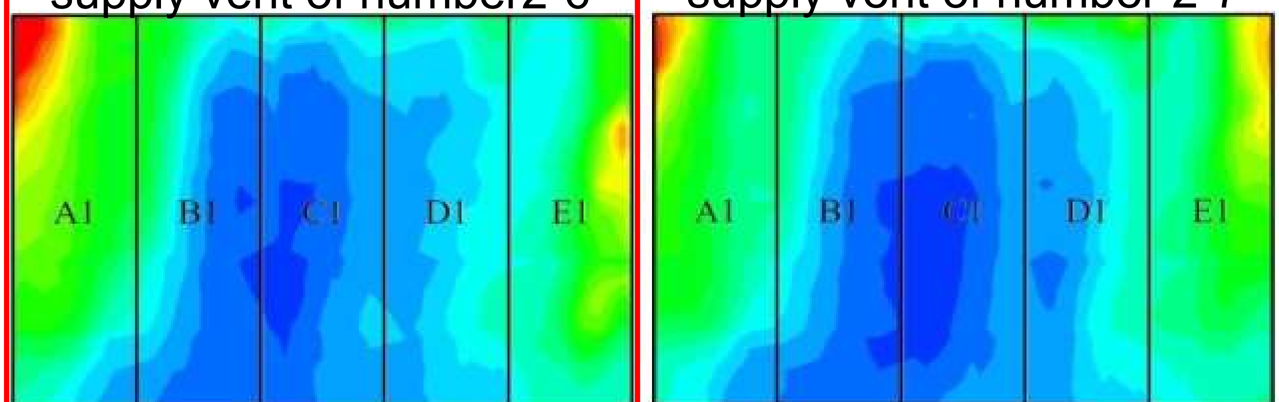




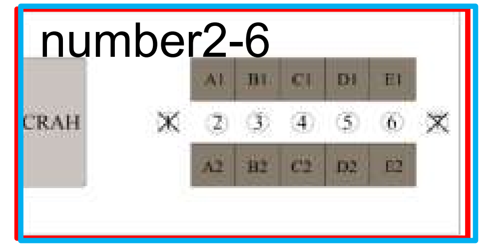
Effect of air supply vent

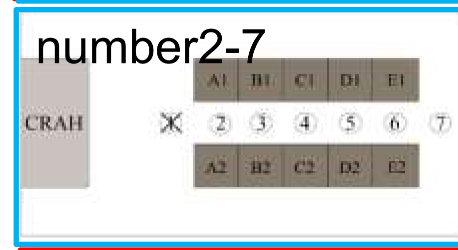


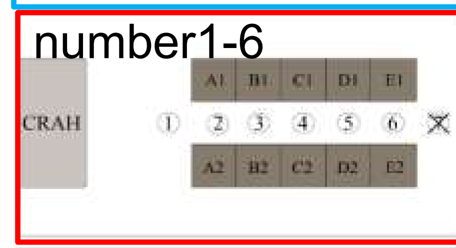
supply vent of number2-6 supply vent of number 2-7

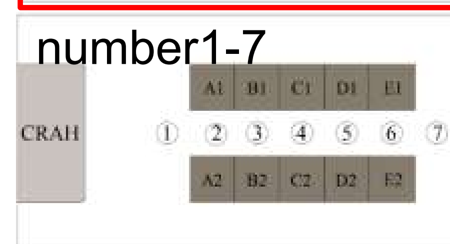


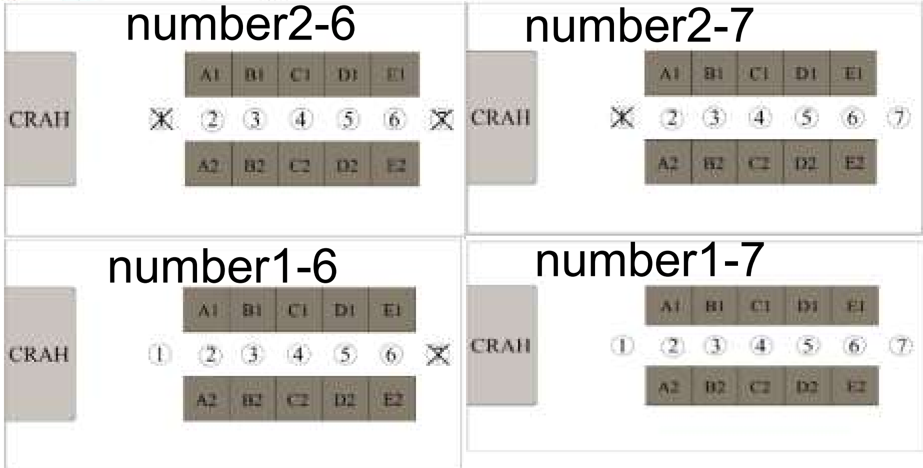
supply vent of number1-6 supply vent of number1-7

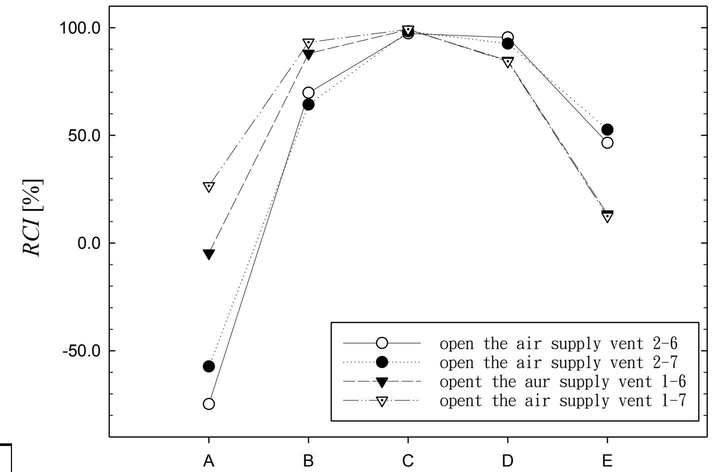




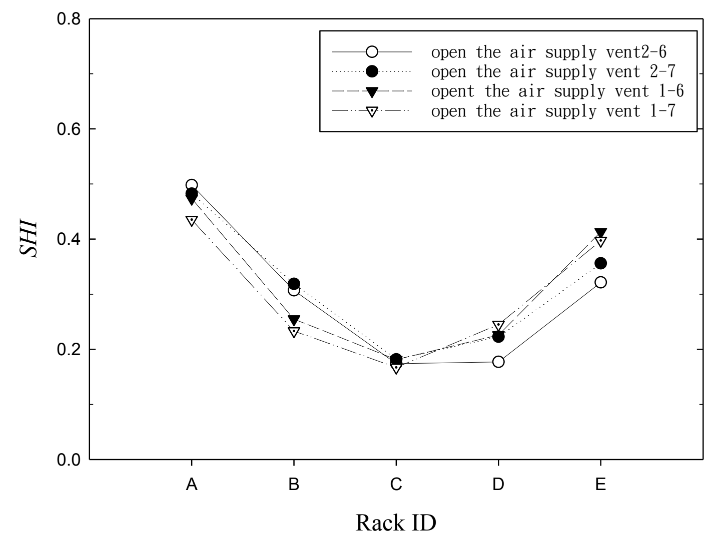








air supply vent opening	2-6	2-7	1-6	1-7
RCI (%)	47	50	56	63
SHI	0.295	0.312	0.31	0.296
T_{max} (℃)	43.9	45.5	44.6	41.6
T_{avg} (℃)	28.6	28.8	28.4	27.9
Rack A RCI(%)	-75	-57	-5	27
Rack E RCI(%)	46	52	13	13

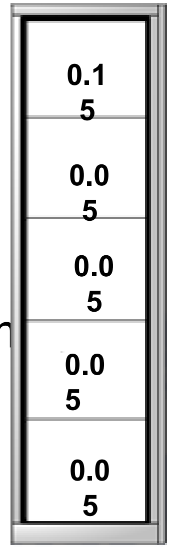


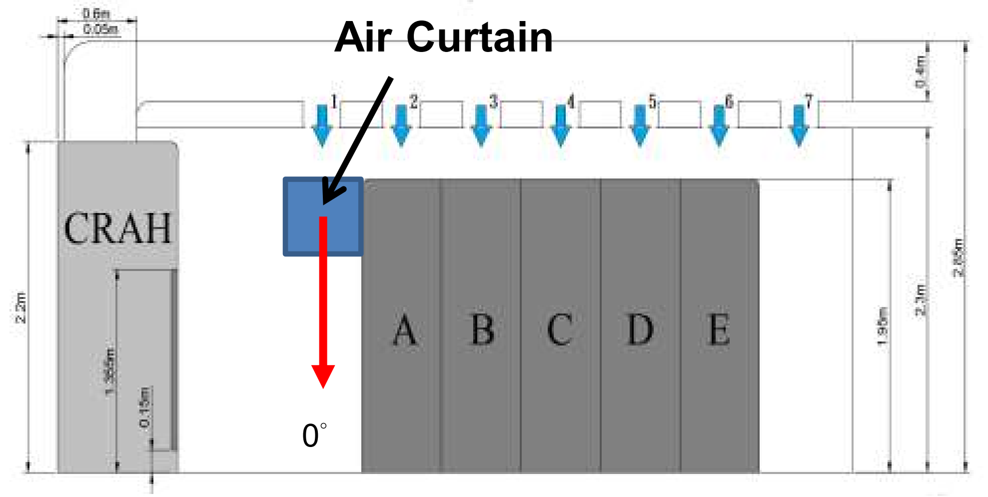
Racks flow rate < CRAH flow rate

國立交通大學
National Chiao Tung University

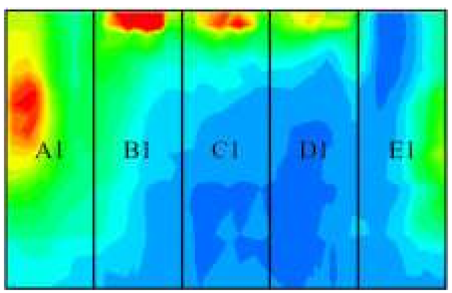
Working conditions:

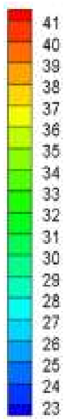
Total heat load :50 kW
CRAH unit temperature :22 ℃
Total CRAH flow rate: 4.32 m^3/s
Each rack flow rate:0.34 m^3/s
Speed of air curtain：7,8.5,10,12m
Angle of air curtain：0°



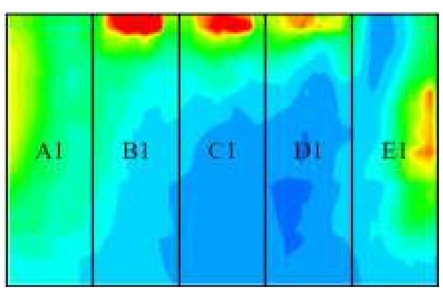


Case5 Close

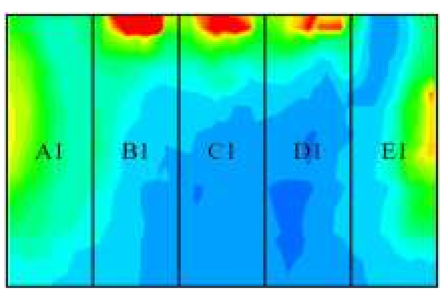




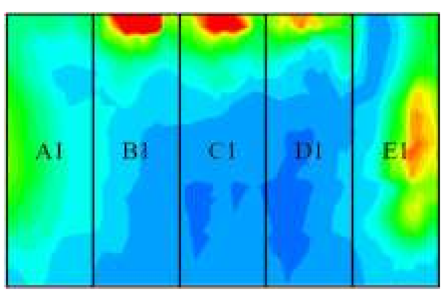
Case6 0° 7m/s



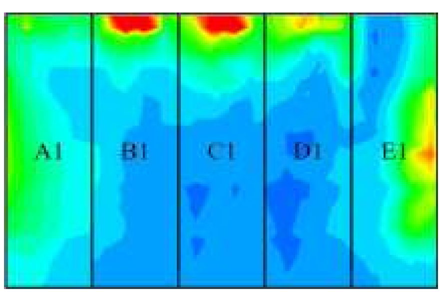
Case7 0° 8.5m/s



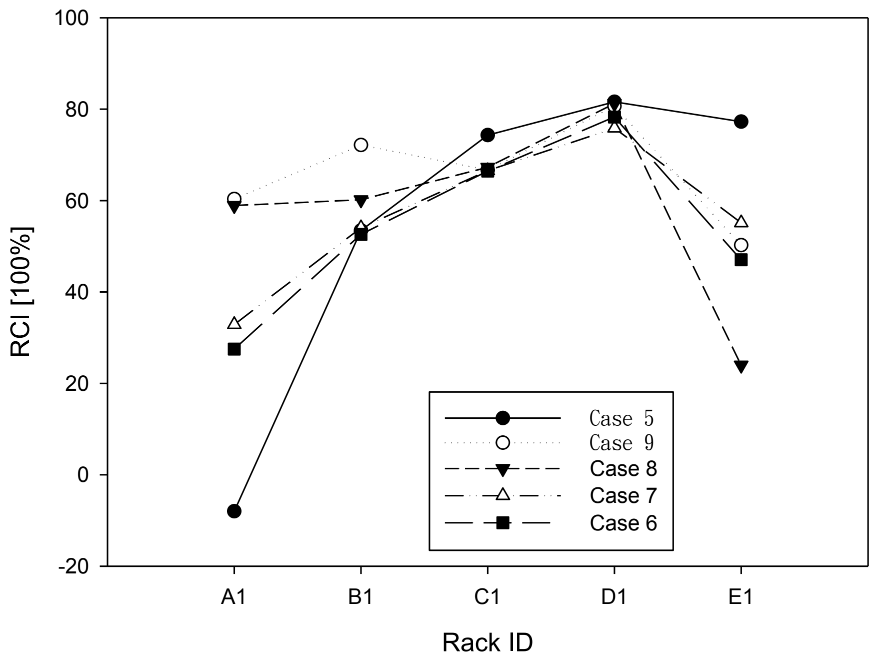
Case8 0° 10m/s

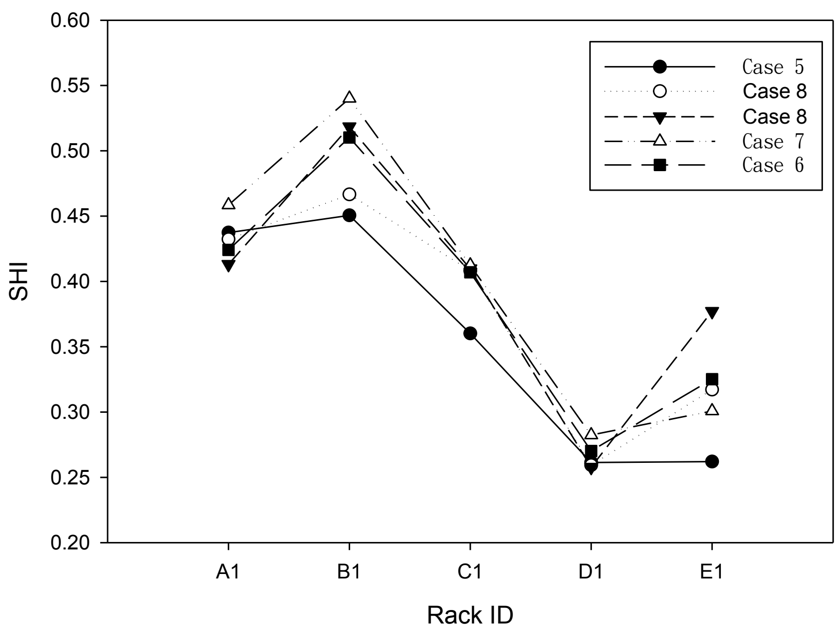


Case9 0° 12m/s



	Case 5	Case 6	Case 7	Case 8	Case 9
T_{max} (℃)	53.7	58.0	63.6	67.3	60.0
T_{avg} (℃)	28.6	29.1	28.7	28.7	28.8
All-RCI(%)	54	51	57	56	55
All-SHI	0.359	0.388	0.385	0.397	0.402
A1- RCI(%)	-8	28	33	59	60

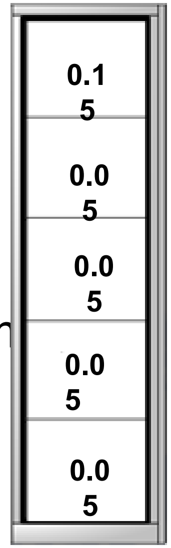


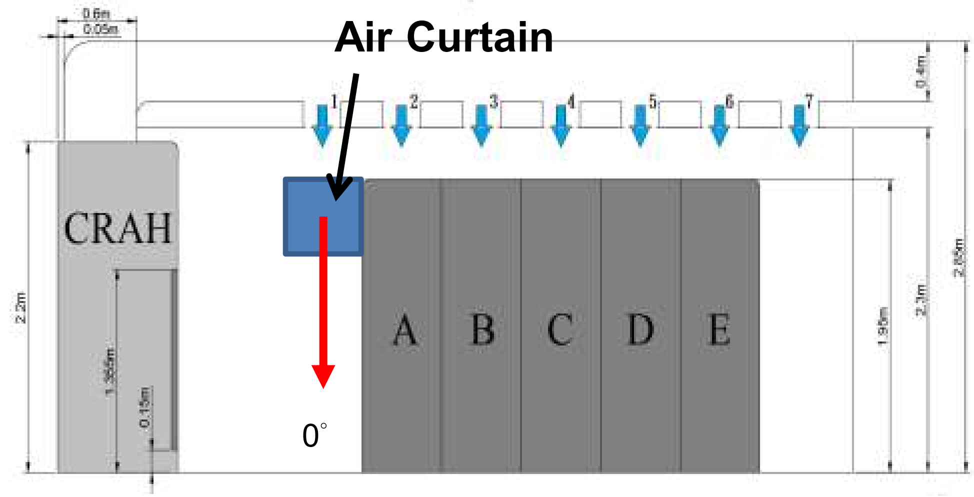


Racks flow rate > CRAH flow rate

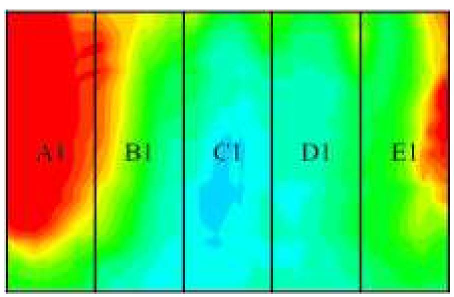
Working conditions:

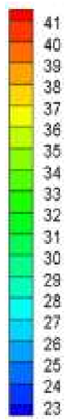
Total heat load :50 kW
CRAH unit temperature :22 ℃
Total CRAH flow rate:2.28 m^3/s
Each rack flow rate: 0.34 m^3/s
Speed of air curtain：7,8.5,10,12m
Angle of air curtain：0°



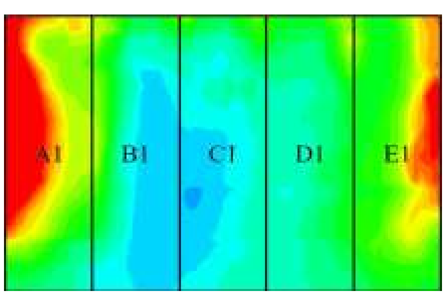


Case10 Close

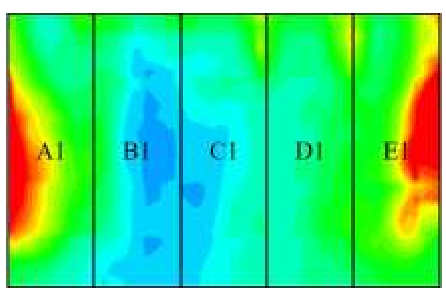




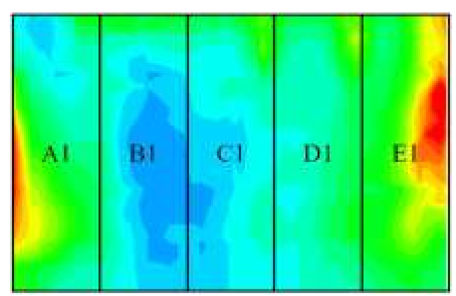
Case11 0° 7m/s



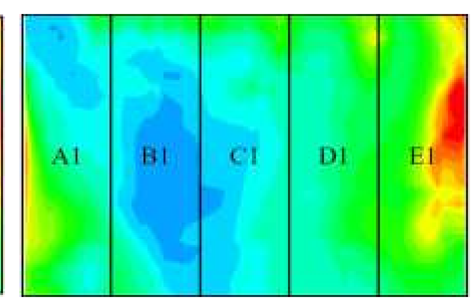
Case12 0° 8.5m/s



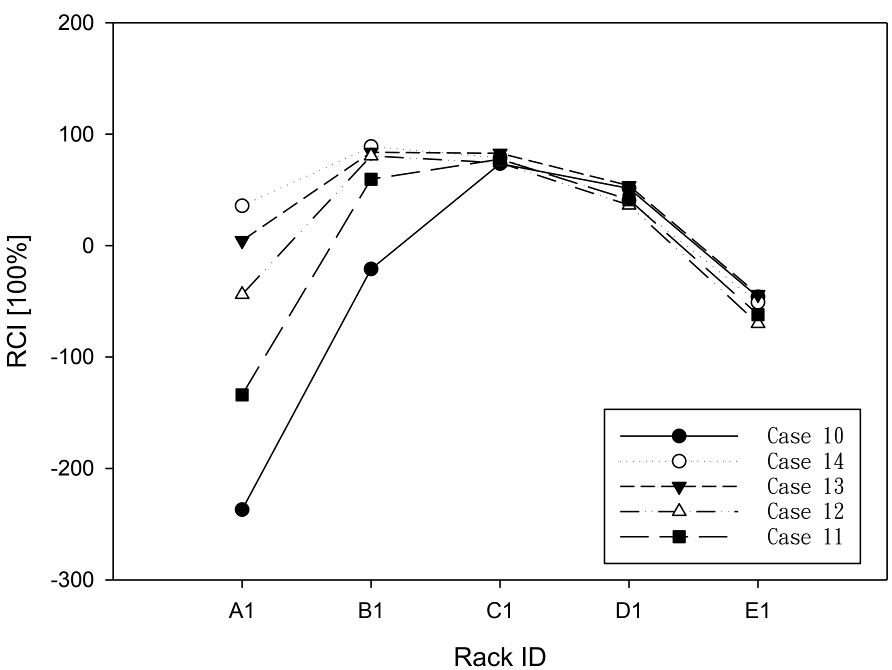
Case13 0° 10m/s

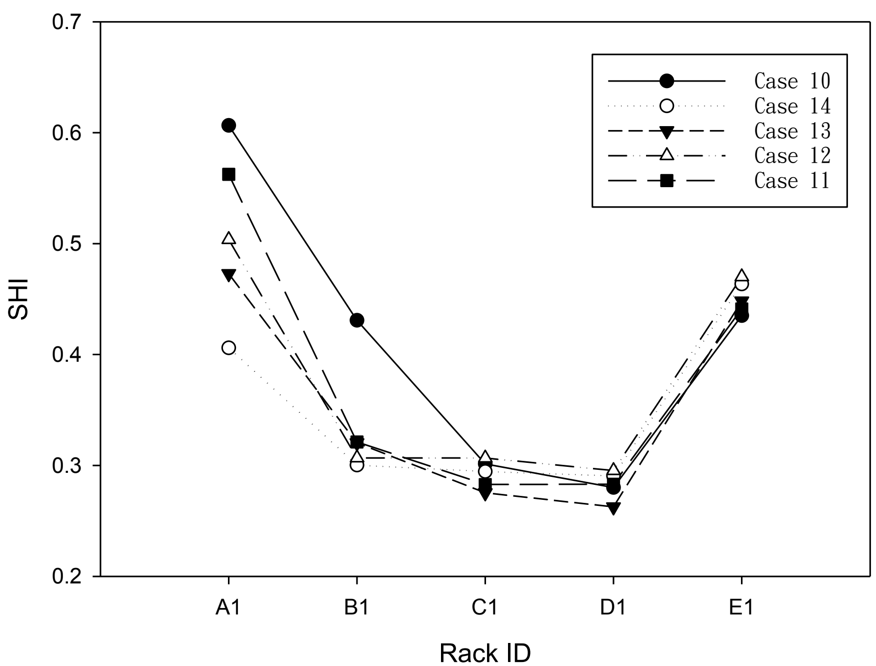


Case14 0° 12m/s



	Case 10	Case11	Case 12	Case 13	Case 14
T_{max} (℃)	55.0	50.8	49.5	45.3	45.5
T_{avg} (℃)	33.5	32.1	31.1	30.2	29.9
All-RCI(%)	-30	-4	16	34	38
All-SHI	0.394	0.369	0.363	0.347	0.346
A1- RCI(%)	-237	-134	-44	4	36





Comparison of each cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Flow Rate Relationship	Rack= CRAH	Rack= CRAH	Rack= CRAH	Rack= CRAH	Rack＜ CRAH	Rack＜ CRAH	Rack＜ CRAH
Angle Speed（m/s）	Close	-20° 12	0° 12	+20° 12	Close	0° 7	0° 8.5
All-RCI（%）	47	57	67	29	54	51	57
All-SHI	0.34	0.32	0.30	0.38	0.36	0.39	0.39
A1-RCI（%）	-52	-21	65	36	-8	28	33
	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14
Flow Rate Relationship	Rack＜ CRAH	Rack＜ CRAH	Rack＞ CRAH	Rack＞ CRAH	Rack＞ CRAH	Rack＞ CRAH	Rack＞ CRAH
Angle Speed（m/s）	0° 10	0° 12	Close	0° 7	0° 8.5	0° 10	0° 12
All-RCI（%）	56	55	-30	-4	16	34	38
All-SHI	0.40	0.40	0.39	0.37	0.36	0.35	0.35
A1-RCI（%）	59	60	-237	-134	-44	4	36

Effect of Under-Floor Obstructions

perforated partitions

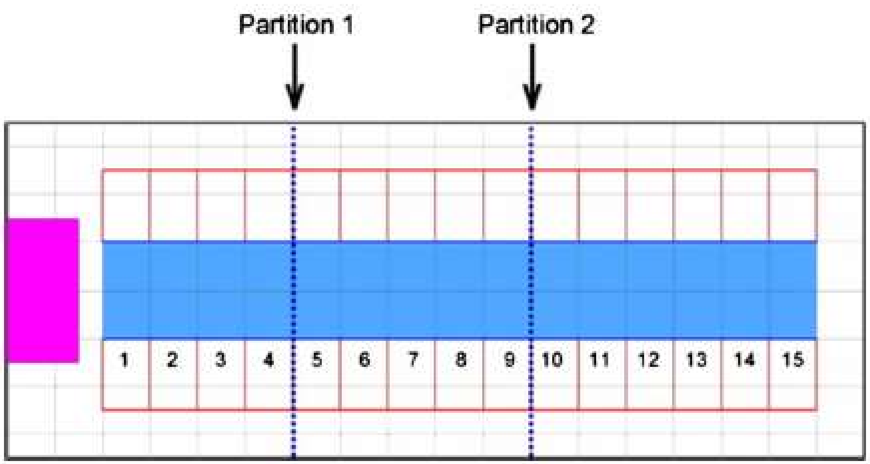
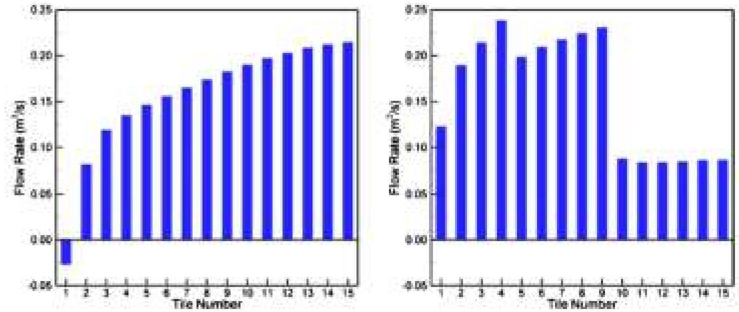


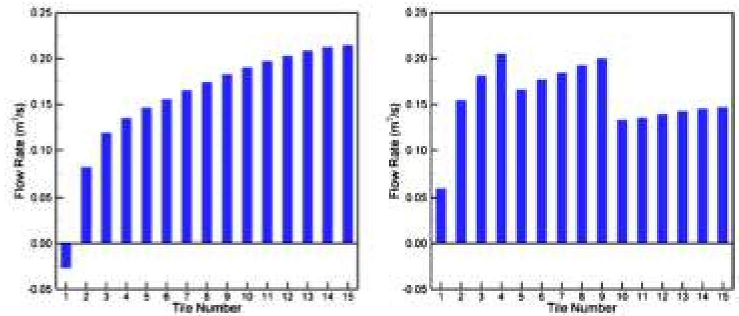
Fig. 24 Use of perforated partitions in the under-floor space



No partitions

With partitions (70% and 30%)

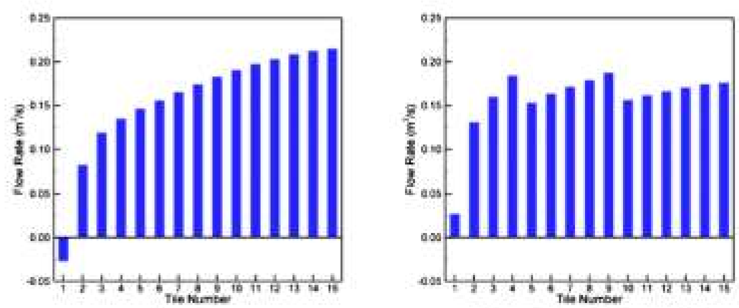
Fig. 25 Airflow distribution with and without perforated partitions (70% and 30%)



No partitions

With partitions (75% and 50%)

Fig. 26 Airflow distribution with and without perforated partitions (75% and 50%)



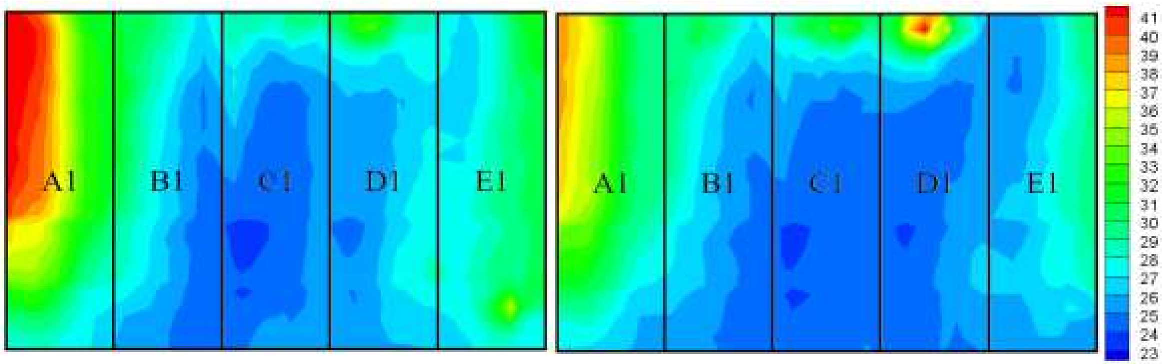
No partitions

With partitions (80% and 65%)

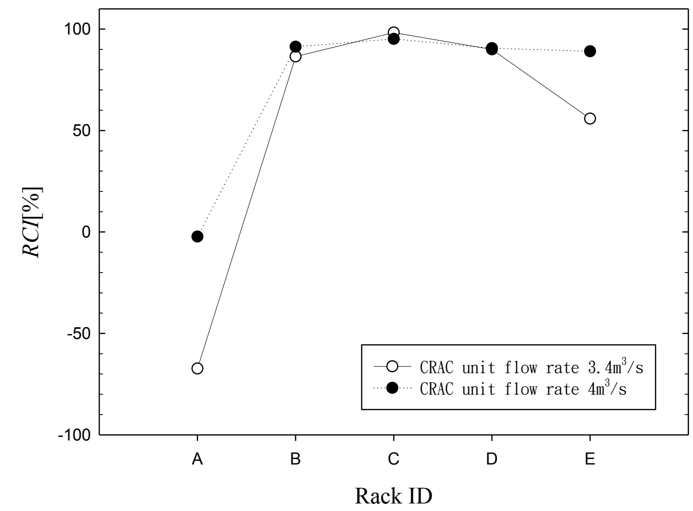
Fig. 27 Airflow distribution with and without perforated partitions (80% and 65%)

Patankar SV (2010) Airflow and cooling in a data center. J Heat Transfer 132:073001

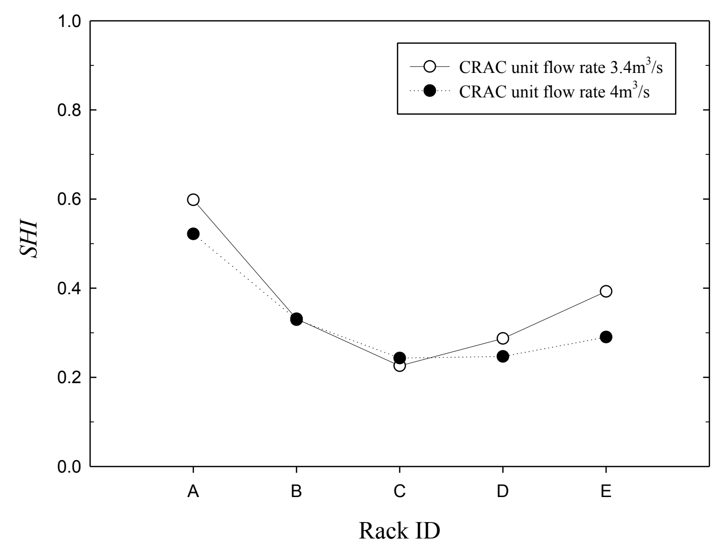
Effect of CRAH flow rate



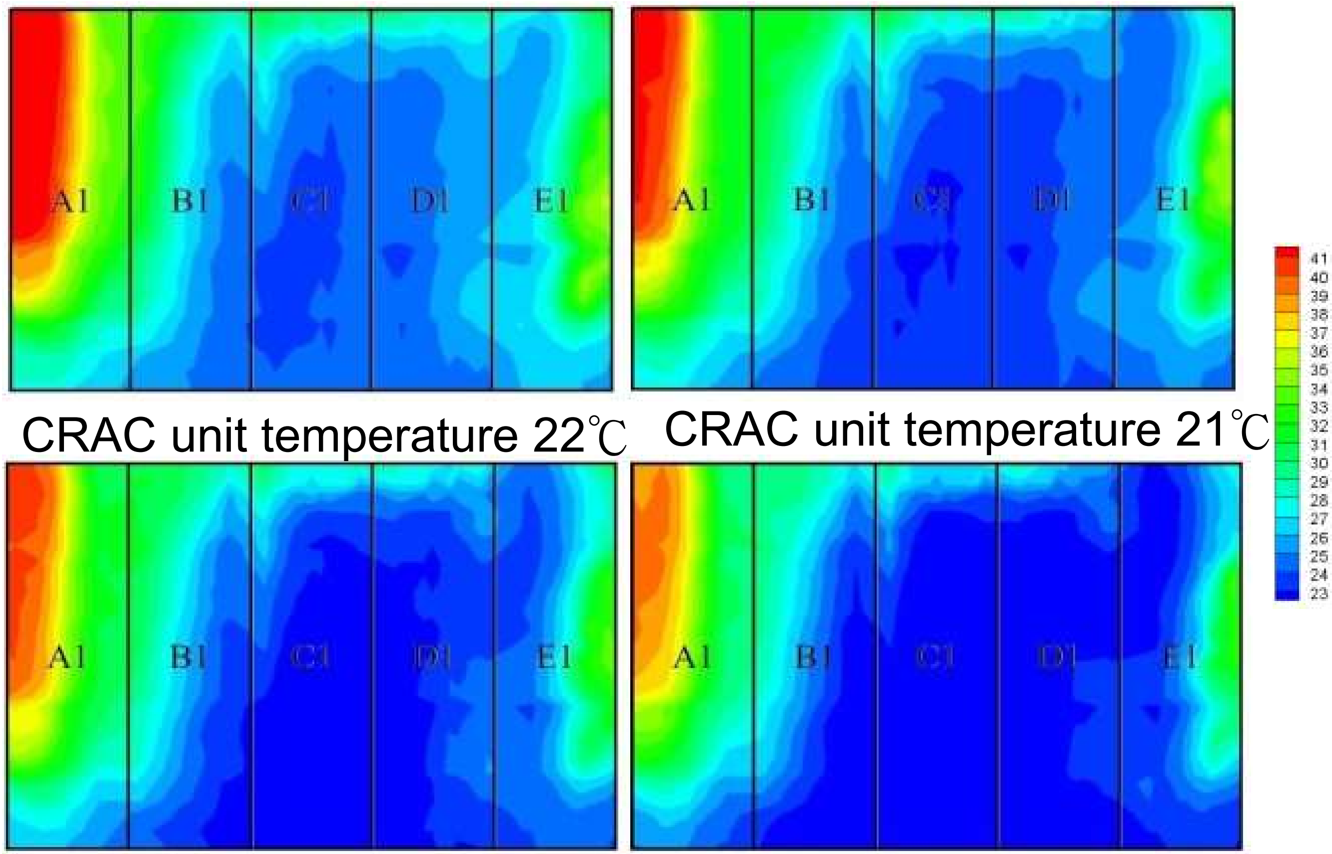
CRAH flow rate = 3.4m^3/s   CRAH flow rate = 4m^3/s



	3.4 m^3/s	4 m^3/s
RCI (%)	53	73
SHI	0.367	0.326
T_{max} (℃)	42.6	41.8
T_{avg} (℃)	28.7	27.3



Effect of inlet supplied temperature

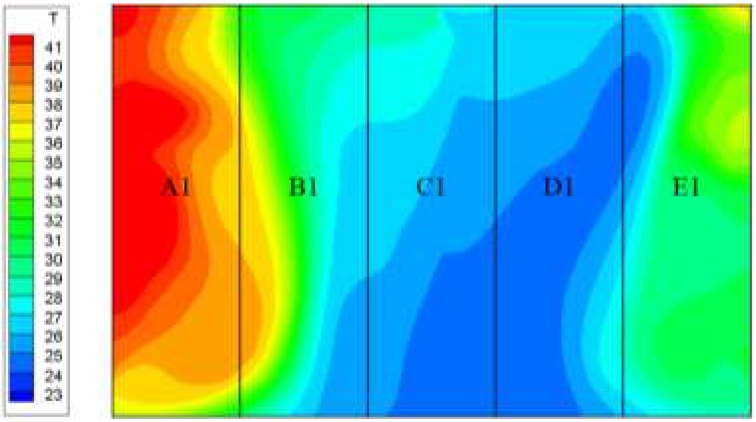


CRAC unit temperature 22℃ CRAC unit temperature 21℃

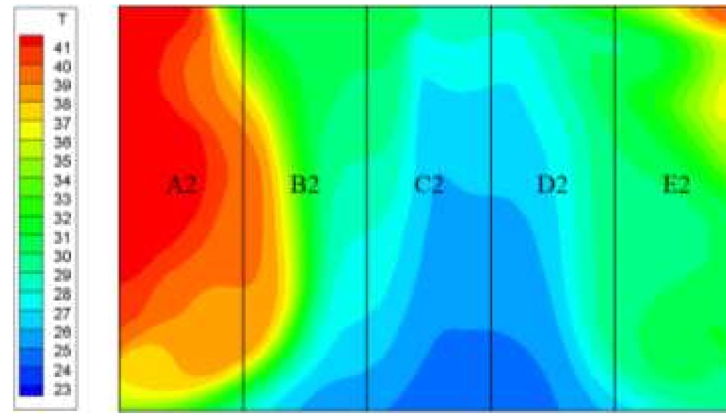
CRAC unit temperature 20℃ CRAC unit temperature 19℃

Comparison between experimental data and simulation

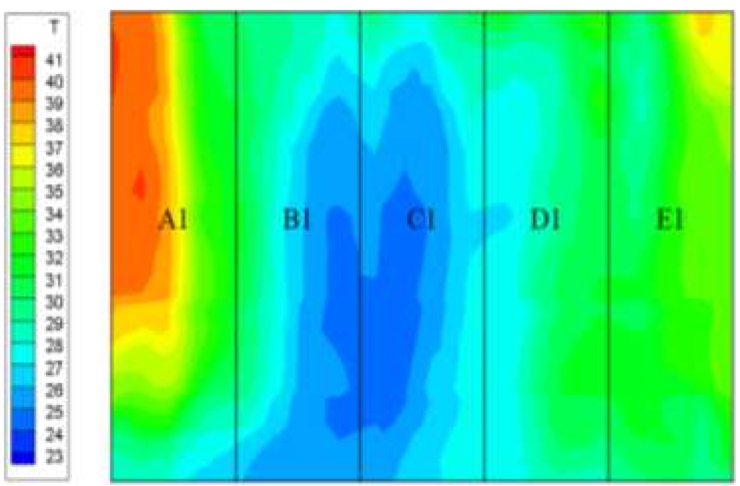
- Rack Inlet temperature distribution



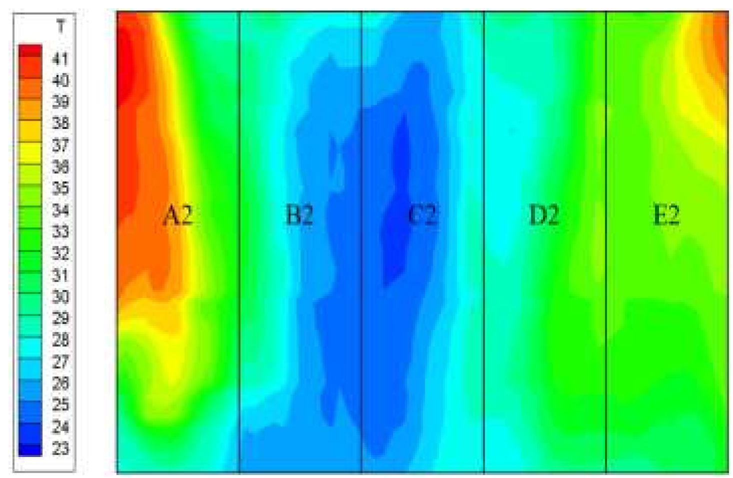
rack A1-E1 (simulation)



rack A2-E2 (simulation)



rack A1-E1 (experiment)



rack A2-E2 (experiment)

Comparison between experiment and simulation

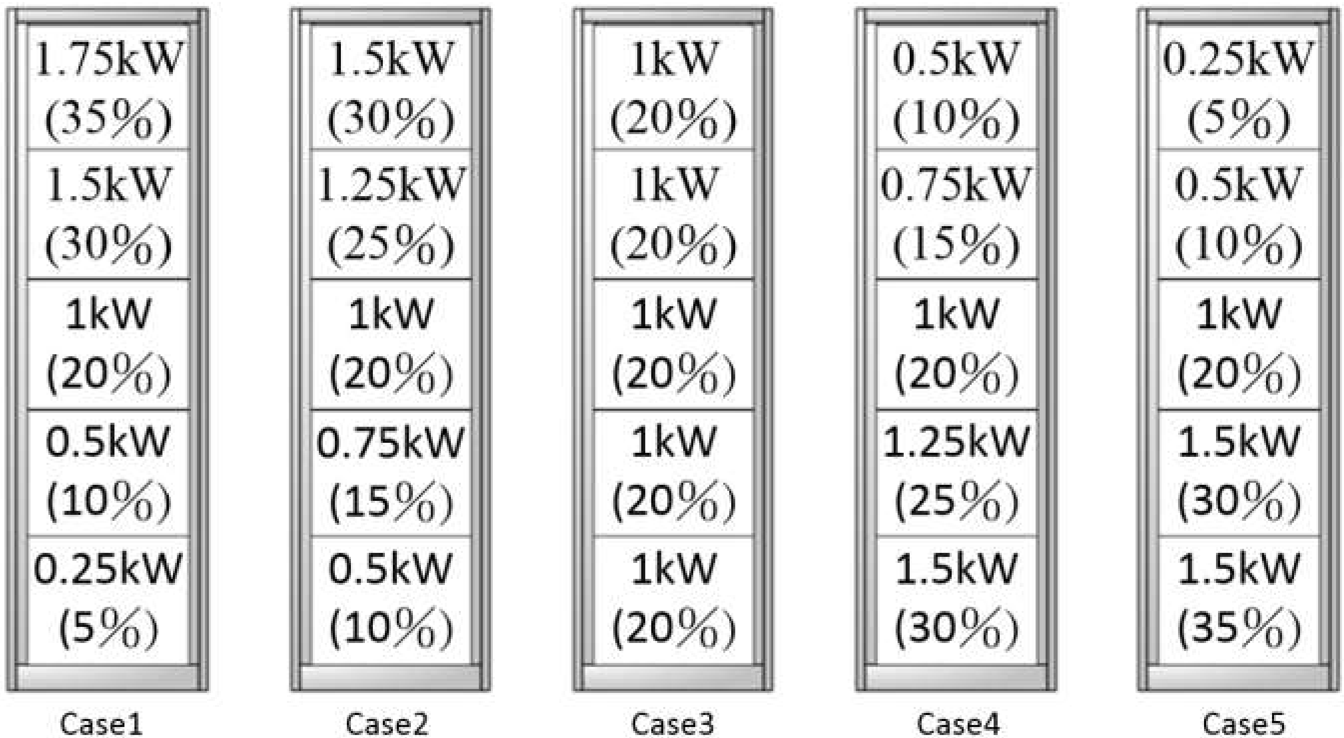
Relative error of rack inlet average temperature

	Experiment	Simulation	Relative error
A1	35.4℃	39.5℃	11.6%
A2	33.8℃	39.9℃	18.1%
B1	27.3℃	30.6℃	12.1%
B2	30.4℃	31.7℃	4.3%
C1	26.2℃	25.9℃	1.2%
C2	25.7℃	26.8℃	4.3%
D1	29.4℃	25.4℃	13.6%
D2	26.9℃	27.2℃	1.1%
E1	32.3℃	29.6℃	8.4%
E2	36.7℃	31.1℃	15.3%

Overall relative error

	RCI	SHI	Tavg	Tmax
Experiment	26%	0.447	30.3℃	42.1℃
Simulation	15%	0.493	30.8℃	46.1℃
Relative error	42.3%	10.3%	1.7%	9.5%

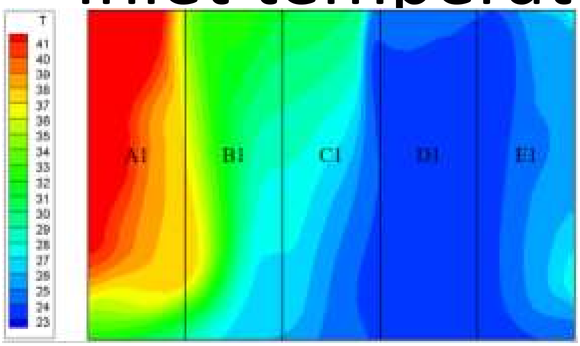
Change heat load distribution of rack upper and lower section



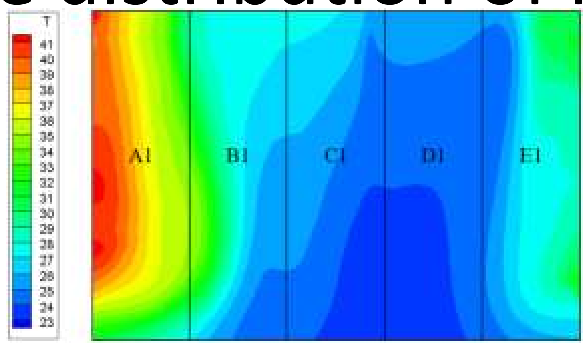
heat load distribution of rack upper and lower section

Change heat load distribution of rack upper and lower section

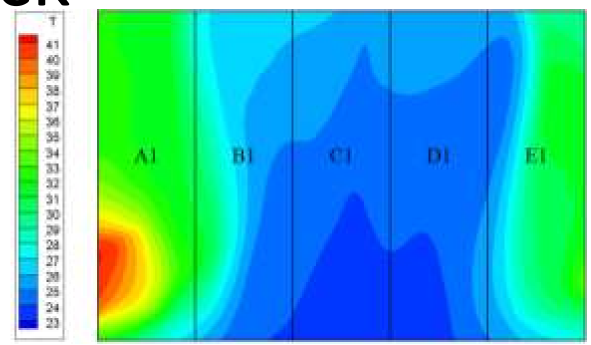
- Inlet temperature distribution of rack



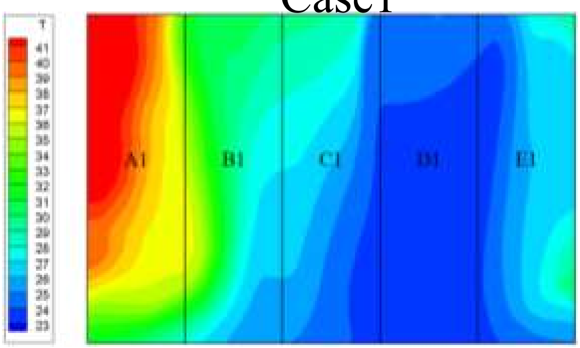
Case1



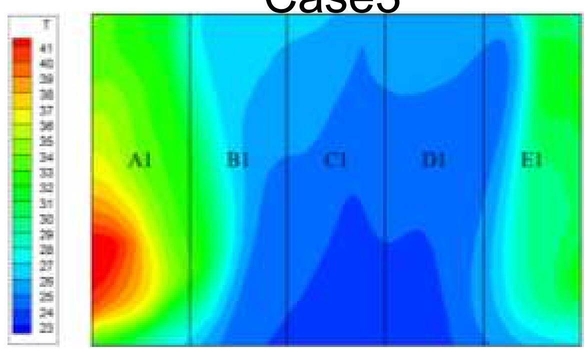
Case3



Case5



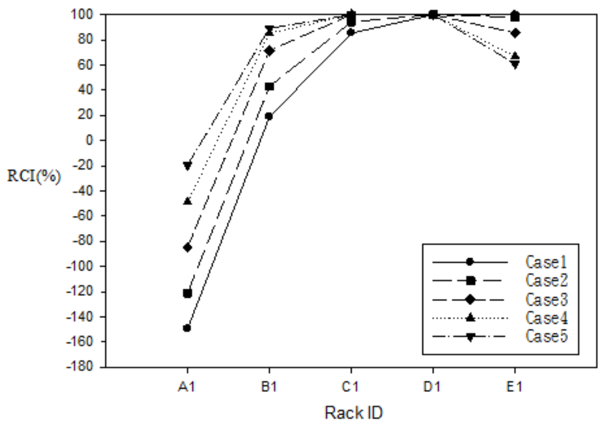
Case2

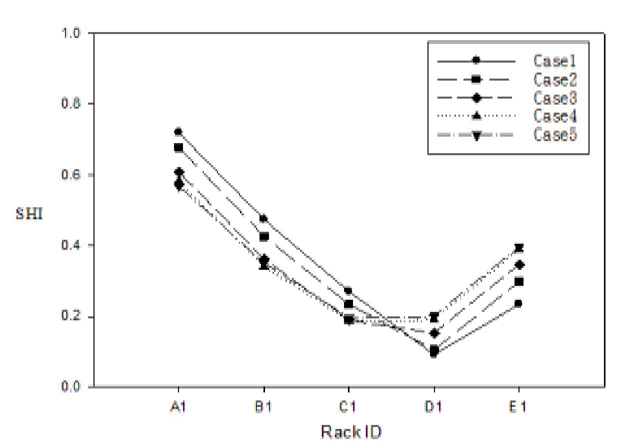


Case4

Change heat load distribution of rack upper and lower section

- Simulation result



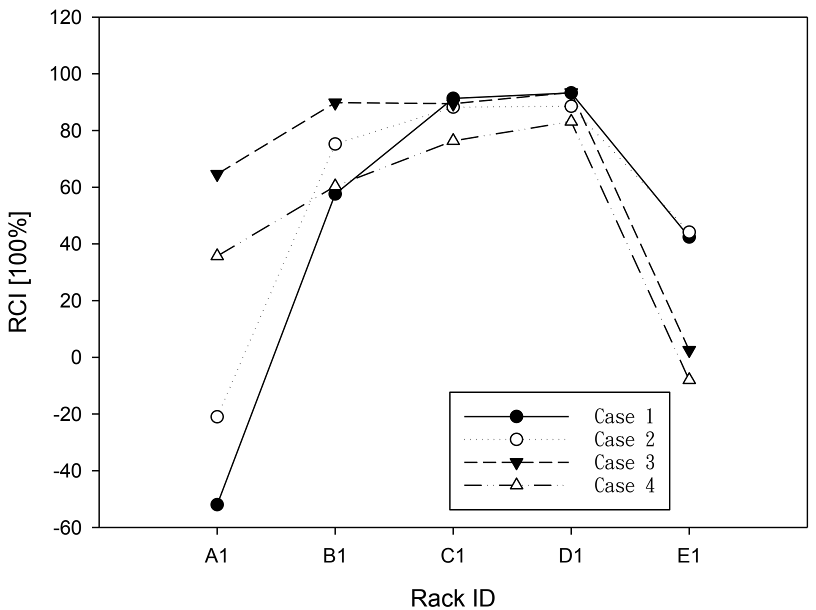


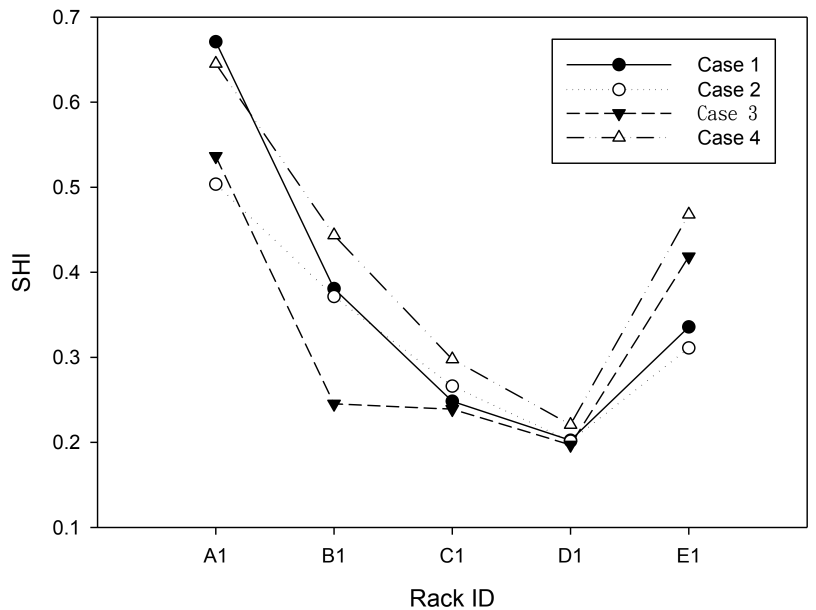
Variation of RCI and SHI with change heat load distribution of rack upper and lower section

Simulation results with change heat load distribution of rack upper and lower sec

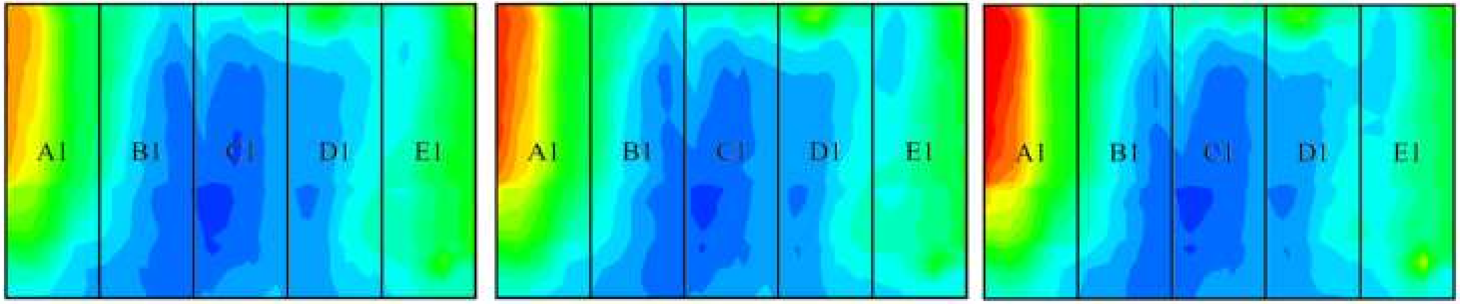
	SHI	RCI(%)	Tavg(℃)	Tmax(℃)
Case1	0.349	31.4	29	48.6
Case2	0.347	44.8	28.6	47.9
Case3	0.334	55.6	28.2	42.5
Case4	0.353	58.5	28	42.5
Case5	0.354	62	27.9	41.1

	Case 1	Case 2	Case 3	Case 4
T_{max} (℃)	45.6	48.0	43.3	60.4
T_{avg} (℃)	29.1	28.4	27.7	29.
All-RCI(%)	47	57	67	29.1
All-SHI	0.337	0.318	0.298	0.376
A1- RCI(%)	-52	-21	65	36

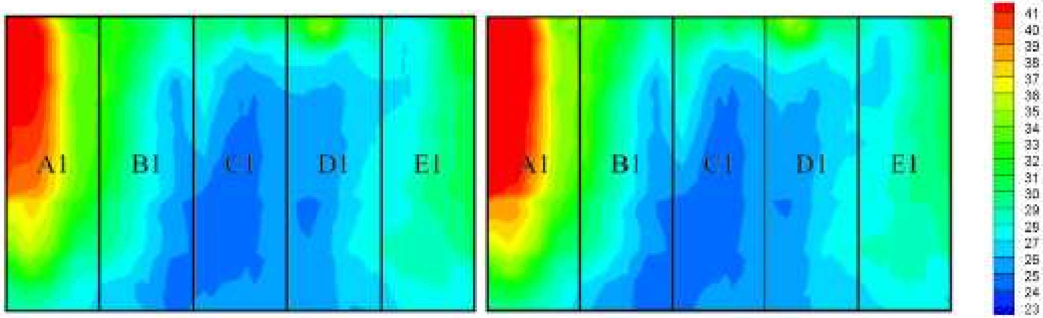




Effect of heat load distribution

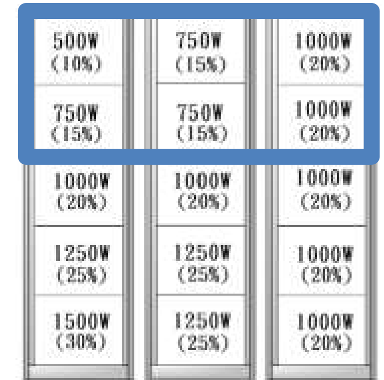


Distribution1 Distribution2 Uniform



Distribution3 Distribution4

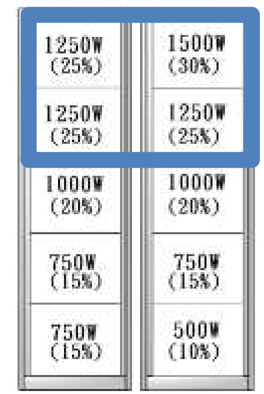
1.25kW 1.5kW 2kW



1 2 Uniform

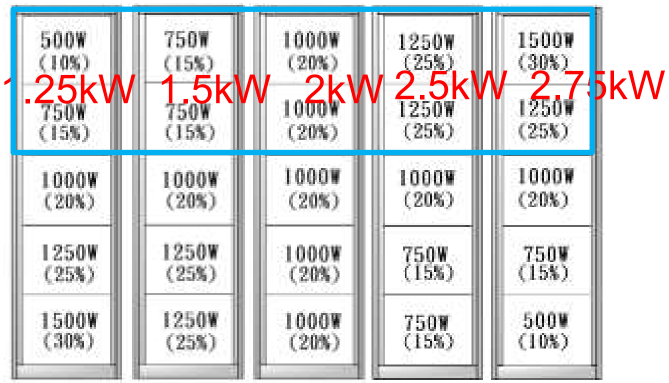
2.5kW 2.75kW

5kW

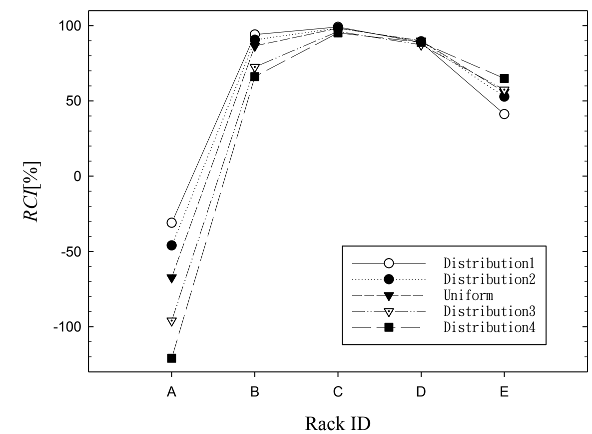


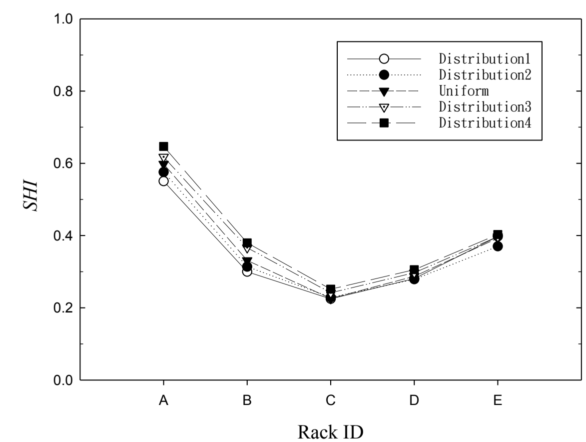
3 4

Same Conclusion: Higher power servers are suggested to placed far from the entrance



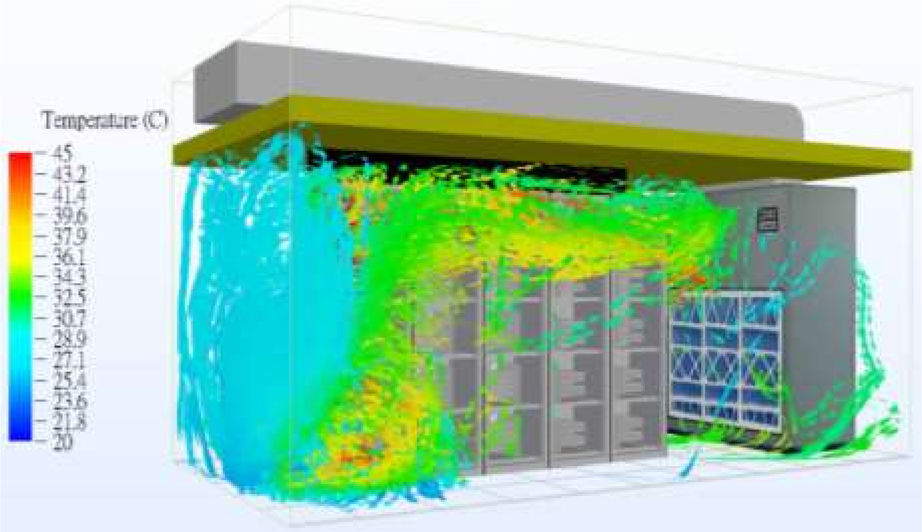
	Distribution 1	Distribution 2	Uniform	Distribution 3	Distribution 4
RCI (%)	58	57	53	43	39
SHI	0.351	0.354	0.367	0.384	0.397
T_{avg}(℃)	28.4	28.5	28.7	29.3	29.6
T_{max}(℃)	39.5	41	42.6	45.5	46.3
Rack A RCI(%)	-31	-46	-67	-96	-121
Rack E RCI(%)	41	53	56	57	65



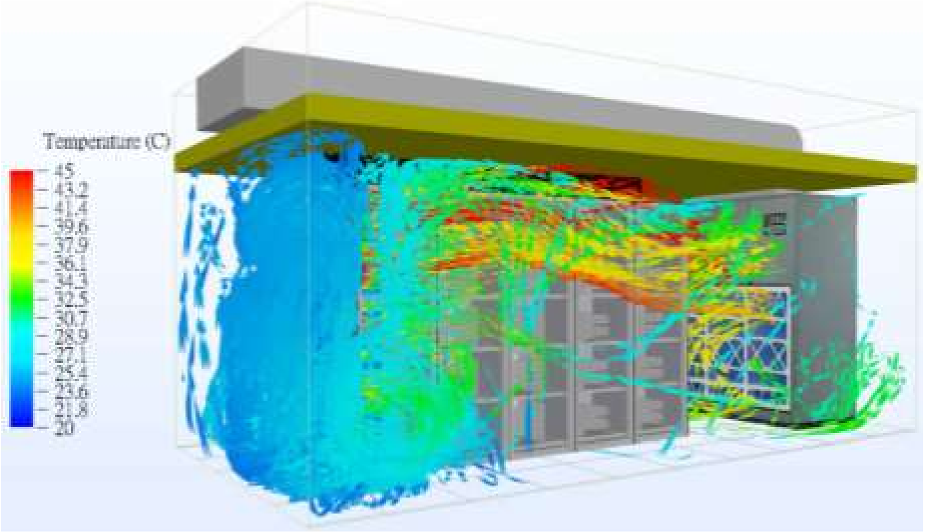


Change heat load distribution of rack upper and lower section

- Streamlines Entering Rack E1



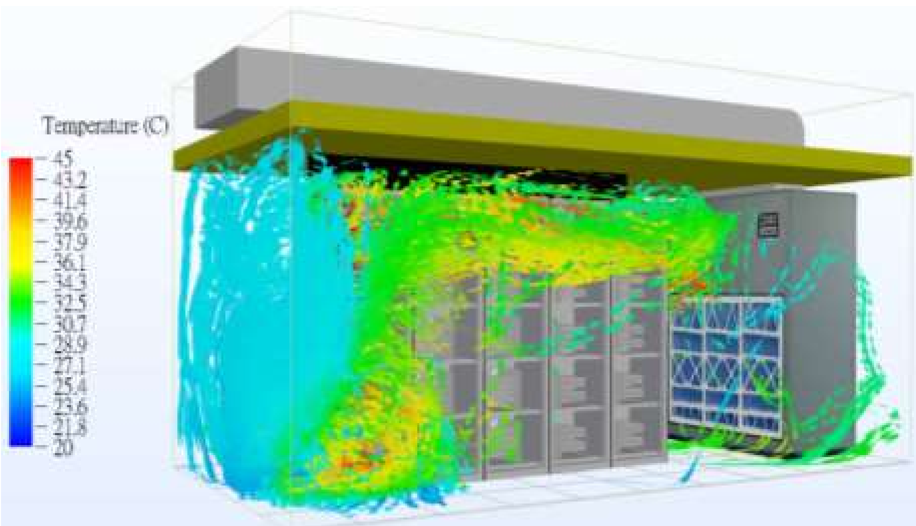
Case3



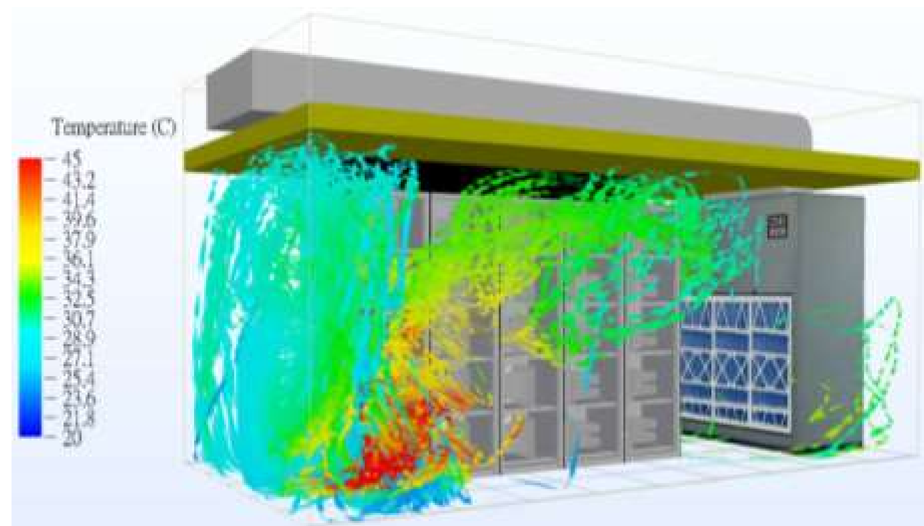
Case1

Change heat load distribution of rack upper and lower section

- Streamlines Entering Rack E1



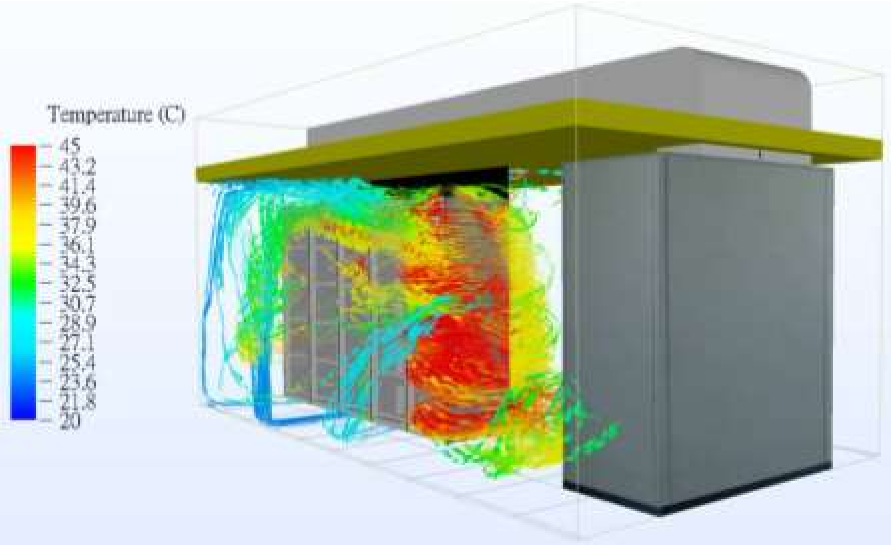
Case3



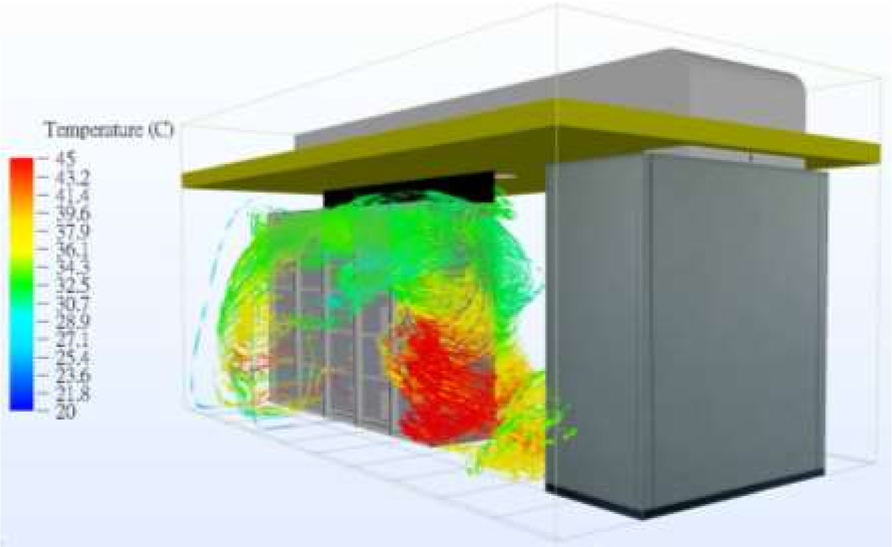
Case5

Change heat load distribution of rack upper and lower section

- Streamlines Entering Rack A1



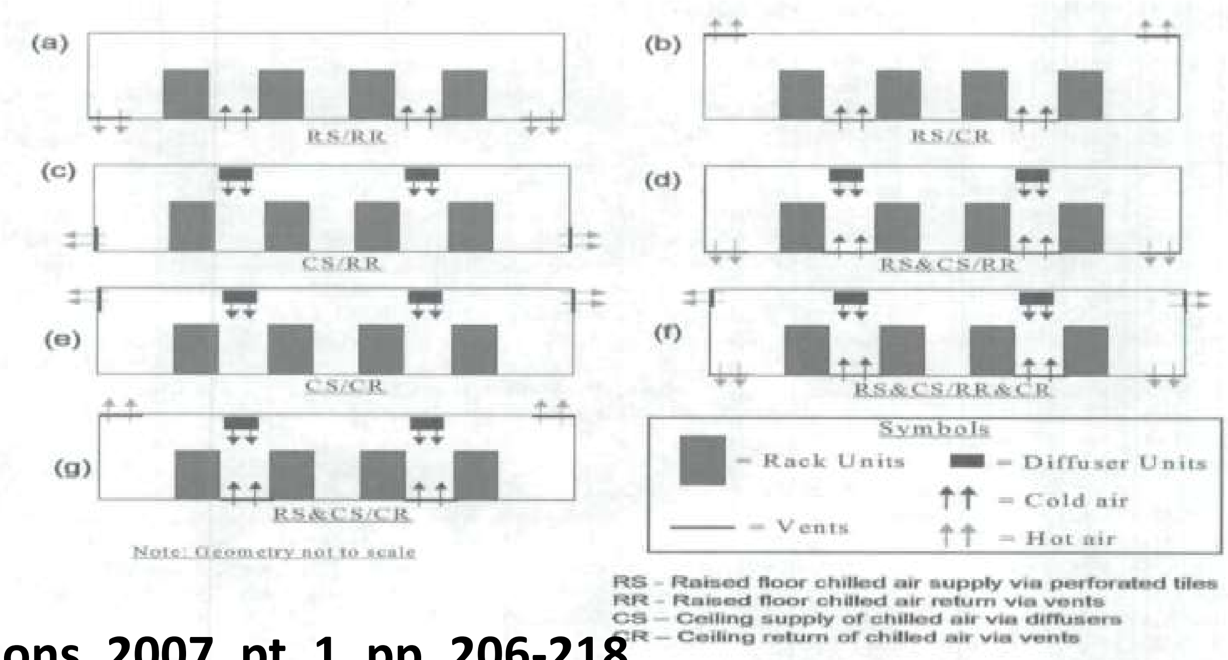
Case3



Case5

Ventilation Design

- A raised floor for chilled air supply (Figure Ib) with exhaust hot air removal from vents in the ceiling or top parts of the walls or venting via CRAC units (Figure la) that reside on the raised floor.
- The worst ventilation scheme is with overhead chilled-air supply (Figure Ic) with exhaust vents at the floor or at the bottom part.
- The typical underfloor supply design (Figure la) can result in hot spots at the very top part of the rack inlet. This does not occur in overhead supply designs.



ASHRAE Transactions, 2007, pt. 1, pp. 206-218.

Figure 1 Different ventilation schemes studied by Shrivastava et al. (2005a, 2005b).

Ventilation Design (Conti..)

- Directing hot exhaust air upward into a ceiling return plenum, gives superior performance than just high ceiling.
- If flexibility exists in the orientation of rows of equipment, a layout that allows hot air unobstructed access to the return of CRAC units (or other cooling system returns) should be superior to a layout with rows perpendicular to the CRAC units
- A cold aisle/hot aisle arrangement should be followed in laying out racks within a data center: the fronts of the racks drawing in chilled air either from overhead or from the raised floor should face the chilled air exhausting into the cold aisle.

ASHRAE Transactions, 2007, pt. 1, pp. 206-218.

Rack Placement (Conti..)

- Some data centers have employed **plastic stripes at the end of an aisle to prevent air recirculation** but allow ease of access.
- If server inlet temperatures meet the demand of Thermal Guidelines, then reducing airflow by turning off or reducing the air conditioning can result in significant energy savings.
- **The inlet air temperature to high-powered racks can be reduced significantly by removing an adjacent rack. Racks in the vicinity of the removed racks also experience a reduced inlet air temperature**.
- For some layouts, the best position for high-powered racks is near the end of the aisles. However, a more recent study has found that the outside racks at the ends of the aisles can experience more hot air recirculation.

"Best Practices for Data Center Thermal and Energy Management—Review of Literature," ASHRAE Transactions, 2007, pp. 206-218.

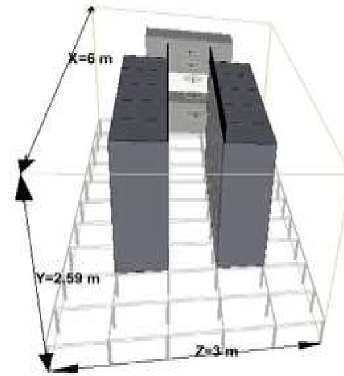
Numerical Simulation

機房物理模型

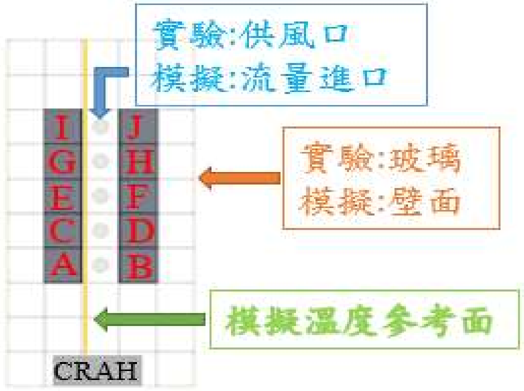
幾何參數設定表

幾何參數	
機房長寬高	6m x 3m x 2.59m
機櫃長寬高	0.615m x 0.6m x 1.95m
地板長寬	0.6m x 0.6m
回風口長寬	1.42m x 0.6m
黑色擋板長寬高	3m x 0.02m x 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

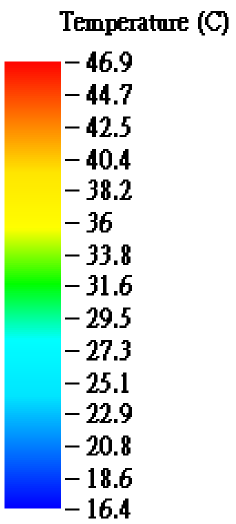


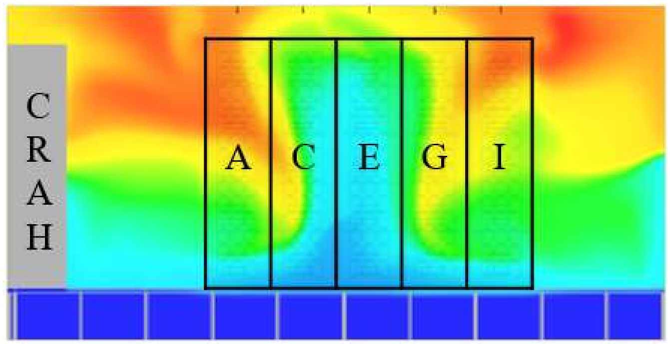
機房上視圖



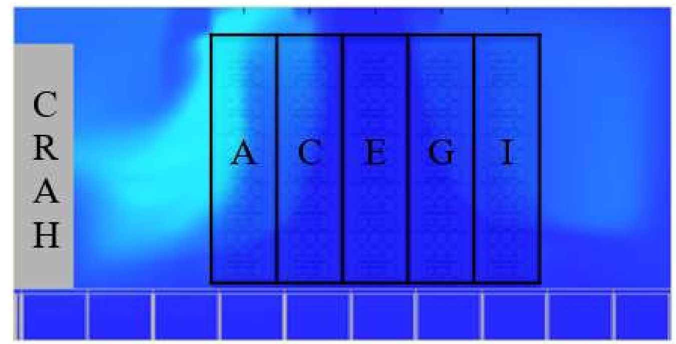
結果與討論

- 改變供風口總流量

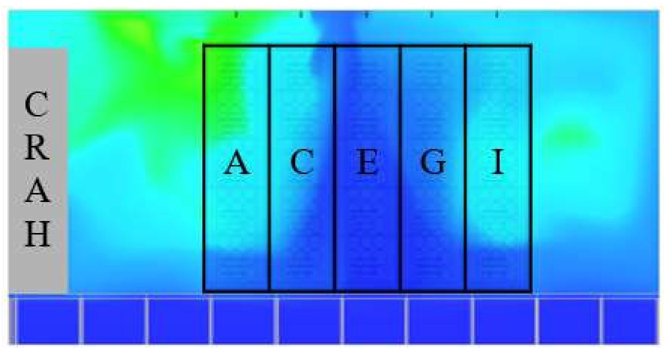




供風口總流量1m^3/s



供風口總流量4m^3/s



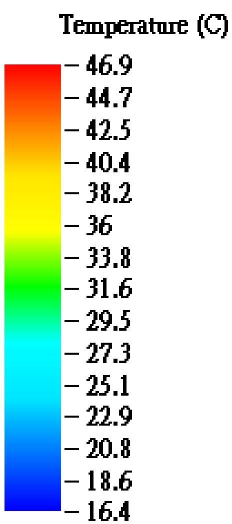
供風口總流量2m^3/s

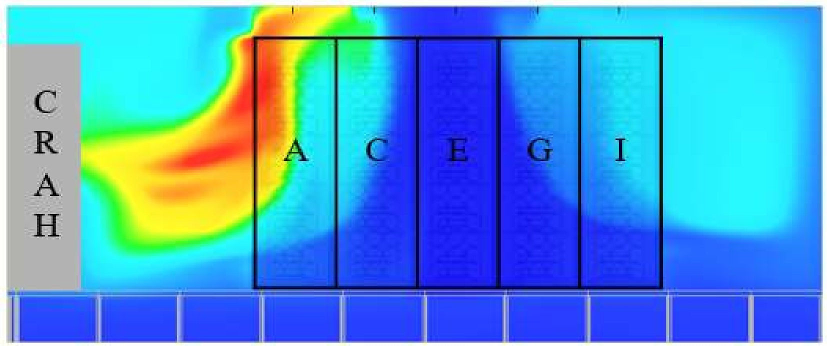
供風口總流量 (m^3/s)	SHI
1	0.73
2	0.51
3	0.35
4	0.25

不同供風口總流量對應之SHI

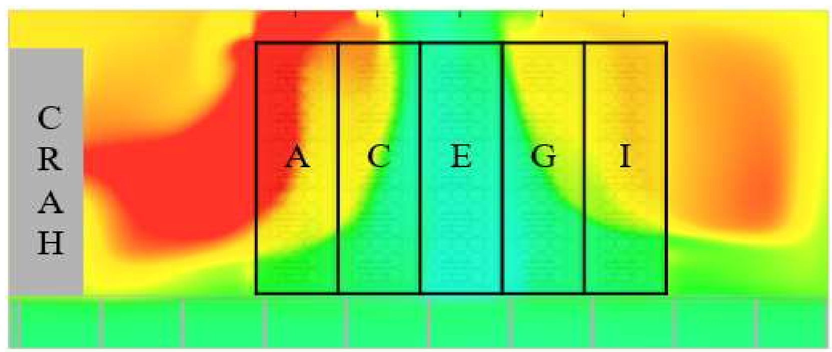
結果與討論

- 改變供風口溫度





供風口溫度16℃



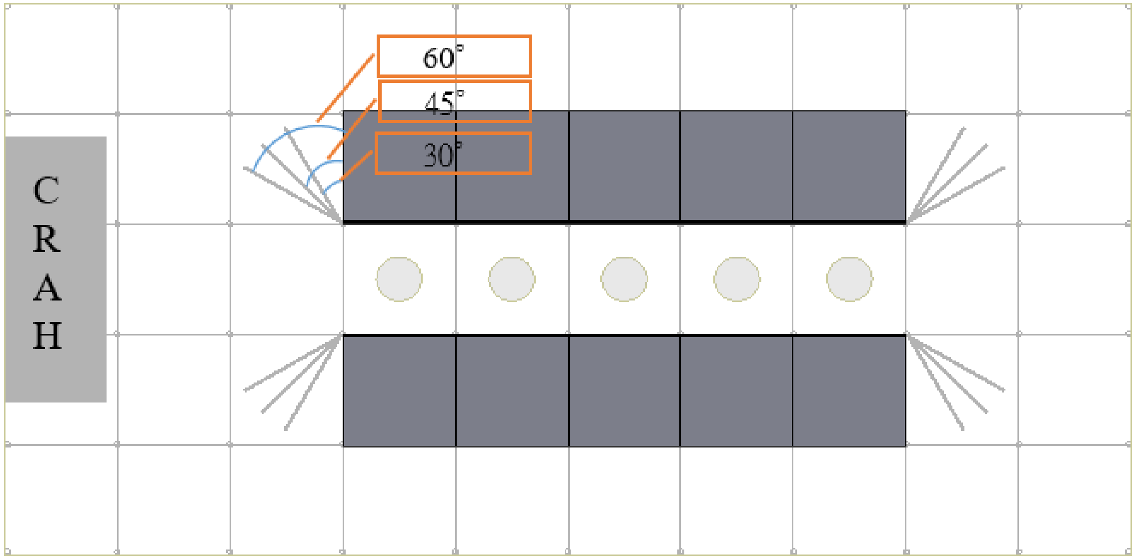
供風口溫度20℃

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

結果與討論

- 機櫃兩側加裝有角度的擋板



機櫃兩側加裝30°、45°、60° 擋板之機房上視圖

結果與討論

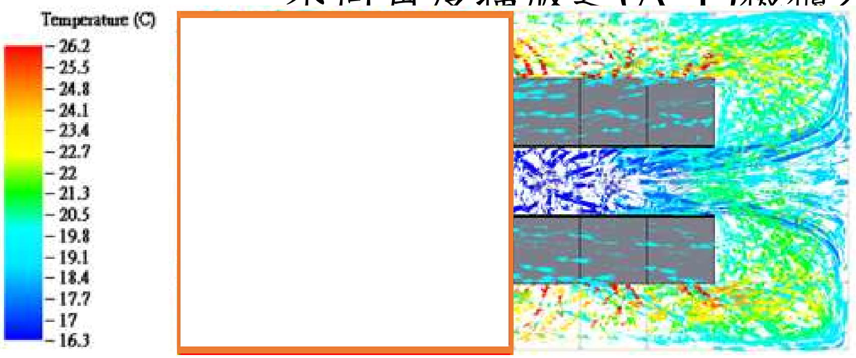
- 機櫃兩側加裝有角度擋板

機櫃入風面 / 擋板角度 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
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

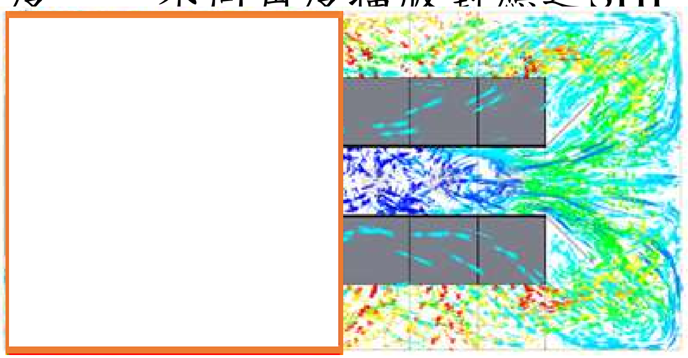
不同角度擋版之(A~F)機櫃入風面平均溫度

擋板角度	SHI
0°	0.255
30°	0.228
45°	0.227
60°	0.223

不同角度擋版對應之SHI



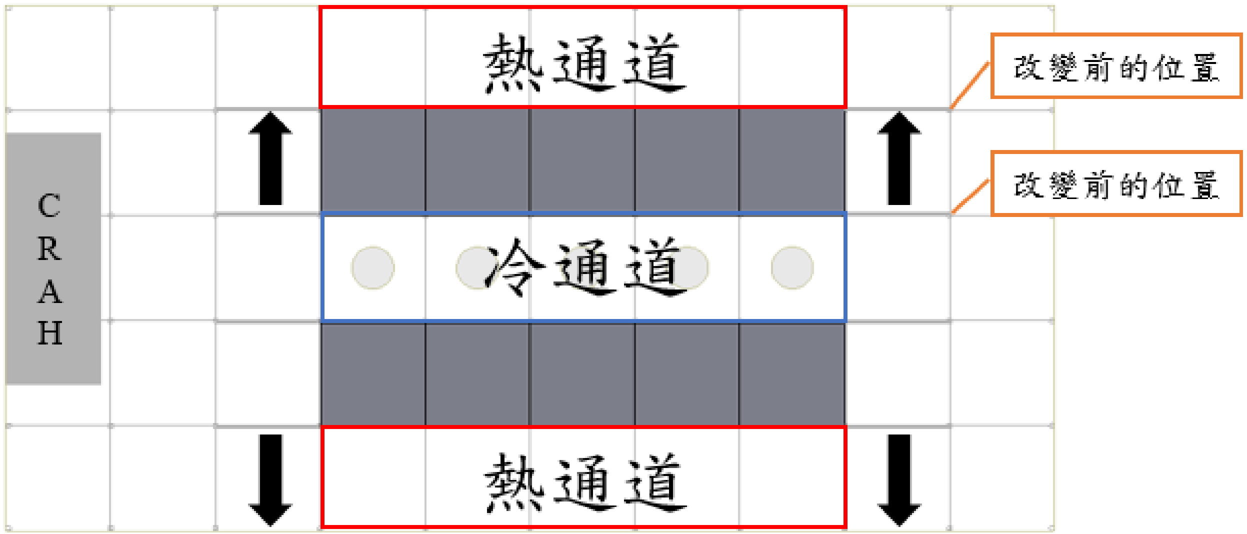
無擋板空氣在機房內流動情形



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

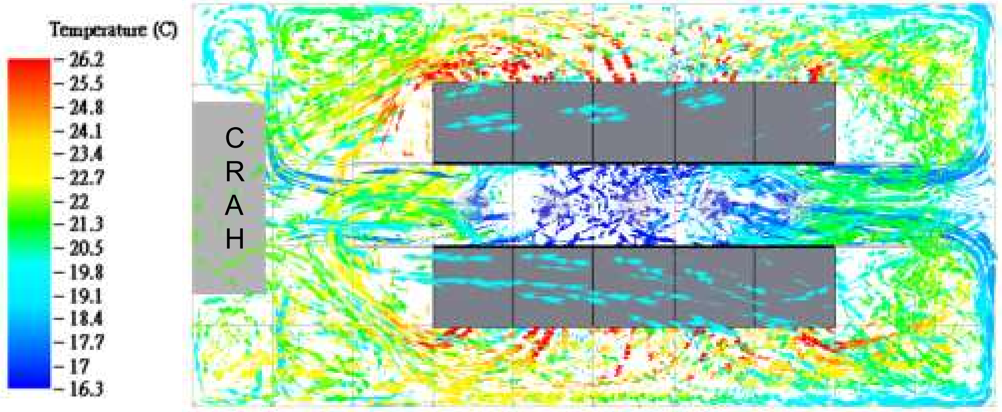


機櫃兩側加裝檔板-改變擋板
位置示意圖

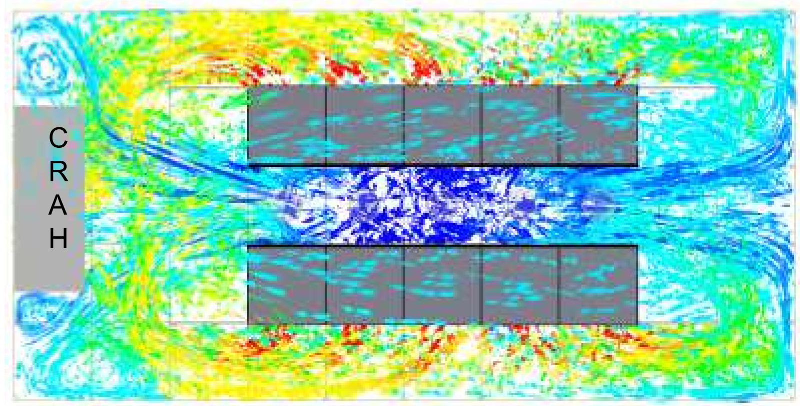
結果與討論

- 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



擋板位置靠近冷通道之空氣流動情形

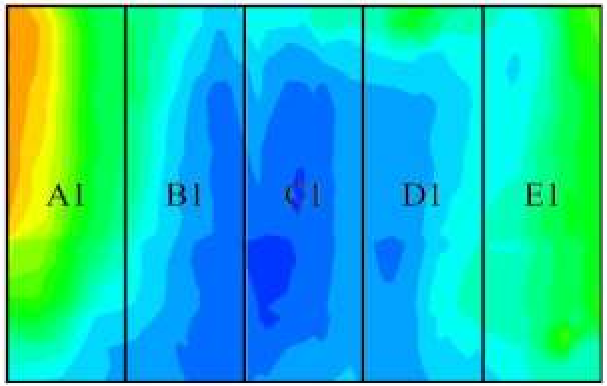


擋板位置靠近熱通道之空氣流動情形

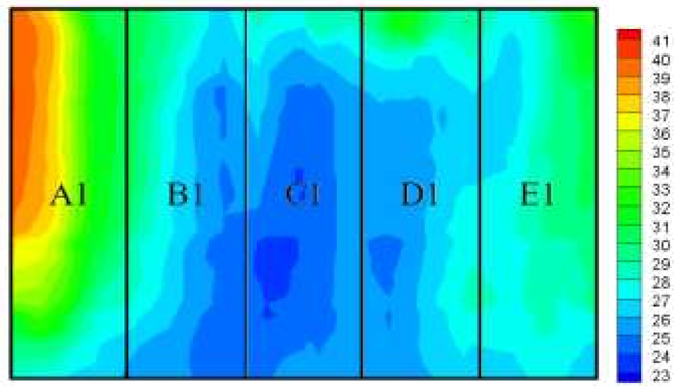
結果與討論

- 當冷空氣流量供給不足時，將會造成機房內熱空氣回流情形嚴重，而當流量供給充足時，能夠有效改善機房內熱空氣回流情形。
- 供風口溫度的高與低，並不會影響機房內空氣的流動，只會影響機房內空氣的溫度。
- 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。

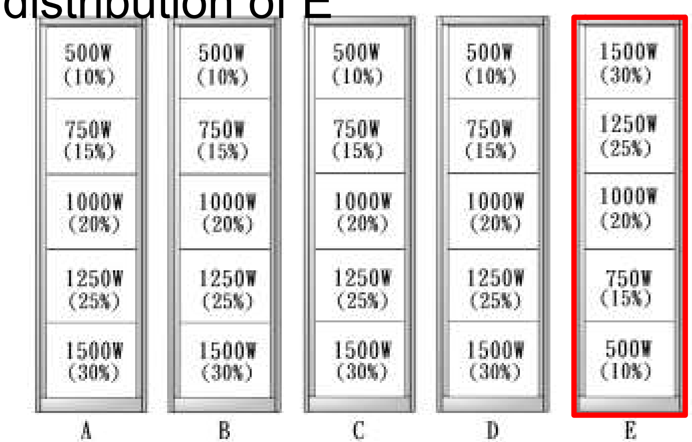
Change the heat load distribution of E



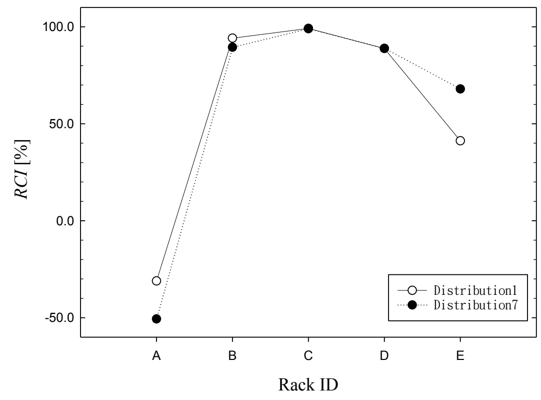
Distribution1

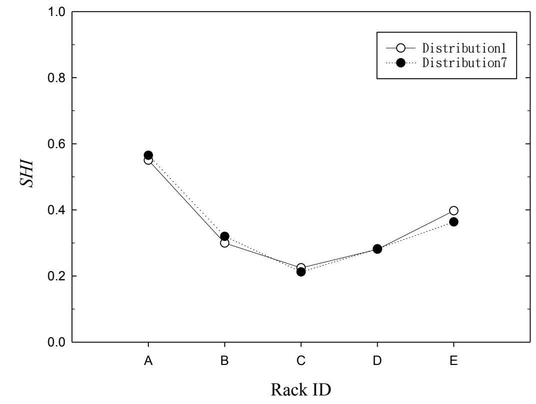


Change the heat load distribution of E

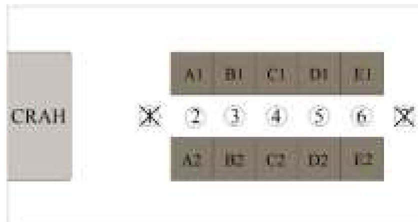


	Distribution1	Distribution7
RCI (%)	58	59
SHI	0.351	0.349
T_{max} (℃)	39.5	40.7
T_{avg} (℃)	28.4	28.3
Rack A RCI(%)	-31	-51
Rack E RCI(%)	41	68

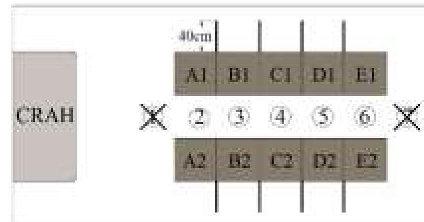




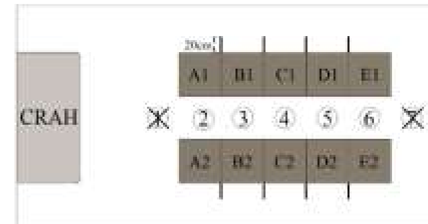
Add partition on hot aisle



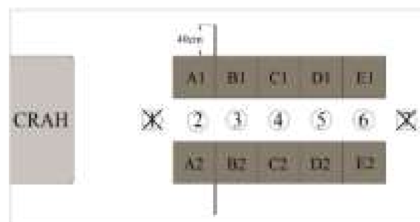
Case1



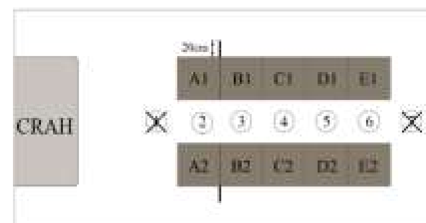
Case2



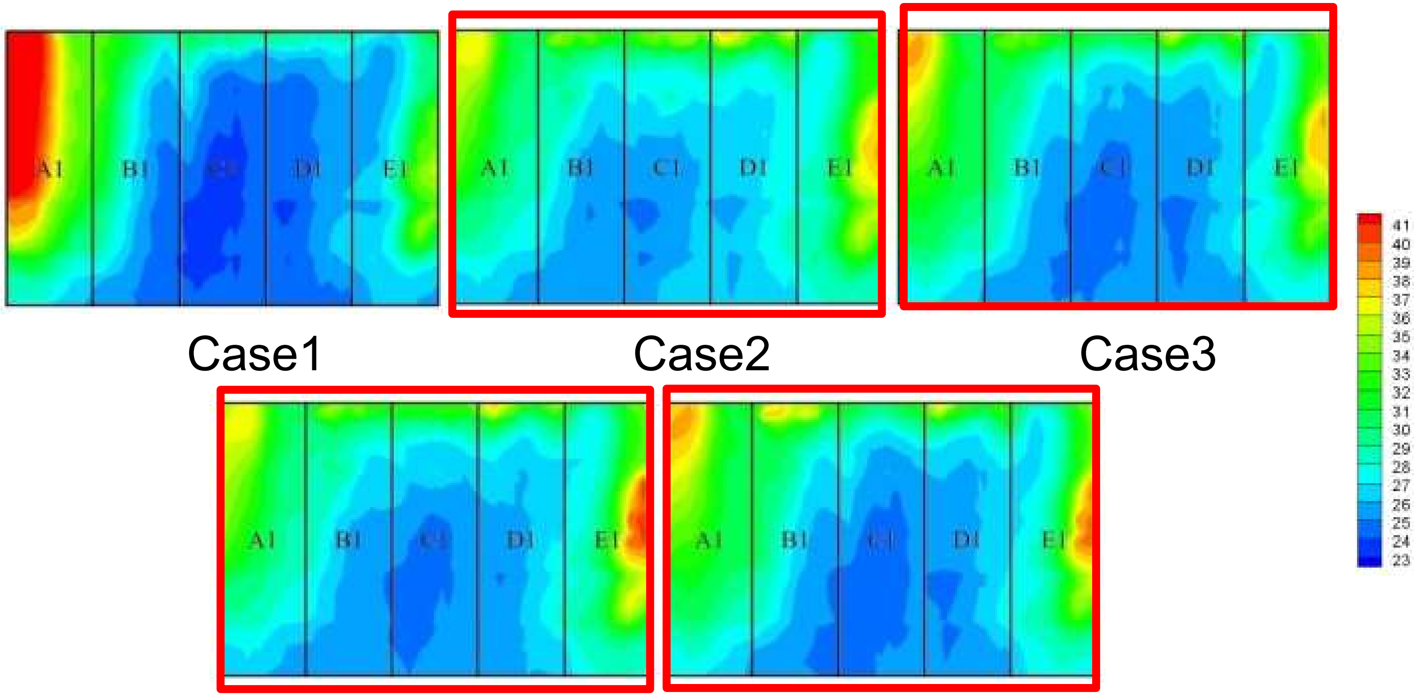
Case3

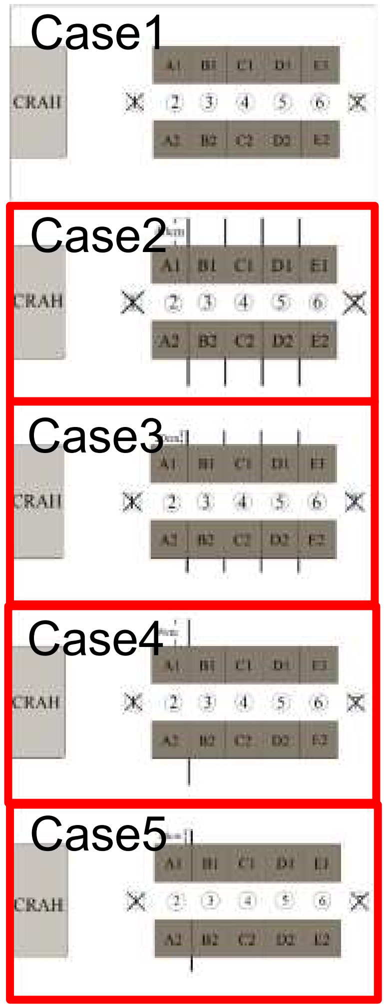


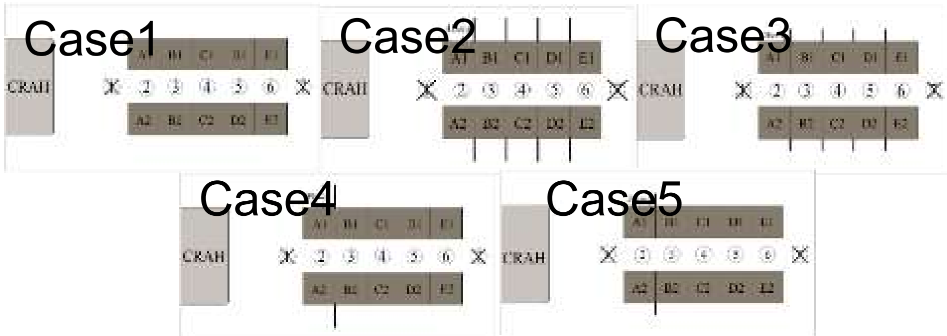
Case4



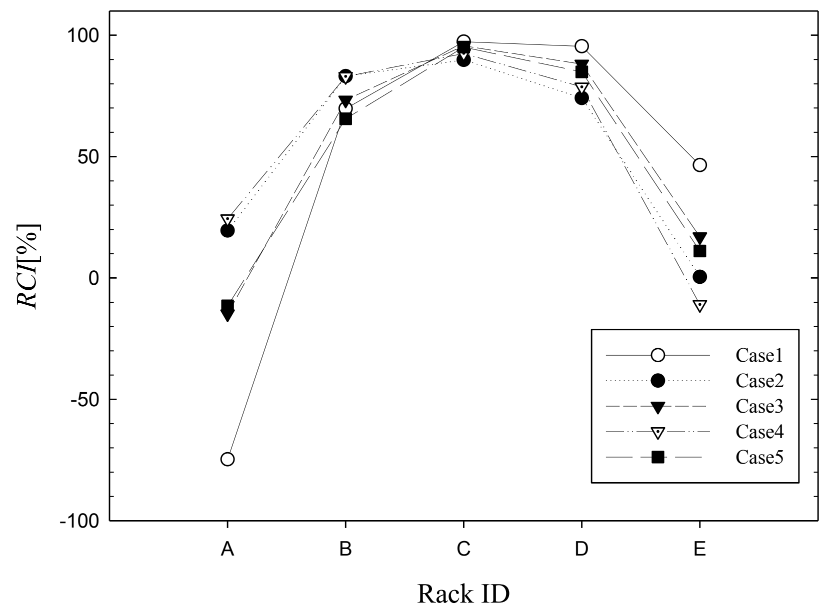
Case5


A1 B1 C1 D1 E1
Case1
Case2
Case3
Case4
Case5
41 40 39 38 37 36 35 34 33 32 31 30 29 28 27 26 25 24 23

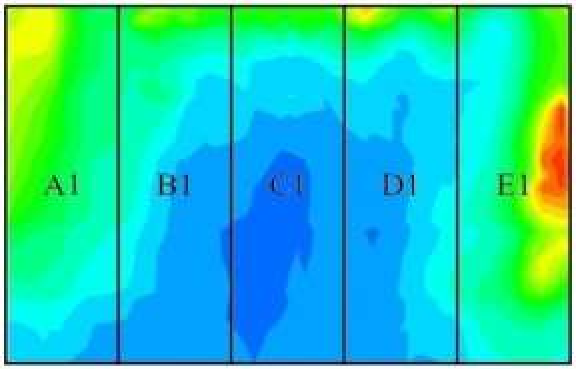

Case1
Case2
Case3
Case4
Case5
CRAH
A1 B1 C1 D1 E1
2 3 4 5 6
A2 B2 C2 D2 E2



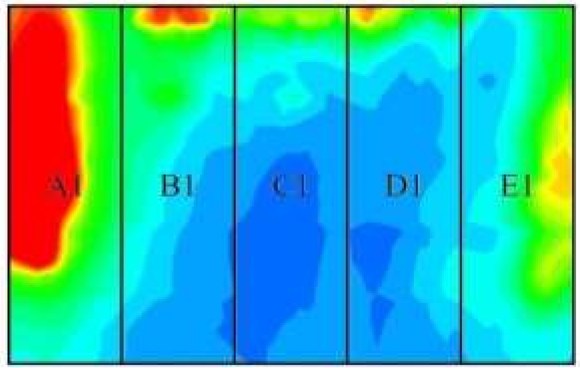
	Case1	Case2	Case3	Case4	Case5
RCI (%)	47	53	52	54	49
T_{max} (℃)	43.9	42.4	42.8	45.2	41.9
T_{avg} (℃)	28.6	28.9	28.8	28.8	29.0
Rack A *RCI*(%)	-75	20	-15	24	-12
Rack E *RCI*(%)	46	0	17	-11	11



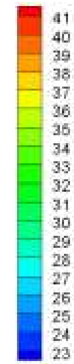
Add partition on rack E

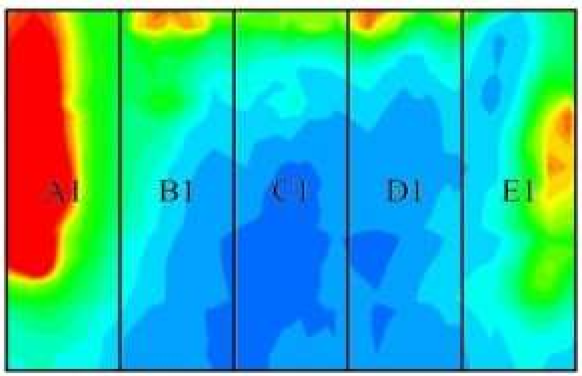


Case4

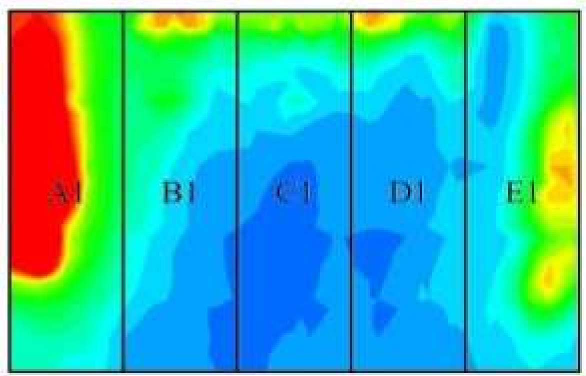


Case7

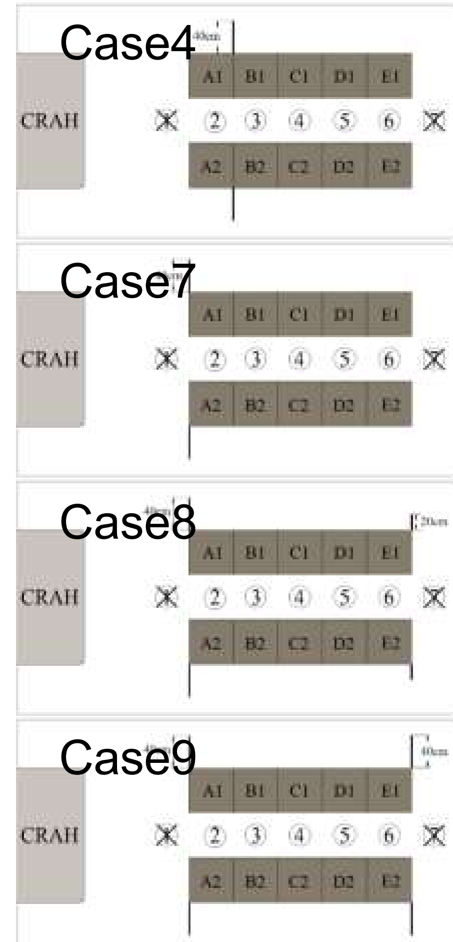


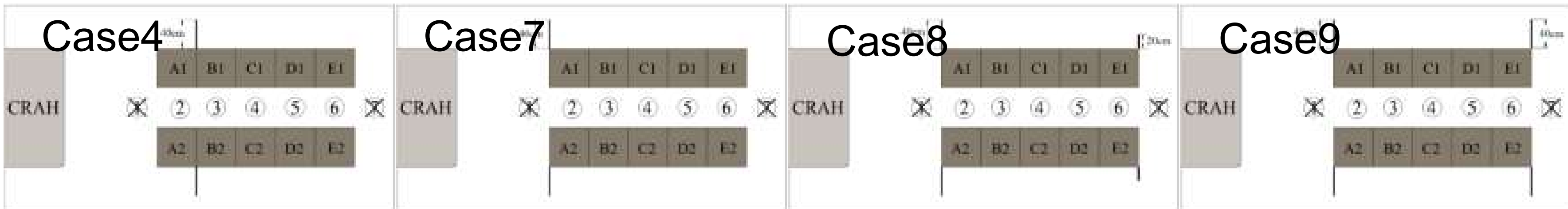


Case8

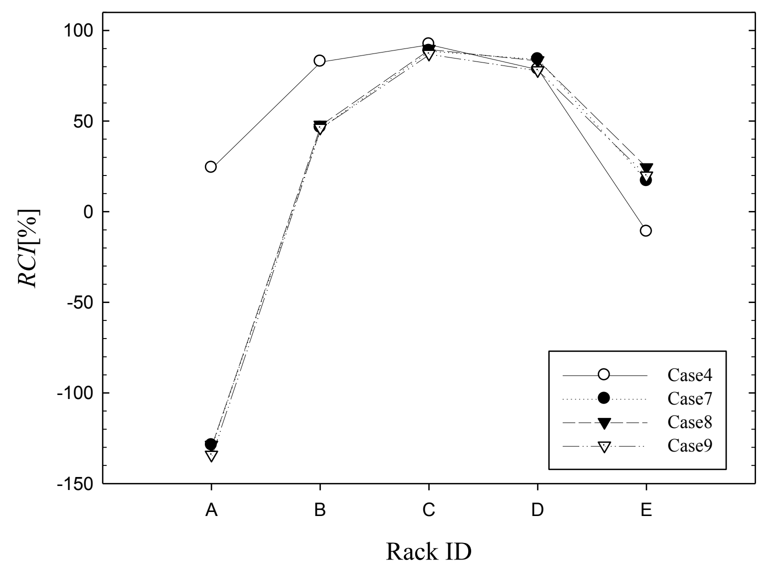


Case9





	Case4	Case7	Case8	Case9
RCI (%)	54	22	23	19
T_{max} (℃)	45.2	72.2	70.3	71.3
T_{avg} (℃)	28.8	30.4	30.3	30.5
Rack A *RCI*(%)	24	-129	-128	-134
Rack E *RCI*(%)	-11	17	24	20



結論

1. 增加空調供風量，供風量由3.4 m^3/s提升至4m^3/s，*RCI*指標也會上升20%以上。
2. 改變發熱量分布使高發熱量區域位於機櫃底部，因熱回流溫度降低，其*RCI*提升約19%，建議將發熱量較大之伺服器置於機櫃底部，或將伺服器由下往上放置。
3. 增加機櫃Part1抽風量至總機櫃抽風量之45% (抽風量等於供風量的情況下)，將使機櫃內部熱回流程度大幅降低，*RCI*最多由26%增至47%。

4. 開啟編號1之供風口，機櫃側邊熱回流之熱空氣事先被冷卻，降低A機櫃入口溫度，大幅且有效提升*RCI*；開啟編號7之供風口，能小幅度的增加*RCI*。

5. 熱通道加入擋板會造成熱通道壓力較大，進入機櫃內的冷空氣會較少，溫度提高，但因BCD機櫃提高後的溫度大部分還未超過建議溫度上限，故*RCI*並沒有明顯的增加。

6. 在熱通道加裝擋板能增加阻抗，使熱空氣較難以在A機櫃處流至回風口，降低A機櫃的過熱程度，但熱空氣則會轉而往機櫃另一側流動，降低DE機櫃的*RCI*，但整體*RCI*數值還是會增加。
7. 僅在回風口附近之機櫃加裝一片 擋板會與在加入數塊擋板的效果相同。
8. 在A機櫃外側加入擋板因熱通道壓力較高，會使原就過熱程度較高的A機櫃吸入更少的冷空氣，造成*RCI*反而大幅的下降。