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WORLD ENGINEERS SUMMIT

APPLIED ENERGY SYMPOSIUM & FORUM

Distinguished Lecturers Seminar by ASHRAE – 21 July 2017

Thermal Comfort and IAQ in High Performing Buildings

Emerging HVAC Technologies for Energy Efficient Healthy Buildings in Hot and Humid Climates

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EDUCATION PARTNER

Emerging HVAC Technologies for Energy Efficient Healthy Buildings in Hot and Humid Climates

By Professor Chandra Sekhar

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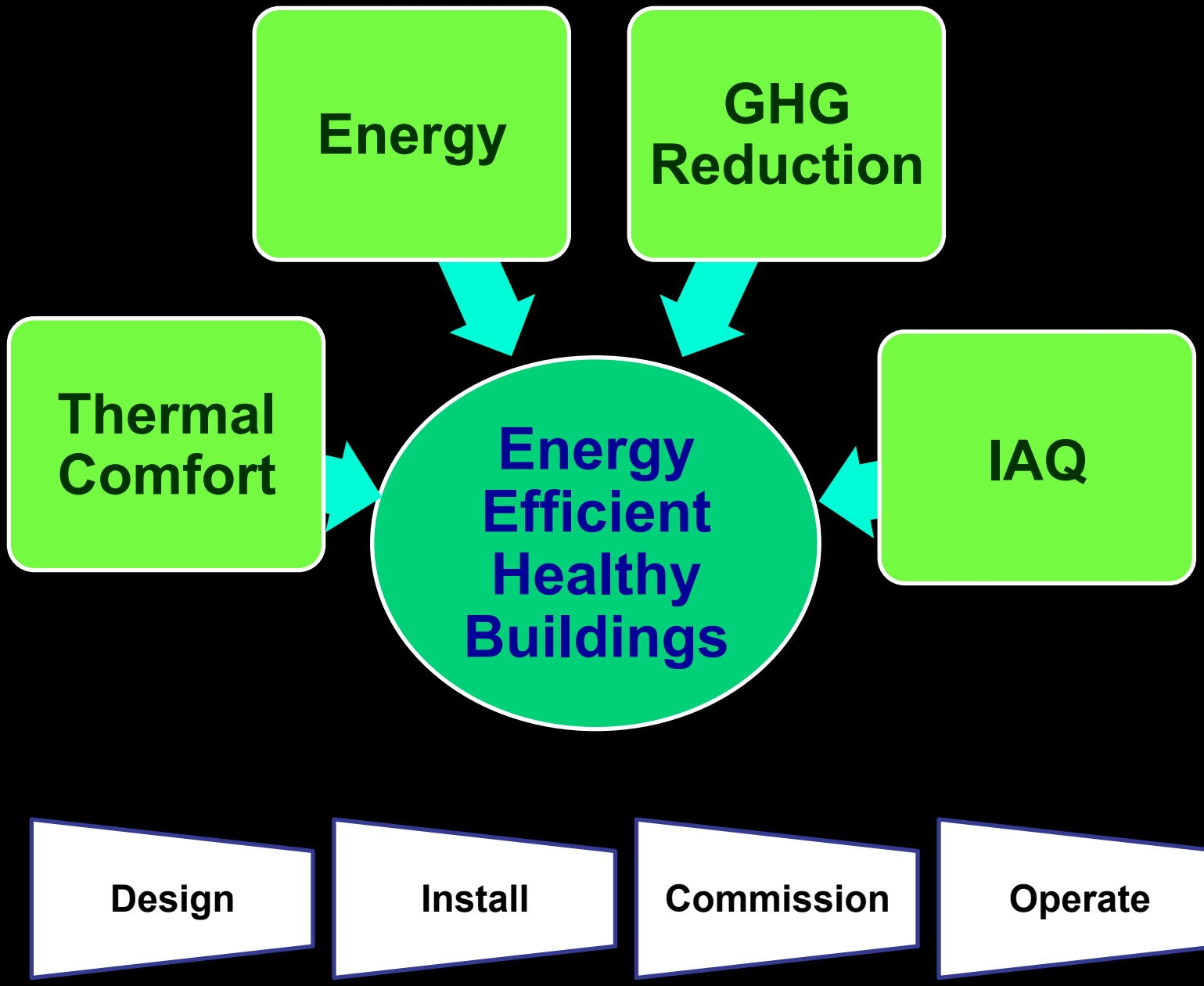
Description

Emerging HVAC technologies for energy efficient healthy buildings in hot and humid climates

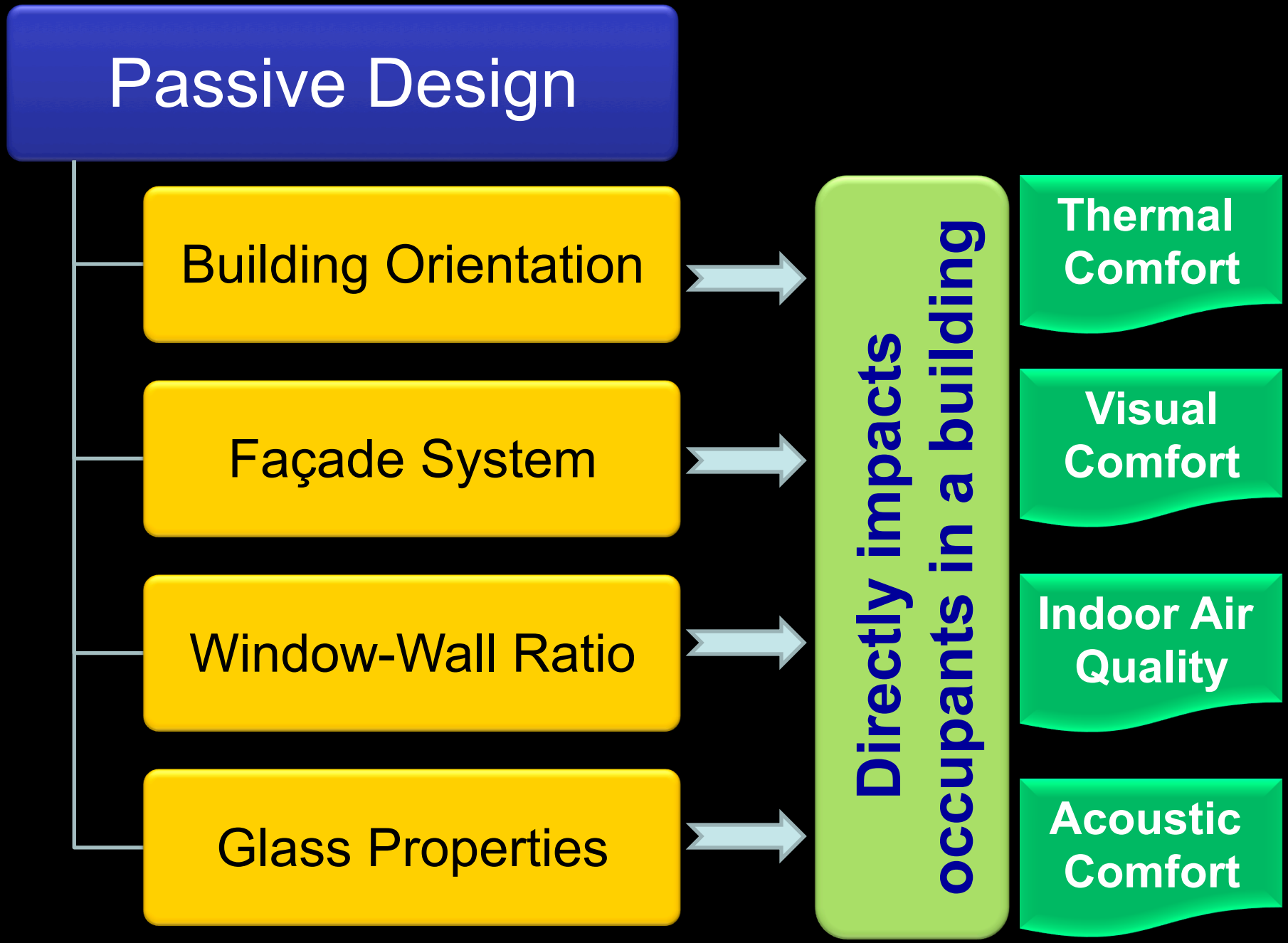
In recent times, clear associations are being established between ventilation rates, Indoor Air Quality (IAQ) and the productivity of workforce in various types of buildings, most significant of which is the commercial and office building sector. It is also an established fact that HVAC systems do consume a significant proportion of national energy budget in any country irrespective of whether the HVAC design is "Cooling Driven" or "Heating Driven". Hence, the notion of Energy Efficient Healthy Buildings is gaining popularity worldwide in the context of sustainable design and it is even more challenging in hot and humid climates that have all-year air-conditioning demand in the form of energy intensive cooling and dehumidification. It is quite apparent that Climate Change effects are only going to make the HVAC designer's job even more challenging in the future. Whilst SOURCE CONTROL is commonly advocated as the fundamental approach to eliminating or containing the contaminant levels inside the building, a more practical and often necessary approach is likely to be EXPOSURE CONTROL. Thus, ventilation plays an important role in providing a quality built environment. The concept of decoupling "ventilation air" from "supply air" is fast emerging as an ideal solution to combat thermal comfort IAQ issues in a sustainable manner. This talk will highlight some of the current and future technologies for air-conditioning and air-distribution that can collectively contribute to the design of energy efficient healthy buildings.

Learning Objectives

1. Describe the logical sequence of SOURCE CONTROL followed by EXPOSURE CONTROL in the sustainable design of healthy buildings
2. Describe the concept of "Decoupled Ventilation Systems" in the context of enhancing IAQ in an energy efficient manner
3. Explain how these Decoupled Ventilation systems operate, such as Dedicated Outdoor Air System, Single Coil Twin Fan system, Heat Pipe integrated Air Handling Unit, Desiccant System and Personalised Ventilation system
4. Quantify the Thermal Comfort and IAQ enhancements as well as the energy saving potential of some of the systems described in (3)


Energy
GHG Reduction
Thermal Comfort
Energy Efficient Healthy Buildings
IAQ
Design
Install
Commission
Operate

Energy


Passive Design
Building Orientation
Façade System
Window-Wall Ratio
Glass Properties
Directly impacts occupants in a building
Thermal Comfort
Visual Comfort
Indoor Air Quality
Acoustic Comfort

Active Design

Artificial Lighting
- Ambient lighting
- Task lighting

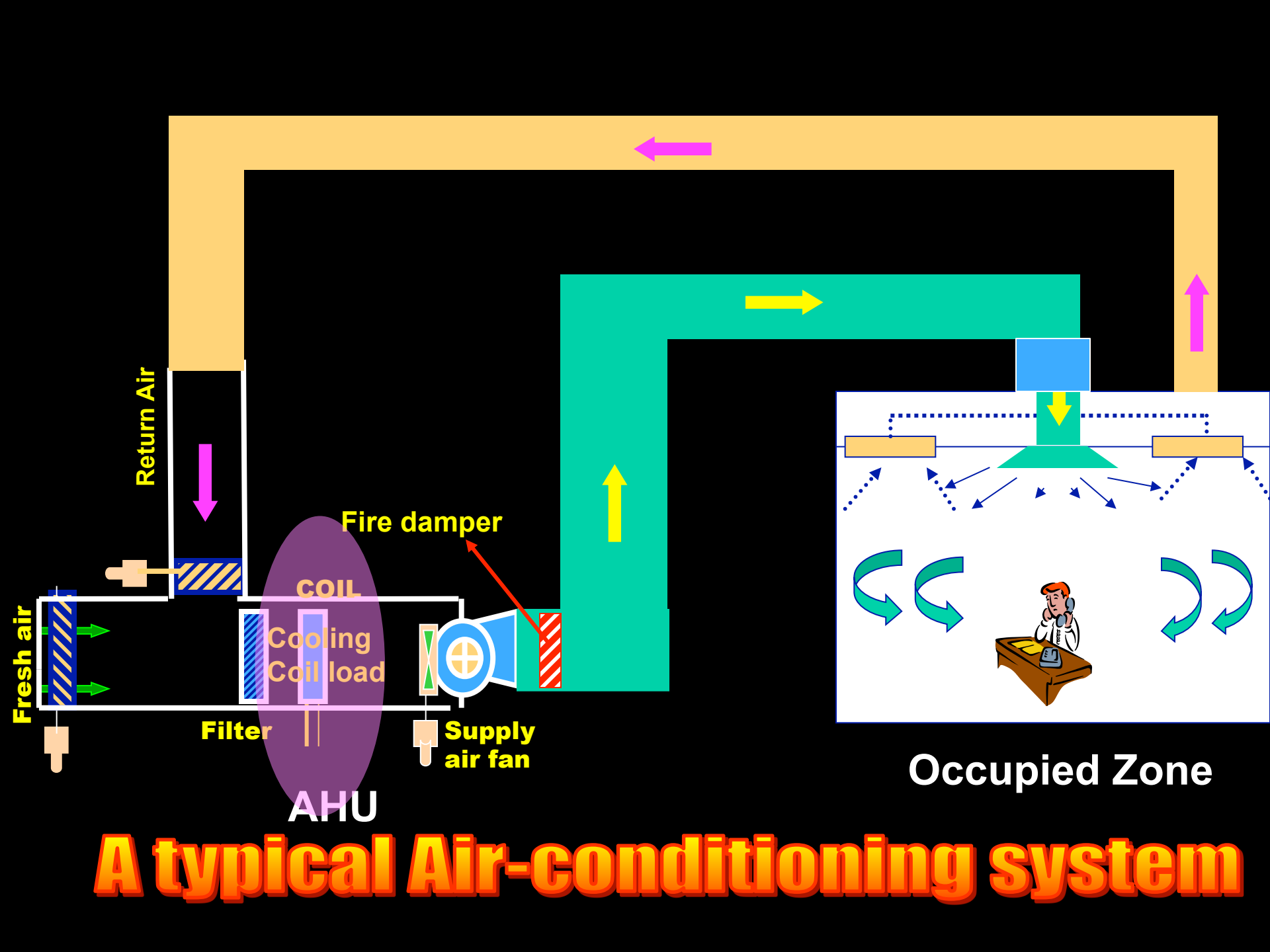
→ **Directly impacts occupants in a building**

HVAC Plant –
- Chiller
- Cooling Tower
- Accessories (Pumps)

→ **No direct impact to occupants in a building**

HVAC Systems
- Air-conditioning Systems
- Air Distribution Systems

→ **Directly impacts occupants in a building**



A typical Air-conditioning system

IAQ

Mendell, M.J., W.J. Fisk, K. Kreiss, H. Levin, D. Alexander, W.S. Cain, J.R. Girman, C.J. Hines, P.A. Jensen, D.K. Milton, L.P. Rexroat and K.M. Wallingford, 2002. Improving the health of workers in indoor environments: Priority research needs for a national occupational research agenda. American Journal of Public Health, Vol 92, No.9, 1430 -1440.

…… improving building environments may result in health benefits for more than 15 million of the 89 million US indoor workers, with estimated economic benefits of $5 to $75 billion annually.

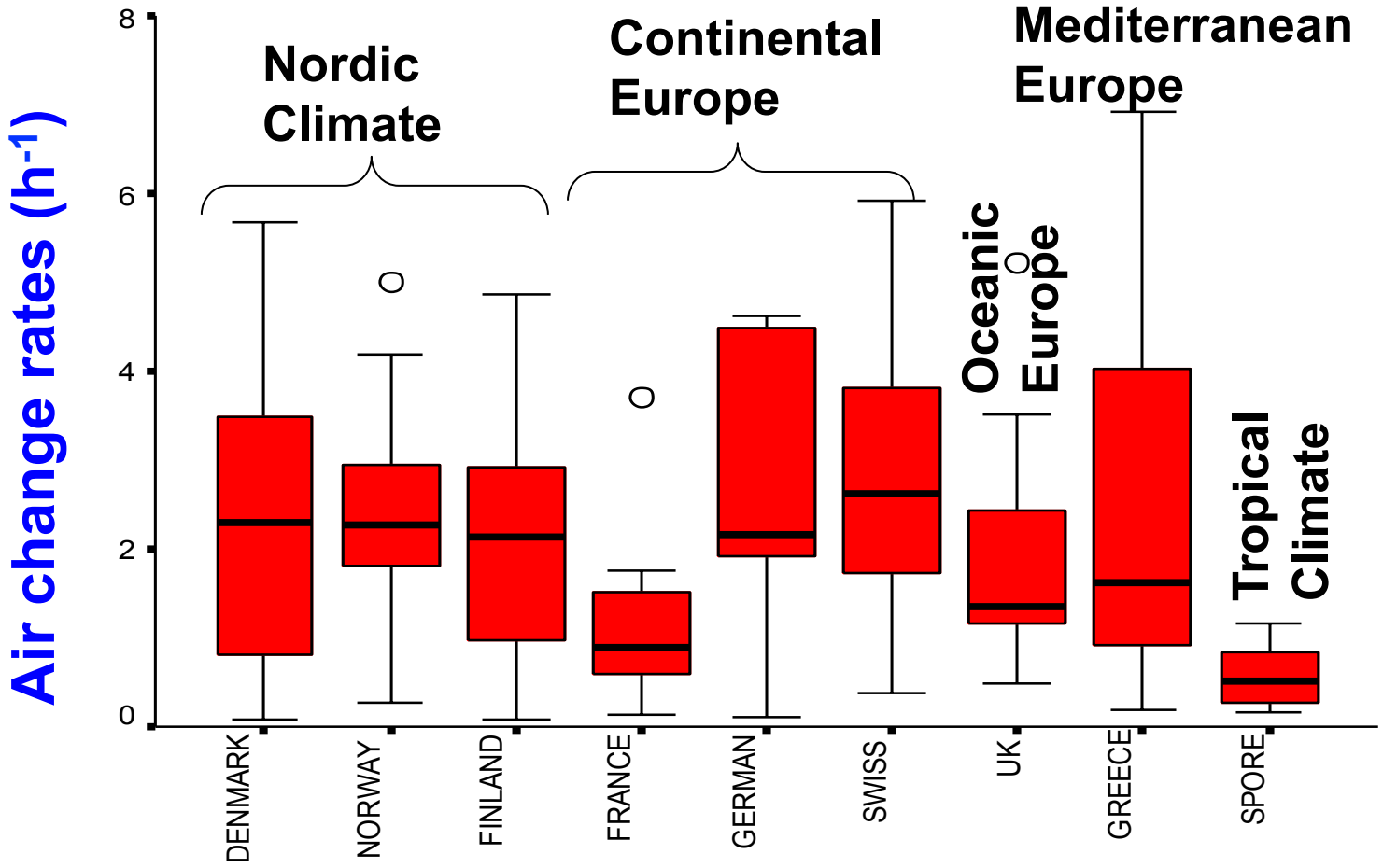
Why IAQ

IAQ - Source Control

“If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure.”

Max Joseph von Pettenkofer (1818-1901), german chemist

Zuraimi MS, Roulet C-A, Tham KW, Sekhar SC, David Cheong KW, Wong NH & Lee HK, 2004. "A comparative study of VOCs in Singapore and European Office Buildings", Building and Environment, *Volume 41, Issue 3, March 2006, Pages 316-329*



Air change rates (ACH) measured in the European and Singapore buildings studied



https://www.ashrae.org/resources--publications/bookstore/indoor-air-quality-guide

Emerging Technologies for Hot Humid Climates

Air-conditioning Systems

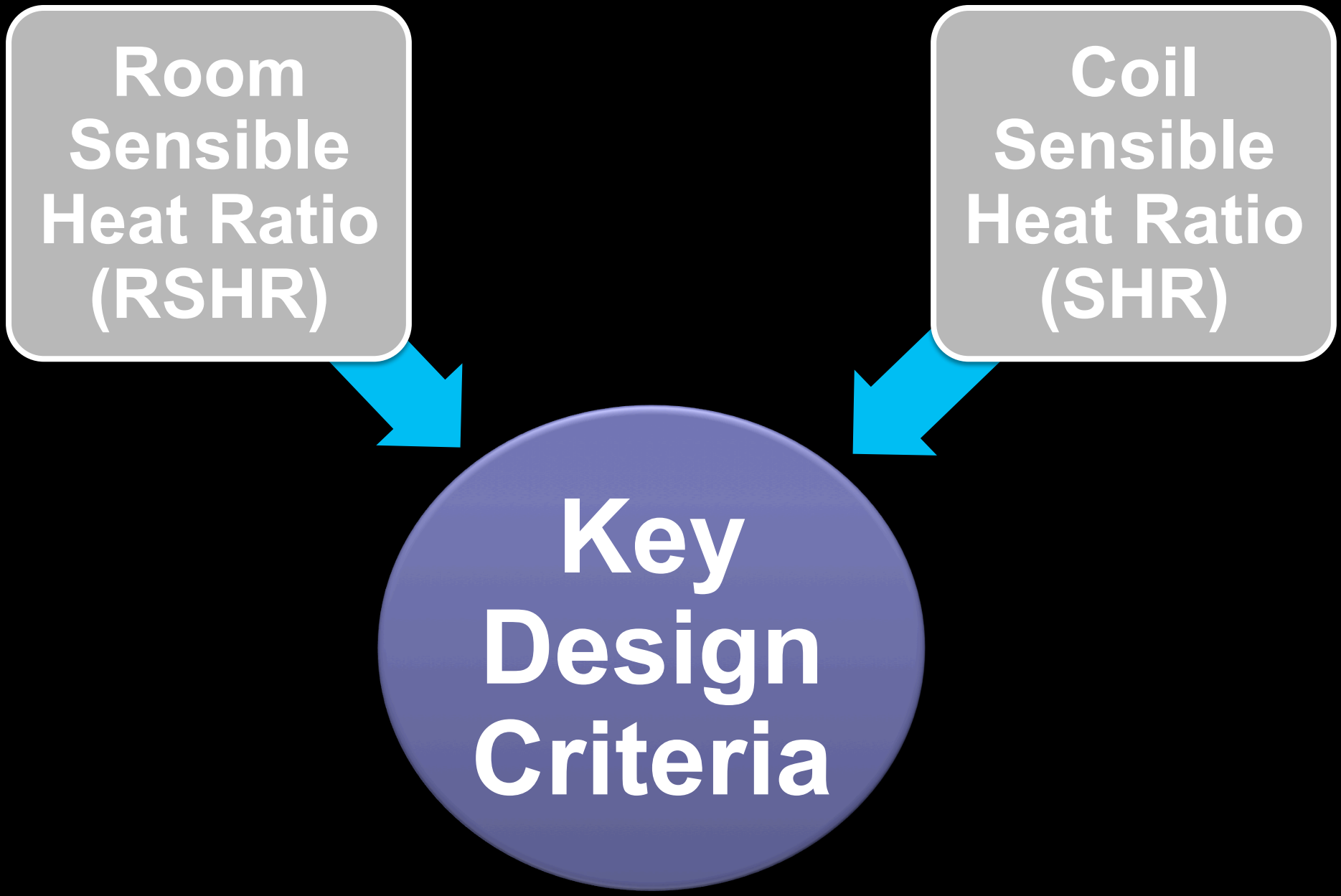
- LFV-HCV system
- Dedicated Outdoor Air System (DOAS)
- SCTF system
- Desiccant System
- Heat Pipes

Air Distribution Systems

- SCTF system
- Desk PV/ Ceiling MV system
- Ceiling PV/ Ceiling MV system
- Desk PV/ UFAD system

Low Face Velocity – High Coolant Velocity (LFV-HCV) method of air-conditioning




Room Sensible Heat Ratio (RSHR)
Coil Sensible Heat Ratio (SHR)
Key Design Criteria

Performance of cooling and dehumidifying coil

Strong bearing on indoor temperature and humidity conditions

Impact on IAQ

Operation controlled by chilled water modulation



Often leads to problems due to overdesign

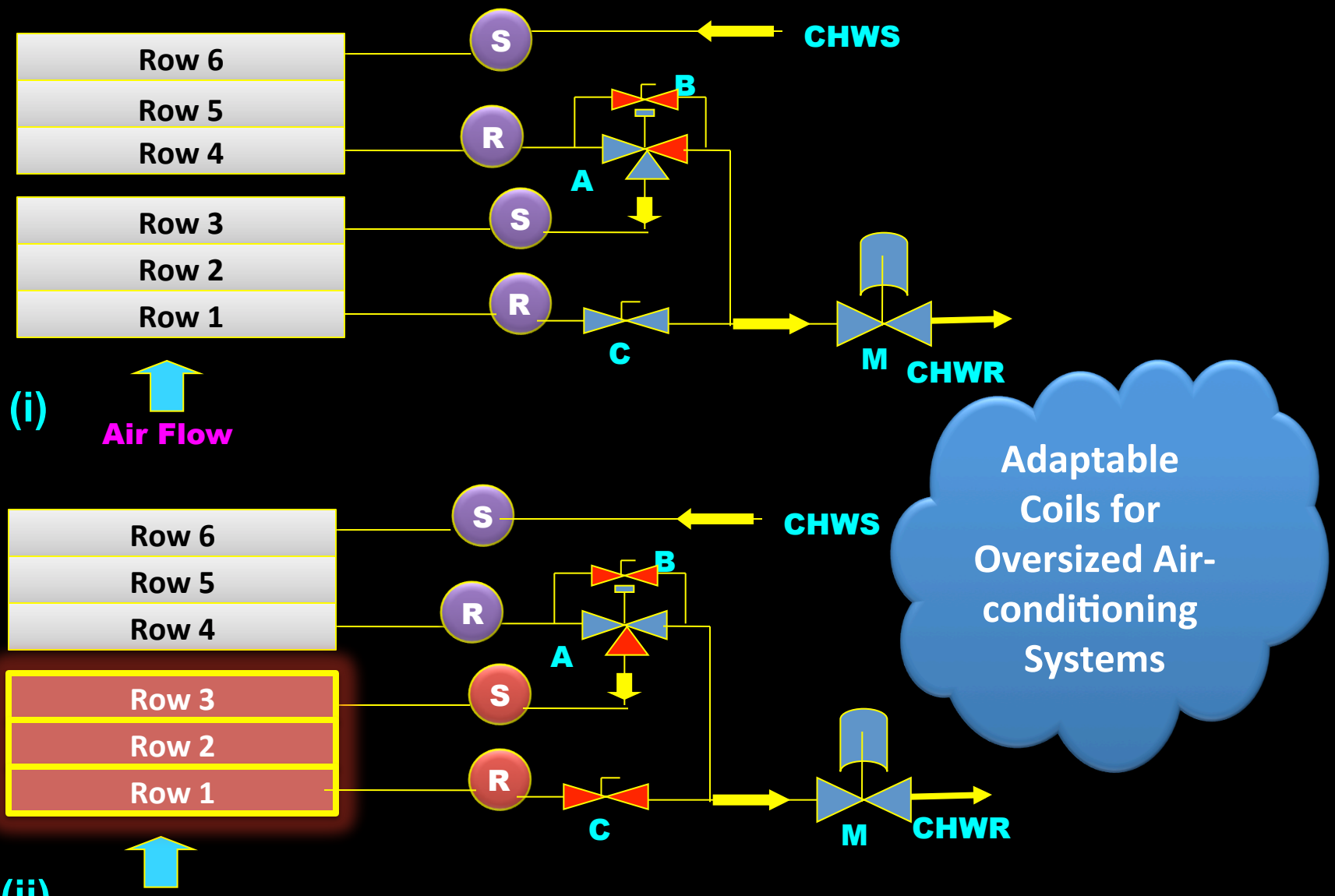


Inhibits dehumidifying performance exactly when it is needed to dehumidify more

Driving force for condensation – Interface temperature

Low heat transfer coefficient on air side
&
High Heat Transfer Coefficient on water side

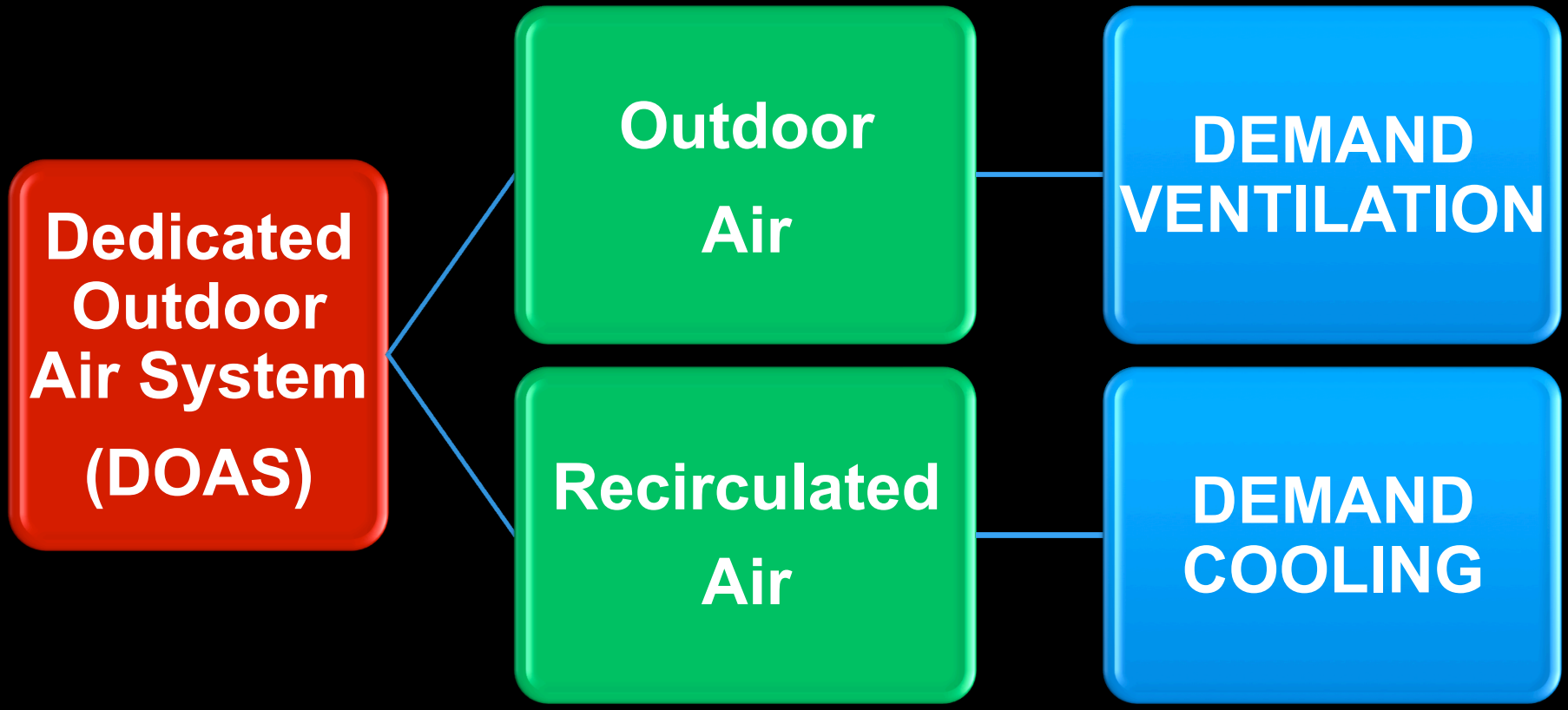
Low Face Velocity – High Coolant velocity
LFV/HCV



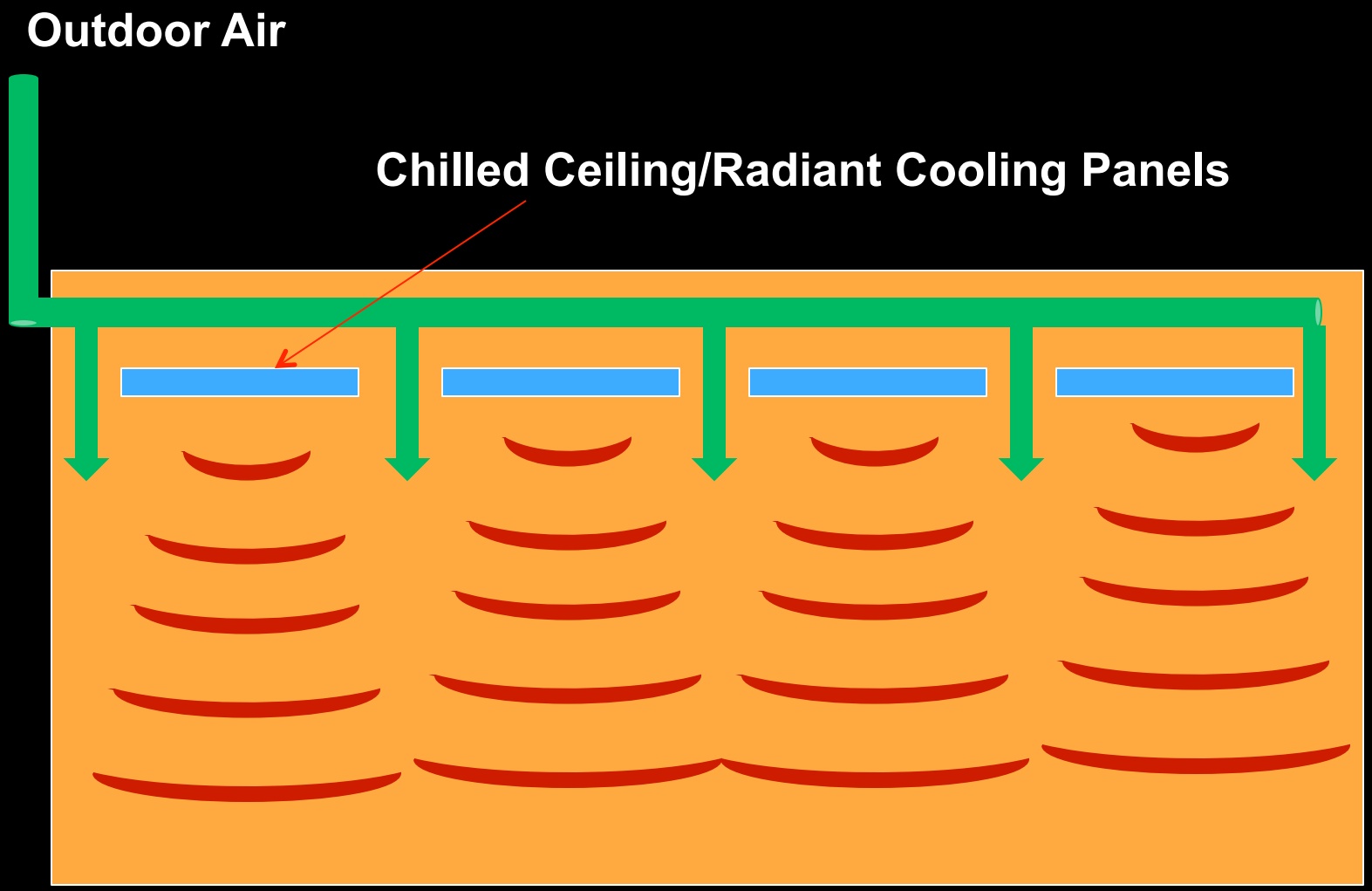
A : 3 Port 2 Way Valve
B : By-Pass Valve
C : On/Off Valve
M : Modulating Valve

CHWS : Chilled Water Supply
CHWR : Chilled Water Return
S : Supply Manifold
R : Return Manifold

Dedicated Outdoor Air System (DOAS


Dedicated Outdoor Air System (DOAS)
Outdoor Air
Recirculated Air
DEMAND VENTILATION
DEMAND COOLING

What is Dedicated Outdoor Air System (DOAS)?

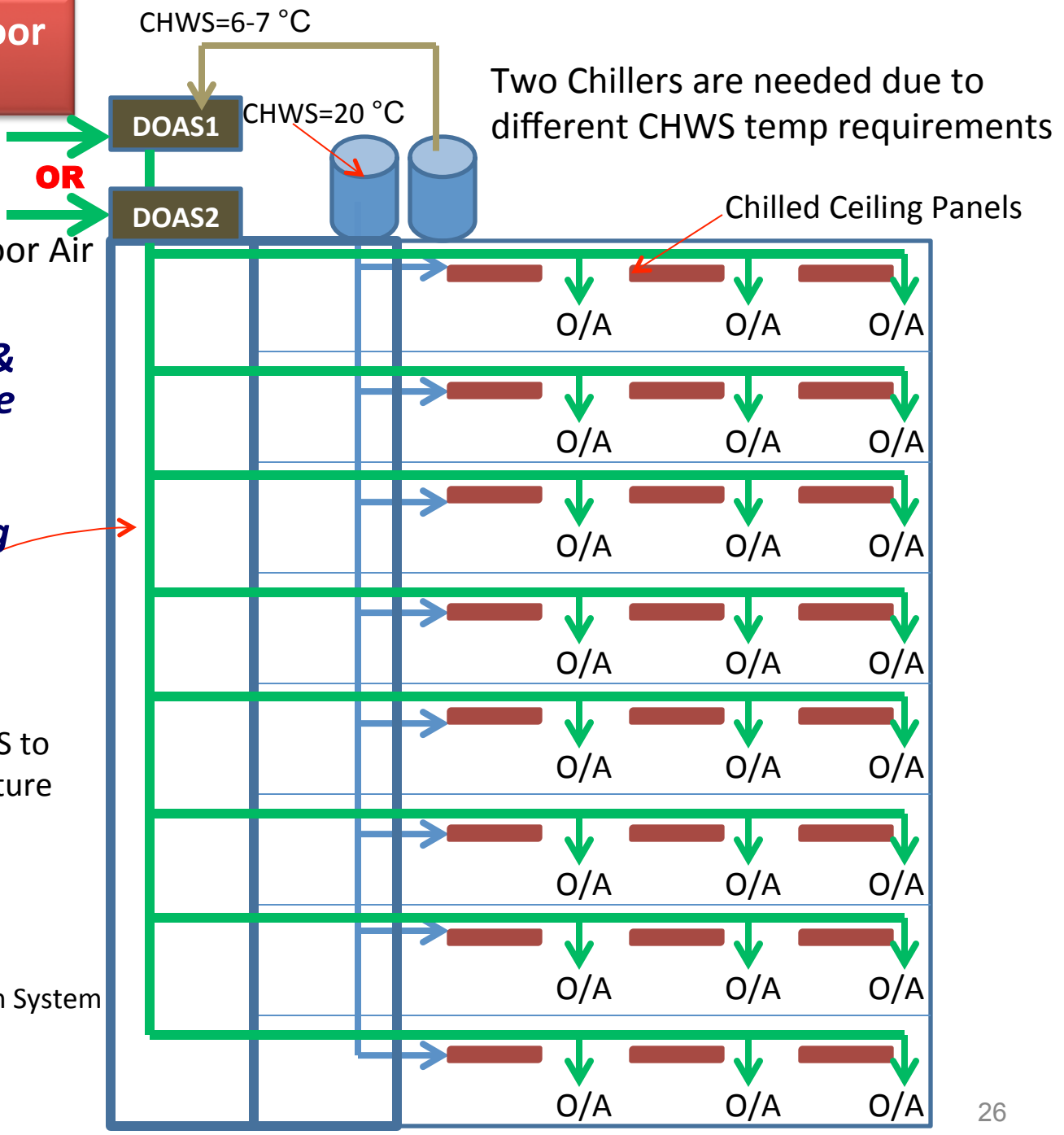


DOAS with Chilled Ceiling

What is Dedicated Outdoor Air System (DOAS)?

Decoupling Ventilation From Cooling

DEMAND VENTILATION & DEMAND COOLING at the Independent zone level Achieved in the case of DOAS with Chilled Ceiling



Outdoor Air (O/A) condition:

- Full dehumidification by DOAS to required Dew Point Temperature
- Insulated duct

DOAS1 – Chilled water coil AHU

DOAS2 – Desiccant Dehumidification System

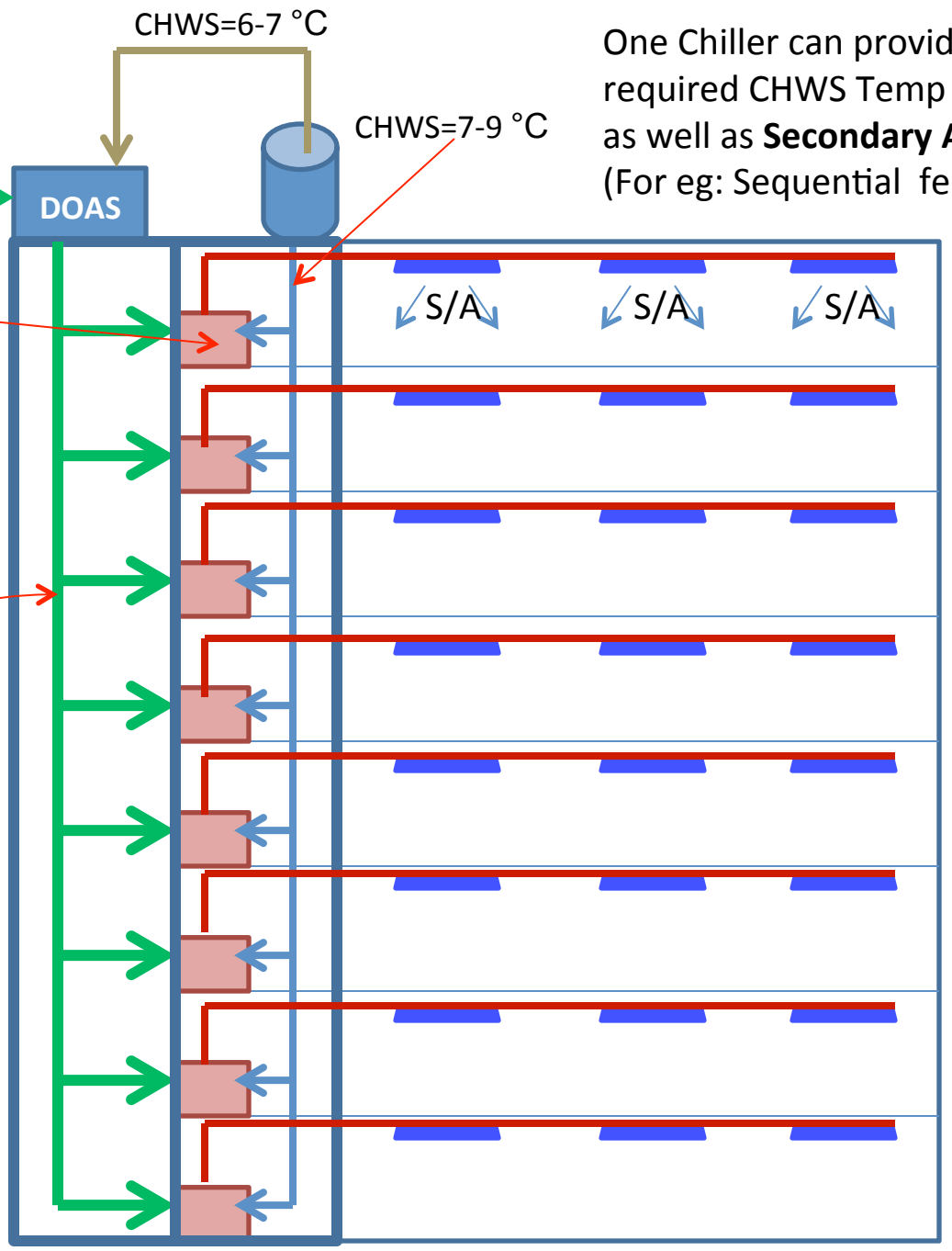
DOAS with Chilled Ceiling

What is Dedicated Outdoor Air System (DOAS)?

Decoupling Ventilation From Cooling

DEMAND VENTILATION & DEMAND COOLING at the Independent zone level

NOT ACHIEVED in the case of DOAS with Secondary AHU



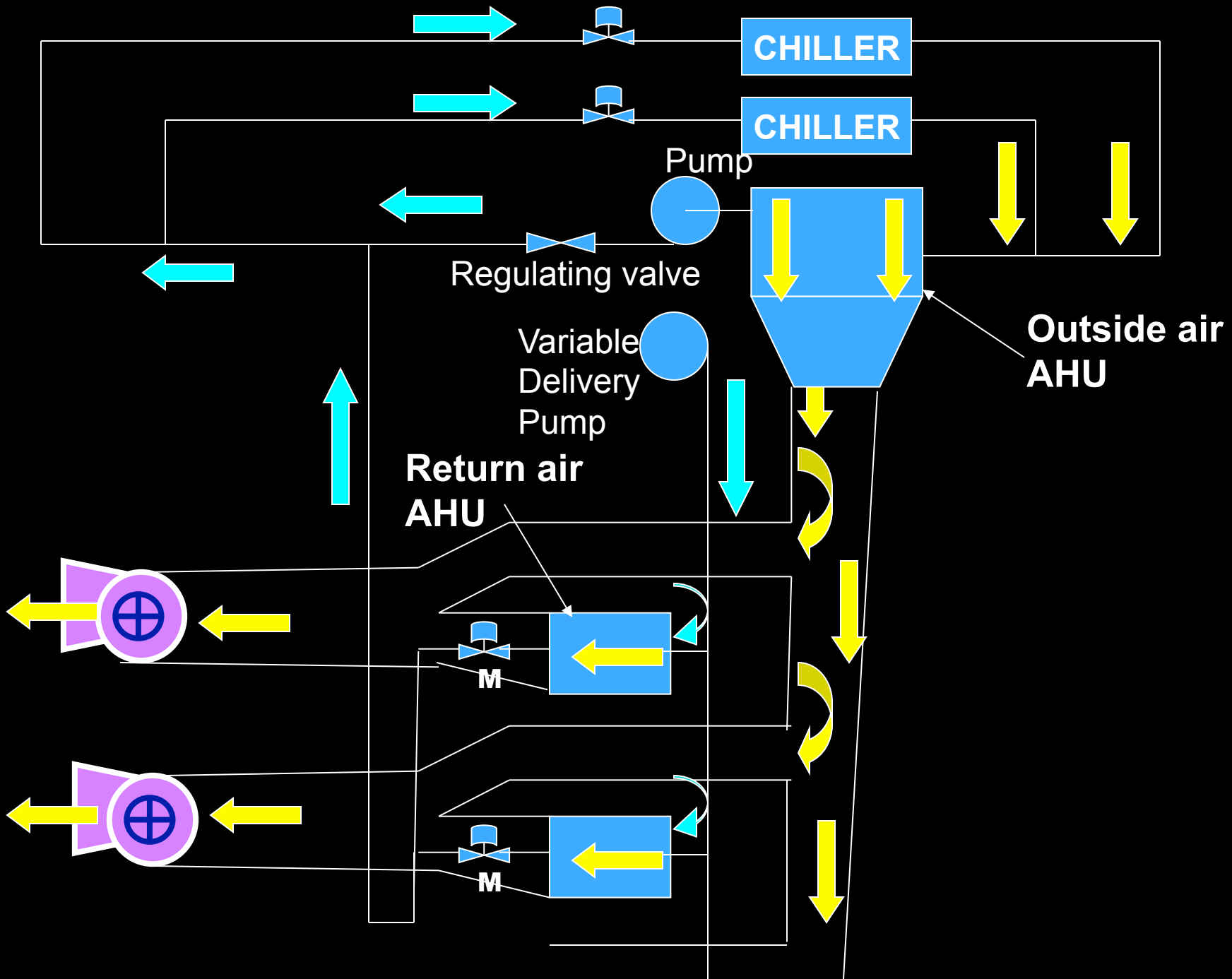
One Chiller can provide the required CHWS Temp for **DOAS** as well as **Secondary AHU** (For eg: Sequential feed)

Outdoor Air (O/A) condition:

- Partially dehumidified by DOAS – additional dehumidification done by secondary AHU

  OR
- Full dehumidification by DOAS to required Dew Point Temperature
- Insulated Duct

DOAS with Secondary AHU


CHILLER
CHILLER
Pump
Regulating valve
Variable
Delivery
Pump
Outside air
AHU
Return air
AHU
M
M

Single Coil Twin Fan (SCTF) Air-conditioning & Air distribution system

Sekhar, S.C., Uma Maheswaran, C.R., Tham, K.W, and Cheong K.W, 2004. Development of energy efficient single coil twin fan air-conditioning system with zonal ventilation control, ASHRAE Transactions, 2004, Vol. 110, Pt 2, pp 204-217 (Paper presented in Nashville, June 2004).

Cheyyar, R U M, S C Sekhar, K W Tham and K W Cheong, "Single coil twin fan air-conditioning and air distribution system - Towards the development of a mathematical model of the compartmented coil". HVAC&R RESEARCH - International Journal of Heating, Ventilating, Air-conditioning and Refrigerating Research, 12, no. 3c, pp 825-842 (Special Issue) (October 2006).

Single Coil Twin Fan (SCTF) System – A form of DOAS

One Chiller can provide the required CHWS Temp for the **SCTF System**

CHWS=6-8 °C

Outdoor Air – Zone level Demand Ventilation

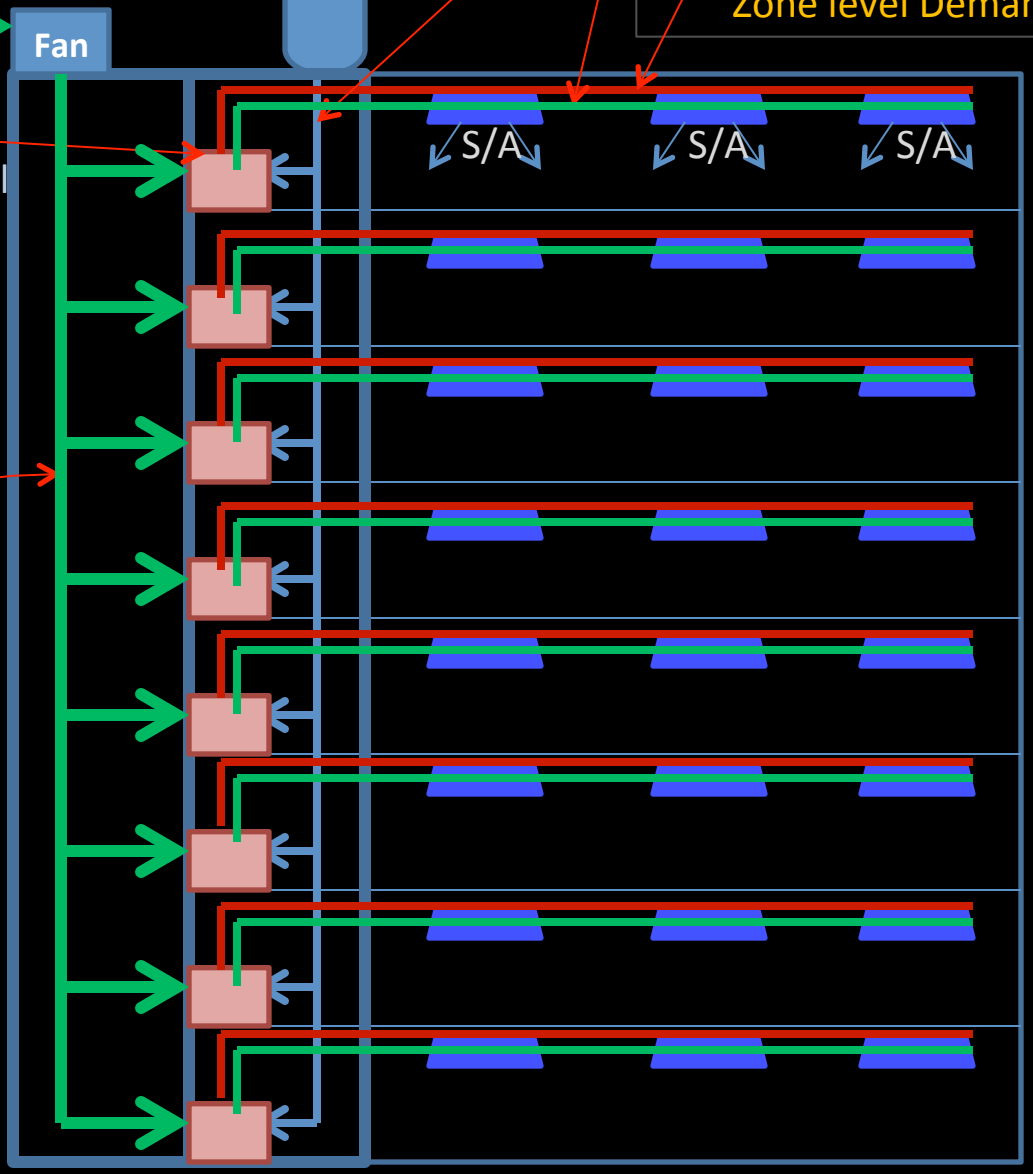
Recirculated Air – Zone level Demand Cooling

Decoupling Ventilation From Cooling

Outdoor Air

SCTF AHU with Compartmented Coil

DEMAND VENTILATION & DEMAND COOLING at the Independent zone level Achieved in the case of SCTF System



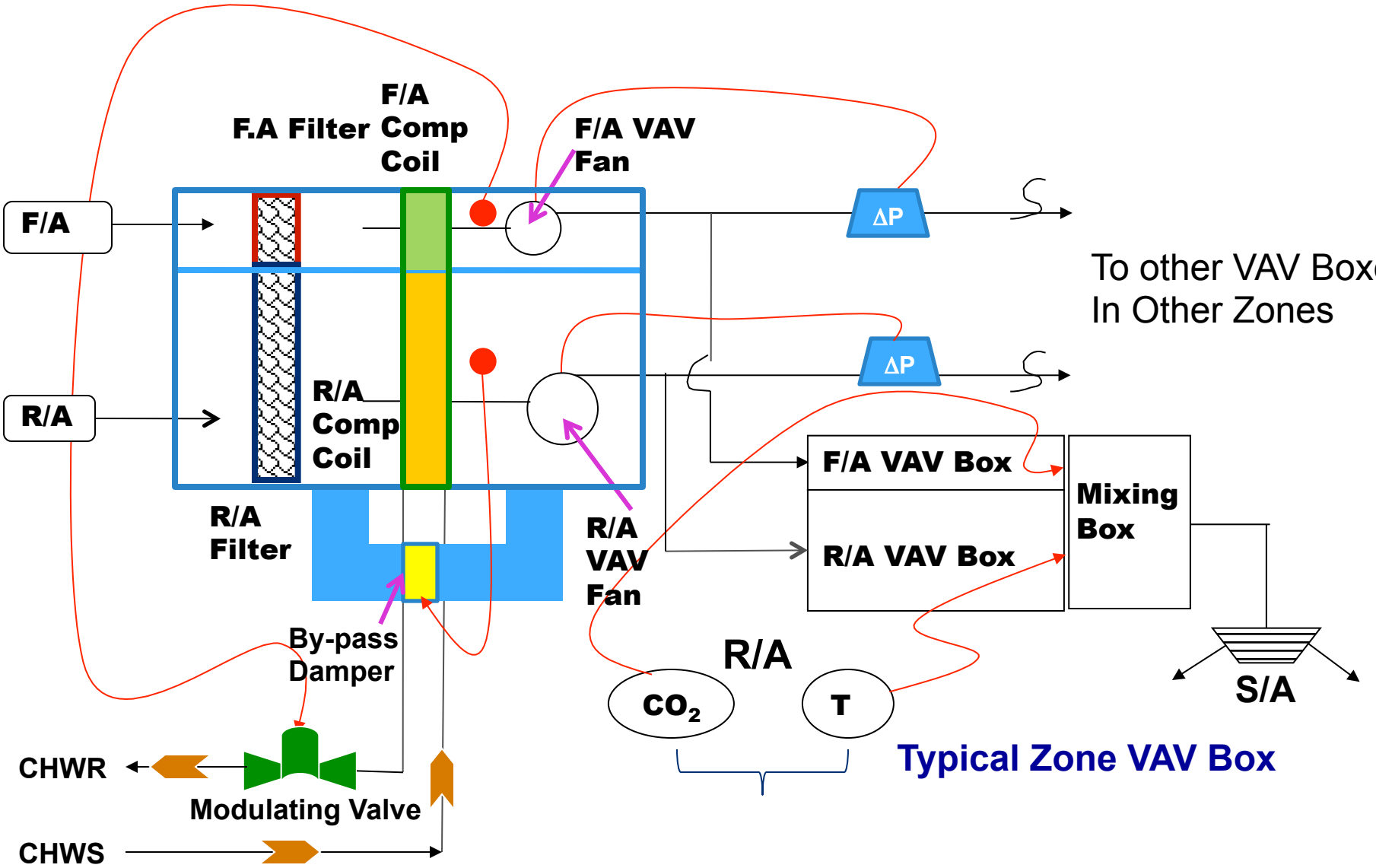
Unconditioned Outdoor Air (O/A)

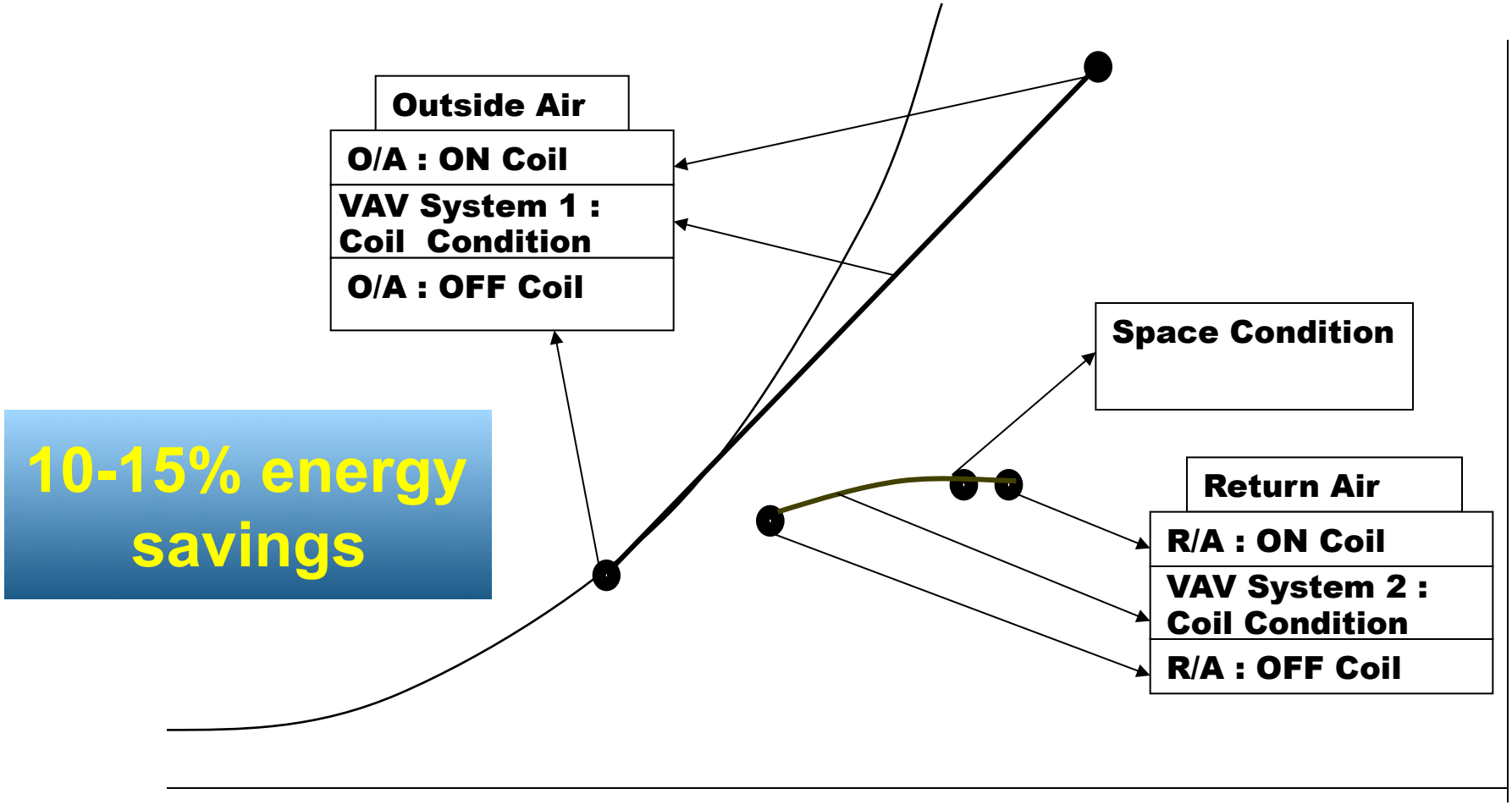
- Uninsulated duct if O/A from roof-top
- Alternatively, O/A can be drawn at each level

SCTF System with Compartmented Cooling Coil

SCTF Air-conditioning and Air Distribution System

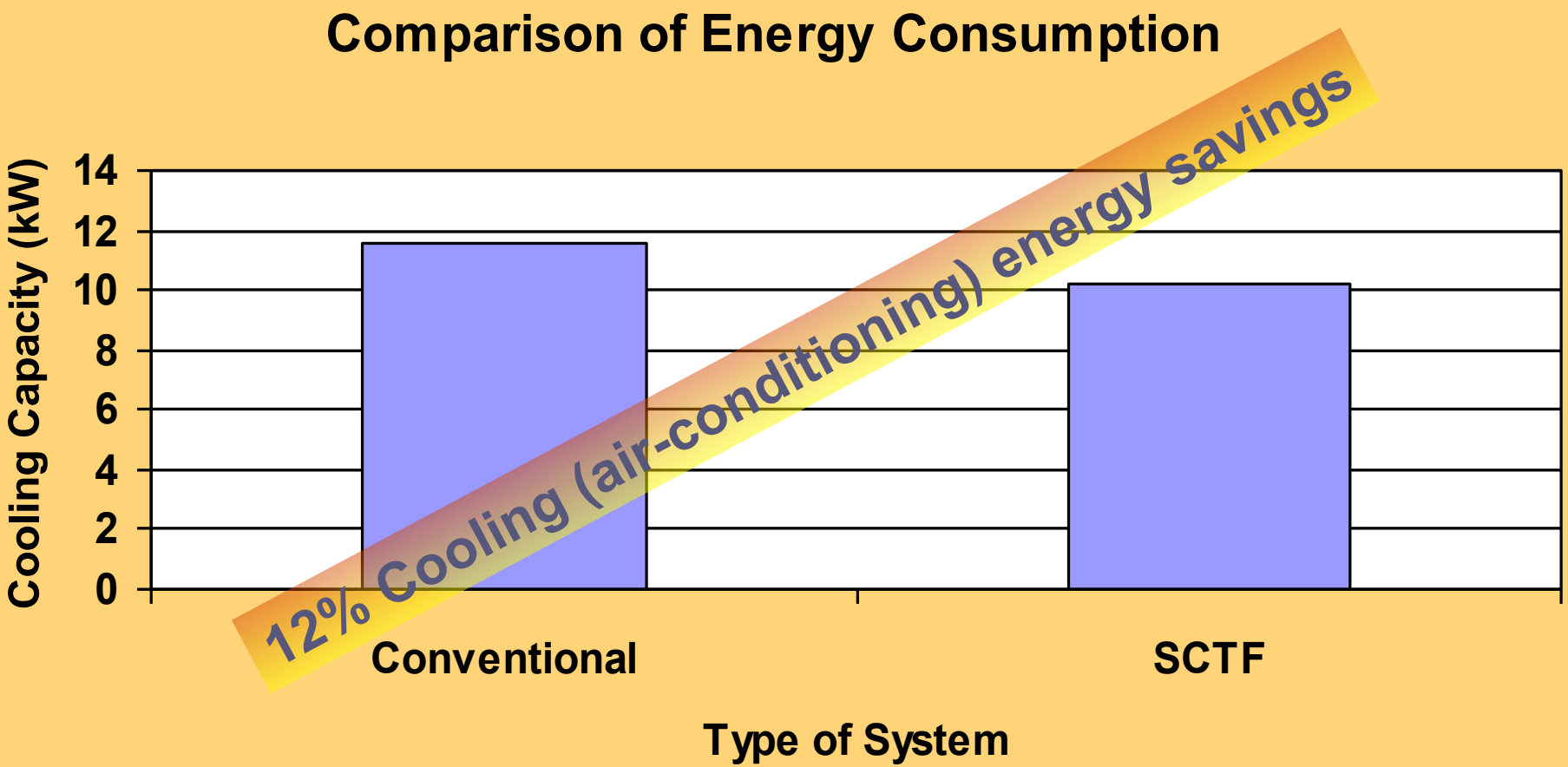
(US and PCO Patents)





SCTF system for independent conditioning of fresh air and return air streams – A Psychrometric Performance

SCTF Prototype Findings



The Enterprise Challenge (TEC) Grant

Field Trial –
A Test-Bedding Project

BIdg TOP = June 2005
SCTF Installed = June 2005

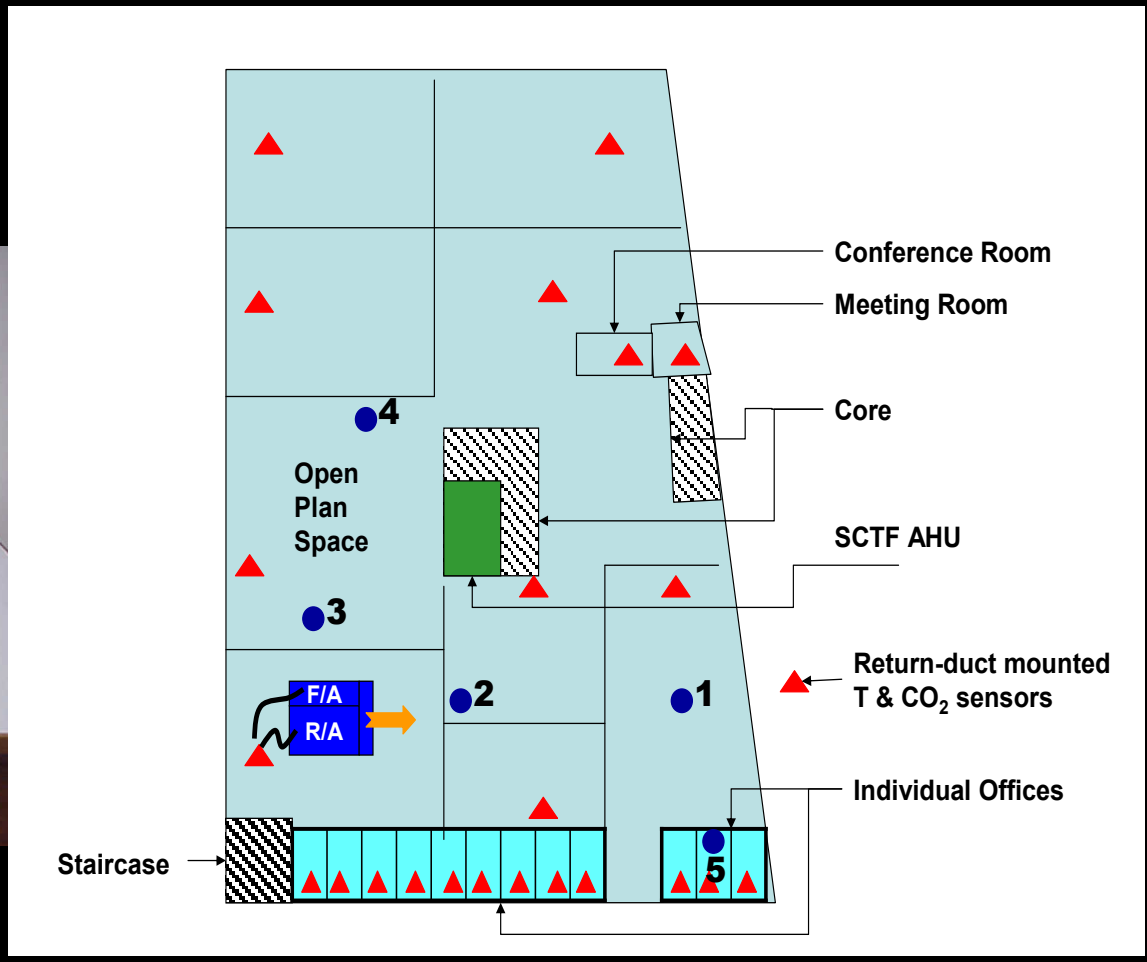
Air-conditioned Floor Area for SCTF system = 2,750m^2

DESIGN DATA

F/A = 5,400 cmh
R/A = 60,000 cmh
Coil Cap = 86 kW (F/A)
233 kW (R/A)

Field Trial – A Test-Bedding Project



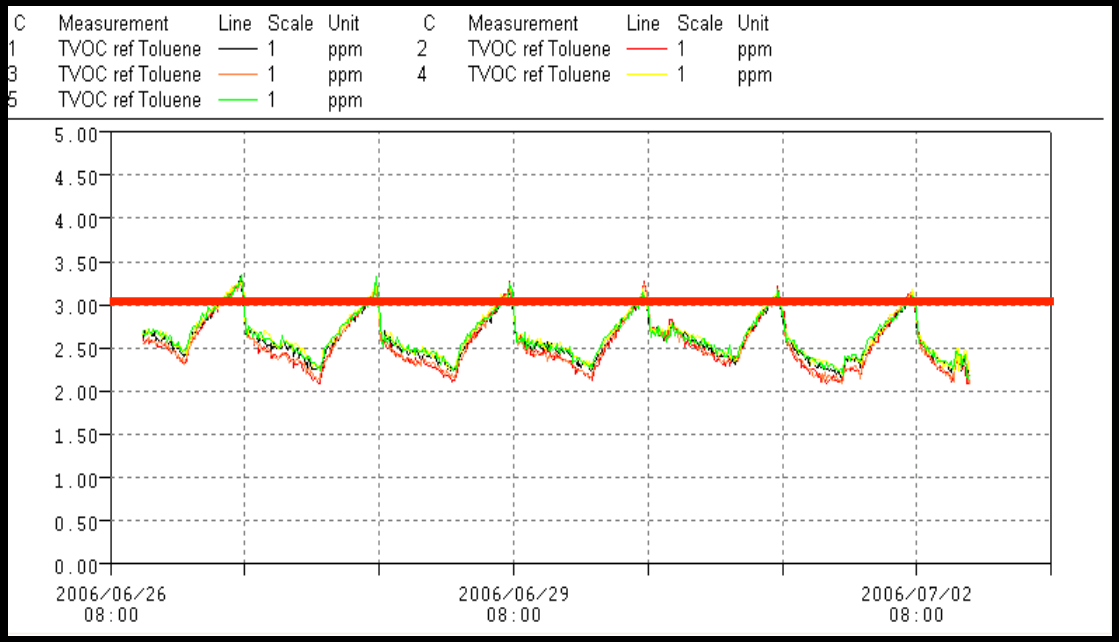


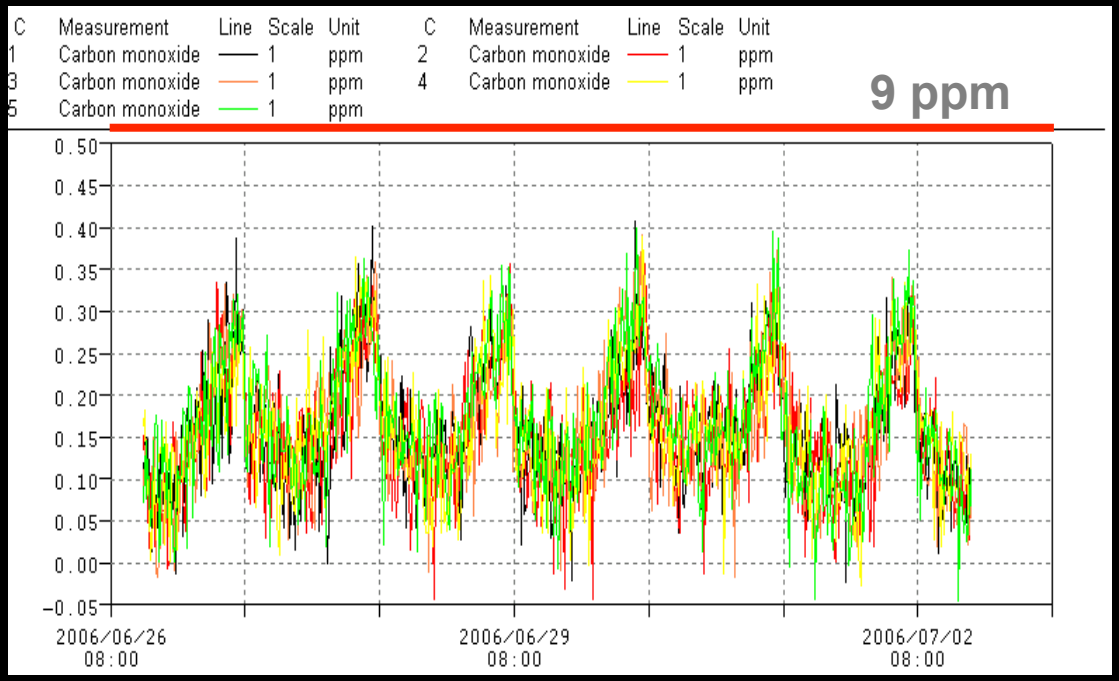
The Enterprise Challenge (TEC) Grant

C	Measurement	Line	Scale	Unit	C	Measurement	Line	Scale	Unit
1	Carbon dioxide	———	1	ppm	2	Carbon dioxide	———	1	ppm
3	Carbon dioxide	———	1	ppm	4	Carbon dioxide	———	1	ppm
5	Carbon dioxide	———	1	ppm					



Field Trial – A Test-Bedding Project

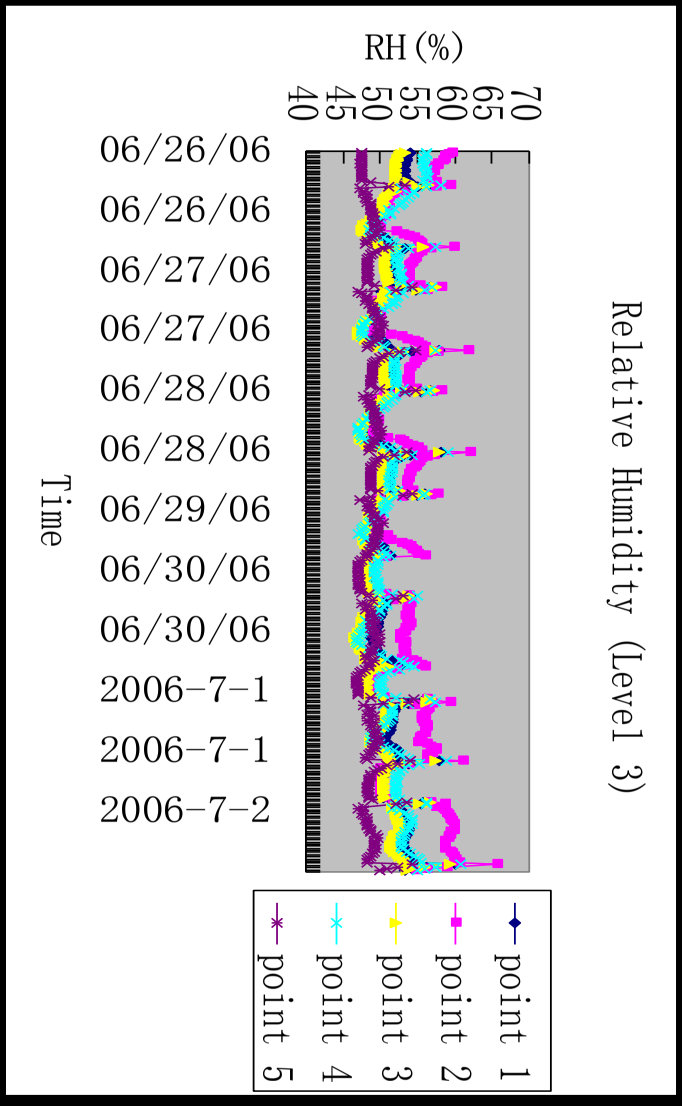


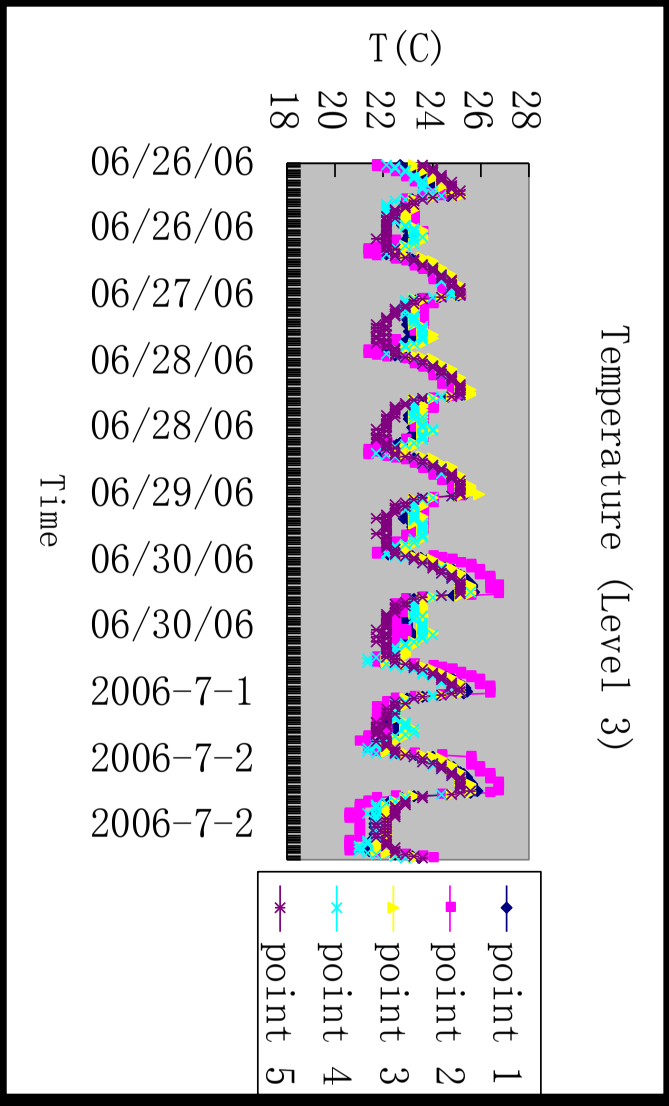


Field Trial –
A Test-Bedding Project

Indoor relative humidity
range : 47 - 54 %RH
Average = 50 %RH

Indoor temperature
range : 21.8 - 23.8 °C
Average = 23 °C





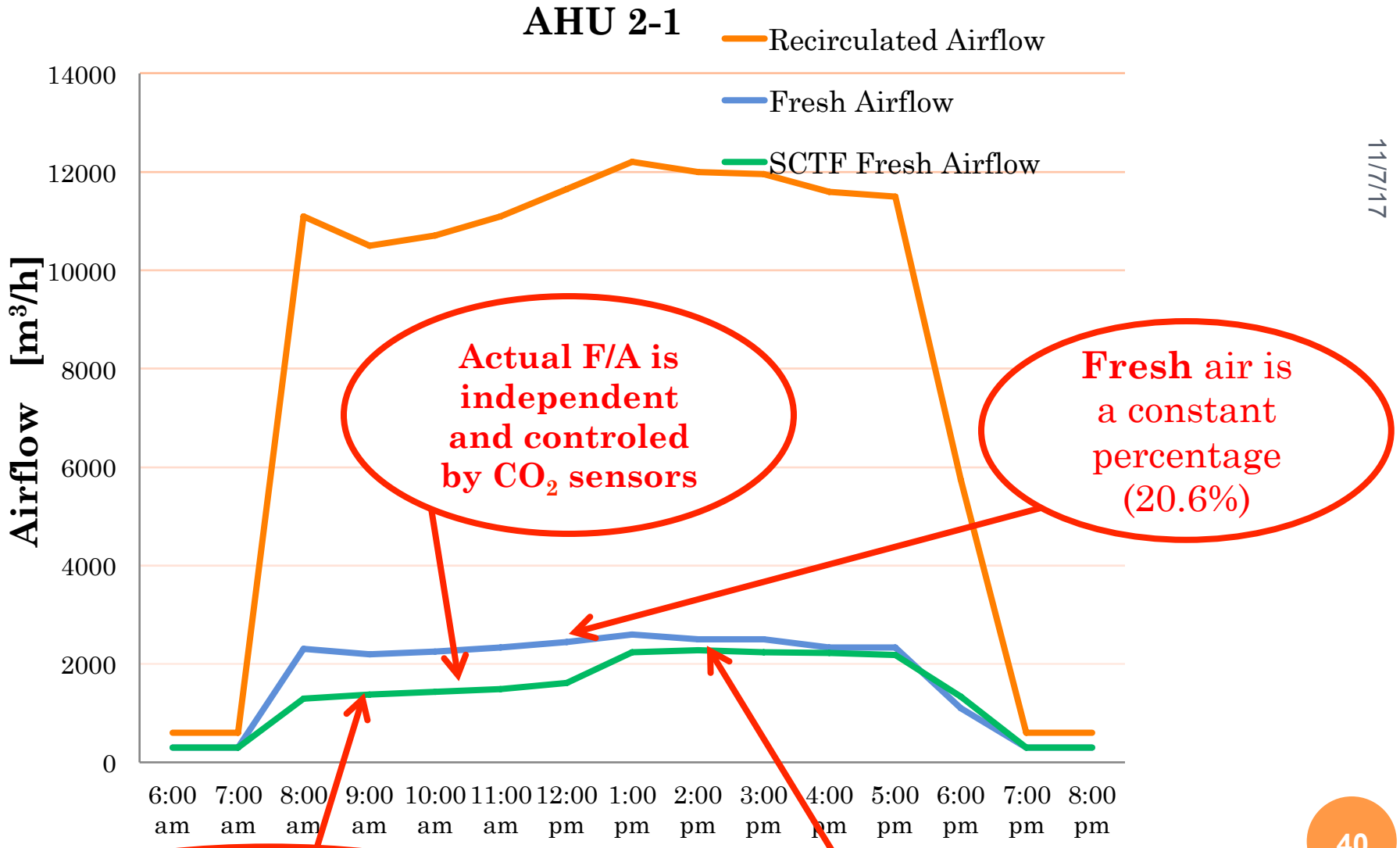


Zero Energy Building @ BCA Academy





Improved Fresh Air control

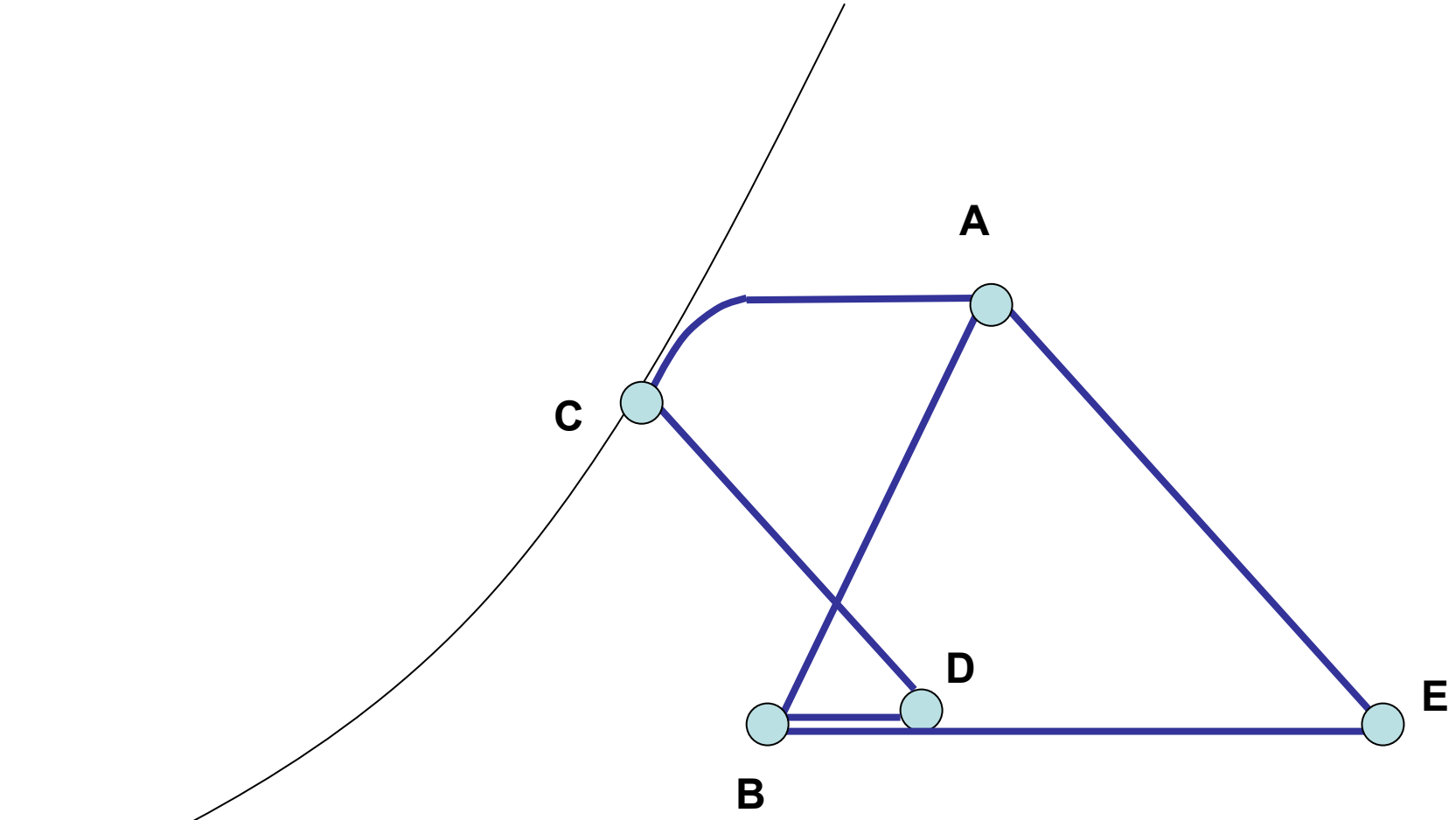


Improved Fresh Air control = Less Energy !!!

		AHU 2-1	AHU 3-1	AHU 3-2	AHU 3-3
Baseline cooling	*[kW]*	14300	7930	5600	4530
Actual cooling	*[kW]*	12400	7530	3950	3890
Percent difference *	*[%]*	**13.28**	**5.05**	**29.46**	**14.13**

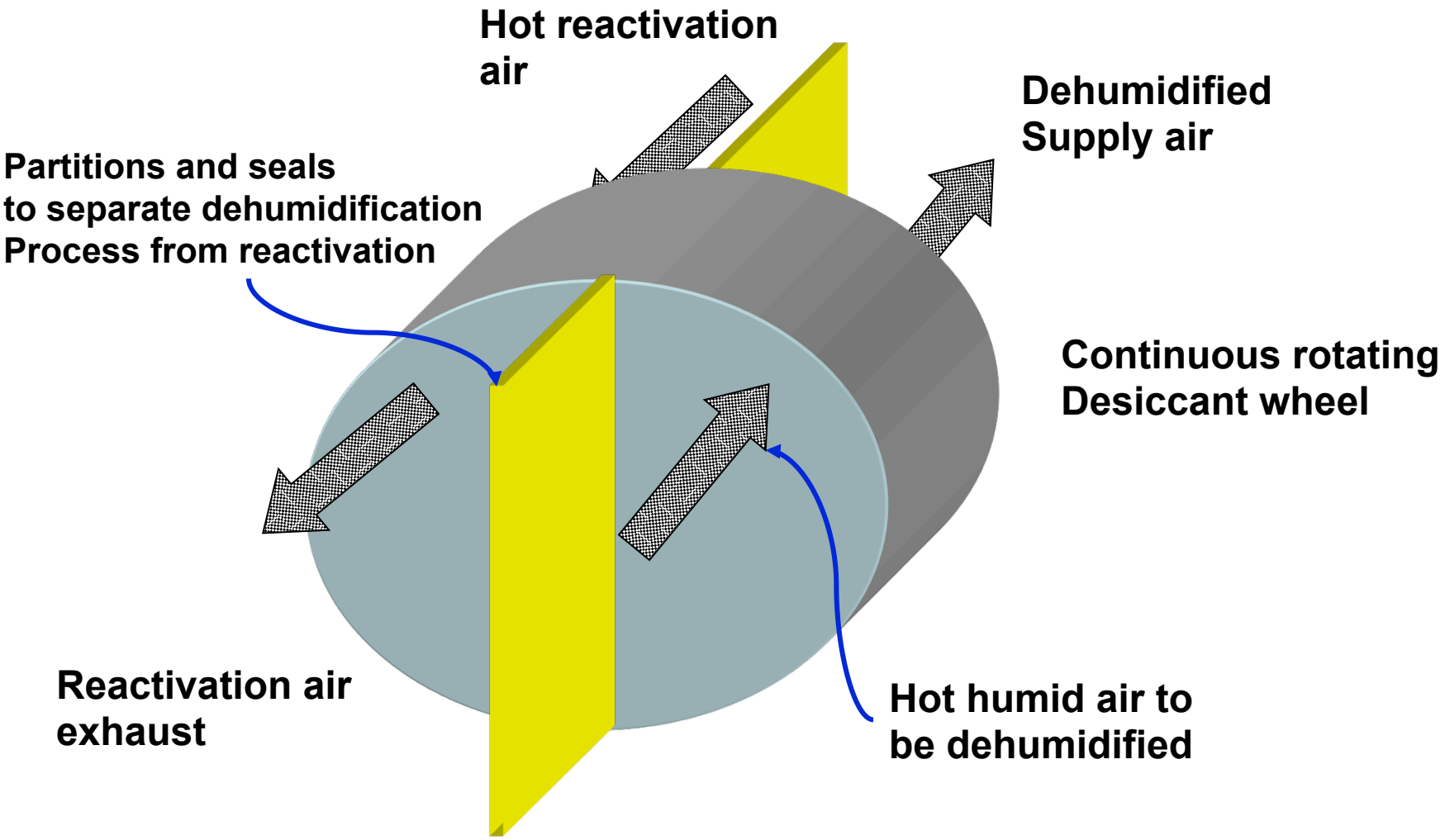
* Savings for April 2010.

Desiccant Dehumidification System



AB	:	Liquid Desiccant unit
AC ⇨ CD ⇨ DB	:	Solid Desiccant unit
AE ⇨ EB	:	Solid Desiccant unit

Desiccant dehumidification systems

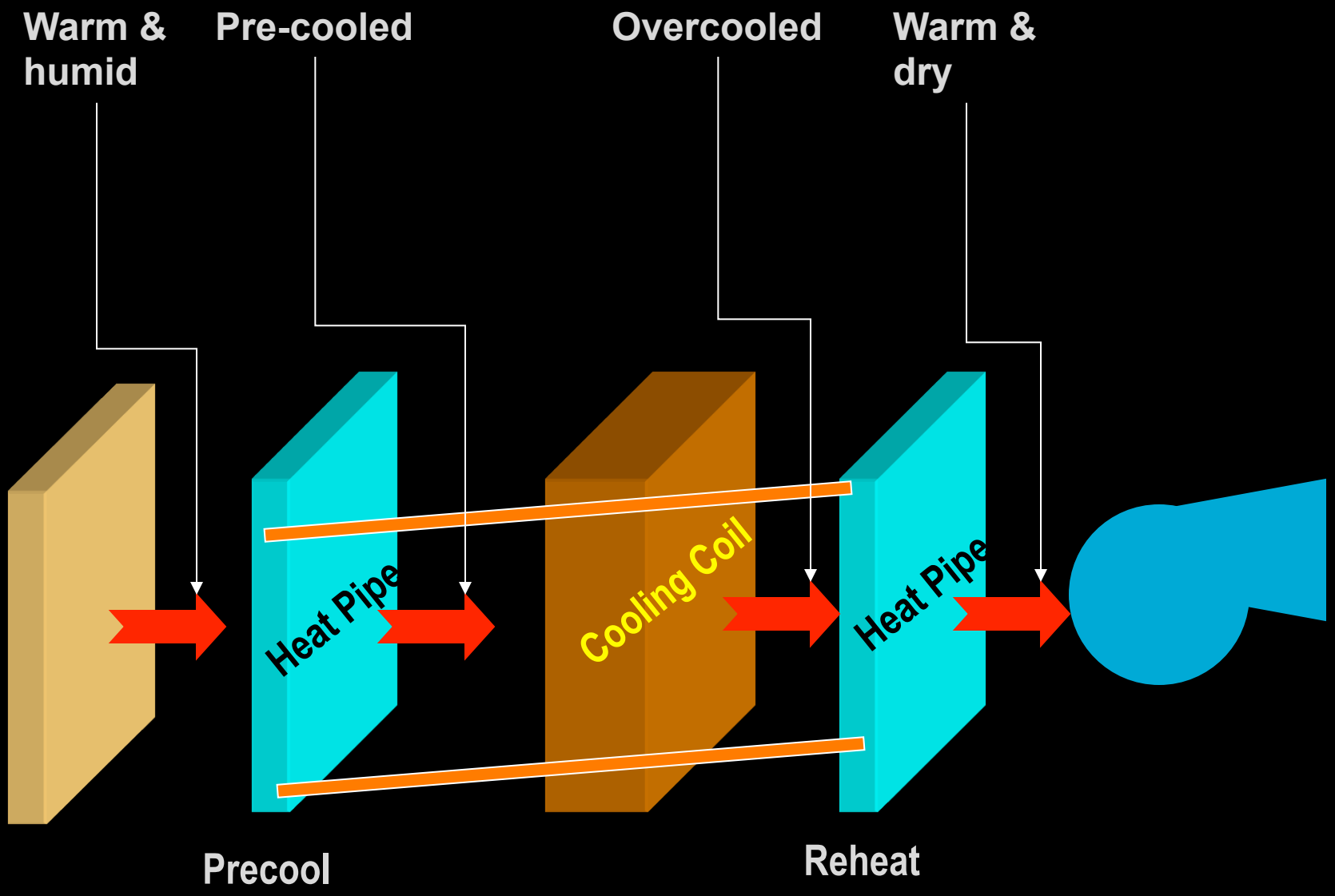

Hot reactivation air
Dehumidified Supply air
Partitions and seals to separate dehumidification Process from reactivation
Continuous rotating Desiccant wheel
Reactivation air exhaust
Hot humid air to be dehumidified

Factors affecting dehumidifier performance

- Inlet air temperature
- Moisture content
- Velocity at face of the desiccant bed

  (to maximize residence time)

Heat Pipes


Warm & humid
Pre-cooled
Overcooled
Warm & dry
Heat Pipe
Cooling Coil
Heat Pipe
Precool
Reheat

The Case Study

Animal Care Facility (ACF)

- specific pathogen-free rodent breeding facility
- approximately 1,000 m^2
- designed to meet international standards of animal care
- Mice and rats held in flexible film isolators or in individually ventilated cages

ACF requires stringent indoor conditions

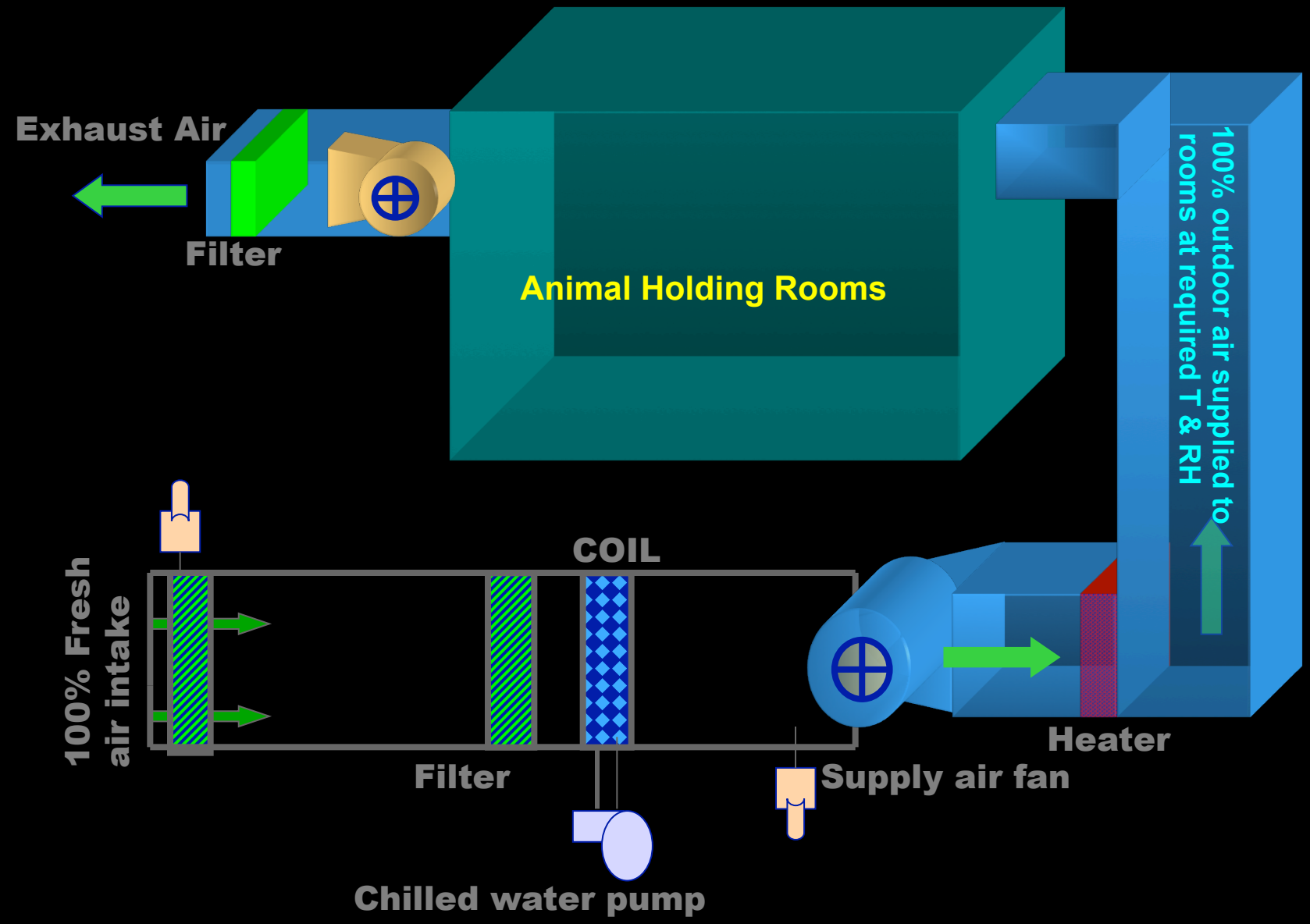
- 100 percent outdoor air throughout the day (24 hours)
- relative humidity (RH) of approximately 55 % with a maximum of 60 %
- temperature of 22 °C (±1 °C)

original design - heaters due to the stringent thermal requirements

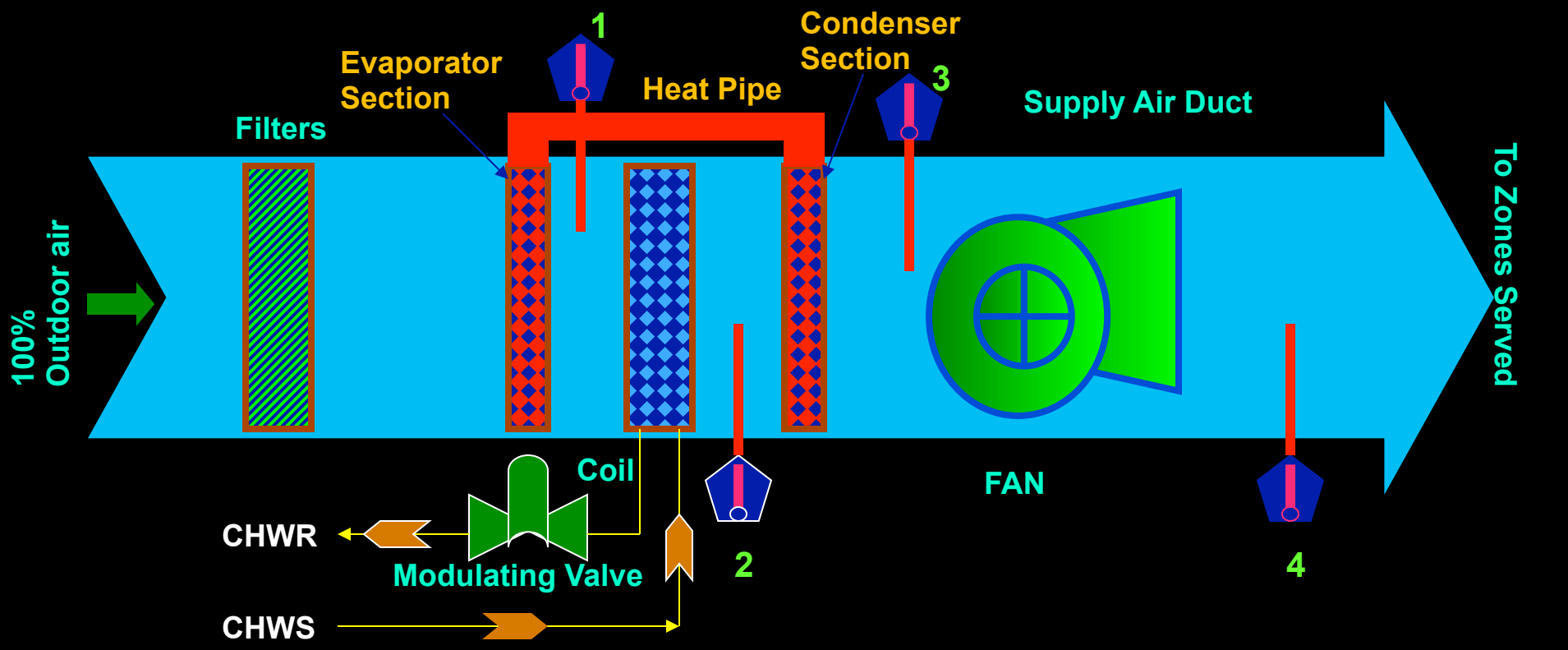
➔ high energy consumption

heat pipes

➔ energy conserving retrofit scheme


Exhaust Air
Filter
Animal Holding Rooms
100% outdoor air supplied to rooms at required T & RH
COIL
100% Fresh air intake
Filter
Heater
Supply air fan
Chilled water pump

Heat Pipe integrated AHU



Energy Savings at the Animal Care Facility (ACF)

	Ave Capacity Without Heat Pipes (kW)	Ave Capacity with Heat Pipes (kW)	Energy Consumption without Heat Pipes (kWh)	Energy Consumption with Heat Pipes (kWh)	Energy Savings (kWh)
7.00 am	315.1	256.5	2520.9	2052	**468.9**
3.00pm	395.5	314.1	3163.9	2512.7	**651.1**
11.00pm	352.5	297.7	2820.3	2381.8	**438.6**
Daily			8505	6946.5	**1558.6**
Monthly			255150.9	208394.1	**46756.8**

Energy Savings due to Heat Pipe → **18.3 %**

Personalised Ventilation (PV) system

Personalised Ventilation (PV) System

Deliver fresh air directly to the Occupant breathing zone

Potential to enhance

- Acceptability of ventilation
- Indoor Air Quality
- Thermal comfort


Brief Review of Personalised Ventilation Research – Since mid 90s

Melikov, A. K., Cermak, R. and Majer, M. (2002) *Personalized ventilation: evaluation of different air terminal devices*, Energy and Buildings, Vol. 34, 829-836.

Muhic, S., and V. Butala. (2006). *Effectiveness of personal ventilation system using relative decrease of tracer gas in the first minute parameter*. Energy and Buildings 38(5):534-42.

Niu, J. L., Gao, N. P., Ma, P., and Zuo, H. G., (2007) *Experimental study on a chair-based personalized ventilation system*. Building and Environment, Vol. 42, no. 2, pp. 913-925

Russo, J. S., Khalifa, H. E., (2010) *CFD assessment of intake fraction in the indoor environment.* Building and Environment (2010), Vol 45, Issue 9, 1968–1975

Desk-mounted PV System integrated with Ceiling Supply MV System

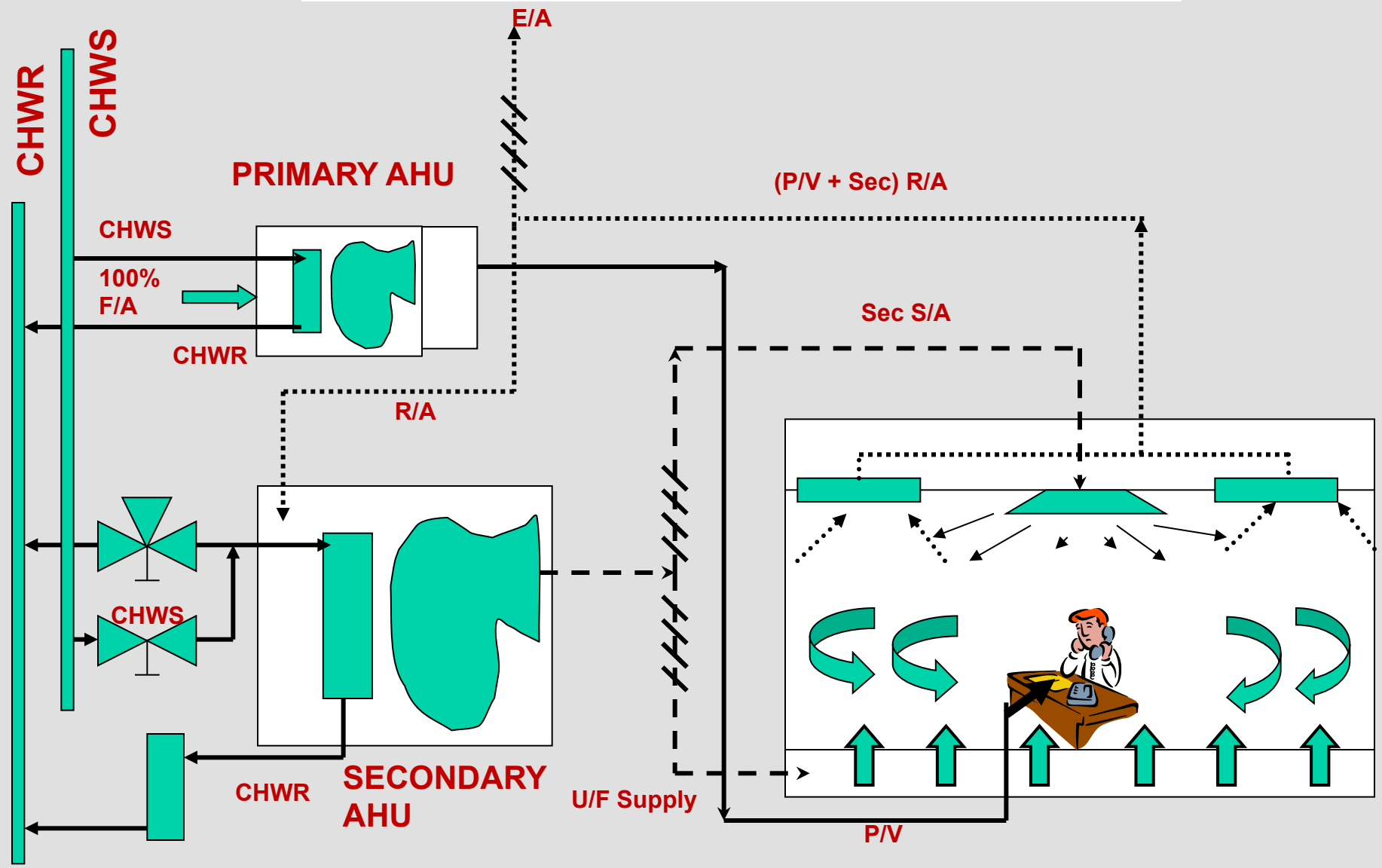
Sekhar, S C, N Gong, K W Tham, K W Cheong, A.K. Melikov, D.P. Wyon and P.O. Fanger, "Findings of personalised ventilation studies in a hot and humid climate". International Journal of Heating, Ventilating, Air-conditioning and Refrigerating Research (HVAC&R Research), Vol 11, no. 4

Gong, N, K W Tham, AK Melikov, DP Wyon, S C Sekhar and K W Cheong, "The acceptable air velocity range for local air movement in the Tropics". HVAC&R Research, International Journal of Heating, Ventilating and Air-Conditioning Engineers (ASHRAE), Vol 12, No. 4, pp 1065-1076, (October 2006). (United States).

CHWS : Chilled water supply
CHWR : Chilled water return
AHU : Air Handling Unit

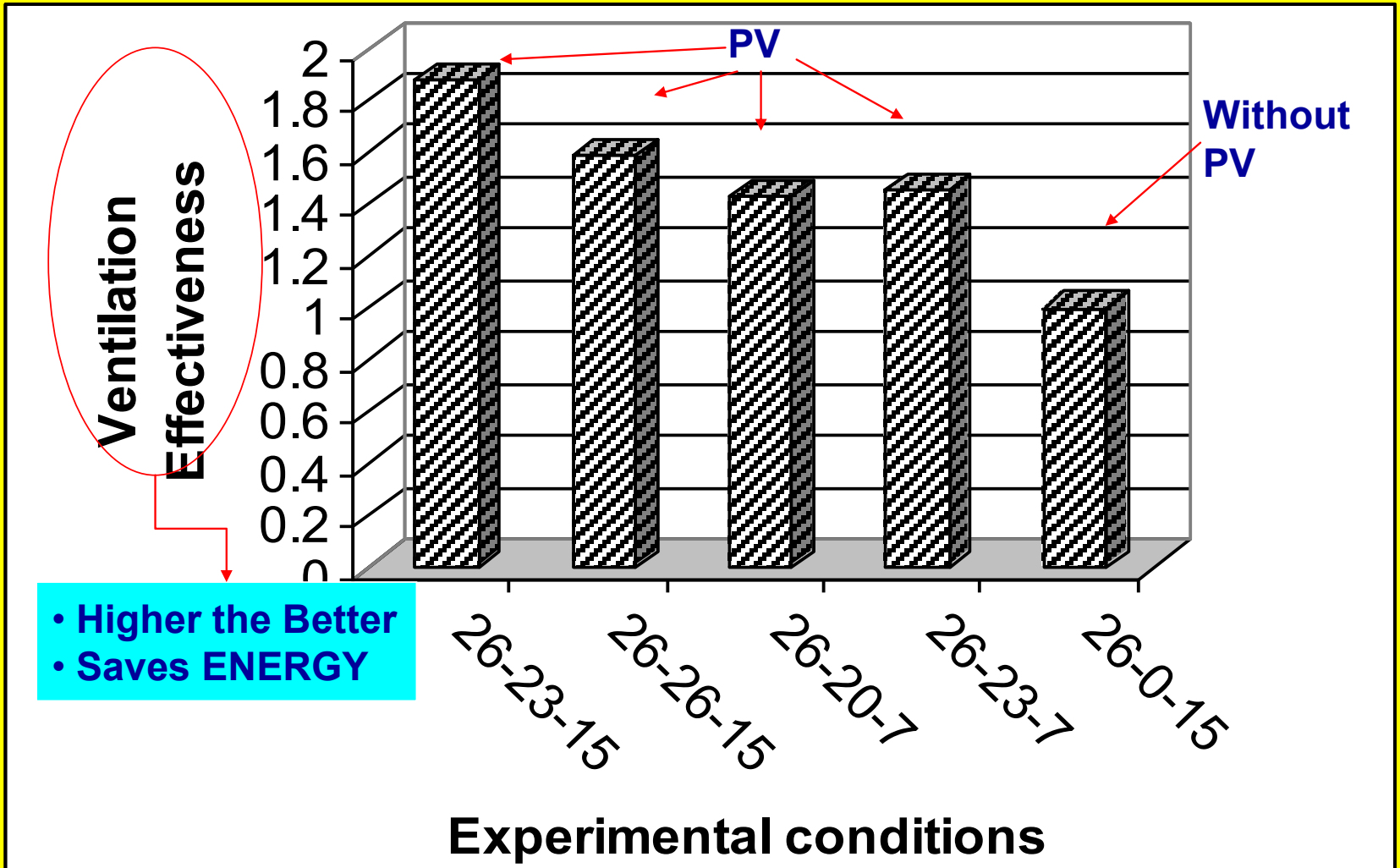
P/V : Personalised ventilation
U/F Supply : Under floor supply
Sec S/A : Secondary supply air

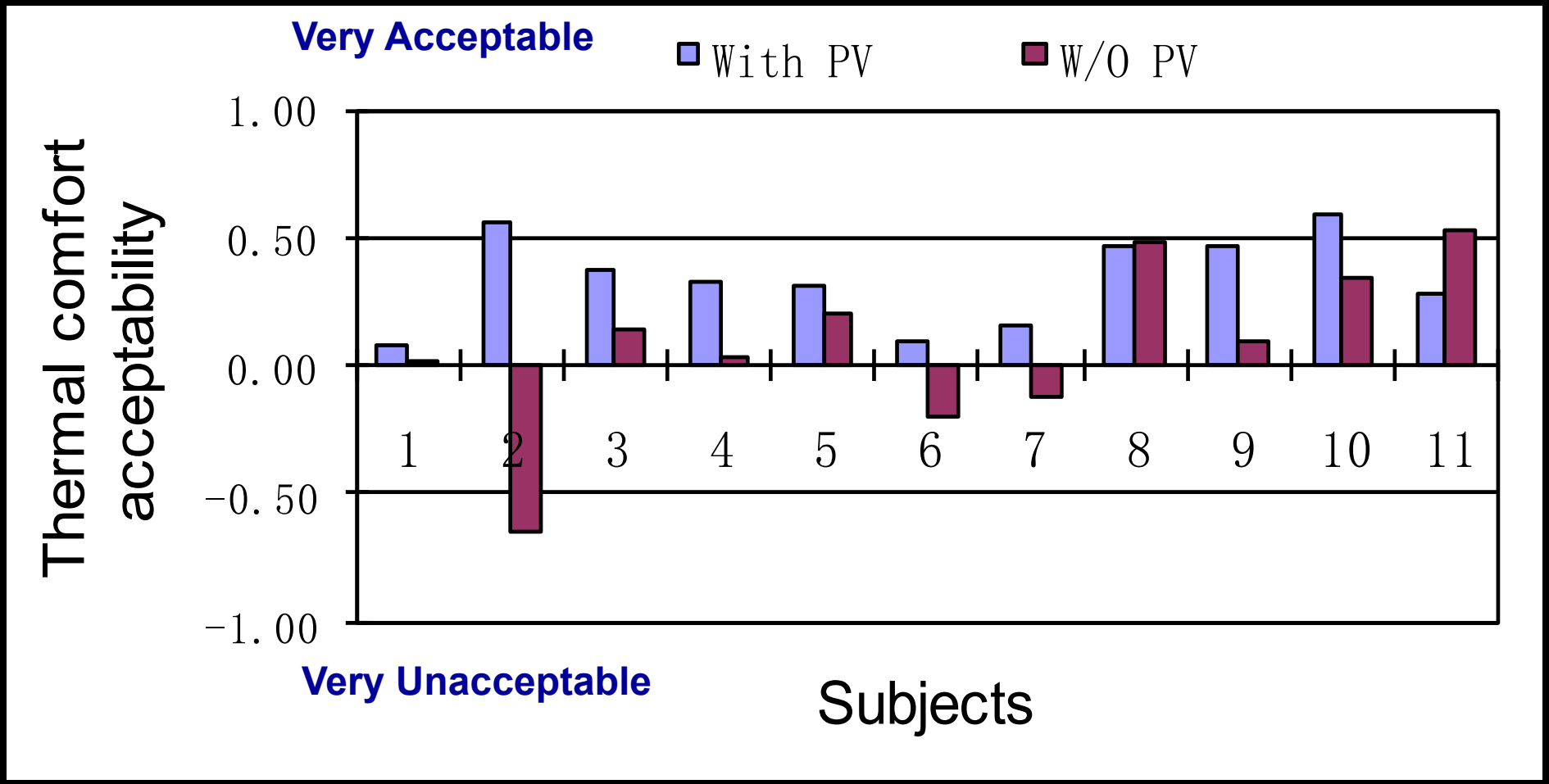
F/A : Fresh air
R/A : Return air
E/A : Exhaust air



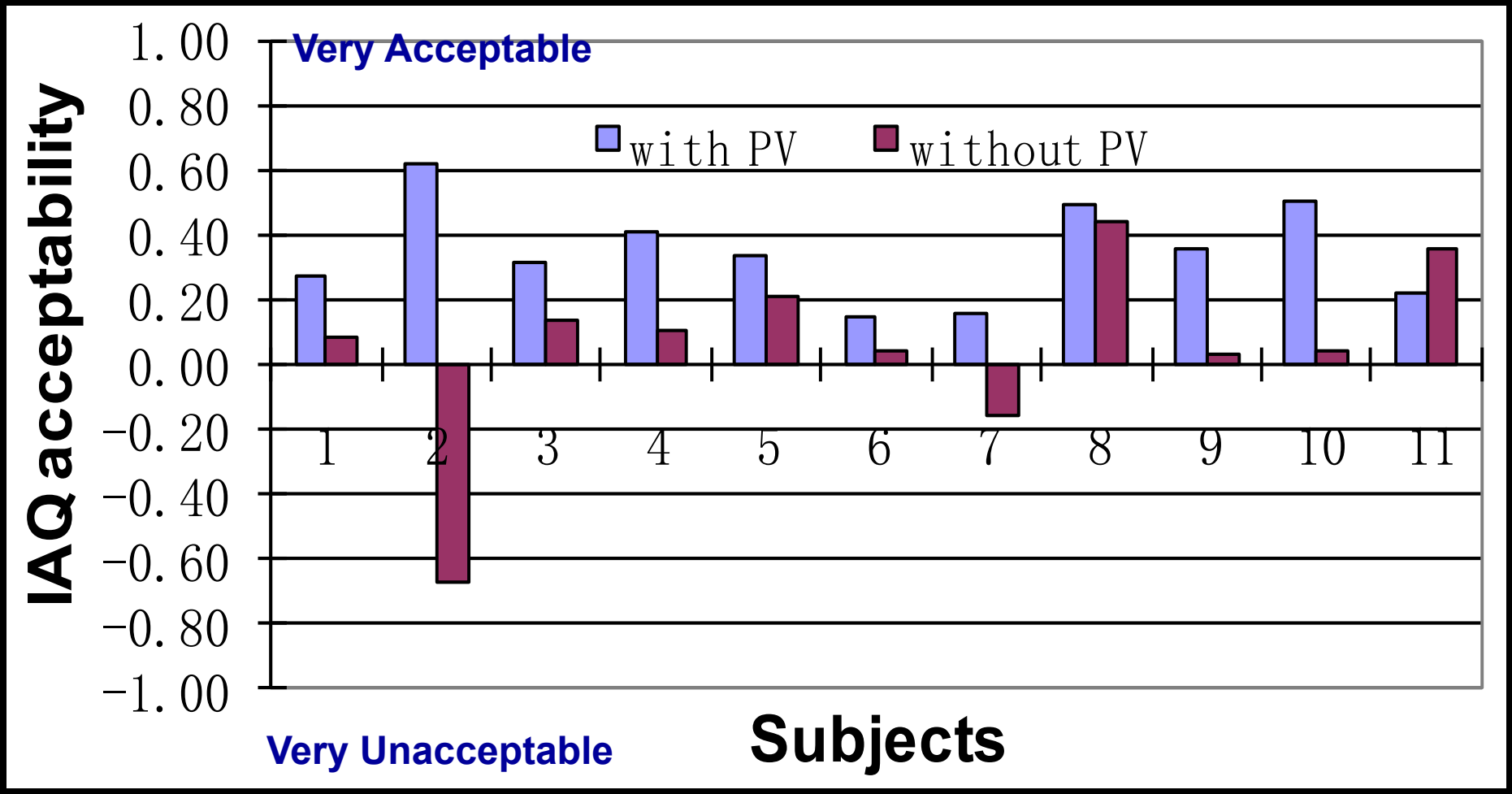
Experimental Protocol

- Ambient and PV air temperatures
- Thermal comfort parameters within the occupied zone
- Breathing temperature in the occupant breathing zone
- Concentration levels of various indoor pollutants
- SF_6 tracer gas measurements - ventilation effectiveness
- Questionnaire responses

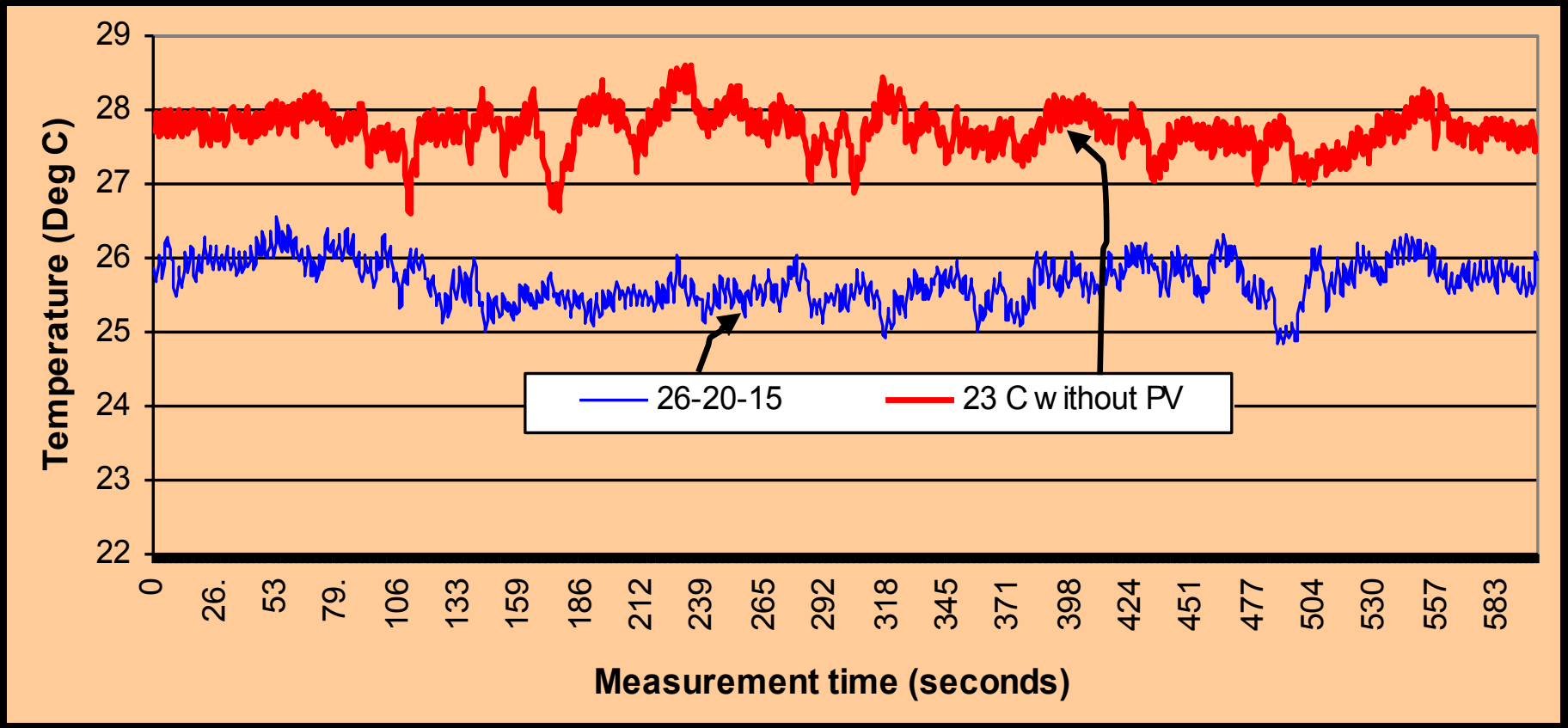

Ventilation Effectiveness
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PV
Without PV
• Higher the Better
• Saves ENERGY
26-23-15
26-26-15
26-20-7
26-23-7
26-0-15
Experimental conditions



Mean responses of Thermal Comfort acceptability



Mean responses of IAQ acceptability



A comparison of breathing temperatures at 23 °C and 26 °C ambient temperatures

PV system

Consistent trends of thermal comfort & IAQ ratings

Observed – INCREASE with INCREASING PV flow rate

And DECREASING with INCREASING PV temps at

Ambient temp of 26° C

Energy savings occur due to

- A warmer space temperature, such as 26 °C, accompanied by a PV air temperature of 23 °C, implies that the space cooling load is reduced in comparison with a conventional air-conditioning system in which the space is typically maintained at 23 °C.

- An absolute reduction in the total fresh air quantity provided is possible, as it is now directly supplied as inhaled air to the occupant breathing zone.

Ceiling-Mounted PV System integrated with Ceiling Supply MV System

Ceiling mounted PV System integrated with ambient MV system

Yang, B and S C Sekhar, "Three dimensional numerical simulations of a hybrid fresh air and recirculated air diffuser for decoupled ventilation strategy". Building and Environment, (2007), Vol.42, Issue 5, pp 1975-1982. (United Kingdom).

YANG, B, Arsen Melikov and S C Sekhar, "Performance evaluation of ceiling mounted personalized ventilation system". ASHRAE Transactions 2009, Vol. 115, Part 2, pp 395-406. (United States).

Yang, B, S.C.Sekhar and Arsen Melikov, "Ceiling mounted personalized ventilation system integrated with a secondary air distribution system – A human response study in hot and humid climate". Indoor Air – International Journal of Indoor Environment and Health (2010). Volume 20, no. 4 (2010): 309-319. (Denmark).

YANG, B, S C Sekhar and Melikov Arsen, "Ceiling mounted personalized ventilation system in hot and humid climate –An energy analysis". Energy and Buildings, (2010). (Switzerland).



Ceiling-mounted PV system in conjunction with ceiling supply mixing ventilation system

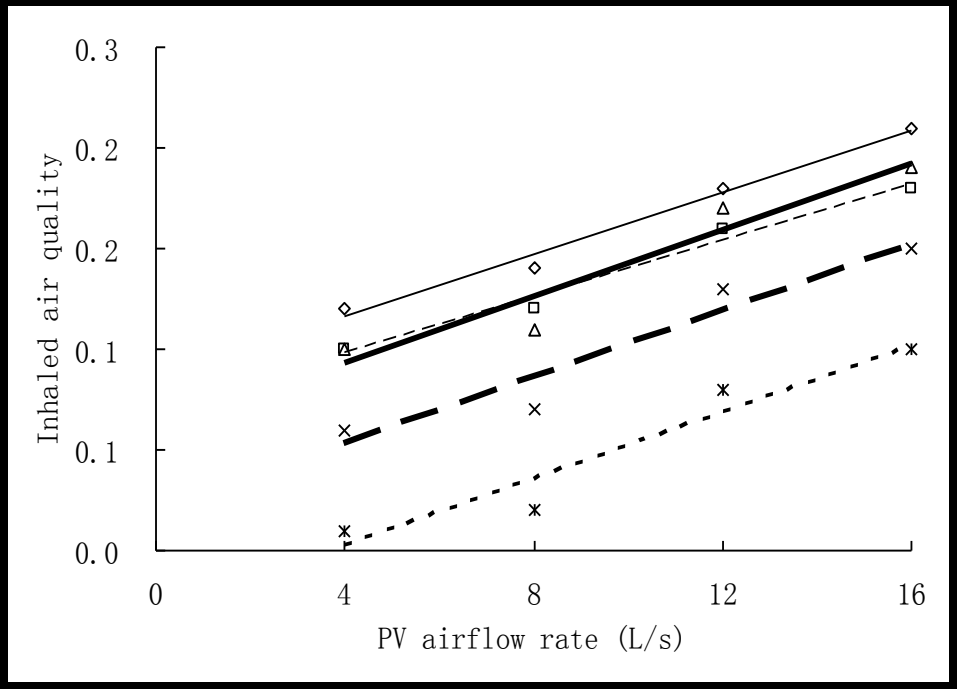
◊ 23.5/21

□ 23.5/23.5

Δ 26/21

X 26/23.5

* 26/26



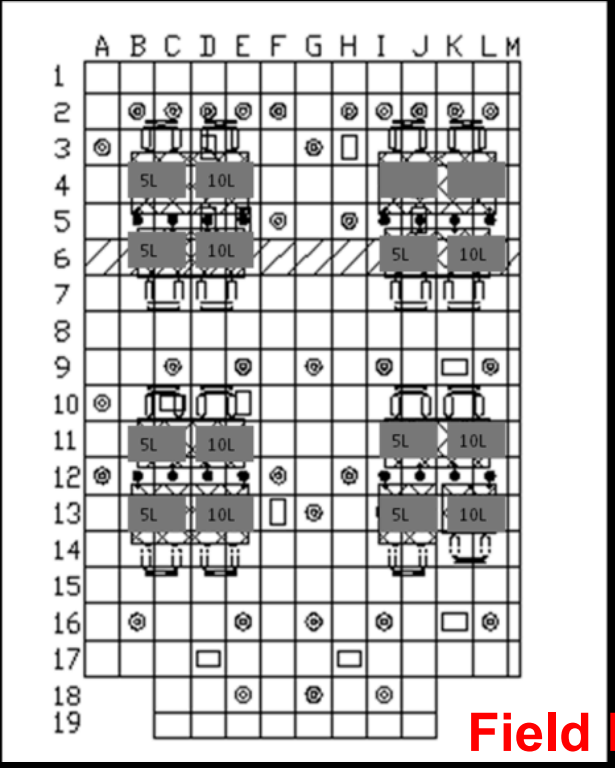
Y-axis
-1 = very unacceptable,
0 = just unacceptable/acceptable,
+1 = very acceptable



Desk-mounted PV System Integrated with UFAD System

Li, Ruixin, S.C.Sekhar and A.K.Melikov, 2011. Thermal Comfort and Indoor Air Quality in rooms with Integrated Personalized Ventilation and Under-Floor Air Distribution Systems. HVAC&R Research, Volume 17, Number 5, pp 829-846 ,*ASHRAE .*

Li Ruixin, S.C.Sekhar and Arsen Melikov, "Thermal comfort and IAQ assessment of under-floor air distribution system integrated with personalized ventilation in hot and humid climate". Building and Environment journal, Vol 45 (2010): 1906-1913. (United Kingdom).

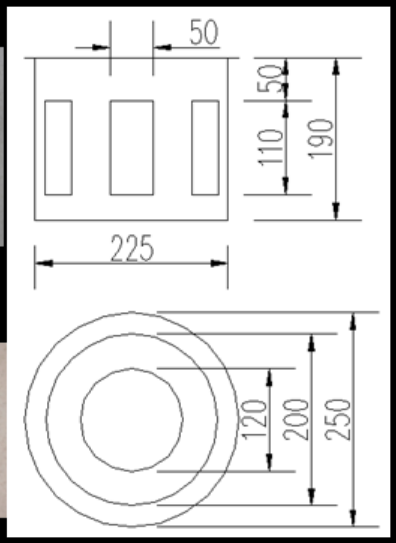




Field Environmental Chamber (FEC) experimental setup - Desk mounted PV with UFAD system





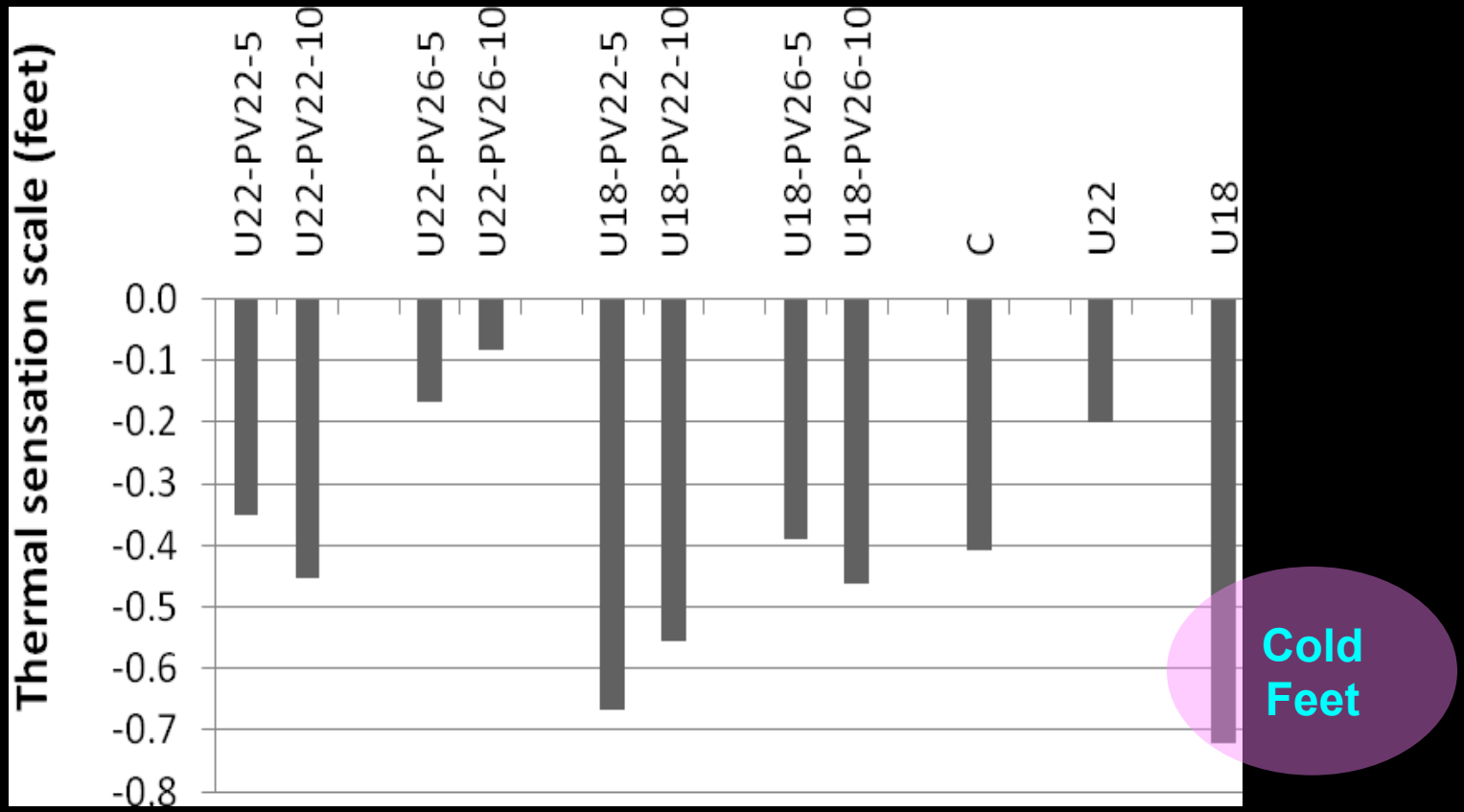




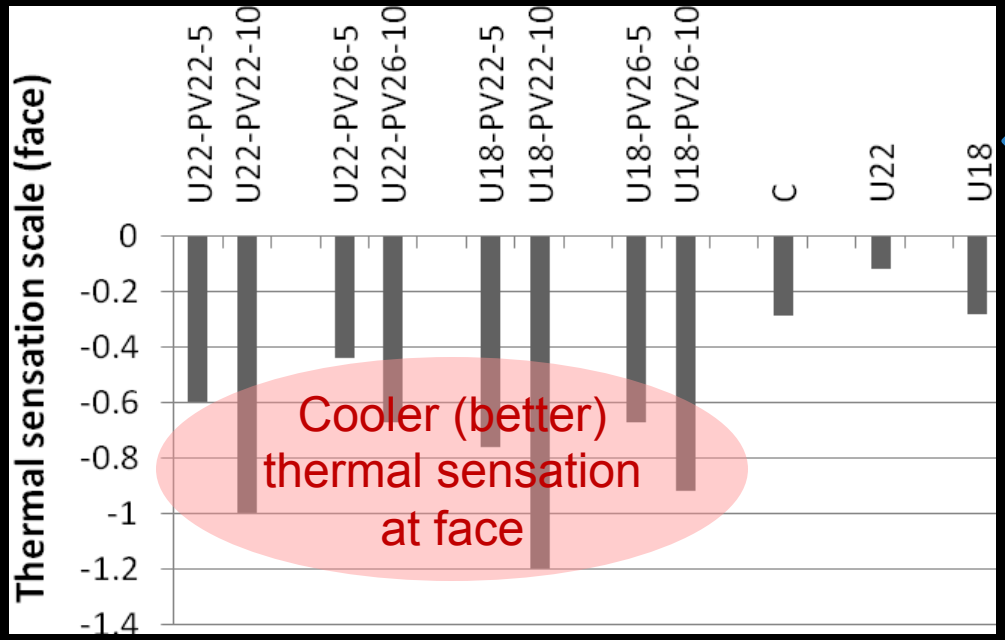
Methods- Experimental Conditions

Table 1 Experimental Conditions

System Type	Exp. Condition (Session no.)	Temperature (˚C)/ (˚F)			PV flow rate (L/s)/(CFM)	Total volume ventilation system (UFAD) flow rate (L/s)/(CFM)
		T_{room}	$T_{UFAD\ supply}$	$T_{PV\ supply}$		
UFAD+PV	22-26-5	26/78.8	22/71.6	26/78.8	5/10.6	480/1017
UFAD+PV	22-26-10	26/78.8	22/71.6	26/78.8	10/21.2	480/1017
UFAD+PV	22-22-5	26/78.8	22/71.6	22/71.6	5/10.6	480/1017
UFAD+PV	22-22-10	26/78.8	22/71.6	22/71.6	10/21.2	480/1017
UFAD+PV	18-26-5	26/78.8	18/64.4	26/78.8	5/10.6	360/763
UFAD+PV	18-26-10	26/78.8	18/64.4	26/78.8	10/21.2	360/763
UFAD+PV	18-26-5	26/78.8	18/64.4	22/71.6	5/10.6	360/763
UFAD+PV	18-22-10	26/78.8	18/64.4	22/71.6	10/21.2	360/763

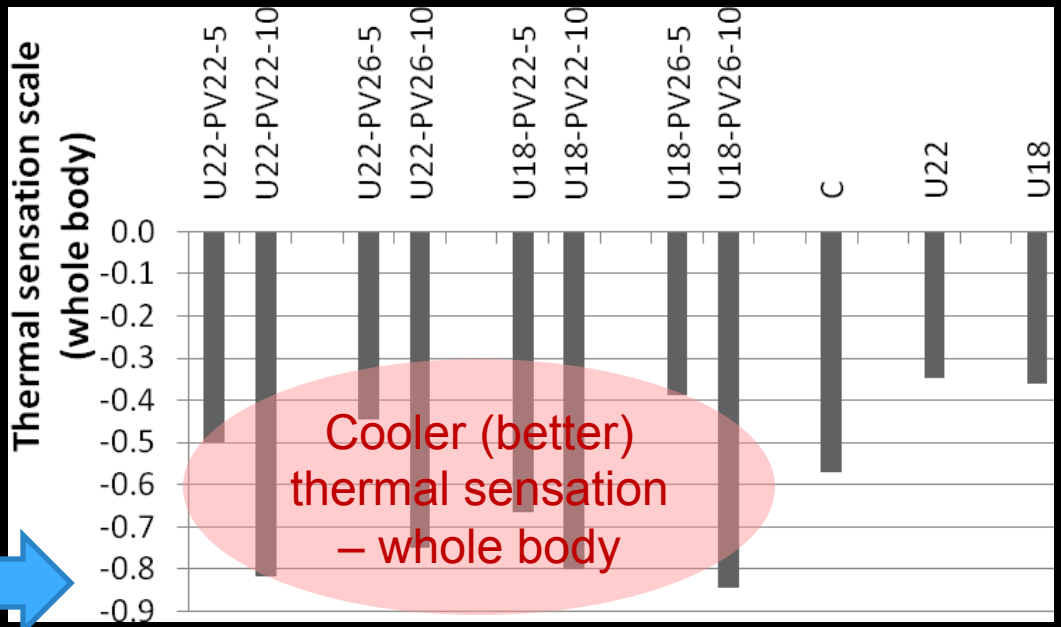


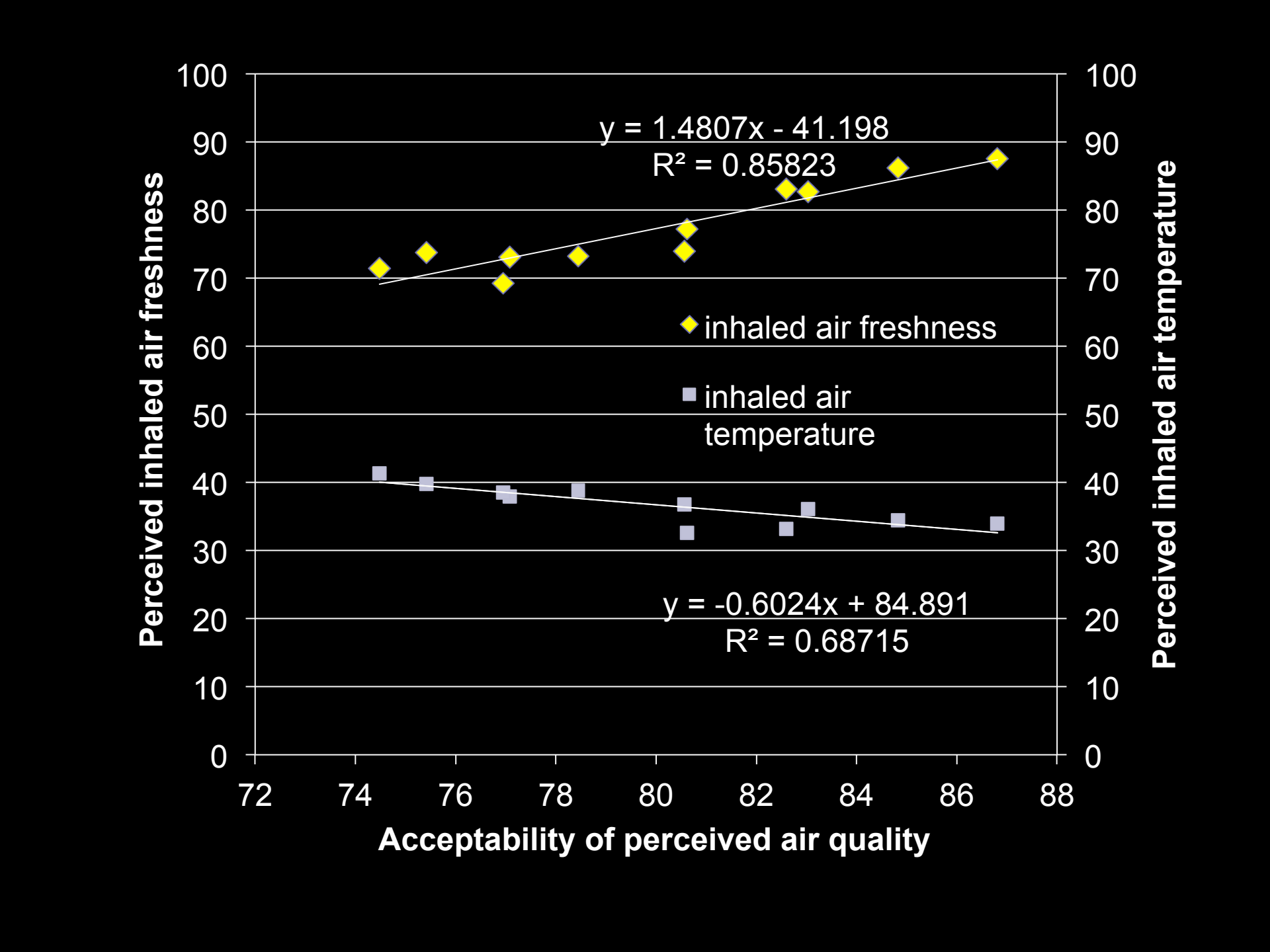
Thermal sensation at feet and acceptability of air movement at feet
(Thermal sensation scale: =-3 cold, =-2 cool, =-1 slightly cool,
=0 neutral, =+1 slightly warm, =+2 warm, =+3 hot;
Air movement acceptability: 0 ~50 = very unacceptable ~ just unacceptable,
50~100 = just acceptable ~ very acceptable)



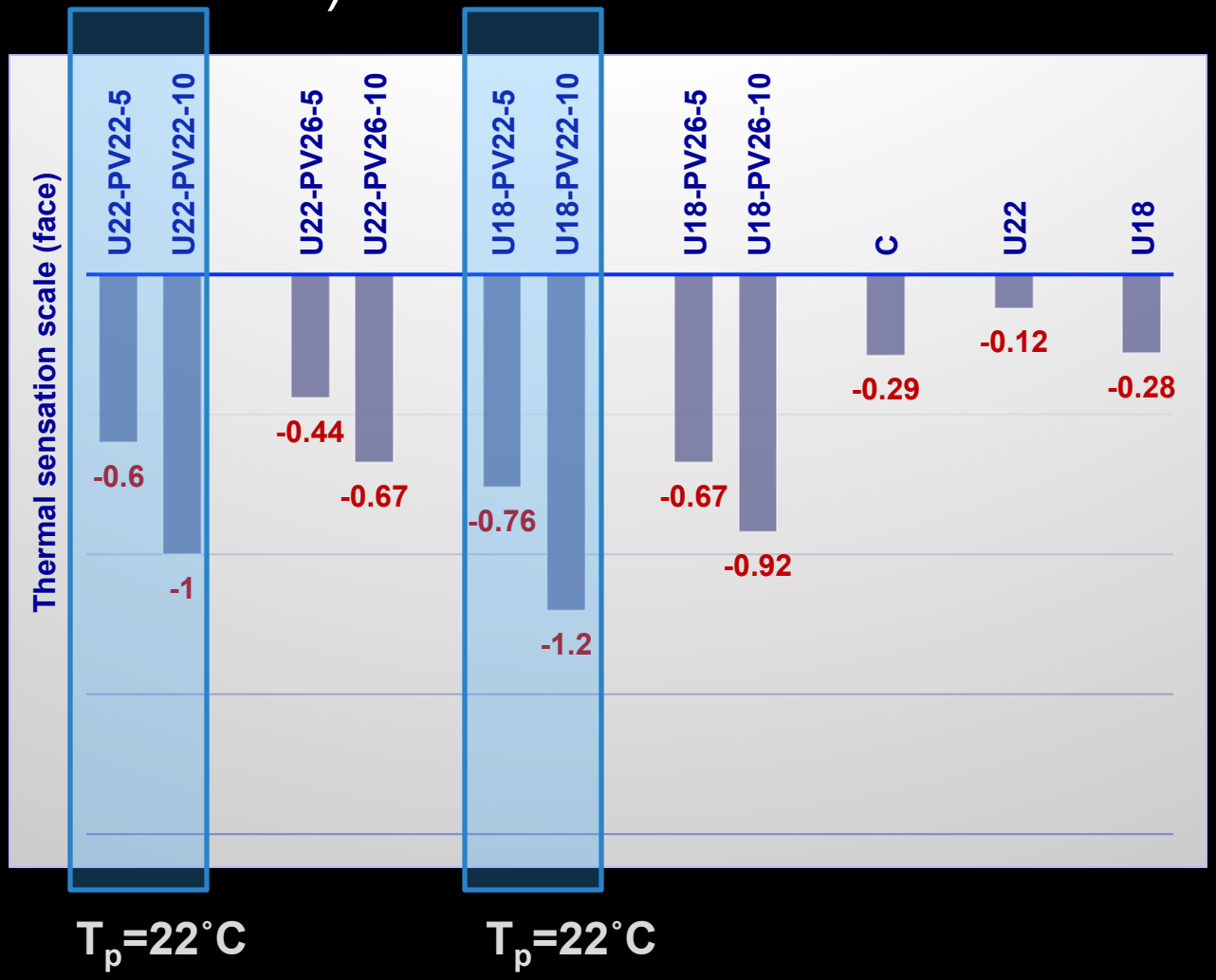
Facial Thermal Sensation

Whole Body Thermal Sensation




y = 1.4807x - 41.198
R² = 0.85823
inhaled air freshness
inhaled air temperature
y = -0.6024x + 84.891
R² = 0.68715
Perceived inhaled air freshness
Perceived inhaled air temperature
Acceptability of perceived air quality
100
90
80
70
60
50
40
30
20
10
0
72
74
76
78
80
82
84
86
88

Human response to thermal sensation at face to PV-UFAD system (Li et al. 2010)



Key Findings

- Use of PV-UFAD improved subjects' thermal sensation in comparison with UFAD alone or MV
  - *"Cold feet" complaint decreased when the temp of the air supplied from UFAD was increased*
  - *Use of PV provided the subjects with the preferred slightly cool thermal sensation at the head and face*
- Local cooling of the head and face could be achieved by decrease of the temperature of the personalized air or increase of its flow rate, i.e. increase of the air velocity at the head and face region.

Final Words

Energy Efficient Healthy Buildings

Air-conditioning Systems

- **LFV-HCV**
- **DOAS**
- **SCTF**
- **Desiccant Dehumidification Systems**
- **Heat Pipes**

Air Distribution Systems

- **SCTF**
- **PV with MV**
- **PV with UFAD**

Thank You for your Attention

Q & A



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