PERFORMANCE EVALUATION OF LOW EXERGY SYSTEMS DEPICTING DECENTRALIZED DEDICATED OUTDOOR AIR SYSTEM COUPLED WITH RADIANT COOLING IN THE TROPICS

ESMAIL MAHMOUDI SABER

(M. Eng.)

A THESIS SUBMITTED

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF BUILDING

NATIONAL UNIVERSITY OF SINGAPORE

2016

DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Esmail Mahmoudi Saber

13 July 2016

ACKNOWLEDGMENT

I wish to express my sincere gratitude to my supervisors Prof. Kwok Wai THAM and Prof. Hansjürg Leibundgut for sharing their expertise and providing guidance throughout my PhD. I thank the managers, principal investigators, collaborators and researchers at Singapore-ETH centre (SEC) and National University of Singapore (NUS) who made the collaboration between future cities laboratory in SEC and department of building in NUS possible. The list includes but not limited to Dr. Remo Burkhard, Prof. Arno Schlüter, Prof. Forrest Meggers, Prof. Chandra Sekhar, Prof. David Kok Wai Cheong, Dr. Matthias Mast, Dr. Marcel Bruelisauer, Dr. Rupesh Iyengar, Dr. Kian Wee Chen, and Mr. Cheng Li. My sincere thanks also goes to Ms. Wu Wei Yi, Mr. Tan Cheow Beng, Mr. Komari Bin Tubi, the laboratories' supervisors in school of design and environment at NUS for their cooperative attitude and helpful advice. Last but not least, I would like to thank my parents, siblings and friends who made my life in Singapore more pleasurable and memorable.

Esmail Mahmoudi Saber

13 July 2016

Table of Contents

Summary

The energy consumption of buildings' air conditioning systems is of prime concern in tropical cities where cooling and ventilation are needed all year round in commercial buildings. The conventional air conditioning system in Singapore commercial buildings is the central all air system. The Low exergy concept in the tropics promotes high temperature cooling strategy using raised chilled water temperature (16 °C) compared to the conventional design (6 °C). This scheme could be a more energy efficient design compared to the all air system, considering the facts that less energy is required for providing the raised chilled water temperature and water is a more efficient medium for heat exchange compared to air. A decentralized dedicated outdoor air system coupled with radiant ceiling panel (DDOAS-RCP) has been designed based on the low exergy concept for tropical buildings. This design aims to engage water more as a medium for cooling and brings chilled water closer to the conditioned space. Decentralized air supply units are embedded into structure of building to take outdoor air directly from façade with the least path-distance and fan energy use. These units provide dehumidified and cooled air into the indoor space and satisfy the ventilation requirement of space. Radiant cooling panels are installed near the ceiling and satisfy the remaining part of sensible load. The main objective of this PhD thesis was to evaluate the performance of a DDOAS-RCP in the tropical context where temperature and humidity is high all year round. The experimental setup was conducted in the BubbleZERO laboratory in which the above-mentioned low exergy cooling systems have been installed. The results of the environmental measurements have shown that

DDOAS-RCP can provide healthy and comfortable indoor space in tropical buildings under different indoor/outdoor scenarios. Nevertheless, more sophisticated control schemes compared to conventional design need to be implemented for operation of the air-water system to avoid condensation on radiant cooling panels. This new conditioned space has lower air movement and mean radiant temperature compared to that for the all air design. With floor supply-ceiling exhaust distribution of DDOAS-RCP, there is approximately a 2 °C vertical thermal stratification in the space and there could be a cold feet concern near floor diffusers. Moreover, ventilation effectiveness indices of DDOAS-RCP with floor supply-ceiling exhaust distribution strategy were found to be close to that in a mixing strategy. With regards to the water based system operation, non-uniformity of radiant panel surface temperature was observed in which panel areas in contact with chilled water pipes were up to 3 °C colder than other surface areas. With the installed specification of radiant panels in the BubbleZERO, the contribution of panels in satisfying the cooling load of space ranged between 20 to 30 % from morning to afternoon. The results of CFD simulations revealed that the cooling capacity of the panel drops at the rate of 10 W/m^2 per 1 °C increase of average panel surface temperature. The results of building energy simulation for a hypothetical one-storey building showed that annual energy saving of this low exergy design compared to the all air VAV system is estimated to be in the range of 10 to 18 %. Based on results of this thesis, collections of system components and control strategies were suggested for actual implementation and operation of high temperature cooling systems in tropical buildings.

List of tables

List of figures

List of abbreviations

AC	Air Conditioned
ACB	Active Chilled Beam
ACE	Air Change Efficiency
ACMV	Air Conditioning and Mechanical Ventilation
ACR	Air Change Rate
AHU	Air Handling Unit
BubbleZERO	Bubble-Zero Emission Research Operation
CAE	Computer Aided Engineering
CAV	Constant Air Volume
CC	Chilled Ceiling
CE	Ceiling Exhaust
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
CRE	Contaminant Removal Effectiveness
CS	Ceiling Supply
DCV	Demand Control Ventilation
DDOAS	Decentralized Dedicated Outdoor Air System
DOAS	Dedicated Outdoor Air System
DV	Displacement Ventilation
ERS	Energy Recovery System
FD	Floor Diffuser
FS	Floor Supply
HX	Heat Exchanger
HTC	High Temperature Cooling

HTCW	High Temperature Chilled Water
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
LACI	Local Air Change Index
LED	Light Emitting Diode
LTC	Low Temperature Cooling
LTCW	Low Temperature Chilled Water
MF	Mechanical Fan
MV	Mixing Ventilation
NV	Naturally Ventilated
PCB	Passive Chilled Beam
PF	Personalized Fan
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PV	Personalized Ventilation
RAS	Recirculated Air System
RCS	Radiant Cooling System
RCP	Radiant Ceiling Panel
RSC	Radiant Slab Cooling
RSP	Respirable Suspended Particles
SBS	Sick Building Syndrome
SHR	Sensible Heat Ratio
SS	Singapore Standards
TABS	Thermally Activated Building Structures
TVOCs	Total Volatile Organic Compounds

UFAD	Under Floor Air Distribution
VAV	Variable Air Volume

List of symbols

β	Coefficient of Expansion
ρ	Density
ρ_{ref}	Reference Density
τ	Age of Air
$\langle\bar{\tau}\rangle$	Room Mean Age of Air
$\bar{\tau}_p$	Age of Air at Point P
τ_n	Nominal Time Constant
μ	Viscosity
λ	Thermal Conductivity
ε	Turbulent Dissipation
ω	Specific Rate of Dissipation
C	Concentration
$\langle C\rangle$	Mean Concentration
C_e	Concentration at Exhaust
clo	Clothing Unit
e	Energy
g	Gravity of Earth
g-value	Exergetic Efficiency
I_{cl}	Clothing Insulation (m^2 K/W)
k	Turbulent Kinetic Energy
M	Metabolic Rate (W/m^2)
met	Metabolic Unit
P	Pressure

PM_1	Particulate Matter Less than 1 μm
$PM_{2.5}$	Particulate Matter Less than 2.5 μm
PM_{10}	Particulate Matter Less than 10 μm
q	Ventilation Flow Rate
T	Temperature
T_d	Dew point Temperature
T_o	Operative Temperature
$\overline{T}_r$	Mean Radiant Temperature
T_{ref}	Reference Temperature
T_s	Surface Temperature
U	Velocity Vector
V	Air Velocity
Vol	Volume

Chapter 1. Introduction

Background information is provided regarding the air conditioning system in the commercial buildings of tropical cities. The main idea behind the low exergy system is introduced and compared to conventional ACMV system in the office buildings. This section is followed by a thorough literature review on different aspects of high temperature cooling systems applications in the tropics. The identified knowledge gaps based on conducted literature review are further elaborated and goals/scope/research questions/hypothesis of the thesis are explained in the subsequent sections.

1.1 Background

In this section, at first, information is provided regarding the conventional air conditioning and mechanical ventilation system in tropical buildings. Later, the exergy concept is introduced and its applications for building systems are discussed. Several emerging cooling technologies in the industry and literature are also presented before proceeding to the concept of high temperature cooling in the tropical context.

1.1.1 Building ACMV system in the tropics

Concerns regarding the global warming encourage efforts to reduce greenhouse gas emission of human activities at different sectors. The report of the intergovernmental panel for climate change (IPCC) revealed that in 2004, the building sector was responsible for one third of global energy related CO_2 emissions and three fifth of halocarbon emissions (IPCC, 2007). This statistic shows the importance of buildings energy efficiency policies on mitigation of the global climate change issue. Based on report of International Energy Agency, Singapore's CO_2 emissions from fuel combustion in 2011 were 12.49 tonnes of CO_2 per capita, considerably higher than in neighbouring countries (Asia average = 1.51) because of its small size, dense population and manufacturing industries (IEA, 2013).

Inside buildings, air conditioning and mechanical ventilation (ACMV) systems makes up the biggest piece of the pie in energy consumption breakdown especially in commercial buildings for the tropical climates of Singapore (NCCS and NRF, 2011). Air conditioning is the process of cooling indoor air space in order to keep the occupied air space in the comfortable condition. In the tropical context, this process means cooling and dehumidifying inside and/or outside air and distributing it into different interior spaces of buildings. Ventilation is the process of replacing indoor air which carries generated pollutants by occupants and other sources in space with outside air to ensure indoor air quality remains acceptable. In the conventional ACMV designs of buildings, these two processes of air conditioning and ventilation are satisfied together through supplying conditioned outside air into space accompanied with reconditioning of return air. In commercial buildings with the central all air system, a mixture of outside and recirculated inside air is conditioned in AHU rooms and then distributed to various zones of the building. Variable air volume (VAV) and constant air volume (CAV) are the main types of all air system in which sensed temperature by thermostat inside zones controls flow rate and temperature of the supplied air, respectively for VAV and CAV.

The tropical climate is the group A of the Köppen-Geiger climate classification (Peel et al., 2007) which includes tropical rainforest, tropical monsoon, and tropical wet and dry (savanna) climates. The tropics are characterized as high temperature (⩾18 °C) and precipitation all year round except for dry season in monsoon and savanna climates. These climates usually occur in the areas near the equator and cover various countries in Asia, Africa and America like Singapore, Malaysia, Thailand, Indonesia, Philippine, Brazil, and India. The average monthly variation of temperature and dew point for three climates of tropical rainforest (Singapore, Kuala Lumpur, Jakarta and etc.), hot desert (Phoenix, Doha, Dubai and etc.) and warm temperate (Hanoi, Hong Kong, Taipei and etc.) are illustrated in Figure 1. In the tropical climate of Singapore, temperature and dew point remain almost unchanged in the course of a year while in two other cities there is a clear warm season which happens between May to September. The warm temperate climate of Hanoi exhibits similar profile to the tropics during warm season where dew point is close to 25 °C. On the other hand, at hot desert climate of Phoenix in Arizona, dew point level is unlikely to exceed 15 °C.

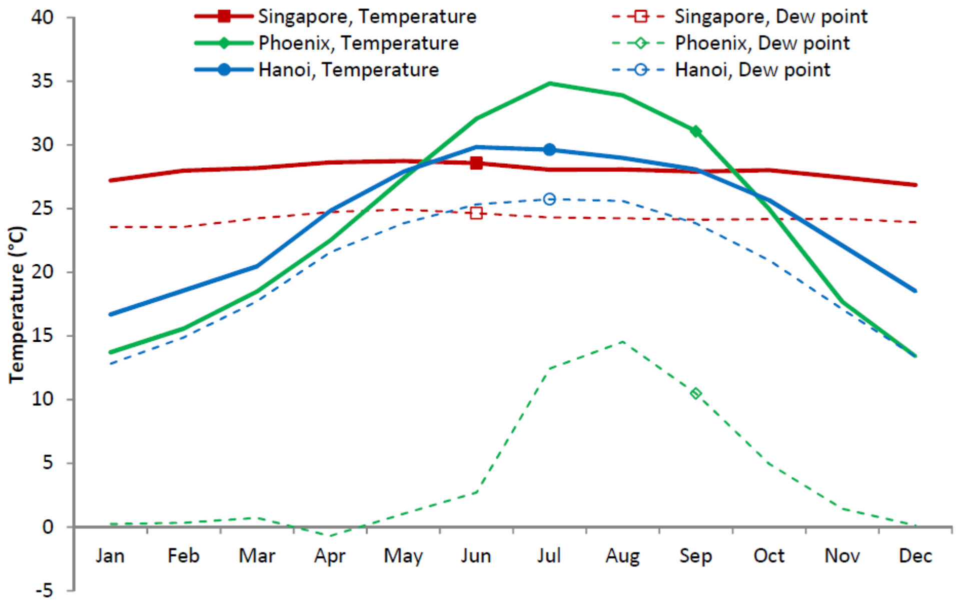


Figure 1 The monthly variation of temperature and dew point for three cities of Singapore (average of 1956-2015), Phoenix (average of 1948-2015) and Hanoi (average of 1959-2015) (WeatherSpark, 2015)

1.1.2 Exergy and building

Exergy is energy, which is entirely convertible into other types of energy. Based on the First and Second Laws of thermodynamics, energy is never destroyed during a process and what is destroyed is exergy which accounts for irreversibility of a process. The destroyed exergy is called anergy and it is proportional to entropy increase of the system. Exergy is a combination characteristic of system and environment and the system has zero exergy when it is in equilibrium with the environment. For example, a car battery with 12 V, 2.3 ampere hour and 1 kg of water at 43 °C (20 °C ambient air), both have same amount of energy potential which is 100 kJ (Figure 2). However, the car battery is more useful and its exergy level is higher than that of hot water. Electricity and mechanical workloads are categorized as high valued energy sources while heat sources near the ambient temperature are low valued sources.

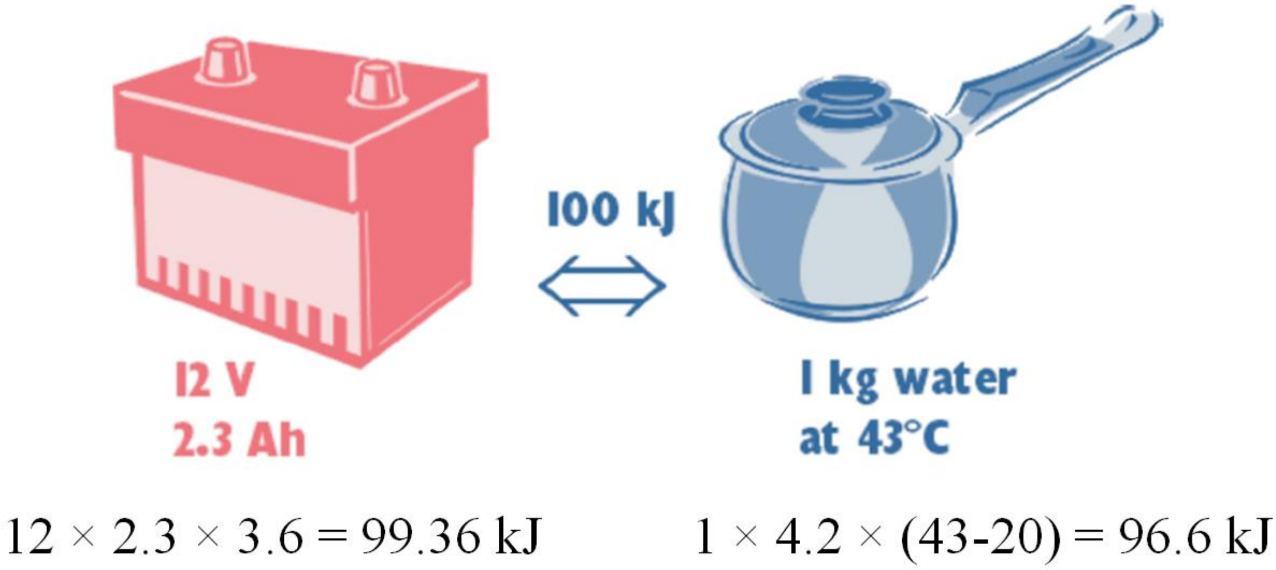


Figure 2 Sources with same amount of energy but different amount of exergy (IEA ECBCS Annex 37, 2003, p. 37)

The concept of exergy can provide an evaluation on level of entropy increase in the environment caused in the whole energy flow chains from electricity generation in power plant to refrigeration cycle in heat pump / chiller. Like any other systems, exergy destruction occurs in building systems and the low exergy concept can bring new insights into the design of low carbon footprint buildings. The low exergy systems provide the least amount of exergy destruction for building service where supplied exergy matches better with exergy demand of buildings. This idea can introduce new air conditioning strategies for tropical buildings, where outdoor temperature is close to the comfort range of human body. Nevertheless, high humidity outdoor condition and required dehumidification for indoor space still remain as exergy intensive aspect of building air conditioning system. The low exergy concept in the tropical context can be translated into using low exergy sources close to human comfort temperature range or high temperature cooling. That means incorporating low exergy sources like solar energy and ground source or using warmer chilled water in order to operate chiller under low temperature lift conditions. In the latter case, a custom designed chiller for the low lift condition is required to fully take advantage of energy and exergy saving potential of this design.

1.1.3 Emerging cooling systems

Several research groups and companies introduced alternative ACMV designs for the tropical and sub-tropical climates in which the separation of the sensible load, the latent load and the ventilation requirements is more pronounced. The motivations behind this further separation are saving energy and better control of indoor air by bringing just enough dehumidified outside air to satisfy the ventilation need of space. In these emerging systems, a parallel cooling device or control strategy is utilized to satisfy the remaining cooling load of space. In the department of building in NUS, single coil twin fan (SCTF) has been proposed to use two separate fans and independent air streams for outdoor air and return air. Flow rates of each air stream are to be regulated based on real time data of temperature and CO_2 sensors (Sekhar et al., 2006). The aim of this design is to separate cooling load and the ventilation requirement of space by bringing just enough outdoor air to satisfy the ventilation requirement of space. Potential energy saving of this design based on a pilot study on a small scale laboratory project was estimated to be around 12 % (Sekhar et al., 2007). Chilled water inside cooling coils passes through both compartments of outdoor and return air. Therefore, the streams are still interconnected on sensible cooling and dehumidifying level while their volumetric flow rates are independent. This design uses the same chilled water supply temperature as of conventional system which is in range of 5-7 °C for both outdoor air and return air streams. In a similar design for the subtropical climate of Hong Kong, two separate air streams and two coils have been designated for outdoor air and return air in a concept which is called dry cooling coupled with dedicated outdoor air ventilation (DCDV). This design aims to decouple dehumidification from sensible cooling by using DV coil to treat all the latent load and part of the sensible load while DC coil treats the remaining space sensible load. DV and DC coils are connected in series where the chilled water supplied to DV at 7 °C and it successively enters the DC coil and the return water leaves the coil at 16 °C. They claimed annual energy reduction of 54 % over CAV (constant air volume) system with reheat for Hong Kong climate. However, the results of energy simulations have shown that a CAV system without reheat still consumes 21 % less energy than DCDV concept on annual basis while there is higher possibility of dissatisfaction in indoor space without reheating (Jia and Lee, 2014). In common practice of the building service industry, CO_2 based demand control ventilation (DCV) has being frequently used for ACMV design of buildings in which there is high variation of occupancy level during the day. In this design the real time CO_2 sensor data is connected to dampers of outdoor air ducts to increase ventilation rate when occupancy is high and also to reduce it to save energy when the occupancy is low. Emmerich and Persily (1997) conducted a literature review on the application of DCV in buildings and concluded that CO_2-based DCV is more likely to be effective when there are unpredictable variations in occupancy and non-occupant sources are negligible. Such buildings include cinemas, theatres, auditoriums, classrooms, lecture halls, meeting rooms and retail establishments. Another alternative solution to the conventional air conditioning and distribution system in Singapore buildings is personalized ventilation (PV) which aims to provide clean outdoor air directly to the breathing zone of occupants. The benefits of personalized ventilation in terms of thermal comfort, indoor air quality and reduction of sick building syndromes and air transmission diseases have been shown by many researchers for the tropical and temperate climates (Melikov et al., 2013; Pantelic et al., 2009). This concept can save energy in tropical buildings by keeping the background temperature at higher level and just maintaining comfort condition around workstations. Potential energy saving of this design for the tropics was estimated to be up to 51 % compared to mixing ventilation (Schiavon et al., 2010). The maximum level of energy saving compared to a mixing CAV base design has been achieved for a scenario with background temperature of 28 °C, ventilation rate of 2.5 L/s/person and variable personalized supply temperature (20-24 °C). Dependency on indoor furnishing, difficulty in equipping nozzle and connecting ducts in various indoor spaces are the main challenges of implementing this concept in buildings. In addition, it is not always possible to keep occupants in fixed locations which restrict the applications of task/personalized ventilation (Yang, 2008). A recent study (Dalewski et al., 2014) investigated the performance of a ductless personalized ventilation design combined with displacement ventilation through a subjective study. The ductless PV takes air from displacement ventilation passing through floor plenum and brings the air to above the desk after filtration. The level of improvement in subjects' thermal comfort was reported to be higher in warm environment due to the increased air velocity by personalized air. This ductless design of PV is more aesthetically pleasing and it could be more appealing to architects. The combination of PV and chilled ceiling is another strategy which has shown to be effective in improving the air quality at workstations (Lipczynska et al., 2015). Based on temperature values and contaminants' concentrations, the maximum flow rate of 13 L/s has been recommended for each PV diffuser which may not be enough to satisfy the latent load of the space in some climates or applications.

1.1.4 High temperature cooling

The air-water ACMV system which promotes the idea of air for ventilation and water for loads has been gaining more attention in the last decades. In this concept a dedicated outdoor air system (DOAS) or recirculated air system (RAS) can be used in parallel to water based cooling systems for the tropics. The water based systems work based on radiative-convective heat transfer with indoor space and the contribution ratio of these two transfer mechanisms depends on the type of system. Radiant panel, slab cooling, passive/active chilled beam are the main types of these parallel cooling systems which are being employed in the building industry. In radiant dominant cooling systems like radiant panel and slab cooling, radiation is the dominant heat transfer mechanism rather than convection. Radiant panel (Figure 3) could be attached to ceiling or wall inside conditioned space and its advantages include flexibility in terms of placement, integration with lighting systems, quick response to change in outdoor temperature, and improved acoustical performance with perforated metal surface (ASHRAE, 2008). On the other hand, chilled slab (Figure 4) is more integrated with structure of building and it provides radiant cooling from floor or ceiling as well as a significant thermal mass to improve utilizing diurnal outdoor temperature fluctuation. In convective dominant cooling systems like passive chilled beams (Figure 5) and active chilled beams (Figure 6), the beam or heat exchanger is suspended from ceiling or integrated into suspended ceiling systems. Both types of chilled beams include a chilled water hydronic system which passes a fin-and-tube heat exchanger near to the ceiling. In PCB operation, warm air rises toward the ceiling and then it gets cooled by the heat exchanger and descends to the floor which provides a natural ventilation flow inside the space. In ACB, the heat exchanger is accompanied by a primary air supply which promotes its cooling capacity compared to PCB. Higher investment cost, maintenance service and system control complexity are the main disadvantages of high temperature cooling which would be discussed in details in Chapter 2.

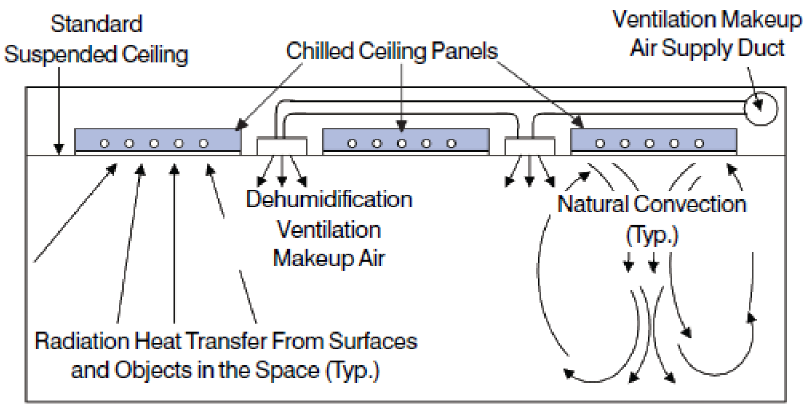


Figure 3 chilled ceiling panel combined with dehumidified ventilation makeup air (Dieckmann et al., 2004)

Figure 4 water pipes in slab cooling system (Sastry and Rumsey, 2014)

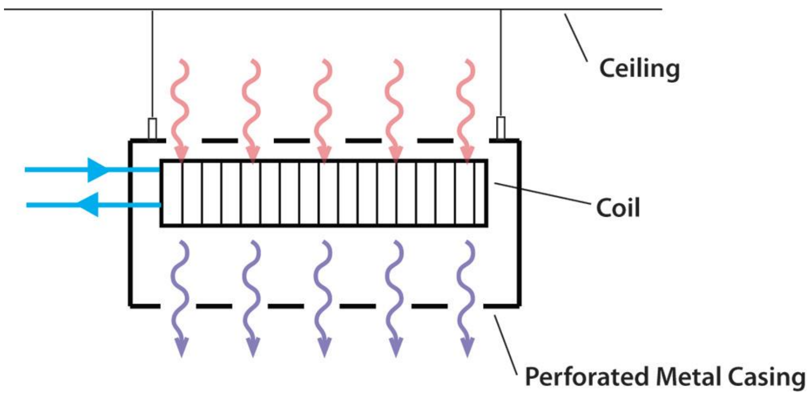


Figure 5 A passive chilled beam in operation (Rumsey and Weale, 2007)

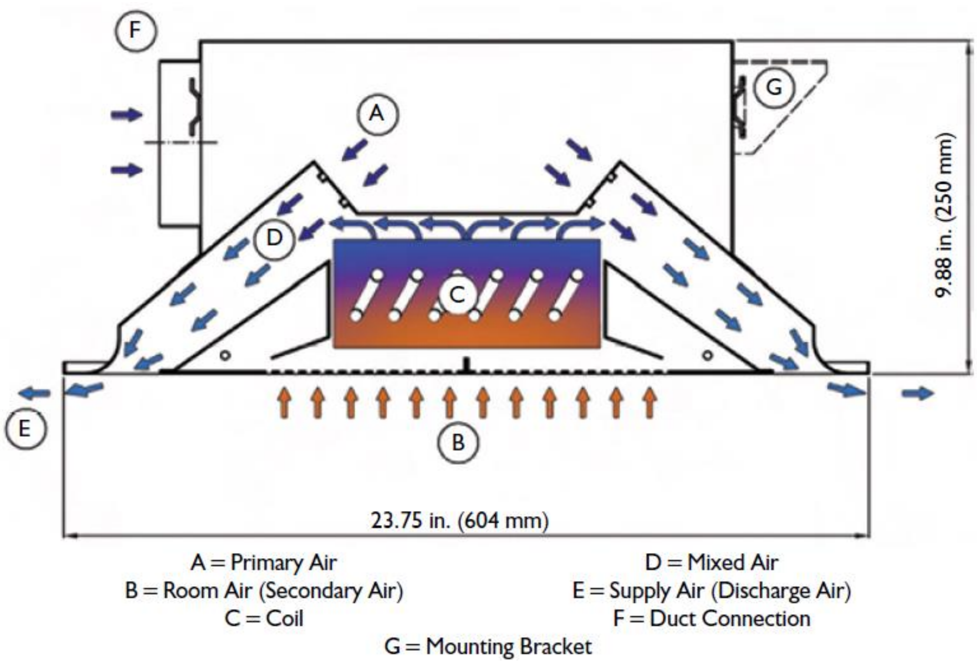


Figure 6 An active chilled beam in operation (Alexander and O'Rourke, 2008)

In the next section, several existing conditioning strategies in Singapore office buildings are explored and the customized low exergy cooling design for this climate is further elaborated.

1.2 Conventional vs low exergy cooling systems

Conventional conditioning systems in tropical buildings including all air and split AC systems are elaborated. In addition, energy saving potentials for implementation of decentralized dedicated outdoor air system coupled with radiant cooling are explained.

1.2.1 Conventional all air system

In high rise commercial buildings of Singapore, the all air systems have been widely used for air conditioning and ventilation through one or more air handling units for each floor. In conventional central air conditioning system of office buildings, conditioned air (mixture of outdoor and return air) is distributed from central points to different zones to satisfy both the sensible and latent loads of building as well as its ventilation requirements. Variable air volume (VAV) and constant air volume (CAV) are the main types of the central all air systems. In VAV design, air flow varies with a fixed supply temperature while in CAV air supply temperature varies with a fixed flow rate. The main advantage of VAV is reduction of fan energy use in large buildings, while CAV is commonly used in small spaces due to its simplicity. The schematic of VAV system without reheat as implemented in Singapore office buildings is shown in Figure 7. In this design, several dampers are installed in return and outdoor air ducts to modulate the ratio of outdoor to return air in supply air flow. In VAV design of office spaces, it is a common practice to have outdoor air constitutes about 10 to 20 % of total supply air volume (Bearg, 1993; Hoyt et al., 2009). This percentage value is called *ventilation fraction* and it has considerable impact on indoor air quality and energy consumption of ACMV system. VAV box is the heart of this design which adjusts the volume of supply air to each zone based on feedback from a user controlled thermostat inside the zones.

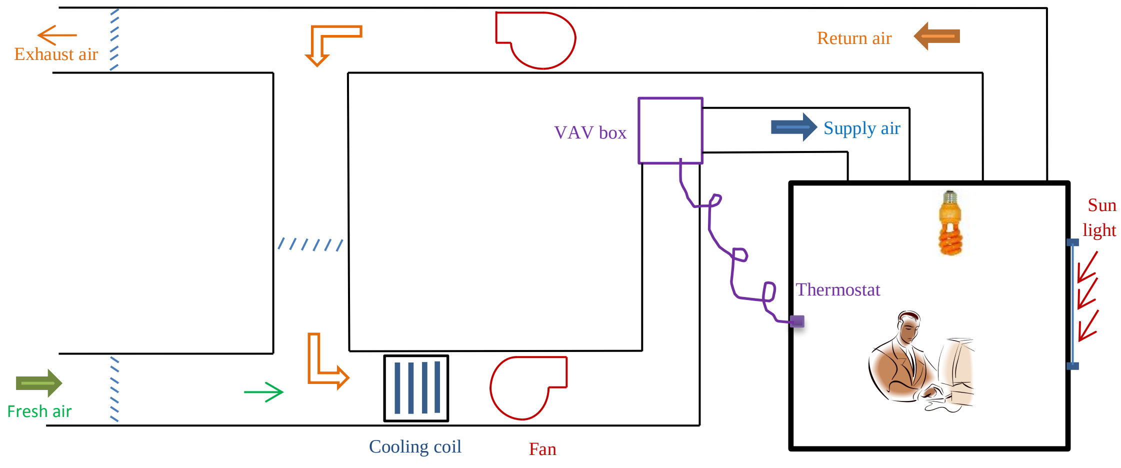


Figure 7 Schematic of VAV system without reheat in Singapore office buildings

The infrared image of an interior office space in NUS (National University of Singapore) campus which conditioned with the central all air VAV system is shown in Figure 8. As shown in the graph, air is supplied from ceiling diffusers at temperature of 16 °C while the temperature of grill fluorescent light fixture is around 33 °C. This design works based on mixing strategy and generated heat by lights and occupants as well as heat gain from façade are extracted to outside through return air. Supply diffusers and return grills are uniformly distributed over the space and located on the suspended ceiling where air ducts and electrical wiring are concealed.

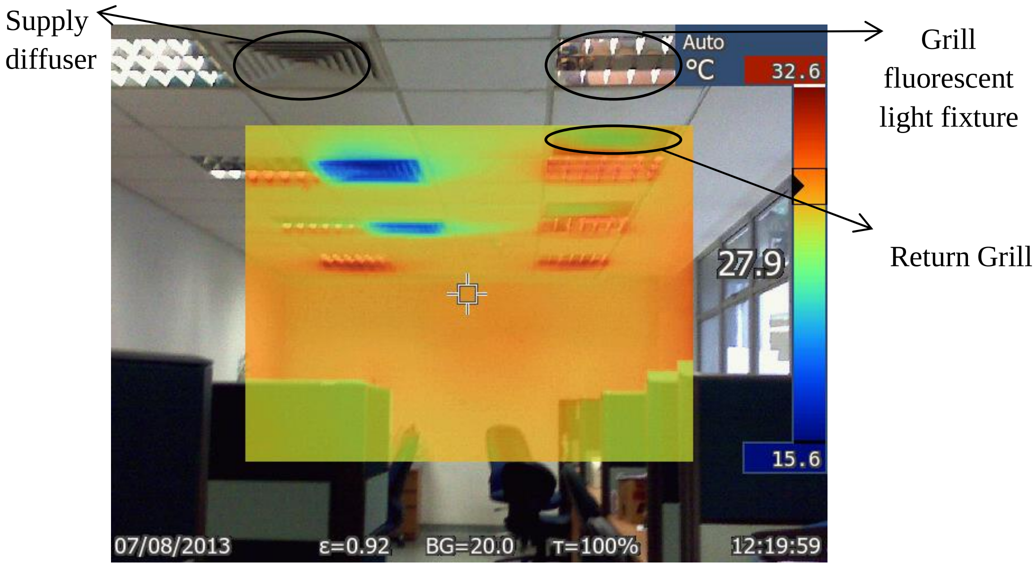


Figure 8 Infrared image of an interior office space with central all air VAV system

1.2.2 Split AC systems

Split AC systems have also been installed sparsely in small office buildings or in special rooms of high rise buildings in Singapore. In this design, extraction of heat from indoor space occurs directly through refrigeration cycles where refrigerant inside coils exchange heat with the surrounding air. The cycle contains two coils and fans as well as a compressor and an expansion valve which are installed in outdoor and indoor unit, respectively. Implemented indoor units could be ductless or connected to air ducts in order to bring outdoor air into space. Each indoor unit contains cold coils and a fan to enhance the absorption of heat from the interior zones while outdoor unit contains hot coils and a fan to enhance the extraction of heat to the ambient air. The cooling capacity of system is usually modulated based on feedback from user controlled thermostats located inside the space. Samples of indoor and outdoor units as well as infrared image of an implemented case of split AC systems in NUS campus is shown in Figure 9. It can be observed that outdoor unit surface temperature could reach 44 °C and its temperature difference with surrounding is apparent with infrared camera.

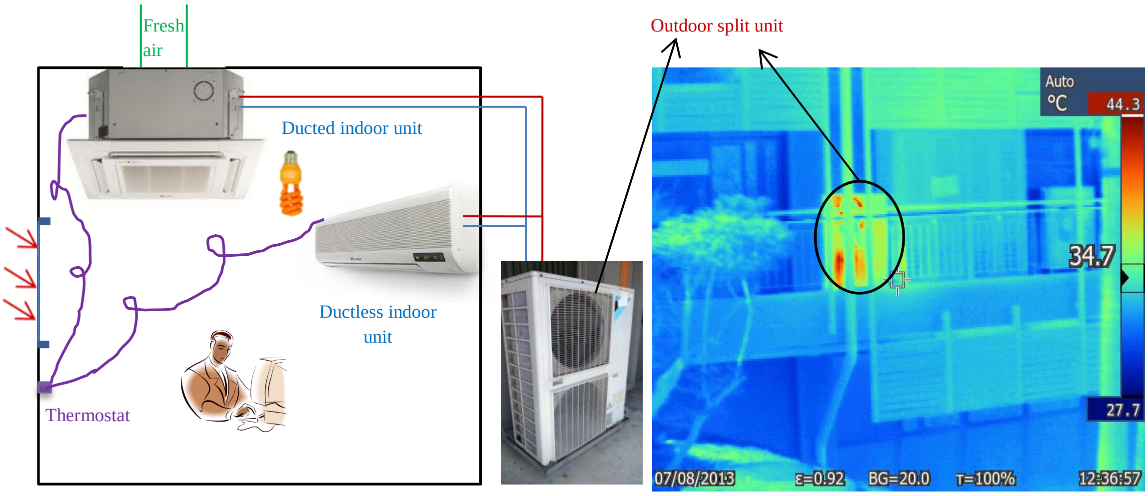


Figure 9 Indoor and outdoor units as well as infrared image of an implemented case of split AC system

1.2.3 Low exergy cooling system

The low exergy concept in the tropics introduces more efficient way of conditioning indoor space by using warmer chilled water in order to reduce exergy destruction in building systems. This shift to warmer chilled water could bring the potential to reduce exergy losses in refrigeration cycle of chiller. The air-water cooling systems are better aligned with the high temperature cooling concept in buildings compared to the all air systems. Dedicated outdoor air system (DOAS) combined with a water based radiative/convective cooling system is one of these low exergy designs. In this concept, conditioned outdoor air is brought into space to satisfy the latent load, the ventilation requirement and part of space sensible load. A parallel radiative/convective cooling system like radiant ceiling panel is usually employed to handle the rest of the sensible load. This separation increases the share of water as heat transport medium in air conditioning system and facilitates the use of demand controlled ventilation (DCV) based on CO_2 level in the indoor space. Compared to the conventional system, the air-water systems can potentially save energy through further use of water as heat transport medium to lower fan energy use and duct size. The heat capacity of water (4.183 kJ/(kg.K) @ 20 °C) is four times more than air (1.005 kJ/(kg.K) @ 20 °C), and consequently the heat transfer exchange process is potentially more efficient with water. In addition, parallel radiant cooling system is categorized as a high temperature cooling system which can result in a higher COP (Coefficient of Performance) of the refrigeration cycle and therefore the chiller if designed accordingly for the low lift condition. The other advantages of DOAS combined with radiant cooling compared to the conventional system are less noise, lower air draft, and better thermal comfort for occupants caused by the radiant heat transfer. DOAS concept is getting more attraction over time especially for applications in which high ventilation rate is required like in hospitals and schools (Munters Co., 2009).

In this research project, decentralized concept is incorporated into DOAS to further reduce fan energy use and air duct size by using decentralized ventilation units, a concept which can be called decentralized DOAS (DDOAS). In this concept instead of several air handling units for each floor, many decentralized air supply units can be embedded into structure of a building to take outdoor air directly from façade. These decentralized units can be installed at different facades to accommodate the shortest and least energy intensive way of supplying fresh air to the conditioned space. In addition, air is supplied to and distributed within space through under floor interlaced ducting systems to take advantage of displacement ventilation strategy. The schematic of decentralized DOAS combined with radiant ceiling panel under floor supply and ceiling exhaust (FS-CE) is shown in Figure 10.

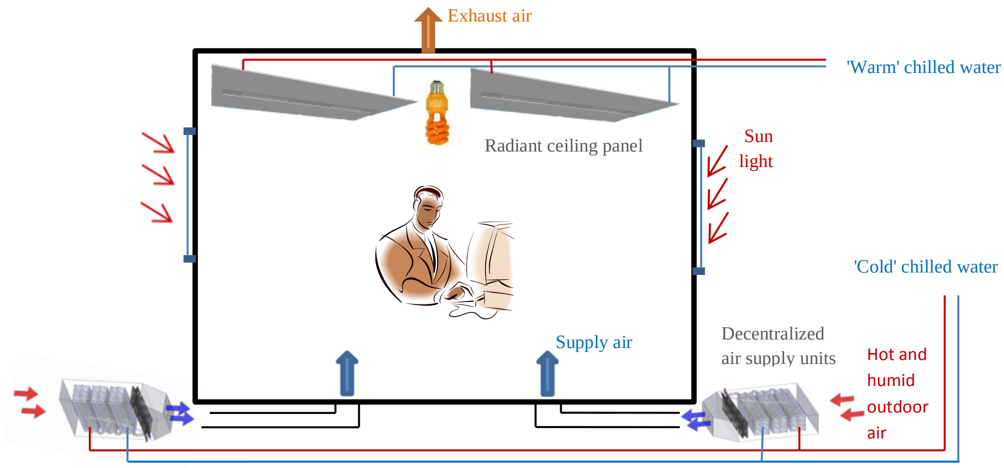


Figure 10 Schematic of decentralized DOAS combined with radiant ceiling panel

With implementation of this design in buildings, floor to floor height could be reduced and also there is no need for AHU rooms in buildings. These low exergy ventilation technologies including decentralized air supply units and radiant cooling panels have been designed by the Building Systems Group at ETH Zurich and customized for the tropical climate of Singapore (Iyengar et al., 2013; Meggers et al., 2012). These technologies have been implemented in a laboratory called BubbleZERO (Figure 11) which is located near the campus of NUS (Bruelisauer et al., 2013). The condensation risk on radiant panel and sophistication of operating this air-water system in tropical buildings are the main challenges of implementing this low exergy design.

Figure 11 The BubbleZERO (zero emission research operation) laboratory located near NUS campus

1.3 Scope and objectives of study

Prospects of the low exergy cooling system motivated this study to explore the performance of such a design in practice for the tropical context. The objective of this study was to evaluate the performance of the low exergy systems in the tropics depicted as DDOAS (decentralized dedicated outdoor air system)-RCP (radiant ceiling panel) in terms of thermal comfort, indoor air quality, energy and exergy saving potentials. The low exergy concept in the tropics encourages using low valued exergy sources for building services in order to minimize exergy destruction of processes inside building. In particular, for air conditioning system, this means satisfying cooling load of space with chilled water closer to thermal comfort temperature range. This change from conventional air conditioning to DDOAS-RCP requires modification and customization of components to accommodate an effective implementation of the concept. The new conditioned space with DDOAS-RCP has different characteristics compared to the conventional all air system which needs to be determined. The second objective was to explore these characteristics and determine the perception of occupants toward these low exergy technologies as well as any possible indoor air quality concerns.

Thermal comfort is the status of human body when it gets into thermal equilibrium with environment without feeling dissatisfied. The main variables which influence the comfort status of human body include dry bulb temperature, mean radiant temperature, clothing level, metabolic rate, water vapour pressure and air velocity. In addition to these parameters, mental condition and well-being of occupants also play some roles which are beyond the scope of this PhD research. Thermal comfort needs to be investigated for the whole occupancy zone as well as for local discomfort concerns if there is considerable variation of environmental parameters in the space. Indoor air quality of the space also needs to meet some minimum requirements for the main pollutants provided by the local and the International guidelines and standards. This is to ensure the pollutant concentrations do not exceed the thresholds and there is no health risk for occupants. This research aimed to investigate the conformability of indoor air space conditioned by DDOAS-RCP with the local/International standards and thermal comfort models.

The main advantages of DDOAS coupled with radiant ceiling panel compared to the conventional all air system are less noise and better thermal comfort for occupants achieved by radiant heat transfer. In addition, this design can reduce the required floor to floor height in buildings and potentially it consumes less energy and exergy compared to the conventional system. On the other hand, the main concerns of this system for the tropics are the potential condensation risk on radiant panels and lower air movement compared to the conventional air conditioning systems in this climate. The latter issue is mostly relevant in the tropical context while in moderate and cold climates, lower air movement or less draft is mostly considered as a benefit. With high outdoor humidity levels all year round, dew point of the interior space has to be actively controlled to be well below the radiant panel surface temperature in order to avoid condensation. With this consideration, there would be some limitations regarding the contribution of radiant ceiling panel in total sensible heat removal of space. Overall, the operating condition of radiant ceiling panel should be optimized based on the sensible cooling load of the space. Developing a better understanding on the ratio of sensible cooling provided by radiant panel compared to sensible and latent cooling provided by decentralized air supply units is one of the main objectives of this research. The air movement in DDOAS-RCP is lower than that for the conventional all air system which may not satisfy the requirement of local standard SS 554 (in range of 0.1-0.3 m/s). Albeit, in DDOAS-RCP design, this lower air movement is compensated by lower mean radiant temperature in space, the response and adaptation of occupants in the tropics to this new indoor environment needs further investigation.

Computer aided engineering (CAE) is gaining more weight in the building related research and industry over time and the advanced simulation models are capable of predicting different aspects of building performance. Inside the buildings, CFD (computational fluid dynamics) can provide insights into indoor air characteristics, spatial distribution of environmental parameters and pollutants in the space. This study utilized CFD simulation to numerically determine indoor air characteristics and radiative/convective heat transfer mechanism around radiant panel and occupants. As a necessary step, it is required to validate the CFD simulation results with experimental data in order to be able to proceed with predictions of different scenarios. Providing a clear understanding on differences between indoor air characteristics of DDOAS-RCP with the all air system was one of the objectives of this thesis.

There is potential for integration of DDOAS-RCP with compatible technologies like low temperature lift chillers. These integrations can further enhance energy saving opportunities of the design. Higher operational efficiency of chiller can be achieved by deploying a separate low loft chiller for radiant cooling system. The level of improvement in COP of chiller is required to be quantified for the tropical context. The order of improvement would determine whether running two parallel chillers in DDOAS-RCP could be economically attractive to building managers.

1.4 Thesis structure

This thesis includes six chapters: Introduction, Literature Review, Methodology, Results, Discussion and Conclusion. In the first chapter, background information on ACMV system in the tropics and the low exergy cooling systems are provided. High temperature cooling as a low exergy concept is introduced and aim of the study is explained with emphasis on the application of radiant cooling system in the tropics. In the literature review chapter, the reported studies on application of high temperature and comfort studies in the tropics are reviewed. Knowledge gaps are identified based on the conducted literature review and research questions are formed to be explored in the thesis. The followed methodologies are elaborated in chapter 3 on different aspects of DDOAS-RCP performance evaluation. Those aspects include description of the BubbleZERO testbed, environmental parameters, system variables, comfort evaluation, ventilation effectiveness analysis, numerical modelling, integration with low lift chillers and potential energy saving of this low exergy design. In chapter 4, results have been categorized in similar sections to present the outcomes of thesis on different aspects of DDOAS-RCP performance in the tropics. The obtained results are further elaborated in chapter 5 and relevant discussions are provided to give a better understanding. In chapter 6, conclusions of thesis are summarized and future work are suggested based on the results and limitations of this study. The report of conducted blower door test in the BubbleZERO and scientific publications from this PhD research are included as appendices in this thesis.

Chapter 2. Literature review

The reported studies in the literature on different aspects of the high temperature cooling system including performance evaluation, thermal comfort analysis and indoor air simulations are reviewed and discussed.

2.1 High temperature cooling systems

The whole idea behind the low exergy concept in buildings is to use low exergetic (or low value) and sustainable energy sources for required energy services inside buildings. Energy and exergy flows through buildings have been investigated in various studies (IEA ECBCS Annex 37, 2003; Tolga Balta et al., 2008) and the results have shown that the main exergy destruction occurs in the primary energy transformation. This fact shows the importance of conducting exergy analysis for power plants which is a necessary step at design stage of plants. On a lower level, exergy destruction also occurs in storage, distribution, and at the end of exergy flow chains are system components and building envelope. Schmidt (2009) used the exergy concept to find efficient ways to supply energy in order to satisfy demand for energy services inside buildings. He found that technologies with low temperature heat sources like solar thermal collectors and ground source heat pumps compared to electricity driven technologies on exergy basis can be better matched with demands of building services like cooking, sauna, domestic hot water and space heating. In another study, Meggers et al. (2012) have shown the potential of the low exergy building systems like hybrid Photovoltaics/thermal collector and low lift ground source heat pump with borehole to heat buildings, which have lower energy and exergy demand. This group also embarked on a cost analysis which demonstrated the importance of considering investment costs for both passive and active systems such as boreholes.

In particular for building cooling systems, various technologies have been categorized as low exergy cooling technologies in IEA Energy Conservation in Buildings and Community Systems (ECBCS) Annex 28 (2000). The addressed technologies include night cooling, ground cooling (air and water), evaporative cooling (direct and indirect), slab cooling (air and water), desiccant and evaporative cooling, displacement ventilation and chilled ceilings. Night cooling is able to reduce the internal peak temperature by 2-3 °C for heavyweight constructions with suitable design and under right climate. This strategy with natural or mechanical ventilation is mostly suitable in the climates where there is a substantial difference between outdoor night temperature and midday air temperature. So it cannot be an effective strategy for the tropical climate of Singapore with warm nights. Slab cooling concept, same as in night cooling, takes advantage of building thermal mass in order to provide a stable indoor air temperature by providing radiative/convective cooling to the space. In this concept, floors or walls are cast with chilled water pipes or cool air ducts and a detailed control strategy is needed to optimize the required cooling and avoid condensation especially in hot and humid climates (IEA ECBCS Annex 28, 2000). The high temperature cooling system applied as slab cooling could be an effective strategy for tropical building when accompanied with a parallel air system to satisfy the latent load and the ventilation requirements.

In evaporative cooling, air is cooled down by evaporation of water in air which happens through water spraying or running in a wet porous media. This low energy and exergy concept is more suitable for dry climates where the rise in relative humidity does not exceed the threshold of the comfort range (e.g. 60 %), certainly not for Singapore. Desiccant cooling is a popular area of research for the tropics which uses a desiccant to extract humidity from supplied air and then release that humidity into exhaust air. While solid desiccant has been implementing in building conditioning system for the long time, relatively new designs of liquid desiccants showed promising results for the hot and humid climates and currently it is shifting from research stage into real applications (Huang and Zhang, 2013). The complexity and maintenance issues of liquid desiccant systems are the main hindrances for widespread implementation of this concept in buildings. Ground cooling is another low exergy technology which tries to take advantage of the lower underground temperature for reduction of heat pump lift or to directly recirculate air or water to the underground source. Ground cooling is an effective strategy when the ground temperature is at 12 °C or below (IEA ECBCS Annex 28, 2000). Nevertheless, ground in the tropical rainforest climate has small fluctuation over the year and it is mostly warm and not suitable for implementation of ground cooling (van Dronkelaar et al., 2014).

The combination of chilled ceiling and displacement ventilation is one of the low exergy ventilation technologies, which has been investigated by many researchers in the literature (Novoselac and Srebric, 2002; Schiavon et al., 2012). A study based on annual energy simulations showed that energy efficiency of this coupled system compared to the all air systems varies for different climate types (from cold and dry to very hot and humid) and ranges between 10 to 40 % (Tian and Love, 2009). Novoselac and Serbric (2002) tried to provide a dimensionless comparison of CC-DV with VAV (e.g. of VAV-RCS) system based on the reported studies in the literature and they concluded that this VAV-RCS design may or may not save energy compared to VAV system. Besides climate type, the amount of energy saving is dependent on system configuration, supply air temperature, outdoor flow rate and cooling load of space. They also showed that minimization of infiltration and proper control of system in transient situations like start-up and shutdown is required to avoid condensation on chilled ceilings. Schiavon et al. (2012) tried to find a relationship between the ratio of cooling load removed by chilled ceiling and thermal stratification inside the space. The results showed that the higher contribution of chilled ceiling in removal of cooling load results in lower room stratification. The conducted experiments on VAV-RCP in which air distributed through floor diffusers (FD) indicated that head to ankle temperature difference of 1.5 °C is achievable with ceiling surface temperature of 18 °C or higher.

While the concept of DDOAS-RCP is unique and its application for the tropical climates has not been reported in the literature, there have been reports on the similar low exergy cooling and heating systems. The closest types of air conditioning systems to DOAS-RCP are DOAS-RSC, DOAS-ACB, DOAS-PCB, RAS-RCP, RAS-RSC, RAS-ACB and RAS-PCB. The high temperature cooling systems of radiant slab cooling (RSC), active chilled beam (ACB) and passive chilled beam (PCB) could be employed instead of radiant ceiling panel (RCP). Each of the above-mentioned HTC systems has unique characteristics in terms of initial cost, cooling capacity and operation strategy. Among HTC cooling system, radiant slab cooling (RSC) can be implemented at lower investment cost, although it requires early-stage planning and integration into structure of building. In active chilled beam (ACB) design, supply air passes through heat exchanger which operates with high temperature chilled water. Passive chilled beam (PCB) is an independent HX beam installed near ceiling and it can provide uniform convective-radiative cooling from the ceiling in the downward direction.

In the recirculated air system (RAS) concept, the supply air is the mixture of fresh air and return air, while in DOAS, the supply air is pure fresh air and there is no return air. Overall, DOAS types of high temperature cooling compared to RAS types provide a lower air movement indoor space in which water based cooling system plays a more effective role and they could be potentially more energy efficient. Convective and radiative heat exchanges are the most dominant heat transfer mechanisms respectively in chilled beam and chilled ceiling. The abovementioned conditioning system can be further categorized based on their distribution types. The air distribution systems could vary from ceiling supply-ceiling exhaust (CS-CE) to floor supply-ceiling exhaust (FS-CE) for each of the combinations of the low exergy systems. Interaction of air and water systems inside the space needs to be understood and optimized at design stage. Mixing ventilation (MV) and displacement ventilation (DV) are the most common types of distribution strategies which can include CS-CE or FS-CE through UFAD.

Mumma (2002) identified the main barriers of ceiling panel cooling combined with DOAS (DOAS-RCP) systems in buildings. These include condensation, capacity and first cost. The conducted hourly energy analysis for humid continental climate of Philadelphia showed that a conventional VAV (variable air volume) system costs about 29 % more to operate compared to DOAS-radiant cooling panel. Regarding the condensation issue, he showed that even if the occupancy increases by a factor of 2 or 3, it could take hours before the condensation film on the panels would be equal to the thickness of a human hair (Mumma, 2001). For the tropical climate of Thailand, Vangtook and Chirarattananon (2007) conducted a whole year energy simulation and thermal comfort analysis for radiant cooling panel system. The results of the study showed that radiant cooling system combined with proper conditioned air can help to attain thermal comfort superior to the conventional system, while energy saving is also achieved. They used the relatively high chilled water temperature of 25 °C provided by cooling tower to avoid condensation which results in low capacity of cooling panels and makes their design applicable only for low heat gain spaces.

A software company in Hyderabad did a side-by-side comparison between VAV and DOAS-slab cooling and they observed 34 % less energy consumption by DOAS-radiant cooling compared to the VAV system on annual basis (Sastry and Rumsey, 2014). This group also did a cost comparison of conventional and radiant cooling system and showed that the cost of the radiant system was slightly lower than the VAV system. The cost saving opportunities from reduction of AHU and duct size was about 6 % of total cost of ACMV system while radiant piping, accessories and installation raised the investment cost for around 23 %. This study considered 33 % reduction in HVAC low side work or commissioning cost in the case of radiant cooling which was not elaborated in the paper. The combination of the central all air system with active chilled beams is also another popular design, which is getting more attention in Singapore. In this regard, Kosonen and Tan (2005) investigated the feasibility of ventilated beam system in Singapore office buildings combined with DOAS and RAS. They concluded that the room design condition of 23 °C and 65 % humidity level is achievable with both DOAS-ACB (10 L/s/person outdoor air) and RAS-ACB (4 L/s/person outdoor air combined with reconditioning of return air). The recommended minimum outdoor air supply for office buildings is 5.5 L/s/person based on the Singapore standard of SS 553 (2009).

Besides energy simulation analysis, experimental and numerical modelling approaches have been chosen by some researchers to explore the implications of radiant cooling and DOAS systems in buildings. Chiang et al. (2012) employed CFD to provide enhanced predictions on implementation of radiant ceiling panel combined with displacement ventilation for the subtropical climate of Taiwan. They supplied the conditioned air at high temperatures of 18-24 °C near the floor to reduce thermal stratification in the space and achieve better thermal comfort. No concern of condensation on radiant ceiling surface was reported for this range of supply temperature which could be due to the low dew point level at supply air or low latent load of the laboratory. They also concluded that energy saving is achievable with rise of supply air temperature which can result in higher cooling capacity of ceiling panel and increase in efficiency of chiller. By this change, they can shift more sensible heat removal of space to ceiling panel and provide a better balance for the whole indoor space. However, maintaining the same level of humidity in supply air with raised temperature is a challenge which needs to be taken care of with a more sophisticated conditioning system. Their results also showed that moving the supply air position from the ceiling to the floor led to better cooling efficiency.

Wang and Tian (2013) also performed CFD simulation and experiments to investigate the thermal comfort of the hybrid radiant cooling and dedicated outdoor air system. Contrary to Chiang et al. (2012)'s results, they found that ceiling delivery and ceiling exhaust of outdoor air is the optimized distribution option. Based on their findings, the magnitude of factors' impact has an order of air supply temperature > panel coverage area > panel temperature > air supply volume. This order of magnitude is aligned with other studies which found air supply temperature as a critical factor for DOAS-RCP. For US office buildings, Schiavon et al. (2012) carried out experiments in a typical office building to assess the impact of a chilled ceiling combined with a displacement ventilation system on room air stratification. The results revealed that the average temperature of radiant panel surface is the best predictor of temperature difference between head and ankle of a seated person in the space. It was also showed that less coverage of the ceiling with radiant panel usually requires cooler surface temperatures, which causes more disruption on room air stratification. The details of the studies in the literature on the high temperature cooling system are listed in Table 1. It is noteworthy that although the researchers in these reported studies have not used the term of low exergy for their suggested design, due to the applied concept of high temperature cooling in their designs, they can be categorized as low exergy cooling systems. The amount of energy saving reported in these studies also determined based on electricity use or pure exergy sources and the values would be equal to exergy saving as it is technically correct to use exergy instead of energy.

Table 1 List of reported studies in the literature on high temperature cooling systems applications in buildings

Authors (year)	High temperature cooling system	Air system / distribution	City / Climate Type	Investigation approach	Main findings- Energy/exergy saving
Mumma (2002)	RCP	DOAS / CS-CE	Philadelphia-USA / humid subtropical	Building performance simulation	VAV costs about 29 % more to operate compared to DOAS-RCP
Novoselac and Srebric (2002)	RCP	DV	Various locations and climates	Literature review	VAV-RCP design may or may not save energy compared to VAV system
Kosonen and Tan (2005)	ACB	CS-CE	Singapore / tropical rainforest	Field Measurements	Comfort room condition is achievable with both DOAS-ACB and VAV-ACB
Vangtook and Chirarattanon (2007)	RCP / TABS	-	Central Thailand / tropical savanna	Building performance simulation	Radiant cooling with chilled water from cooling tower can be applied for low heat gain spaces
Tian and Love (2009)	TABS	DOAS	cold and dry to very hot and humid	Building performance simulation	Annual energy saving of DOAS-TABS compared to all air systems ranges between 10 - 40 % for different climates
Schiavon et al. (2012)	RCP	DV	-	Test chamber	Higher contribution of chilled ceiling in removal of cooling load results in lower room stratification
Chiang et al. (2012)	RCP	CS-CE	Taipei-Taiwan / humid subtropical	Test chamber / CFD simulation	Air supply temperature plays the most important role and rise of this temperature can result in higher cooling capacity of ceiling panel
Wang and Tian (2013)	RCP	DOAS	-	Test chamber / CFD simulation	magnitude of factors' impact has an order of air supply temperature > panel coverage area > panel temperature > air supply volume
Sastry and Rumsey (2014)	TABS	DOAS	Hyderabad-India / tropical	Field Measurements	DOAS-slab cooling consumes 34 % less energy compared to VAV system on annual basis

			savanna		

The applications of the low exergy technologies are abundant for temperate and dry climate, although their applications for the tropics are sparse. In particular for the high temperature cooling strategy, the condensation problem imposes restriction on supply chilled water temperature and as a consequence on cooling capacity of radiant system. The building system group at Department of Architecture in ETH, Zurich has conducted extensive research on the application of the low exergy technologies in the buildings. These low exergy technologies including decentralized air supply units and radiant panels have been designed by this group for the continental climate of Zurich and successfully installed in a building inside the ETH campus (HPZ building). This design is a combination of decentralized concept with DOAS-RCP which seeks integration with building structure and other building services including lighting. The group further expanded this design and customized it for the tropical climate of Singapore inside a laboratory called BubbleZERO (Bruelisauer et al., 2013). In this concept, dehumidified and cool outdoor air satisfies the latent load, the ventilation requirement and part of space sensible load while radiant panels satisfy the rest of sensible load. The results of the preliminary evaluation in this laboratory showed that humidity level in the supplied outdoor air and infiltration rate of space should be closely controlled to avoid condensation on radiant panels (Meggers et al., 2013). In another evaluation study in the BubbleZERO on the feasibility of high temperature cooling, it was concluded that a water-based radiant cooling is feasible in the tropics and supply air condition at diffuser level and stored humidity in the façade during system start up are the critical parameters (Iyengar et al., 2013).

Overall, the air-water system can potentially save energy compared to the all air system by using water as a more efficient heat transfer medium and reducing the amount of supply air. This decrease in supply air volume can result in downsizing AHU and duct size for a centralized air conditioning system. In decentralized DOAS-RCP concept, water has been further circulated in the building by bringing the decentralized air supply units just close to the conditioned space. So, the reduction in the fan energy compared to that for the all air system would be more substantial. While this change increases the water pump energy use in buildings, the overall required energy for air circulation is much higher than that for water circulation.

The high temperature cooling concept can accommodate another aspect of energy saving through implementation of DDOAS-RCP instead of the all air system. Incorporating radiant cooling systems in buildings facilitates use of higher chilled water temperature which can potentially save energy and exergy by using a custom designed chiller for low temperature lift conditions. This higher evaporator temperature can reduce the compressor work because of lower temperature and pressure lift. The refrigeration cycles on pressure-enthalpy diagrams for two cases of low temperature and high temperature cooling is shown in Figure 12. As can be seen in this graph, with reduced lift between low and high pressure side of refrigeration cycle, the compressor is needed to perform less work done. This graph indicates the efficiency superiority of the high temperature cooling concept over conventional air conditioning system in the tropics. It is also noteworthy that by using low exergy sources like solar power and ground, energy and exergy destruction inside the refrigeration cycle can be further reduced.

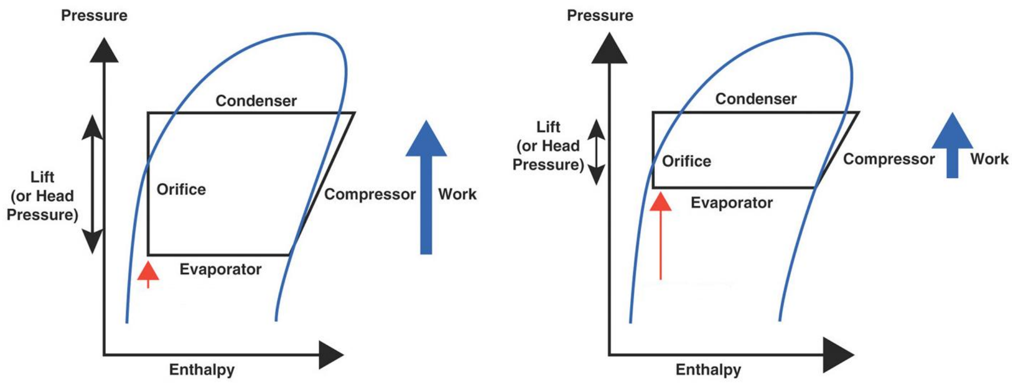


Figure 12 Impact of raising the evaporative temperature on refrigeration cycle diagram (Doyon, 2008)

Overall, most of the cited studies found an increased energy efficiency of DOAS/radiant cooling systems compared to conventional systems with higher perceived comfort for occupants in the conditioned space. Based on the reported studies, supply air temperature and panel surface temperature have the most dominant impacts on thermal stratification, energy saving and acceptance of occupants. According to the knowledge of this author, no study has been undertaken on performance evaluation of decentralized concept incorporated into DOAS-RCP design for the tropics. Therefore, there is a lack of understanding of key system related parameters in DDOAS-RCP design.

2.2 Thermal comfort and indoor air quality in the tropical context

DDOAS-RCP provides a new type of conditioned indoor space for the occupants in the tropics and its compatibility with the International and local standards and thermal comfort models needs to be investigated. Acclimatization can also play a role in the tropical context which requires a detailed understanding of the preference of locally acclimatized occupants. Various studies have been conducted in the tropics to investigate the acclimatization theory of the human body to hot and humid climates (Ole Fanger and Toftum, 2002; Wong et al., 2002). The mainstream research on this matter conducted to identify and quantify any possible acclimatization behaviour among the habitants for naturally ventilated (NV) and air conditioned spaces in this climate. Webb (1959) has investigated the overall thermal sensation of fully acclimatized subjects in the equatorial climate of Singapore and he provided an equation for Singapore index comfort which was slightly higher than temperate climate standards. The optimum value of the Singapore index was 25.9 ± 0.4 °C when 68 ± 8 % of occupants felt comfortable. Thirty years later, in two separate studies by Busch (1992) and de Dear et al. (1991), field experiments and thermal comfort studies have been conducted respectively in Bangkok and Singapore. Busch's study in Bangkok revealed that the upper bound of acceptable effective temperature is 28 °C for air conditioned spaces and 31 °C for naturally ventilated buildings. Both of these values were significantly higher than the ASHRAE 55-81 (1981) standard limit at the time of the study, which was 26.1 °C. Although these results showed the evidence of the acclimatization for tropical occupants, it lacks detailed information on air speed in space and clothing level of office workers. On the other hand, the results of de Dear et al. (1991)'s study have shown that occupants find the NV spaces at 29.6 °C and 74 % RH (0.22 m/s, 0.26 clo.[1]) slightly warm, while their response was on the cool margin in the air conditioned space at 23.5 °C and 56 % RH (0.11 m/s, 0.44 clo.). No sign of

[1] Clothing level

acclimatization has been observed for air conditioned space in this investigation.

de Dear et al. (2013) reviewed the trend of thermal comfort studies in the last two decades and they observed the paradigm shift from heat-balanced thermal comfort models toward adaptive models. They also noticed the rehabilitation of air movement perception from negative to positive language. As an example of such studies in recent years for the tropical climates, in two large cities in the south of India (Chennai and Hyderabad), Indraganti et al. (2014) found the mean comfort temperature to be 28.0 °C and 26.4 °C for NV and AC offices, respectively. They proposed a linear correlation between indoor comfort and outdoor temperature and the slope of the curve was close to the reported slope in ASHRAE standard 55 (2004), CEN standard (2007) and CIBSE guide (2006). In a similar study at hot and humid climates of Changsha, Guangzhou, and Shenzhen in central south of China, Han et al. (2007) obtained a higher neutral operative temperature than Fanger's PMV model prediction and the difference was attributed to the thermal adaptation of humans. However, the survey was conducted at both AC and NV homes and the subjects were allowed to adjust their heat balance by other means like clothing, windows and fan. So the results do not necessarily support the acclimatization theory. In another study at the tropical climate of Brazil, the volunteers' response in air conditioned spaces was similar to the PMV predictions, while in NV buildings, there was a significant difference between thermal sensation vote and predicted mean vote (Andreasi et al., 2010).

In local context of Singapore, Chen and Chang (2012) investigated the overcooling perception of office workers in Singapore and the results showed the average indoor temperature of 24.5 °C is too cold as expressed by actual occupants' thermal sensation vote while it is in-line with the PMV model comfort range. This study identified overcooling as the main concern for office buildings in the tropics and attributed this observation to acclimatization of occupants and design of ACMV system. Contrary to these results, Willem and Tham (2007) showed that tropically acclimatized subjects prefer a neutral to slightly cool thermal sensation, which is optimized when the thermal sensation was -0.4. In another field study in high rise public housing in Singapore, de Dear and Leow (1990) found that acclimatized human in the tropics prefer 2 °C warmer temperatures than the value predicted by the PMV model and the ISO standard. Physiological acclimatization was suggested as the possible explanation of this discrepancy between temperate climate models and actual perception of subjects in the tropics. Regarding the impact of air movement, Gong et al. (2006) showed that more than 30 % of locally acclimatized people in the tropics still prefer higher air movement even at local temperature of 23.5 °C and local air velocity of 0.15 m/s. However, the results of this study are mostly relevant for the applications of personal ventilation where the subjects are exposed to the outdoor air coming toward their face. In a recent study, Schiavon et al. (2015) investigated the effect of personally controlled air movement on comfort level of tropically acclimatized occupants and they found 98 % of subjects satisfied at temperature of 29 °C when they have access to personal fan. This finding shows the higher draft tolerance of occupants in the tropics which can be utilized for enhancing the energy saving in building ACMV system by raising the indoor temperature. In a subjective study on application of personal desktop fans (Melikov et al., 2013), no concerns regarding the SBS has been reported and better perceived air quality has been observed with increased air movement. However, humidity concern has been reported by some studies (Shirey and Henderson, 2004) at part load operation of CAV design which could cause IAQ issues in indoor environment with increased set point temperature. Regarding the application of radiant cooling in office buildings, Bolashikov et al. (2013) investigated the thermal comfort level in an office environment with four different types of convective/radiant cooling systems. The results of experiments with 24 human subjects revealed that the indoor space with radiant cooling had a more homogenous thermal environment and occupants were more satisfied with radiant cooling rather than convective cooling. Nevertheless, this comfort study was conducted with local subjects in Denmark and local occupants in tropical context may have different comfort preferences. The details of the studies in the literature on thermal comfort sensation of occupants in conditioned spaces of warm and humid climates are listed in Table 2.

Table 2 List of reported studies in the literature on thermal comfort sensation of occupants in warm and humid climates

Authors (year)	Air system / distribution	City / Climate Type	Investigation approach (No. subjects)	Main findings
De Dear et al. (1991)	NV / MF / AC	Singapore / tropical rainforest	Field study (818)	Occupants prefer warmer temperature in NV spaces but no sign of acclimatization has been observed for AC spaces
Busch (1992)	NV / MF / AC	Bangkok-Thailand / tropical savanna	Field study (1100)	Upper bound of acceptable effective temperature is 28 °C for AC spaces and 31 °C for NV buildings
Gong et al. (2006)	AC (MV-PV)	Singapore / tropical rainforest	Test chamber study (24)	30 % of locally acclimatized occupants prefer higher air movement even at local temperature of 23.5 °C and air velocity of 0.15 m/s

Han et al. (2007)	NV / MF / AC	Central southern china / Summer	Field study (110)	Higher neutral operative temperature than Fanger's PMV model prediction due to the thermal adaptation of humans
Willem and Tham (2007)	AC (MV)	Singapore / tropical rainforest	Test chamber study (96)	Tropically acclimatized subjects prefer a neutral to slightly cool thermal sensation, which is optimized when the thermal sensation was -0.4
Andreasi et al. (2010)	NV / MF / AC	3 cities in Brazil / tropical savanna	Field study (1301)	Occupants' response in AC spaces was similar to PMV, while in NV buildings, there was a significant difference
Chen and Chang (2012)	AC (MV)	Singapore / tropical rainforest	Field study (210 onsite and 98 online)	Average indoor temperature of 24.5 °C is too cold as expressed by actual occupants' thermal sensation vote
Indraganti et al. (2014)	NV / MF / AC	2 cities in India / tropical savanna	Field study (2787 subjects and 6048 responses)	Mean comfort temperatures were 28.0 °C and 26.4 °C for NV and AC offices, respectively
Schiavon et al. (2015)	AC (MV-PF)	Singapore / tropical rainforest	Test room study (56)	98 % of subjects were satisfied at temperature of 29 °C when they have access to personal fan

The main goal of sustainable healthy buildings is to achieve healthy, comfortable and productive indoor spaces with least amount of exergy consumption and environmental impacts. The low exergy designs incorporating decentralized dedicated outdoor air system coupled with radiant cooling could be effective in achieving this for the tropical climate. For conventional means of mechanical dehumidification, a design prerogative is to minimize ventilation rates, since dehumidification entails exergy destruction due to the required low temperatures. With improved ventilation effectiveness of the design, the minimum required ventilation rate can be lowered without compromising the indoor air quality. Depending on the location of air supply outlets, and exhaust grilles as well as ventilation rate and supplied air condition, air flow pattern could be close to the ideal scenarios of fully mixed (air change efficiency (ACE)=50%) or piston (ACE=100%) strategies. An indoor air pattern with ACE between 50-100 % is categorized as displacement flow and with ACE below 50%, it is called a short-circuit flow (REHVA Guidebooks No. 2, 2004).

Ventilation effectiveness indices including air change efficiency (ACE) and contaminant removal effectiveness (CRE) are used to quantify the ability of air flow patterns to exchange air and remove air-borne contaminants, respectively. Several standards and handbooks provide guidelines on the procedure of calculating these values based on data from experiments or numerical modelling (ASHRAE 129, 2002; REHVA Guidebooks, 2004; REHVA Guidebooks, 2007). Although it was shown by several studies (Awbi, 1998; Gan, 1995) that displacement ventilation is more effective, Simon and Waters (1998) and Lin et al. (2006) concluded that in operation, indoor air pattern with near floor supply diffusers is more complicated than expected. Depending on the locations of heat sources and diffusers, near floor supply of air may not necessarily improve the air quality near occupants. Tomasi et al. (2013) investigated the ventilation effectiveness of residential rooms with mixing ventilation and floor heating / cooling and they found that ACE and CRE could give contradictory information on the effectiveness of air distribution. They recommended considering both values in the design process and accompanying experiments with computational fluid dynamics (CFD) simulations.

The majority of research results in the literature showed that the PMV model fails to predict the actual response of acclimatized occupants in the tropics especially for naturally ventilated spaces. However, for conditioned spaces in the tropics, slightly warmer neutral temperature compared to PMV prediction has been reported and this difference ranges from 0 to 2 °C while one study even reported slightly cooler temperature is preferred by local occupants (Andreasi et al., 2010; de Dear and Leow, 1990; Indraganti et al., 2014; Willem and Tham, 2007). The bilateral (upper and lower) deviation of actual perception of locally acclimatized occupants toward PMV prediction as reported in the literature shows the moderate stance of this model and improves its credibility for the conditioned spaces in the tropics. While a general comfort model like PMV can provide a good understanding of the actual perception of occupants for this design, it still cannot capture all the details of such an indoor space. Thermal perception, adaptation and acceptability of locally acclimatized occupants toward this new concept are taken into account through considering local standards of Singapore. It was also understood that ventilation effectiveness analysis of the selected air distribution strategy is necessary to evaluate the ability of system for purging the generated pollutants.

2.3 Indoor air CFD simulation

In the literature, CFD simulation has been extensively used in indoor air studies to capture air flow and temperature distribution as well as contaminant dispersion in indoor spaces. CFD also opened new directions of research to be further explored like near-body micro-environment and disease transmission research (Li and Nielsen, 2011; Siddiqui et al., 2012). Good agreements have been achieved between the CFD results and measured data for air velocity, temperature, and concentration of pollutants like TVOCs, formaldehyde, CO_2 and toxic gas release in indoor spaces (Bulińska et al., 2014; Hayashi et al., 2002; Panagopoulos et al., 2011; Siddiqui et al., 2012). Bulinska et al. (2014) showed that numerical models can be successfully incorporated to predict the spatial distribution of carbon dioxide exhaled by a person in a room. The results have shown the strong impact of the geometry of the components inside the room like window and radiator on dispersion pattern of CO_2 in the space. Hayashi et al. (2002) conducted a CFD analysis on the characteristics of contaminant inhalation by occupants under different postures. The results have shown that standing occupant inhales air from area close to the floor which rises due to the metabolic heating and the region of inhalation extends horizontally around the head for the case of sleeping occupant. In another study, Panagopoulos et al. (2011) used CFD techniques to predict TVOCs and formaldehyde distribution in an apartment with full-scale kitchen and living room. They concluded that CFD model can improve indoor pollution management system by optimizing sizing and siting of ventilation schemes. Siddiqui et al. (2012) also investigated different accidental release scenarios of dense gases in the indoor space with CFD simulations. The results have shown that the dense toxic chlorine gas spreads like a liquid close to the floor.

Computational fluid dynamics (CFD) is gaining more weight in ventilation and indoor air research due to the increase in computer hardware capabilities. CFD has been widely used in the past to investigate buoyancy driven flow around human body (Rim and Novoselac, 2009; Sørensen and Voigt, 2003), air pollutant dispersion and inhalation (Bulińska et al., 2014; Hayashi et al., 2002; Panagopoulos et al., 2011) and thermal comfort criteria (Catalina et al., 2009; Chiang et al., 2012) for different types of air conditioning and distribution strategies. Catalina et al. (2009) used CFD technique to explore the characteristics of an indoor space with chilled ceiling panel and they found vertical thermal stratification to be less than 1 °C. In another study, Chiang et al. (2012) employed CFD tool to provide design solutions to improve the performance of radiant cooling ceiling for the subtropical climate of Taiwan. They concluded that cooling efficiency can be improved by supplying air on the floor level and distributing it to multiple diffusers all over the floor. Sørensen and Voigt (2003) conducted a CFD study to predict heat transfer and flow pattern around a seated manikin and they achieved good agreement with particle image velocimetry (PIV) measurements on velocity magnitude above manikin head as well as for radiative and convective heat transfer coefficients of different body segments. In similar studies, Hayashi et al. (2002) and Rim and Novoselac (2009) investigated thermal plume near human body in indoor space through CFD simulation and they found that buoyancy driven flow plays an important role in transport of pollutants near occupants and their inhalation through breathing. These results show the significance and potential contributions of CFD technique to analyse the characteristics of DDOAS-RCP with FS-CE distribution for the tropical context.

The k-ε turbulence model is the most widespread model in the industry and also in the building research field. However, it has been reported in the literature that the shear stress transport (SST) turbulence model, which is the combination of the standard k-ε model (in far field flow) and the k-ω model (in wall boundary layer) perform better in indoor air CFD studies especially for flows dominated by wake and shear regions (Yang et al., 2007; Yousaf et al., 2011). Yang et al. (2007) used CFD predictions of air flow and temperature distribution around a computational thermal manikin to determine convective and radiant heat transfer coefficient around human body. The results showed good agreement with published data in the literature. This group tried to find the whole-body values of heat transfer coefficient and they have not embarked on calculation of coefficients for each body segment. Yousaf et al. (2011) also conducted a full scale analysis of buoyancy air flow around human body with CFD and particle image velocimetry (PIV) and the results of simulation and experiments compared very well. In indoor air CFD simulation, the details of air flow patterns and heat transfer near the diffusers and human body are mostly the points of concerns. This matter has been elaborated by Abdilghani et al. (2009) and Sorensen and Voigt (2003), respectively for inlet turbulence intensity and flow around the simulated manikin. Martinho et al. (2012) investigated the inherent error with CFD computation of air flow and heat transfer around the human body. The results demonstrated that grid refinement, boundary conditions, turbulence models, and human body model can have significant impacts on the flow pattern around the simulated person. They also achieved a good agreement compared to experimental data with the mixed turbulence model (SST) of k-ε and k-ω. Overall, the results of the previous studies showed that grid refinement, boundary conditions, and turbulence models are the main factors, which could affect the accuracy of the CFD results.

The characteristics of a conditioned indoor space with DDOAS-RCP are unique in terms of thermal stratification, air movement and the difference between mean radiant and dry bulb temperatures. CFD is a complimentary approach with experimental setup and it has the potential to reveal and further illustrate features of this low exergy design. The literature is abundant with studies of the numerical modelling of indoor air spaces and the majority of them have achieved good agreement with experimental results. The CFD model has the potential to provide insights into characteristics of indoor space conditioned with DDOAS-RCP in the tropics.

In the next section, the identified knowledge gaps based on the conducted literature review are summarized and discussed.

2.4 Identification of knowledge gap

Implemented cases of low exergy air conditioning strategies like RAS-RCP and RAS-ACB have been reported in the previous research projects and actual buildings in the tropics, although no case has been found on the implementation of DOAS-RCP. In particular, the combination of decentralized concept with DOAS-RCP is a new design for both temperate and tropical buildings. The amount of supply in DOAS types of high temperature cooling is considerably lower than RAS types of HTC which has impacts on operational condition, indoor environment and fan energy use of the design. In the first part of a group project conducted at the low exergy module of Future Cities Laboratory, the feasibility of DDOAS-RCP operation in the tropics has been investigated. However, there are still many unanswered questions on performance, thermal comfort and indoor air quality aspects of this design in the tropical context.

DDOAS-RCP provides unique indoor air characteristics with lower air movement and mean radiant temperature and it is required to further elaborate and quantify the differences of such a system with that of conventional concept. Thermal response of human body to conditioned space with DDOAS-RCP would also be different compared to the all air concept and it requires further investigation through experimental setup or simulation models. Performance of system components and their matchability with typical sensible and latent cooling load ratio in the tropics is also another interesting aspect which needs to be explored. Inquiring the impact of various space and system related parameters like occupancy level, ventilation rate and chilled water temperature could reveal the optimum operational scenario of the system and pave the way for establishing an automatic control of the system.

The majority of results of comfort studies in the tropics were in favor of acclimatization theory and the predictions of Fanger's PMV comfort model may not match the actual perception of locally acclimatized occupants in the tropics. It is necessary to evaluate the comfort and IAQ performance of this low exergy system in both context of the International comfort models and local standards in order to get a more realistic understanding of occupants' perception toward this design. The indoor air quality concerns associated with the all air system with UFAD distribution like cold feet, thermal stratification and rise of dust were understood in the literature (Leite and Tribess, 2006; Sekhar and Ching, 2002). However, the existence of these implications for DDOAS-RCP with lower volume of supply air from floor is unknown and required to be explored. The basis for the threshold of air pollutants concentration and comfort criteria are chosen based on the local and the International standards, guidelines, and models for local and whole space comfort and indoor air quality criteria. Ventilation effectiveness is also another important performance metrics which needs to be determined through experimental setup for a typical design of DDOAS-RCP under FS-CE distribution.

The potential and usability of CFD for indoor air science has been shown by numerous numerical studies in the literature. The aim of the present work was to develop a CFD model to capture the indoor air characteristics of DDOAS-RCP in the tropical context. A verified and validated simulation model can be used to explore spatial distribution of environmental parameters under various operational scenarios of system and space. It also can help to identify any comfort or air quality issues associated with configuration of supply diffusers and exhaust points in the conditioned space.

One of the energy and exergy saving opportunities in application of DDOAS-RCP in the tropics comes from the high temperature cooling idea behind this design. This saving compared to conventional system is more pronounced when the high temperature cooling system which is radiant cooling panel in this design is connected to a designated chiller for low temperature lift condition. A significant enhancement in efficiency of chiller for radiant cooling can outweigh the added maintenance cost of having two separate chillers in DDOAS-RCP design. This study tried to explore the potential benefits of incorporating a low temperature lift chiller in the tropical context.

The feasibility of the low exergy technologies depicted as DDOAS-RCP in the tropics has been investigated through experimental setup in the BubbleZERO. However, there are too many unanswered questions remained which need further investigations. The indoor air characteristics of the conditioned space with DDOAS-RCP and thermal response of human body to this system can be further explored. The thorough understanding of impacts of system and space related parameters on capacity of components and indoor air conditions can reveal the optimal control strategy in the actual building. The current thesis aimed to give further insights into implementation of this innovative decentralized design of DOAS coupled with radiant cooling and evaluate the performance of DDOAS-RCP design in terms of thermal comfort and indoor air quality and energy saving for the tropical context.

2.5 Research questions and hypothesis

The PhD research title is ”Performance evaluation of low exergy systems depicting decentralized dedicated outdoor air system coupled with radiant cooling in the tropics”. This thesis covers three fields of studies: low exergy technologies as DDOAS (decentralized DOAS) and radiant ceiling panel concept, performance, thermal comfort and IAQ evaluation of DDOAS-RCP, and Integration of DDOAS-RCP with low temperature lift chillers (Figure 13).

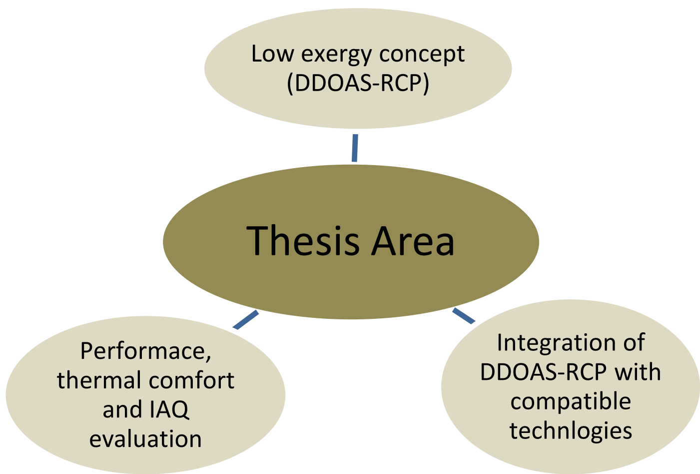


Figure 13 PhD thesis areas

This research aimed to evaluate performance, thermal comfort and indoor air quality aspects of conditioned spaces with the low exergy ventilation technologies in the tropics. The research questions of the thesis are as follows,

- What are the indoor air characteristics of a conditioned space with DDOAS-RCP in the tropics under various system and space related parameters?
- Are there any particular indoor air quality and comfort concerns for implementation of decentralized DOAS-radiant ceiling panel in tropical office buildings?
- Where does DDOAS-RCP with FS-CE distribution stand in terms of ventilation effectiveness indices?
- How much is the energy and exergy saving potential for DDOAS-RCP when it is connected to low lift chillers?

The hypothesis of the PhD thesis is as follows,

"Low exergy ventilation technologies depicted as decentralized dedicated outdoor air system coupled with radiant cooling can provide acceptable indoor air quality and thermal comfort in tropical buildings with less destruction of exergy"

In the next chapter, the followed methodology in experimental setup and numerical simulations are presented.

Chapter 3. Research methods

The methodologies adopted for the evaluation of different aspects of DDOAS-RCP performance in the tropics are elaborated. The low exergy technologies implemented in the BubbleZERO including decentralized air supply units and radiant cooling panel are introduced. In the subsequent sections, the measured environmental and system parameters are discussed as well as thermal comfort, air quality and ventilation effectiveness indices. Regarding the CFD simulation procedure, information is provided on geometry modelling and mesh generation. In addition, energy and exergy saving potentials of high temperature cooling applications are explained and explored.

3.1 Research design

In order to answer the research questions, the investigation has been divided into three areas of experimental studies, numerical indoor air simulation and analysis of integration with low lift chillers. The research workflow of the thesis is shown in Figure 14. At first, knowledge gaps and research questions were identified based on the literature review. After defining the scope and objectives of study, experiments were conducted in the test bed of the low exergy cooling and ventilation technologies (BubbleZERO) under various operational scenarios of the system. These experiments could reveal the optimal operating conditions of the system in terms of thermal comfort and indoor air quality. For thermal comfort evaluation of the system, local and whole space comfort models available in the literature were used to predict the mean vote of occupants in each scenario. In parallel to these experiments, CFD simulation model was utilized to get a better understanding of indoor air spatial distribution (e.g. thermal stratification) and flow pattern in the space. In addition, the integration of DDOAS-RCP with low lift chillers was investigated based on the collected data in the experimental setup and available studies in the literature. At the end, the outcomes of the investigations are discussed and recommendations are provided for future work.

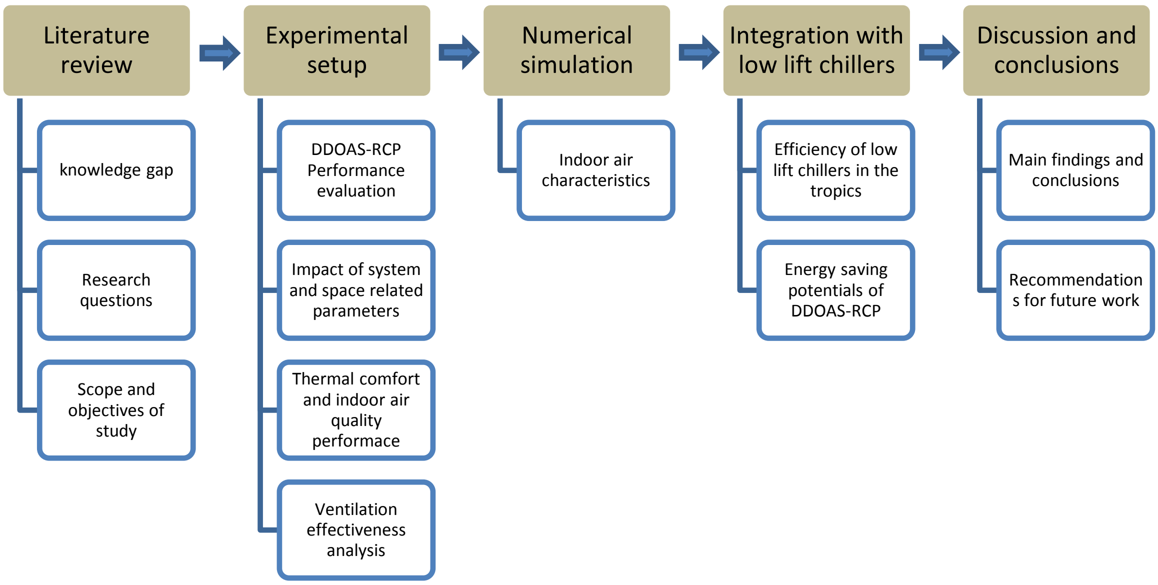


Figure 14 PhD thesis research workflow

Various metrics and indices have been employed to systematically evaluate the performance of this low exergy system in tropical buildings. This evaluation covers different aspects of DDOAS-RCP including thermal comfort, air quality, energy saving and practical implications. The employed indices and metrics as well as the corresponding approaches in this investigation are listed in Table 3. Detailed information is provided on each aspect of these performance evaluations in the subsequent sections. The BubbleZERO was assumed to be representative of a typical office space in which low exergy cooling system of DDOAS-RCP has been installed.

Table 3 Performance metrics and indices employed in this research

Performance aspect	Metrics and Indies	Approaches
Thermal comfort	Temperature, humidity, air speed, mean radiant temperature values and local / whole space comfort models and criteria	Experiments and simulation based on the International and local standards and guidelines
Air quality	CO_2, TVOCs, $PM_{2.5}$, PM_{10} concentrations and ventilation effectiveness indices	Experiments and simulation based on the International and local standards and guidelines
Design, operation and control scenarios	System and space related parameters e.g. air and water flow rates and temperatures	Experiments based on the acceptable indoor space condition
Energy/Exergy saving potentials	Annual energy saving and exergectic efficiency	Simulation and theoretical approaches based on reference case of all air cooling system

Experiments and simulations have been designed to investigate the performance of DDOAS-RCP in terms of air quality, thermal comfort, energy/exergy saving, design, operation and control scenarios. Environmental and system parameters have been measured in the BubbleZERO for different indoor/outdoor scenarios. The lists of investigated parameters on different aspects of DDOAS-RCP performance are provided in the subsequent sections. Tracer gas decay test has been conducted for ventilation effectiveness analysis of this low exergy system. In addition, CFD simulation tool has been employed to get a more elaborate understanding on variation of parameters in the BubbleZERO. Several sampling strategies have been chosen for this investigation. On one hand, some parameters have been measured continuously at different locations inside the space to provide spatial and temporal distribution of parameters over the course of experiments. On the other hand, some parameters have been measured only at one location in which spatial distribution was negligible. Spot measurements have also been conducted from location to location and time to time to check the spatial and temporal variations. The details of selected sampling strategy for each environmental and system parameter are provided in the subsequent sections of this chapter.

3.2 BubbleZERO as test bed of low exergy systems

The BubbleZERO was the main test bed of this PhD thesis in which various low exergy technologies have been installed. Its façade consisted of two shipping containers that are attached to each other on their longitudinal side, while the intersection surfaces of containers were removed. The BubbleZERO is located in the open space with an inflated skin on north, south, and roof of laboratory to provide a strong heat transfer barrier with the help of air film and insulations. An air compressor was designated below the container to maintain the necessary air pressure in the inflated skin. The infrared image of the BubbleZERO including air compressor and its connections to the inflated air skin is shown in Figure 15. East and west facades were mostly made of glasses, metal frames and doors which introduce enough cooling load and infiltration to the space to resemble a real office space. The visual illustrations of the technologies installed in this laboratory are shown in Figure 16. Decentralized air supply units embedded into the structure of BubbleZERO can bring in enough outdoor air through façade and dehumidify it to keep the dew point of space below radiant panel surface temperature and avoid condensation. As can be seen from the figure, conditioned air is distributed in the space through embedded air ducts in the floor which are connected to seven floor diffusers. The air ducts on one side of the laboratory are cast into concrete and on the other side they are within the raised floor. These two floor configurations have been implemented to investigate the performance of each design. The concrete side has the potential to act as a thermal mass and provide some level of heating to air supply ducts. On the other hand, the raised floor side has enough free space to accommodate other building services. The generated heat and pollutants leave the space via the four exhaust flaps installed in the middle of radiant panel. The CO_2-sensor controlled exhaust flaps and ducts as well as LED lighting are embedded in these multifunctional ceiling panels. The exhaust flap fully opens when the sensed CO_2 level exceeds an upper limit and it returns back to be partially open when the concentration goes down below a lower limit. The back of LED strips are adjacent to exhaust air stream and some part of generated heat by LED leave the space directly through exhaust air flow.

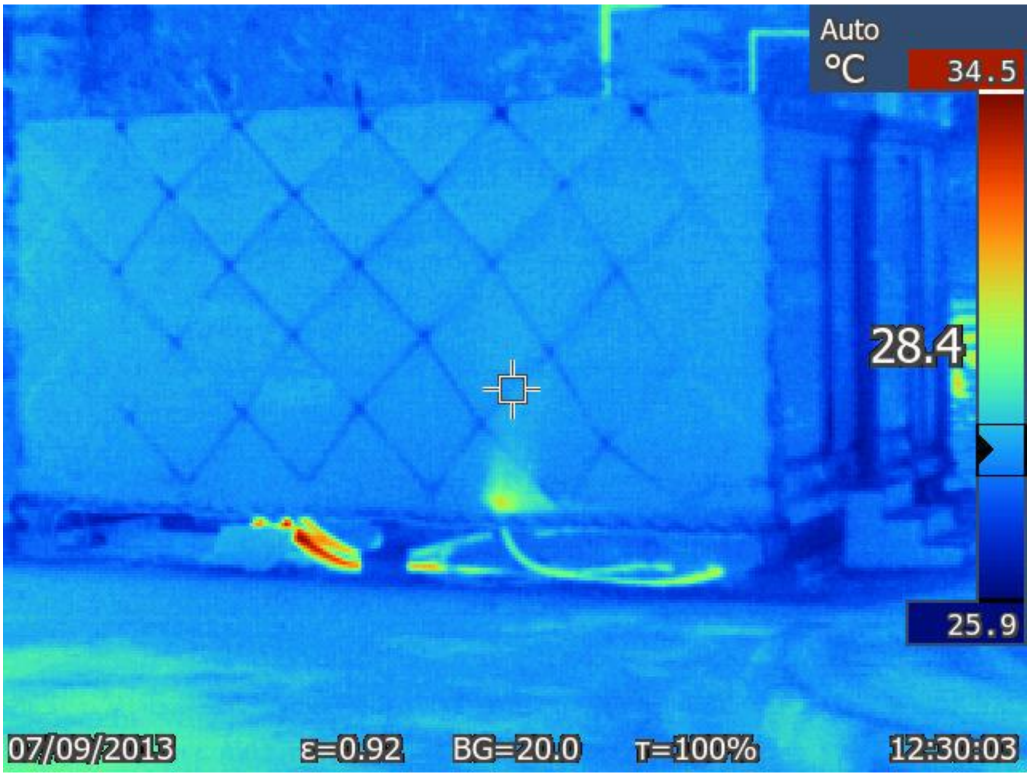


Figure 15 Infrared image of the BubbleZERO laboratory located in outdoor space (red points below the container are the air compressor and its connections to the inflated air skin façade)

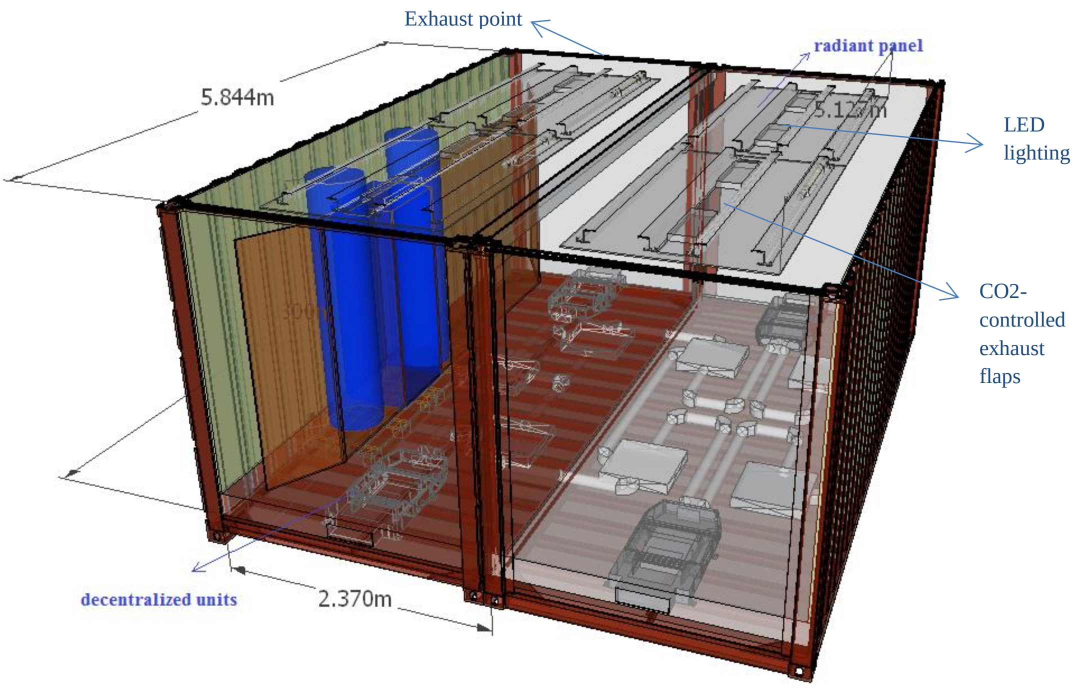


Figure 16 Decentralized air supply units and radiant ceiling panel in the BubbleZERO

DDOAS-RCP design installed in the BubbleZERO portrays the low exergy technologies by incorporating the concept of the high temperature cooling as radiant cooling system. Experimental studies were conducted in the BubbleZERO for different scenarios of the system operations to explore the impact of each parameter on indoor environmental conditions. The main space related parameters that affect the thermal comfort, IAQ and energy usage of decentralized DOAS are the outdoor air flow rate (ventilation rate), air supply condition, and radiant panel surface temperature. The modular control system of chillers, pumps and decentralized units in the BubbleZERO provides the opportunities to assess the impact of these parameters. Independent control of components has been designed to provide a suitable platform for conducting experiments on each system separately. The schematic overview of DDOAS-RCP installed in the BubbleZERO including the two chillers and tanks is shown in Figure 17. The temperature lift of chiller is defined as the difference between outdoor temperature and required chilled water temperature. In this investigation, the chiller which is connected to radiant panel (15-17 °C chilled water) labeled as low lift chiller and the one which is connected to decentralized units (8-12 °C chilled water) labelled as high lift chiller. With this arrangement, the designated low lift chiller for radiant cooling can operate at higher COP (coefficient of performance) and reduce the energy consumption as well as exergy destruction in the compressor of the chiller. Nevertheless, this energy and exergy saving is significant when a custom designed chiller for low temperature lift applications is used instead of typical chillers which are available in the market. The level of improvement in exergetic efficiency of refrigeration system for these types of low lift chillers compared to typical chillers has also been explored in this research.

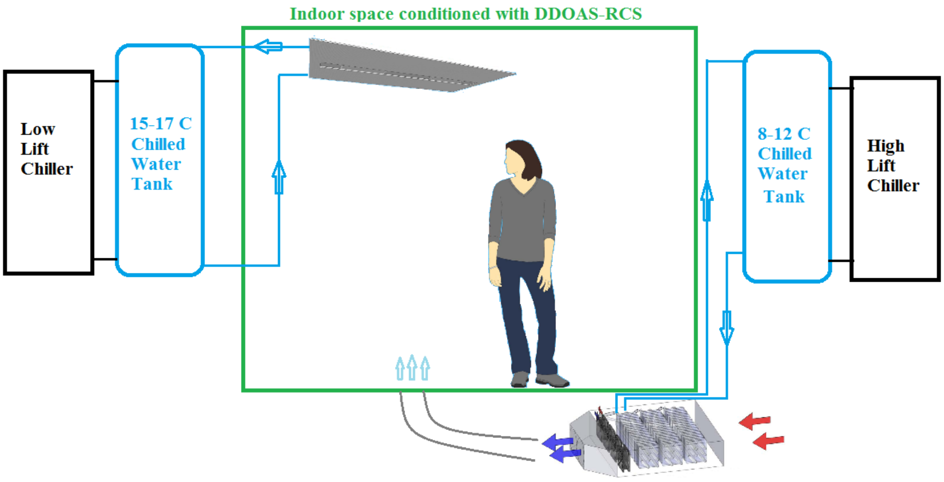


Figure 17 Schematic diagram of DDOAS-RCP installed in the BubbleZERO

Implemented control strategies in the BubbleZERO

Two main control strategies have been implemented in the BubbleZERO to evaluate the performance of the whole system and the individual components. A control software has been designed as the main platform to modulate different system related parameters. In the manual control mode, operational conditions of each system components have been controlled individually based on user input values. There is no interconnection between operation of decentralized air supply units and radiant panel in this mode. This control strategy is suitable for parametric analysis of system parameters. The main parts of research in this thesis have been conducted in this mode and the impacts of various system related parameters have been analysed. An automatic control mode also has been designed for daily operation of the laboratory. In this mode, operational conditions of system components have been modulated based on an algorithm to maintain a pre-determined indoor temperature and dew point. This automatic control has been used to explore the impact of space related parameters like outdoor temperature. The BubbleZERO is located in the outdoor space and its cooling load varies depending on weather conditions and time of the day. These variations have been utilized in this investigation to explore the response of system to different indoor/outdoor scenarios.

3.3 Environmental parameters and air pollutants measurements

Various types of fixed or portable sensors were installed and used during the experiments in the BubbleZERO to control and also to continuously monitor the condition of the laboratory. Environmental parameters like dry bulb temperature, relative humidity and mean radiant temperature were measured at different locations continuously over time while parameters like air velocity was measured as spot samples from time to time. These parameters have direct impact on thermal comfort perception of occupants inside the space. In addition, air pollutants like carbon dioxide, total volatile organic compounds (TVOCs) and respirable suspended particles (RSP) were measured inside the BubbleZERO. Carbon dioxide and TVOCs have been measured as the main human related pollutants which are existent commonly in occupied office spaces. The background concentrations of these pollutants in the laboratory were measured in unoccupied period to take into account the possibilities of emissions from non-human related sources like materials. Respirable suspended particles also have been measured to evaluate the possibility of resuspension of particles from floor supply diffusers into breathing level. Locations of sampling points and seated occupants during the experiments in the test bed are illustrated in Figure 18.

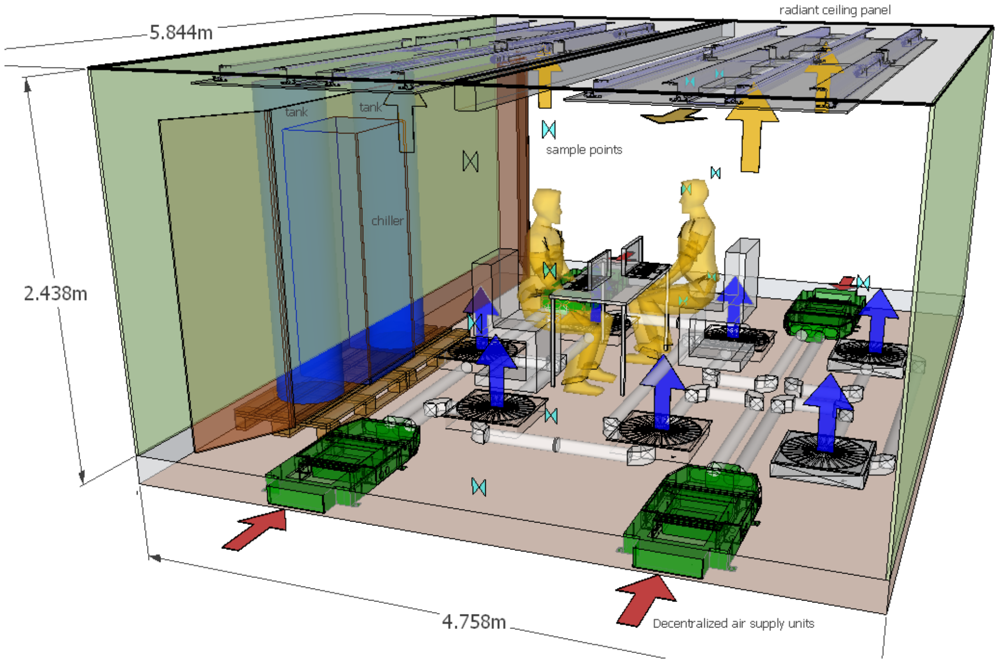


Figure 18 Illustration of sample points and seated occupants during experiments

Thirteen sensor points have been considered for indoor environmental measurements at four locations with three different heights and only one height at the fifth location. Three heights of 0.1 m, 1 m and 1.8 m have been chosen to cover three air zones corresponding to feet level, desk level and standing breathing point. A wireless sensor network and control system has been used to collect the real-time data and adjust system settings based on measured values and user controlled set points. Air velocity, mean radiant temperature and air pollutants concentration were measured with portable devices, although these values have not been fed into control system. Details of sampling design plan including sensor types, location and duration of measurements are provided in Table 4. The frequency of sampling varied for different parameters based on the level of change in that variable over time during each scenario of experiment. Dry bulb temperature and humidity level at each point were measured with Onset HOBO data loggers (U12) as well as Sensirion Pin-type digital sensors (SHT75). The placement of HOBO data loggers at different heights inside the BubbleZERO is illustrated in Figure 19. Testo Globe Thermometer and Globothermometer BabucA have been used to measure mean radiant temperature in the BubbleZERO. Kanomax Anemomaster Model A031 Series has been employed to measure air movement level in the space. In addition, IAQ-CALC™ Indoor Air Quality Meters Model 7545, DUSTTRAK™ DRX Aerosol Monitors Models 8533 and Portable Handheld VOC Monitor- ppbRAE 3000 have been used respectively for measurements of CO_2, RSP and TVOCs.

Table 4 Sampling design plan of experimental setup in the BubbleZERO for environmental parameters and air pollutants

Sensor type	**Parameters**	**Location**	**Duration**
Environmental sensors	dry bulb temperature, T	different locations and heights	continuous measurements
	humidity level, T_d	different locations and	continuous measurements

		heights	
	mean radiant temperature, $\overline{T_r}$	different locations	continuous measurements
	air velocity, V	different locations	spot measurements
Air pollutants sensors	Carbon dioxide, CO_2	different locations	continuous measurements
	Respirable suspended particles, RSP	different locations	spot measurements
	Total Volatile Organic Compounds, TVOCs	different locations	spot measurements

Figure 19 Onset HOBO data loggers U12 placed at three different heights of 0.1 m, 1 m, 1.8 m for measurement of temperature and humidity

3.4 DDOAS-RCP system and space control and monitoring

The operational conditions of any ventilation and air conditioning system are required to be modulated and controlled based on indoor/outdoor conditions as well as thermostat feedback from building users. The DDOAS-RCP design as an alternative solution to the conventional ACMV system in the tropics is required to be investigated to get an understanding of the impact of each operational scenario. Different sensors were installed on the system components of DDOAS-RCP to monitor and control operational scenario based on indoor/outdoor conditions. The schematic of sensor locations and types on decentralized air supply units and radiant ceiling panels is shown in Figure 20. Temperature sensors (S_t) were placed on supply and return water pipes and flow rate sensors (S_f) were designated on chilled water loops to determine the capacity of each component separately. The sensed data was collected with a distributed wireless network system and real time control decision was made to keep the indoor temperature in the comfort range. The cooling capacity of each component has been determined based on collected data on air and water sides of system. The air flow rate from each unit was measured by an air flow hood on the floor diffuser and it was controlled through modulation of fan speed installed in the unit. The interaction of air system and water system happens through cooling coming from floor and ceiling in opposite directions. In a free standing laboratory like the BubbleZERO, outdoor condition is not controlled and it varies from morning to afternoon. This variation has been utilized in this investigation to explore the response of system to different outdoor scenarios.

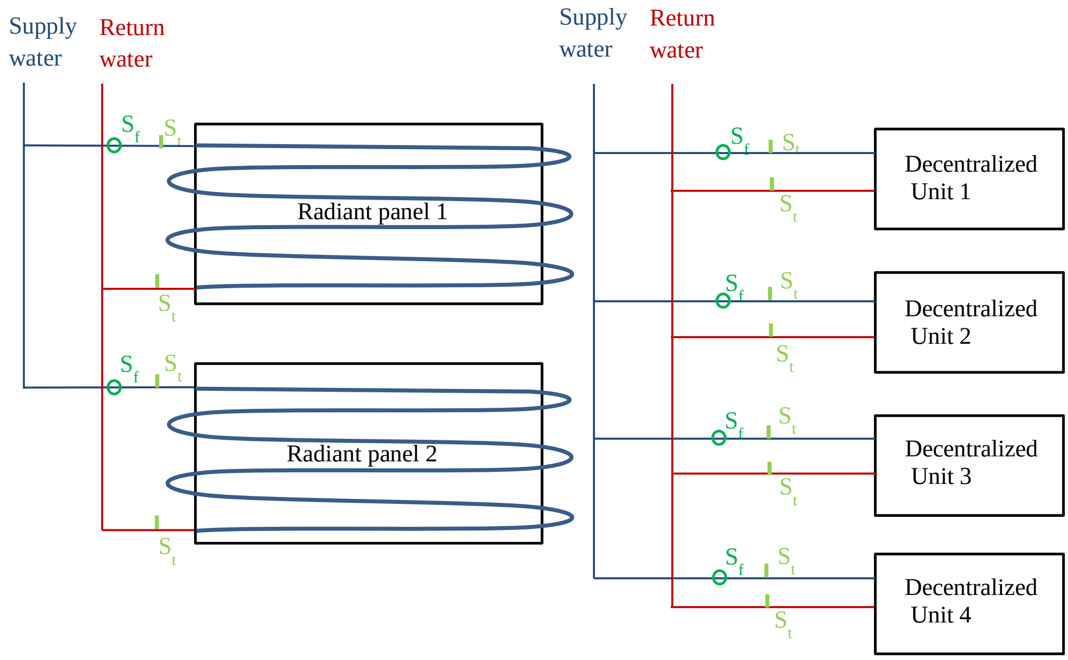


Figure 20 Schematic of sensor locations and types on DDOAS-RCP components

In the conventional all air system, the volume or temperature of supply air is modulated based on a user controlled thermostat inside the indoor space. For a sophisticated design like DDOAS-RCP, the interaction between user set point temperature and operation of system would be more complicated. Modulations could be required for both the air based system delivering conditioned air from the floor and the water based system providing cooling to the chilled ceiling to achieve specific indoor conditions. The main system related parameters in DDOAS-RCP design which have been investigated in this research are listed in Table 5. These operational parameters of system can affect thermal comfort and indoor air quality of conditioned space and their level of impact need to be specified. Onset HOBO data loggers T type thermocouples and Parker inline flow transmitter have been used to measure water temperature and flow rate at supply and return points of decentralized air supply units and radiant cooling panel. The ventilation rate or air exchange rate of space was calculated based on the results of tracer gas decay test with photoacoustic multi-gas monitor Innova 1312.

Table 5 Main system related parameters in DDOAS-RCP design

System Parameters	Variable (Unit)	Range
Decentralized ventilation unit capacity	Flow rate (L/s)	2.5-5 L/s
Decentralized ventilation unit water supply/return temperature	Water temperature (°C)	Supply/Return: 8-18 ˚C / 13-23 ˚C
Decentralized ventilation unit water flow rate	Water flow rate (mL/s)	10-30 mL/s
Radiant panel water supply/return temperature	Water temperature (°C)	Supply/Return: 16-19 ˚C / 18-21 ˚C
Radiant panel water flow rate	Water flow rate (mL/s)	15-40 mL/s

In addition to the system related parameters, there are some space related variables which their impacts on indoor air conditions are coupled with system control settings. The abovementioned system parameters have direct or indirect impacts on air supply condition near indoor diffusers and surface temperatures. Indoor space related parameters like surface temperatures and air supply condition are dependent to operational setting of system, outdoor condition, internal load and space heat gain. The main space related parameters which have been monitored in the conditioned space with DDOAS-RCP are listed in Table 6. The air supply condition including dry bulb and dew point temperature were measured with Sensirion Pin-type digital sensor (SHT75) placed inside the air stream. Fluke Dual Input Contact Digital Thermometer

(54-ii) and Fluke Building Diagnostic Thermal Imagers (TiR32, IR fusion technology) have been used to measure surface temperatures inside the BubbleZERO. Besides tracer gas decay test, a custom-designed air flow hood was manufactured to get an estimate of supply air flow rate from each floor diffuser (Figure 21). This custom-designed hood narrows down air stream from floor diffuser to a smaller cross section in which uniform air velocity profile could be measured with anemometer at one point.

Table 6 Main space related parameters in DDOAS-RCP design

Space related parameters	**Variable (Unit)**	**Range**
Air supply flow rate from each diffuser	Flow rate (L/s)	1-3 L/s
Air supply condition	Dry bulb and dew point temperature (°C)	Temperature/dew point: 12-22 ˚C / 10-20 ˚C
Radiant panel average surface temperature, T_s	Surface temperature (°C)	17-20 ˚C
Other surfaces temperature (floor, roof, walls, windows), T_s	Surface temperature (°C)	21-34 ˚C
Human load	Number of people (person)	1-2 person

Figure 21 A custom-designed air flow hood for measurement of air flow rate from diffusers

Data analysis has been conducted on the monitored and collected data in the BubbleZERO over a specific period of time. Layout, location of panels relative to loads of façade and occupancy as well as the locations of sensors are illustrated in Figure 18. The simple and multiple linear regression models have been used to analyse these environmental and system component related data. 17280 sample data points were collected during twelve days of measurements with sample time period of one minute. This range and frequency of data has been chosen in order to provide a comprehensive analysis of this low exergy system under different indoor/outdoor conditions and experimental scenarios. At first, the simple regression model based on the least square estimator was incorporated to find the correlation between dependent design parameters (e.g. indoor temperature and dew point) and independent DDOAS-RCP system parameters (e.g. water supply temperature and ventilation rate). Later, the multiple linear regression model was implemented to extend the correlation for several independent variables all at the same time. The coefficient of determination (R^2) of regression analyses has been calculated to determine the compatibility of regression line and sampled data. In addition, the “t” statistic test (Tan, 2011) has been employed to test the significance of the found correlations. In the t-test, at first a null hypothesis is constructed and then “t” value is calculated based on mean and variance of sample data. A tabulated “t” values available in statistics reference books (Tan, 2011) has been used to determine the correctness of hypothesis based on the degree of freedom of sample. If “t” value exceeds the tabulated value for a specific level of probability, it could be said that there is a significant correlation between the two investigated variables. In the next step, P-value has been calculated based on the “t” statistic test. P-value is defined as the probability of obtaining a result equal to the null hypothesis. A large P-value indicates that there is weak evidence to support the found correlation.

3.5 Thermal comfort and Indoor air quality criteria

The main goal of a building ventilation and air conditioning system is to provide comfortable and healthy indoor environment for occupants. Thermal comfort perception of occupants for the new designed concept of DDOAS-RCP is required to be explored in the tropical context. In this investigation, objective measurements and simulations have been undertaken to assess response of people to this type of conditioned space. The whole space and local comfort criteria based on the International/local standards and comfort models which have been used in this research are listed in Table 7. In this investigation, Fanger's PMV model has been chosen accompanied with other criteria from the International standards as well as the local standard of SS 554 (2009). PMV provides a comfort index in correlation with six parameters of metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. The local standard of SS 554 only provides recommended temperature (24 to 26 °C), relative humidity (< 65 %) and air movement (0.1-0.3 m/s) ranges which does not cover the conditioned space of DDOAS-RCP with lower air movement than that for the typical all air system in the tropics. For an indoor space with lower air movement (< 0.1 m/s), the PMV model can provide a comfort index considering the six abovementioned parameters altogether. Albeit, the comfort perception of locally acclimatized occupants in the tropics has been considered by taking into account the acceptable air velocity range as recommended by the local standard of SS 554. Relevant comfort criteria to application of radiant cooling system in buildings like floor temperature and radiant temperature asymmetry have been obtained from the International standard of ISO 7730. No relevant comfort criteria on radiant cooling applications have been provided in the local standard of SS 554.

Table 7 Whole space and local thermal comfort criteria relevant to operation of high temperature cooling system

Thermal comfort criteria	Standard	Acceptable range
Fanger's PMV model	ISO 7730	Category A: -0.2 < PMV < 0.2 PPD < 6 % Category B: -0.5 < PMV < 0.5 PPD < 10 %

Indoor air velocity	SS 554	0.1 - 0.3 m/s
Vertical air temperature difference	ISO 7730	Category A: $\Delta T <$ 2 °C Category B: $\Delta T <$ 3 °C
Floor temperature	ISO 7730	19-29 °C
Radiant temperature asymmetry	ISO 7730	Cool ceiling: < 14 °C

Besides comfort perception of occupants, it is necessary to make sure that air quality in DDOAS-RCP design can satisfy the requirements of a healthy indoor space. Any conditioned space is required to comply with indoor air quality criteria based on the local and the International standards. The list of considered indoor air pollutants and their maximum threshold values are listed in Table 8. Carbon dioxide and volatile organic compounds have been monitored as the main and secondary human related pollutants, respectively. The concentration of resiprable suspended particles ($PM_{2.5}$, PM_{10}) also was measured to evaluate the concerns regarding the rise of dust from floor due to distributing air from floor diffusers in this design. These parameters are also typically measured in indoor air quality audits in Singapore office buildings.

Table 8 Indoor air quality criteria relevant to operation of high temperature cooling system

Air pollutants	**Standard**	**Maximum threshold**
Carbon dioxide	SS 554	700 ppm above outdoor (around 1100 ppm)
Total volatile organic compounds (TVOCs)	SS 554	3000 ppb
Respirable suspended particles (PM_{10})	SS 554	50 µg/m^3

Respirable suspended particles ($PM_{2.5}$)	SS 554	35 µg/m^3

3.6 Ventilation effectiveness and contaminant distribution

DDOAS-RCP with floor supply- ceiling exhaust distribution system has its own specific ventilation and air flow characteristics. On one hand, it cannot be categorized as mixing ventilation since the amount of supplied air and point of distribution in space does not portray a perfect mixing condition. On the other hand, volume of supplied air in DDOAS-RCP is 0.2 to 0.4 fraction of conventional all air displacement system which could exhibit different characteristics from the typical displacement ventilation system. Several indicators have been considered in this research to get a better understanding of DDOAS-RCP conditioned air characteristics. Ventilation effectiveness is an indicator of how well a supply-exhaust distribution system performs compared to a perfect mixing condition. The ASHRAE standard 129 (2002) provided a guideline on how to measure age of air and ventilation effectiveness with tracer gas step-up or decay tests. In addition, REHVA guideline No. 2 (2004) introduced the procedure to determine ventilation effectiveness indices including air change efficiency and contaminant removal effectiveness based on tracer gas tests and pollutant dispersion. These indices are used at design stage of HVAC system to calculate the ventilation requirement of space. The ASHRAE standard 62 (2007) introduced the parameter of air distribution effectiveness to determine the minimum outdoor air flow requirement to maintain acceptable air quality.

The ventilation effectiveness can be measured with different methods through injection of a tracer gas in the space. A step down tracer gas method has been used in this study and SF_6 was selected as the tracer gas. The experiments have been conducted in the freestanding test bed (BubbleZERO) located in outdoor space whose exterior is subjected to the ambient air but the interior is conditioned. The setup for the experiments including system components and location of sample points are shown in Figure 22 and Figure 23. Decentralized air supply units (green components) located within the floor take outdoor air directly from the façade, condition it and distribute it through underfloor ducts and floor diffusers. Radiant cooling panels were installed at the ceiling and air exhaust flaps were located in the middle of panels where air leaves the space through exhaust ducts. During the test, two persons were seated in the centre of the room and working with their laptops. Tracer gas has been injected in the centre of the room and the concentrations of SF_6 as well as CO_2 have been monitored with a Photoacoustic multi-gas monitor Innova 1312. The gases concentrations were measured at 10 points in the space by means of the multipoint sampler Innova 1309. Two sample points were put at exhaust ducts (9&10), two sample points (1&2) in front of occupants at a height of 1 m, and six other sample points (3-8) at heights of 1.7 m at different locations throughout the space.

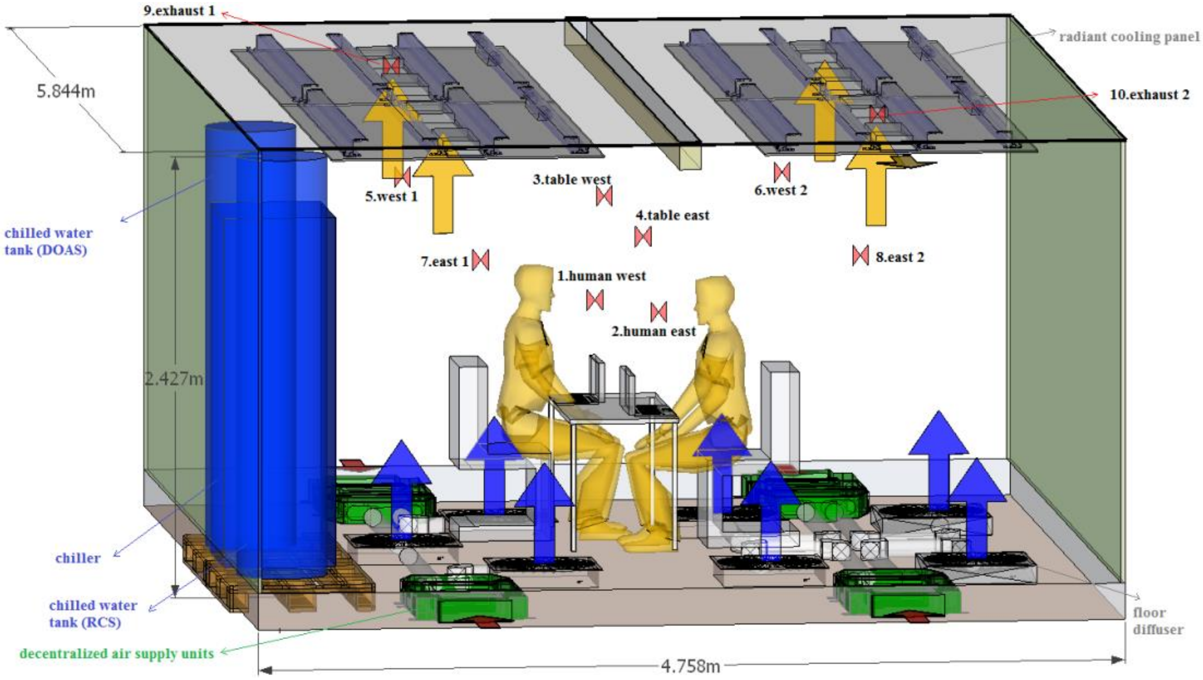


Figure 22 Setup of ventilation effectiveness experiments including sample points

Figure 23 Sample points placed in different locations inside the BubbleZERO for ventilation effectiveness analysis of DDOAS-RCP

The concentration of tracer gas was measured for three hours after injection. Due to the small size of the BubbleZERO, SF_6 dispersed uniformly in the space over a short period of time. The air change rate was determined through decay slope of logarithmic curve of concentration over time. The ventilation effectiveness indices ACE and LACI have been calculated based on the age of air concept. The age of air at a point is defined as the time elapsed for the incoming air to reach that point ($\bar{\tau}_p$). The younger is the age of air at a point indicates the better quality of air in that point. Having more outdoor air at breathing level would result in improved air quality perception of occupants. In this regard, nominal time constant (τ_n=Vol/q) is defined as local mean age of air at exhaust and can be calculated as the ratio between volume to ventilation flow rate of space. ACE is defined as the ratio of the lowest possible mean age of air (τ_n/2) and the room mean age of air $\langle\bar{\tau}\rangle$. An indoor space with ACE below 50 % is a short-circuit flow pattern, at 50 % is fully mixed, between 50 to 100 % is displacement flow and at 100 % it is a piston flow (REHVA Guidebooks No. 2, 2004). Contaminant removal effectiveness is defined as the ratio between steady state pollutant concentration in the space and exhaust air concentration. The CRE indicates how fast the generated pollutants are removed from the space. The CRE value is equal to 1 for fully mixed scenario and values above 1 indicates a more effective air distribution strategy. The indices of ACE, LACI (local air change index), and CRE were calculated using the Eq. 1-3 (REHVA Guidebooks No. 2, 2004),

$$ACE = \frac{\tau_n}{2\langle\bar{\tau}\rangle}.100 \ \ [\%] \qquad \text{(Eq. 1)}$$

$$LACI = \frac{\tau_n}{\bar{\tau}_p}.100 \ [\%] \qquad \text{(Eq. 2)}$$

$$CRE = \frac{c_e}{\langle c \rangle} \qquad \text{(Eq. 3)}$$

In the above equations, $\langle \bar{\tau} \rangle$ is the room mean age of air, c_e is the contaminant concentration in the exhaust air, and $\langle c \rangle$ is the steady state mean concentration of the space. The abovementioned parameters have been chosen as the indicators of ventilation effectiveness of DDOAS-RCP with FS-CE distribution. ACE and LACI can provide information on average age of air in the occupied zone compared to the fully mixed flow scenarios. CRE can also reveal the effectiveness of this design strategy in terms of extracting contaminated air compared to the fully mixed scenario. The temporal and spatial variations of CO_2 level in the space with DDOAS-RCP cooling system were assessed after changes in occupancy and ventilation rate of space. Carbon dioxide has been chosen for the contaminant distribution analysis as the main human related air pollutants.

3.7 CFD simulation of indoor air flow

CFD technique was used to simulate different operational scenarios of the low exergy technologies depicted as decentralized DOAS-RCP in the BubbleZERO test bed. The ventilation and thermal characteristics of the space were analysed by solving the Navier-Stokes and energy equations which account for air movement and heat transfer through convection and radiation.

In the simulated experiment, two persons were sitting in the middle of laboratory and they were working with their laptops. The BubbleZERO is located outdoors with mostly glass facades on east and west directions. The other directions including south, north and roof are well insulated with a layer of rigid insulation and an inflated “bubble” skin. The conditioned indoor space of laboratory was modelled in the afternoon when the main heat gain was coming from the west façade. During the experiments, temperature sensors were positioned at different locations (A-B-C-D) and heights (0.1-1-1.8 m) inside the space (Figure 24). Interior surface temperatures were measured to be used as boundary conditions for the CFD simulation. These boundary conditions represent the steady state heat gain through the façade. Supply air conditions and flow rates were also measured and provided as inlet boundary conditions for the simulations. The seated occupants were modelled based on reported dimensions of human body parts in the literature (Šmíd, 1977) for a male body of 1.75 m height. The surface area of seated occupants was divided into five segments including feet, calf-thigh, abdomen, hand-arm and chest-head. Temperature of each segment was specified based on reported experimental studies (Yao et al., 2007) of skin temperature at thermal comfort condition.

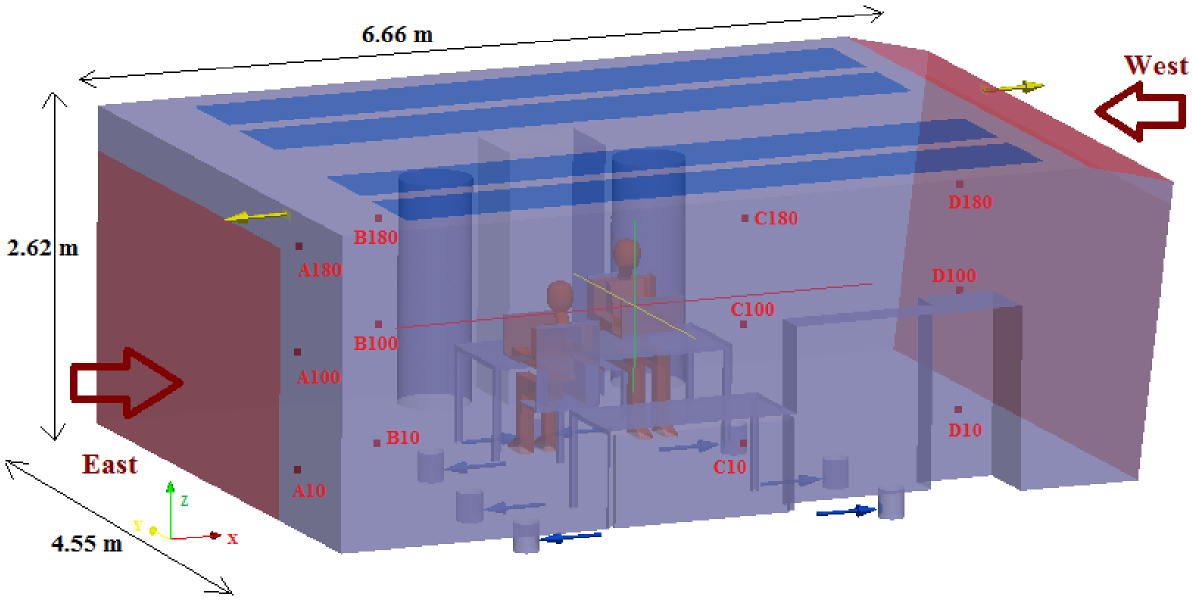


Figure 24 Sample points at different locations and heights inside the BubbleZERO

The created geometry of laboratory was discretized into tetrahedral cell volumes on which Navier-Stokes and energy equations were solved. In order to achieve mesh independent CFD results, tetrahedron cells with two mesh densities of 355 K (coarse) and 1467 K (fine) were generated (Figures 25 and 26). For the fine unstructured cell volumes, density of mesh was refined near human body and wall boundary conditions in order to get a more elaborate understanding of flow pattern near those areas. While a further refined mesh can provide more information on distribution of variables in the space, it requires higher computation cost and could lead to more convergence problems.

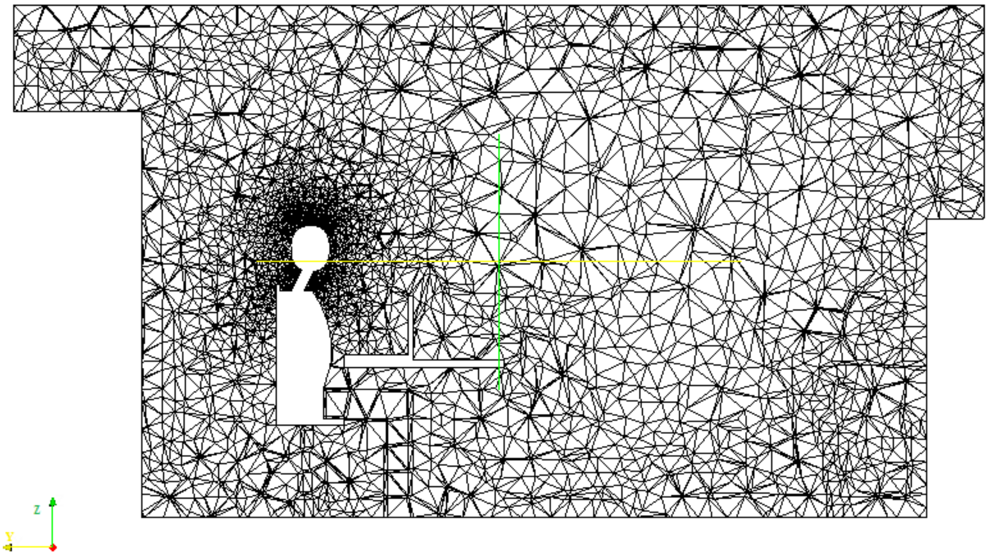


Figure 25 Coarse tetrahedral cell volumes (355 K)

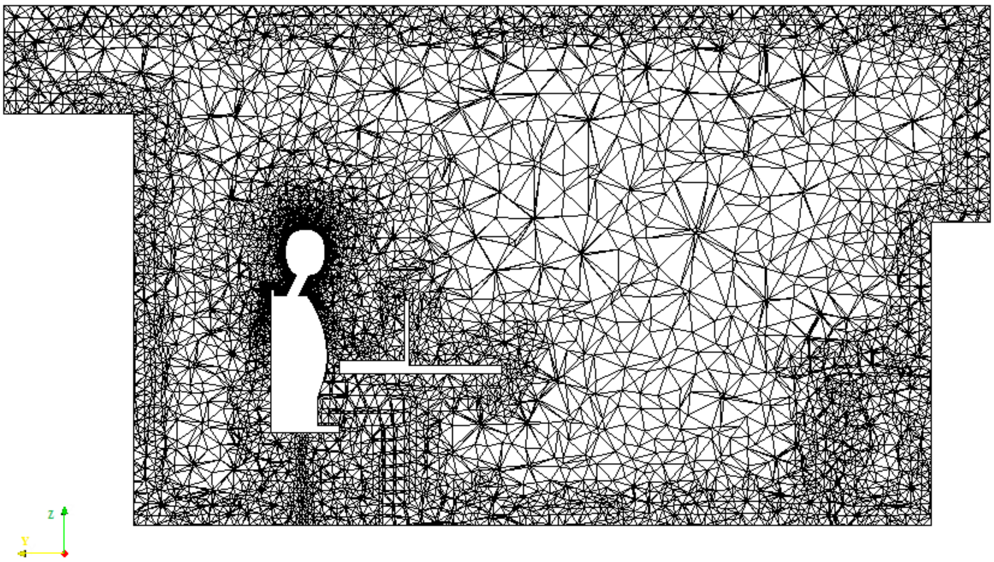


Figure 26 Fine tetrahedral cell volumes (1467 K)

In this investigation, the open source CFD toolbox of OpenFOAM (open source field operation and manipulation) 2.3 has been used to solve Navier-Stokes and energy equations over the domain of interior space. OpenFOAM is a C++ simulation platform for easy development of customized numerical solver and pre-/post- processing utilities in which physical entities are described by tensors (OpenFOAM Foundation, 2014a). The standard solver of *bouyantBoussinesqSimpleFoam* from OpenFOAM library has been used to analyse heat transfer and buoyancy-driven flow of indoor air space. This solver is a steady-state solver for buoyant, turbulent flow of incompressible fluids which was modified in this study to include radiation in order to capture radiant cooling panel impacts. P-1 approximation which is a simple form of the general P-N method was implemented to numerically solve radiant heat transfer terms. The P-N approach employs a finite set of moment equations to approximate transfer relations of radiant transfer in participating media through expansion of intensity in an orthogonal series of spherical harmonics (Siegel and Howell, 1992). Since in the current indoor air simulations, temperature variation over the space is not significant, the Boussinesq approximation has been used for prediction of buoyancy driven flows in the space. In this approximation, variation of air density is neglected in all Navier-Stokes and energy equations terms except in the buoyancy term. The Boussinesq approximation in the implemented solver of OpenFOAM can be expressed by the following equation,

$$\rho = \rho_{ref}\left[1 - \beta\left(T - T_{ref}\right)\right] \qquad \text{(Eq. 4)}$$

where β is the coefficient of expansion (K^{-1}), ρ_{ref} and T_{ref} are reference density and temperature which are specified as input into the model. Turbulence model is another important setting for CFD simulation of indoor air flows. Several studies (Chen, 1995; Zhang et al., 2007) tried to find the most suitable turbulence model for indoor space CFD simulation in terms of accuracy and computational cost. The mainstream results showed that RNG k-ε and k-ω based SST have superior performance compared to other two-equation based turbulence models. In the preliminary investigation of the BubbleZERO, it was concluded that the standard k-ε and k-ω based SST models result in slightly different temperature profiles in the space while k-ω based SST and Reynolds stress models have close predictions. Three turbulence models of standard k-ε, renormalization group (RNG) k-ε and k-ω based SST were employed in the final investigation in order to achieve more reliable results. The standard k-ε model is the most prominent turbulence model in the industry because of its robustness and stability which used as a reference turbulence model for this investigation. In the renormalization group k-ε model, RNG techniques are used to modify transport equations in order to handle small-scale and large-scale velocity fluctuations with different schemes (Chen, 1995). The k-ω based shear stress transport (SST) model is designed to give highly accurate predictions of flow patterns in adverse pressure gradient condition which could occur in low Reynolds flows near walls (Menter, 1994). The governing heat/mass transfer and momentum equations for the simulated indoor air are as follows (OpenFOAM Foundation, 2014b),

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \qquad \text{(Eq. 5)}$$

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho UU) - \nabla.\mu\nabla U = -\nabla P + S_{buoyancy} \qquad \text{(Eq. 6)}$$

$$\frac{\partial \rho e}{\partial t} + \nabla.(\rho Ue) - \nabla.(\lambda\nabla T) = P\nabla.U \qquad \text{(Eq. 7)}$$

In the above equations, $S_{buoyancy}$ is defined as $(\rho-\rho_{ref})g$ which can be calculated from Eq. 4. Viscosity (μ) in two equations turbulence models is defined based on turbulent kinetic energy (k) and turbulent dissipation (ε) or specific rate of dissipation (ω) which are derived from transport equations. Uniform set of temperature and velocity values have been set as initial conditions in these simulations. In addition, the CFD algorithm of SIMPLE with residual control of 10^{-6} has been employed to achieve iterative independent results. Several probes on different locations in the simulation domain have been designated to track the changes in mass flow rate or temperature and velocity over the iterations. The simulations deemed to be converged when residual criteria have been satisfied and no considerable changes were observed in the probes' values.

3.8 Integration with low temperature lift chillers

The benefits of the high temperature cooling can be understood from the theoretical thermodynamic cycle of Carnot. This cycle is the most efficient possible set of processes to convert a certain amount of energy of a heat source into usable works. The Carnot cycle (engine) and the reversed Carnot cycle (refrigerator) between a hot reservoir (T_H) and a cold reservoir (T_C) on a temperature-entropy diagram is shown in Figure 27. Q_H and Q_C are the amount of heat transferred from/to hot sources and cold sources, respectively. W is the amount of given or taken work. Based on the First Law of thermodynamics, the amount of work for reversible processes is equal to difference between Q_H and Q_C. The COP of the cycle in heating and cooling modes can be determined as follows in Eq.8-9,

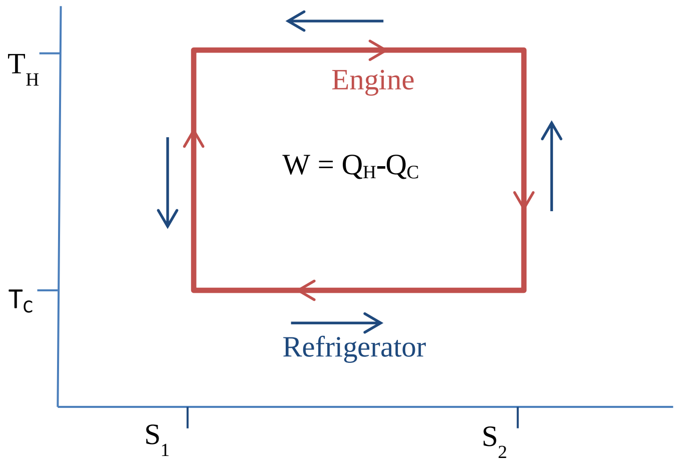


Figure 27 Ideal Carnot and reverse Carnot cycles in Temperature-Entropy diagram

$$COP_{Heating} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C} \qquad \text{(Eq. 8)}$$

$$COP_{Cooling} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C} \qquad \text{(Eq. 9)}$$

It is clear from the above equations that the COP of system drops with rise of temperature difference between hot and cold sources. This fact justifies the energy saving potential of the high temperature cooling system compared to low temperature conventional system. Implementing a low temperature lift chiller is a necessity for an effective implementation of high temperature cooling. A case design of low temperature lift chiller has been analysed in order to provide a quantitative estimation of the amount of energy saving for implementation of DDOAS-RCP in the tropics. This low temperature lift chiller has been designed and tested through a collaborative research project in the Switzerland (Wyssen et al., 2010). The COP and exergetic efficiency of this low lift chiller have been compared with conventional air/water cooled chillers which are commonly used in the tropics. The improvement in COP of chiller for high temperature cooling has been used for estimation of energy/exergy saving of DDOAS-RCP in the tropics.

3.9 Energy/Exergy saving potentials

The energy/exergy saving potentials from implementation of a low exergy system in buildings are multifaceted. Radiant cooling system in DDOAS-RCP can operate with warmer chilled water temperature which could be provided at higher chiller efficiency. In addition, using more water for heat transfer medium in building bring the opportunity to reduce fan energy use in ACMV system of building. Energy simulation analysis was conducted for a typical one-storey building for the tropical climate of Singapore in order to get an estimate on energy saving potential of an air-water system like DDOAS-RCP in this climate. The layout and three dimensional schematic of this hypothetical building are shown in Figures 28 and 29. The geometry of this building was modelled in the SketchUp 3D (SketchUp make Version 15.3) modelling software through use of the OpenStudio plugin tool. OpenStudio (Version 1.8) is an open source collection of software which is used as a platform to conduct building energy modelling using EnergyPlus (Version 8.1) building energy simulation program. Standard types of materials and constructions for roofs, floors, walls and windows as well as Singapore IWEC (International Weather for Energy Calculation) file have been used in this simulation.

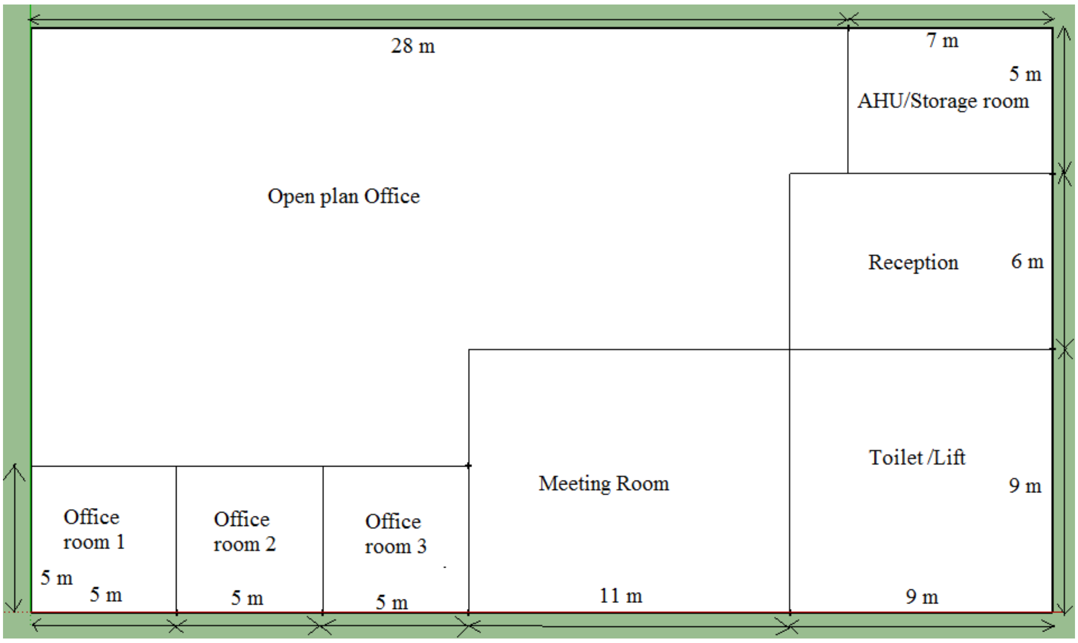


Figure 28 Floor layout of the simulated hypothetical office building in Singapore

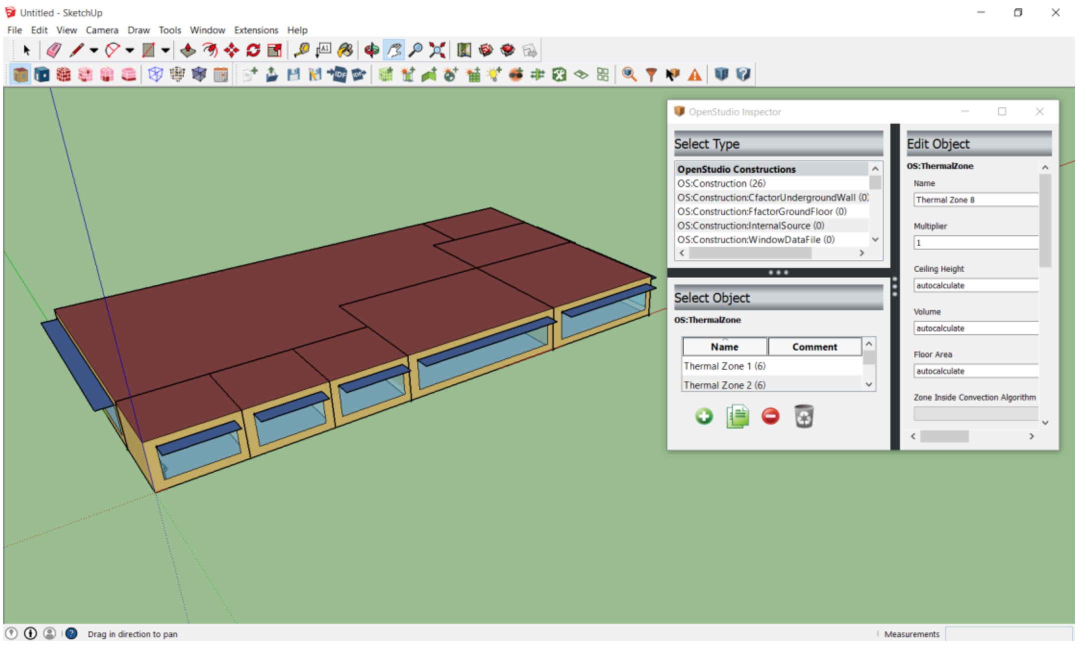


Figure 29 Three-dimensional geometry of the hypothetical one-storey office building

The energy simulation has been conducted for a conventional all air based system in which air distributed to different conditioned zones from air handling units located in each floor of the building. A typical all air ACMV layout of building including supply and return ducts is plotted in Figure 30. Supply and return fans are installed inside the AHU room to supply and return air to or from zones. It is assumed that the Toilet and AHU/Storage room areas are naturally ventilated or in other words are not conditioned with the central ACMV system. The annual energy consumption of this one-storey building with all air system has been determined for the tropical climate of Singapore through use of EnergyPlus building energy simulation program (Version 8.1).

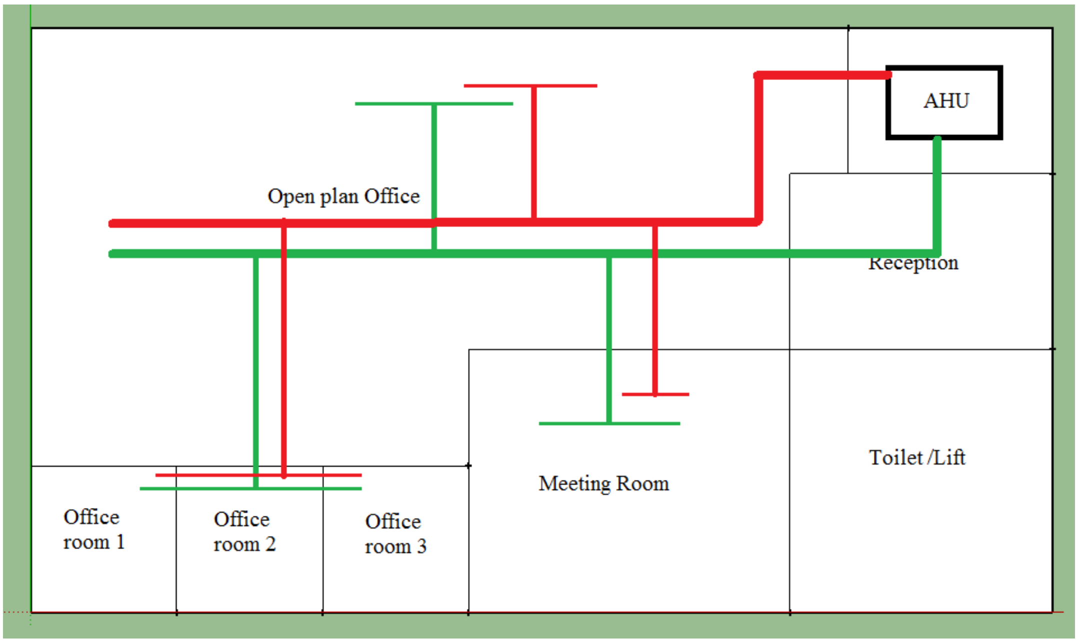


Figure 30 A typical layout of an all air ACMV system (Green lines are supply ducts, red lines are return ducts)

In the low exergy cooling strategy of DDOAS-RCP, instead of one AHU per floor, numerous decentralized air supply units are installed near the facade to take the outdoor outside air at the shortest distance. These units bring in cool and dehumidified air to satisfy the latent load and the ventilation requirement of the space while implemented radiant ceiling panels satisfy the remaining sensible load. A suggested ACMV layout for actual implementation of DDOAS-RCP in the simulated hypothetical building is shown in Figure 31. The annual energy consumption of this suggested system is estimated and compared to the all air system for several design scenarios. These design scenarios include cases where a separated low lift chilled is used for HTC system and/or where a more effective radiant ceiling panel design is implemented compared to the original design.

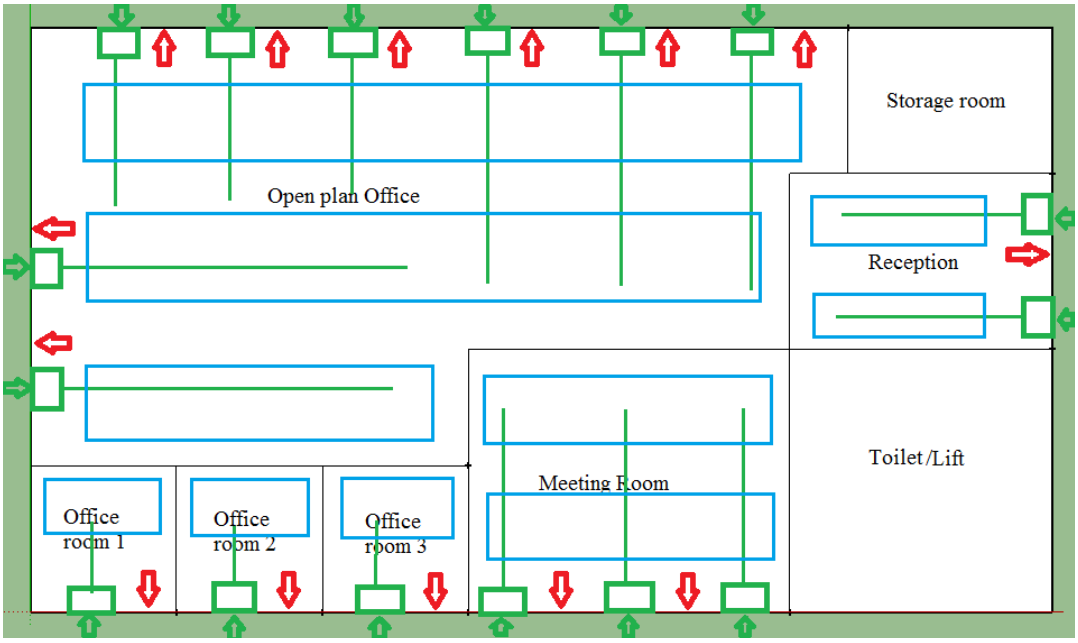


Figure 31 A suggested ACMV layout for implementation of DDOAS-RCP in the building (green boxes are decentralized units, blue boxes are radiant panels, green lines are supply ducts, green arrows are outdoor air points and red arrows are exhaust points)

Chapter 4. Results

At first, the results of experimental setup and statistical analysis on decentralized air supply units and radiant ceiling panel are presented individually. Later, the outcomes of data analysis on coupled DDOAS-RCP design are provided in terms of thermal comfort, indoor air quality and ventilation effectiveness. The conducted uncertainty analyses based on measurement accuracies and propagated errors are elaborated in the subsequent section. The results of CFD simulation in the testbed of BubbleZERO are explained regarding the air flow pattern, temperature distribution and radiant flux on surfaces. In the last two sections of this chapter, the potential integration of DDOAS-RCP with low lift chiller is elaborated. The research outcomes of “experimental setup”, “numerical simulation” and “integration with low lift chiller” stages from the PhD thesis research workflow (Figure 14) are presented in this chapter.

4.1 Decentralized air supply units

The Decentralized air supply units in DDOAS-RCP system play the most important role for humidity control, ventilation, and consequently on indoor air quality and energy consumption of the whole system. From the energy efficiency point of view, the amount of outdoor air should be minimized and kept close to the minimum ventilation requirement of the space. To achieve this scenario in the tropics, having an air tight façade is a necessity to minimize the amount of latent load in the space. Three sets of heat exchangers have been incorporated into the decentralized air supply units. The arrangements of these cooling coils in terms of supply and return water position affect the dehumidification capacity and off coil air condition. The two selected arrangements of coils for the current design of units in the BubbleZERO are shown in Figure 32. Arrangement B follows the main stream coil design strategy rule where chilled water is supplied to coil close to the off coil side for the best efficiency. The locations of supply and return chilled water pipes to coil have been modified in Arrangement A to evaluate the possibilities of having some level of reheat within the decentralized air supply unit.

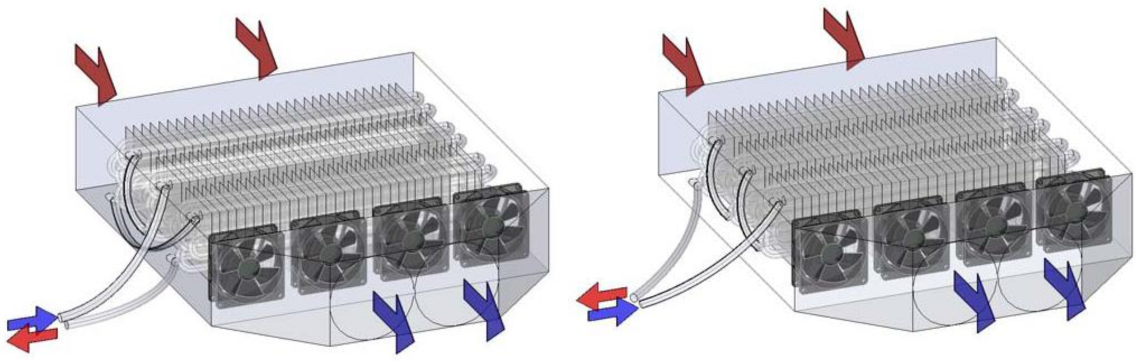


Figure 32 Two arrangements (left-arrangement A, right-arrangement B) of three heat exchangers inside the units

Two decentralized supply units for each arrangement of the heat exchangers were installed on each side of laboratory. In arrangement A, the first two cooling coils provide cooling and dehumidification while the third one is utilized to provide sensible reheat. The chilled water flowing through the first two coils gets warm and it provides some level of heating for the air at the third coil. For these units, the off coil air reaches the diffusers through air ducts located in a floor plenum. However, in arrangement B, all three heat exchangers provide cooling and dehumidification and the off coil stream of these units is attached to air ducts embedded into the concrete floor slab, which provides some level of reheating before the air is supplied to the space through FD. The units' off coil air temperature and dew point for these two types of arrangements are compared to each other in Figure 33. It can be seen that units with arrangement B can provide cooler and dryer air compared to arrangement A. However, supplying air at that temperature range could result in cold feet issue and it requires some level of reheating before being supplied into the space. During this experiment, decentralized air supply units were operating in manual mode with similar and fixed chilled water temperature and flow rates on both water and air sides.

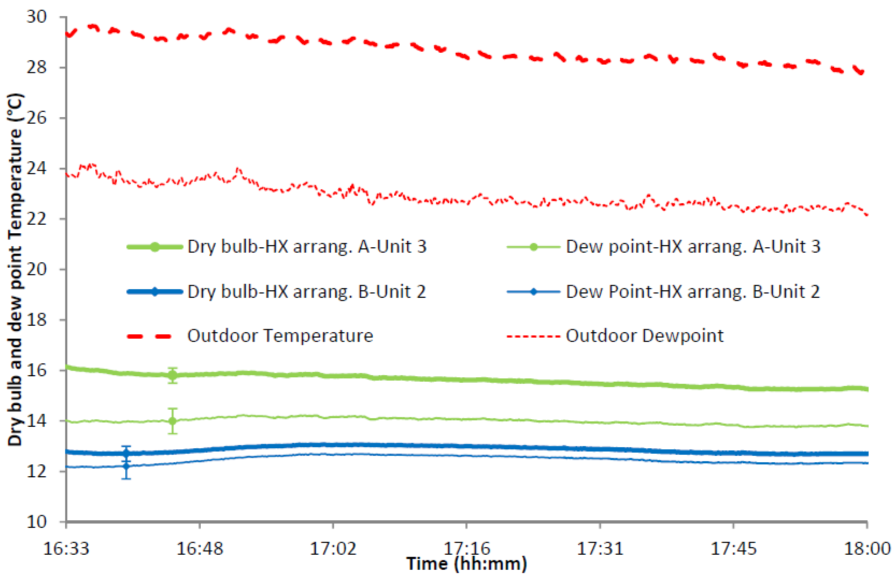


Figure 33 Off coil air condition of decentralized air supply units with different heat exchanger (HX) arrangements

The capacity of these decentralized units in the course of a day with fluctuating outdoor temperature and supply chilled water is shown in Figure 34. There was an increase in supply water temperature in the morning due to the chiller on/off control setting which caused a slow decrease of unit capacity. In the afternoon, cooling capacity of units increased considerably because of higher outdoor temperature. The capacity of unit was around 800 W in the morning which rose to around 1000 W in the afternoon. This profile of unit capacity was commonly observed during twelve days of consecutive experiments except for fully rainy days when the curve line of capacity was almost flat. It is noted that in this graph, water flow rate was 28 mL/s and air flow rate passing through unit was 2.75 L/s.

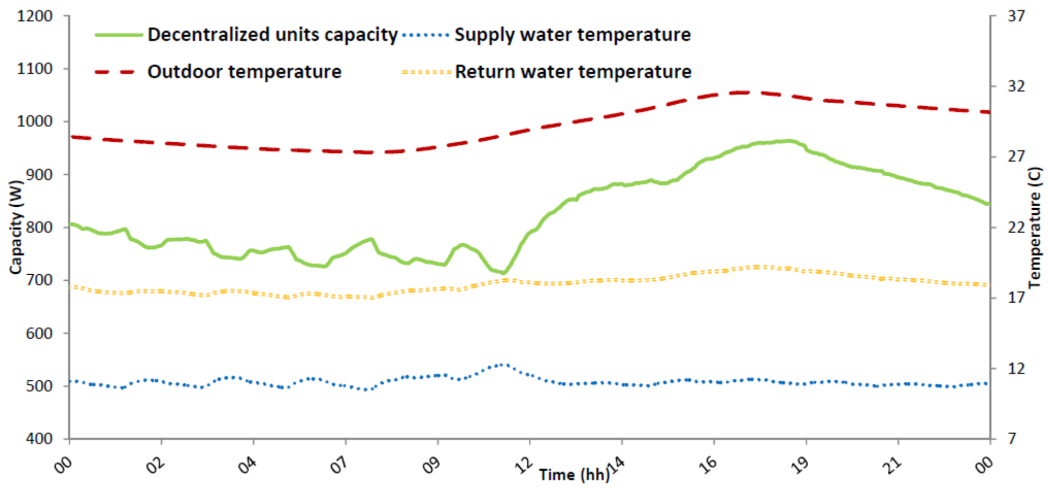


Figure 34 Daily profile of decentralized units' capacity caused by fluctuation of outdoor air condition and supply water temperature

The main parameters which have impacts on capacity of decentralized air supply units and off coil air condition of units include outdoor temperature, water supply temperature, water supply flow rate and air flow rate passing through unit. The simple and multiple linear regression models were used to analyse the collected data and find an estimated correlation between dependent decentralized unit variables (e.g. unit capacity and off coil temperature) and independent input parameters (e.g. chilled water temperature and flow rate, air flow rate). The pool of sampled decentralized unit capacity and supply chilled water temperature are plotted in Figure 35. For supply water temperature in the range of 8 to 18 °C, the unit capacity varies between 400 to 1400 W. The simple linear regression analysis shows the strong correlation between these two parameters. It was also observed that the difference between supply and return water temperatures ranges between 5 to 8 °C and the value is higher for lower supply water temperatures. In Figure 36, the pool sample data of decentralized unit off coil temperature and water supply temperature are plotted. There is a strong correlation between these two variables and slope of linear regression line is close to 1. It can be seen that off coil air temperature is approximately 2 °C (shown as dashed line in Figure 36) higher than supply water temperature over the range of measured data. Nevertheless, for the range of water flow rate (10-30 mL/s) and air flow rate (2.5-4 L/s) passing through unit, this temperature difference could vary from 1 to 3 °C. The condition of air at off coil point of decentralized unit was usually at saturation point and there was a little difference between dry bulb and dew point temperatures. The coefficient of determination (R^2) are in the acceptable range for both of the above regression analyses which show there are good fits between sampled data and regression line.

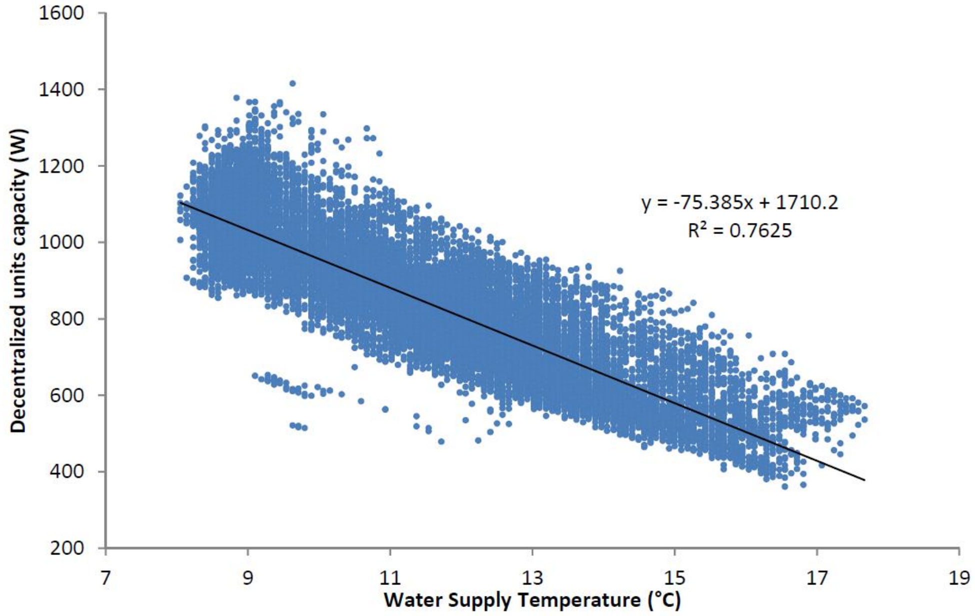


Figure 35 Pool of sampled decentralized unit capacity and supplied water temperature

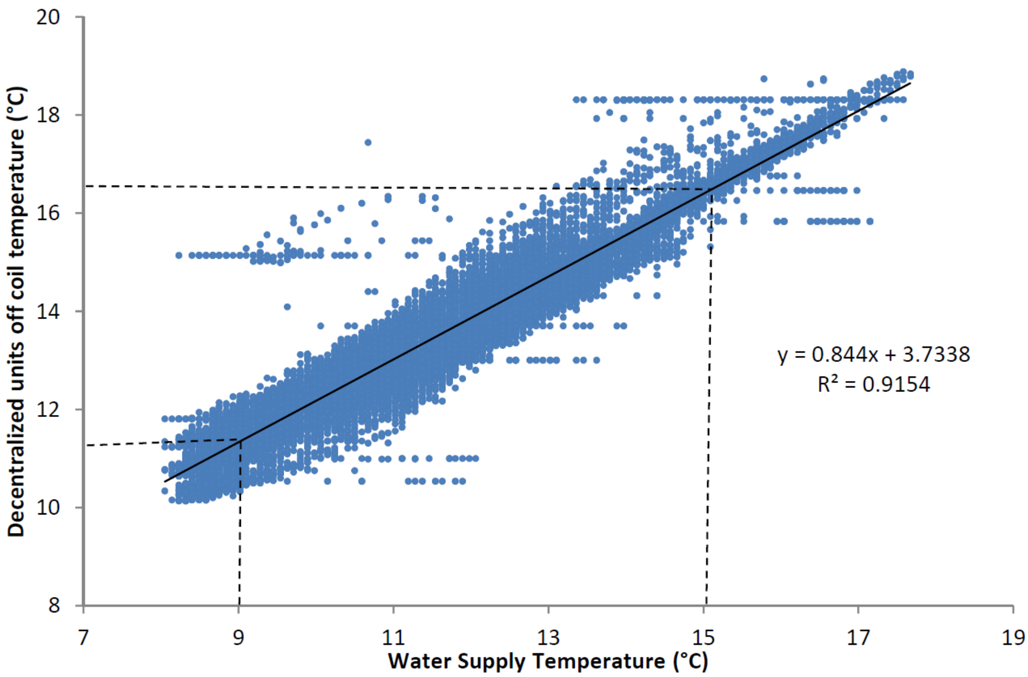


Figure 36 Pool of sampled decentralized unit off coil temperature and supplied water temperature

In addition to supply chilled water temperature, other design input parameters like air flow rate and outdoor temperature also play some roles on capacity and off coil condition of decentralized units. The pools of sampled data regarding the air flow rate passing through decentralized units on capacity of units and off coil temperature are shown in Figures 37 and 38. 17280 sample points were analysed using the simple linear regression model. The air flow rates in the collected sample data did not continuously cover the whole range and they were clustered in three groups for different fan speed levels. The unit's fan speed and the corresponding air flow rate are plotted in Figure 39. The unit's capacity ranges from 500 to 1200 W and off coil temperature ranges from 10 to 18 °C while air flow rate is between 2.5 to 5 L/s. Higher air flow rate passing through heat exchangers inside the unit results in rise of convective heat transfer around tubes which enhances heat transfer mechanism between air and water and consequently cooling capacity of unit. With higher air speed in units, each control volume of air has less residence time to interact with heat exchangers. The pool of sampled decentralized unit capacity and outdoor temperature are plotted in Figure 40. From morning to afternoon, outdoor temperature ranges from 27 to 33 °C, while the capacity of unit fluctuates from 500 to 1200 W. The higher outdoor temperature increases the temperature difference between on coil hot air entering the unit and supply water which consequently enhances the cooling capacity of units. The coefficients of determination (R^2) in all three abovementioned regression analyses (Figures 37, 38 and 40) are not near a good fit range which shows the multiple regression analysis is required to get an understanding on the impacts of these variables on dependent parameters.

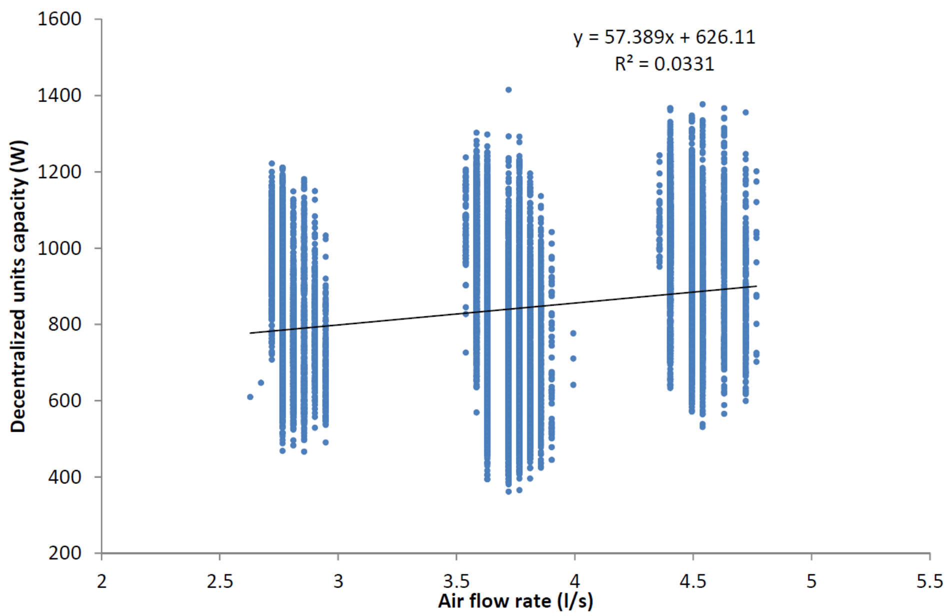


Figure 37 Pool of sampled decentralized air supply unit capacity and air flow rate

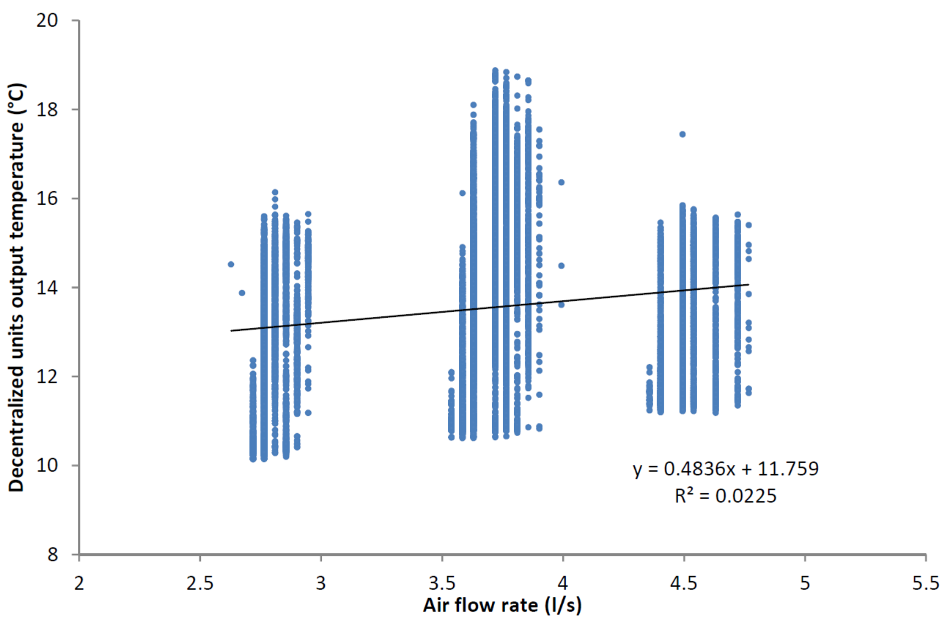


Figure 38 Pool of sampled decentralized air supply unit off coil temperature and air flow rate

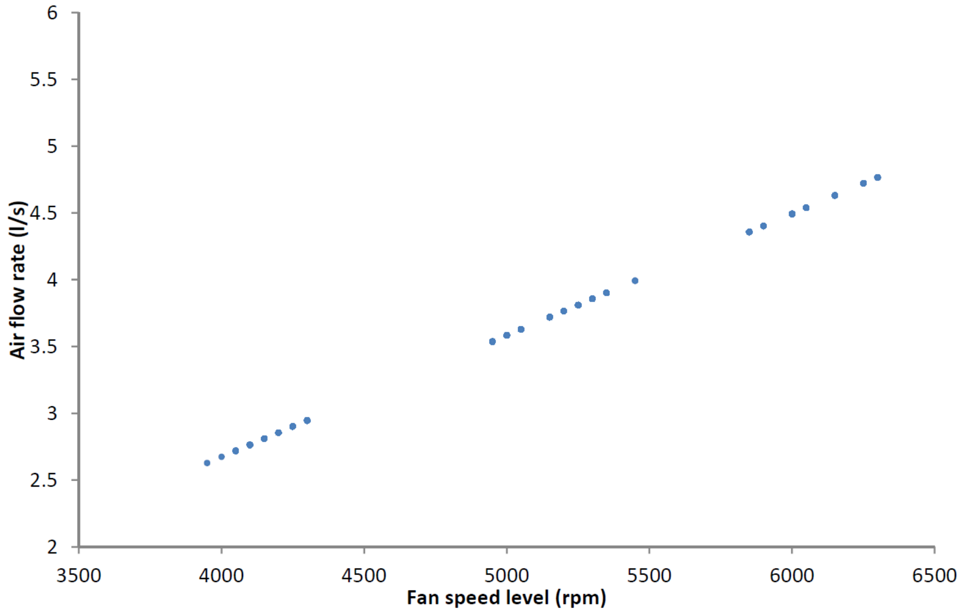


Figure 39 Air flow rate of unit in terms of fan speed level

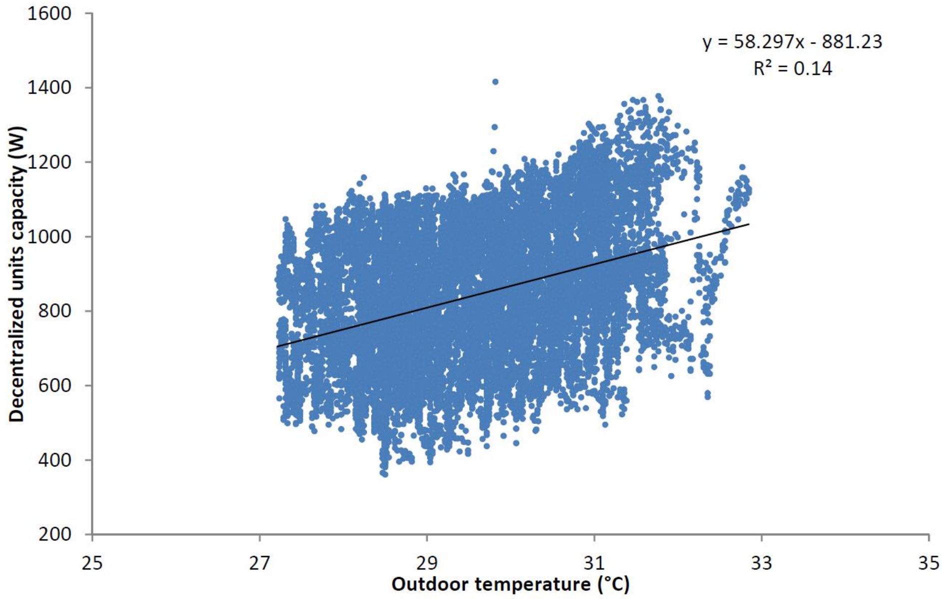


Figure 40 Pool of sampled decentralized air supply unit capacity and outdoor temperature

The simple linear regression models only analyse the change in dependent parameters based on variation of one independent parameter at a time. A multiple linear regression analysis was conducted to get an overall understanding of the impacts of all input parameters on capacity and off coil air condition of decentralized air supply units. This analysis can identify and compare the significance of independent parameters in affecting the dependent variables. Four independent variables of outdoor temperature (°C), water supply temperature (°C), water flow rate (mL/s) and air flow rate (L/s) have been considered in this analysis. The outcomes of the statistical analysis for dependent variables of unit capacity (W) and off coil temperature (°C) are listed in Tables 9 and 10. The coefficient of determination (R^2) for unit capacity and off coil temperature was found to be around 0.92 and 0.94, respectively. These coefficients of determination indicate good fit between regression lines and actual sample data where R^2 is 1 in the ideal perfect fit regression. The calculated P-values based on the "t" statistics test are also near zero which indicates that the found correlations are significant. The sign of coefficients can be justified with the physical concept behind the heat transfer phenomena inside the units. The capacity of unit rises with increase of outdoor temperature, water flow rate and air flow rate and it decreases with rise of water supply temperature. It can be observed in Table 10 that unit off coil temperature ascends with increase of water supply temperature and air flow rate and it decreases with rise of water flow rate. A positive correlation also was found between unit off coil temperature and outdoor temperature.

Table 9 Multiple linear regression analysis for dependent variable of decentralized air supply unit capacity

Y Variable – Decentralized unit capacity (W)	*Coefficients*	*Standard*	*P-value*

			Error	
Intercept		-324.808	14.84852	1.2E-104
X Variable 1	Outdoor temperature (°C)	44.26123	0.282263	0
X Variable 2	Water supply temperature (°C)	-76.3313	0.191589	0
X Variable 3	Water flow rate (mL/s)	17.74559	0.430033	0
X Variable 4	Air flow rate (L/s)	65.38009	0.684847	0

$$Y^* = -324.81 + 44.26\,X_1 - 76.33\,X_2 + 17.75\,X_3 + 65.38\,X_4$$
$$(\pm 0.28) \quad (\pm 0.19) \quad (\pm 0.43) \quad (\pm 0.28)$$
$$Coefficient\ of\ determination\ R^2 = 0.92$$

Table 10 Multiple linear regression analysis for dependent variable of decentralized air supply unit off coil temperature

Y Variable – unit off coil temperature (°C)		*Coefficients*	*Standard Error*	*P- value*
Intercept		6.240734	0.124467	0
X Variable 1	Outdoor temperature (°C)	0.007885	0.002366	0.000862
X Variable 2	Water supply temperature (°C)	0.860672	0.001606	0
X Variable 3	Water flow rate (mL/s)	-0.16543	0.003605	0
X Variable 4	Air flow rate (L/s)	0.493466	0.005741	0

$$Y^* = 6.24 + .008\,X_1 + 0.86\,X_2 - 0.16\,X_3 + 0.49\,X_4$$
$$(\pm 0.002)\ (\pm 0.001)\ (\pm 0.003)\ \ (\pm 0.006)$$
$$Coefficient\ of\ determination\ R^2 = 0.94$$

As explained in Section 3.2, the two sides of attached containers in the BubbleZERO have different floor construction components. On one side, decentralized air supply units and air ducts were cast into concrete floor and on the other side, the units and ducts are within the raised floor. A clear trace of cooling stored in the concrete was observed near the decentralized air supply units which were embedded into concrete (Figure 41). The thermal trace follows embedded chilled water pipes into concrete as well as the air ducts to floor diffusers. This observation shows that some level of reheating to air supply could be expected when ducts are cast into concrete floor.

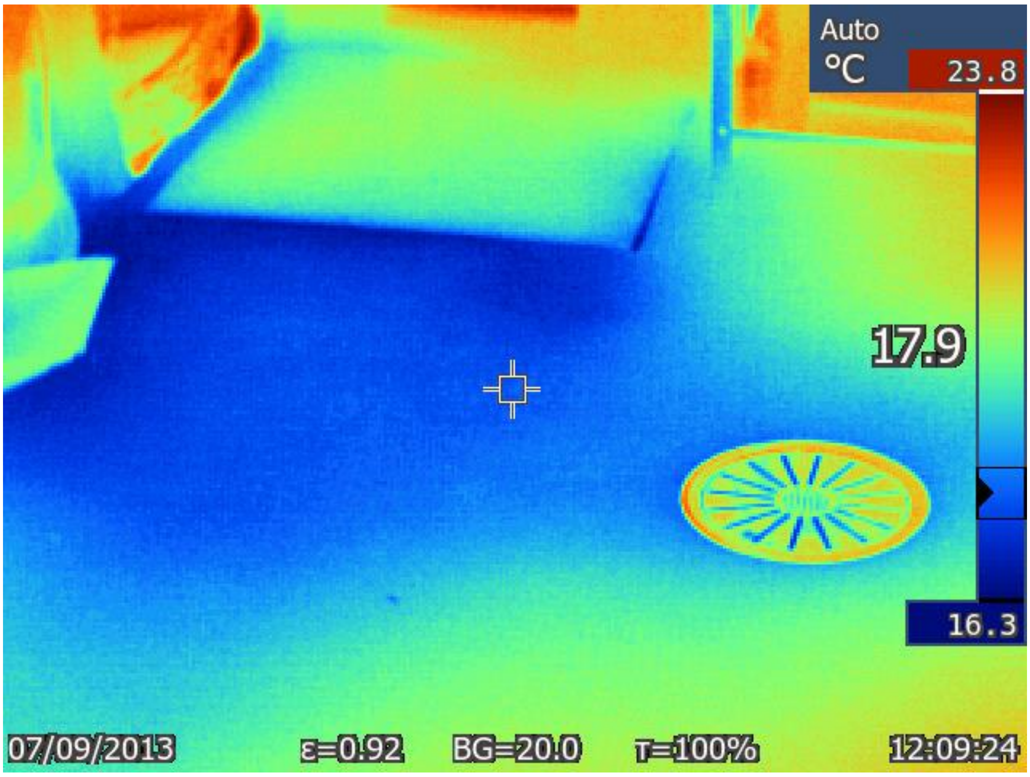


Figure 41 Infrared image of floor diffuser connected to decentralized air supply units within the concrete

The decentralized units take outdoor air directly from façade and distribute it to floor diffusers in a relatively low pressure drop air path. Inside each unit, four 20 W axial DC fan was installed in parallel as is shown in Figure 32. Long term operation of these decentralized units in actual buildings would have some implications on function of the installed axial fans. Erosion of fan blades was observed (Figure 42) after three years of operation of units on the site and it is suggested to be exchanged biennially or triennially with new fans. In addition, erosion of filter sheets was observed (Figure 43) in the air filter installed in the decentralized air supply units. It is recommended that these filters are replaced at least once a year to maintain the efficiency of filter for separating dust in incoming outdoor air.

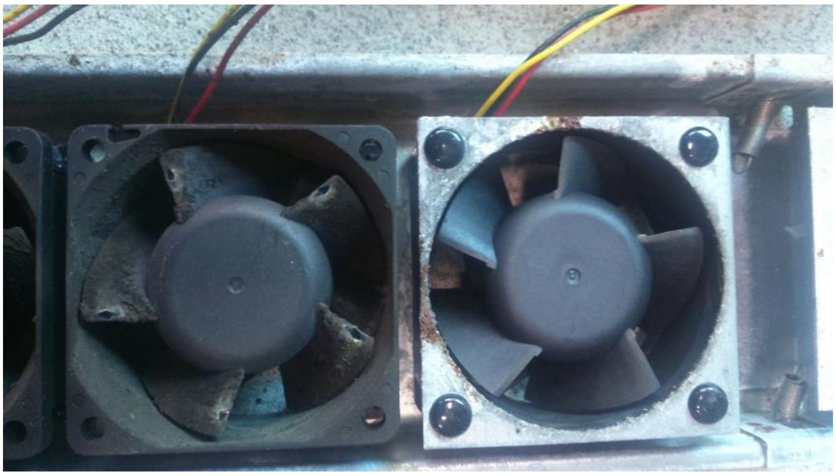


Figure 42 Erosion of fan blades inside the air supply units after three years of operation

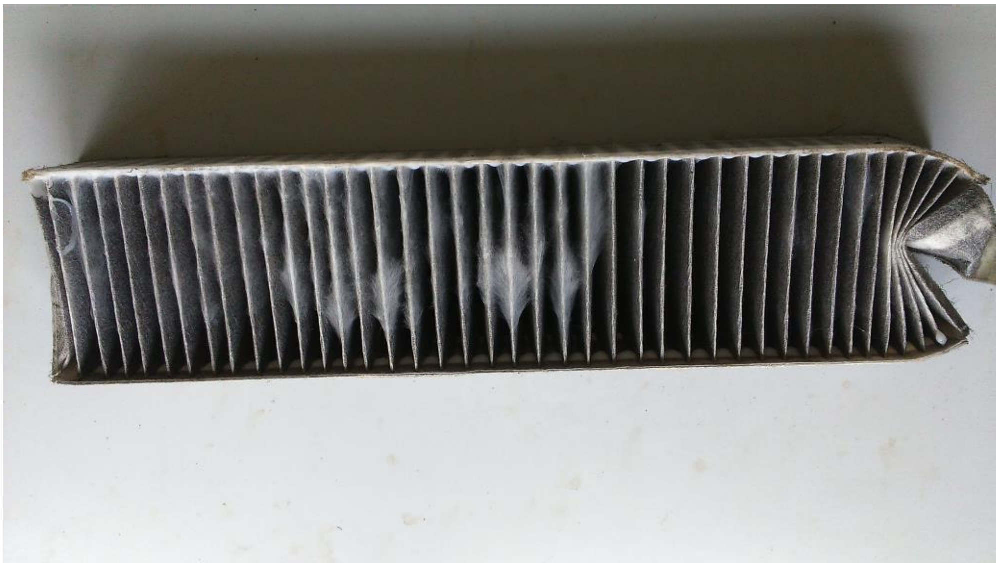
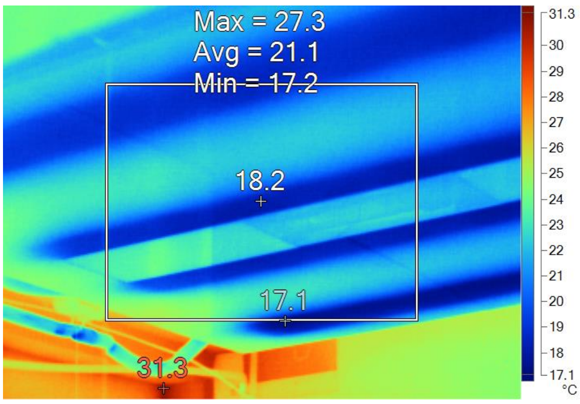


Figure 43 Erosion of filter sheet inside the air supply units after one year of operation

4.2 Radiant cooling panel

Radiant ceiling panel has been considered as the parallel sensible cooling system for the designed decentralized DOAS system. A multifunctional ceiling panel with integrated LED lighting, CO_2-sensor controlled exhaust flap and exhaust ducting in behind was implemented in the BubbleZERO. The decentralized air supply units satisfy the ventilation requirement, the latent load and some part of the sensible load, while the radiant ceiling panel satisfies the remaining sensible load. The panel surface temperature should be set in a way to avoid condensation and at the same time provide enough cooling capacity to satisfy some part of space sensible load. Heat transfer on panel surface occurs mostly through radiation to other surfaces in the space and partly through convection with surrounding air. The driving force in the radiant heat transfer mechanism based on Stefan-Boltzmann law is the difference between fourth power of panel and body absolute temperature. The variation of temperatures inside the conditioned space from panel surface to hot façade can be seen in the infrared images of panels (Figure 44). Panel surface temperature varies between 17 to 20 °C and the areas behind installed chilled tubes are clearly identifiable from other parts of the panel.



Infrared image of radiant panel

Real image of radiant panel

Figure 44 Infrared image of radiant cooling panel in the conditioned laboratory

One of the common problems associated with radiant panels is the non-uniformity of temperature on the panel surface. In order to obtain more accurate temperature distributions on panels, a digital contact thermometer also has been used during the whole set of experiment. Temperatures measured with the contact thermometer at different points on the panel surface are shown in Figure 45. This variation depends on the number of passes of the hydronic system behind the panel and also the sensible cooling load. In the current two-pass pipe configuration of hydraulic system, the area behind the track of water pipe is 1 to 3 °C colder than rest of the panel during day time. Increasing the number of cold water passes behind the panel could improve the uniformity level and increase the cooling capacity of panel per surface area. It was also observed that the temperatures on the surface of LED lamps are much higher than the rest of the panel. In the designed multifunctional panel, the back of LED lights is adjacent to exhaust duct, so some part of generated heat by lighting would be transferred directly to the exhaust air. The infrared image of radiant cooling panel together with human body skin is shown in Figure 46. This level of temperature difference would result in a considerable radiant heat exchange between human body and radiant panel surface.

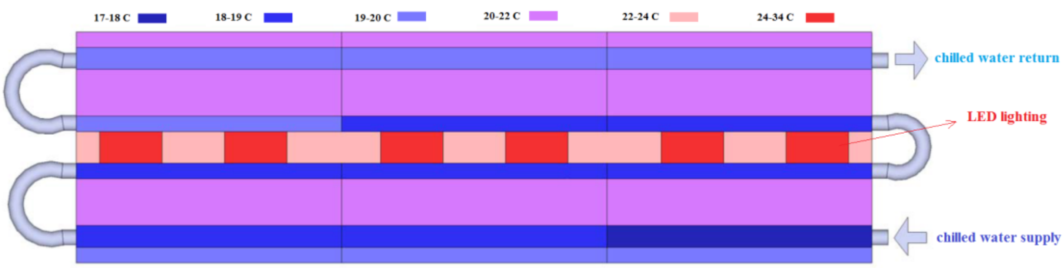


Figure 45 Measured temperature distribution on the ceiling panel surface

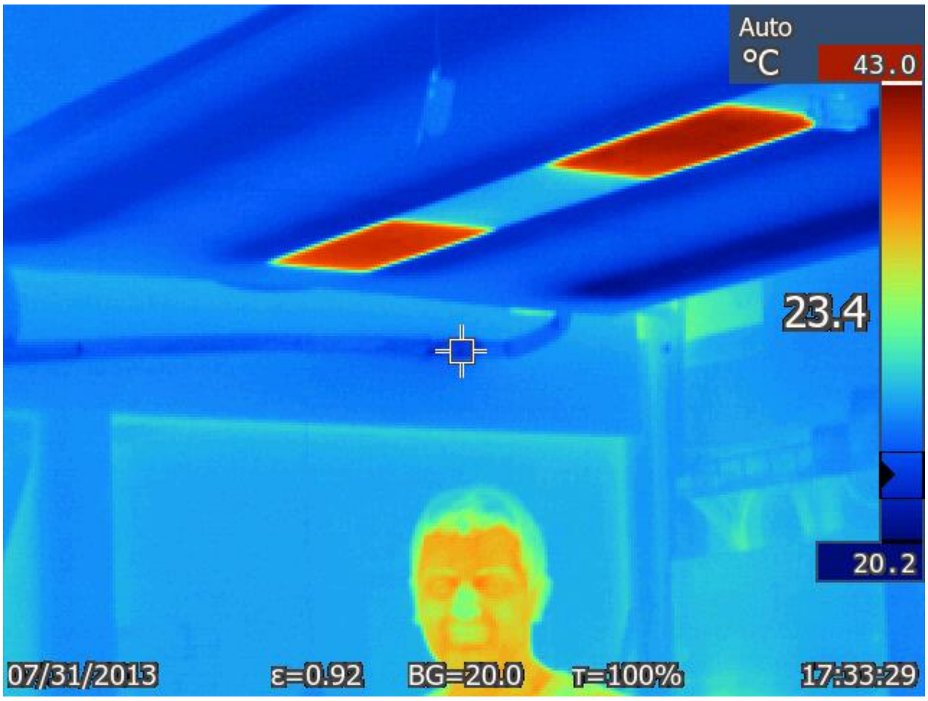


Figure 46 Infrared image of radiant cooling panel together with human body skin

Daily profile of the radiant panel unit capacity with fluctuating outdoor temperature and supply water temperature is shown in Figure 47. The supply water temperature fluctuates between 17 to 19 °C due to the chiller on/off control setting. Capacity of the panel was around 200 W in the morning which rose to about 300 W in the afternoon. This observation shows the strong impact of outdoor temperature as a proxy of space sensible cooling load on capacity of panel. Higher interior façade surface temperature in the afternoon increases the radiant heat transfer between cool panel and hot windows or walls. During the experiments, the difference between supply and return water temperature was around 2 °C and this value was higher for lower supply water temperatures.

This daily pattern of radiant panel capacity was commonly observed during the experiments except for fully rainy days when there was no peak point in the afternoon.

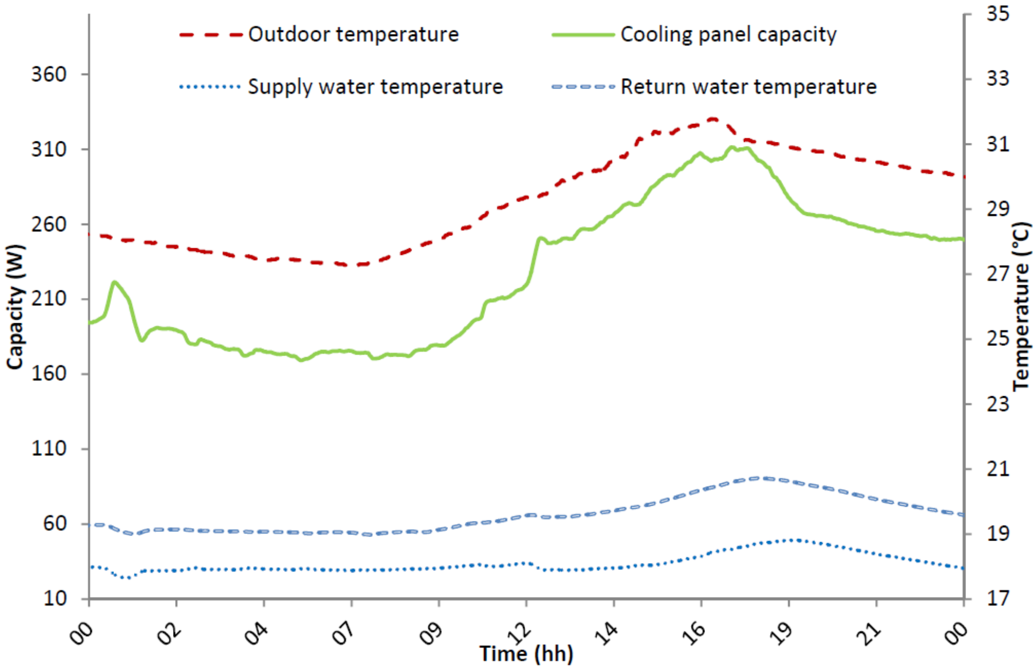


Figure 47 Daily profile of radiant cooling panel unit capacity caused by fluctuation of outdoor air temperature and supply water temperature

The simple linear regression analysis has been conducted to investigate the correlations between radiant panel capacity and input design parameters. Three independent parameters of outdoor temperature, panel water supply temperature and panel water flow rate have been considered in the analysis. 17280 sample data points and the simple linear regression of radiant panel unit capacity in terms of water supply temperature and outdoor temperature are plotted in Figures 48 and 49. Panel capacity varies between 50 to 350 W for water supply temperature in the range of 16 to 19 °C and the outdoor temperature in the range of 27 to 33 °C. Nevertheless, the coefficients of determination (R^2) for the regression analyses are not near a good fit range and the multiple regression analysis is required to adequately realize the impact of these variables on capacity of radiant panel.

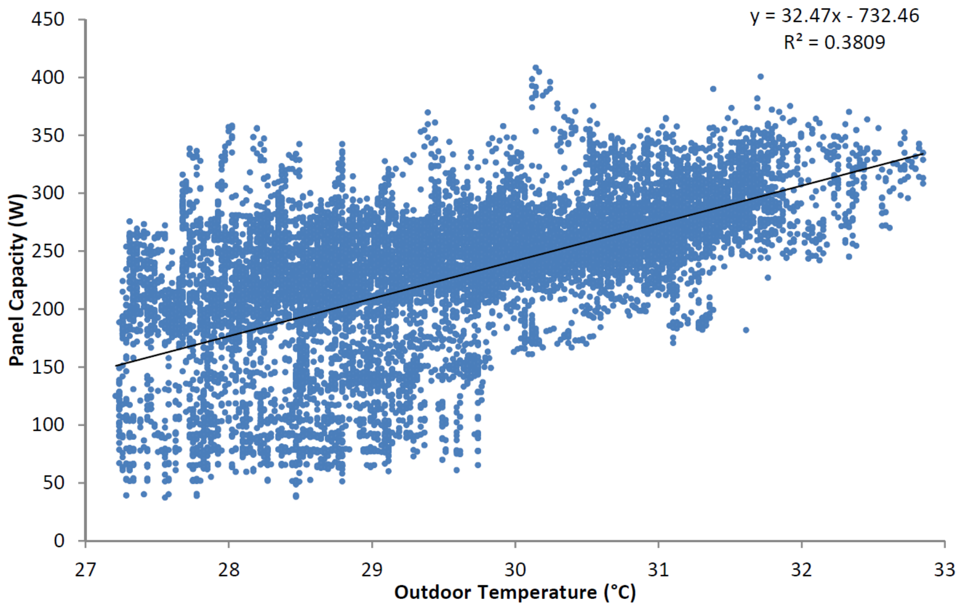


Figure 48 Pool of sampled radiant panel unit capacity and outdoor temperature

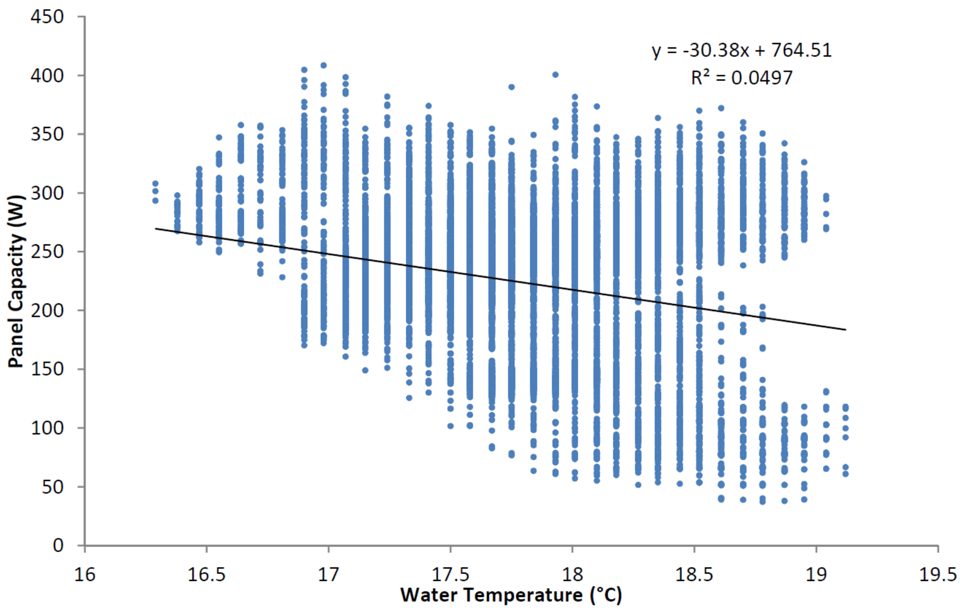


Figure 49 Pool of sampled radiant panel unit capacity and water supply temperature

The multiple linear regression analysis has also been conducted to get an overall understanding of the impacts of several input parameters on capacity of radiant panel. Three independent variables of outdoor temperature (°C), water supply temperature (°C) and water flow rate (mL/s) have been chosen in this analysis. The results of statistical analysis for linear coefficients, standard error and P-values based on the "t" statistic test are listed in Table 11. The coefficient of determination (R^2) for the radiant panel capacity is 0.73 which is an acceptable fit for these high variation parameters. The calculated P-values based on the "t" statistics test are also near zero which indicates that the found correlations are significant. The capacity of radiant panel rises with higher outdoor temperature and water flow rate and it drops with increase of water supply temperature.

Table 11 Multiple linear regression analysis for dependent variable of radiant panel capacity

Y Variable – radiant panel capacity (W)		*Coefficients*	*Standard Error*	*P- value*
Intercept		164.0364	9.941282	1.06E-60
X Variable 1	Outdoor temperature (°C)	38.47231	0.231891	0
X Variable 2	Water supply temperature (°C)	-66.0153	0.587623	0
X Variable 3	Water flow rate (mL/s)	3.095883	0.037765	0
$Y^* = 164.04 + 38.47\,X_1 - 66.01\,X_2 + 3.09\,X_3$ $(\pm 0.23) \quad (\pm 0.59) \quad (\pm 0.038)$ $Coefficient\ of\ determination\ R^2 = 0.73$				

An operational scenario of DDOAS-RCP has been tested in which the air based system was switched off while radiant panel was operating. Depending on the initial dew point of indoor space, it may take several hours till the condensation droplets appear on the panel surface. It was observed that the water droplets mostly form on the panel areas where there is a direct contact with chilled water pipes. The condensation pattern on radiant panel surface for the current two chilled water passes design is shown in Figure 50.

Figure 50 Condensation pattern on the radiant cooling panel when air system is switched off

4.3 DDOAS combined with RCP

Different set of experiments have been conducted under various operational scenarios of DOAS-RCP inside the BubbleZERO test bed. As shown in pervious sections, each change in input parameters of decentralized units and radiant panel have some impacts on their capacity and off coil conditions. So these design parameters of components could affect the overall conditions of indoor air space and their interactions required further investigation as well. A certain range of values for each input parameter have been identified from preliminary experiments which were conducted to achieve indoor air condition in the BubbleZERO near to acceptable range. As discussed in the methodology section, different environmental parameters including, dry bulb temperature, mean radiant temperature and relative humidity have been monitored and recorded at different locations inside the BubbleZERO. The sensors were located at various locations and heights to get a sense of spatial distribution of environmental parameters in the space.

Dry bulb temperature at different heights (average of four points) of 0.1 m, 1 m, 1.8 m inside the space and also outdoor air temperature are plotted in Figure 51. The data is shown for eleven consecutive days in which ventilation rate of space reduced from 0.72 to 0.44 L/s/m^2. The reduction of outdoor air flow rate affected the cooling capacity of decentralized units which caused approximately one degree increase of space temperature at the same outdoor condition (as shown by lines in Figure 51). DDOAS-RCP system was operating in manual control mode with fixed operational conditions besides ventilation rate of space. It was also observed that with FS-CE distribution and ceiling radiant panel, there is a two degree vertical thermal stratification in the space and the temperature gradient is steeper below 1 m height level. The selected range of ventilation rates is close to the minimum ventilation requirement of office buildings in Singapore which is 0.6 L/s/m^2 based on SS 553 (2009).

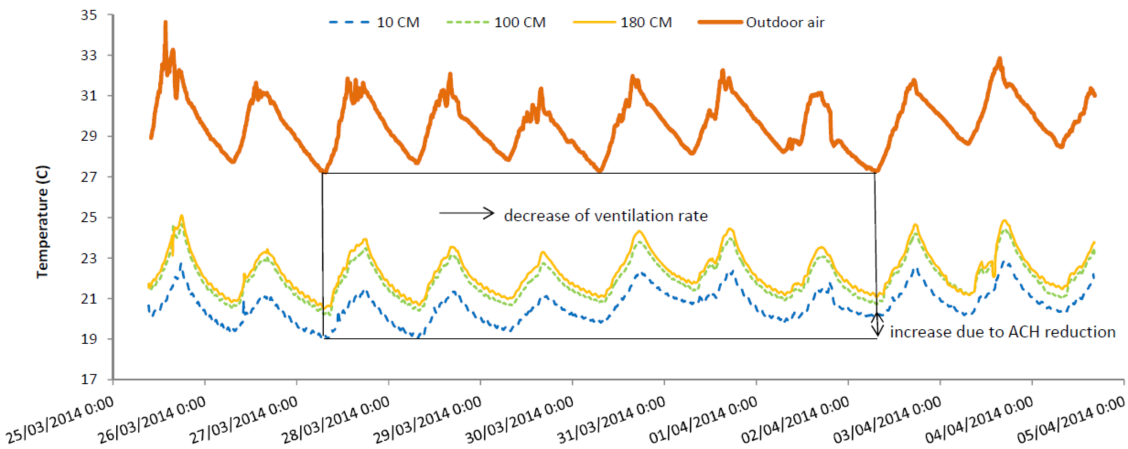


Figure 51 Measured temperatures at different height levels inside the space and outdoor during reduction of space ventilation rate (0.72 to 0.44 L/s/m^2)

Dew point temperature (humidity level) and mean radiant temperature also continuously were measured at different locations inside the BubbleZERO. These temperature values including calculated operative temperature for a typical day are plotted in Figure 52. Mean radiant temperature was roughly two degree lower than dry bulb temperature in the areas below the ceiling panels due to the impact of radiant cooling. The mean radiant temperature curve followed the same trend as dry bulb in which peak point occurred in the afternoon. Without change in system control settings for different outdoor conditions, the maximum dew point temperature also occurred around 5 pm, although the span of variation in dew point value was lower than dry bulb fluctuation from 9 AM to 5 PM.

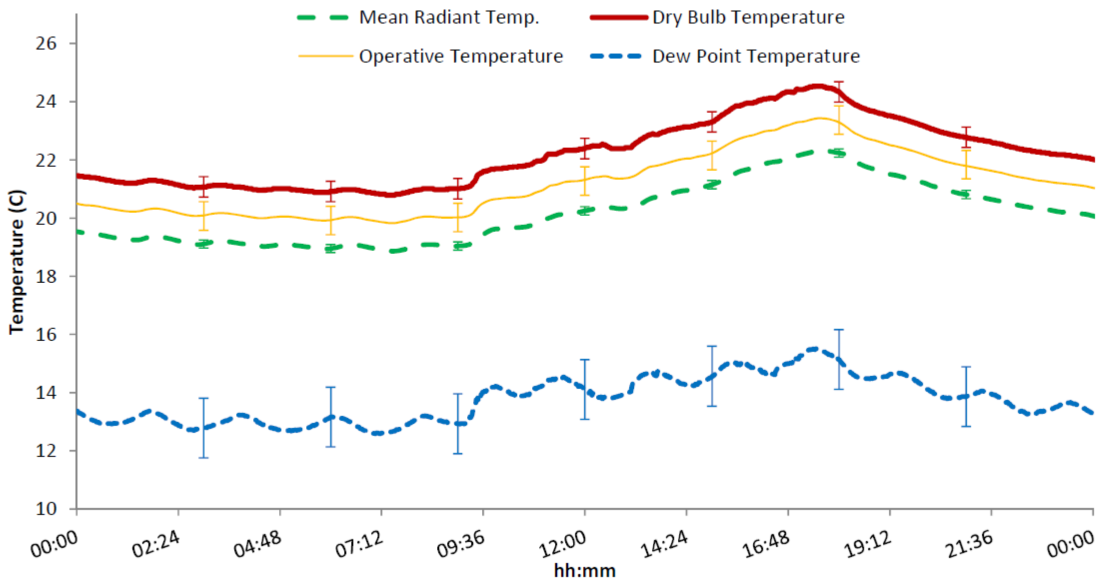


Figure 52 Variation of dry bulb, mean radiant, operative and dew point temperatures during a typical day

The capacities of decentralized air supply units and radiant cooling panels were monitored during the experiments and the outcomes were used to determine the contribution of each system in satisfying the sensible and latent loads of the space. This separation of sensible and latent cooling could provide detailed information on level of air supply units' contribution for satisfying the sensible and latent loads of the space. The main function of these units is to provide dehumidified outdoor air for the ventilation requirement and the latent load of the space, while they provide sensible cooling as well and the amount of this sensible cooling is of importance. The ratios of sensible and latent cooling capacities of decentralized air supply units and radiant panels as well as sensible heat ratio (SHR) of the BubbleZERO for a typical day are shown in Figure 53. SHR is the ratio of sensible cooling load to total cooling load. This parameter could reveal the level of the latent load imposed on the typical office spaces in the tropics. It was observed that share of air supply units in satisfying the sensible load of space was 10 % higher than radiant panels in the morning. SHR was around 0.5 in the morning which rose to about 0.6 in the afternoon. Due to the higher sensible heat ratio in the afternoon, the contribution of radiant panel increased to about 30 % and it played a more important role in satisfying the cooling load of space.

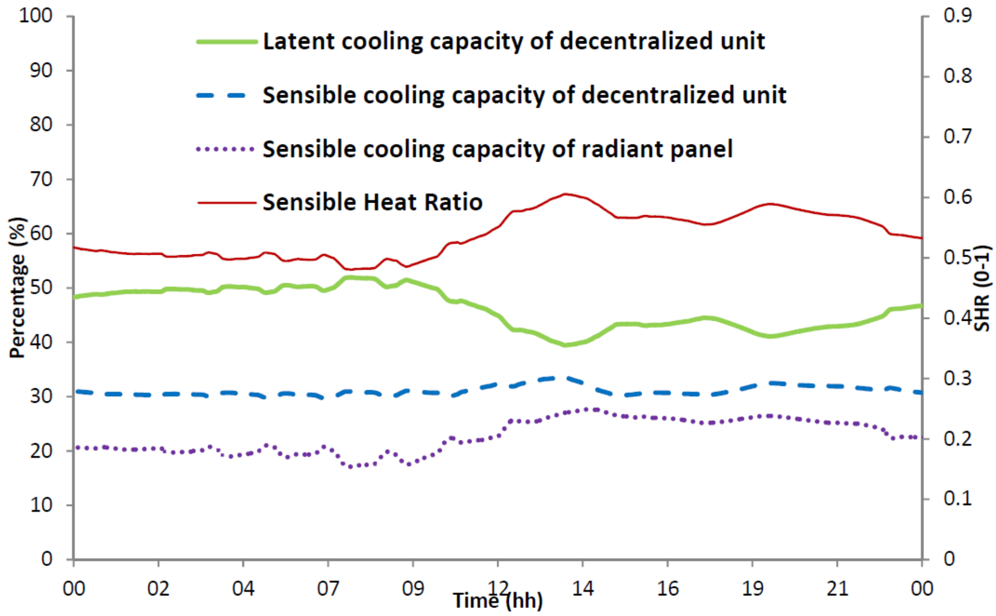


Figure 53 Ratio of sensible cooling and latent cooling capacities provided by air supply units and panel as well as sensible heat ratio during a typical day

The simple linear regression analysis has been used to explore the correlation between indoor temperature and input independent variables. 14401 sample data points of collected indoor temperature and outdoor temperature are plotted in Figure 54. Without change in system control settings of decentralized air supply units and radiant cooling panel, indoor temperature rises from 20 to 24 °C when outdoor temperature increases from 27 to 33 °C. The coefficient of determination (R^2) for this regression is near to fit range. The pool of sampled indoor temperature and dew point in terms of outdoor temperature, decentralized unit water supply temperature and panel water supply temperature are shown in Figures 55, 56, 57 and 58. The average dew point temperature of the laboratory varies from 12 to 16 °C over the range of outdoor temperature (27 to 33 °C) and decentralized unit water supply temperature (8 to 17 °C). The average indoor temperature also varies from 20 to 24 °C over the range of decentralized unit water supply temperature (8 to 17 °C) and panel water supply temperature (16 to 19 °C). The coefficients of determination in the abovementioned regression analyses are not close to fit range and the multiple regression analysis has been conducted to understand the impact of these variables on indoor temperature and dew point.

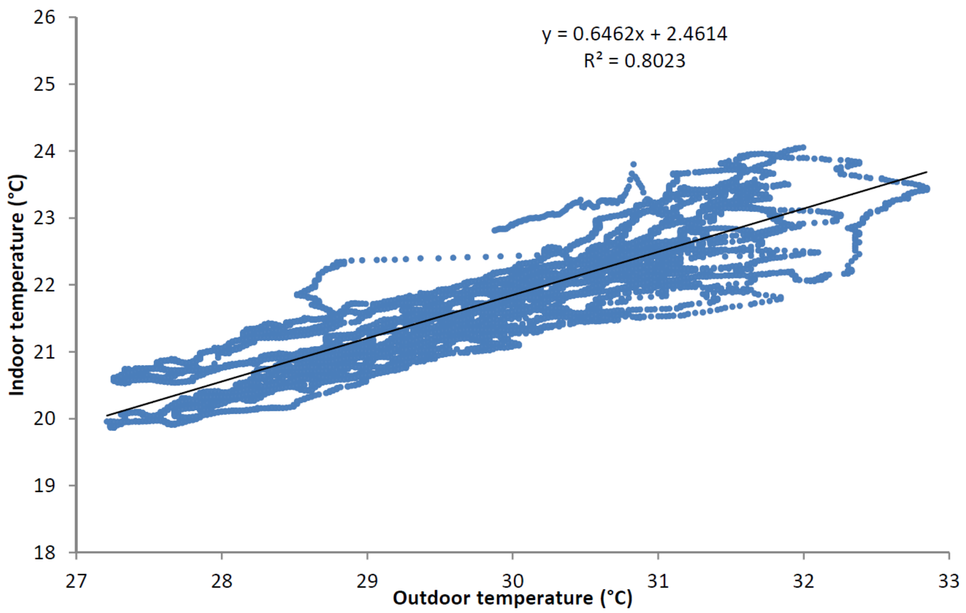


Figure 54 Pool of sampled indoor temperature and outdoor temperature

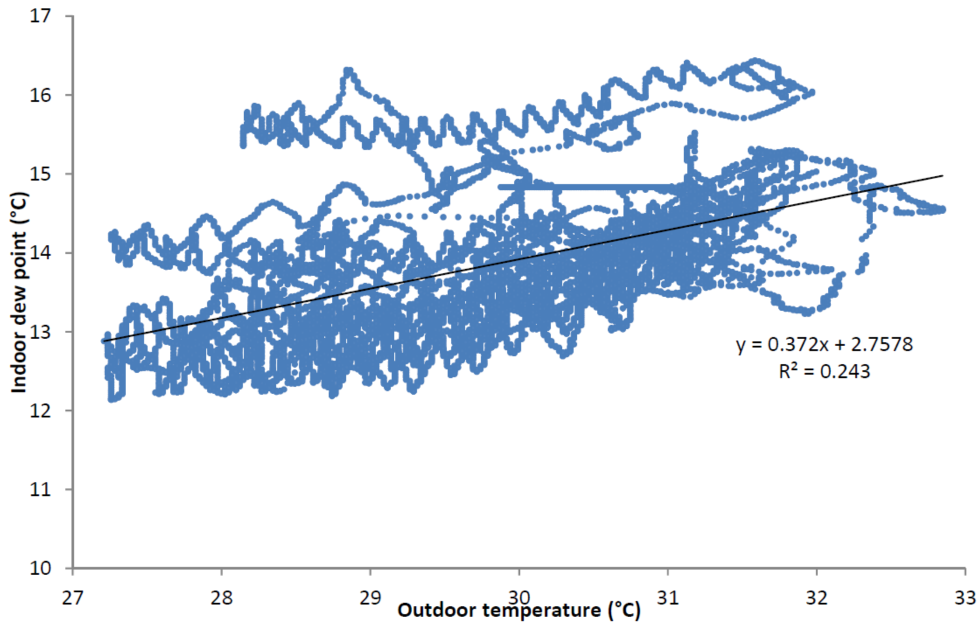


Figure 55 Pool of sampled indoor dew point temperature and outdoor temperature

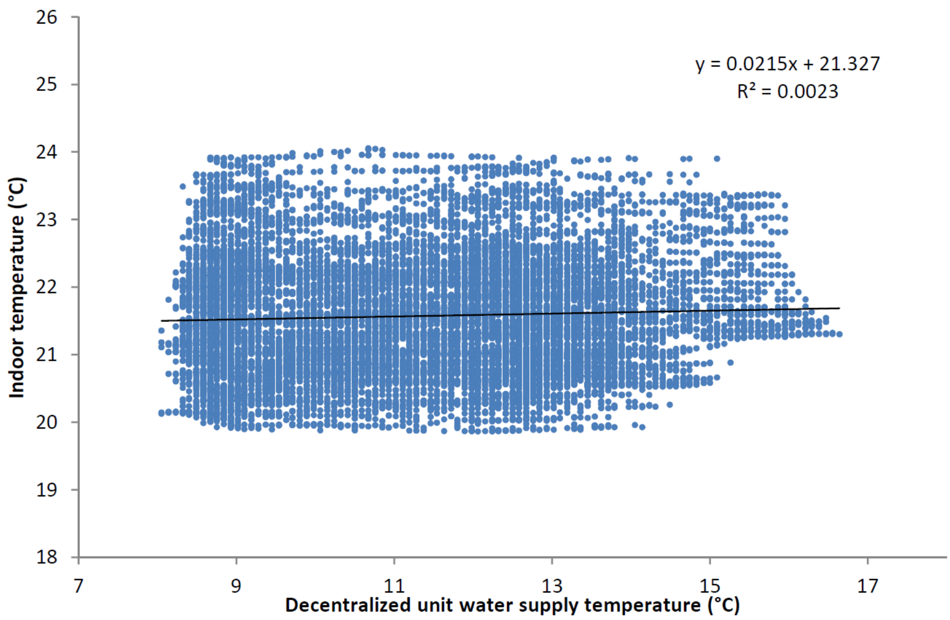


Figure 56 Pool of sampled indoor temperature and decentralized unit water supply temperature

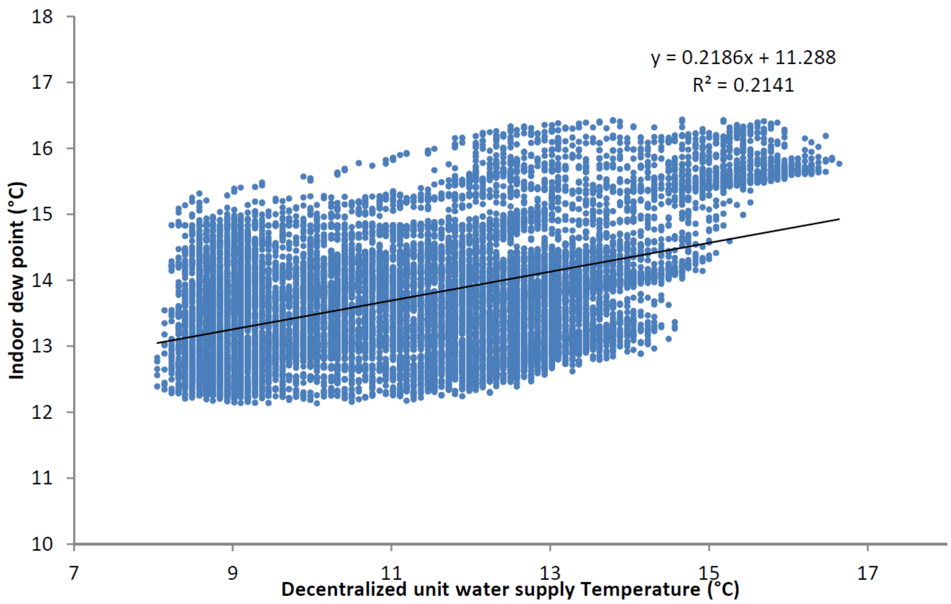


Figure 57 Pool of sampled indoor dew point temperature and decentralized unit water supply temperature

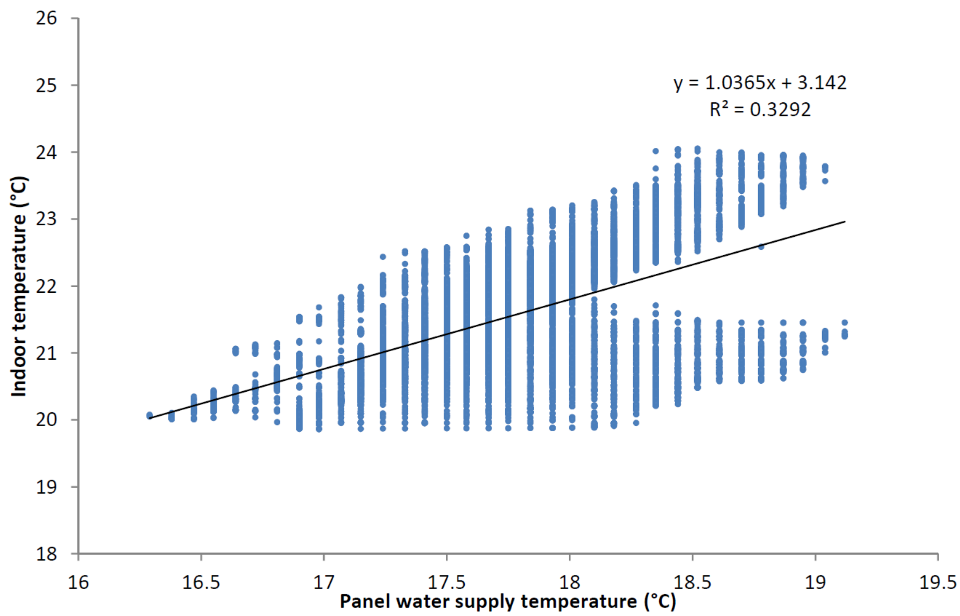


Figure 58 Pool of sampled indoor temperature and panel water supply temperature

The multiple linear regression analysis has been implemented to get an estimate of importance of different independent input variables on average indoor space temperature. Five independent variables of outdoor temperature

(°C), decentralized unit water supply temperature (°C), decentralized unit water flow rate (mL/s), outdoor air flow rate (L/s), and radiant panel water supply temperature (°C) have been considered in this investigation. The outcomes of statistical analysis for linear coefficients, standard error and P-values based on the "t" statistic test are listed in Table 12. The coefficient of determination (R^2) for the indoor air temperature is 0.87 which is a good fit between linear regression line and measured data. The calculated P-values based on the "t" statistics test are also near zero which indicates that the found correlations are significant. The dependent variable of average indoor air temperature ascends with rise of outdoor temperature, decentralized unit water supply temperature and panel supply water temperature and it drops with increase of decentralized unit water flow rate and outdoor air flow rate.

Table 12 Multiple linear regression analysis for dependent variable of indoor temperature

Y Variable – indoor temperature (°C)		*Coefficients*	*Standard Error*	*P-value*
Intercept		0.884087	0.143734	7.91E-10
X Variable 1	Outdoor temperature (°C)	0.596047	0.002384	0
X Variable 2	Decentralized unit water supply temperature (°C)	0.037066	0.001359	8.3E-160
X Variable 3	Decentralized unit water flow rate (mL/s)	-0.0174	0.000697	1.1E-134
X Variable 4	Air flow rate (L/s)	-0.04122	0.001012	0
X Variable 5	Panel water supply temperature (°C)	0.297756	0.006531	0

$$Y^* = 0.88 + 0.6\,X_1 + 0.04\,X_2 - 0.02\,X_3 - 0.04\,X_4 + 0.3\,X_5$$
$$(\pm 0.002)\ \ (\pm 0.001)\ \ (\pm 0.0007)\ \ (\pm 0.001)\ \ (\pm 0.006)$$
$$Coefficient\ of\ determination\ R^2 = 0.87$$

4.4 Thermal comfort and indoor air quality

Thermal comfort index and indoor air pollutants level are the main parameters which should be evaluated for any new designed air conditioning system in buildings. DDOAS-RCP in the tropics introduces a new indoor environment with lower air movement and mean radiant temperature compared to that for the conventional all air system. The measured mean radiant temperature in space was roughly 2 °C less than dry bulb temperature at locations below the radiant panels. Although Fanger's PMV model has not been fully accepted as a reference thermal comfort model for the tropical climates, it still can provide some insights into the possible range of acceptable indoor air condition by occupants. The calculated PMV for a typical day based on average of measured values inside the BubbleZERO conditioned with DDOAS-RCP is shown in Figure 59. The categories of A and B of thermal environment in the standard of ISO 7730 (2005) have been chosen as thresholds which respectively corresponds to $-0.2 < PMV < 0.2$ and $-0.5 < PMV < 0.5$ (Predicted Percentage Dissatisfied (PPD) < 6 and 10 %). It can be seen in Figure 59 that with fixed operational settings of system (set based on maximum cooling load), indoor air was slightly overcooled in the morning and eventually it went into the comfort range in the afternoon time. As mentioned in the literature review chapter, the predictions of Fanger's PMV model do not truly match the perception of locally acclimatized occupants. The neutral temperature based on occupants' perception could be slightly warmer or cooler (Andreasi et al., 2010; de Dear and Leow, 1990; Indraganti et al., 2014; Willem and Tham, 2007) than PMV predictions and low air speed in indoor space is likely to be the point of comfort concern for this climate.

The relevant local discomfort criteria of categories A and B in the ISO standard includes draft risk (maximum air velocity), vertical air temperature difference, range of floor temperature, and radiant temperature asymmetry. Draft risk is not a concern for this design because of low air movement in the space. Vertical temperature difference is less than 2 °C which is in the acceptable range of both categories (A: < 2 °C, B: < 3 °C). The floor temperature during the experiments was in the range of 20 to 22 °C which is in tolerable range of the standard (19-29 °C). In addition, the maximum measured surface temperature difference inside the BubbleZERO was around 10 °C which is less than radiant temperature asymmetry threshold of the ISO standard for cool ceiling (< 14 °C). Regarding the compliance with the Singapore standard, spot measurements with anemometer revealed that the indoor air velocity is less than 0.01 m/s (resolution of device) in most of locations inside the space (except close to diffusers) which is below the acceptable range of Singapore standard SS 554 (0.1-0.3 m/s). Although the calculated PMV shows that lower dry bulb and mean radiant temperature could compensate the impact of lower air movement, the preference of locally acclimatized occupants in the tropics requires further investigation. It is also noteworthy that the calculation of PMV has been done for a normal male employee in Singapore’s offices with sedentary activity (1.2 met), normal trousers and long sleeves shirt (0.79 clo). 1 met is the metabolic unit which is equal to metabolic rate (M) of 58.2 W/m^2 and 1 clo is the clothing unit which is equal to clothing insulation (I_{cl}) of 0.155 m^2 K/W.

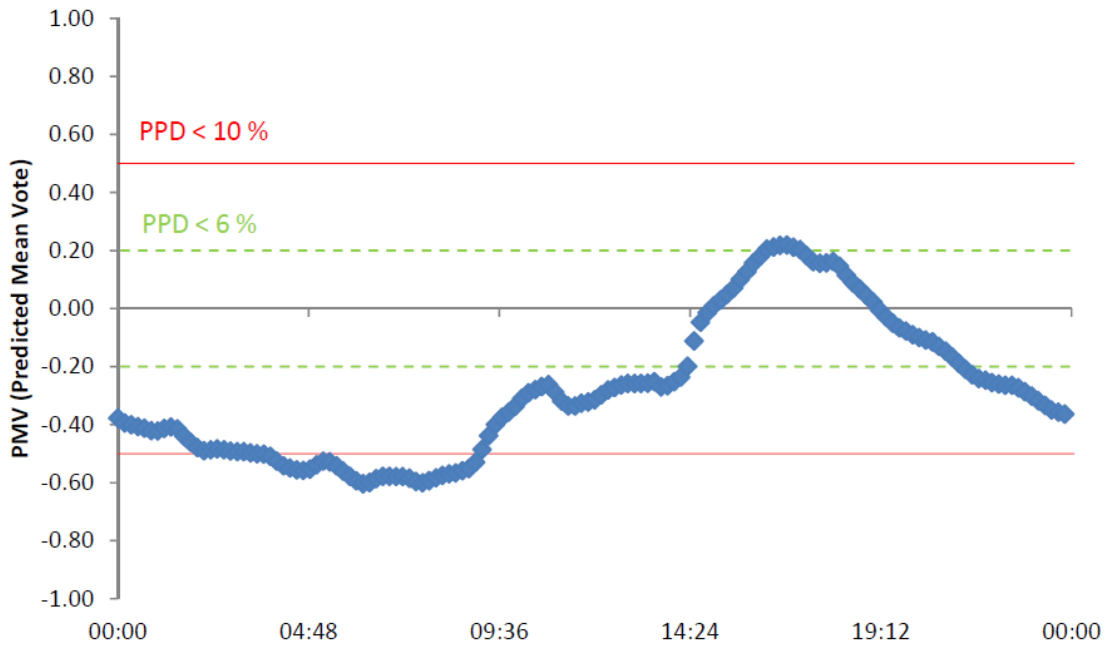


Figure 59 Calculated daily PMV in the BubbleZERO under fixed operational settings of system

Besides the whole space and local comfort criteria, air quality level in a conditioned space with DDOAS-RCP is also an important aspect of this design. Continuous and spot measurements have been done during the experiments for the main indoor air pollutants of carbon dioxide (CO_2), total volatile organic compounds (TVOCs) and respirable suspended particles (RSP). Carbon dioxide as the main human related contaminant in the indoor space has been monitored inside the test chamber. The variations of CO_2 concentration under steady state indoor conditions with different ventilation rates are shown in Figure 60. During the experiments, the occupancy level was 0.1 person/m^2. As can be seen in Figure 60, CO_2 level is below threshold of 1100 ppm (700 ppm more than outdoor concentration based on SS 554) in all the cases. At the ventilation rate of 0.44 L/s/m^2, the CO_2 concentration was close to the threshold, while at higher rates, it was well below the limit. These results are consistent with the recommended ventilation rate for office spaces in Singapore set by the local standard of SS 553, which is 0.6 L/s/m^2.

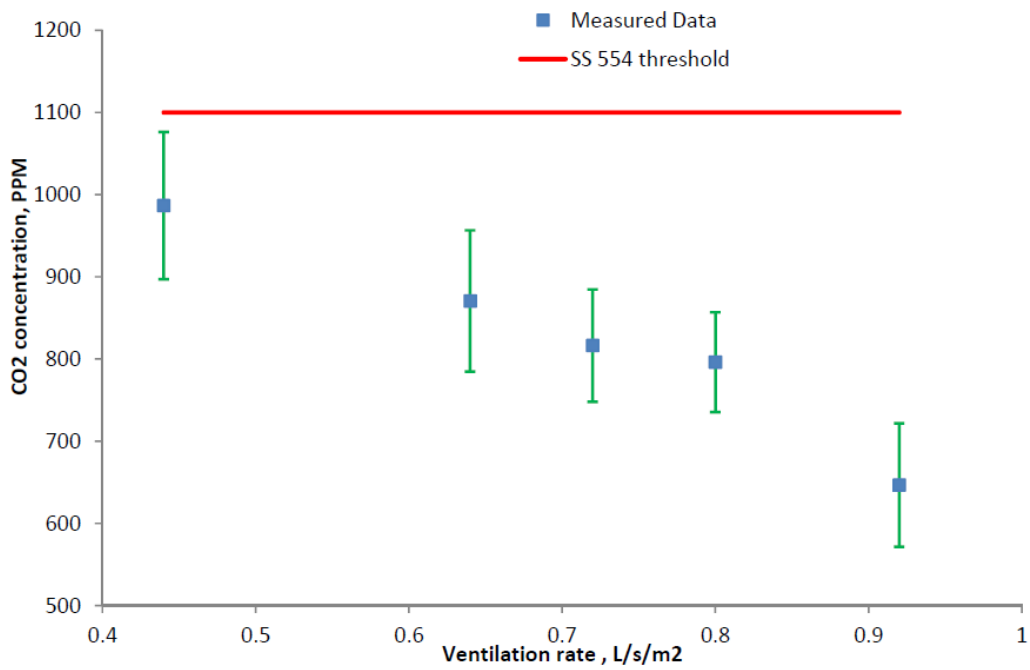


Figure 60 Carbon dioxide concentrations for five considered ventilation rates and threshold value set by local standard SS 554

Besides overall and steady state level of carbon dioxide, the spatial and temporal distribution of CO_2 in the indoor space was also explored during the measurements. The transient CO_2 level in the BubbleZERO for a typical day with occupants entering and leaving the space is shown in Figure 61. It can be seen that after each change in occupancy it takes about two hours to reach a steady state CO_2 concentration in the space. In addition, a 30% reduction in ventilation rate of the laboratory resulted in 100 ppm increase in steady state carbon dioxide concentration. During these measurements in occupied period, two persons were sitting in the laboratory which is equal to an occupancy level of 0.1 person/m^2. The high points in Figure 61 are representative of CO_2 level near breathing points of seated occupants. A spatial representation of CO_2 concentrations at different locations within the test chamber is provided in Figure 62. Near the occupants (points 1 and 2), the mean CO_2 concentration was marginally higher than at other locations, while the variation of concentration was significantly higher than at other points. This observation could be justified based on diffusion characteristics of carbon dioxide in air and low turbulence mixing in this design. This observation shows that in the areas near occupants on average basis, CO_2 level is similar to other points while fluctuation in concentration occurs frequently because of breathing exhalation flow. It was also observed that the concentration levels of CO_2 at exhaust and interior points are close to each other.

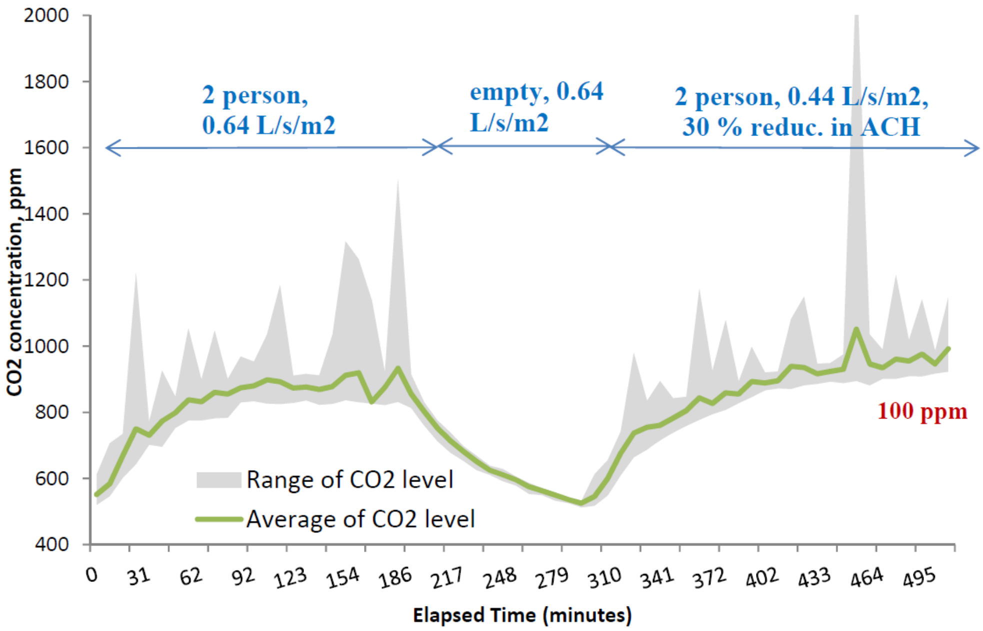


Figure 61 Range and average of CO_2 concentration for transitional occupancy

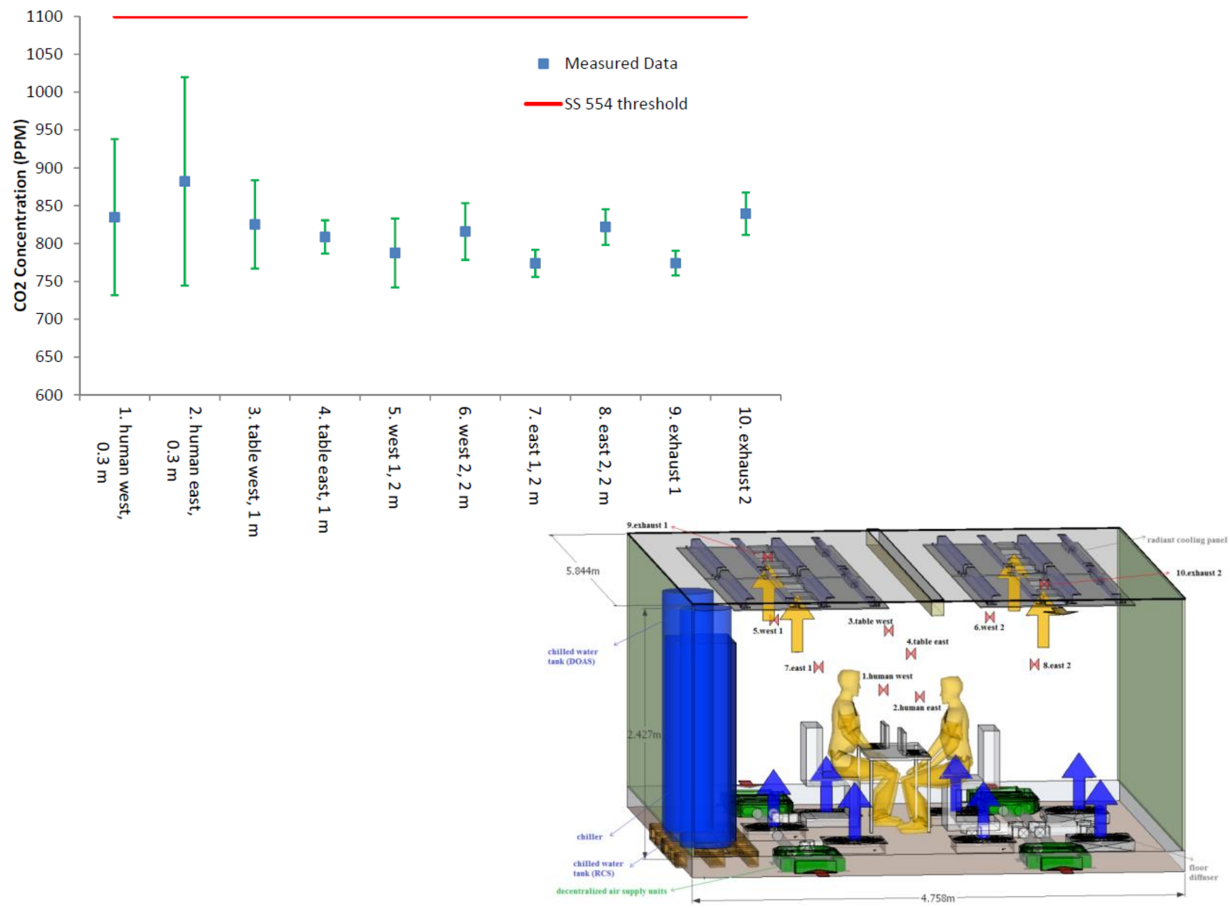


Figure 62 Spatial variation of carbon dioxide in space in order of distance from occupants

TVOCs concentration also has been measured at several spot points in the BubbleZERO and observed values were around 150 ppb in occupancy period which is well below SS 554 limits (3000 ppb). The background level of TVOCs in the space without occupants ranged between 40 to 50 ppb. This measured range shows that there is no concern regarding the emitted organic compounds from materials of walls, floor, roof, tables and other objects in the space. VOC monitor of ppbRAE 3000 has been used for these measurements which is a third generation photoionization detector with built-in correction factor for more than 200 VOC compounds. RSP concentration has also been measured for several hours and the maximum reported value in the whole sampling period was around 30 μg/m3 which is below SS 554 standard limit (50 μg/m^3 for PM_{10}). These results indicate that there is no risk regarding the resuspension of particles from floor to occupant level through floor supply diffusers. The amount of supply air in under floor air distribution (UFAD) of DOAS-RCP is considerably lower than conventional UFAD system (about 1/5 to 1/4). This lower air movement results in lower risk in terms of particle dispersion in space, the problem which is associated with conventional UFAD design.

4.5 Ventilation effectiveness analysis

Ventilation effectiveness indices can provide a better understanding on the performance of the DDOAS-RCP in terms of purging generated pollutants in the space. Tracer gas decay test method has been used to determine these parameters for the designed low exergy systems in the tropics. The SF_6 concentration curves over time for a tracer gas test conducted in the BubbleZERO are shown in Figures 63 and 64. The maximum value reached around 15 ppm (parts per million volume) and it took about half an hour to achieve uniform distribution in the space. The exponential trendline of usable data part of curve was calculated and the power of this exponential decay (0.019 min^{-1}) is equal to ventilation rate of space. In addition, the room mean age of air was calculated from the weighted area under the usable part of curve and the ventilation effectiveness indices were determined using Eq. 1-3. This tracer gas test has been conducted twice for each specific ventilation rate to test the repeatability of the experiments. The variations of ventilation effectiveness indices for repeated cases as well as different locations are included in the presented values as error bars. The red line in Figures 63 and 64 shows the usable data part of curve for the calculation of ventilation rate and ACE. The exponential trendline of the usable data and the corresponding equation are also shown (green line) here.

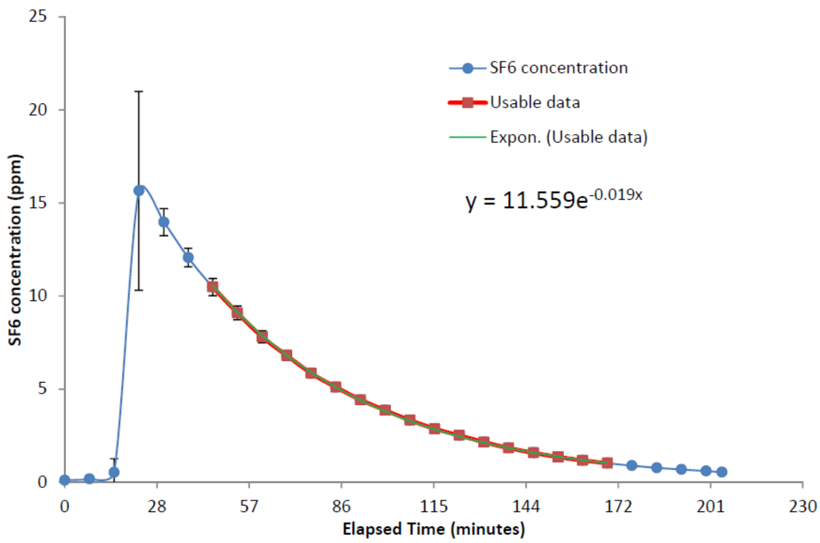


Figure 63 Measured SF_6 concentration and interpolated curve for a SF_6 step down tracer gas decay test

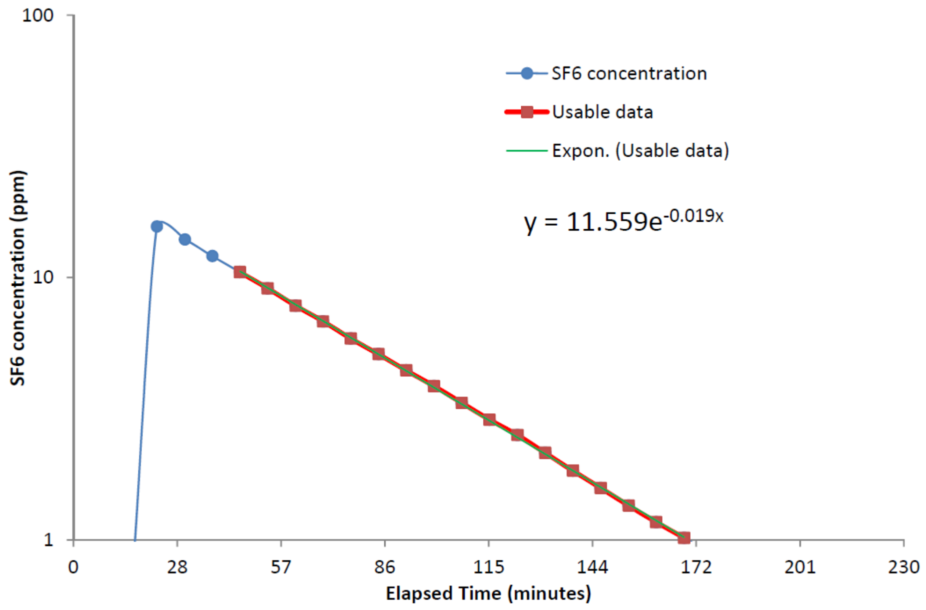


Figure 64 Measured SF6 concentration and interpolated curves in the logarithmic scale

The calculated ACE and LACI for the five considered ventilation rates are plotted in Figure 65. This range of ventilation rates (0.44-0.92 L/s/m^2) has been considered to include both values below and above of recommended ventilation rate in the local standard of SS 553 (0.6 L/s/m^2). During the whole sets of experiments, the average surface temperature of radiant panel was around 20 °C. It can be seen that the ventilation effectiveness indices for DDOAS-RCP are close to the values of a mixing strategy. The variation of contaminant removal effectiveness over the range of ventilation rates are shown in Figure 66. A slight increase in the CRE level of the indoor space can be seen for higher ventilation rates. However, these differences may be partially due to the propagation of uncertainties of measurements in ventilation effectiveness calculation. The propagated uncertainty for ACE and CRE are approximated to be around 2.5 % and 1.4 %, respectively. The methodology followed for calculation of these propagated uncertainties is explained in Section 4.6.

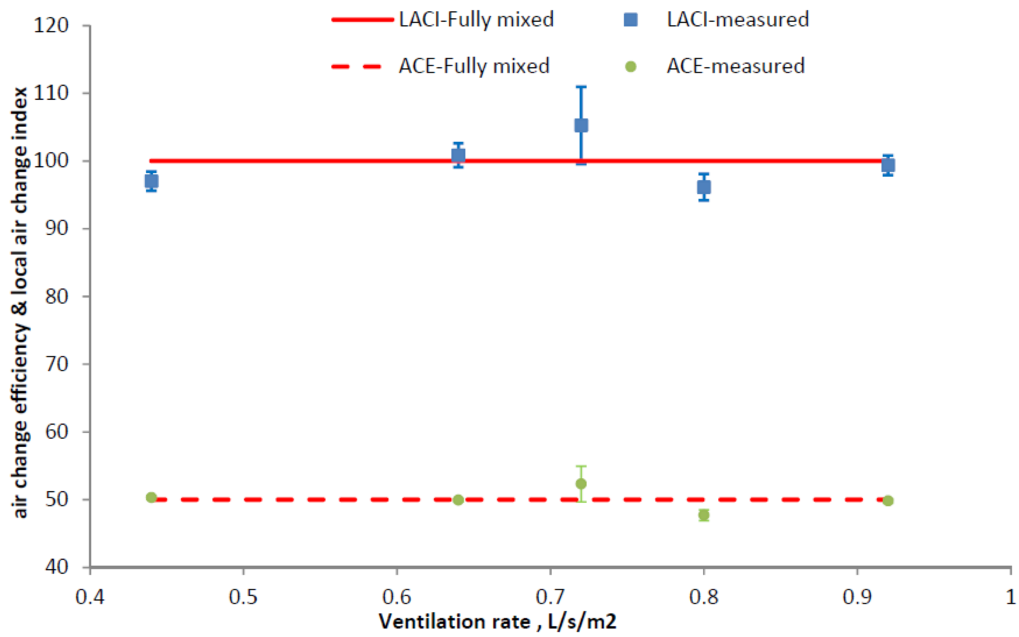


Figure 65 Calculated air change efficiency (ACE) and local air change index (LACI) for five considered ventilation rates

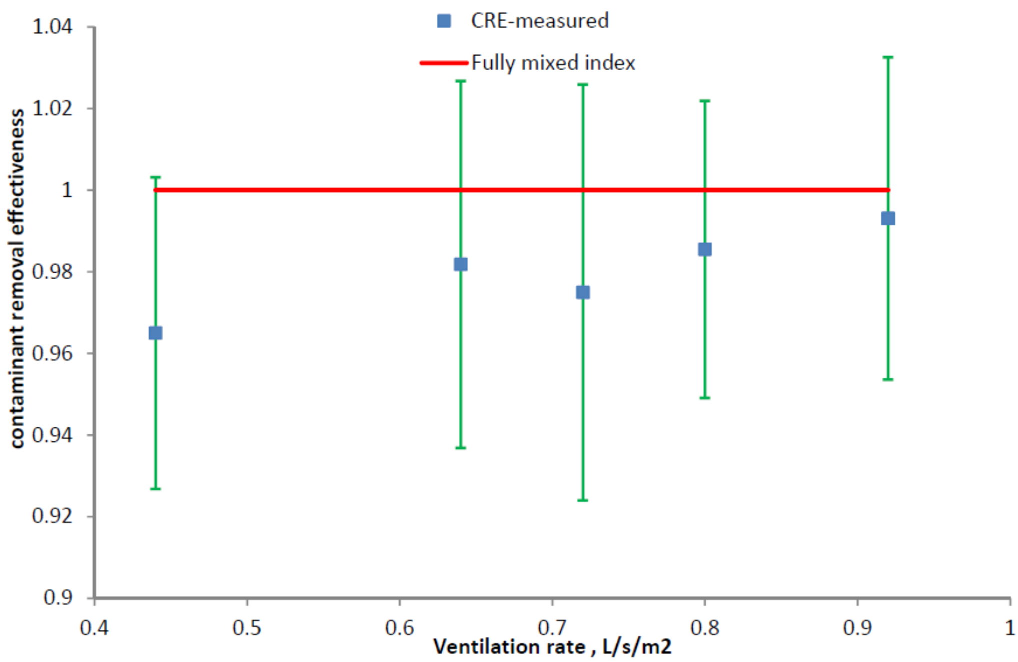


Figure 66 Calculated contaminant removal effectiveness for five considered ventilation rates

4.6 Uncertainty analysis

The measured values during the experiments are subjected to some uncertainties due to the various measurement errors including instruments' precision or observational error. The accuracy, resolution and repeatability of instruments are parts of systematic and random errors in the measurements which can be determined from the technical specification of the used instruments. The continuous and spot measuring instruments, which have been used for the experiments, are listed in Table 13, including their accuracy, resolution and repeatability. Accuracy describes how close the measured value is to the true value, and resolution is the smallest increment, which can be detected by an instrument. Repeatability of a test is defined as the variation of a measured value with same person, instruments and condition in the repeated times. These values can be used to get an idea of the range of true values in respect to the measured values.

Table 13 Measuring instruments and their technical specifications and uncertainties

Parameters & Pollutants	Measuring Instruments	Accuracy/ Resolution / Repeatability
Respirable Suspended Particles (RSP), PM_1, $PM_{2.5}$, PM_{10}	DUSTTRAK™ DRX Aerosol Monitors Models 8533	**Res.**: ± 0.1% of reading or 0.001 mg/m3, whichever is greater
Carbon Dioxide, CO_2	IAQ-CALC™ Indoor Air Quality Meters Model 7545	**Acc.**: ± 3.0% of reading or ±50 ppm, whichever is greater **Res.**: 1 ppm
	Photoacoustic multi-gas monitor Innova 1312	**Rep.**: 1% of measured value
Sulfur Hexafluoride,	Photoacoustic multi-gas	**Rep.**: 1% of measured value

SF_6	monitor Innova 1312	
Total Volatile Organic Compounds (TVOCs)	Portable Handheld VOC Monitor- ppbRAE 3000	**Res.**: 1 ppb
Indoor Air Velocity, V_{ar}	Kanomax Anemomaster Model A031 Series	**Acc.**: ± 2% of reading or ± 0.015 m/s whichever is greater **Res.**: 0.01m/s
Surface Temperature, T_s	Fluke Dual Input Contact Digital Thermometer 54-ii	**Acc.**: ± 0.05% of reading or ± 0.3 °C
	Fluke Building Diagnostic Thermal Imagers Models: TiR32, IR fusion technology	**Acc.**: ± 2 °C or 2 % (at 25 °C nominal, whichever is greater)
Mean Radiant Temperature, $\overline{T}_r$	Testo Globe Thermometer	**Acc.**: ± 0.5 °C
	Globothermometer BabucA	**Acc.:** ± 0.14 °C **Res.:** ± 0.01 °C
Temperature, T_a	Onset HOBO data loggers U12	**Acc.:** ± 0.35 °C **Res.:** ± 0.03 °C
	Sensirion Pin-type digital sensor, SHT75	**Acc.**: ± 0.3 °C **Res.**: ± 0.01 °C
Relative Humidity, RH	Onset HOBO data loggers U12	**Acc.:** ± 3.5 %RH **Res.:** ± 0.03 %RH
	Sensirion Pin-type digital sensor, SHT75	**Acc.**: ± 1.8 %RH **Res.**: ± 0.05 %RH
Water flow temperature, T_W	Onset HOBO data loggers T type Thermocouples	**Acc.**: ± 1.5 °C
Water flow rate, F	Parker inline flow transmitter	**Acc.**: ± 2 % of measured value **Rep.**: ± 1% of measured value

In addition to independent measured variables, there are some dependent variables which are calculated as a function of measured values. The measurement uncertainties are propagated into those dependent parameters and the level of diffusion depends on the function and number of variables in the calculated formula. The propagated uncertainties for the introduced dependent variables in this thesis are listed in Table 14. These values were calculated for each parameter based on the corresponding mathematical formula and mean values in the operational range of the relevant independent variables. An open source calculator called “abacus” has been used to estimate the propagation of uncertainty in dependent parameters based on the mean values and range of independent variables.

Table 14 Propagated uncertainties in the introduced dependent variables

Dependent parameters	Calculated variables	Propagated uncertainty
Dew Point temperature, T_d	Temperature-T, Relative Humidity-RH	± 0.9 °C
Operative temperature, T_o	Temperature-T, Mean Radiant Temperature-$\overline{T}_r$	± 0.2 °C
Air Change Rate, ACR	Sulfur Hexafluoride, SF_6	± 0.008 (± 0.6 %)
Air Change Efficiency, ACE	Sulfur Hexafluoride, SF_6	± 1.2 (± 2.5 %)
Contaminant Removal Effectiveness, CRE	Carbon Dioxide, CO_2	± 0.014 (± 1.4 %)
Local Air Change Index, LACI	Sulfur Hexafluoride, SF_6	± 2 (± 2.1 %)

4.7 CFD results

Verification and validation are essential stages of any CFD simulation in order to achieve reliable results and confidently employ the outcomes for design process. CFD verification is a process for evaluation of numerical uncertainty through examining programming code, iterative convergence, grid convergence and comparing with benchmark numerical solutions. On the level of consistency with physical reality, CFD validation is defined as the evaluation of modelling accuracy through comparing of simulated results with benchmark experimental data and estimating the modelling error. In this investigation, verification of CFD simulations was assessed for three turbulence models (k-ε, RNG k-ε, k-ω SST) and two mesh densities of 355 K (coarse) and 1467 K (fine). The predicted temperatures at different locations (A-B-C-D) and heights (0.1-1-1.8 m) were compared to measured data in Table 15. Temperatures at these points were monitored over 5000 iterations steps of CFD scheme in order to obtain iterative independent values. The average percent error of CFD predictions compared to eleven measured data points in the space was around 2 %. The estimated temperature values with k-ω SST turbulence model were slightly closer to measurements while accuracy of all three turbulence models was in the acceptable range. It is noteworthy that computation time for fine mesh simulations was around 120,000 seconds which was about six times more than coarse mesh simulations. There was no considerable difference in running time for different turbulence models, although discretization scheme needed to be modulated to achieve convergence in all scenarios.

Table 15 Measured and simulated temperatures and percentage error of CFD predictions compared to measured data at several points in the space

	A10	**A100**	**A180**	**B10**	**B100**	**B180**	**C10**	**C100**	**C180**	**D10**	**D100**	**D180**	
Measured temp. / **Mesh density, Turbulence model**	21.6	22.8	N.A.	21.0	23.3	23.6	20.7	23.4	23.7	21.2	22.9	23.5	**Ave. Error (%)**
355k, k-ε	22.4	23.0	23.1	22.4	23.0	23.1	21.7	23.0	23.2	22.0	23.0	23.3	**2.5**
1467k, k-ε	22.4	23.0	23.1	22.5	23.1	23.1	21.9	23.1	23.2	22.1	23.1	23.3	**2.7**
355k, RNG k-ε	22.3	23.0	23.1	22.2	23.0	23.1	21.5	23.0	23.2	21.9	23.1	23.3	**2.3**
1467k, RNG k-ε	22.4	23.0	23.1	22.4	23.1	23.2	21.8	23.1	23.2	22.1	23.1	23.3	**2.5**

355k, k-ω SST	22.1	23.0	23.1	22.1	23.1	23.1	21.5	23.1	23.2	21.8	23.1	23.3	**2.1**
1467k, k-ω SST	22.3	23.1	23.2	22.4	23.1	23.2	21.8	23.1	23.3	22.0	23.2	23.3	**2.4**

Predicted vertical thermal stratification with different turbulence models and mesh densities at a point (C) in the centre of the BubbleZERO are plotted in Figure 67 including measured data range. The temperature profile is specific to the conditioned space with floor air supply and ceiling panel where air is cooler near floor and chilled ceiling. Since heat transfer near chilled ceiling occurs mostly through radiation rather than convection, the slope of transition from mid-height level temperature to ceiling is steeper than that of floor to mid-height values. The predictions are closer to experimental data at mid-height temperature while near floor and ceiling, the difference is more pronounced. CFD simulations with fine and coarse mesh elements resulted in similar temperature profiles except near cooling panels where there is a slight difference between them. Overall, the curves are fairly close to each other which shows the negligible impact of turbulence model and cell size on CFD predictions for these types of flow patterns.

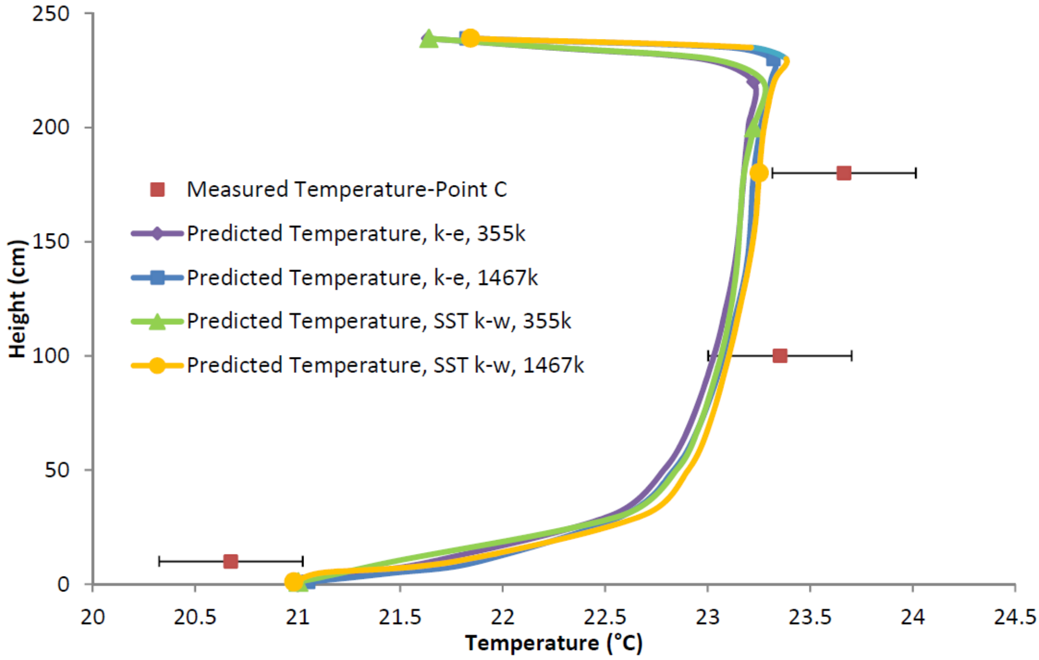


Figure 67 Predicted thermal stratification with different mesh densities and turbulence models vs measured data at point C in centre of laboratory

A verified and validated CFD model can be employed for evaluation and optimization of design parameters of air conditioning and distribution systems of indoor spaces. CFD simulation can provide detailed information on spatial variations of indoor air parameters like air velocity and temperature. These types of elaborate information require intensive placement of sensors in the indoor space if it would be acquired through experiments. These results could reveal possible thermal comfort and indoor air quality issues which could occur from pollutant sources locations or other space design parameters. After verification and validation of the CFD model for the BubbleZERO, the results were utilized to evaluate thermal comfort and IAQ performance of DDOAS-RCP concept with FS-CE distribution strategy in the tropical context. The interaction of human body thermal boundary layer with supply air coming from floor diffusers was also explored based on obtained CFD results.

The predicted air velocity and temperature contours near floor diffusers are shown in Figures 68 and 69, respectively. Air velocity is less than 0.1 m/s in most of locations in the interior space except near floor diffusers and exhaust points. The details of supply air openings, including dust collection basket and floor swirl diffuser were not modelled in this simulation so the actual velocity pattern near diffuser are expected to be more uniform in reality. It can be observed in Figure 68 that the temperature in the radius of 0.2 m from floor diffusers is in the range of 18 °C which raises the concern of cold feet for occupants seated close to them. In the conducted experimental scenarios, cool outdoor air was supplied at temperatures in the range of 13-14 °C and this operational condition caused low air temperature conditions at diffuser outlet. Besides locations nearby to diffusers, temperature is approximately 21 °C at feet level which rises to the range of 23 °C at breathing level. Below the chilled ceiling, only a 0.05 m layer of cool air was formed, since radiation is the main heat transfer mechanism from panel surface to the BubbleZERO space.

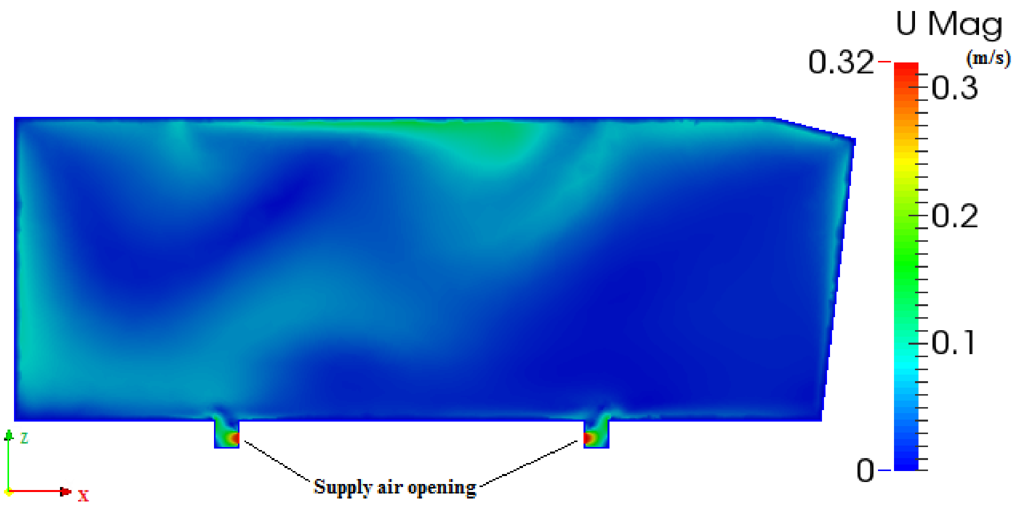


Figure 68 Predicted air velocity pattern near diffusers

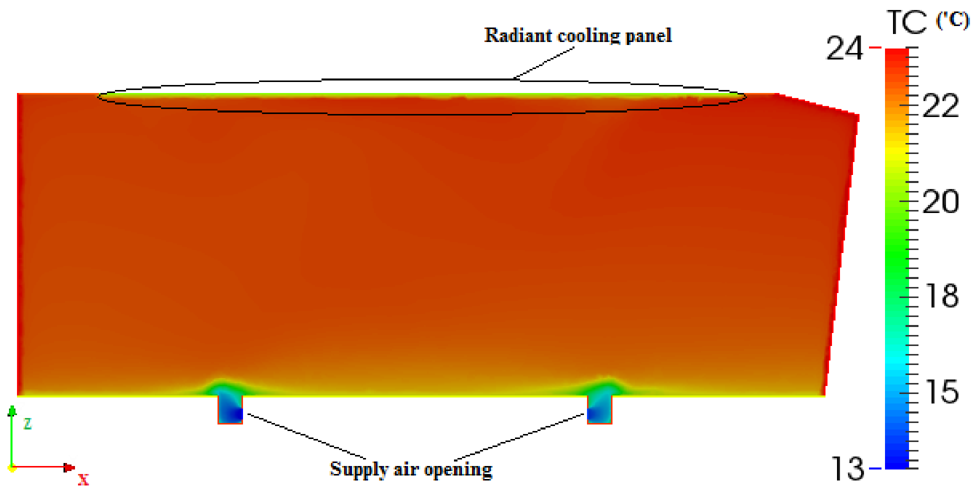


Figure 69 Predicted temperature distribution near diffusers

The thermal plumes generated around a seated human body in the space are illustrated in Figures 70 and 71. There is a considerable increase of air velocity above the head of the simulated occupants where buoyancy flow starts forming above the chest area. Similar observations on rising thermal plume above the head of human body have been reported in several numerical and experimental studies in the literature (Gao and Niu, 2004; Sørensen and Voigt, 2003). The air temperature adjacent to human body segments is warmer than average temperature of the space. The warm plume grows over the chest and face and it extends to about 1 m above the head before fading away near the ceiling. The heat generated by laptop also caused a small thermal boundary layer around its hot surfaces. Figure 72 displays the velocity vector field for the whole interior space where vectors are scaled by air velocity magnitude and they are coloured by temperature index. The velocity field near and above occupants head is stronger than at other points in the space and this natural convection flow is mainly vertical toward the ceiling. Besides seven supply air openings near the floor, air speed is also high near exhaust openings at two sides of the façade where air leaves the space. No prevailing air velocity vector was observed in upward direction and there was random velocity fluctuation everywhere except for vertical buoyancy flow around human body.

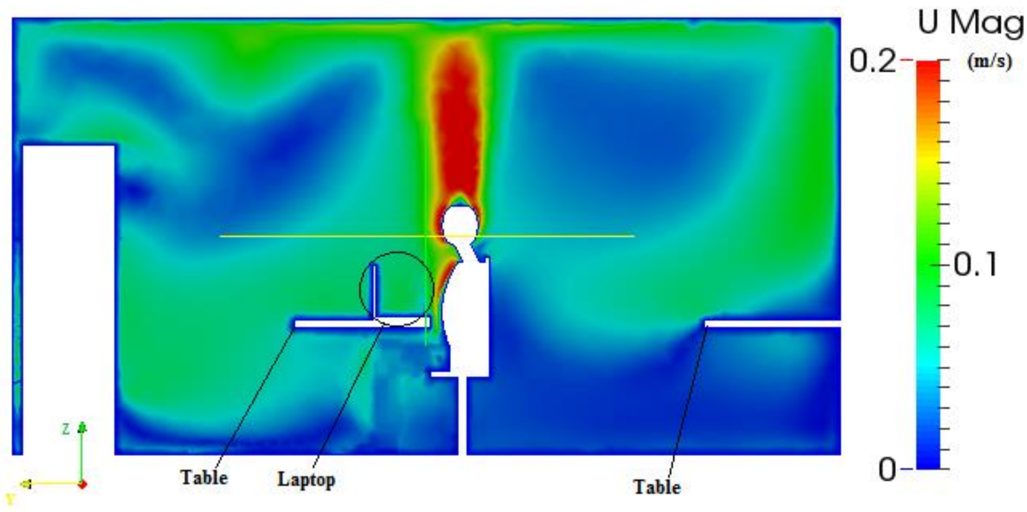


Figure 70 Predicted air velocity pattern near human body

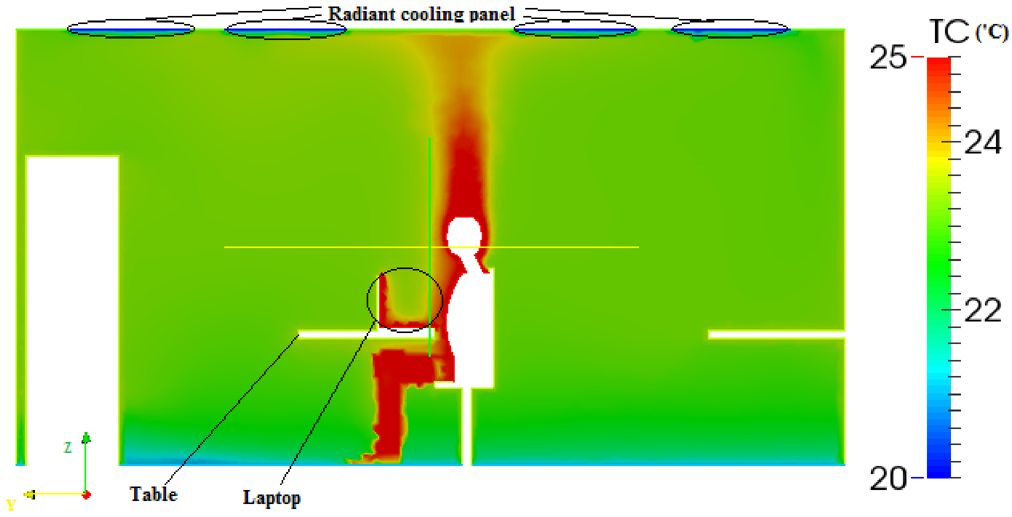


Figure 71 Predicted temperature distribution near human body

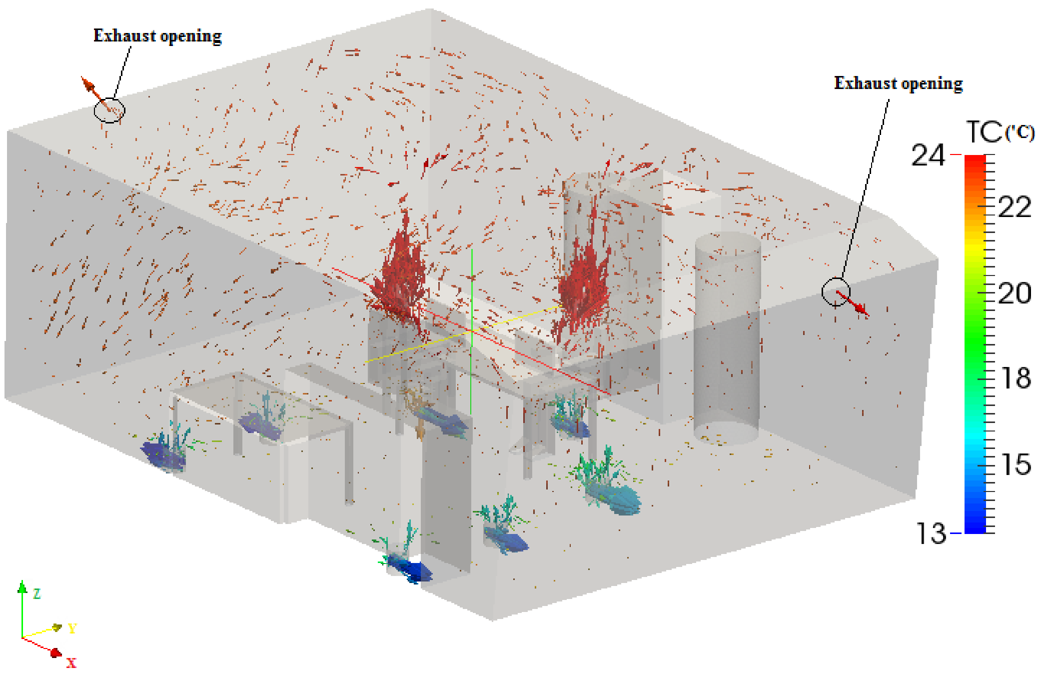


Figure 72 Velocity vectors in the BubbleZERO scaled by velocity magnitude and colored by temperature

Surface temperature of radiant cooling panel is a key design parameter in operational condition of DDOAS-RCP. This design parameter plays a critical role in the tropical context where condensation risk is more serious than in a moderate climate and control of indoor humidity level is essential. On the one hand, panel surface temperature needs to be above indoor dew point level, but on the other hand, higher surface temperatures decreases panel cooling capacity and its effectiveness for satisfying sensible cooling load of space. The indoor dew point temperature is in the range of 17 °C for comfort criteria of 24 °C dry bulb temperature and 65 % relative humidity (SS 554, 2009). For the previous simulations, a uniform temperature of 20 °C was assumed over the whole panel surface. However, an infrared image of the panel installed in the BubbleZERO showed that in reality there could be up to 3 °C temperature difference over the panel surface. In this investigation, the validated and verified CFD model has been employed to get a better understanding of the impact of panel temperature on indoor space condition. Simulations were conducted for several uniform panel surface temperatures in the range of 18 to 22 °C while other boundary conditions were fixed. The radiant flux absorbed by radiant panel under various panel surface temperatures is shown in Figure 73. The radiant capacity of panel which is 43 W/m^2 at 18 °C panel surface temperature drops to 13 W/m^2 at 22 °C surface temperature, a decrease of 10 W/m^2 in capacity per 1 °C surface temperature increase. This steep reduction in radiant flux of panel with a small increase in surface temperature can be explained based on the Stefan-Boltzmann law, which shows the driving force in the radiant heat transfer mechanism is the difference between fourth power of panel and surrounding surfaces temperatures. The estimated capacity of radiant ceiling panels based on design guideline of ASHRAE handbook (2008) is also shown in Figure 73. This design guideline under area-weighted average uncooled surfaces temperature (AUST) of 23.5 °C provides lower estimation compared to CFD predictions which could be caused due to the uncertainties in measurements of boundary conditions. The results of simulations also revealed that convective flux constitutes 15 % of total heat flux absorbed by radiant panels and this flux rate drops for higher panel surface temperature at slightly lower rate compared to radiant flux.

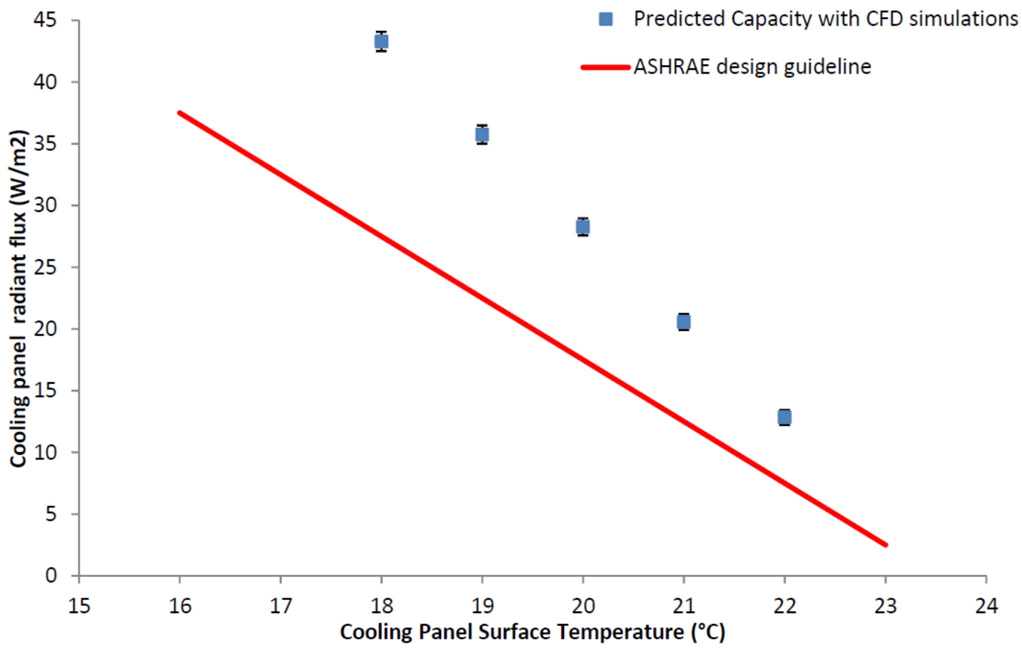


Figure 73 Radiant flux of cooling panel for various panel surface temperatures under area-weighted average uncooled surfaces temperature (AUST) of 23.5 °C

The impact of panel surface temperature on vertical thermal stratification of the indoor space conditioned with DDOAS-RCP is illustrated in Figure 74. In all the scenarios, there is a steep increase in air temperature up to 0.5 m height, and above that, the steepness of the curves drops except for the points directly below the ceiling panel. For a panel surface temperature of 18 °C the indoor space has an almost one degree lower head to ankle temperature difference compared to the scenario when the radiant ceiling panel is switched off which is 2.5 °C. A similar observation has been reported by Schiavon et al. (2012) for a chilled ceiling system combined with displacement ventilation in which room air stratification increased with higher radiant ceiling surface temperatures.

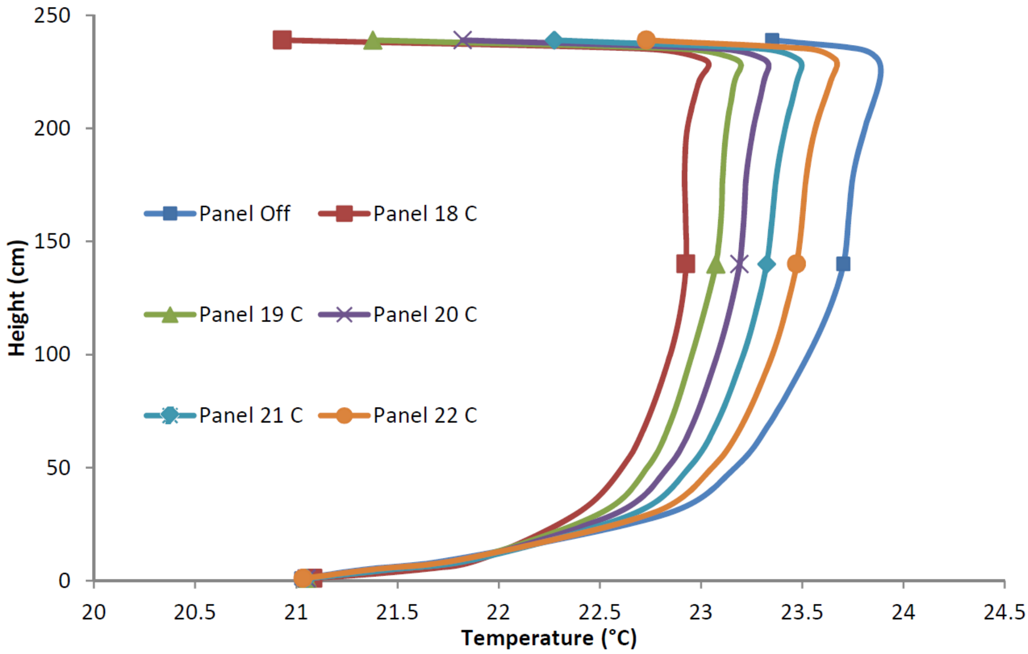


Figure 74 Predicted air temperature for various panel surface temperatures under area-weighted average uncooled surfaces temperature (AUST) of 23.5 °C

It has been shown in Figure 73 that a lower panel surface temperature results in a significant increase of panel radiant flux. However, not all of this increase in radiation would directly or indirectly impact thermal comfort of occupants since some part of it would be transferred to hot façade surfaces and result in higher heat gain to the space. It was shown in a simulation study (Feng et al., 2013) that 24 hours cooling energy of radiant cooling system could be 5 to 15 % higher than air systems due to the increase of conduction heat transfer from the facade. The validated CFD model has been employed to explore the emitted radiant flux of different body segments under various panel surface temperatures. The level of increase in radiant flux for five body segments including chest-head, hand-arm, abdomen, calf-thigh and feet are depicted in Figure 75. Head, chest, hand, and arm for a seated occupant working on a table have the highest view factor toward the radiant ceiling panel and the most significant increase in radiant flux can be observed for these parts of body. The amount of increase in radiant flux ranges between 2 to 5 % compared to panel off scenario for panel surface temperatures in the range of 18 to 22 °C. The abdomen, thigh and calf areas of a seated human are mostly hidden by the table surface from radiant panel and the increase of flux is less significant for these parts. Since no modesty panel installed on the table inside the BUbbleZERO, feet is mostly viewed by ceiling panel and there is a 4 % increase of heat flux for this part at a panel temperature of 18 °C compared to panel off scenario.

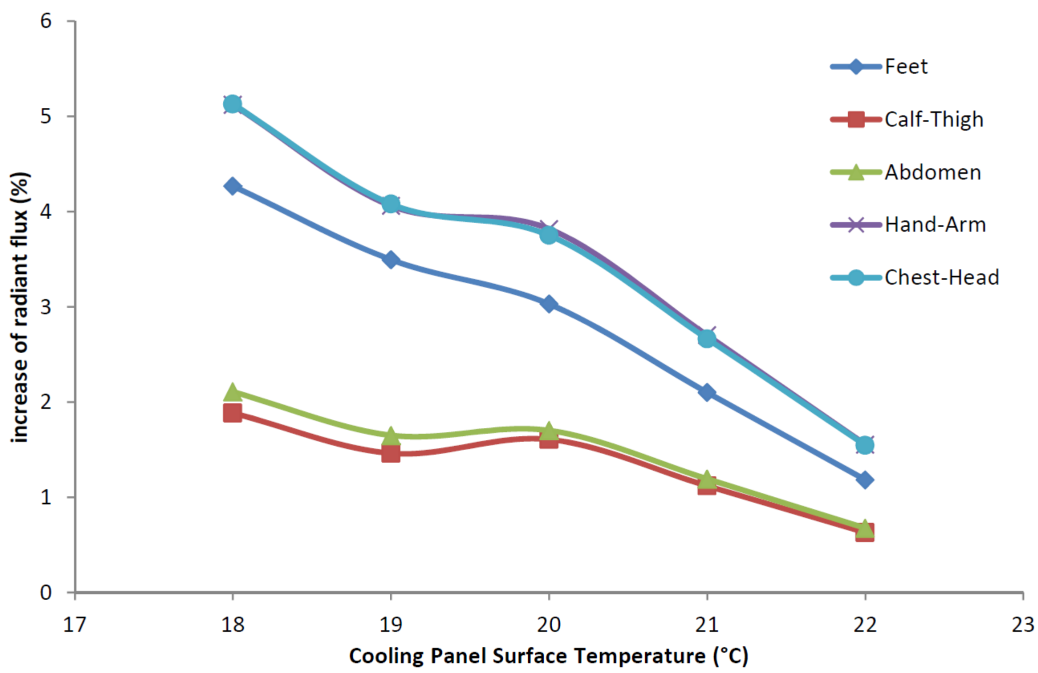


Figure 75 Increase in radiant flux compared to panel off scenario for different human body segments

4.8 Integration with low lift chillers

In the introduced DDOAS-RCP system, chilled water is supplied to radiant panel at temperature of 16 °C while in conventional design, the supply temperature is around 6 °C. COP of refrigeration systems in the tropical context of Singapore with assumed outdoor temperature of 30 °C (ranges between 27 to 33 °C) can be calculated as follows in Eq. 10-11,

$$COP_{Carnot,low\ temperature} = \frac{T_c}{T_h - T_c} = \frac{273.15+6}{30-6} = 11.6 \qquad \text{(Eq. 10)}$$

$$COP_{Carnot,high\ temperature} = \frac{T_c}{T_h - T_c} = \frac{273.15+16}{30-16} = 20.6 \qquad \text{(Eq. 11)}$$

Based on the theoretical Carnot cycle, there is a 77 % increase in operational COP of chillers for the high temperature cooling system in the tropical climate of Singapore. However, because of the exergy losses in different sub-processes inside the chiller, the COP of actual refrigeration systems operating in cooling system of buildings are far below the theoretical Carnot values. The level of increase in COP for high temperature cooling is also less likely to be in the same order. In addition, radiant cooling system in DDOAS-RCP design only satisfies part of space cooling load. It was shown in the Section 3.3 that radiant cooling panel covers around 20 to 30 % of space cooling load and the rest of the load is still required to be met with low temperature cooling systems like decentralized air supply units.

The ideal Carnot and actual COP of typical air cooled and water cooled chillers under various temperature lift at evaporative temperature of 5 °C are shown in Figure 76. The cooling capacity and electricity usage of a 9 kW air cooled chiller with hermetic reciprocating compressor and a 100 kW water cooled chiller with scroll compressor were obtained from the available data in the catalogue of selected manufacturers. The COP of the small size air cooled condensing unit is around 2 over the range of temperature lift while efficiency of the large size water cooled chiller is in the range of 4. For the same range of temperature lifts, the ideal Carnot COP drops from 11 at 25 °C lift to about 6 at 45 °C. The exergy loss in the refrigeration system components brought down the efficiency far below the ideal scenario and also the potential saving for low temperature lift conditions has not been utilized in these chillers.

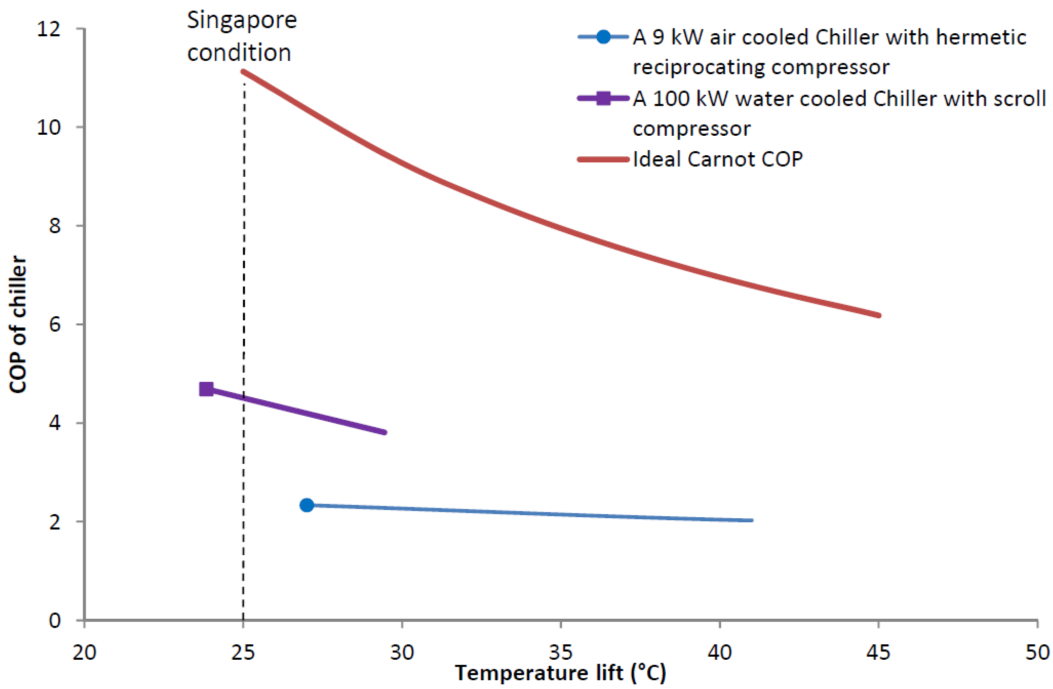


Figure 76 COP of ideal Carnot cycle and a small size chiller at evaporative temperature of 5 °C

The chillers in building cooling system are usually designed and regulated to efficiently provide chilled water at temperature of 6-7 °C which matches the requirement of conventional air conditioning system in buildings. Custom designed chillers for low temperature lift conditions have been introduced and investigated by some research institutes and manufacturing companies for high temperature cooling applications or other process cooling requirements. Doyon

(2008) investigated the critical design parameters of centrifugal chillers for superior efficiency at low temperature lift conditions. He found open-drive/gear-drive compressors with variable orifice and oil education system as the most suitable features in chillers for the high temperature cooling applications. He also concluded that chillers with hermetic drive motors and fixed variable orifice would not be able to utilize the potential energy saving of HTC operational conditions due to the required high head pressure for cooling of motor windings. The oil management system in open-drive centrifugal chiller needs to be employed with an oil education system to separate oil from refrigerant in the evaporator and avoid oil loss in low temperature lift applications. In a collaborative project for implementation of the low exergy system in the Switzerland, Wyssen et al. (2010) designed a chiller prototype for low temperature lift conditions which was equipped with a semi-hermetic reciprocating compressor. The outcomes of this research showed that at evaporative temperature of 15 °C, the COP of this chiller increases from 4 at 40 °C temperature lift to about 11.4 at 13 °C lift. The COP of this custom designed chiller as well as ideal Carnot and typical air/water cooled chillers are plotted in Figure 77. It can be seen that performance curve of this prototype chiller fits in between typical chillers and ideal efficiency curves. The low lift chiller performs better than air cooled/water cooled chillers both in terms of COP value at any specific lift and increase rate for lower temperature lift. This shows some part of exergy losses in chiller sub-processes has been eliminated in this design. It is noteworthy that the 9 kW air cooled chiller has been installed in the BubbleZERO and the measured COP of this chiller was in agreement with the reported values in the catalogue of the manufacturer.

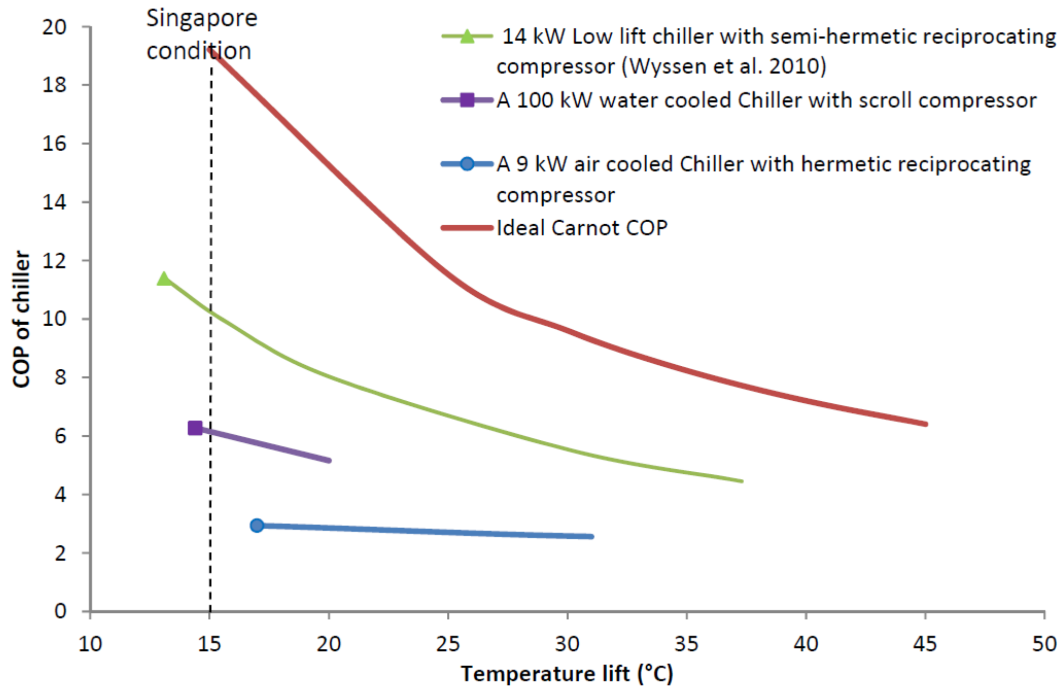


Figure 77 COP of ideal Carnot cycle, low lift chiller and two typical air cooled/water cooled chillers at evaporative temperature of 15 °C

Exergetic efficiency or g-value could be employed to get a better understanding on the performance of the abovementioned chiller types against the ideal Carnot cycle. g-value is defined as the ratio of chiller actual COP to the ideal Carnot when operating between the same hot and cold sources (Eq. 12).

$$g - value = \frac{COP_{chiller}}{T_C/(T_H - T_C)} \qquad \text{(Eq. 12)}$$

This value represents the chiller inefficiency in terms of exergy losses in sub-processes in the refrigeration components of chiller (Bruelisauer et al., 2014). The exergetic efficiencies of the low lift chiller as well as the typical air cooled/water cooled chillers are plotted in Figure 78. It can be seen that g-values of typical chillers range between 0.2 to 0.4 which indicates that there are considerable exergy losses in their refrigeration system. On the other hand, g-value of the low temperature lift chiller is in the range of 0.5-0.6 and it performs better in terms of exergy losses within the chiller.

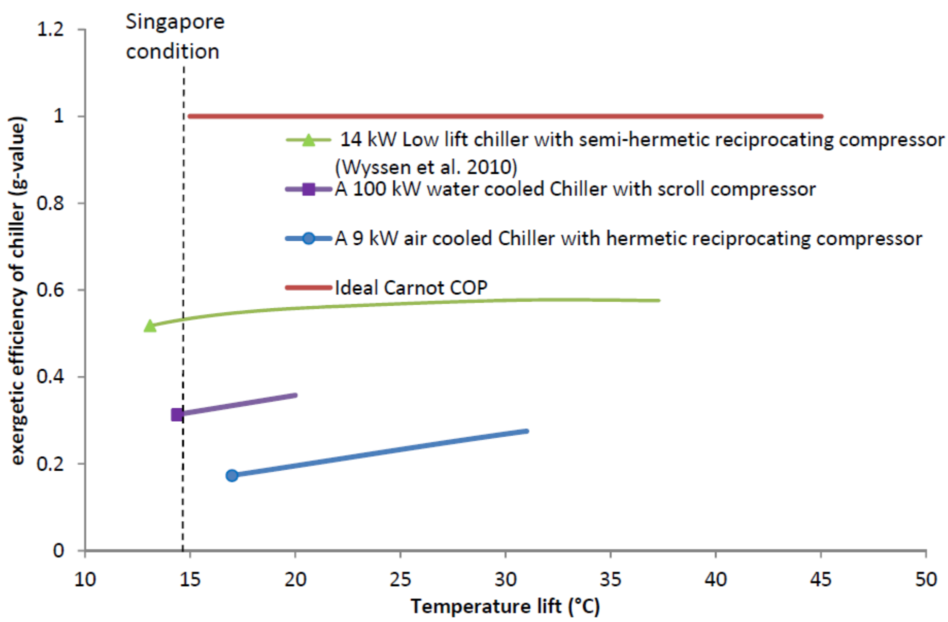


Figure 78 Exergetic efficiency of the low lift chiller and the two typical air cooled / water cooled chiller at evaporative temperature of 15 °C

4.9 Energy/Exergy saving potentials

Building energy simulation has been conducted for a hypothetical one-storey office building in the tropical climate of Singapore. The monthly electricity consumption of this building for different stacks of building services are shown in Figure 79. In this base design scenario, the all air ACMV design has been simulated to distribute the conditioned air from AHU room to different thermal zones. VAV boxes with no reheat were considered in this simulation to modulate the amount of supply air to each thermal zone based on cooling demand of that space. The details of building layout and conditioned areas are presented in Section 3.9. This one-storey building has the total area of 700 m^2 in which 584 m^2 floor area is conditioned and the rest is non-conditioned or naturally ventilated. As expected for the tropical climate of Singapore, cooling or chiller electricity consumption constitutes the biggest piece of the bar every months of the year. Lighting and interior equipment like computer also consumes considerable amount of energy in office building which indirectly would add to the cooling load of space. ACMV fan and pump energy use are the smallest stacks in the monthly bar charts of building energy use. Supply and return fans were considered for AHU to supply and extract air to and from zones. Water pump was also considered for ACMV system to distribute provided chilled water by chiller to the AHU. For this ACMV design and building configuration fan energy use was predicted to be almost three times more than pump electricity consumption.

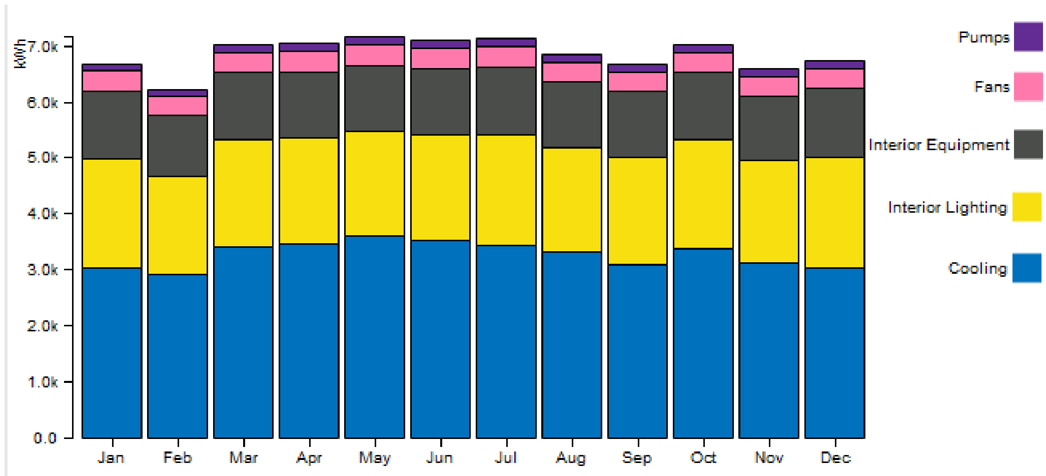


Figure 79 Monthly electricity consumption of the simulated one-storey building for different stacks of building services

The simulated building with the all air ACMV system has total annual energy use of 82 MWh in which 45 MWh is consumed for air conditioning system. It was attempted to estimate the ACMV energy use of this hypothetical building when it is conditioned with a high temperature cooling design like DDOAS-RCP. For this air-water cooling system it is expected that fan energy use significantly drops while there would be an increase in pump electricity consumption. It was shown by several studies in the literature (Khan et al., 2015; Vangtook and Chirarattananon, 2007) that fan energy consumption can be reduced up to 70 % through implementation of DOAS combined with radiant cooling system. It was also reported in these investigations that pump energy use is expected to increase by up to three times due to the higher required water circulation in the building. With implementation of high temperature cooling, more significant energy saving could be achieved when a separate low lift chiller was incorporated to provide chilled water for HTC system. The results of experimental setup in the BubbleZERO (Section 3.3) revealed that radiant cooling panel in DDOAS-RCP satisfies between 20 to 30 % of space cooling load. Chiller COP of 5.5 for LTC system and 10 for HTC system based on the prototype low lift chiller of Wyssen et al. (2010) were assumed in this investigation. For current radiant panel design and building configuration, it is estimated that there would be 10 % energy saving for implementation of DDOAS-RCP when HTC is connected to a low lift chiller (Figure 80). The variations of this estimated saving value from the available data in the literature has been shown in this graph as error bars. This amount of saving could be increased to 18 % if the contribution of HTC is enhanced for satisfying the cooling load of space from 30 to 50 %. This modification could be achieved through increasing the number of chilled water passes behind the panel or improving the airtightness of the façade. It is noteworthy that energy saving terms in this analysis are determined based on pure exergy sources like electricity and the values would be equal to exergy saving percentages.

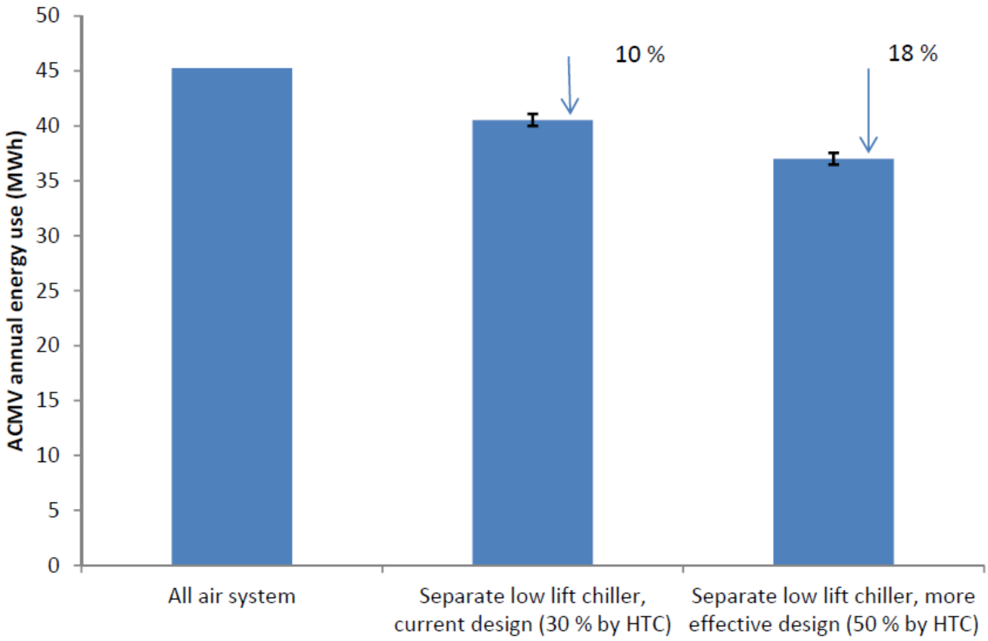


Figure 80 predicted annual energy saving of high temperature cooling for the hypothetical one-storey building

Chapter 5. Discussions

5.1 Decentralized air supply units

The results of experiments for different arrangements of heat exchangers (HX) inside the decentralized air supply units showed that the arrangement of HX has some impact on off coil condition of units (Figure 33). In the case where two HX is utilized for cooling and one for reheating, both off coil temperature and dew point are higher compared to the case where all the three HX are employed only for cooling. The first arrangement brings less concern regarding the cold feet issue near diffusers, although it provides less dehumidification capacity. The locations of decentralized unit and air ducting path to floor diffusers could be the deciding point for choosing the right heat exchanger arrangement. If enough reheating can be provided to the air stream inside a lengthy path with low insulation duct material, then the second arrangement would be more suitable. However, in the cases where there is a short distance between decentralized unit and floor supply, first arrangement of HX can provide some level of reheating to rise supply air temperature. The number of heat exchangers inside decentralized unit and arrangement of cooling coil in terms of chilled water supply order can be further optimized to provide suitable supply air condition.

The results of regression analyses have shown that there are significant correlations between decentralized unit's off coil temperature/capacity and its operational conditions (Tables 9 and 10). At supply temperature in the range of 8 to 10 °C, the capacity of unit is approximately 1000 W (Figure 34). Unit's off coil temperature is almost 2 °C degree above the supply water temperature and it varies between 10 to 12 °C for the above range (Figure 36). This range of temperatures requires some level of reheating before being supplied from floor diffusers. Air flow rate and chilled water flow rate are other influencing variables for off coil condition of units. To have a fixed off coil temperature under part load condition, one can reduce chilled water flow rate or increase air flow rate passing through units. The volume of supply air flow in DDOAS-RCP is usually determined by the ventilation requirement of space rather than the latent load of the space. However, this design consideration may shift to latent load satisfaction for spaces with high latent load. Reduction of chilled water flow rate could be a better strategy for handling part load scenarios, although its impact is less effective than raising the supply water temperature. Increasing supply water temperature above 10 °C is not recommended as a control strategy for part load since that could increase the SHR of coil and humidity level of space. Based on the local standard of SS 554 (2009) in order to avoid IAQ issues, it is advised to keep the indoor humidity level below 65% and 70 %, respectively for new and existing buildings. The capacity of the unit fluctuates for about 300 W from morning till afternoon when outdoor temperature varies between 27 and 33 °C (Figure 40). Increase of enthalpy difference between on coil outdoor air and coil surface temperature could result in increase of capacity.

Actual application of DDOAS-RCP in high rise buildings in the tropical climate would have some practical implications in terms of installation of decentralized air supply units into floor. Outdoor air openings at different locations of façade are required to be properly designed to avoid penetration of rainwater into buildings. The type of air filter inside the units needs to be selected based on level of dust and haze in outdoor air. Two strategies could be chosen for distribution of air into different parts of floor layout. In the first strategy, decentralized air supply units are not connected to each other and they provide dehumidified outdoor air directly to zones near the facade and core of the building. In the second strategy, decentralized units are connected through an interlaced duct network which is integrated into floor construction (Baldini and Meggers, 2008). The first strategy is simpler and more straightforward in the aspect of control of indoor conditions in different thermal zones. The interlaced network system can lower the pressure drop in distribution of air to zones in the core of building, although it adds complexity to dusting system and control of thermal zones.

5.2 Radiant cooling panel

The infrared image of radiant cooling panel illustrated the non-uniformity of temperature on panel surface (Figures 44 and 45). The area behind chilled water pipe was found to be colder than other areas. This variation of temperature could degrade the capacity of panel and impose further restriction regarding the condensation risk for a fixed average panel temperature. For the investigated radiant panel with a two-pass pipe, 3-4 °C temperature variation was observed on the panel surface and there is potential to reduce this variation by implementing a four-pass chilled water pipe. This change could also enhance the cooling capacity of radiant panel per surface area. However, a higher number of water pipe loops means increased cost of piping and pressure drop in hydronic system. The design specification of radiant panel needs to be optimized based on trade-off considerations between cooling capacity and cost.

The measurement results on radiant panel revealed that capacity of RCP rises up in afternoon due to the higher sensible cooling load in the space compared to morning. This observation brings the question that whether implementing radiant cooling panel potentially leads to increase of cooling load for space. It has been reported by several studies in the literature and there would be an increase of building cooling load for the implemented cases of radiant cooling compared to the all air system (Feng et al., 2013; Olesen, 2008). Nevertheless, this concern is more relevant to floor cooling systems and it is improbable of sun shine incidence on cooling panel near the ceiling. Chilled water supply temperature was found to be effective in influencing the capacity of RCP as well as chilled water flow rate (Table 11). For cooling of space under part load conditions, one could increase chilled water supply temperature or reduce water flow rate to radiant ceiling panel. Utilizing a three-way control valve for achieving a well-controlled supply temperature could be a more effective control strategy for handling part load conditions compared to modulation of water flow rate scheme. The results of experiments revealed that there is an estimable offset value between chilled water supply temperature and average panel temperature. This observation shows that attaining any desired panel surface temperature is plausible with a modular supply water temperature which is necessary for the tropical context to avoid condensation under various indoor/outdoor scenarios.

5.3 DDOAS combined with RCP

DDOAS-RCP with floor supply-ceiling exhaust and radiant ceiling panel provides a unique type of conditioned indoor space which exhibits different characteristics to the all air conditioning system. This design is a combination of decentralized concept with radiant cooling system in which low momentum flow is supplied from the floor diffusers. The results of measurements in the BubbleZERO have shown that there is a two degree vertical thermal stratification for this design and configuration (Figure 51). The level of vertical thermal stratification for a typical DV+CC design could be up to 4 ˚C (Schiavon et al., 2012). The temperature gradient was found to be steeper below 1 m height due to the positioning of air supply diffusers on the floor. This distribution pattern is prone to change for other configurations of supply and exhaust diffusers. It is expected that space temperature would be more uniform for ceiling supply-ceiling exhaust distribution strategy of this design. Ceiling cooling panel resulted in having mean radiant temperature 2 °C lower than dry bulb temperature in the areas below the panel (Figure 52). The level of difference between mean radiant and dry bulb temperature for the actual implementation of DDOAS-RCP in buildings could vary based on cooling panel coverage ratio and façade heat gain. Based on the Singapore standard of SS 554, operative temperature can be defined as $T_o = \frac{T+\bar{T}_r}{2}$ for occupants with metabolic rates between 1 and 1.3 met, not in direct sunlight and being exposed to air velocities less than 0.2 m/s. The recommended operative temperature based on this standard is within 24 to 26 °C.

The measured values on system components of DDOAS-RCP revealed that radiant cooling panel satisfies about 20 to 30 % of space sensible load (Figure 53). This percentage value is the key measure to evaluate the effectiveness of this design strategy for tropical buildings. In the ideal scenario, it is expected that HTC system provides the main part (⩾ 50 %) of space sensible cooling. This ideal scenario would result in more energy saving compared to the conventional design since HTC can play a more significant role in cooling of space and the required chilled water can be provided at higher efficiency. LTC or the air based system is designated to mainly cover the latent cooling and ventilation needs of space. These facts make this design more suitable for spaces with high sensible load or sensible heat ratio. The estimated SHR of the BubbleZERO was in the range of 0.5 to 0.6 (Figure 53) from morning to afternoon which is close to typical cooling profile in Singapore office buildings (Sekhar and Tan, 2009). Providing an airtight façade is a prerequisite for implementation of high temperature cooling in the tropical context to enhance the effectiveness of this design. The Singapore standard of SS 212 (2007) provides a guideline for acceptable leakage rate of windows on the envelope and doors opening to non-conditioned areas. Improving uniformity level of radiant panel surface and increasing panel coverage area in the space are other tactics for boosting the contribution of radiant ceiling panel. Enhanced cost of system due to the increased piping and metal sheet for radiant cooling panel is the main practical constraint for these tactics. Elevated capacity of RCP means reduced air supply volume and it requires less fan power for circulation.

The outcomes of the simple and multiple regression analyses showed that input variables of system components have significant impacts on indoor air conditions. These outcomes guide us in finding the best control strategies for operation of DDOAS-RCP in actual implementation of this concept in tropical buildings. Both LTCW and HTCW are modulated based on central chilled water plant settings and operational conditions of the air-water system. This is to ensure impactful cooling provided by decentralized units and radiant cooling system without causing condensation on RCP. Modulating LTCW flow rate and HTCW temperature could be the best feasible strategies for operation of DDOAS-RCP under part load conditions. Effective and efficient implementation of these control strategies in building requires real time modulation of three-way control valves and pumps in hydraulic system. The proposed hydraulic system design for implementation of high temperature cooling has been detailed in Section 5.9.

5.4 Thermal comfort and indoor air quality

The conditioned laboratory with DDOAS-RCP was found to be compatible with the local and whole space requirements of thermal comfort standards (Figures 59 and 60). PMV values were in the acceptable range, although it has not been fully accepted in the literature for estimation of locally acclimatized occupants' perception in tropical buildings. Low air movement in indoor space was the only identified comfort deficiency which based on the Singapore standards of SS 554, it should be in a certain range (0.1 – 0.3 m/s). Similar observation has also been reported for application of radiant cooling systems in the tropical context of Malaysia (Kwong et al., 2014; Yau and Hasbi, 2013). The Malaysian standard of MS 1525 (2007) has the recommended air speed range of 0.15 to 0.5 m/s for temperature in the range of 23 to 26 ˚C. This problem can be addressed by using personalized fan on workstations to raise air movement level near the occupants. Higher draft tolerance of locally acclimatized occupants has been observed in a recent study for personally controlled air movement scenarios (Schiavon et al., 2015). Sastry and Rumsey (2014) provided ceiling fan in conjunction with radiant slab cooling and achieved higher satisfaction among occupants compared to the all air system for the tropical climate of Hyderabad in India. However, employing ceiling fans to augment air movement could have consequences on ventilation effectiveness indices and air quality at the breathing level.

The CO_2 level in the conditioned space with DDOAS-RCP can be kept well below the threshold of Singapore standards (700 ppm above ambient level) with the ventilation rate in the range of 0.6 L/s/m^2. On average basis, carbon dioxide concentration was found to be uniform throughout the space. However, there was temporal high level CO_2 concentration near breathing points of occupants. It was also observed that transient and steady state carbon dioxide level in space is strongly correlated with occupancy schedule and ventilation rate. These types of transitional CO_2 concentrations are not uncommon in actual buildings due to the chaotic nature of office activities and occupants' movements from one zone to another. Deploying CO_2 sensors for the spaces where there is high variation of occupancy level like in meeting room could be a good strategy to enhance the performance of DDOAS-RCP. A more sophisticated control strategy of the design needs to be employed to truly utilize the potential benefits of this integration with demand control ventilation.

5.5 Ventilation effectiveness analysis

The outcomes of ventilation effectiveness analysis through tracer gas decay method revealed that the characteristics of DDOAS-RCP with FS-CE distribution are close to mixing strategy and it does not display any substantial displacement features (Figures 65 and 66). This observation could be justified by the fact that the convective force of floor supply air in this design is not strong enough to generate a considerable upward flow pattern in indoor space. The supply air flow rate for this concept is designed to be 1/5 to 1/4 of the all air system with UFAD or DV distribution. Under higher ventilation rates, contaminant removal effectiveness of the system improved slightly. However, no profound correlation was observed between air change efficiency and air change rate of space for the investigated range of ventilation rates (0.44-0.92 $L/s/m^2$). This correlates with findings by Krajčík et al. (2012) who measured the ventilation effectiveness of a mixing strategy with floor heating and concluded that higher ventilation rates does not always result in better ventilation effectiveness. The placement of supply diffusers and arrangement of furniture can also have some impacts on ventilation effectiveness indices in this design.

5.6 CFD simulations

CFD predictions were in close agreements with measured data and the average error for the eleven sampling points was around 2 % (Table 15). It was shown that mesh density and turbulence model do not play important roles on accuracy of simulations for the current indoor air scenarios. Considering the computation cost and convergence complexity of using more sophisticated models and refined mesh, it can be recommended to use the standard k-ε model with coarse mesh for general applications of such a system in buildings. Nevertheless, these results cannot be generalized to all indoor air flow scenarios like rooms with air jets where choosing right turbulence model and refining mesh near inlets have more important impacts. More refined mesh near boundary conditions is required if detailed flow pattern near occupants or other heat sources is needed. In a similar CFD investigation, Zhang et al. (2007) evaluated the performance of eight turbulence models in indoor air simulations and they showed that all turbulence models provide good or acceptable mean temperature and velocity predictions for mixed convections flow regimes. In the current thesis, boundary conditions including air supply condition and interior surface temperatures were set based on actual measured data in the BubbleZERO which facilitated achieving a good level of accuracy with experiments. Concurrent measurements of temperature at indoor air points and interior surfaces are necessary for validation of CFD simulations in actual buildings' conditions where surfaces' temperature change in the course of the day.

It was also shown that air velocity is less than 0.1 m/s for most of the locations in the BubbleZERO except near floor diffuser, exhaust points and above the head of occupants (Figure 68). This low air speed may degrade the comfort level of occupants in the tropics where occupants prefer higher air movement as expressed by the Singapore standard of SS 554, which sets a minimum velocity of 0.1 m/s (SS 554, 2009). The other finding was the cold feet concern for occupants seated near diffusers where the air temperature is around 18 °C in the case of supplied outdoor air at 13-14 °C. Nevertheless, the amount of supply air for an air-water system like DDOAS-RCP is considerably lower than that of the all air system with floor distribution and the cold feet concern is less likely to be a serious issue. In the current design of the system in the BubbleZERO, supply air is distributed over seven diffusers in the floor and the amount of cool air coming from each diffuser is too small to have a serious impact on comfort of occupants. The air velocity at floor diffuser point does not exceed 0.3 m/s as can be seen in velocity contours of Figure 68. For implementation of this concept in a real building, a practical consideration raised from this observation is to distribute supply air uniformly over the floor through using many diffusers.

The temperature distribution around human body revealed that buoyancy flow forms around chest and it develops above the head of seated occupants (Figures 70 and 71). This observation shows that there are some signs of displacement ventilation strategy in the space where cool air warms by heat sources like occupants and laptop and the generated warm plume rises up toward the ceiling. However, buoyancy signs are only limited to areas near occupants and there is no strong upward velocity directions in other locations.

Similar observations have been reported by Simon and Waters (1998) and Lin et al. (2006) for indoor air patterns of spaces with floor supply diffusers. They concluded that air pattern is more complicated in operation and depending on location of heat sources and diffusers, this distribution strategy may not necessarily improve the air quality near occupants.

The results of CFD simulations also showed that radiant panel performance drops at a rate of 10 W/m^2 in capacity per 1 °C surface temperature increase (Figure 73). The related experimental investigation in the BubbleZERO revealed that there could be up to 3 °C temperature variation over the panel surface area. That means in actual application of radiant cooling panel, the capacity varies significantly over the surface and its value is higher in the areas of direct contact with hydronic water pipes because of its lower temperature. It was also found that thermal stratification in the simulated indoor space decreases for lower radiant panel surface temperatures (Figure 74). This observation can be explained considering the two parallel cooling systems in the space, which are providing cooling from two opposite sides. Cooling is provided by the supply air from the floor diffusers and the radiant panel at the ceiling. Reduction of panel surface temperature brings its provided cooling capacity closer to that of air side and therefore makes the temperature distribution more uniform. A similar trend has been reported by Schiavon et al. (Schiavon et al., 2012) for applications of chilled ceiling system in buildings where they concluded room air stratification increases with higher radiant ceiling surface temperatures. This fact adds another consideration besides condensation risk and panel capacity for choosing the right radiant ceiling panel temperature in order to keep thermal stratification below the threshold.

The analysis of radiant flux from human body revealed that increase in emitted radiant flux due to the lower panel temperature is not uniform for all body segments (Figure 75). The amount of increase is dependent on the view factor of that body part toward radiant ceiling panel. For a seated occupant, head, chest, hand and arm skins are more exposed to radiant cooling compared to other body parts. Mustakallio et al. (2016) also determined manikin based equivalent temperatures for different body segments of a seated thermal manikin in an office environment with convective/radiant cooling systems. Experimental results showed that the effect of radiant cooling could be clearly seen for the upper body parts and locally on the front surface of the body. Other design parameters which can influence the direct thermal interaction between occupants and radiant panel include ceiling panel coverage ratio, clothing level, location of occupants and furniture design.

5.7 Integration with low lift chillers

The reverse Carnot cycle for applications of high temperature cooling in Singapore condition revealed that there is considerable potential for energy saving through implementing this concept. However, the main challenge is it to incorporate a custom designed chiller for low temperature lift condition to fully utilize the benefits of HTC designs like DDOAS-RCP. The reported prototype of low lift chillers in the literature (Wyssen et al., 2010) proved to be capable of providing cooling at significantly higher efficiency for HTC scenarios compared to LTC (Figures 76 and 77). Employing two separate chillers for HTC and LTC could be a good strategy for implementation of DDOAS-RCP design in tropical buildings. Nevertheless, this strategy could be advantageous when the benefits of enhancement in COP of chiller for HTC system outweigh the investment and operational costs of running two separate chillers for DDOAS and RCP. There are also other considerations regarding the spatial requirements and chilled water network in buildings which require further investigation for implementing of this strategy.

5.8 Energy/Exergy saving potentials

The energy simulation showed that implementing an air-water system like DDOAS-RCP instead of the all air VAV system would result in considerable annual energy saving for a typical one-storey office building in Singapore. The energy saving comes from reduction of fan energy use for circulation of air in the building and enhanced operational efficiency of chiller. A significant level of saving could be achieved for application of high temperature cooling when a separate low temperature lift chiller has been designated for HTC system. The level of energy saving for DDOAS-RCP when connected to the selected design of low lift chiller (Wyssen et al., 2010) is estimated to be 10 % compared to the based design of the all air system. This level of saving could be increased up to 18 %, if more effective HTC designs and façade characteristics are implemented (Figure 80). In the current design of DDOAS-RCP in the BubbleZERO, radiant cooling system satisfies up to 30 % of space cooling load and there is opportunity to improve the contribution of radiant system. Radiant ceiling panel could be redesigned with higher number of chilled water passes to achieve higher cooling capacity and more uniform surface temperature. A more airtight façade could also decrease the latent load of the space and reduce the required dehumidification for the indoor space. This change could potentially boost the contribution of radiant system for satisfying the cooling load of space. It is noteworthy that having a separate low lift chiller for HTC system and more effective radiant system would increase the investment cost of this concept and overall benefits of these strategies need to be evaluated in the context of added cost and saved energy.

5.9 Selected design/control strategy

The outcomes of experimental and numerical research in this thesis could be used to introduce adequate and effective designs and control strategies for application of high temperature cooling in the tropics. Two selected control schemes of HTC including system components and chilled water pipelines are shown in Figures 81 and 82. In the first selected design (Figure 81), only one chiller is designated to provide low temperature chilled water (6 °C) for both the air based and water based systems. Three-way control valves are to be used to maintain the required chilled water temperature for HTC system through modulating pressure in the hydraulic line. The level of energy saving for this selected design strategy would be only limited to reduction of fan energy use and the possibility of using energy recovery system. However, a more significant energy saving could be acquired if the required high temperature chilled water for HTC is to be provided through alternative strategies like a separate low lift chiller. A custom designed chiller which operates at considerably higher efficiency in low temperature lift conditions could be a more efficient solution compared to a central plant for providing high temperature chilled water (HTCW). The schematic of this design is illustrated in Figure 82 where low lift chiller provides HTCW and high lift chiller provides LTCW. As explained before, the level of improvement in COP of designated low lift chiller needs to outweigh the added cost of having a separate chiller for HTC, in order for this alternative solution to be economically competitive.

User controlled temperature and humidity sensors are considered in indoor space to provide necessary changes on operation of the water and air based systems depending on different indoor/outdoor scenarios. It was concluded that chilled water supply temperatures to DOAS and RCP have strong impact on indoor dew point and dry bulb temperature, respectively. On the lower level, chilled water flow rates supplied to the air and water based systems also have some influence on indoor air conditions. With increase of humidity or dew point temperature above the specified threshold, signal would be sent to actuators on air supply units' pumps and three-way control valve to reduce water supply temperature and/or increase water flow rate. This change would bring more dehumidified outdoor air into conditioned space to avoid any risk of condensation on radiant panel. Three-way control valve and pump on HTC hydronic system could modulate its capacity based on feedback from temperature sensors to provide the required sensible cooling for space. Installing CO_2 sensors can also bring further value to this design for the thermal zones where there is high variation of occupancy level like in meeting rooms. Based on the feedback from these sensors, the volume of outdoor air coming into space could be regulated through modulating supply air fan speed.

In these design strategies (Figures 81 and 82), an energy recovery system (ERS) is also designated for DOAS to recuperate some part of cooling from exhaust air stream. This ERS device could be an active/passive desiccant wheel or a membrane based air to air heat exchanger which transfers heat and humidity between two air streams. The high enthalpy difference between indoor and outdoor condition in the tropical context would make ERS an effective system for the applications of DOAS.

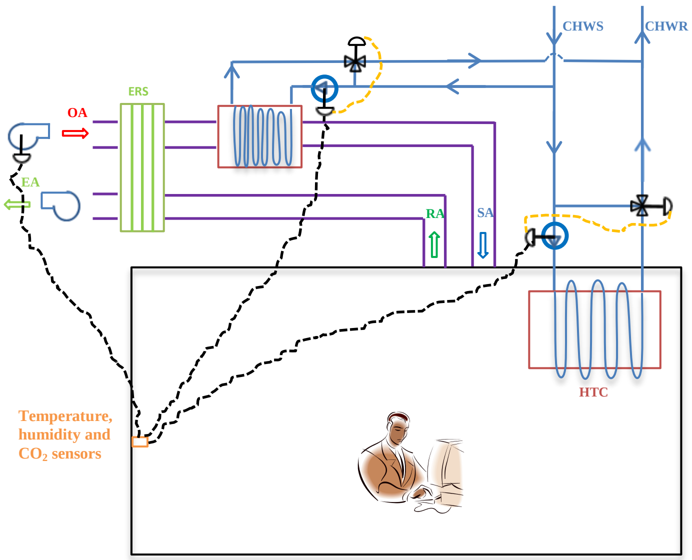


Figure 81 selected design and control strategies scheme for application of high temperature cooling with one chiller

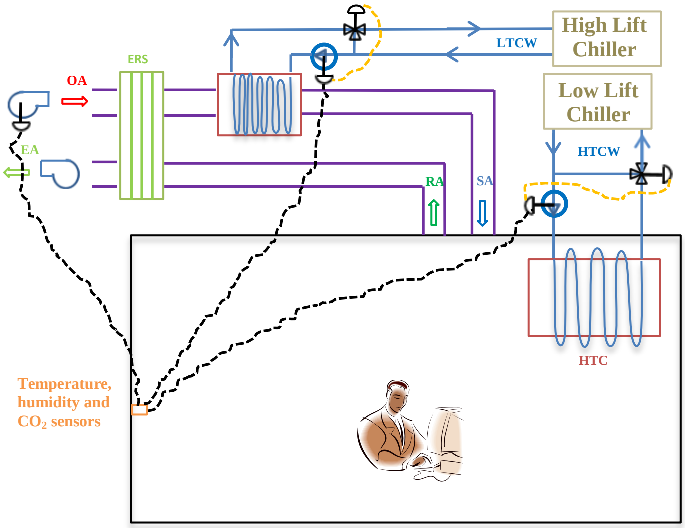


Figure 82 Selected design and control strategies for application of high temperature cooling with two separate chillers

Chapter 6. Conclusions and future work

The main conclusions from the research are summarized and elaborated separately in bullet points. In addition, recommendations are provided for future work based on limitations of this study and some suggestions have been made regarding the actual implementation of high temperature cooling in tropical buildings.

6.1 Conclusions

The application of the low exergy cooling systems in tropical buildings depicted as decentralized dedicated outdoor air system coupled with radiant cooling has been explored in this thesis. The significance of this research is on providing a better understanding for applications of high temperature cooling in the tropics and identifying the most suitable control and operation strategies for the actual implementation in buildings. Characterizing an indoor space conditioned with the low exergy cooling systems in the tropics was one of the objectives of this study. It has been shown that DDOAS-RCP can provide a comfortable and healthy indoor environment for occupants in the tropics with less destruction of exergy. The main part of hypothesis on performance evaluation of the low exergy cooling system in terms of thermal comfort, air quality and energy saving has been demonstrated. The levels of energy saving and comfort perception of occupants in tropical building need to be further explored through implementation of this design in actual buildings.

More sophisticated control and operation strategies compared to the all air system need to be implemented in order to avoid condensation risk in the water based system located inside the conditioned space. The selected control schemes for operation of high temperature cooling in tropical buildings are elaborated in Chapter 5 (Figures 81 and 82). This high temperature cooling design provides a conditioned indoor space with lower mean radiant temperature and air movement compared to that for the all air systems. Based on thermal comfort model's predictions, it is likely that occupants find this new indoor space comfortable and acceptable. However, there have been reported studies in the literature (Gong et al., 2006; Kwong et al., 2014) that locally acclimatized occupants would prefer higher air movement. This deficiency of the design could be rectified by using personal fans near workstations. It has been shown in a recent study that locally acclimatized occupants in the tropics have higher draft tolerance (Schiavon et al., 2015). Nevertheless, enhancing air movement level in the space would have some impact on ventilation effectiveness, IAQ and contaminant mixing level. Thermal stratification is below the threshold with floor supply–ceiling exhaust distribution scheme of DDOAS-RCP, although cold feet concern still exists near floor diffusers. In addition, ventilation effectiveness indices of the design were found to be close to that of mixing strategy. These observations are prone to change for other air distribution configurations like ceiling supply – ceiling exhaust. Cold feet concern would not be an issue in CS-CE distribution system and it is expected that indoor flow pattern would be close to mixing strategy. Nevertheless, supply and exhaust diffusers on the ceiling should be arranged in a way to avoid short circuiting flow condition between diffusers.

The other objective of this research was to explore the contribution ratio of the air and water systems in this coupled design. The contribution of radiant cooling panel in satisfying the total cooling load of the BubbleZERO was found to be between 20 to 30 %. It is recommended to improve air tightness level of façade and enhance uniformity level of panel surface temperature in order to increase the effectiveness of radiant ceiling panel. There are also potentials for integrations of DDOAS-RCP with low temperature lift chillers, although the efficiency of this separate chiller needs to meet some minimum requirements in order to be economically competitive compared to the original design. This study has advanced the technical knowledge required for effective implementation of high temperature cooling in tropical buildings. The detailed outcomes of this thesis can be summarized in the following points:

- The arrangement of cooling coils inside the decentralized air supply unit affects dehumidification capacity and off coil air condition of unit. For the applications where cold feet near floor diffusers is a concern, ceiling supply-ceiling exhaust air distribution strategies or coil arrangements with some level of reheating function inside the units are recommended.
- It was concluded that with a two-pass pipe hydronic system behind radiant cooling panel, there is up to 3 °C temperature variation on panel surface. Non-uniformity level of temperature on panel surface could be mitigated by increasing the number of chilled water passes behind the panel.
- For floor supply-ceiling exhaust distribution of DDOAS-RCP, there is a two degree vertical thermal stratification in the space and the

temperature gradient is steeper below 1 m height level. This conclusion could be generalized for all the applications of DDOAS-RCP with similar operational ranges, air distribution strategy, building configuration and load pattern.

- In this high temperature cooling design, mean radiant temperature is approximately two degree lower than dry bulb temperature for the areas below the ceiling panel. However, this difference could be negligible for some locations due to the exposure to warm radiation. The capacity of radiant cooling system could be enhanced near these locations to provide enough cooling for occupants.
- For the current design specification of DDOAS-RCP, the contribution of radiant cooling panel in satisfying the cooling load of space ranges between 20 to 30 % from morning to afternoon. The contribution of radiant system could be enhanced by employing a more effective panel design and improving airtightness of façade.
- There are significant correlations between indoor condition and operational scenarios of system components which are required to be considered for adequate control of this low exergy design under different indoor/outdoor scenarios. .
- Based on Fanger’s PMV model, indoor comfort condition is achievable with this low exergy cooling system under different indoor/outdoor scenarios. However, this comfort model has not been fully accepted in the literature for prediction of occupants’ perception in the tropics.

- Low air movement in the conditioned space has been identified as a comfort deficiency for this design in the context of Singapore where there is a minimum requirement for air movement level based on the local standards.
- For the coupled DDOAS-RCP concept, the ventilation rate of 0.44 L/s/m^2 closely fulfills the criteria of CO_2 concentration in the space and at the rate of 0.64 L/s/m^2, carbon dioxide level is well below the threshold set by the local standards. Higher ventilation rate may be required for increased occupancy level or other sources of pollutants in the space.
- On average basis, there is a uniform distribution of CO_2 concentration throughout the space, although the variation of concentration is considerably higher at locations near to occupants' breathing point.
- Ventilation effectiveness of DDOAS-RCP design with FS-CE distribution is close to that of mixing strategy and there is no significant difference for the range of investigated ventilation rates.
- For the current operational condition of DDOAS-RCP, the air temperature near floor diffusers is estimated to be around 18 °C. This level of supply temperature requires distributing air uniformly over the floor and raising supply air temperature in order to avoid cold feet for occupants seated near diffusers. Ceiling supply-ceiling exhaust distribution strategy could also be employed instead of floor supply-ceiling exhaust to avoid this comfort concern.

- Radiant capacity of cooling panel drops significantly at a rate of 10 W/m^2 in capacity per 1 °C increase of panel surface temperature. Considering the condensation risk on panels, the surface temperature is recommended to be kept just above the indoor dew point level in order to effectively employ radiant cooling system.
- Reducing panel surface temperature increases panel contribution in satisfying overall cooling load of space, which furthermore results in a reduction of thermal stratification in the space. Similar observations have been reported in the literature for the same conditioning and distribution strategies in buildings.
- Rising plume of warm air above the seated occupants shows that there are some signs of displacement ventilation in the space. However, this buoyancy flow pattern is only limited to areas near occupants and there is no strong upward velocity directions in other locations.
- Radiant cooling from ceiling panel does not have uniform impact for all body segments of a seated person working on a table. The upper body parts including head, chest, hand and arm get more direct influence from ceiling panel compared to lower body parts.
- There is energy saving potential for integration of the low exergy design with low temperature lift chillers. Nevertheless, the efficiency of this custom designed chiller needs to be superior at high temperature cooling applications in order to make this idea financially attractive.

- The results of energy simulation for a hypothetical one-storey office building in Singapore showed that annual energy saving of this low exergy design compared to the all air VAV system is 10 % and with a more effective design strategy, the level of saving could be increased up to 18 %.

6.2 Contributions to the body of knowledge

This PhD thesis has provided new insight into application and performance of high temperature cooling system. It clearly introduced the main energy saving potentials behind application of HTC system and tried to explore the most effective design strategies and operational conditions to materialize those benefits. The reported studies in the literature on the application of HTC fell short in finding the missing connection between HTC system and chiller design. This PhD thesis presented a comprehensive view on interdependence function of HTC system and chiller operation in order to clarify the potential energy saving of this concept. This study was also successful in providing more refined and detailed information on operational conditions of radiant cooling system and decentralized units in buildings. No study in the literature has undertaken experimental investigations on these systems with this level of details. In addition, CFD tool has been employed to further explore the characteristics of an indoor space conditioned with radiant cooling system. This numerical research went beyond investigating spatial distribution and flow pattern which have been commonly reported in the literature. The validated CFD model has been utilized to explore the performance of radiant ceiling panel and its impact on different occupants' body segments. The outcomes of this PhD thesis have been used to introduce collections of system designs and control strategies for effective implementation of high temperature cooling system in the tropics. These outcomes could help other researchers to get a better understanding on application of radiant cooling and it paves the way for industry practitioners to implement this design into actual buildings.

6.3 Limitations and recommendations

This research has been conducted in a free standing laboratory located in the outdoor space which may not truly represent the configuration of a typical office space. The specific façade design and chiller capacity in this laboratory make it moderately different compared to typical office spaces in high rise commercial buildings. To overcome this limitation in future work, it is suggested to conduct a side by side comparison between the low exergy and conventional systems. This comparison of the air-water and the all air system under similar façade design and building usage could reveal the real benefits and disadvantages of high temperature cooling in tropical buildings. The advantages and drawbacks of the proposed design compared to the conventional all air system could be in terms of investment cost, energy usage and the required maintenance service over the life cycle of the system. The impacts of different control strategies on performance of HTC design and system components could also be investigated as part of this implementation. Some of the provided conclusions in this thesis are specific to the investigated laboratory conditions and operational scenarios and an actual implementation of this low exergy cooling system could provide more generalized conclusions. In addition, the level of energy saving for application of high temperature cooling has been estimated based on a simple energy simulation and available data in the literature. A more elaborate and comprehensive energy simulation tool can provide more accurate saving values for different building configurations and applications. Annual energy saving of DDOAS-RCP compared to the all air system could vary depending on cooling load pattern, operational hours and number of floors.

In this research, Fanger's PMV model has been employed to predict the perception of occupants in the tropics toward the new conditioned indoor space provided by the high temperature cooling system. However, it was shown by several studies in the literature (Chen and Chang, 2012; Willem and Tham, 2007) that the PMV comfort model may not be able to fully capture the perception and preference of locally acclimatized occupants in the tropical context. An actual implementation of this low exergy cooling system in building can bring the opportunity to conduct a subjective study with local human subjects in the field. The outcomes of the proposed subjective test could identify the difference between actual perception of occupants in building and Fanger's model.

Low air movement in DDOAS-RCP conditioned space has been identified as a thermal comfort concern for locally acclimatized occupants. This issue could be rectified by using personalized fans near workstations to provide enough air movement near occupants and improve their comfort perceptions. It was shown in the literature that locally acclimatized occupants in the tropics have higher draft tolerance. The personalized fans could be mounted on chair or desk near office occupants as chair mounted fans or desk mounted fans which could enhance displacement flow around human body. Besides, considering the level of improvement in comfort level and increase in fan energy use, the impacts of this enhancement in air movement level on ventilation effectiveness and contaminant distribution in the space are required to be investigated. Future studies could explore the potential integration of the high temperature cooling systems with personalized fans to improve the comfort perception of local occupants in the tropics. This integration could be investigated through field studies in an implemented case of radiant cooling system or through numerical modelling of air flow on workstations.

The concept of DDOAS-RCP introduces a new type of air conditioned spaces with lower air movement and mean radiant temperature compared to the all air system. This change in indoor air condition has an impact on the type of heat transfer mechanism between human body and surrounding. It was shown through CFD simulation that there would be different level of increase in radiative flux of body segments depending on their view factor to radiant ceiling panel. Future work can further investigate the ratio of convective to radiative heat transfer coefficients under various human body seating and standing postures. The convective/radiative heat transfer coefficients of body segments could be measured by using heat flux sensors on skins of real subjects or thermal manikin located inside the conditioned space with the high temperature cooling system.

For actual implementation of DDOAS-RCP or similar high temperature cooling designs in tropical buildings, it is recommended to provide an air tight façade and minimize the infiltration rate from façade. A uniform panel surface temperature can enhance effectiveness of radiant cooling panel and reduce the risk of condensation. In addition, employing energy recovery system can be an effective strategy in DOAS to recover some part of cooling from exhaust air streams into outdoor air. Regarding the distribution scheme of DDOAS-RCP, it is advised to choose ceiling supply-ceiling exhaust instead of floor supply-ceiling exhaust where no reheating is available to avoid cold feet concern. The selected design and control strategies based on the outcomes of this thesis are elaborated in the discussion chapter (Figures 81 and 82).

Bibliography

Alexander, D., O'Rourke, M., 2008. Design Considerations for Active Chilled Beams. ASHRAE J. 49, 50–58.

Andreasi, W.A., Lamberts, R., Cândido, C., 2010. Thermal acceptability assessment in buildings located in hot and humid regions in Brazil. Build. Environ. 45, 1225–1232. doi:10.1016/j.buildenv.2009.11.005

ASHRAE, 2008. ASHRAE Handbook: HVAC Systems and Equipment, SI Edition. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.

ASHRAE 55, 2004. ANSI/ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.

ASHRAE 55-81, 1981. Thermal environment condition for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.

ASHRAE 62, 2007. ANSI/ASHRAE Standard 62.1-2007: Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.

ASHRAE 129, 2002. ANSI/ASHRAE Standard 129-1997 (RA 2002): Measuring Air-Change Effectiveness. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.

ATTMA TS L2, 2010. Measuring air permeability of building envelopes (Non-Dwellings). The Air Tightness Testing & Measurement Association, Northampton, UK.

Awbi, H.B., 1998. Energy efficient room air distribution. Renew. Energy, Renewable Energy, Energy Efficiency, Policy and the Environment 15, 293–299. doi:10.1016/S0960-1481(98)00176-1

Baldini, L., Meggers, F., 2008. Advanced Distribution and Decentralized Supply: A Networked Approach for Minimum Pressure Losses and Maximum Comfort, in: Proceedings of Advanced Building Ventilation and Environmental Technology. Presented at the 29th AIVC Conference, Kyoto, Japan.

Bearg, D.W., 1993. Indoor Air Quality and HVAC Systems. CRC Press, Lewis Publishers, Boca Raton, FL, USA.

Bolashikov, Z., Mustakallio, P., Kolencikova, S., Kostov, K., Melikov, A.K., Kosonen, R., 2013. Thermal Conditions in a Simulated Office Environment with Convective and Radiant Cooling Systems, in: 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Building (Clima). Prague, Czech Republic.

Bruelisauer, M., Chen, K., Iyengar, R., Leibundgut, H., Li, C., Li, M., Mast, M., Meggers, F., Miller, C., Rossi, D., Saber, E.M., Schlueter, A., Tham, K.W., 2013. BubbleZERO—Design, Construction and Operation of a Transportable Research Laboratory for Low Exergy Building System Evaluation in the Tropics. Energies 6, 4551–4571. doi:10.3390/en6094551

Bruelisauer, M., Meggers, F., Saber, E., Li, C., Leibundgut, H., 2014. Stuck in a stack—Temperature measurements of the microclimate around split type condensing units in a high rise building in Singapore. Energy Build. 71, 28–37. doi:10.1016/j.enbuild.2013.11.056

Bulińska, A., Popiołek, Z., Buliński, Z., 2014. Experimentally validated CFD analysis on sampling region determination of average indoor carbon dioxide concentration in occupied space. Build. Environ. 72, 319–331. doi:10.1016/j.buildenv.2013.11.001

Busch, J.F., 1992. A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. Energy Build. 18, 235–249. doi:10.1016/0378-7788(92)90016-A

Catalina, T., Virgone, J., Kuznik, F., 2009. Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling. Build. Environ. 44, 1740–1750. doi:10.1016/j.buildenv.2008.11.015

Chen, A., Chang, V.W.-C., 2012. Human health and thermal comfort of office workers in Singapore. Build. Environ. 58, 172–178. doi:10.1016/j.buildenv.2012.07.004

Chen, Q., 1995. Comparison of different k-ε models for indoor air flow computations. Numer. Heat Transf. Part B Fundam. Int. J. Comput. Methodol. 28, 353–369.

Chiang, W.-H., Wang, C.-Y., Huang, J.-S., 2012. Evaluation of cooling ceiling and mechanical ventilation systems on thermal comfort using CFD study in an office for subtropical region. Build. Environ. 48, 113–127. doi:10.1016/j.buildenv.2011.09.002

Dalewski, M., Melikov, A.K., Vesely, M., 2014. Performance of ductless personalized ventilation in conjunction with displacement ventilation: Physical environment and human response. Build. Environ. 81, 354–364. doi:10.1016/j.buildenv.2014.07.011

de Dear, R.J., Akimoto, T., Arens, E.A., Brager, G., Candido, C., Cheong, K.W.D., Li, B., Nishihara, N., Sekhar, S.C., Tanabe, S., Toftum, J., Zhang, H., Zhu, Y., 2013. Progress in thermal comfort research over the last twenty years. Indoor Air 23, 442–461. doi:10.1111/ina.12046

de Dear, R.J., Leow, K.G., 1990. Indoor climate and thermal comfort in high-rise public housing in an equatorial climate: A field-study in Singapore. Atmospheric Environ. Part B Urban Atmosphere 24, 313–320. doi:10.1016/0957-1272(90)90037-U

De Dear, R.J., Leow, K.G., Foo, S.C., 1991. Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. Int. J. Biometeorol. 34, 259–265.

Dieckmann, J., Roth, K., Brodrick, J., 2004. Radiant ceiling cooling. ASHRAE J. 46, 42–42.

Doyon, T., 2008. Chiller Design For Low-Lift Conditions. Air Cond. Heat. Refrig. News 234, 13–15.

Emmerich, S.J., Persily, A.K., 1997. Literature review on CO2-based demand-controlled ventilation,. ASHRAE Trans. 103, 229–243.

Feng, J. (Dove), Schiavon, S., Bauman, F., 2013. Cooling load differences between radiant and air systems. Energy Build. 65, 310–321. doi:10.1016/j.enbuild.2013.06.009

Gan, G., 1995. Evaluation of room air distribution systems using computational fluid dynamics. Energy Build. 23, 83–93. doi:10.1016/0378-7788(95)00931-0

Gao, N., Niu, J., 2004. CFD study on micro-environment around human body and personalized ventilation. Build. Environ. 39, 795–805.

Gong, N., Tham, K.W., Melikov, A.K., Wyon, D.P., Sekhar, S.C., Cheong, K.W., 2006. The Acceptable Air Velocity Range for Local Air Movement in The Tropics. HVACR Res. 12, 1065–1076. doi:10.1080/10789669.2006.10391451

Han, J., Zhang, G., Zhang, Q., Zhang, J., Liu, J., Tian, L., Zheng, C., Hao, J., Lin, J., Liu, Y., Moschandreas, D.J., 2007. Field study on occupants' thermal comfort and residential thermal environment in a hot-humid climate of China. Build. Environ. 42, 4043–4050. doi:10.1016/j.buildenv.2006.06.028

Hayashi, T., Ishizu, Y., Kato, S., Murakami, S., 2002. CFD analysis on characteristics of contaminated indoor air ventilation and its application in the evaluation of the effects of contaminant inhalation by a human occupant. Build. Environ. 37, 219–230. doi:10.1016/S0360-1323(01)00029-4

Hoyt, T., Lee, K.H., Zhang, H., Arens, E., Webster, T., 2009. Energy savings from extended air temperature setpoints and reductions in room air mixing, in: 13th International Conference on Environmental Ergonomics. Boston, MA, USA.

Huang, S.-M., Zhang, L.-Z., 2013. Researches and trends in membrane-based liquid desiccant air dehumidification. Renew. Sustain. Energy Rev. 28, 425–440. doi:10.1016/j.rser.2013.08.005

IEA, 2013. CO2 emissions from fuel combustion IEA Statistics International Energy Agency highlights (IEA Statistics). International Energy Agency, Paris, France.

IEA ECBCS Annex 28, 2000. Low Energy Cooling Systems (Technical Synthesis Report). International Energy Agency, Coventry, UK.

IEA ECBCS Annex 37, 2003. Low Exergy Systems for Heating and Cooling Buildings - Guidebook. VTT Technical Research Centre of Finland, Helsinki, Finland.

Indraganti, M., Ooka, R., Rijal, H.B., Brager, G.S., 2014. Adaptive model of thermal comfort for offices in hot and humid climates of India. Build. Environ. 74, 39–53. doi:10.1016/j.buildenv.2014.01.002

IPCC, 2007. Climate change mitigation in the buildings sector: the findings of the 4th Assessment Report of the IPCC. Intergovernmental Panel for Climate Change, New York, USA.

ISO 7730, 2005. Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for Standardization, Geneva, Switzerland.

Iyengar, R.S., Saber, E., Meggers, F., Leibundgut, H., 2013. The feasibility of performing high-temperature radiant cooling in tropical buildings when coupled with a decentralized ventilation system. HVACR Res. 19, 992–1000. doi:10.1080/10789669.2013.826065

Jia, J., Lee, W., 2014. Energy performance and condensation risk of DCDV system in subtropical Hong Kong. Trans. Tianjin Univ. 20, 42–47. doi:10.1007/s12209-014-2092-2

Khan, Y., Khare, V.R., Mathur, J., Bhandari, M., 2015. Performance evaluation of radiant cooling system integrated with air system under different operational strategies. Energy Build. 97, 118–128. doi:10.1016/j.enbuild.2015.03.030

Kosonen, R., Tan, F., 2005. A feasibility study of a ventilated beam system in the hot and humid climate: a case-study approach. Build. Environ. 40, 1164–1173. doi:10.1016/j.buildenv.2004.11.006

Krajčík, M., Simone, A., Olesen, B.W., 2012. Air distribution and ventilation effectiveness in an occupied room heated by warm air. Energy Build., Cool

Roofs, Cool Pavements, Cool Cities, and Cool World 55, 94–101. doi:10.1016/j.enbuild.2012.08.015

Kwong, Q.J., Arsad, M.A., Adam, N.M., 2014. Evaluation of Indoor Thermal Environment in a Radiant-Cooled-Floor Office Building in Malaysia. Appl. Mech. Mater. 564, 228–233. doi:10.4028/www.scientific.net/AMM.564.228

Leite, B.C.C., Tribess, A., 2006. Analysis of Thermal Comfort in an Office Environment with Underfloor Air Supply in a Tropical Climate. HVACampR Res. 12, 215–229. doi:10.1080/10789669.2006.10391176

Li, Y., Nielsen, P.V., 2011. CFD and ventilation research. Indoor Air 21, 442–453. doi:10.1111/j.1600-0668.2011.00723.x

Lin, Z., Jiang, F., Chow, T.T., Tsang, C.F., Lu, W.Z., 2006. CFD analysis of ventilation effectiveness in a public transport interchange. Build. Environ. 41, 254–261. doi:10.1016/j.buildenv.2005.02.011

Lipczynska, A., Kaczmarczyk, J., Melikov, A.K., 2015. Thermal environment and air quality in office with personalized ventilation combined with chilled ceiling. Build. Environ. 92, 603–614. doi:10.1016/j.buildenv.2015.05.035

Martinho, N., Lopes, A., Gameiro da Silva, M., 2012. Evaluation of errors on the CFD computation of air flow and heat transfer around the human body. Build. Environ. 58, 58–69. doi:10.1016/j.buildenv.2012.06.018

Meggers, F., Pantelic, J., Baldini, L., Saber, E.M., Kim, M.K., 2013. Evaluating and adapting low exergy systems with decentralized ventilation for tropical climates. Energy Build. 67, 559–567. doi:10.1016/j.enbuild.2013.08.015

Meggers, F., Ritter, V., Goffin, P., Baetschmann, M., Leibundgut, H., 2012. Low exergy building systems implementation. Energy 41, 48–55. doi:10.1016/j.energy.2011.07.031

Melikov, A.K., Krejciríková, B., Kaczmarczyk, J., Duszyk, M., Sakoi, T., 2013. Human response to local convective and radiant cooling in a warm environment. HVACR Res. 19, 1023–1032. doi:10.1080/10789669.2013.842734

Melikov, A.K., Skwarczynski, M.A., Kaczmarczyk, J., Zabecky, J., 2013. Use of personalized ventilation for improving health, comfort, and performance at high room temperature and humidity. Indoor Air 23, 250–263. doi:10.1111/ina.12012

Menter, F.R., 1994. Two-equation eddy-viscosity turbulence models for engineering applications. AIAA J. 32.

MS 1525, 2007. Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings. Department of Standards Malaysia, Putrajaya, Malaysia.

Mumma, S.A., 2002. Chilled Ceilings in Parallel with Dedicated Outdoor Air Systems: Addressing the Concerns of Condensation, Capacity, and Cost. ASHRAE Trans. 108, 220–231.

Mumma, S.A., 2001. Condensation issues with radiant cooling panels. ASHRAE IAQ Appl. 1–3.

Munters Co., 2009. School application guideline. Munters Corporation, Kista, Sweden.

Mustakallio, P., Bolashikov, Z., Kostov, K., Melikov, A., Kosonen, R., 2016. Thermal environment in simulated offices with convective and radiant cooling systems under cooling (summer) mode of operation. Build. Environ. 100, 82–91. doi:10.1016/j.buildenv.2016.02.001

NCCS, NRF, 2011. Air-con system efficiency primer: a Summary (National Climate Change Secretariat & National Research Foundation). Prime Minister's Office, Republic of Singapore, Singapore.

Novoselac, A., Srebric, J., 2002. A critical review on the performance and design of combined cooled ceiling and displacement ventilation systems. Energy Build. 34, 497–509. doi:10.1016/S0378-7788(01)00134-7

Ole Fanger, P., Toftum, J., 2002. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Build. 34, 533–536. doi:10.1016/S0378-7788(02)00003-8

Olesen, B.W., 2008. Radiant Floor Cooling Systems. ASHRAE J. 50, 16–22.

OpenFOAM Foundation, 2014a. OpenFOAM: The Open Source CFD Toolbox User Guide. OpenFOAM Foundation.

OpenFOAM Foundation, 2014b. OpenFOAM: The Open Source CFD Toolbox Programmers Guide. OpenFOAM Foundation.

Panagopoulos, I.K., Karayannis, A.N., Kassomenos, P., Aravossis, K., 2011. A CFD Simulation Study of VOC and Formaldehyde Indoor Air Pollution Dispersion in an Apartment as Part of an Indoor Pollution Management Plan. Aerosol Air Qual. Res. 11, 758–762. doi:10.4209/aaqr.2010.11.0092

Pantelic, J., Sze-To, G.N., Tham, K.W., Chao, C.Y.H., Khoo, Y.C.M., 2009. Personalized ventilation as a control measure for airborne transmissible disease spread. J. R. Soc. Interface 6, S715–S726.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11, 1633–1644. doi:10.5194/hess-11-1633-2007

REHVA Guidebooks No. 2, 2004. Ventilation Effectiveness. Federation of European Heating, Ventilation and Air Conditioning Associations, Forssa, Finland.

REHVA Guidebooks No. 10, 2007. Computational Fluid Dynamics in Ventilation Design. Federation of European Heating, Ventilation and Air Conditioning Associations, Forssa, Finland.

Rim, D., Novoselac, A., 2009. Transport of particulate and gaseous pollutants in the vicinity of a human body. Build. Environ. 44, 1840–1849. doi:10.1016/j.buildenv.2008.12.009

Rumsey, P., Weale, J., 2007. Chilled Beams in Labs Eliminating Reheat & Saving Energy on a Budget. ASHRAE J. 49, 18–25.

Sastry, G., Rumsey, P., 2014. VAV vs. Radiant Side-by-Side Comparison. ASHRAE J. 56, 16–24.

Schiavon, S., Bauman, F., Tully, B., Rimmer, J., 2012. Room air stratification in combined chilled ceiling and displacement ventilation systems. HVACR Res. 18, 147–159. doi:10.1080/10789669.2011.592105

Schiavon, S., Melikov, A.K., Sekhar, C., 2010. Energy analysis of the personalized ventilation system in hot and humid climates. Energy Build. 42, 699–707. doi:10.1016/j.enbuild.2009.11.009

Schiavon, S., Yang, B., Chang, W.-C., Nazaroff, W., 2015. Effect of air temperature and air movement on thermal comfort for tropically acclimatized persons. Presented at the the 3th International Conference on Building Energy and Environment (COBEE 2015), Tianjin, China.

Schmidt, D., 2009. Low exergy systems for high-performance buildings and communities. Energy Build. 41, 331–336. doi:10.1016/j.enbuild.2008.10.005

Sekhar, C., Tham, K.W., Cheong, D.K.W., Wong, N.H., 2006. Single-coil twin-fan variable-air-volume (VAV) system for energy-efficient conditioning of independent fresh and return air streams.

Sekhar, S.C., Ching, C.S., 2002. Indoor air quality and thermal comfort studies of an under-floor air-conditioning system in the tropics. Energy Build. 34, 431–444. doi:10.1016/S0378-7788(01)00128-1

Sekhar, S.C., Tan, L.T., 2009. Optimization of cooling coil performance during operation stages for improved humidity control. Energy Build. 41, 229–233. doi:10.1016/j.enbuild.2008.09.005
Sekhar, S.C., Yang, B., Tham, K.W., Cheong, D.K.W., 2007. IAQ and Energy Performance of the newly developed Single Coil Twin Fan air-conditioning and air distribution system – Results of a Field Trial, in: Proceedings of Clima. Presented at the Proceedings of Clima 2007 WellBeing Indoors, Helsinki, Finland.
Shirey, D.B., Henderson, H.I., 2004. Dehumidification at part load. ASHRAE J. 46, 42–47.
Siddiqui, M., Jayanti, S., Swaminathan, T., 2012. CFD analysis of dense gas dispersion in indoor environment for risk assessment and risk mitigation. J. Hazard. Mater. 209–210, 177–185. doi:10.1016/j.jhazmat.2012.01.007
Siegel, R., Howell, J.R., 1992. Thermal Radiation Heat Transfer. Hemisphere Publishing Corporation, Washington DC, USA.
Simons, M.W., Waters, J.R., 1998. Local ventilation effectiveness parameters in air distribution system design. Build. Serv. Eng. Res. Technol. 19, 135–140. doi:10.1177/014362449801900304
Šmíd, M., 1977. Ergonomické parametry. Praha : Státní nakladatelství technické literatury.
Sørensen, D.N., Voigt, L.K., 2003. Modelling flow and heat transfer around a seated human body by computational fluid dynamics. Build. Environ. 38, 753–762. doi:10.1016/S0360-1323(03)00027-1
SS 212, 2007. Specification for aluminium alloy windows. SPRING Singapore, Singapore.
SS 553, 2009. Code of practice for air-conditioning and mechanical ventilation in buildings. SPRING Singapore, Singapore.
SS 554, 2009. Code of practice for indoor air quality for air-conditioned buildings. SPRING Singapore, Singapore.
Tan, W., 2011. Practical research methods, Fourth edition. ed. Pearson Custom Publishing, Singapore.
Tian, Z., Love, J.A., 2009. Application of radiant cooling in different climates: assessment of office buildings through simulation, in: 11th International IBPSA Conference. Glasgow, Scotland.
Tolga Balta, M., Kalinci, Y., Hepbasli, A., 2008. Evaluating a low exergy heating system from the power plant through the heat pump to the building envelope. Energy Build. 40, 1799–1804. doi:10.1016/j.enbuild.2008.03.008
Tomasi, R., Krajčík, M., Simone, A., Olesen, B.W., 2013. Experimental evaluation of air distribution in mechanically ventilated residential rooms: Thermal comfort and ventilation effectiveness. Energy Build. 60, 28–37. doi:10.1016/j.enbuild.2013.01.003
van Dronkelaar, C., Cóstola, D., Mangkuto, R.A., Hensen, J.L.M., 2014. Heating and cooling energy demand in underground buildings: Potential for saving in various climates and functions. Energy Build. 71, 129–136. doi:10.1016/j.enbuild.2013.12.004
Vangtook, P., Chirarattananon, S., 2007. Application of radiant cooling as a passive cooling option in hot humid climate. Build. Environ. 42, 543–556. doi:10.1016/j.buildenv.2005.09.014
Wang, W., Tian, Z., 2013. Indoor thermal comfort research on the hybrid system of radiant cooling and dedicated outdoor air system. Front. Energy 7, 155–160. doi:10.1007/s11708-013-0244-z

WeatherSpark, 2015. Weather Graphs and Maps - WeatherSpark [WWW Document]. URL https://weatherspark.com/ (accessed 11.24.15).
Willem, H.C., Tham, K.W., 2007. Associations between thermal perception and physiological indicators under moderate thermal stress, in: 6th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings: Sustainable Built Environment. Sendai, Japan.
Wong, N.., Feriadi, H., Lim, P.., Tham, K.., Sekhar, C., Cheong, K.., 2002. Thermal comfort evaluation of naturally ventilated public housing in Singapore. Build. Environ. 37, 1267–1277. doi:10.1016/S0360-1323(01)00103-2
Wyssen, I., Gasser, L., Wellig, B., Meier, M., 2010. Chiller with small temperature lift for efficient building cooling, in: Proc. Clima. Antalya, Turkey.
Yang, F., 2008. Progress in Applied Mathematical Modeling. Nova Publishers, New York, USA.
Yang, T., Cropper, P.C., Cook, M., Yousaf, R., Fiala, D., 2007. A new simulation system to predict human-environment thermal interactions in naturally ventilated buildings. Presented at the Building Simulation, Beijing, China.
Yao, Y., Lian, Z., Liu, W., Shen, Q., 2007. Experimental Study on Skin Temperature and Thermal Comfort of the Human Body in a Recumbent Posture under Uniform Thermal Environments. Indoor Built Environ. 16, 505–518. doi:10.1177/1420326X07084291
Yau, Y.H., Hasbi, S., 2013. Field analysis of indoor air quality in high rise and low rise green offices with radiant slab cooling systems in Malaysia. Indoor Built Environ. 24, 174–184. doi:10.1177/1420326X13506130
Yousaf, R., Wood, D., Cook, M., Yang, T., Hodder, S., Loveday, D., Passmore, M., 2011. CFD and PIV based investigation of indoor air flows dominated by buoyancy effects generated by human occupancy and equipment, in: 12th Conference of International Building Performance Simulation Association. Presented at the Building Simulation, Sydney, Australia.
Zhang, Z., Zhang, W., Zhai, Z.J., Chen, Q.Y., 2007. Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 2—Comparison with Experimental Data from Literature. HVACR Res. 13, 871–886.

Appendices

BubbleZERO blower door test

The BubbleZERO was the main testbed of this PhD thesis and the airtightness level of this laboratory needs to be identified for any generalization of the obtained results. The blow door test was conducted in this free stand laboratory to quantitatively determine the airtightness level of the façade. Air permeability is one of the indicators which is commonly used in the building air leakage standards. This value defined as the leakage rate of space per surface area of the envelope which includes boundary walls, floor and ceiling ($m^3.h^{-1}.m^{-2}$). The recommended range of air permeability based on ATTMA TSL 2 (Air Tightness Testing & Measurement Association, Technical Standard L2) is shown in the below table,

Table-Appendices 1 – Building regulation requirement for non-domestic building in United Kingdom (ATTMA TS L2, 2010)

Type	**Air permeability $m^3.h^{-1}.m^{-2}$ @ *50 Pa***		**Air Change Rate h^{-1} @ *50 Pa***
	Best practice	**Normal**	
Offices			
Naturally ventilated	3.0	7.0	
Mixed mode	2.5	5.0	
Air conditioned/low energy	2.0	5.0	
Factories/warehouses	2.0	6.0	
Superstores	1.0	5.0	
Schools	3.0	9.0	
Hospitals	5.0	9.0	
Museums and archival stores	1.0	1.5	
Cold Stores	0.2	0.35	
PassivHaus Standard	-	<1.0	0.6

The air permeability of the BubbleZERO based on the results of the conducted blower door test is estimated to be 1.9 $m^3.h^{-1}.m^{-2}$ (leakage rate: 63.65 L/s @ 50 Pa, Envelope ≈ 120 m^2). Based on the recommended range in the above Table, this value is close to the best practice façade of office space with air conditioned / low energy settings. This result shows that the airtightness of the BubbleZERO façade was in the acceptable range. The details of the conducted blower door test in the BubbleZERO are shown in the following pictures.

ESAN ENGINEERING

NUS,ETH CENTRE - Blower Door Test

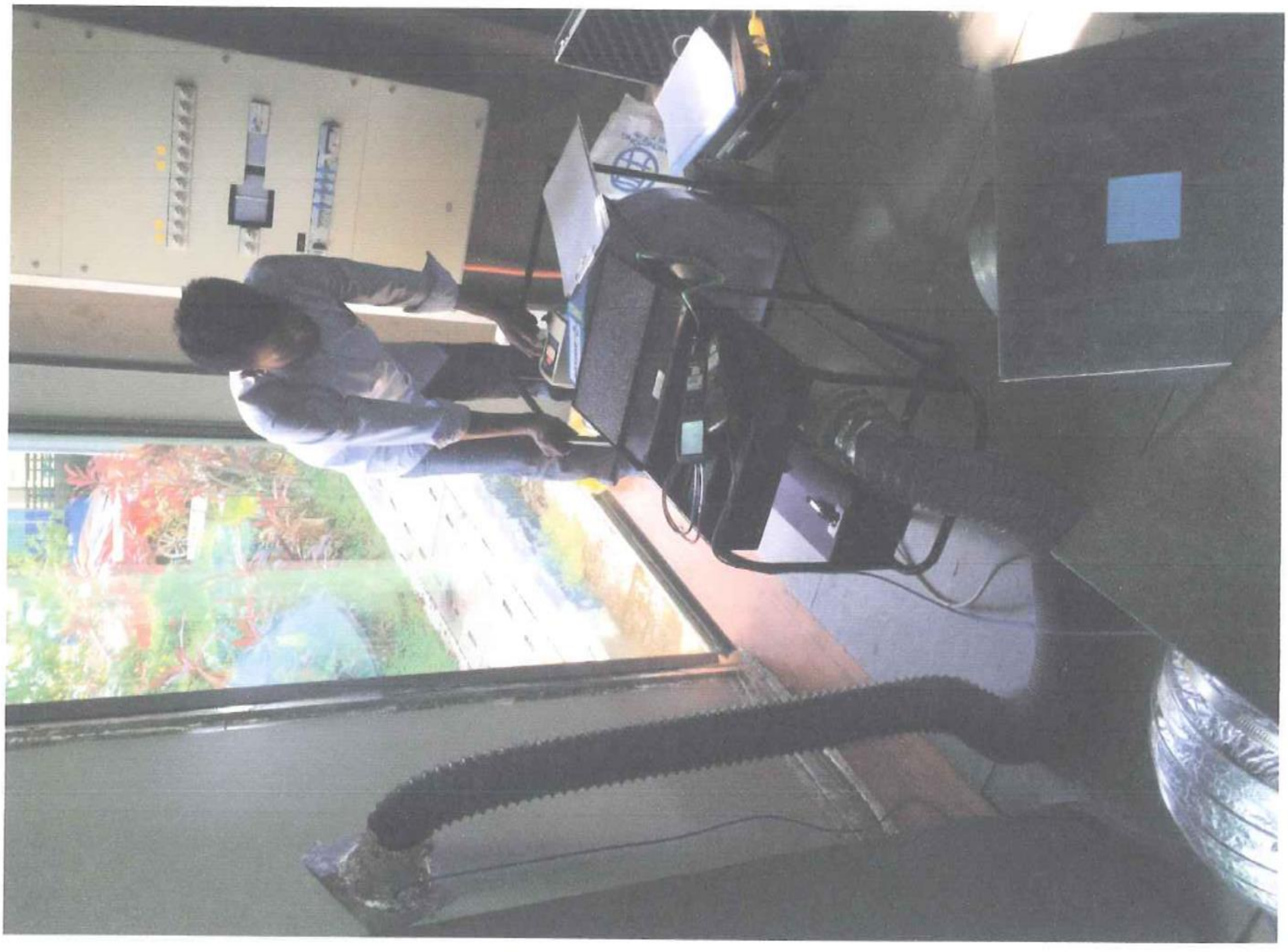
Scope:

Use a blower (usually entrance door) to blow the air into or out of the building (test area) to pressurize or depressurize the building. The pressure difference between inside and outside of the building will cause air to force its way through any creaks in the building thermal envelope. Measuring the flow rate at the specified test pressure indicates the leakiness of the envelope.

Test procedure:

A. Preparation
   1. All other outside doors and the windows are closed to prevent air leakage, all inside doors remain open.
   2. Duct work leading from or into the test enclosure may be permanently sealed off air tight with metal plates caulked and screwed into place or use neoprene seals (100% air tight)
   3. All holes, creaks or penetrations leading into or out of the test enclosure must be sealed (includes pipe runs and cable trays)
   4. All walls should be sealed around the perimeter of the test enclosure.
   5. Block walls / masonry walls must be sealed to prevent the air leakage.
   6. Floors drains should have traps, (water in them at all times)
   7. At door, 100 mm to be provide which use to pressurize / depressurize the room using blower.

B. Test method
   1. The blower is installed in an external door of the building
   2. ON the blower fan to create the artificial pressure differential (depressurization or pressurization) between the building interior and the outside air. This pressure differential leads to a constant flow of air through the leakage in the building envelope.
   3. The air tightness test includes leakage detection at 10Pa, 20Pa, 30Pa, 40Pa & 50Pa (-ve or +ve) pressure as advised.
   4. During the leakage test the fan constantly sucks (or discharge) the air out (or inside) of the building. This creates depressurization / pressurization which adjusted at a pressure differential of 50Pa.
   5. Through joints and other leakages outside/inside air will constantly infiltrate the building. The air flow can be measured using an air velocity meter.



ESAN ENGINEERING

Blower Door Test report

Project: NUS - ETH CENTRE

A **Room to be tested**

1 Location: NUS - ETH Centre

2 Test static pressure +10Pa, +20Pa, +30Pa, +40Pa & +50 Pa

3 Surface area of the room 65 sq.m

B **Test Data**

No.	Room pressure (Pa)	Leakage rate (L/s)
1	+ 10.6	33.40
2	+ 21.6	44.21
3	+ 29.8	50.72
4	+ 40.3	59.49
5	+ 49.7	63.65

C **Test Instruments Details**

1 Manufacturer Air flow

2 Type PANDA

3 Range 1 L/s ~ 200 L/s

4 Model TA465/PVM620

5 Serial No TA41512190C/PVM621218005

6 Calibration Date 19-May-14/19-May-14

Remarks: **Positive pressure test**

All supply diffusers and Return/Exhaust grilles sealed during the test.

Tested By

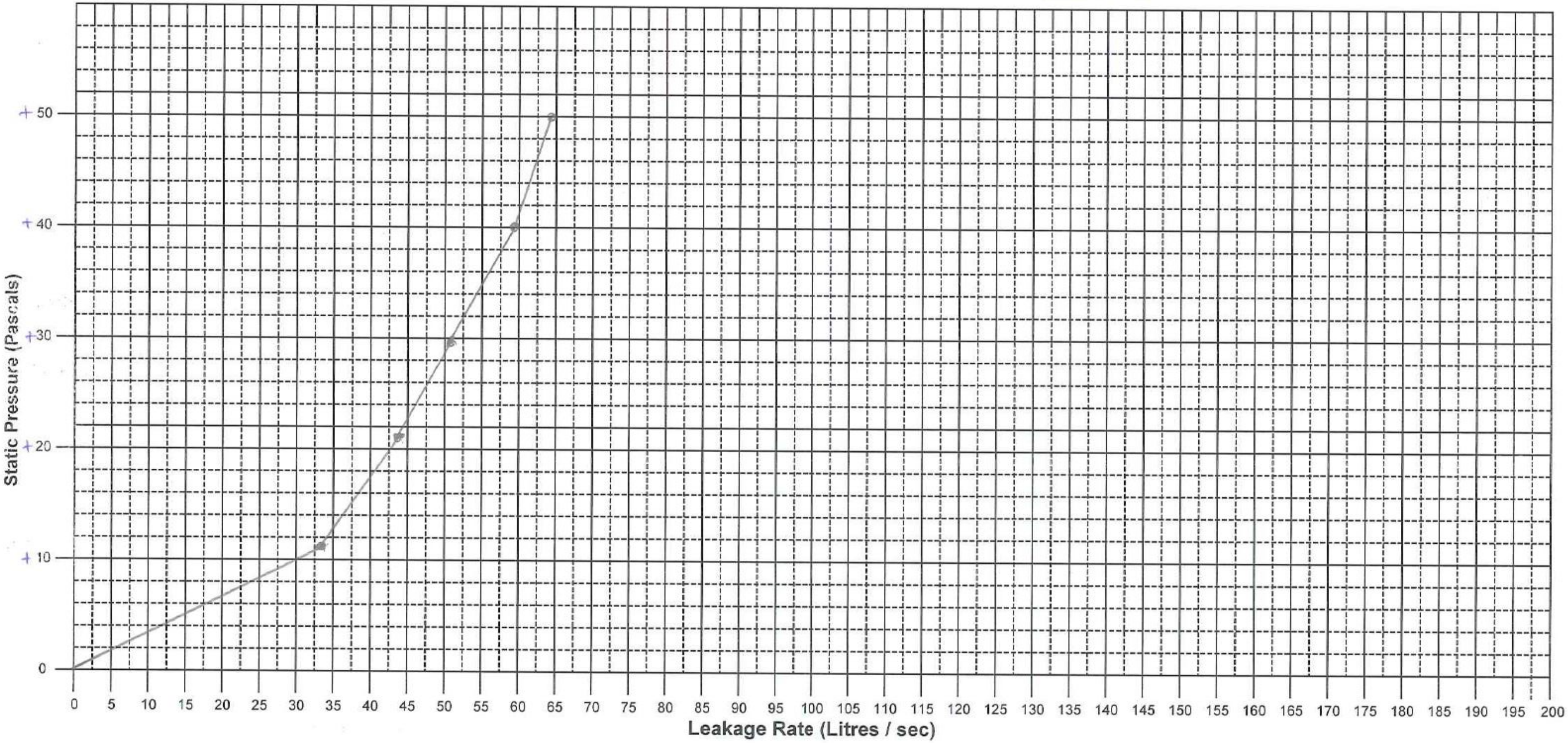
Name Mr. Kumar Signature [signature] Date: 4-Mar-15

Witnessed By

Name Mr. Esmail Signature Date: 4-Mar-15

ESAN ENGINEERING

ROOM LEAKAGE FLOW RATE CHART – POSITIVE



Tested by

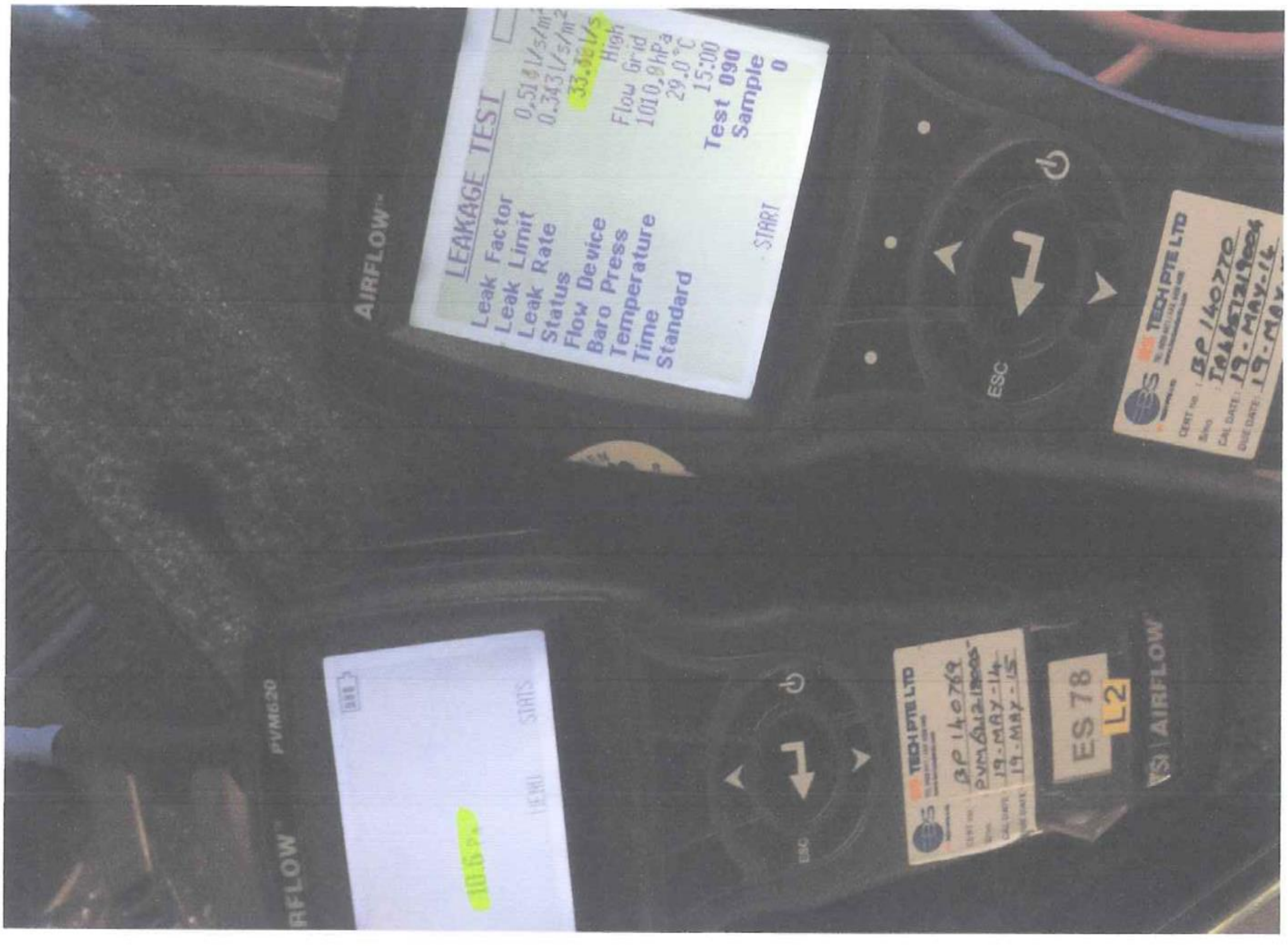
Name KUMAR Signature [signature] Date 04-MAR-2015

Witnessed by

Name ______ Signature ______ Date ______

TEST AT POSITIVE PRESSURE

+21.6 pa



+10.6 pa

Scientific publications from the PhD thesis

Saber, E., Meggers, F. and Iyengar, R. (2013) The potential of low exergy building systems in the tropics - Prototype evaluation from the BubbleZERO in Singapore. In: Proceedings of Clima 2013: Energy efficient, smart and healthy buildings, Prague, Czech Republic. (Saber et al., 2013)

Saber, E., Mast, M., Tham, K.W. and Leibundgut, H. (2014) Numerical Modelling of an Indoor Space Conditioned with Low Exergy Cooling Technologies in the Tropics. In: 13th International Conference on Indoor Air Quality and Climate, Hong Kong. (E. Saber et al., 2014)

Saber, E.M., Iyengar, R., Mast, M., Meggers, F., Tham, K.W. and Leibundgut, H. (2014) Thermal comfort and IAQ analysis of a decentralized DOAS system coupled with radiant cooling for the tropics, Building and Environment, 82, 361–370. (E. M. Saber et al., 2014)

Saber, E.M., Mast, M., Tham, K.W. and Leibundgut, H. (2015) Ventilation effectiveness and contaminant distribution in an occupied space conditioned with low exergy ventilation technologies in the tropics, Healthy Buildings 2015 Conference, Eindhoven, Netherlands. (Saber et al., 2015)

Saber, E.M., Tham, K.W. and Leibundgut, H. (2016) A review of high temperature cooling systems in tropical buildings, Building and Environment, 96, 237–249. (Saber et al., 2016)

Saber, E.M. (2015) Green Cooling Systems in the Tropical Buildings, ASHRAE Singapore Chapter Magazine, 76–77. (Saber, 2015)

INTERNATIONAL SOCIETY OF INDOOR AIR QUALITY AND CLIMATE

&

Technische Universiteit **Eindhoven** University of Technology

would like to present this

Best Student Paper Award

to

Esmail Mahmoudi Saber

Matthias Mast, Kwok Wai Tham and Hansjürg Leibundgut

For the paper with title

VENTILATION EFFECTIVENESS AND CONTAMINANT DISTRIBUTION IN AN OCCUPIED SPACE CONDITIONED WITH LOW EXERGY VENTILATION TECHNOLOGIES IN THE TROPICS

Congratulations with this achievement!

On behalf of the organization

Marcel Loomans
President - Healthy Buildings 2015 Europe

Glenn Morrison
President of ISIAQ