EFFECTS OF PARTITION ON THERMAL COMFORT, INDOOR AIR QUALITY, ENERGY CONSUMPTION, AND PERCEPTION IN AIR-CONDITIONED BUILDING

BY

PRADIP ARYAL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)

SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY

THAMMASAT UNIVERSITY

ACADEMIC YEAR 2015

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A Thesis Presented

By

PRADIP ARYAL

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Approved as to style and content by

Advisor and Chairperson of Thesis Committee ______________________

(Prof. Thananchai Leephakpreeda, Ph.D)

Committee Member and
Chairperson of Examination Committee ______________________

(Asst. Prof. Anotai Suksangpanomrung, Ph.D)

Committee Member ______________________

(Assoc. Prof. Supachart Chungpaibulpatana, D.Eng)

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Abstract

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by

PRADIP ARYAL

B.Eng, Aeronautical Engineering (Aircraft Design and Engineering),
Nanchang Hangkong University, 2013

Partitions are integral entities of modern building design. Thermal sensation and contaminant distribution in an indoor air-conditioned space of modern building has particular significance to a vast range of engineering applications. However, the effects of modern partitions in an air-conditioning space on thermal comfort, air quality and other factors has received far less attention. A quantitative indicator in decision making process on the installation or removal of partition is still lacking. The development of the relationship of the effect of partitions in an indoor air conditioning space on thermal comfort, air quality, energy consumption and occupant's perception is of paramount importance in the decision making process of installation or removal of partitions. This research investigates the effects of partition on thermal comfort, indoor air quality and energy consumption in an air-conditioned space with mixing ventilation system via CFD (Computational Fluid dynamics). Numerical simulations are performed to determine the variables of indoor air parameters before and after installation or removal of a partition. Accordingly, the Predicted Mean Vote (PMV) is determined as an indicator of thermal comfort while the carbon dioxide concentration within an air-conditioned space is used for the assessment of indoor air quality. The rate of energy consumption based on the difference of heat content of air is evaluated and compared before and after installation of a partition. An overall perception index deduced using the proximity theory of Hall is used in assessing the occupants' feeling of spaciousness for each model. A case study of a library was studied by a numerical simulation where a partition is used to separate a rest area from a study area at the normal occupancy level. The results obtained from the numerical simulation of a case study of a library without partition was compared with the physical measurement data of the same case. Results from simulation and experiment were highly correlated with acceptable differences. After installation of the partition, significant effects of partition were observed where the area with neutral sensation and slightly-cool sensation changes to cool sensation. The occupants feel uncomfortably cold in larger areas whereas the occupants with neutral sensation are likely to perceive ambient environment less comfortable than before installation of the partition. Increase in energy consumption approximately by 8.3% was observed while the distributions of carbon dioxide concentration were within the acceptable limit. Occupant's perception of space slightly reduces after installation of the partition but it expected that occupant's still feel quite comfortable. Installation of a partition is encouraged in regards to current scenario. However, reinforcement of air-conditioned conditions and adjustment of interior arrangements are necessary to further improve the perceived sensation and energy consumption. Supply air temperature is recommended to increase by couple degree Celsius higher. Increasing supply air temperature by 2 °C significantly improves the thermal sensation with majority of the occupied regions perceiving thermally neutrality. Furthermore, decrease in energy consumption by as much as 27.6 % is observed when the supply air temperature is increased. From analysis, it is apparent that the proposed methodology yields quantitative indicators for recommendation and decision-making of installation or removal of partitions for diverse purposes. The interior design of partition height, relative location and other partition parameters can be subsequently case studied before making real physical changes.

Keywords: Partition, thermal comfort, indoor air quality, energy consumption, perception, CFD

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Chapter 1
Introduction

Nowadays, a significant proportion (more than 80%) of lives is spent in an indoor environment [1]. Such indoor environment besides providing shelter should also ensure proper thermal comfort and air quality. With global rising in socio-economic standard, spacious indoor environment with sophisticated interior arrangement are equally desired in current scenario. Specifically, the need for clean, fresh, and comfortable indoor thermal environment are achieved by building HVAC (Heating, Ventilating and Air-Conditioning) system, while a partition is introduced to divide the indoor space into multi-zones according to their desired functions. The foundation behind increasing use of transparent/ translucent partitions in an air-conditioning space is to obtain the air-tightness for efficient consumption of building energy. Besides, partitions are used for several different purposes e.g. to create privacy ambience, to contain sound, to flexibly divide the indoor workspace, to decorate the indoor atmosphere, to diffuse the natural light and etc. [2]. However, the decision making process of partitioning an indoor space is very challenging for building architect and interior decorator. In order to justify the decision-making process of partition installation, the interacting effects of partitions towards thermal comfort, air quality, and energy consumption need a quantitative study. Dividing larger indoor space into smaller compartments however enhances the variance in running time of HVAC unit as per demand but the distribution of air within the air-conditioned space of each compartments will alter from the original pattern by partitions [3]. Interior decoration is usually done at the later stage of the building design, especially after designing building HVAC system therefore the abrupt installation of partitions may either sustain/improve or deteriorate indoor thermal comfort and air quality. Furthermore, partition changes the perspective visual response of indoor occupants towards the air-conditioned space. The shape and the spatial configuration of an indoor air-conditioning space changes from the occupant point of view with the introduction of partition. In other words, partitions influence the individual perception of occupants towards the partitioned space. Therefore, a study on how we can partition space so as to maximize the occupant's feeling of spaciousness in an indoor environment is deemed necessary. In a study of proxemics, Hall [4] found that satisfaction of occupants on spaciousness during social interaction/activities can be determined from the availability of a social space of an individual. The more the space available, the better the perception enhances [5]. Thus, it is of significance to qualitatively study interacting effects of partitions in the air-conditioned space on thermal comfort, air quality, energy consumption, and perception when the partitions are installed in or removed from the air-conditioned space.

1.1 Thermal comfort

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers has defined thermal comfort as "The condition of the mind in which satisfaction is expressed to the existing environment" [6]. Thermal comfort is the state of mind which is a psychological phenomenon and not directly related to physical environment or physiological state. Thermal comfort is often ignored but it is the true sixth sense and is often considered to be fundamental for human existence. Outdoor thermal comfort can only be controlled by occupant's behavior, e.g. changing the activity, adjusting the clothing, moving to the shade etc. Thermal comfort in an indoor environment can be controlled by appropriate design of building envelope and accommodating HVAC systems. In hot and humid tropical and sub-tropical climate, thermal comfort is achieved through a number of natural ventilation or forced convection. Several models of thermal comfort have been proposed over the years to predict indoor thermal comfort. One of the most common and broadly used models of thermal comfort under various conditions is the widespread PMV model. The PMV model however is fairly accurate in air-conditioned building but the recent analysis of the data collected from 160 buildings from the varied climatic conditions of four continents shows the PMV model deviates widely when applied to the occupants in naturally ventilated buildings [7, 8]. These discrepancies were overcome by newer model of thermal comfort known as adaptive thermal comfort. Adaptive thermal comfort is based on the theory that suggest a connection to the outdoors and control over their immediate environment allows humans to adapt to (and even prefer) a wider range of thermal conditions than is generally considered comfortable [9].

Therefore, ASHRAE Standard 55 encourages the use of adaptive thermal comfort model as an alternative method to the PMV model in the naturally ventilated building. However it is often impossible to achieve satisfactory thermal conditions via natural ventilation in a modern day residential and buildings. Currently, such demands of comfortable indoor environment are conventionally met by the use of mechanical equipment including HVAC system. HVAC system (or air conditioning units) varies depending upon the size of conditioned space, thermal load and the purpose of building. Split-type air-conditioners are usually common for smaller office cabin and residence while centralized air-conditioning system is normally used for larger spaces as they are capable of serving multiple spaces from one base location. These air-conditioning systems typically use chilled water which will be distributed to different air handling unit throughout the building and subsequently to extensive ductwork for air distribution and return to air-handlers.

1.2 Indoor Air Quality (IAQ)

Indoor Air Quality (IAQ) is technically referred to the quality of air within and around the buildings and structures. IAQ can be evaluated in terms of the concentration of gaseous materials. Numerous gaseous materials like volatile organic compounds, formaldehyde, NO_x, SO_x, CO, CO_2, particulate matters and microbial contaminant often deteriorate the indoor air quality. The higher concentration of these contaminants induces severe health effects and occupants discomfort [10]. Contaminants other than carbon dioxide are usually recorded to be sufficiently lower than the standard limit [10]. Hence carbon dioxide concentration is widely used as an indicator of IAQ [11] in delivering the minimum quantities of outdoor fresh air to air-conditioned space of buildings. Furthermore carbon dioxide concentration is dependent on a number of indoor occupants and it is the typical pollutant to be elevated in general cases. Therefore, the concentration of carbon dioxide is investigated for changes after installation and/or removal of partitions. For a typical HVAC system, a filtered ventilation unit brings in fresh air from outdoor environment in order to dilute the return air [12]. Portion of fresh air is to be circulated to maintain initial comfort and reduce energy costs associated with cooling/heating outdoor air after partitioning.

1.3 Energy consumption

Building energy consumption especially the one associated with HVAC systems have raised remarkably over the years and the trend still continues. Despite several researches, building energy consumption often contradicts with the indoor occupant comfort and vice versa. Currently, majority of people on daily basis mostly remain inside building and their performance, productivity and health are significantly affected by indoor environment [13]. Thus, occupants are unlikely to compromise their personal comfort with energy saving. Meanwhile installation of partition is gaining popularity in tropical countries for air tightness and to reduce the cooling space to be served by air conditioning system. Rooms in high rise residential are often partitioned to separate living room/ bedroom and kitchen. Similarly partitioning office cabins from hallways and larger spaces into smaller compartments are equally common. The increasing popularity of using transparent/translucent plane glass-wall to partition spaces is due to its high flexibility and aesthetic visual appearance. Partitioning facilitates dissimilar operating condition as per demand on either side of partition. However there is no solid evidence whether installation/ removal of partition enhances energy saving.

1.4 Perception of space

Indoor environments are not only to provide acceptable occupant comfort and air quality but also to ensure proper spaciousness. Spaciousness is the degree of comfort based on the available amount of workspace for indoor occupants. The amount of space is considered the most important parameter for workspace satisfaction [14]. Study on spaciousness and human behavior suggest, larger room are perceived more positively by occupants than smaller room [15].

In a general term, perception of space is a process through which humans become aware of their relative position and objects around them, that are important for movement and orientation to the environment [16]. Hall in his book, *The Hidden Dimension*, [4] has described the area with highest degree of freedom of movement is the most preferred environmental area. Theories suggest that even if the actual available space is fixed, proper modification of the shape of indoor space often enhances perceived spaciousness [5]. Therefore, architects and interior designer should be well aware of how the indoor designing influence individual perception. Indoor space is characterized by entities such as doors, walls, hallways and partitions that enable and constrain movement. These entities should be built/place in such a way that maximizes occupant's mobility to achieve overall comfort and efficiency. However, installing partition to divide larger space into multiple smaller compartment, may constrain occupant movement over a large spatial extent. Thus, it is promising to study the effect of interior partition on individual perception.

1.5 Research motivation

The study of thermal comfort and indoor air quality has been conducted widely in residences and offices however the study of thermal comfort and indoor quality coupling with energy saving and occupant's perception has been slim across the world. The strategy to have energy efficient building has been understood for several decades now. Therefore setting air conditioning unit to highest possible temperature with minimum occupant discomfort has been effective in offices around the tropical climate [17, 18]. The proposed setting temperature as high as 28 $°C$ has been effectively manipulated for a sustainable development, energy saving and reduce greenhouse gases. However maintaining higher temperature has not been adopted so far in residences and houses because of the complexities involved with unconventional design, furniture and partitions. Modern building usually accommodates glazing walls and glass partition for various purposes. Partitions nowadays are commonly deployed to obtain air tightness in energy efficient buildings. Such partitions often enforce reduced ventilation. The idea to provide thermal comfort and optimum air quality coupled with energy saving in an air-conditioning space with partitions is of paramount importance.

1.6 Statement of problem

Partitions are integral entities of modern building design. Interior sophisticated transparent, semi-transparent and translucent partitions are installed for various purposes in modern buildings. Partitions are usually a trade-off to create privacy ambience, to manage proper occupant's workspace and to contain sound. Currently, the importance of an energy efficient building is remarkably gaining global concern and the partitions are utilized to obtain air tightness. It is relatively common to observe partitions separating conditioning space from hallways, living room from bed room and kitchen. In the same way partitions are also used to manage proper size of air-conditioning workspace for occupants by dividing larger space into smaller compartments. However maximum occupant satisfaction in a building with complex interiors including partitions is fairly hard to achieve. With partitions gaining so much popularity in modern buildings, the effect of partitions on air flow behavior, thermal comfort, ventilation effectiveness and indoor air quality need a detail study. Inappropriate location of partitions not only obstructs occupants from proper mobility and spaciousness inside the conditioned space but it may also involve complexities with acoustics and lightening. The decision-making process of partition installation/ or removal are usually carried out at the later stage of building design, mainly after designing ductwork mechanism for HVAC system. In such case, installation of partition considerably alters airflow behavior and may have significant impact on occupant's comfort. Furthermore, thermal comfort in a glass partitioned spaces is a complex phenomenon because it deals with the cold jet flow reflecting back form the surfaces and transfer of radiant heat between the surfaces. Thermal comfort and indoor air quality has enormous effect in occupant's performance. Satisfactory indoor atmosphere improves workspace performance, productivity and stability of mind. On the other hand thermal discomfort and poor air quality leads to several respiratory problems and various health related issues. One of the most common diseases prevalent in air conditioning space due to poor air quality is the sick building syndrome. Wooden partitions, old furniture and floor are also found to release some toxic gases in an air-conditioning environment [19]. Proper ventilation is needed to ensure the discharge of toxic gases to the outside environment.

1.7 Objectives of the study

The thesis work is generally aimed to resolve the relevant issue involving the effect of partition on air flow behavior and indoor contaminant distribution. The thesis precisely focuses on the difference in perceived thermal sensation, carbon dioxide concentration distribution and building energy consumption due to change in interior configuration brought by the installation/ or removal of partition. The study also aims to explore human-environment relationship in occupant's workspace and the effect of partition on one's perception of space. Eventually, the thesis aims to obtain factual evidences and quantitative data based on the selected indicators to make recommendations in decision-making process of installation/ or removal of partition at the desired location.

1.8 Scope of the study

In this work, a library at SIIT, Thammasat University is chosen to investigate the effect of partition on thermal comfort, air quality, energy consumption and perception of space. An ideal location for installation of the partition is chosen to separate the conditioning space into study area and resting area. The motive behind partition installation is to provide quiet and sound ambience to the students in study area and consequently to investigate the effect due to the change in interior configuration. CFD tool is used to investigate the difference in perceived thermal sensation, carbon dioxide concentration distribution and energy consumption. Subsequently, objective measurement is carried out to validate the results obtained from CFD simulation. In case of analyzing the difference in perception of space, popular Hall's theory of proximity is used. The analysis of the effect of partition on perceived spaciousness of the indoor occupants is restricted to two dimensional planar surfaces even though the effect on occupant's spaciousness is generally felt on three dimensional spaces.

1.9 Latest progress

With increase in socio-economic living standard of people across the world, the importance of having thermally comfortable environment with improved air quality has been realized for many years now. Research and studies on thermal comfort are opted worldwide in several areas of application such as residential rooms, working place, vehicles, trains, aircraft cabin and etc. With advancement in computational powers and numerical codes, several building related issue, indoor airflow, indoor thermal comfort, contaminant transport, smoke flow, ventilation analysis can be successfully determined by the application of CFD. During the early age of construction, indoor thermal comfort and the occupants' behavior were neglected due to the complexity involved in analyzing building related issue. However CFD technique nowadays can resolve all the building related problems in relatively shorter period of time with low cost and convenience and encourage to design thermally comfortable, healthy and energy efficient buildings. Development in CFD has led researcher to easily identify complex airflow modeling, heat and mass transport in a building and examine efficiency and effectiveness of various heating, ventilating and air conditioning (HVAC) systems by simply configuring different types and dimension of air inlet diffuser, exhaust, heat source and number of outdoor parameters. There are a number of commercially available CFD simulation software such as SolidWorks Flow simulation augmented with HVAC module, Ansys, Airpak, Pheonics, and Star CCM+ to evaluate building performance which includes thermal comfort, indoor air quality, mechanical system efficiency and energy consumption. CFD simulation can be widely used in different type of HVAC system such as cooling ceiling, Air-conditioning, stratum ventilation, floor cooling and as well as to natural ventilation system.

HVAC (heating, ventilating and air conditioning) system is easily analyzed and optimized by using CAD-embedded SolidWorks Flow Simulation, augmented with the HVAC application module. HVAC and Product Engineers can efficiently evaluate thermal comfort, air quality, contaminant transport, gas movement, heat transfer, ventilation effectiveness, as well as lightening applications using HVAC application module. It helps to ensure whether the living or working environment receives the right amount of ventilation delivered in the most effective way possible. SolidWorks can be easily used to build a computer model and quickly test a variety of design options to find the best solutions. The ability of a SolidWorks to rapidly create the model and automatically generation and refinement of meshing is coupled with fast, accurate and well-proven solver engine. The additional capabilities of SolidWorks Flow Simulation: HVAC module includes the easy determination of as many as 8 comfort parameters of which PMV and PPD are the most important. The air quality and contaminant control information can also be simultaneously analyzed using Contaminant Removal Effectiveness (CRE) and Local Air Quality Index (LAQI). It also enables users to model absorption of radiation in solid bodies along with the radiation spectrum for a more accurate radiation simulation.

1.10 Structure of thesis

The proposed paper is arranged in following order. Chapter 2 describe the important, most relevant and concise study performed by various researcher in the different part of world. It clearly outlines a number of researches being performed in different sectors on thermal comfort using CFD simulation, various approaches to energy saving in air-conditioning space and perception of space. Chapter 3 presents governing equation and theory involved in distribution of airflow, temperature, humidity, velocity inside the room. It also describes CFD model in detail, the boundary condition and the assumption that were made before carrying out the simulation. It also present the methodology of determining individual's perception of space based on Hall's theory. Chapter 4 presents validity of the obtained result and comparison of results for two different cases, discussion, analysis and understanding based on the simulation result. The recommendations to the library administrator about the pros and cons of partition based on the studied indicators were also presented. Chapter 5 provides the conclusions, recommendations and future works in the installation of partition in an indoor environment. The conclusive recommendations are well supported by quantitative indicators studied on this research.

Chapter 2

Literature Review

2.1 History of human thermal comfort

The generalization of an individual feeling comfort or complaining of discomfort is a complex phenomenon. To define thermal comfort is hard and it's even harder to achieve it. The complexity associated with thermal comfort is the contrary opinion among the indoor occupants sharing the similar ambience. Occupants in similar attire and sharing a common climatic condition have different opinions on thermal comfort. Some opinions are rather contrary to each other. Thus the conclusion remains that, there are no absolute standards of thermal comfort. However, in general, thermal comfort is achieved when the body temperatures are kept as narrow range as possible with low skin moisture and minimized regulation of physiological effort. Though the scientific study on thermal comfort has taken a huge leap only a few decades back but it has always been in consideration as early as the human civilization began. Since then people has been adjusting their clothing, activity, shelter and etc. to cope with the indoor and outdoor environment change. Much of the work in early 20th century was spent on trying to develop a system of integrating relevant thermal comfort parameters to provide a single number as an index to measure thermal comfort. Some early discoveries remarks the development of Kata thermometer in 1916 by Leonard Hill *et al* [20]. But it was not until 1962 when Macpherson pioneered the field of thermal comfort research and achieved a groundbreaking milestone when he identified the total of 6 factors influencing thermal comfort [21]. Those six factors are categorized into four physical variables (air, temperature, air velocity, relative humidity, mean radiant temperature) and two personal variables (clothing insulation and activity level i.e. metabolic rate). His discoveries laid the foundation to carry out the research in the years to follow which eventually drew the attention of many researchers in providing thermal comfort to the occupants in the rapidly revolutionizing industrial world.

2.2 Thermal Comfort and indoor air quality

In general, there is extensive literature coverage in the field of thermal comfort and indoor air quality (IAQ). Thermal comfort and IAQ research covers many forms of residential houses, offices, classrooms, lecture theaters, hospitals and other buildings. Research on thermal comfort and air quality in an indoor environment can be performed in a number of ways such as Computational Fluid Dynamics (CFD), full-scale measurements, reduced-scale measurement, analytical method and etc. Full-scale measurement methods possess the capacity to study the indoor situation to its fullest in real time irrespective of the building design. However, it is often impossible to control the overall boundary conditions and to measure the air parameters at all the points [22]. In reduced-scale method, controlling the boundary condition is possible as they are usually performed inside a controlled laboratory but similarity constraint is a major issue [23]. Analytical method is simple, easier and reliable without the need for high computational power. However, the method is usually suitable for simple cases including the building geometry and the involved physics [23]. On the other hand, CFD has emerged as a potential tool to predict the detailed indoor air flow behavior and in the entire computational domain. CFD allows the full scale simulation and boundary conditions can be perfectly imitated into the model. Recent development in CFD and numerical analysis is capable of predicting airflow with reasonable accuracy in a complicated thermo-fluid boundary conditions and geometry. Additionally, the application of CFD for investigating indoor air flow in naturally as well as mechanically ventilated buildings, thermal sensation, contaminant distribution and air quality is continuously increasing as it is mostly difficult to perform with other methods. Despite growing popularity and several advantages, the accuracy and the reliability of predicting indoor air flow via Computational Fluid Dynamics (CFD) are still biased by numerous researchers. Therefore, the validations of the obtained CFD results are equally important and need to be carried out simultaneously. Some of the excellent literature in the field of thermal comfort, indoor air quality performed using CFD and measurements are discussed below.

The basic study of the effect of internal partitioning on indoor air quality and ventilation performance was performed by Lee and Awbi [24]. A small model test room as shown in Fig. 2.1 with mixing ventilation from ceiling was selected for the study. CFD techniques were applied to evaluate different conditions with variable partition parameters such as partition height, location and the gap underneath. Significant effect of partition on contaminant removal effectiveness and air change efficiency were reported. The research was conducted in isothermal conditions on a small-scale model test room. Practical focus of the research was on the effect of semi-scale partitions used in an open-space plan offices, therefore the obtained results may not be applicable in case of full-scale partitions used in demarcating indoor air-conditioning spaces.

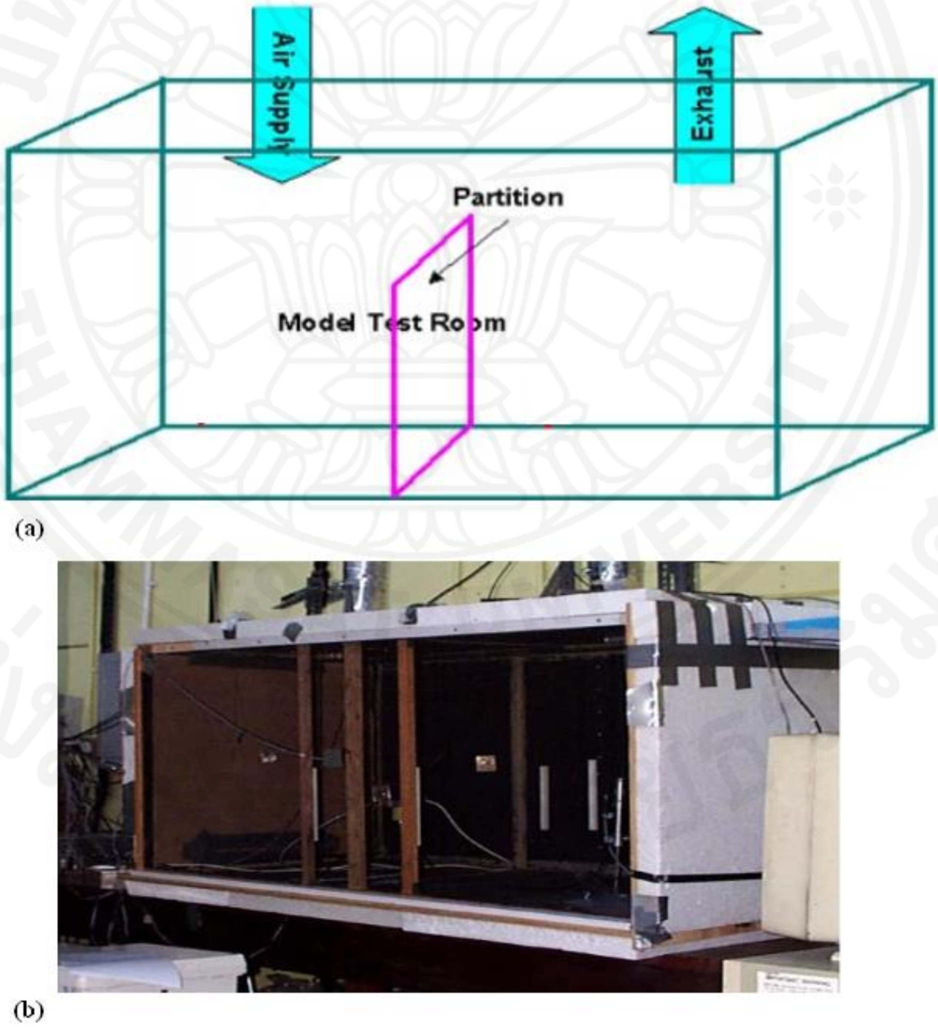


Fig. 2.1. Model test room (a) Schematic diagram. (b) Photograph of the model test room [24]

The recent study of the effect of partitions on thermal comfort and indoor air quality was performed by Lin et al [25]. A typical office room with under floor air supply ventilation system is modeled and numerically studied using CFD techniques. A couple of case study where full scale partition from floor to ceiling and a partial partition with a gap of 0.5 m near the ceiling were comparatively studied. Simulation results showed that partitions considerably affect the airflow behavior at the occupied region and the upper region. The partial partition gap near ceiling significantly reduces air re-circulation and improves thermal comfort and IAQ. The studied case was for a typical office with fewer occupants in an UFAD ventilation system therefore the idea may not be valid for a mixing ventilation system in a large indoor facility with higher occupancy.

Cheong et al [26] performed a full-scale experiment in a lecture theater as shown in Fig. 2.2 using objective measurement, CFD simulation and subjective assessment. Several indoor comfort parameters such as air temperature, air velocity, relative humidity and airflow rate were simulated using a CFD tool. Additionally, carbon dioxide concentration during the peak hour of 100 occupants was measured to assess the indoor air quality. The results obtained from CFD simulation showed fair agreement with measured empirical data and were within the limit of comfort standards. Thermal comfort indices such as PMV and PPD were calculated from the simulation results and compared with the subjective questionnaire assessment of the occupants. Both results revealed the occupants were feeling slightly cool and slight rise in air temperature was recommended. Furthermore, changing ventilation system from variable air volume (VAV) to demand control ventilation system is recommended to improve the build-up carbon dioxide concentration during the peak occupancy load.

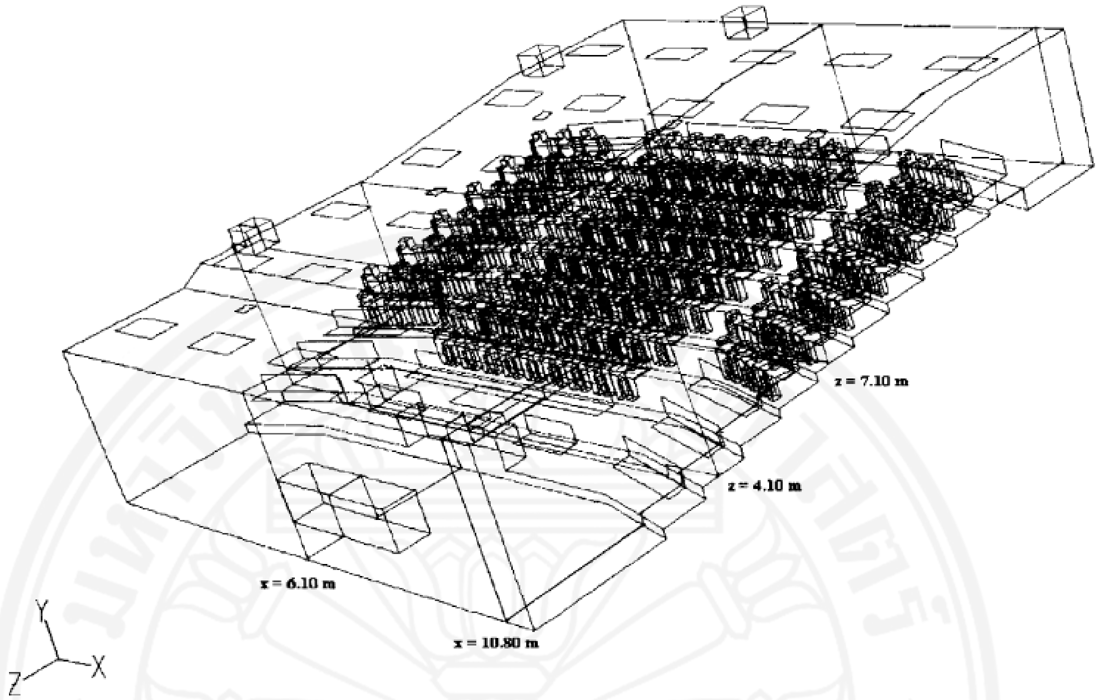


Fig. 2.2. Illustration of Cheong *et al.* model [26]

Rohdin and Moshfegh [27] evaluated the performance of CFD in large indoor industrial facilities. CFD was employed to evaluate whether the existing ventilation system need renovation or a replacement. The performance of a mixing ventilation and displacement ventilation system were compared in terms of the effectiveness of contaminant and heat removal. Results from the CFD analysis shows the displacement ventilation system increases contaminant removal efficiency and heat removal efficiency compared to the mixing ventilation system. However, displacement ventilation has slightly higher risk of causing local discomfort and draughts.

In [28], the effects of return air vent height in thermal comfort and indoor air quality (IAQ) is investigated by applying computational fluid dynamics (CFD) methods. PMV-PPD and vertical temperature gradient were used as indices to analyze thermal comfort. Mean local age of air were numerically calculated to assess the indoor air quality in an under floor air distribution (UFAD) system as shown in Fig. 2.3. The return air vent is positioned at four different heights (2.0, 1.3, 0.65 and 0.3 m) from the floor and each case was studied individually. All the heights except 1.3 m exceed the specified thermal comfort and temperature gradient range specified by ISO7730.

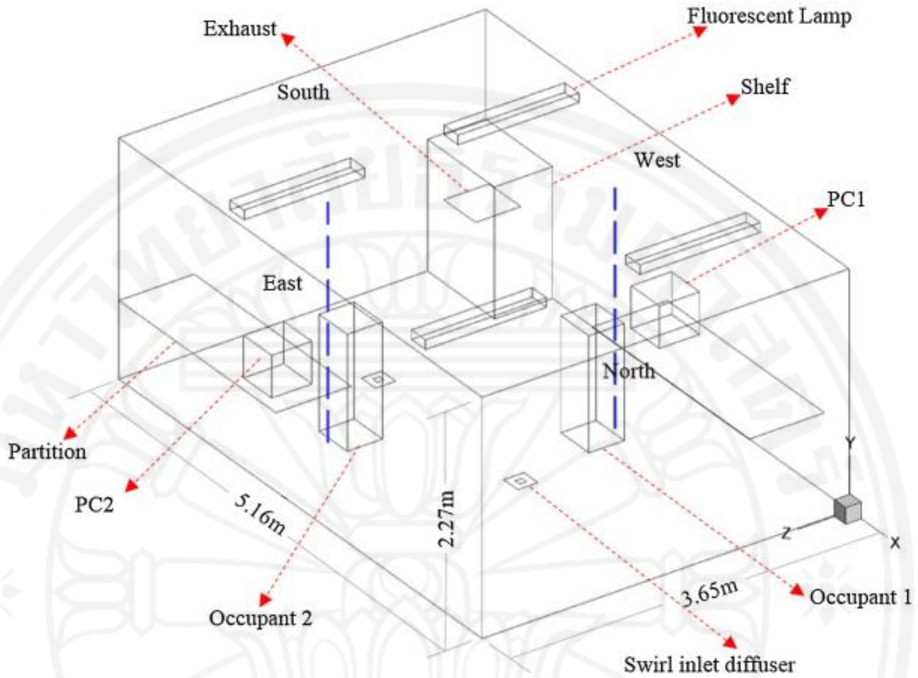


Fig. 2.3. Configuration of the UFAD model room [28]

In [29], the effect of the position of an air conditioning units and indoor furniture on thermal comfort is studied in small Hong Kong residential. Air temperatures, air velocities and air diffusion performance index (ADPI) were analyzed at three different positions of air- conditioning units by using computational fluid dynamics (CFD) tool. Maximum benefits in terms of thermal comfort for sleeping occupant are identified and architectural recommendations were given to take account of such factors in building design.

The effects of room height on thermal comfort conditions were studied by Igor *et al* [30]. Air- conditioning units were mounted on a wall of a similar rooms but different heights. The effect of space heights on the distribution of air temperature and air velocity were numerically analyzed using CFD methods. Significant differences in temperature distribution at the lower layers are noticed for room with higher height. The consequences are explained as the buoyancy effect which can be canceled out by increasing air velocity at the air-conditioning inlet.

Similarly CFD methods were implemented by numerous researchers to study thermal comfort and indoor air quality in an educational premises [26, 31], offices [32, 33] healthcare units and hospitals [34, 35], industrial premises [27], laboratories [36, 37], stadiums [38] etc.

2.3 Air-conditioning energy consumption

Most indoor equipped air conditioning units are ineffective and consume huge amount of energy [39]. HVAC system in a building comprises of a significant portion (30-60%) of the total energy required for building operation [40]. Optimal comfort, better IAQ and reduced energy consumption are inevitable for sustainable development however there exist a massive dispute among those parameters in building ventilation. The idea of air-tight building easily possible by introducing partitions are fair example of energy efficiency building however it has often come at the price of sick building syndrome in occupants. Most existing air conditioning system is operated only to control temperature with the help of thermostat. Temperature is mostly kept constant in such system which are inefficient in making occupants comfortable [11]. The basic idea for saving energy in an air conditioning system is to determine thermal loads and to set the supply temperature to higher possible value with in comfort limit. Furthermore, air conditioning system decreases the energy consumption that maintains low humidity therefore by an idea of effective temperature, the dry bulb temperature can be increased with decreasing relative humidity while maintaining the same comfort level. Several improvements in indoor environment are adopted to simultaneously achieve occupants comfort and energy saving. Such as small fan assisted air conditioner [41] to increase set point temperature, personalized air conditioning system [42] to shorten operation time for same level of comfort and etc. In [43], Ahmed *et al* proposed a scheme using a fuzzy logic to program a thermostat setting for an AC unit that serves more than one room. The limitation of users not being able to control the set point of humidity in conventional AC system was overcome to a greater extent. 25° *C* temperature and 70 % humidity were successfully maintained even though the AC compressor remained off for an appreciable period of time leading to significant energy saving. Heidarinejad *et al* [28] studied the effect return air vent height on energy consumption. Computational fluid dynamics (CFD) methods were used in an under floor air-distribution system (UFAD) with variable return vent height. The amount of energy consumption for each case was compared to mechanical ventilation (MV) system. Substantial energy saving up to 25.7% was recorded. In [44], CFD was used to investigate thermal comfort and energy consumption of a localized air-conditioning system in a vehicle compartment. At a satisfied neutral thermal comfort level, localized air-conditioning system with optimized ceiling and front vent noticeably reduces the energy consumption compared to conventional system.

2.4 Perception of space

Abundant research has been conducted in the field of psychology and social science related to perception of space among individual. The majority of studies investigating interpersonal space issues has been carried out in public places such as shops, libraries and workplaces [45]. The concept of interpersonal space was first introduced by E.T. Hall [4]. The study of social spaces is very important because it eventually leads to a better understanding of social norms in different culture thereby improving the standard of life and work by optimizing the personal space available for individuals. Interpersonal space is such that if one threatens the boundary of personal space of individual, it might result in feelings of anxiety and discomfort [46]. Steve [45] studied the effect on the perception of space of an individual when the occupants next to the individual are engaged in conversation using a mobile phone. The findings of the experiment suggest the formation of an uncomfortable environment where individuals are felt being drawn into the personal space of a phone receiver. Nagar and Pandley [47] studied the spaciousness of a room with varied occupant density. The room with higher occupant density was reported being perceived crowded and annoying than low density rooms. The concept of interpersonal has also been realized in the field of virtual humanoids, avatars and robots intending to support virtual humans in near space interactions [48]. Extensive research on the influence of the horizontal shape of the space on spaciousness were carried out by Sadalla and Oxaley [49] and Ishikawa et al [50].

Chapter 3
Methodology

3.1 Theoretical background

3.1.1 Thermal comfort model

Among available several models of thermal comfort, the most common and perhaps the best understood model are the PMV (Predicted Mean Vote) model and the PPD (Predicted Percentage Dissatisfied) model [51]. The PMV model was originally proposed by Fanger in 1970 [52]. The PMV model is still predominant in current scenario and has been adopted by several international standard e.g. ISO 7730 [51], ASHRAE Standard 55 [53]. PMV is the mean thermal sensation response of a large number of subjects in a given environment. The principle of PMV depends upon the phenomenon of heat transfer between the body and the ambient environment at the steady-state condition. The PMV model considers the collective thermal effects of two individual characteristic variables: metabolic activity (M) and clothing insulation (I_{cl}) and four environment variables: air temperature (T_a), relative humidity (RH), air velocity (v), and mean radiant temperature (T_r). A complex mathematical equation of PMV is given in Eq. (3.1).

$$PMV = (0.303e^{-0.036M} + 0.028)\begin{Bmatrix} (M-W) - 3.05\times10^{-3}[5733 - 6.99(M-W) - P_a] - 0.42[(M-W) - 58.15] \\ -1.75\times10^{-5} M(5867 - P_a) - 0.0014M(34 - T_a) \\ -3.96\times10^{-8} f_{cl}\left[(T_{cl}+273)^4 - (T_r+273)^4\right] f_{cl} h_c (T_{cl} - T_a) \end{Bmatrix} \tag{3.1}$$

with,

$$T_{cl} = 35.7 - 0.028(M-W) - I_{cl}\left\{3.96\times10^{8} f_{cl}\left[(T_{cl}+273)^4 - (T_r+273)^4\right] + f_{cl} h_c (T_{cl} - T_a)\right\} \tag{3.2}$$

$$h_c = \max\left\{2.38(T_{cl} - T_a)^{0.25}, 12.1\sqrt{v}\right\} \tag{3.3}$$

$$f_{cl} = \begin{cases} 1.09 + 1.29 I_{cl} & for I_{cl} \le 0.078 \\ 1.05 + 0.645 I_{cl} & for I_{cl} > 0.078 \end{cases} \quad (3.4)$$

$$P_a = P_s \times RH / 100 \quad (3.5)$$

where, M is metabolic rate that depends upon the activity of an individual. It is measured in a unit of *Met* (1 *Met* = 58.2 *W/m*^{2}). W is the external work, I_{cl} is the level of clothing insulation. It is measured in a unit of *Clo* (1 *Clo*=0.155 m^2K/W), f_{cl} is the ratio of clothed surface area to the nude surface area also known as clothing area factor, T_a is the air temperature, V is the relative air velocity, P_a is the partial pressure of water vapor, P_s is the saturated vapor pressure, *RH* is the relative humidity of ambient air expressed in percentage, h_c is the convective heat transfer coefficient, T_{cl} is the surface temperature of clothing ensemble, T_r is the mean radiant temperature

The values of metabolic activity M for various activities can be referred to ANSI/ ASHRAE standard 55 [54]. Some of the common activity and their corresponding values are given in Table 3.1.

Table 3.1 Metabolic activity values for typical task

Activity	Metabolic Values	
	Met	W/m^2
Resting		
Sleeping	0.7	40
Seated, quiet	1.0	60
Standing relaxed	1.2	70
Walking (on plane surface)		
3.2 km/h	2.0	115
4.3 km/h	2.6	150
6.8km/h	3.8	220
Office activities		
Reading, seated	1.0	55
Writing	1.0	60
Typing	1.1	65
Filing, seated	1.2	70
Filing, standing	1.4	80
Walking about	1.7	100
Lifting/packing	2.1	120
Miscellaneous activities		
Cooking	1.6-2.0	95-115
House cleaning	2.0-3.4	115-200
Sawing	1.8	105
Dancing, social	2.4-4.4	140-255
Exercise	3.0-4.0	175-235

Clothing prevents body's excessive heat loss to the surrounding. Proper adjustment of clothing is necessary to maintain comfort at different temperature level. However, the mechanism of heat transfer through clothing layers is very complicated. Thus an alternative is preferred where each clothe has its own insulation value measured in a unit of *Clo* (1 *Clo* =0.155 $m^2 °C /W$). *Clo* value is usually referred to ANSI/ASHRAE Standard 55. The total *Clo* value of an ensemble is the sum of the individual *Clo* value of all the garments. Some *Clo* value of typical garment insulation is given in in Table 3.2.

Table 3.2 *Clo* value of typical garment

Garment description	I_{cl} (*Clo*)	Garment description	I_{cl} (*Clo*)
Underwear		Dress and Skirts	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Short-sleeve shirtdress	0.29
T-shirt	0.08	Long-sleeve shirtdress	0.33
Half-slip	0.14	Sweaters	
Long underwear bottoms	0.15	Sleeveless vest, thin	0.13
Full slip	0.16	Sleeveless vest, thick	0.22
Long underwear top	0.20	Long sleeve, thin	0.25
Footwear		Long-sleeve, thick	0.36
Athletic socks	0.02	Suit Jacket and Vests	
Panty hose	0.02	Sleeveless vest, thin	0.10
Sandals	0.02	Sleeveless vest, thick	0.17
Shoes	0.02	Single breasted, thin	0.36
Slippers	0.03	Single breasted, thick	0.44
Knee socks	0.06	Double breasted, thin	0.42
Boots	0.10	Double breasted, thick	0.48
Shirts and Blouses		Sleepwear and Robes	
Sleeveless blouse	0.12	Sleeveless short gown thin	0.18
Sport shirt	0.17	Sleeveless long gown thin	0.20
Dress shirt short-sleeve	0.19	Short sleeve short robe	0.34
Dress shirt long sleeve	0.25	Short sleeve pajamas, thin	0.42
Sweatshirt	0.34	Long sleeve pajamas, thick	0.57
Trousers			
Short shorts	0.06		
Walking shorts	0.08		
Straight trousers, thin	0.15		
Straight trousers, thick	0.24		
Sweatpants	0.28		

Human thermal sensation is described by PMV on a 7 point scale that ranges from -3 to +3 which correspond to cold and hot respectively. The value of 0 means thermal neutrality where majority of the occupants feel comfortable. The ASHRAE recommendation of a thermally comfortable environment should have PMV value at the range of -0.5 to +0.5. Table 3.3 shows the relationship between PMV value and occupant thermal sensation.

Table 3.3 Thermal sensation and PMV value

cold	cool	slightly cool	neutral	slightly warm	warm	hot
-3	-2	-1	0	+1	+2	+3

PMV is only the average expected value from a group of large number of subjects. With this realization, Fanger extended his PMV model to predict the quantity of the number of people who will be dissatisfied at a given time in the environment. Fanger used PMV comfort vote to model a newer index of thermal comfort called PPD. PPD index quantifies the percentage of people who vote outside the recommendation range of PMV in ASHRAE scale. Statistically, a thermally comfortable environment should have less than 10% of dissatisfied people. The relationship that shows the distribution of PPD based on PMV is expressed in Eq. (3.6).

$$PPD = PMV\ exp^{[(-0.03353\ PMV^4 + 0.2197\ PMV^2)]} \quad (3.6)$$

PPD value ranges from 5% to 100%, as it is impossible for every occupant to be satisfied in the given environment. The relationship between PMV-PPD and thermal sensation is depicted in Fig. 3.1 [55].

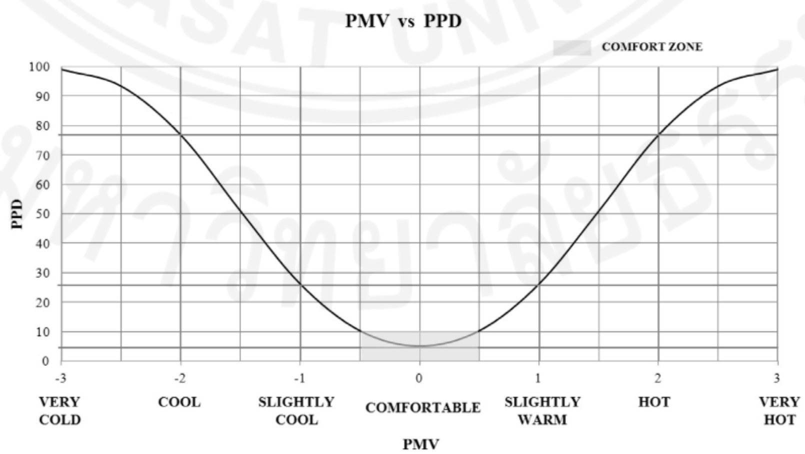


Fig. 3.1. PPD as a function of PMV

3.1.2 Indoor air quality index

Maintaining adequate indoor air quality is amongst a top priority in an indoor environment for building operating engineers. Currently, the popular way of assessing indoor air quality is by the measurement of carbon dioxide concentration. There are several advantages associated with using carbon dioxide concentration as an indicator of indoor air quality. The measurement of carbon dioxide is relatively easy and inexpensive. The primary purpose behind measuring carbon dioxide concentration as an indicator of IAQ in modern building and large indoor facilities is because the other contaminant are sufficiently lower than the standard limit. Furthermore, importing fresh air and exhausting the portion of circulated air to reduce the indoor carbon dioxide concentration would also check the buildup concentration of the remaining contaminants. In school and educational premises, workers and students spend significant amount of time indoor in a densely populated area rich in carbon dioxide concentration. Carbon dioxide concentration in such spaces are often reported to exceed the threshold limit [10, 56]. Therefore carbon dioxide concentration is investigated as an indicator of IAQ before and after the installation of partition. The effect of partition on the buildup carbon dioxide concentration is justified quantitatively in this study Previously devised ASHRAE standard [57] recommends the highest acceptable indoor carbon dioxide concentration of 1000 ppm however the current ASHRAE standard [58] suggest that the differential indoor-outdoor carbon dioxide concentration should not exceed 700 ppm.

3.1.3 Energy consumption

Fig. 3.2 shows a typical building HVAC system. Usually air handling unit (AHU) in typical building ventilation is centralized and responsible to distribute fresh and conditioned air to several regions within the building. Different rooms and regions within the building have different heating and cooling loads. These loads may come from equipment, electrical appliances, occupants, weather and various other factors. In the simplest case, such loads are addressed by providing a constant supply of cool air which is then managed by HVAC distribution system. Outdoor fresh air is mixed with the portion of recirculated air to dilute the indoor contaminant concentration at the mixing chamber. Mixed air is cooled by chilled air or water. Air handling unit (AHU) blows the conditioned air into the building ductwork. Ductwork provides a passage for the conditioned air from the air handling unit to the environment. Ductwork is followed by an automated or manual damper to control the amount of airflow to different room as required. Damper is followed by a square, circular or rectangular diffusers or grilles which are usually placed at the ceiling to deliver the conditioned air into the occupied space Diffusers and grilles are air outlet. They distribute and direct the air flow throughout the occupied space in the most effective manner. The fresh conditioned air moves around the thermal space and finally extracted into the return inlets. A portion of return air (10-20%) is vented out to the atmosphere and replaced by fresh outdoor air in each cycle.

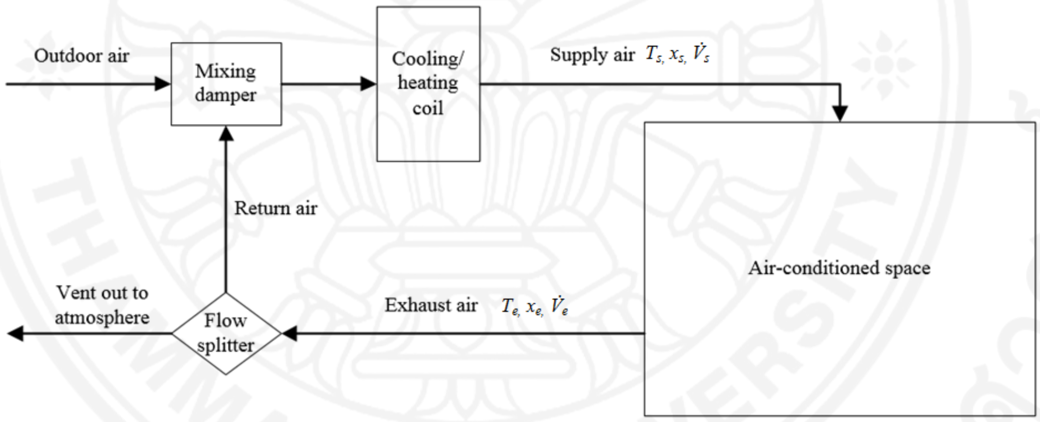


Fig. 3.2. Air-flow diagram of typical HVAC system

The main energy supplied to HVAC system proportionally relates to cooling/ heating load [59]. Cooling/ heating load is the energy used up in making supply air and return air satisfactory for thermal comfort and IAQ. Prediction of heating/cooling load of room makes it possible to achieve energy efficient building. Heating/cooling or thermal load of a room is calculated as the change of enthalpy of supply air and exhaust air in the room [60]. Enthalpy is the heat content of the substances. Enthalpy of the moist air in HVAC system is expressed as the sum of partial enthalpies of dry air and saturated water vapor as given in Eq. (3.7).

$$h = h_a + xh_g = 1.006T + x(1.84T + 2501) \quad (3.7)$$

where T is the dry bulb temperature °C, x is the humidity ratio kg/kg, h_a is the specific enthalpy of dry air and h_g is the enthalpy of saturated water vapor.

In the simplest case of cooling and humidifying by an HVAC system, the difference of enthalpy of moist air at the supply and the return represents the consumed energy. In a general case, the volumetric inflow from the supply vent to the occupied space is equivalent to the volumetric outflow from the exhaust of an air-conditioning room. The rate of energy consumption of an air-conditioning system based on the enthalpy difference can thus be expressed as in Eq. (3.8).

$$\dot{Q} = \left(\sum \rho \dot{V}_e \left(1.006T_e + x_e\left(1.84T_e + 2501\right)\right) - \sum \rho \dot{V}_i \left(1.006T_i + x_i\left(1.84T_i + 2501\right)\right)\right) \quad (3.8)$$

Where, ρ is the density of air, $\dot{V}_e$ and $\dot{V}_i$ is the volumetric flow rate at each exhaust outlet and at each supply inlet respectively. T_e and T_i is the dry bulb temperature of air at the exhaust outlet and at each supply inlet respectively, x_e and x_i is the humidity ratio of moist air at each exhaust outlet and at each supply inlet respectively.

From Eq. (3.8), the variables such as the dry bulb temperature, volumetric flow rate, and moisture content of the supply air are manually or automatically adjusted to obtain optimal thermal comfort and indoor air quality with efficient energy usage. However, installation/removal of partitions within an air-conditioned space which are usually carried out at the later stage of building design subsequently alter the indoor air distribution and energy consumption. Accordingly, the rate of energy consumption due to the effect of partition installation/removal is investigated based on the difference of enthalpy in each case by using Eq. (3.8).

3.1.4 Perception index

The perception index studied in this work is the measurement of an individual feeling of spaciousness or discomfort based on the available space for an individual. According to Hall's theory, every individual subconsciously forms a reaction bubble for interpersonal communication in occupied space and outdoor environment [4]. The imaginary reaction bubble is categorized into series of four spaces as shown in Fig. 3.3. Intimate space is the space up to a distance of 45 cm from the person which is reserved only for the most trusted and loved ones. Personal space is the space at a distance between 45 cm and 1.2 m reserved for family members and close friends. Social space is a space reserved for colleagues, classmates, strangers, newly formed groups and new acquaintances for everyday interactions. The social space has a range at a distance between 1.2 m to 3.6 m from the center of individuals. The outermost space at a distance larger than 3.6 m is public space usually reserved for public speaking and addressing a mass. This concept of interpersonal space is effective for interactions with others in everyday life and for space organization in houses and buildings [61].

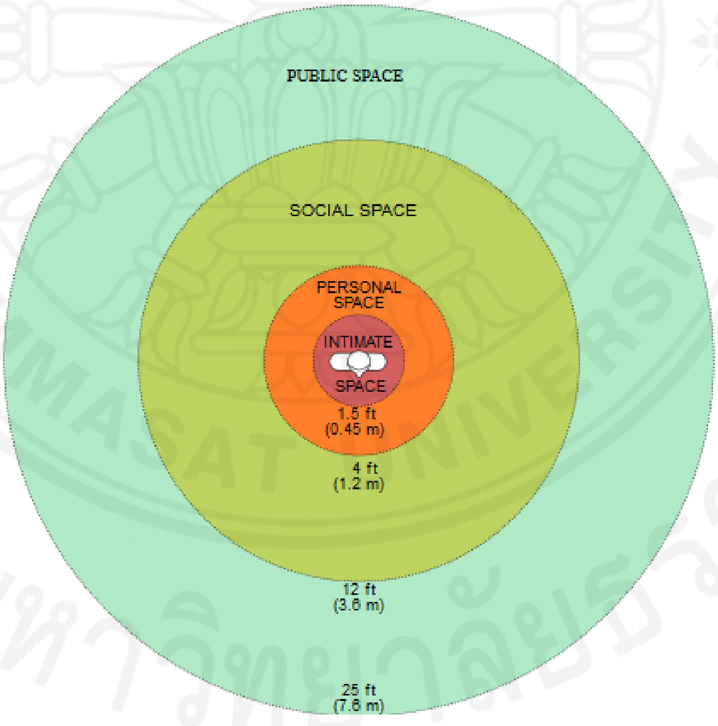


Fig. 3.3. Series of space in personal reaction bubble

The perception due to partition in this work is an indicator to quantify the degree of spaciousness felt by an individual in an indoor environment consisting of partitions. However, it is restricted only to the visual viewpoint and the available space for occupants. The highest degree of spaciousness for an occupant is assumed when the available space surrounding the occupant is equal to or larger than the area of social space described in Hall's theory. Area of social space is chosen as the base point for spaciousness because occupants feel comfortable in conducting routine social interactions within this area. The invasion of an occupant's social space due to partitions causes a decrease in degree of spaciousness. The perception index ranges from 0 to 1. A value of 0 is considered the worst perception from partitions whereas a value of 1 is the best. In an indoor environment consisting of partitions, the overall perception index, associated with several numbers of occupants, is determined as in Eq. (3.9).

$$I_P = 1 - \frac{\sum_{j=1}^{m}\left(\sum_{i=1}^{n} A_{j,i}\right)}{\sum_{j=1}^{m}\left(\sum_{i=1}^{n} \hat{A}_{j,i}\right)} \tag{3.9}$$

where I_P is the perception index, m is the number of partitions, n is the number of circle of social space formed by the arrangement of one or more occupants, $A_{j,i}$ is the area of social space of occupant j invaded by partition i, and $\hat{A}_{j,i}$ is the maximum area of social space of occupant j invaded by partition i, at center.

With Eq. (3.9), Fig. 3.4 shows the simplest case of a perception index of a single occupant due to a partition. In Fig. 3.4(a), the partition is located at a distance greater than 3.6 m. The partition has no effect on the social space of an occupant, so the corresponding perception index has a value 1. Fig. 3.4(b) shows a part of social space being invaded by a partition, which is at a distance less than 3.6 m from the occupant's center, so the perception index has a value between 0 to 1. Fig. 3.4(c) shows the partition coinciding with the centre of occupant, invading the entire half of the circle of social space, so the perception value is 0.

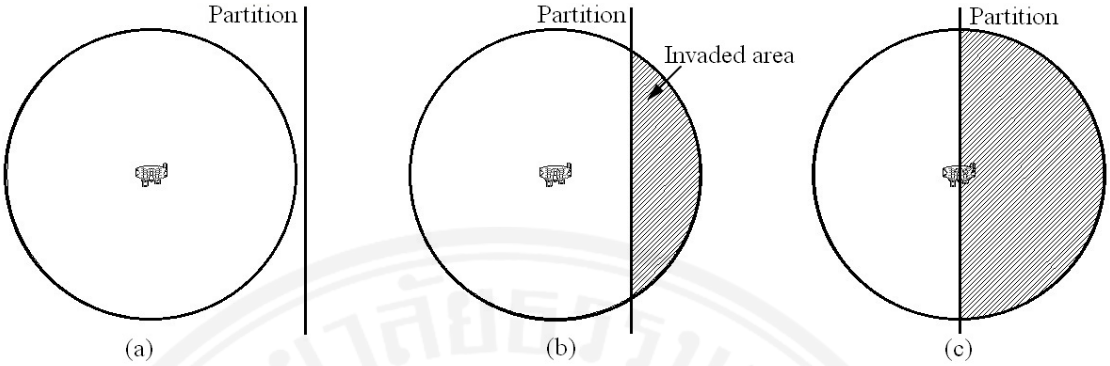


Fig. 3.4. Perception index in the simplest case at various partition locations:
(a) I_p =1 (b) 0< I_p <1 (c) I_p =0

Fig. 3.5 shows the relationship between the perception index value and the distance of partition from occupant's center. The corresponding perceived feeling as a function on distance of partition from the occupant's center is categorized into narrow, ample, and spacious. Spacious is when a partition is outside the social space of a person. Ample is when a partition invades a part of occupant's social space. Narrow is when a partition is closer than a distance of 1.2 m from the occupant's center severely affecting the occupant's mobility freedom.

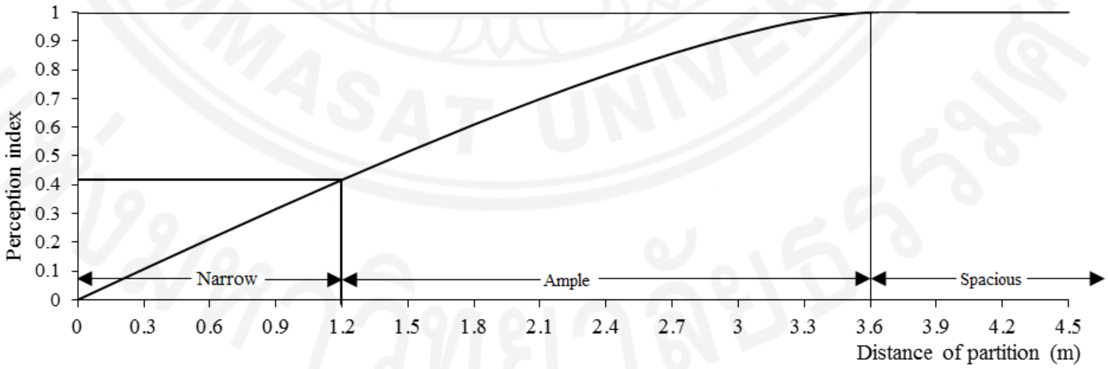


Fig. 3.5. Perceived feeling and the perception index value

3.2 Experimental setup of CFD study

3.2.1 Description of CFD model

The proposed study was conducted on the first floor of SIIT library, Thammasat University. Fig. 3.6 shows the studied configuration of the library. The library measures 38 m in length, 27.3 m in width and the finished ceiling height of 3m accompanied with dropped ceiling in most part of the library.

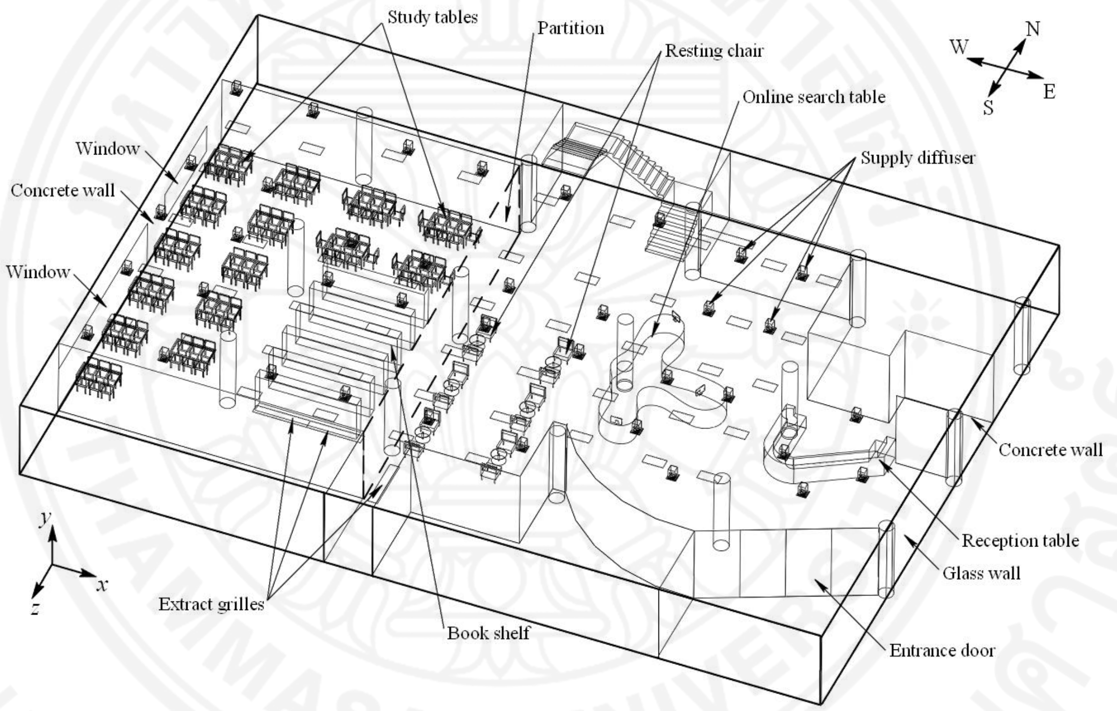
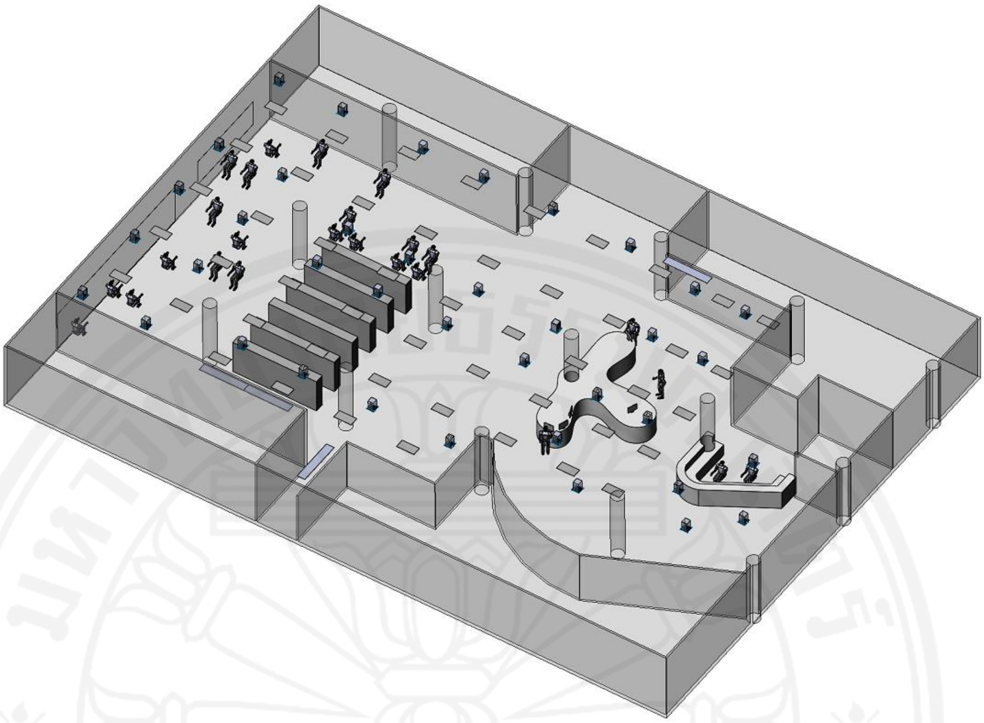


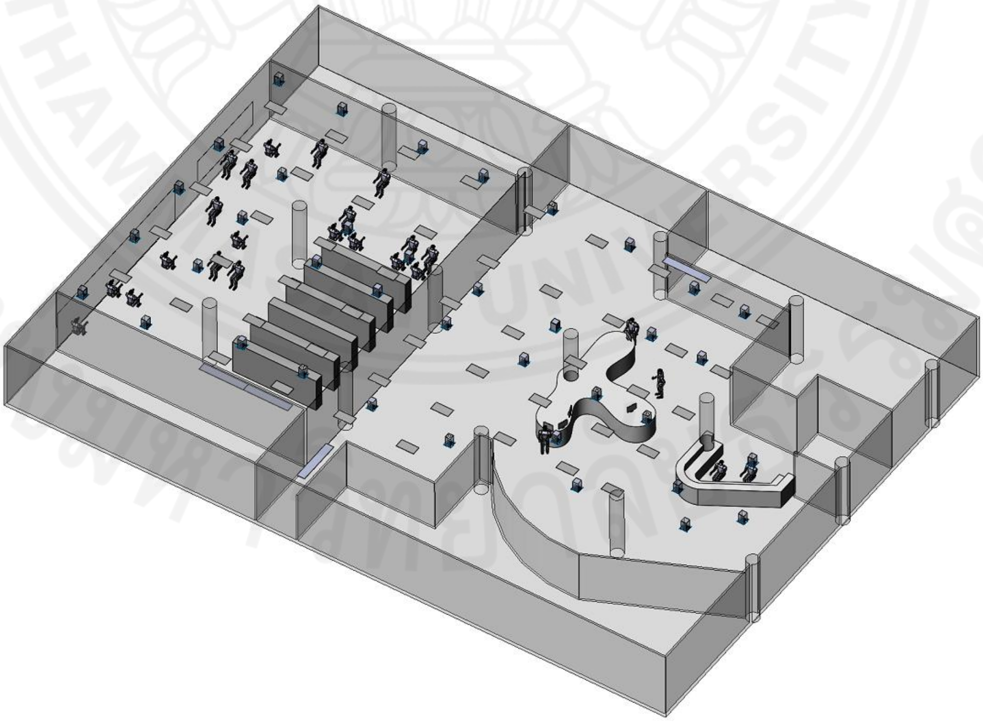
Fig. 3.6. Configuration of SIIT library

Almost at the middle section of the library, there is a stair-way to the second floor. The western wall is concrete and partially covered with one large (24 m^2) and one small (7.4 m^2) window of 3 mm thickness. The western side of the library mostly consists of study tables and chairs. Each table has 6 chairs. Series of six bookshelves are placed next to the study tables. The middle section of the library has resting sofa with newspaper and magazine stand. Online database browsing “T” shaped table has twelve computers atop to facilitate online searches and printing services for students. The eastern side of library has reception table and the entrance door. The sliding entrance door is automated to self-open and close. The eastern wall is mostly covered by a glass walls to facilitate well-lightening, view and in-out convenience. The desired location for the installation of full scale partition to investigate effects on thermal comfort, indoor air quality, energy consumption and perception of space is indicated by dotted line. The desired location for the installation of the partition is chosen such that the quiet study area on the west side is separated from an accessing area on the east side.

Fig. 3.7 shows the simplified 3D CAD modeling of the studied two cases: 3.7(a) library without partition and 3.7 (b) library with partition. Both models were built with precise geometry. Heat sources such as occupants, ceiling lights, computers and library furniture such as reception table, "T" shaped table, study table, and book–shelf were subsequently added to the 3D model. However some entities that don't significantly contribute to the building heating and airflow distribution pattern were removed to simplify the model and to ease the meshing procedure. SolidWorks solid modeling was used to generate the complicated 3D modeling of the library. The modeling is assisted by SIIT library ground division by generously providing the 2D CAD drawing.



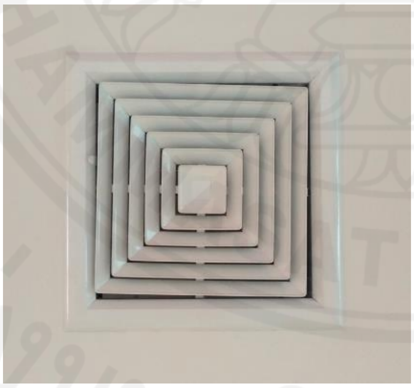
(a)



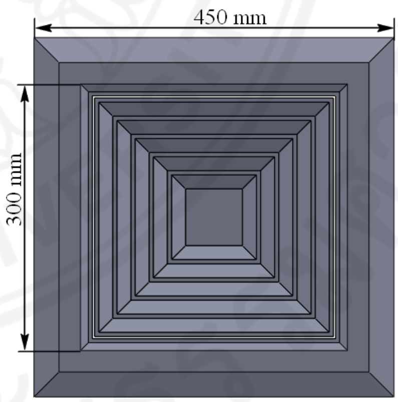
(b)

Fig. 3.7. 3D CAD modeling of SIIT library (a) without partition (b) with partition

The library premises are suitably facilitated by a centralized air conditioning system with thirty-eight ceiling-type square supply diffusers. Most of the diffuser outlets are mounted on ceiling whereas it hangs freely in the region without dropped ceiling. Each supply diffuser is connected to the ductwork via diffuser neck of dimension 300 mm × 300 mm. Each diffuser outlet is composed of 6 vanes in all four directions. The overall face dimension of diffuser outlet is 450 mm × 450 mm. Fig. 3.8 shows the real 4-way square supply diffuser mounted on the ceiling and the corresponding 3D model generated using SolidWorks. A square supply diffuser is widely used for passages of airflow in all directions. The air distribution pattern can be changed by adjusting the inner cones or deflecting vanes. Ceiling diffusers are very effective for higher supply air temperatures and for conditioned space with low head space. Room air is extracted to the ceiling plenum via four rectangular extract grilles. A ceiling mounted extract grilles are shown in Fig. 3.9. Each extract grilles has a of dimension of 2.5 m × 0.4 m. Thirty-eight number of diffusers are named in numerical order from D1 to D38. Four extract grilles are named from E1-E4. The location of the supply diffuser and extract grilles on the ceiling are shown in Fig. 3.10.



(a)



(b)

Fig. 3.8. Square supply diffuser (a) Real ceiling mounted diffuser (b) 3D CAD model

Fig. 3.9. Extract grilles mounted on ceiling

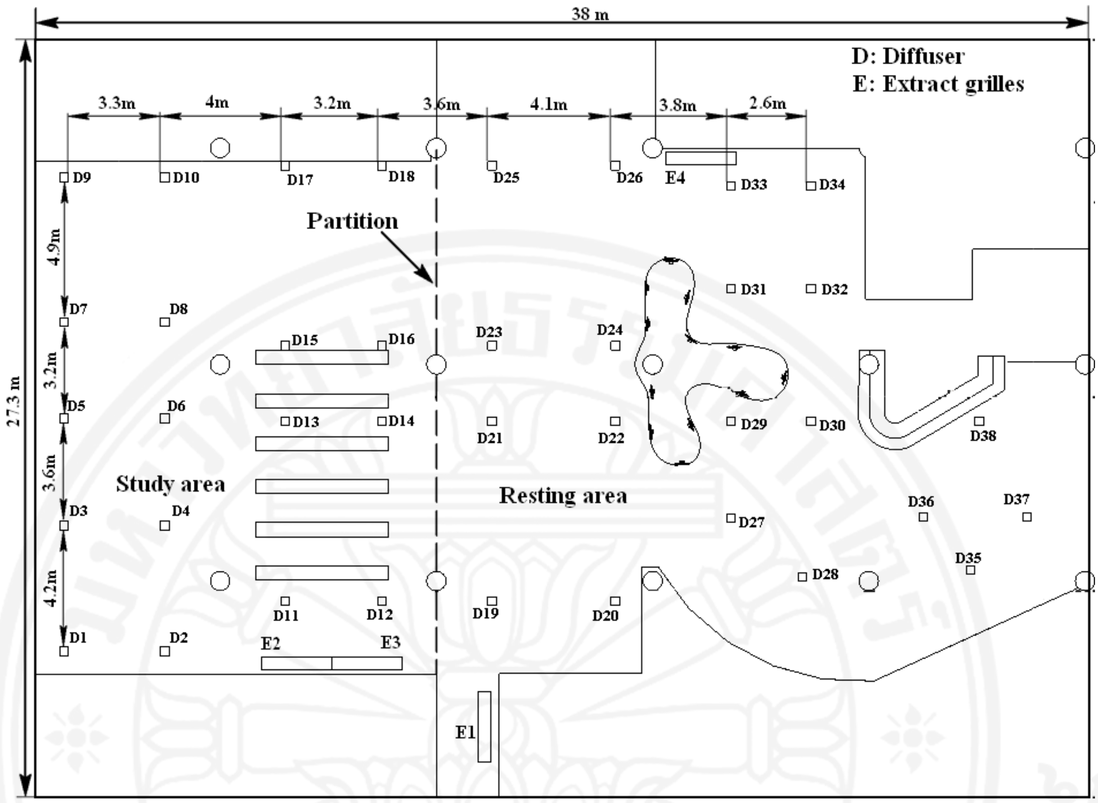


Fig. 3.10. Location of supply diffusers (D1-D38) and extract grilles (E1-E4)

3.2.2 Mesh generation

Meshing is one of the most important job and considerable attention should be given during the mesh generation while carrying out any kind of fluid flow simulation. It is not exaggeerated that the simulation result are direclty influenced by the quality of meshes. Flow Simulation computational approach is based on locally refined rectangular mesh near geometry boundaries. The mesh cells are rectangular parallelpipeds with faces orthogonal to the specified axes of the cartesian coordinate system [62]. However, near the boundary, mesh cells are more complex. The near-boundary cells are portions of the original parallelpiped cells that cut by the geometry boundary. The curved geometry surface is approximated by set of polygons which vertexes and surface's interaction points with the cells' edges. These flat polygons cut the original parallelpiped cells. Thus, the resulting near boundary cells are polyhedron with box-axis oriented and arbitrary oriented plane faces as shown in the Fig. 3.11.

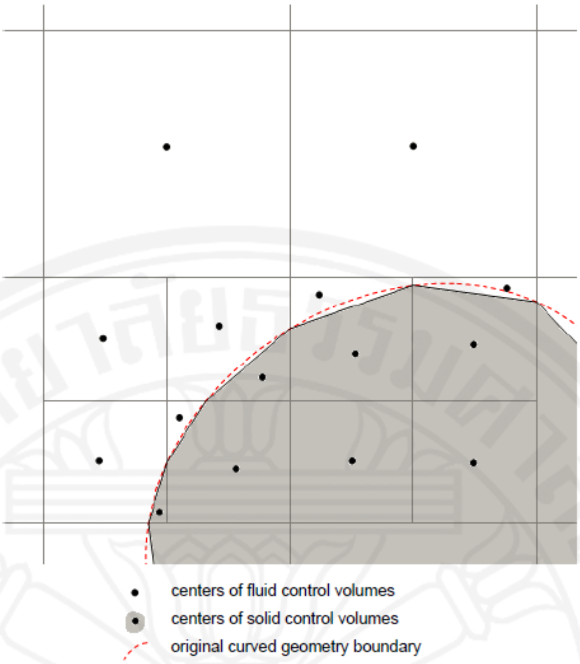


Fig. 3.11. Computational mesh cells near the solid/fluid interface

The cut cells are named partial cells. The original parallelepiped cells containing boundary are split into several control volumes that are referred to only fluid or solid medium. In the simplest case there are only two control volumes in the parallelepiped, one is solid and another is fluid. Flow Simulation at first, creates a basic mesh automatically which can be changed manually later on. To construct a basic mesh, the computational domain is divided into slices by the basic mesh planes, which are evidently orthogonal to the axes of the Cartesian coordinate system. Refinement of mesh includes splitting of rectangular computational mesh cell into eight cells by three orthogonal planes that divide the cells edges into halves. The initial mesh cells with non-splitting cells are called basic mesh or zero level cells. The automatic initial mesh of level 5 was created for the preliminary calculations. The preliminary meshing is followed by the grid refinement to increase resolution and accuracy. Critical locations and crucial boundary conditions such as supply diffusers, extract grilles, surface of heat sources, and walls were highly refined. Grid independencies were repeatedly checked and a model consisting of 1.2 million control volumes resulted in a difference of less than 3% in the values of the calculated air parameters. Thus, the model was concluded sufficiently reliable to investigate the effect of partition. The generated mesh of the entire computational domain is shown in Fig. 3.12.

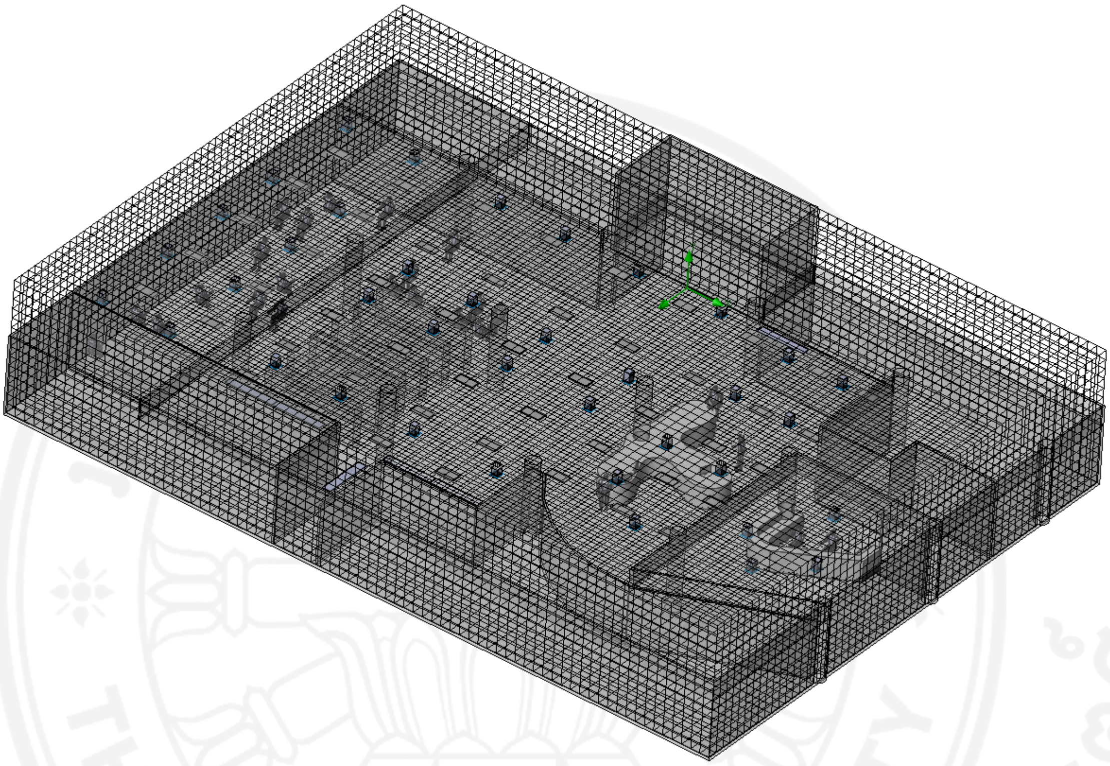


Fig. 3.12. Perspective view of computational mesh over the entire domain

3.2.3 Governing equations

The distribution of indoor air variables and the concentration of species are governed by the conservation laws of mass, momentum and energy balance. The effects of partition on thermal comfort, IAQ and energy consumption were analyzed using a commercial CFD code SolidWorks Flow Simulation. The spatial distribution of indoor air in three-dimensional domain is assumed steady, incompressible and turbulent. The governing equations were solved using the Finite Volume (FV) method. Based on the assumptions made above, the governing time-averaged steady state equations can be written as:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{3.10}$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial P}{\partial x_i} = \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{ij}{}^{R}) + S_i \tag{3.11}$$

Energy equation:

$$\frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}\left(u_j(\tau_{ij} + \tau_{ij}{}^{R}) + q_i\right) - \tau_{ij}^{R}\frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H \tag{3.12}$$

where, Q_H is the rate of heat generation per unit volume.

and, $H = h + \frac{u^2}{2}$ (3.13)

The heat flux q_i is determined as:

$$q_i = \left(\frac{\mu}{\mathrm{Pr}} + \frac{\mu_t}{\sigma_c}\right)\frac{\partial h}{\partial x_i}, \quad i = 1,\ 2,\ 3 \tag{3.14}$$

Here P_r is the Prandtl number, and h is the thermal enthalpy.

The effect of turbulence is modeled using the modified $k-\varepsilon$ turbulence model with damping function. It was first proposed by Lam and Bremhorst in 1981. This model is widely known and it has been validated for a number of turbulent flows. This model fairly predicts the turbulence flow behavior of a fluid in a reduced computational grids and time. In this model, the turbulence kinetic energy k and its dissipation rate ε are determined as:

$$\frac{\partial \rho k u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right) + \tau_{ij}^R \frac{\partial u_i}{\partial x_j} - \rho\varepsilon + \mu_t P_B, \tag{3.15}$$

$$\frac{\partial \rho \varepsilon u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}\left(f_1 \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + C_B \mu_t P_B\right) - f_2 C_{2\varepsilon}\frac{\rho \varepsilon^2}{k} \tag{3.16}$$

$$\tau_{ij} = \mu\, s_{ij},\ \ \tau_{ij}^{R} = \mu_t\, s_{ij} - \frac{2}{3}\rho k \delta_{ij},\ \ s_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}, \tag{3.17}$$

δ_{ij} is the Kronecker delta function which is equal to unity when $i=j$ and zero otherwise.

The production of turbulent kinetic energy due to the force of buoyancy P_B is determined as:

$$P_B = -\frac{g_i}{\sigma_B}\frac{1}{\rho}\frac{\partial \rho}{\partial x_i}, \tag{3.18}$$

$$C_B = \begin{cases} 1 & P_B > 0 \\ 0 & P_B < 0 \end{cases}, \tag{3.19}$$

The turbulent viscosity μ_t is determined as:

$$\mu_t = f_\mu \cdot \frac{C_\mu \rho k^2}{\varepsilon} \tag{3.20}$$

where, f_μ is the damping function in Lam and Bremhorst's modified turbulence model. It is determined as:

$$f_\mu = \left(1 - e^{-0.025 R_y}\right)^2 \cdot \left(1 + \frac{20.5}{R_t}\right) \tag{3.21}$$

and,

$$R_y = \frac{\rho \sqrt{k} y}{\mu} \tag{3.22}$$

$$R_t = \frac{\rho k^2}{\mu \varepsilon} \tag{3.23}$$

where, y is the distance from point to the wall. The damping functions f_1 and f_2 is determined as:

$$f_1 = 1 + \left(\frac{0.05}{f_\mu}\right)^3, \quad f_2 = 1 - e^{R_t^2} \tag{3.24}$$

when, $f_\mu = f_1 = f_2 = 1$, the modified turbulence model reverts back to the standard $k - \varepsilon$ model.

The transport of carbon dioxide concentration within the computational domain is governed by the conservation equation of chemical species which can be written as:

$$\frac{\partial \rho c u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_c}\right)\frac{\partial c}{\partial x_i}\right) + S_c, \quad (3.25)$$

Here c is the carbon dioxide concentration and S_c is the rate of generation of carbon dioxide.

Overall, ρ is the air density, u_i is the velocity component in i^{th} Cartesian coordinate, P is the absolute pressure, g is the gravitational acceleration, ρ_r is the reference density of air, T is the air temperature, μ is the molecular dynamic viscosity, and the remaining empirical constant used in above equations are shown in Table 3.4 with their corresponding values.

Table 3.4 Empirical constant used in flow equations

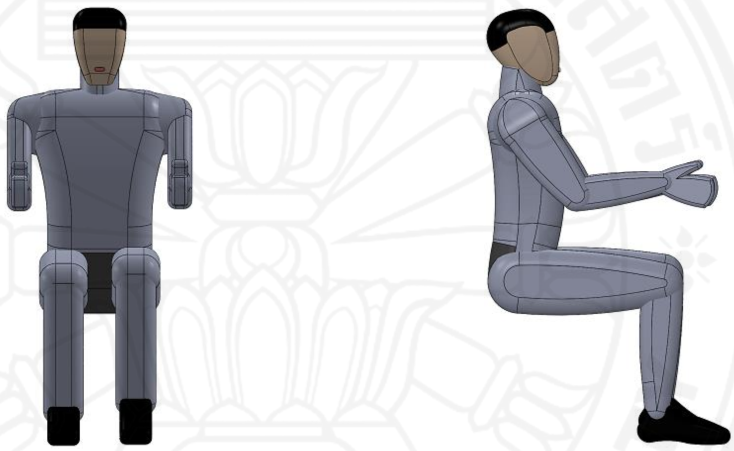
C_μ	$C_{1\varepsilon}$	$C_{2\varepsilon}$	$C_{3\varepsilon}$	σ_k	σ_ε	σ_B	σ_T	σ_c
0.09	1.44	1.92	0.8	1	1.3	0.9	0.9	1

Furthermore, wall function approach proposed by Launder and Spalding [63] was used to model the near-wall region with high velocity and temperature gradient. The approach fairly reduces the computational mesh in solving Navier-Stokes equations with two equation turbulence model. This approach resolves the need for very fine computational mesh in viscous sub layer.

In addition, Discrete Ordinate (DO) [27] radiation model is used to govern the radiation heat transfer between radiative surfaces. In this model, Flow Simulation assumes that the fluid neither emit nor absorb heat radiation but the radiative surfaces emit, absorb and reflect both the solar and thermal radiation [64].

3.2.4 Boundary conditions

The boundary conditions in CFD simulation are set in such a way so that it virtually reveal the real scenario of an air-conditioned library room. The measured outdoor temperature and relative humidity at the time of experiment is in the range of 34±1°C and 55±3% respectively. The air conditioned space at the time of the experiment was occupied by 25 students and staffs under daily maximum loading capacity around 2 PM. Indoor occupants are modeled as a mannequin consisting of detailed body parts as shown in Fig. 3.13.



(a) (b)

Fig. 3.13. CAD Model of indoor occupant (a) Front view (b) Side view

The location of twenty-five occupants inside the air-conditioning library room at the time of experiment is shown in Fig. 3.14.

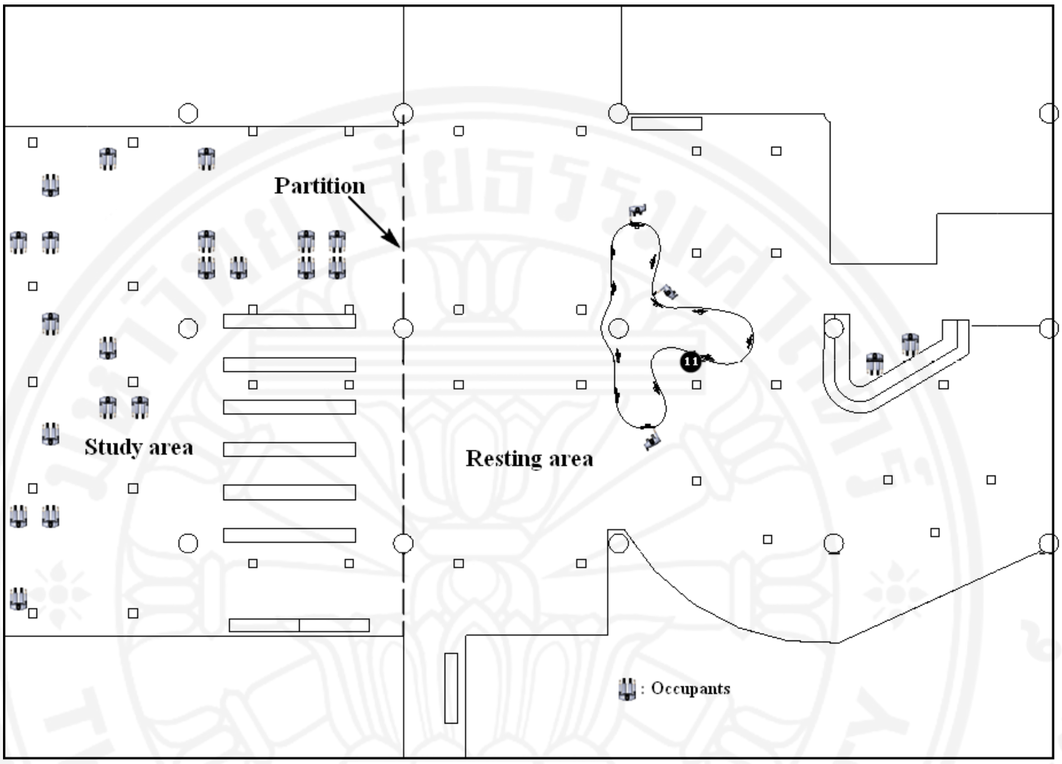


Fig. 3.14. Location of indoor occupants

Heat fluxes were modeled to represent the amount of heat generated by occupants, ceiling lights and idle computers and various electrical appliances Considering occupants are seated and involved in light work, each occupant is modeled to generate 130 W of heat [65]. Each ceiling lights and computers are modeled to generate 60 W and 45 W heat [66] respectively. Table 3.5 presents the types and quantities of internal heat sources present inside the library.

Table 3.5 Internal heat souces inside library

Objects/ appliances	Power (W)	Quantity	Total Power (W)
Occupants	130	25	3250
Ceiling lights	60	48	2880
Computers	45	12	540

Additionally, heat flux entering the thermal boundary conditions through walls, windows and doors surface were calculated using Eq. (3.26)

$$q'' = \left[\frac{(T_a - T_s)}{\frac{1}{h_o} + \frac{L}{\kappa} + \frac{1}{h_i}} \right] \tag{3.26}$$

where T_a is the outdoor ambient temperature, T_s is the indoor air temperature at the surface, h_o and h_i are the combined convective and radiative heat transfer coefficient at the exterioir surface and interior surface. L is the thickness of the surface and κ is the thermal conductivity of the surface. Adjecent walls of a small group-study rooms are individually operating to split type air conditioning system and exchange negligible heat with the larger indoor library. Those walls, ceilings and ground are considered as adiabatic surfaces.

The conditioning air is delivered into the library room at 17 ºC with 70% of relative humidity. Measured Carbon dioxide concentration at the mixing chamber was 400 ppm which distribute uniformly to each supply diffuser. Twenty-nine supply diffusers out of total thirty-eight were under operation at the time of the experiment. The measured value of air velocity at the diffuser neck of each supply diffusers is given in Table 3.6.

Table 3.6 Air velocity at supply diffuser

Diffuser	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Air velocity [m/s]	1.67	1.29	0.88	2.07	0.82	1.82	1.58	1.09	1.26	1.52
Diffuser	D11	D11	D13	D14	D15	D16	D17	D18	D19	D20
Air velocity [m/s]	1.03	-	0.93	1.6	1.29	1.38	1.47	1.96	1.65	-
Diffuser	D21	D22	D23	D24	D25	D26	D27	D28	D29	D30
Air velocity [m/s]	1.46	1.56	1.57	1.69	-	0.6	1.38	1.94	-	-
Diffuser	D31	D32	D33	D34	D35	D36	D37	D38		
Air velocity [m/s]	1.63	2.01	2.08	1.94	-	-	-	-		

Boundary conditions for numerical calculations at the supply diffuser, extract grilles and walls are treated as shown in Table 3.7. The value of air parameter and carbon dioxide concentration at the supply inlet are considered as known value.

Table 3.7 Boundary conditions for the numerical calculations

At supply inlets: $k_0 = \frac{3}{2}(u_0 I_0)^2, \varepsilon_s = \frac{C_\mu k_0^{1.5}}{l_s}, I = 0.05, l_0 = 30mm, C_0 = 400\,ppm$
At walls: $U = V = W = 0, \frac{\partial k}{\partial x} = \frac{\partial k}{\partial y} = \frac{\partial k}{\partial z} = 0, \frac{\partial C}{\partial x} = \frac{\partial C}{\partial y} = \frac{\partial C}{\partial z} = 0$
At extract grilles: $\frac{\partial U}{\partial x} = 0, \frac{\partial k}{\partial x} = 0, \frac{\partial \varepsilon}{\partial x} = 0, \frac{\partial T_a}{\partial x} = 0, \frac{\partial C}{\partial x} = 0$

where k_0 is the initial turbulence kinetic energy, ε_0 is the initial turbulence dissipation rate, u_0 is the air velocity at the supply inlet, I_0 is the initial turbulence intensity. For medium turbulence case and flow in not so complex devices such as pipes and ducts, typical turbulence intensity is between 1% and 5% [67], l_0 is the turbulence length scale at the supply inlet (10% of inlet width [68]), and C_0 is the carbon dioxide concentration at the supply inlet.

Typical summer clothing and sedentary activity values of 0.5 Clo and 1.2 Met [69], respectively, are considered for PMV calculation. For the assessment of IAQ, each occupant is modeled to emit Carbondioxide concentration at the rate of 0.018 m^3/h. Some of the important numerical parameters used in CFD simulations are listed in Table 3.8.

Table 3.8 Numerical values used in CFD simulation

Parameters	Numerical value
Stefan-Boltzmann constant, σ (W/m^2K^4)	$5.6704\text{x}10^{-8}$
Ambient temperature, T_{amb} (ºC)	35
Convective and radiative heat transfer coefficient for exterior surface, h_o (W/m^2K)	22.7
Convective and radiative heat transfer coefficient for interior surface, h_i (W/m^2K)	8.29
Thermal conductivity of concrete wall (20 mm thickness), κ (W/mK)	0.6
Thermal conductivity of glass wall/ window/ sliding entrance door (3 mm thickness) κ (W/mK)	0.9
Heat source, q Humans, (W per occupant) Computers, (W per computer) Ceiling lights, (W per light)	 130 45 60
Carbon dioxide generation rate of humans (m^3/h per occupant)	0.018
Clothing insulation, I_{cl} (Clo)	0.5
Metabolic activity, M (Met)	1.2
Reference density of air, ρ_r (kg/m^3)	1.2
Molecular dynamic viscosity of air, μ (kg/ms)	$1.8\text{x}10^{-5}$
Specific heat of air, C_a (kJ/kgK)	1.006
Specific heat of water vapor, C_v (kJ/kgK)	1.84
Latent heat of evaporation, h_v (kJ/kgK)	2501

3.2.5 Numerical simulations and assumptions

SolidWorks Flow Simulation^{TM} is used to calculate distributions of air parameters, thermal sensation and carbon dioxide concentration at the height of breathing level for all analyzed spaces. Numerical simulations are carried for couple of cases i.e a) Library without partition and b) Library with partition. Experimental measurement from the case study of a library without partition were compared to the results from CFD simulation. Both results showed good agreement. Thus, numerical solution is adopted to study the effect of partition on thermal comfort, IAQ and energy consumption. The experimental study with the installation of a real full scale partition in such a large indoor facilitites may not be practical and economical. Furthermore indoor heat source and outside climatic conditions are constantly changing in qasi-equlibrium state. So the numerical simulation approach for the quantative analysis on the effect of partition with relevant boundary contition seem fabourable.

Flow Simulation solves the governing equations with a discrete numerical technique based on the finite volume (FV) method. The Navier stokes equation in the form of partial differential equations (PDEs) are used to get the solution of the problem defined. Second-order implicit difference operators approximates the spatial derivatives and an implicit first-order Euler scheme approximates the time derivative. Second-order upwind scheme is used for the convective fluxes and central approximations is used for diffusive terms. Finally, time-implicit approximations of the continuity and convection/diffusion equations were treated with SIMPLE-like approach together with an operator-splitting technique. This technique efficiently resolves the problem of pressure-velocity decoupling. CFD simulation was performed using Intel Xeon CPU with 32 GB of virtual memory. The computational running time for each case lasted approximately 40 hour. Several assumptions were made to simplify the simulation problem. Some of them are as follows:

- Indoor air is an incompressible fluid and conforms to Boussinesq hypothesis.
- The effect of infiltration is neglected under assumption that the flow rate of fresh air from supply diffuser is much larger than the flow rate caused by infiltration [70].

3.2.6 Experimental materials

The distributions of air parameters and carbon dioxide concentrations were measured in the occupied region using various sensors. Air velocity and air temperature were measured using Testo-425 hot wire thermal aneomoeter as shown in Fig. 3.15. The velocity measurement range of the sensor is from 0 to 20 m/s with accuracy of ± 0.03 m/s and dynamic response time of 0.3 s. Similary, the temperature measuring range of the sensor is from -20 °C to +70 °C. The sensor has the accuracy of ±0.5 °C at the range of 0 to 60 °C and ±0.7 at the remaining range.

Fig. 3.15. Hot wire thermal anemometer

Relative humidity of the indoor/outdoor air was measured using Testo 610 humidity meter as shown in Fig. 3.16. The Testo developed humidity sensor is reliable and has accuracy of ± 2.5%. The measurement range is from 0 to 100% with 0.1% resolution. Additionally, the sensor is also capable of displaying dewpoint, dry bulb and wet bulb temperature. It is very handy, small and easy to operate.

Fig. 3.16. Humidity meter

Indoor carbon dioxide concentration is measured using Telaire 7001 carbon dioxide sensor as shown in Fig. 3.17. The measuring range of the sensor is from 0 - 10000 ppm with ± 1 ppm sensitivity and ± 50 ppm accuracy. All the sensors are mounted on a tripod with adjustable height to stabalize the sensors. Time average reading is recorded from each sensors at the desired location.

Fig. 3.17. Carbon dioxide sensor

Chapter 4
Results and Discussions

Simulated results of the effect of partition on air flow patterns, air parameters, thermal sensation, carbon dioxide concentration and energy consumption were comparatively studied before and after installation of the partition. The distribution of air parameters, PMV-PPD and carbon dioxide profiles were presented at the horizantal plane of 1.1 m above floor level. This level represent the breathing height of the occupied zone and the best representation of the occupant's sensation and condition of the library

4.1 Validation of CFD model

Total 14 measuring points as shown in Fig. 4.1 at a breathing level of 1.1 m above floor are selected for measurement of air temperature, air velocity, relative humidity and carbon dioxide concentration. The experimental measurementes were carried for a case study before installation of the partition. The objective measurements were carried out with the sensors described in chapter 3.

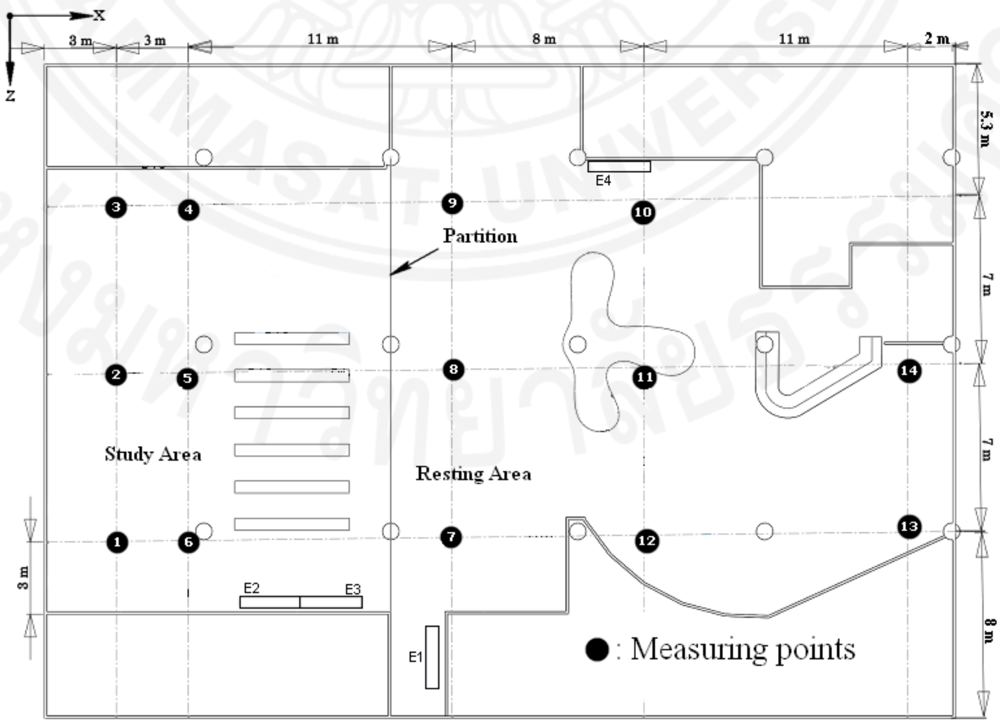


Fig. 4.1. Measuring points

Slight differences in values between the results obtained from CFD simulations and the experiments at the corrosponding height are observed for air temperature, relative humidity and carbondioxide concentration. The simulated results noticeably deviates from the experimental resluts at the region around entrance door which is far away from partition. In observation, the significant variations at those locations are due to the infiltration of air through the sliding entrance door. Infiltrated air is at lower carbondioxide concentration and higher temperature. Therefore, as shown in Fig. 4.2(a), the measured air temperature at the point 13 and 14 are noticeably higher than the one predicted by CFD. Similarly, the measured concentration of carbon dioxide concentration are lower than predicted by CFD as shown in Fig. 4.2(d). However, for the remaining points, the data obtained from CFD and measurement highly corelate with each other. The maximum variation for the remaining points were below 10%. CFD simulation was carried out with considering sliding entrance door to be closed however in reality it opens up for a short period of time along with the student's in and out movement. Similar boundary conditions are applied to evaluate the variables of indoor air and thermal sensation after installation of the partition.

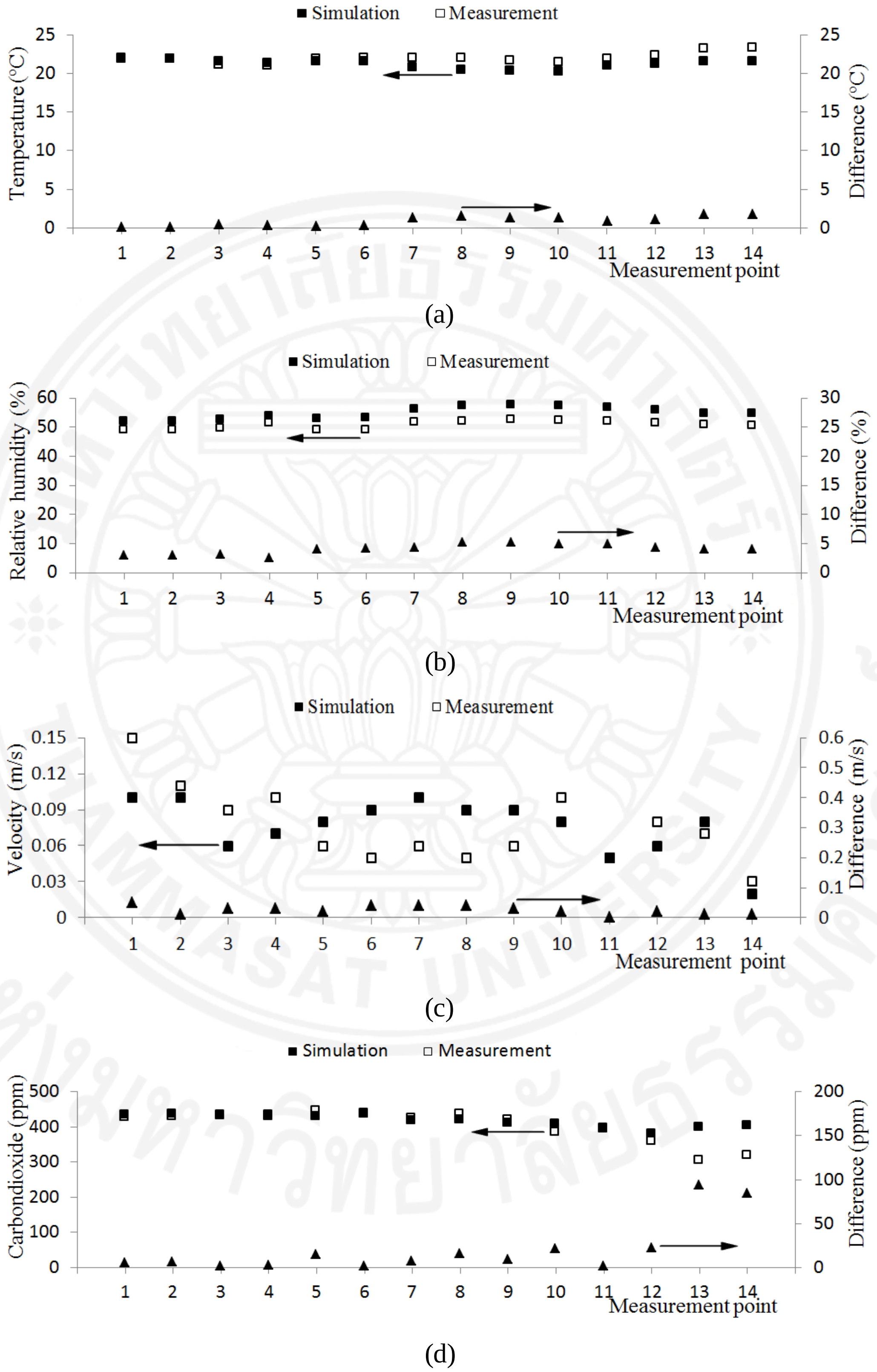


Fig. 4.2. Comparisons of simulated results with measurement data: (a) air temperature, (b) relative humidity, (c) air velocity, and (d) carbon dioxide concentration

4.2 Comparison of temperature distribution

Temperature is the most important factor in the determination of thermal comfort. Simulated results of temperature are reported at the breathing level of height 1.1 m above floor level. Temperature distribution before and after installation of the partition are shown in Fig. 4.3(a) and Fig 4.3(b) respectively.

In case 1, before installation of the partition, the majority of the area on the west, where study tables are located has temperature distribution in the range of 21-22° C. A thin layer of region close to the windows has temperature of 23° C or slightly higher. Similarly, the entrance door and reception area has the temperature distribution in the range of 21-22° C. However, the area within and around bookshelf on the west side has temperature distribution in the range of 20-21 °C. In a similar manner, the entire central region of library including resting areas, stairways, and "T" shaped table has temperature distribution between 20 and 21 °C. The difference in temperature distribution between the central region and east/west region is due to the presence of higher heat load generated by several occupants in the study area. Additionally, significant portion of heat flux and radiation enters the conditioned space in the east/west region through the walls and the windows.

In case 2, after installation of the partition as reported in Fig. 4.3(b), the overall average temperature in the study area slightly increases whereas it decreases in the resting area of the library. The discharged cool air into the sudy area has relatively higher space heating load. Therefore slight rise in average temperature is observed in some specific regions around the bookshelf and near the partition. On the other hand, the average temperature noticeably decrease in the resting side of the library as the discharged cool air has relatively lower space heating load. The average temperature around the stairway regions drops down to the range of 19-20 °C. Similarly, the average temperature around the entrance door and "T" shaped table falls approximately by 1.5 °C.

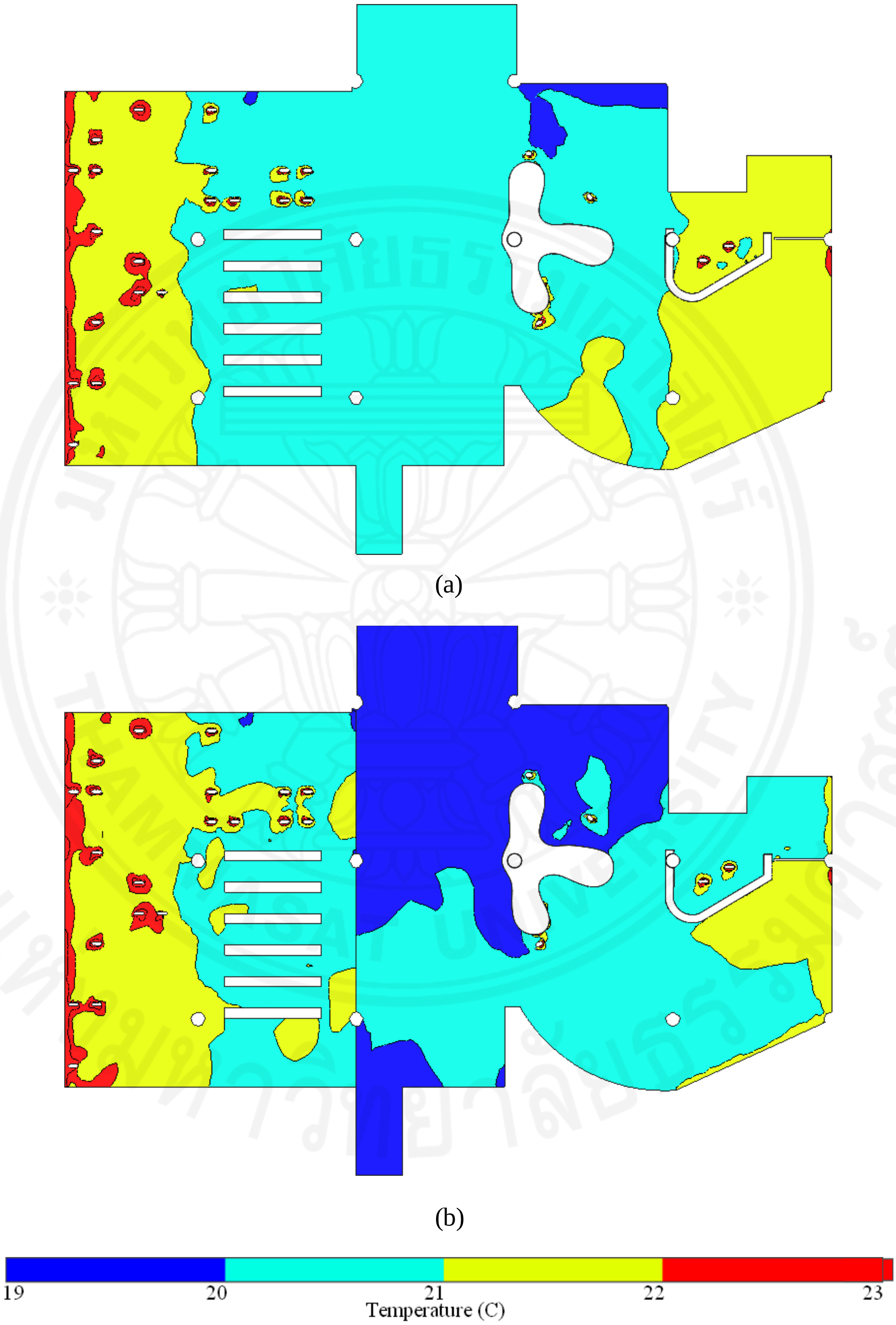


Fig. 4.3. Comparison of temperature (°C) distribution
(a) without partition (b) with partition

4.3 Comparison of relative humidity distribution

Relative humidity is the other important factor that significantly alters the perceived sensation and subsequently the thermal comfort. Simulated results of relative humidity are reported at the breathing level of height 1.1 m above floor level. Relative humidity distribution before and after installation of the partition are shown in Fig. 4.4(a) and Fig 4.4(b) respectively.

In case 1, before installation of the partition, the majority of the area on the west has relative humidity distribution in the range of 50-56%. Similarly, the entrance door and reception area has relative humidity value approximately 55%. The entire central region of library including resting areas, stairways, and "T" shaped table has relative humidity distribution between 56 to 58 %. The small variation in relative humidity distribution between the central region and east/west region is due to the variation of heat load in those areas. Higher heat load is generated by several occupants in the study area. Additionally, significant portion of heat flux and radiation enters the conditioned space in the east/west region through the walls and the windows. The moisture content of the room is distributed more or less uniformly throughout the library therefore the relative humidity changes inversely with the distribution of temperature. Area with higher temperature distribution has lower relative humidity and vice versa.

In case 2, after installation of the partition as reported in Fig. 4.4(b), the change in relative humidity distribution is very insignificant. The relative humidity distribution brought by the effect of installation of the partition alters marginally before and after installation of the partition. The west region with study area and bookshelf has relative humidity distribution approximately same as before installation of the partition. Relative humidity ranges between the value of 50-55 % for both cases. The relative humidity distribution in entrance and reception area increases by a nominal value of 1%. Similarly, the distribution in central region with resting chair, stairways and near partition increases by roughly 1-2%. The distribution of relative humidity remains at the recommended range of ASHRAE standard for both cases therefore the indoor occupants are unlikely to perceive the change in relative humidity.

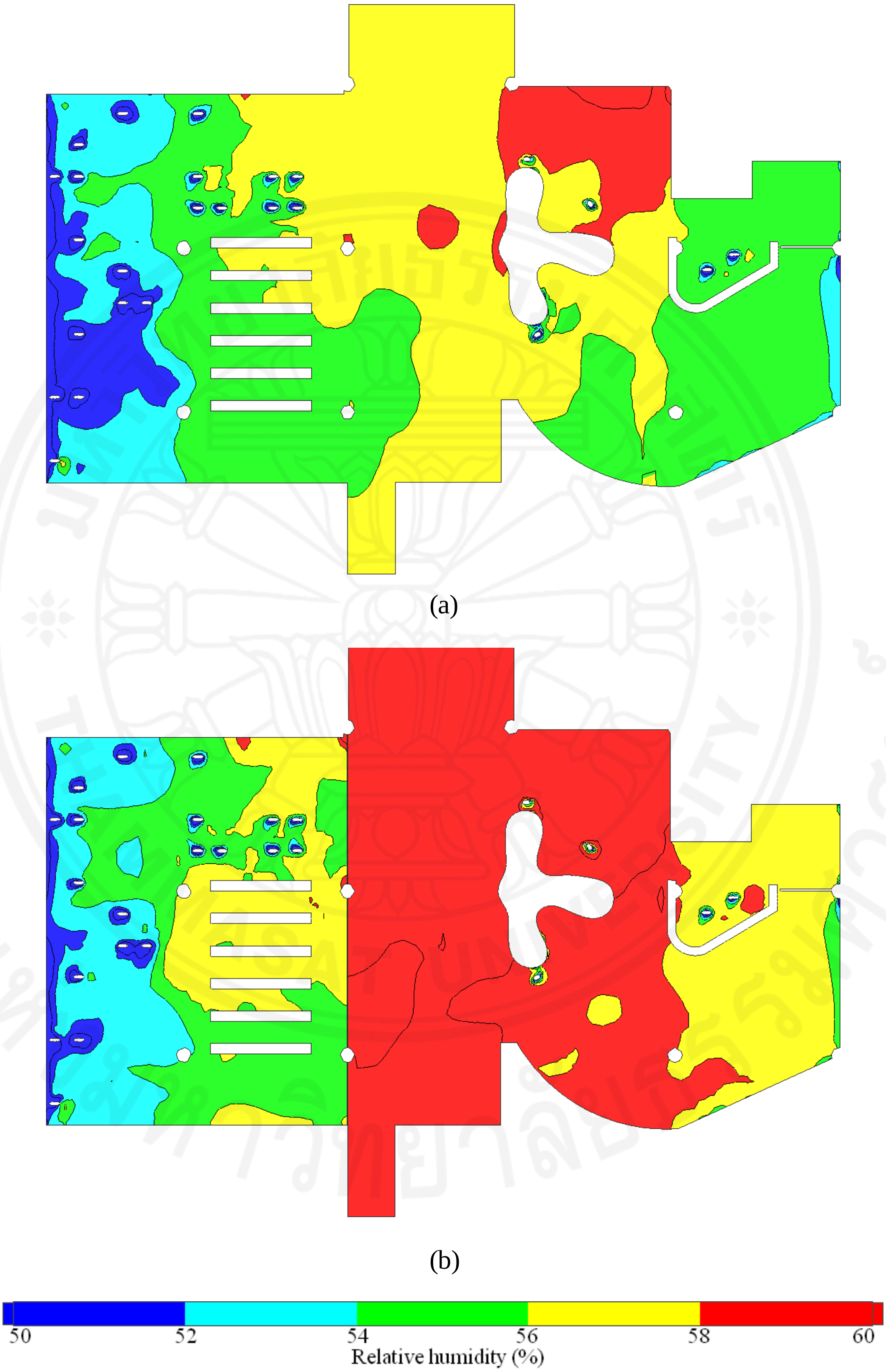


Fig. 4.4. Comparison of relative humidity (%) distribution
(a) without partition (b) with partition

4.4 Comparison of PMV distribution

Simulated results of the Predicted Mean Vote (PMV) are reported at the height of 1.1 m above floor level. PMV distribution for both cases: before and after installation of the partition are shown in Fig. 4.5.

PMV distribution, in case of a library without partition as shown in Fig. 4.5 (a) has slightly cool thermal sensation in major region of the study area on the west side where students are seated. The average PMV value in this region is approximately -0.7. Similarly, the region around the entrance door and reception table on the eastern side is also under slightly cool thermal sensation. PMV value has a range between -0.7 to -0.9. However, the resting area at the central library and around "T" shaped table, the sensation is cool. The PMV value varies from -1.0 to -1.5. The difference in perceived sensation is due to the presence of higher heat load in the form of occupants. Additionally, heat flux entering the conditioned space through the west windows and east glass wall at the study area and the entrance region respectively contributes to the sensation being slightly cool. Conversely, the resting area has relatively less amount of heat load as the numbers of occupants present are fewer, so the perceived sensation is cool in this region. Furthermore, the occupants seated near the windows at the study area have PMV value in a range between 0 to -0.5. The occupants at this area are likely to perceive ambient environment quiet comfortable. However, the occupants in the other region are likely to perceive ambient environment slightly cool and bit uncomfortable.

After installation of the partition as reported in Fig. 4.5 (b), the study area shows no major differences in the perceived sensation. This area mostly retains the slightly-cool sensation in major part. However, the PMV value at the small region on the left of bookshelf decreases from -0.9 to roughly around -1.2. The perceived sensation after installation of the partition changes from slightly cool to cool. Moreover, the nearby area of the seated occupants near the window with PMV value less than -0.5 has reduced its size after installation of the partition. Therefore, the occupants at this region are likely to perceive the thermal environment less comfortable after installation of the partition. At the resting side of the library, there is overall decrease in PMV value. The most notable effect is observed around the entrance door and the reception area. PMV value decreases from approximately -0.8 to roughly around -1.2. Accordingly, the thermal sensation changes from slightly-cool to cool. The air supply diffusers at the resting side is more in number than actually required to overcome thermal load after installation of the partition. The library staffs and the students at resting side of the library are likely to perceive the environment uncomfortably cold after installation of the partition. The region with cold sensation slightly increases around the corner at the resting side of library.

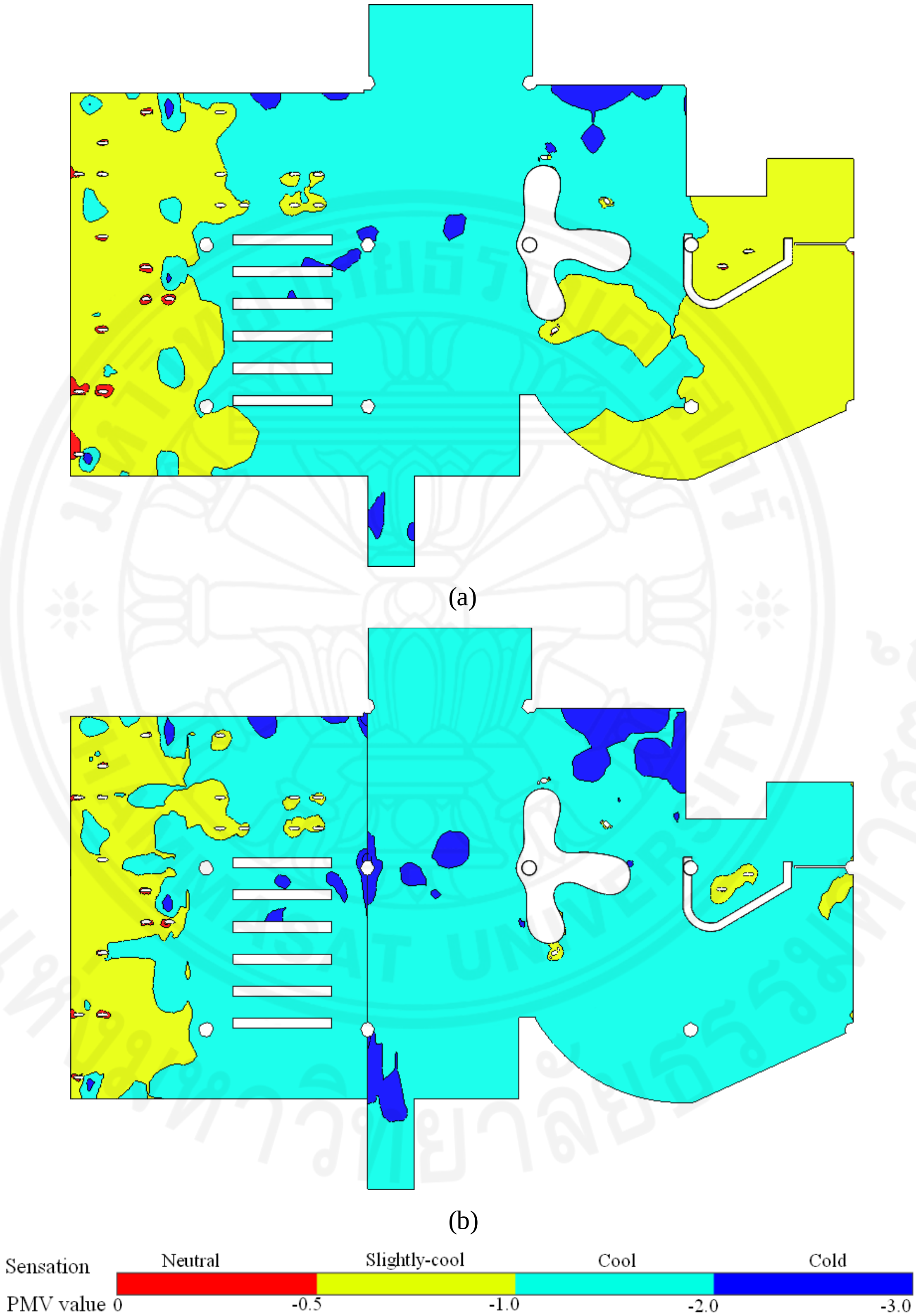


Fig. 4.5. Comparision of PMV distribution
(a) without partition (b) with partition

4.5 Comparison of PPD distribution

Simulated results of the Predicted Percentage Dissatisfied (PPD) are reported at the height of 1.1 m above floor level. PPD distribution for both cases: before and after installation of the partition are shown in Fig. 4.6.

PPD distribution before installation of the partition is shown in Fig. 4.6(a). The major region of the study area on the west has PPD value between 15-25 %. The PPD value of the overall study area is approximately 20%. Similarly, the region around the entrance door and reception area on the eastern side has parallel PPD distribution as in the study area. However, the resting area at the central library, the bookshelf area and around "T" shaped table, percentage of people who are likely to be dissatisfied is relatively higher. These regions have PPD distribution value between 25-45%. Some specific areas around the corner of the room have PPD value more than 45%. Furthermore, the nearby region of the occupants seated near the windows at the study area has PPD distribution value close to the recommended value of ISO 7730 which is less than 10%. However, the occupants seated in the other region have PPD distribution value in the range of 15-25%.

After installation of the partition as reported in Fig. 4.6(b), the study area near windows has little effect on PPDdistribution by the installation of partition. PPD distribution range of 15-25% is visibly observed in this region even after the intriduction of partition. However, the area to the left of bookshelf within study area has substantial effect in PPD distribution. The PPD distribution in the range of 15-25% increases to the range of 25-35%. Higher number of occupants will be dissatisfied at this location after the change brought by the installation of the partition. The Neighboring areas of occupants near the windows with PPD distribution close to the recommended value significantly reduces in size after installation of the partition. At the resting side of the library, there is overall increase in PPD value. Accordingly, more number of occupants will be dissatisfied with the thermal environment in resting area PPD value at the stair-way to second floor near the partition increases to more than 45%. Similarly, PPD value in the central library with resting sofas approximately increases by 10% The region around "T" shaped table also has the similar change in PPD distribution where the value increases by 10-15% after installation of the partition. Near the entrance door and reception, PPD distribution at the range of 15-25% increases to nearly 35%. Therefore, 10% more occupants near entrace door and reception area are likley to be dissatisfied after installation of the partition.

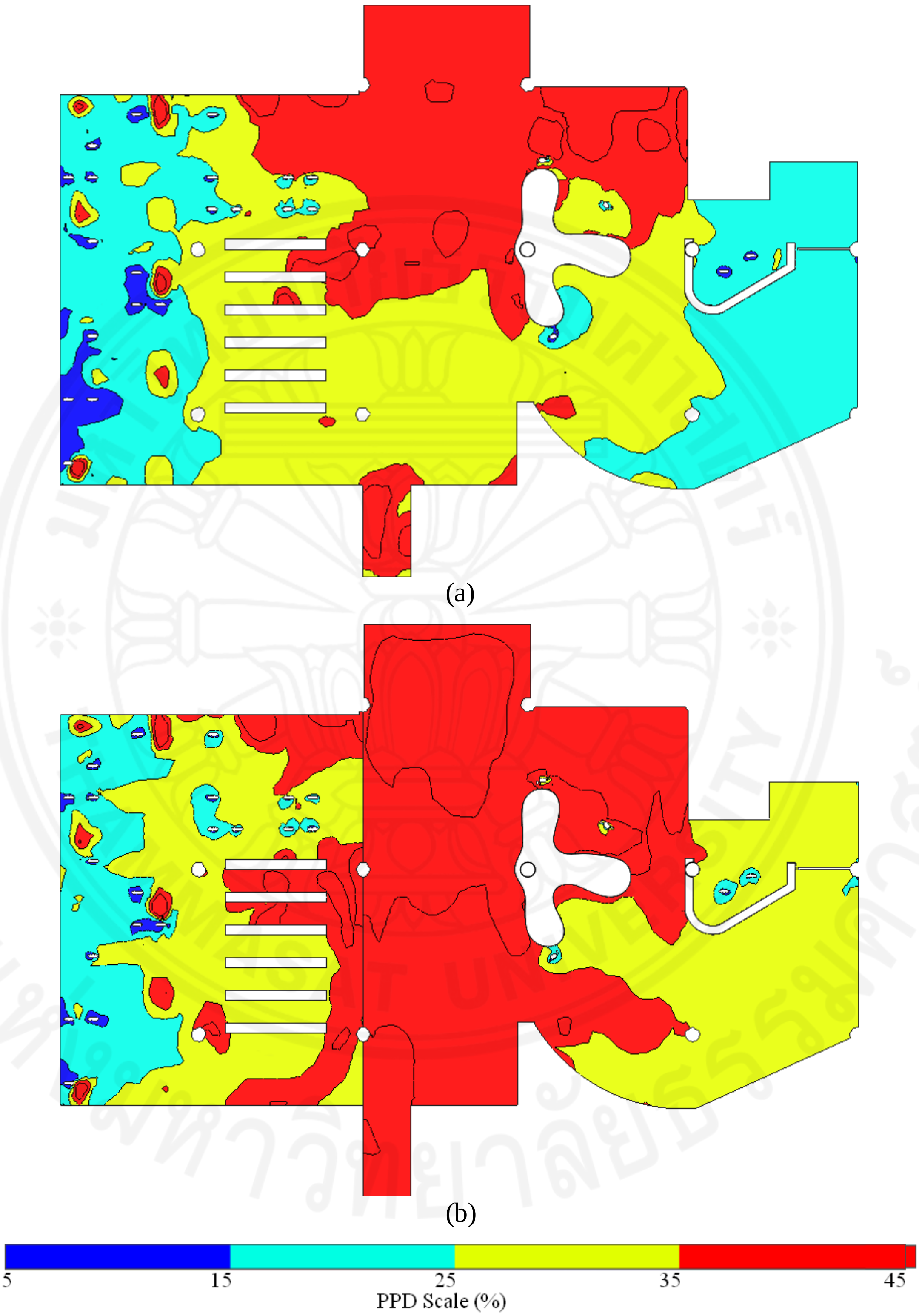


Fig. 4.6. Comparison of PPD distribution
(a) without partition (b) with partition

4.6 Comparison of carbon dioxide concentration distribution

Distribution of carbon dioxide concentration at the height of breathing level is reported for both cases in Fig. 4.7. On a normal day, higher numbers of students are present in the study area than the resting area as testified at the time of the experiment. The resting side of library is usually occupied with couple of staffs and few students. The distribution of carbon dioxide concentration at the breathing level within the library space before installation of the partition is shown in Fig. 4.7(a). The average value of carbon dioxide concentration for the major regions in the study area is approximately around 440 ppm. However the overall carbon dioxide concentration at this region has a range of 425 ppm – 475 ppm. The average concentration of carbon dioxide at the study area is higher than the rest of the areas due to the presence of most number of occupants. In the resting side of the library, the average carbon dioxide concentration of approximately 420 ppm is observed in an overall range of 400 – 450 ppm.

Fig. 4.7(b) shows the carbon dioxide concentration distribution profile at the breathing level after installation of the partition. In the east side of the library, the area with carbon dioxide concentration values of 425 ppm or slightly higher is observed only in the nearby region of the occupants. The carbon dioxide concentration at the reception table with seated staffs decreases from the approximate value of 450 ppm to 425 ppm. The areas around the entrance door and near the partition has noticeable decrease in carbon dioxide concentration by value of approximately 50 ppm. On the other hand, the west side of the library with study area and bookshelf has noticeable increase in carbon dioxide concentration after installation of the partition. The average concentration values ranges from 450 ppm to 475 ppm in majority of the study areas. The area in front of the bookshelf in. The carbon dioxide concentrations within the library space for both cases remain below the indoor recommended level of 1000ppm [57]. Therefore, occupants are unlikely to perceive the difference in indoor air quality in either cases. The occupant's comfort regarding indoor air quality may not be affected due to installation of the partition.

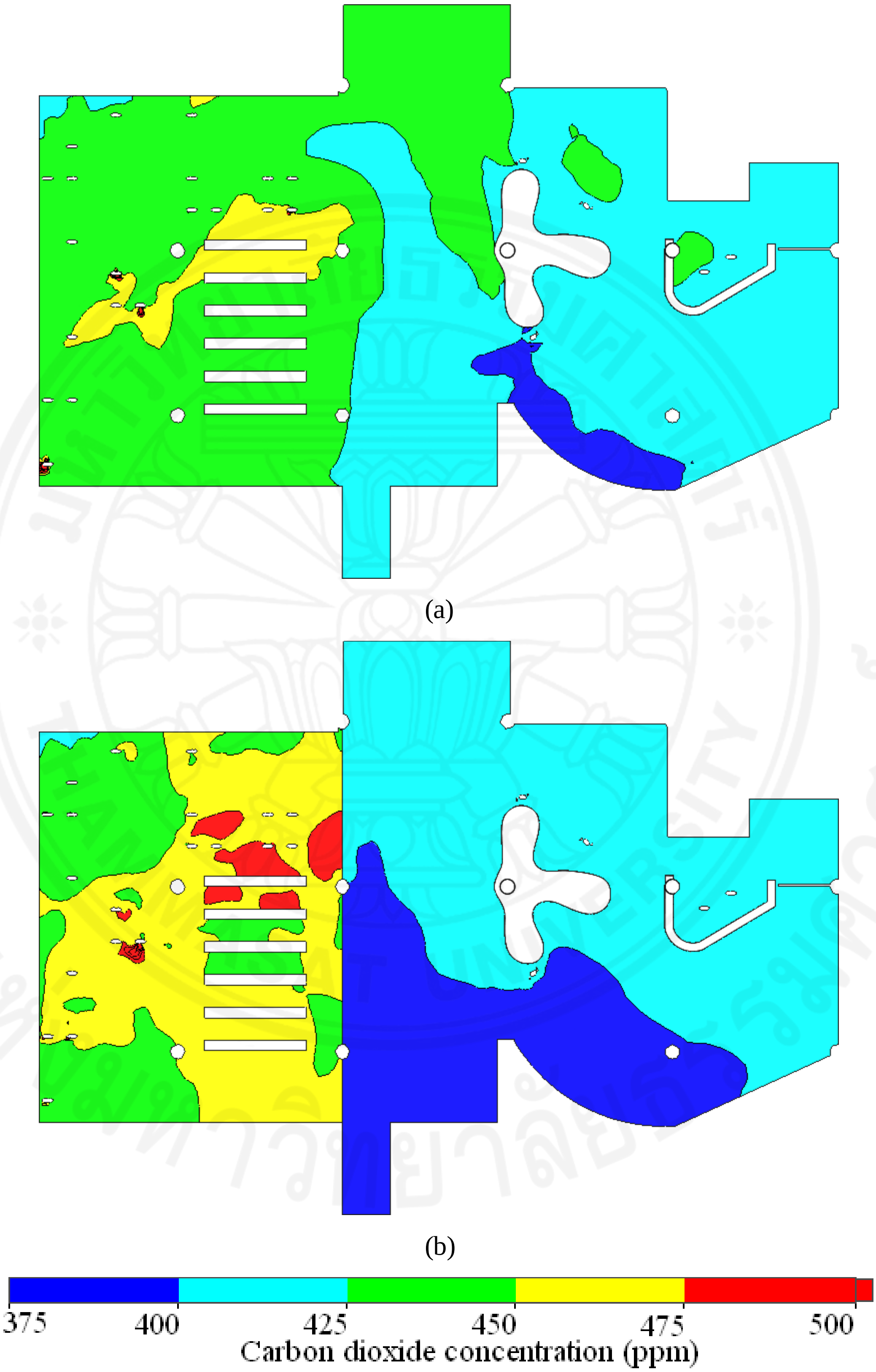


Fig. 4.7. Comparison of carbon dioxide concentration distribution
(a) without partition (b) with partition

4.7 Impact assessment on energy consumption

The total energy flowing into the room in calculated from the known boundary conditions at the supply diffusers described in Chapter 3. The total rate of energy flowing into the room is the sum of volumetric flow rate of conditioned air discharged into the room from each supply diffuser. From CFD analysis, indoor air variables within the library space for both cases are numerically calculated. Accordingly, the average value of the air parameters such as temperature, velocity, and relative humidity are numerically determined at each extract grilles with the boundary conditions defined in Chapter 3. Psychometric chart is used to find humidity ratio based on the available data of air temperature and relative humidity. Table 4.1 shows the value of air variables numerically determined at each extract grilles. Return air temperature at the extract grilles E2 and E3, which are located at the west of the partition, slightly increases after installation of the partition. The conditioned air on the west of the partition compensates larger load after installation of the partition, therefore the return air temperature marginally increases. On the other hand, the conditioned air at the resting side of the library compensate lower load. Therefore, return air temperature slightly decreases at E1 and E4 extract grilles after installation of the partition. The change in relative humidity at the extract grilles after installation of the partition is opposite to the change in air temperature. It is because when the absolute humidity is constant, relative humidity changes inversely to the change in air temperature. Table 4.1 also shows the average value of air velocity at each extract grilles which distribute more or less in uniform manner. All the obtained variables from Table 4.1 are applied in Eq. (3.8) to calculate the rate of energy consumption for making up satisfactory air in each case. Table 4.2 shows the rate of energy consumption calculated before and after installation of the partition. It is inferred that the rate of energy consumption while partitioning the library at the desired location increases by 8.3 %.

Table 4.1 Air variables at the extract grilles

	Before installation of partition				After installation of partition			
Extract grilles (E)	E1	E2	E3	E4	E1	E2	E3	E4
Air Temp., (℃)	20.67	21.33	21.11	20.1	20.34	21.81	21.79	19.8
RH (%)	57.30	54.63	55.07	59.59	60.61	53.57	53.49	61.17
Air velocity (m/s)	1.03	1.04	1.04	1.03	0.94	1.14	1.13	0.93
Hum. ratio(Kg/Kg)	0.00869	0.00863	0.00858	0.00872	0.00901	0.008717	0.00869	0.00879

Table 4.2 Rate of energy consumption for each case

Cases	Rate of energy consumption (kW)
Before installation of partition	33.83
After installation of partition	36.65

4.8 Impact assessment on perception of space

Fig. 4.8 shows circles of social space formed by the spatial arrangement of one or more occupants and the area invaded by the partition. From the observational analysis, occupants and staffs are found spending most of the time in study tables, resting sofas, online search table, and reception area. Therefore, the circles of social space are subjectively positioned at the center of each of those tables and sofas in order to best accommodate the workspace of the indoor occupants. Before installation of the partition as shown in Fig. 4.8(a), occupant's movement is not constrained in any particular orientation. Indoor occupants are able to fully access their social space and move freely in their workspaces of the library. In this situation, occupants perceive the indoor space to be spacious. Correspondingly, an overall perception index of 1 is determined by Eq. (3.9). However, after installation of the partition, some parts of the circles of social space in the study area and in the resting area are invaded by the partition. The shaded region in Fig. 4.8(b) is the area of the social space that is barred from accessing by the corresponding occupants due to installation of the partition. The mobility of the occupants near the partition in the study area and in the resting area is limited in particular directions. The invaded area of the circle of social space in study area and resting area is calculated using 2D CAD drawing model of the floor plan. From Eq. (3.9), the overall perception index of 0.9 is numerically determined. This is 10% of the original unity overall perception index. This result can be interpreted that the occupants feel comfortably ample in the library space after installation of the partition.

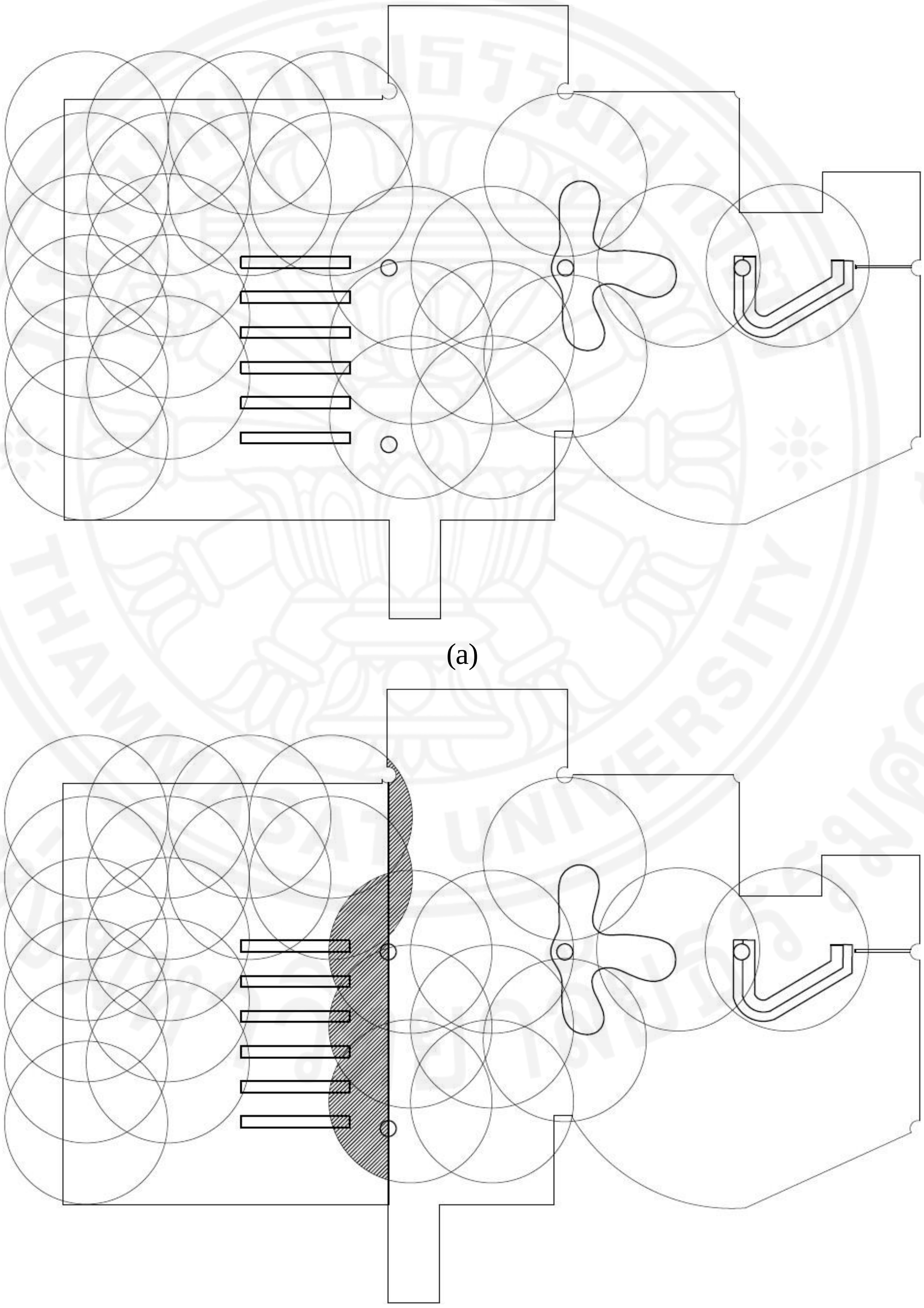


Fig. 4.8. Comparison of perception
(a) without partition and (b) with partition

4.9 Recommendations

According to the comparison analysis from the section 4.1 to 4.8, some recommendations regarding installation of the partition were suggested to the building and ground division of library administration. The highlighting recommendations are listed below:

- Installation of the partition is not encouraged without the reinforcement of the air conditioned conditions and the adjustment of interior arrangement.
- The occupants are likely to perceive cold in more areas after installation of the partition. Slight increase in supply air temperature is recommended.
- Distribution of carbon dioxide concentrations is unaffected by installation of the partition. Therefore, indoor air quality should not be regarded as a critical factor for installation of the partition during a normal occupancy level.
- Increased areas with uncomfortably cool sensation after installation of the partition can subsequently be improved with reduced volumetric flow rate of conditioned air. Closing some of the operational supply diffusers in deserted areas is recommended on the resting side of the library.
- Reduced volumetric flow rate of conditioned air on the resting side is also expected to resolve the problem with increasing rate of energy consumption after installation of the partition.
- Occupant’s perception of space is slightly affected but the students still feel reasonably spacious. Resting sofas are recommended to move slightly away to the right from the partition whereas study tables are suggested to arrange slightly closer to each other to ensure superior perception even after installation of the partition.

Further recommendations were suggested to improve indoor thermal sensation and energy saving by increasing the temperature of the discharge conditioning air at the supply. Increasing supply air temperature from 17 °C to 19°C greatly changes the perceived sensation of the library after installation of the partition. A separate analysis carried out with adjusting supply air temperature in each diffuser to 19 °C and 70 % *RH* shows the significant improvement in thermal comfort value as reported by PMV contour in Fig 4.9. Entire occupied regions of study area, entrance area and reception is perceived thermally neutral where the PMV value is approximately -0.3 in most areas. However, the central region with resting sofas, stairways and near partition regions are perceived slightly-cool but the PMV value is only slightly above the recommended comfort value from ASHRAE standard. PMV value is approximately -0.6 at these regions. The regions with cool sensation in previous condition with supply temperature of 17 °C are considerably reduced therefore the indoor occupants are likely to perceive the indoor environment comfortable and neutral.

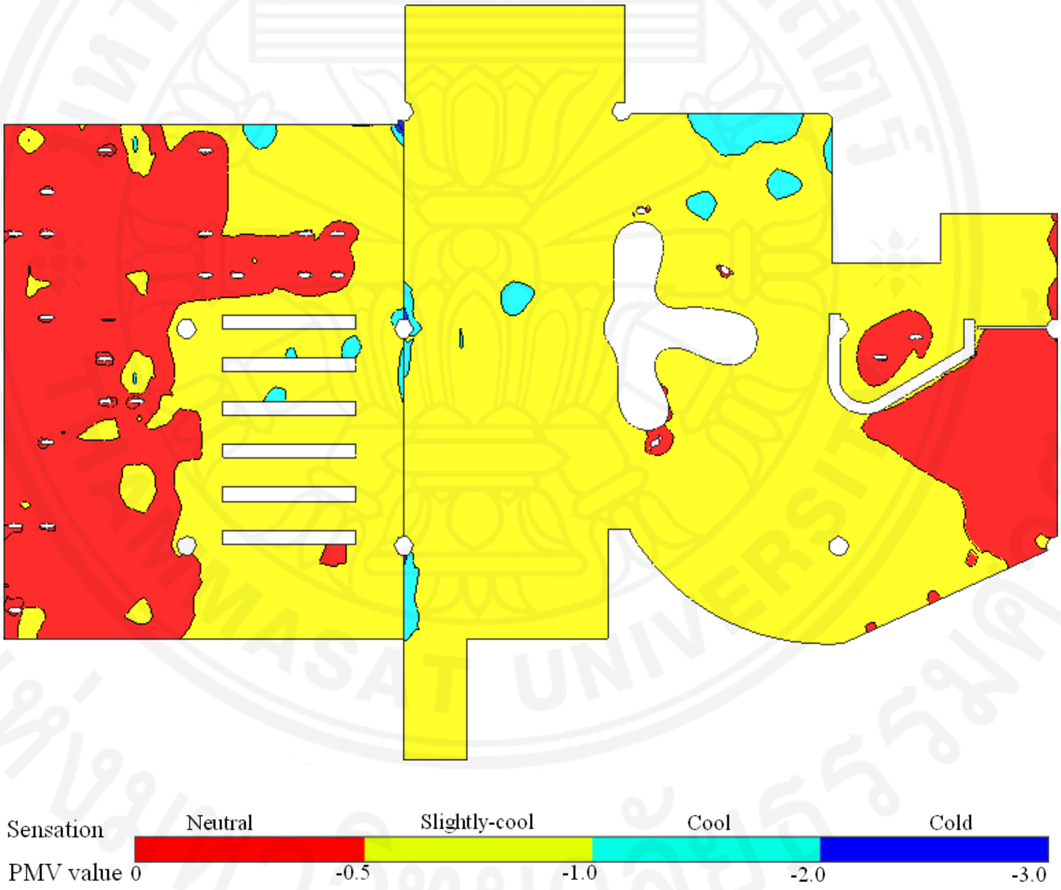


Fig. 4.9 Improved thermal sensation with increased supply temperature

Furthermore, indoor air variables at each extract grilles were numerically determined to calculate the energy consumption for a case study of a library with increased supply temperature. The average value of the air parameters such as temperature, velocity, and relative humidity at each extract grilles for a library with improved thermal sensation are shown in Table. 4.3. The difference of enthalpy at the supply and at the return is evaluated to obtain the energy consumption value.

Table 4.3 Air variables at each extract grilles when supply temperature is 19 °C

Extract grilles (E)	E1	E2	E3	E4
Air Temp., (°C)	21.59	22.5	22.52	21.49
RH (%)	60.21	52.72	54.18	61.41
Air velocity (m/s)	1.02	0.96	1.31	0.85
Hum. ratio(Kg/Kg)	0.00968	0.00895	0.00921	0.00981

All the obtained variables from Table 4.3 are applied in Eq. (3.8) to calculate the rate of energy consumption when supply air temperature is increased to 19°C. Table 4.4 shows the comparison of the rate of energy consumption when the discharged air-conditioning temperature at the supply is 17°C and 19°C respectively. It is inferred that the rate of energy consumption decreases by a whopping 27.6% when the supply air temperature is increased to 19°C.

Table 4.4 Comparison of energy consumption at air temperature 17°C and 19°C

Parameters	Supply air temperature (T_i)	
	17°C	19°C
Energy flow in $\dot{Q}_{in}$ (kW)	179.38	202.39
Energy flow out $\dot{Q}_{out}$ (kW)	216.04	228.91
Rate of energy consumption $\dot{Q}$ (kW)	36.66	26.52

Chapter 5
Conclusions and Future works

5.1 Conclusion

In this work, the decision making parameters for installation or removal of partition were developed and comparatively investigated in a case study of a library at the ground floor. The work included numerical simulation of the variables of indoor air within the air-conditioned library before and after installation of the partition during the normal occupancy level. Experimental measurement at various locations throughout the library at the height of breathing level is performed to validate data from numerical simulation. The developed numerical model showed a fair agreement with acceptable differences of the measured indoor air variables. Same model with a partition as control variable and specific boundary conditions was then applied to investigate the effects of partition. Accordingly, the thermal comfort, IAQ, energy consumption, and perception of space were investigated after installation of the partition at the desired location. It is found that the thermal sensation changes from slightly-cool to cool in major areas after installation of the partition. PPD value significantly increases at the both sides and higher number of occupants is expected to be dissatisfied with the indoor thermal conditions after installing partition. Carbon dioxide concentration distribution remains well within an acceptable limit for both cases. Change in indoor air quality is unlikely to be distinguished by indoor occupants after installing the partition. The rate of energy consumption is marginally higher by 8.3% after installation of the partition. Energy consumption is also found to have increased with installation of partition; therefore, adjusting supply air temperature slightly higher is recommended. At the same time, overall mean sensation of the library space can be brought down to slightly-cool or neutral. Additionally, supply diffusers in deserted areas should be closed to reduce the volumetric flow rate of conditioned air. Installation of the partition however noticeably intrudes onto the social space of some occupants but the average overall perception of space remains marginally below the spacious level. From analysis, it is apparent that the proposed methodology yields quantitative indicators for recommendation and decision-making of installation or removal of partitions for diverse purposes. The interior design of partitions can be performed before making real physical changes.

5.2 Future works

To further improve the quality of the research and to enhance its applicability, following further studies and future work in this area are expected:

- The accuracy of the simulation results using steady-state should be compared at various vertical heights using thermal comfort data logger.
- To investigate the effects of partition with varied occupancy load in the present model.
- To investigate the effects with varied partition parameters such as height, location, gap underneath etc.
- To investigate the effects of partial partition in some specific locations.
- To investigate perceived spaciousness in 3-dimensional space.
- To obtain more comprehensive energy analysis through coupling CFD simulations with a building energy simulation tool such as DesignBuilder, EnergyPlus, OpenStudio etc. that estimates the energy consumption of the overall HVAC system.

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Appendices

Appendix A: Correlation between measurement and simulation data

Appendix A of this thesis contains information of air parameters used to validate the experimental and simulations data of the case study of a library without a partition. Air parameters include air temperature, air velocity, relative humidity and carbon dioxide concentration measured at 14 different locations at the height of breathing level (i.e. 1.1 m above floor level). Measurement data and simulation data are presented below

Air Temperature (ºC)

Measuring point	Simulation (ºC)	Measurement (ºC)	Differences (ºC)	Relative error (%)
1	21.93	22.0	0.07	0.31
2	21.95	21.9	0.05	0.22
3	21.65	21.2	0.45	2.07
4	21.35	21.0	0.35	1.63
5	21.65	21.9	0.25	1.15
6	21.64	22.0	0.36	1.66
7	20.82	22.1	1.28	6.14
8	20.52	22.0	1.48	7.21
9	20.38	21.7	1.32	6.47
10	20.22	21.5	1.28	6.33
11	21.05	21.9	0.85	4.03
12	21.32	22.4	1.08	5.06
13	21.55	23.3	1.75	8.12
14	21.62	23.4	1.78	8.23

Relative humidity (%)

Measuring point	Simulation (%)	Measurement (%)	Differences (%)	Relative error (%)
1	51.94	49	2.94	5.66
2	51.86	48.9	2.96	5.70
3	52.53	49.5	3.03	5.76
4	53.69	51.2	2.49	4.63
5	52.81	48.8	4.01	7.59
6	53.13	49	4.13	7.77
7	56.03	51.7	4.33	7.72
8	57.13	52	5.13	8.97
9	57.68	52.5	5.18	8.98
10	57.12	52.3	4.82	8.43
11	56.59	51.8	4.79	8.46
12	55.71	51.4	4.31	7.73
13	54.68	50.7	3.98	7.27
14	54.49	50.5	3.99	7.32

Air velocity (m/s)

Measuring point	Simulation (m/s)	Measurement (m/s)	Differences (m/s)
1	0.1	0.15	0.05
2	0.1	0.11	0.01
3	0.06	0.09	0.03
4	0.07	0.1	0.03
5	0.08	0.06	0.02
6	0.09	0.05	0.04
7	0.1	0.06	0.04
8	0.09	0.05	0.04
9	0.09	0.06	0.03
10	0.08	0.1	0.02
11	0.05	0.05	0
12	0.06	0.08	0.02
13	0.08	0.07	0.01
14	0.02	0.03	0.01

Carbon dioxide concentration (ppm)

Measuring point	Simulation (ppm)	Measurement (ppm)	Differences (ppm)	Relative error (%)
1	435.11	429	6.11	1.40
2	437.74	431	6.74	1.54
3	435.34	433	2.34	0.53
4	434.23	431	3.23	0.74
5	431.54	447	15.45	3.58
6	437.82	440	2.17	0.49
7	418.19	426	7.80	1.86
8	420.96	437	16.03	3.80
9	412.49	422	9.50	2.30
10	409.14	387	22.14	5.41
11	394.86	397	2.13	0.54
12	382.27	360	22.27	5.82
13	399.96	306	93.96	23.49
14	404.59	320	84.59	20.90