# A Study On A Real Case Indoor Thermal Environment Installed With An Under-Floor Air Distribution System In The Tropics

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# APPROVAL

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A project dissertation submitted to the
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# DECLARATION

I, the undersigned, hereby declare that this report is my own independent work except as specified in the references and acknowledgements. I have not committed plagiarism in the accomplishment of this work, nor have I falsified and/or invented the data in my work. I am aware of the University regulations on Plagiarism. I accept the academic penalties that may be imposed for any violation.

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# ABSTRACT

In recent decades, the heating, ventilating, and air conditioning (HVAC) system has been introduced to the worldwide for air treatment in a closed room, office, and building. As a matter of fact, it holds a rather important role especially in multi-floors building to supply clean, fresh, and comfortable air to the occupants in the building. Convectional overhead (OH) air conditioning system is found getting eliminated from the industry due to high energy consumption, low ventilating efficiency, over cooling or heating. On the other hand, under-floor air distribution (UFAD) system is gaining more attention in the recent years due to its lower energy usage feature. TM Tower is believed as the first building which implemented UFAD system in Malaysia. However, according to some previous researches done, there is a need of improvement for the current UFAD design in order to adopt it in the tropics. In this paper, the impact of supply air temperature on the overall thermal comfort and energy consumption are studied. TRNSYS Simulation Software is used to investigate the effect of different supply air temperature on the conditioned space's thermal condition and compute the cooling load that accountable. Besides that, FloEFD acts a supporting tool in this project to provide a visual result for local mean age (LMA) of indoor air which indicates the air quality. ASHRAE Standard 55 and Standard 62 in HVAC system design are used as the guidelines throughout the project. It is revealed that as the supply air temperature increases, the overall indoor air temperature became higher, while the relative humidity became lower on the other hand. Also, the total cooling load of the system responds to the increasing supply air temperature in a proportional way. Supply air temperature of 20°C had seemed to be optimum value of providing acceptable thermal comfort and saving energy at the same time.

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First of all, I would like to express my greatest gratitude to my supervisor, Ir. Prof. Dr. Yau Yat Huang who offered me the opportunity to do this research. He was not only giving me with endless guidance and supports along the way, but also motivating me to think critically, work independently, and most importantly practice the way an engineer resolving a problem. I would also like to thank him for driving all the way from University of Malaya to Nilai every week just to give me an hour to consult him with the problems I have had. Without his patient, this project will not be completed.

Secondly, I would like to thank my seniors, Go Kah Hou and Siew Mun Tatt, in giving me the basic concept on how UFAD system is working as well as teaching me how to use the simulation software in the first place. Also, I truly appreciate both of them for providing me with the building data and the environment parameters of TM Tower that they measured, helping me to do this extension research of mine.

Besides, I also want to extend my gratitude to Dr. Abdulwehab for pointing out the mistakes that I have did in stage one, and advising me to know the mathematical models used in the simulation software as its engineering fundamentals.

Last but not least, I am grateful with my friends, Ivan Ng and Hui Jin, that we always exchanged the knowledge we knew even though our research topic is different. But it is good to learn more about other HVAC systems that exist in the industry today. They are great motivations to me and I do appreciate it as one of the most important thing that I have got in this project.

# DEDICATION

*This thesis is dedicated to my beloved mother.*

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| HVAC | Heating, Ventilating, and Air Conditioning |
| UFAD | Under-floor Air Distribution |
| OH | Overhead |
| SAT | Supply Air Temperature |
| RH | Relative Humidity |
| IAQ | Indoor Air Quality |
| PMV | Predicted Mean Vote |
| PPD | Predicted Percentage of Dissatisfaction |
| MRT | Mean Radiant Temperature |
| LMA | Local Mean Age |
| SBS | Sick Building Syndrome |
| VOC | Volatile Organic Compound |
| UZ | Upper Zone/Unoccupied Zone |
| OZ | Occupied Zone |
| CFD | Computational Fluid Dynamics |
| AHU | Air Handling Unit |
| TSP | Total Suspended Particulate |

# NOMENCLATURE

| *Symbol* | *Definition* |
|---|---|
| $\dot{Q}$ | Heat Transfer Rate [w] |
| $K$ | Thermal Conductivity [w/mK] |
| $h$ | Heat Transfer Coefficient [w/m$^2$K] |
| $R$ | Thermal Resistance [K/w] |
| $T$ | Temperature [$^o$C] |
| $L$ | Thickness [m] |
| $\dot{m}$ | Mass Flow Rate [kg/s] |
| $\rho$ | Density [kg/m$^3$] |
| $C_p$ | Specific Heat of Air [kj/kgK] |
| $f$ | Friction [N] |
| $u$ | Velocity of Fluid Flow [m/s] |
| $\mu$ | Dynamic Viscosity of Fluid [kg/ms] |

# CHAPTER 1

# INTRODUCTION

## 1.1. Background

### 1.1.1. Under-Floor Air Distribution (UFAD)

In the early development stage, the idea of supplying conditioned air to the computer rooms, where there are very few or no occupants inside, through a raised floor had been invented many years ago. Other than that, under-floor air distribution was first found implemented in Federal Republic of Germany in the early 1960s. At that time, it is used to supply cold air to those high heat production industrial spaces. This system was employed mainly to cool the equipment and machines in the industries and factories. Then in later, such system was also begun to be installed in general offices of European countries during the mid-1970s.

In a short term, UFAD system is a ventilation strategy which supplies air from the floor in to an indoor space.

### 1.1.2. Air Conditioning and Air Ventilation in Tropics

In Malaysia, there is no four seasons. Instead, Malaysia is a tropic country where the climates are generally hot and humid throughout the year. Malaysia Meteorological Department came out with a report that the average temperature in Malaysia in year 2013 is ranged between minimum 23°C and maximum 32°C, and the average humidity ratio is 80%. Working in an office space for a whole day under this kind of hot and humid situation is very easy to get uncomfortable. Therefore, a proper functional air conditioning system is badly needed especially in office buildings to provide comfortable working environment, provide cleaner air to the office space, increase productivity, improve working efficiency, and ensure occupants' health. However, as a matter of fact, different people might have different perception towards thermal comfort, whether it is too cold, too hot, too humid or too dry.

Thermal comfort had been expressed as a state of mind, rather than a state of condition, in which satisfaction sensation towards the given thermal environment is achieved (Djongyang et al, 2010). Thermal comfort could be influenced by personal differences in mind, culture, and individual's mood, organizational as well as social factors. Even at the similar location and a numerical comfort value of temperature, not every person will achieve the thermal comfort condition of mind. In fact, there was no absolute standard for which thermal comfort of an indoor environment can be clearly defined because it is mainly depending on the occupants' perceptions. There were six parameters affecting thermal comfort which are mainly classified into four physical parameters and two human factors. The four physical factors are air temperature, relative humidity, air velocity, and mean radiant temperature (MRT). Meanwhile, the two human factors would be clothing and metabolic rate.

Today, heating, ventilation, and air conditioning (HVAC) system have already been introduced to the worldwide. It serves the purpose of enhancing thermal comfort and indoor air quality in a conditioned space. In recent years, in accordance to the rapid development of HVAC system, the indoor thermal comfort was found have been greatly improved. Nonetheless, health problems associated to bad quality of air were frequently appeared. This is due to a lot of indoor pollutants and contaminants in the indoor air. Therefore, in order to promote a good indoor air quality (IAQ), the air-conditioning system installed in the building must have good contaminant removal feature to keep the contaminant concentration at acceptable level.

This study focuses on the offices in Unilever Malaysia, also known as TM Tower. It is a typical high-rise building in a tropical country. Office rooms at levels 33, 34, and 35 had been selected to investigate the thermal comfort level and indoor air quality in the offices in accordance to the current equipped air distribution system. Under-floor Air Distribution (UFAD) system is used in these offices where air is supplied from the floor and returned through the ceiling grilles. UFAD system is comparable to a displacement type ventilation system. It replaces high volume of 'old' air in the office with fresh air from outside, and contaminants are removed at the same time. A lot of researches are focused UFAD system in recent years. It is being developed and will be replacing the traditional overhead (OH) system in most of the buildings due to the potential benefits it can bring. Typically, a well-designed UFAD system provides better thermal comfort, good quality of air, energy saving, architectural flexibility and reduced life cycle building cost.

## 1.2. Problem Statement

As the living standard of the people is improving from time to time, the demand of the people for combatable and healthful environment is getting higher and higher. In an indoor environment, indoor air temperature, humidity ratio, ventilation, air movement, air exchange rate, and contaminant concentration are the parameters that are defining how good or bad the environment is. A good air distribution system should be good not only in terms of thermal comfort, but also able to maintain good quality of indoor air.

However, it is not an easy task to achieve thermal comfort in indoor offices in tropics. Warm temperature and high moisture of air are the general factors that cause discomfort to the occupants. In a hot and humid environment, even the temperature of the indoor air can be kept cooler, but the air humidity is often high in general case. Therefore, long hours of working in this office environment are quite easy to feel uncomfortable for the occupants.

It is an undeniable fact that the factors that influencing the thermal comfort are known. However, due to working requirement and purpose, the occupants are usually dressed with the common dress code of employees that set by the company. Besides that, there are also limits for the work activities in office. Hence, the occupants have only limited control over the human factors. As thermal comfort is critical to productivity of the occupants, this means that the physical factors are the remaining parameters that should be looked into to improve thermal comfort since the control over human factors had been limited.

Among the four physical parameters, supply air temperature possesses significant impacts on the overall UFAD system's performance (Lee et al, 2013). It is also the fastest method to control the thermal comfort. Because under hot and humid climate, the occupants in indoor office will tend to feel comfortable if the temperature is low. Although decreasing the supply air temperature could relatively lower down the overall temperature in the office space, but it might give a significant impact to the energy consumption of the system. Moreover, if the temperature too cold, it can cause cold feet and will not be comfortable to the occupants anyway. In addition, changes in supply air temperature not only influence the overall temperature in the space, but also affect the humidity and the contaminant removal activities.

Unlike the oversea seasonal countries where UFAD system has widely been used, there is still a lot of optimization works need to be carried out for UFAD system in tropics. This project aims to investigate the impacts of supply air temperature on relative humidity, energy saving, thermal comfort, and pollutants in the office air. And then come out with the design parameters, based on supply air temperature, of a more efficient air distribution system.

## 1.3. Objectives of the Research

The objectives of this project are:

- To study the characteristics of thermal environment of an office space equipped with an UFAD system in tropics
- To investigate the supply air temperature impacts on air temperature, relative humidity, energy saving, comfort, and indoor air quality of the office air
- To improve the performance of UFAD system in the tropics

## 1.4. Scope of the Research

This project covers the study of thermal environment condition over a high-rise building which is located in a tropical country where the climate is hot and humid throughout a year. In this project, supply air temperature is selected as the function to be investigated. The characteristics of the indoor air temperature, relative humidity, and contaminants/pollutants concentration are the parameters will be look into in order to determine thermal comfort and healthy indoor air quality. The air velocity and mean radiant temperature will not be focused in detail nevertheless only basic study of their influence in thermal comfort.

The results of relative humidity, energy consumption and pollutants concentration will be mainly based on simulation data. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) will be computed in this project by using ASHRAE Thermal Comfort Program. However, the PMV and PPD that require subjective measurement of occupants' opinions will only be acquired if opportunity arises. Throughout the study, ASHRAE Standard 55 of year 2010 and ISO 7730 will be used as the main guidelines for thermal comfort; ASHRAE Standard 62 for indoor air quality.

The office spaces are divided into several zones to get a more average data. Since this is an extension research from senior works, the building data of TM Tower is replicated from senior research because opportunity of field visiting is not offered this time. Also, it is assumed that the building materials of the office in each level are the same, so that the air temperature with respect to building material is a constant.

## 1.5. Report Organization

In this project report, the contents are mainly divided into six chapters. In Chapter 1, the background and problem statement of this research are shown. Besides that, the objectives of doing this research and the project scope are defined. Chapter 2 is literature review which states the theories and principles that are needed to understand when doing this research. Chapter 3 explains the methodology, software, and steps that used to obtained the results data. Meanwhile in Chapter 4, the process of modelling the offices into TRNSYS Simulation software is discussed. Chapter 5 is the result and discussion part in which the obtained results are organized, analyzed, and explained. Last but not least, Chapter 6 provides conclusion for this research as well as recommendation and future work. The very last part of this report lists the references of this research and follows by the appendix.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. Thermal Comfort

Thermal comfort is expressed as an individual state of mind which defines the personnel satisfaction in a given thermal environment. This means that when an individual feels good and comfortable with temperature sensation of the surrounding, thermal comfort is achieved and likewise. It is very important and must be reviewed because thermal comfort has direct relationship with human productivity and affects personal mood of occupants in a building (Akimoto & Tanabe, 2010). As a matter of fact, if an individual is feeling comfortable in term of the thermal sensation, his/her ability to perform work will be high; vice versa, if an individual is feeling uncomfortable and unhappy with the thermal environment, his/her performance of work will be distracted by the discomfort.

Different people may have different opinion towards the term of thermal comfort. For example, people from the tropics may prefer a "slightly cool" environment and on the other hand, people from cold climate would find a "slightly warm" environment comfortable (Wang, 2006). In fact, it is very subjective because thermal sensations among people will not exactly be the same even in the same environment. Moreover, even persons sharing the common culture, staying in the same space, and subjected to a similar climate, issue very different opinions toward thermal comfort because of factors from every aspect that combined and affected the perceptions of human beings. Thermal comfort satisfaction thus, becomes a subjective response towards the environment where the people stay. In short, no absolute standard is existed for which thermal comfort can be exactly defined.

However, there were evaluation methods for thermal comfort established for the urgent need to cut down the cost of energy consumption by air conditioning system, economically and environmentally. At present, there are two different approaches coexist to define of thermal comfort. First approach is rational approach;

whereas the second one is known as adaptive approach (Djongyang et al, 2010). Each of them has its own potentialities and limits.

In general, thermal comfort can be achieved when an individual body temperature is held within narrow range, skin is less moisture, and physiological regulation activities are minimized (Ogbonna & Harris, 2008). This statement can also be applied to the case in the tropics. There was a field study conducted by (Dear et al, 1990) in a tropical country, the mean thermal comfort votes showed that low temperature of 23.5°C, and medium relative humidity of 56%, in an office are acceptable. As mentioned above, there are mainly six factors which could affect the thermal comfort level. Besides that, thermal comfort is also influenced by the design of different air distribution system. All these factors are important and shall be considered in order to design a proper HVAC system.

2.1.1. Factors that Affecting Thermal Comfort

The four physical factors that affect thermal comfort are:

1. Indoor Air Temperature

Basically, this air temperature refers to the average or mean temperature of air in an indoor environment. It is usually measured in (°C) or (°F). The temperature different between air temperature and the human body influence the heat exchanging rate between body and the surrounding. Human body changes temperature by changing the metabolic rate, then the temperature different will eventually come to a steady condition after a period of time. At that moment, whether the temperature is too cold or too hot, human body will sense it and human activities will be affected.

Air temperature can be varied with respect to locations in the area, time zones, building materials and outdoor factors. As an assumption mentioned above, the building material of the office in each level are the same, therefore the air temperature with respect to building material is a constant. In addition, air temperature can be measured using a dry-bulb method where a temperature transducer is placed into an air flowing environment to sense the temperature. According to (ASHRAE Standard 55, 2010), the recommended range for indoor air temperature is between 23°C to 26°C.

2. Air Velocity

It is describes as the speed of air moving across the occupants. It has great influences in thermal comfort as humans are sensitive to it. Air is the medium which helps to cool human body if it has lower temperature than the body. Hence, faster air movement results in higher rate of removing heat from human body, but this does not mean thermal comfort is good. On the other hand, stagnant or still air in a space may cause occupants to feel stuffy when heat is transferred in to the indoor environment through radiation or generated by human body activities. Moreover, air velocity is important in controlling the thermal comfort by removing moist and contaminants in the air. In a proper air distribution system, air velocity must be sufficient so that moist and contaminants can be removed from the occupied zone and replaced with outdoor fresh air.

According to (ASHRAE Standard 55, 2010), air velocity is described as the amount of air which a body is exposed to, with respect to location and time. An average air velocity of approximately 15m/min is acceptable and most people feel comfortable with it.

3. Relative Humidity

It is also known as humidity ratio of air which describes the ratio of the partial water vapor pressure to the saturated water vapor pressure. In another word, it is the actual amount of water vapor in the air divided by the maximum amount of water that the air can carry. Relative humidity very much influences the thermal comfort because if the relative humidity of air is high, it slows down the evaporation of sweat from the skin. As sweating is the main method of heat loss from body, high humidity is easier to cause discomfort especially if it is a hot environment.

In a dry climate where the relative humidity is about 20%, people tend to feel uncomfortable due to the effect of mucous membranes. In most of the air conditioned buildings, relative humidity is usually kept in range of 40% to 70% (ASHRAE Standard 55, 2010), depending on the other factors being considered, to control the sweating of body because sweating in an air conditioned indoor environment is usually not comfortable. Nevertheless, humidity in indoor environment can also be affected if there is any drying or humidifying process by machine or office equipment.

4. Mean Radiant Temperature (MRT)

MRT is referring to the average temperature in which the amount of heat transferred in the actual non-uniform enclosure and the heat transferred from the human body become the same (ISO 7726, 1998). Radiant heat may come from sources like the sun, electric fire, furnace, oven, steam roller cooker, dryer, machine and hot surfaces. MRT may have greater influence than the air temperature on the heat exchanging process between surrounding and a human body. Human skin is sensitive to radiant heat and able to absorb a lot of radiant heat. Nevertheless, this can be reduced if reflective clothing is worn.

In a building that usually exposed to strong solar radiation, MRT is very significant in affecting the thermal comfort level (Atmaca & Kaynakli, 2007). According to (ASHRAE Standard 55, 2010), MRT will equal to indoor air temperature and become constant in all directions when temperature is equilibrium among floors, ceilings, walls, and the indoor air. During winter climate, the MRT nears to the window, measured from indoor, is significantly lower than the indoor air temperature; whereas in hot climate like summer, the mean radiant temperature will exist above the air temperature. Thus for the case in Malaysia with typical tropics climate, the buildings are exposed to high solar radiation throughout the year. This results in a lot of difficulties to control thermal comfort in an indoor environment with using conventional indoor temperature and humidity control. A series of considerations must be taken into account when designing a HVAC system in a building so that the balance between the mean radiant temperature and operative temperature can be obtained in order to achieve thermal comfort.

The two human factors that affect thermal comfort include:

1. Clothing Insulation

Clothing helps human to reduce heat lost to the environment. Clothing insulation is the thermal insulation prediction for the cloth that a person is wearing. It is usually measure in 'clo' unit where $1\,clo = 0.155\,m^2$ K/W. The insulation level of the clothing possesses a significant impact on thermal comfort. If a person wearing too much or too thick clothing, the insulation level is high and heat stress may be caused. On the other hand, if the clothing is too thin or insufficient, the wearer may put him/herself at risk from cold injuries. However, it is also highly dependent on the material of the clothing made of. Figure 2.1 below shows the insulation values for different clothing ensembles.

| Ensemble Description | clo* |
|---|---|
| Trouser, short sleeve shirt | 0.57 |
| Knee-length skirt, short-sleeve shirt (sandals) | 0.54 |
| Trousers, long-sleeved shirt, suit jacket | 0.96 |
| Knee-length skirt, long-sleeved shirt, half slip, panty hose, long-sleeved sweater | 1.10 |
| Long-sleeved coveralls, T-shirt | 0.72 |

Figure 2.1: Insulation Values for Different Clothing Ensembles *(Source: ASHRAE Standard 55, 2010)*

2. Metabolic Rate

Metabolism in human is the set of life-sustaining chemical transformation within the cells in human body. Metabolic rate is defined as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within organism (ASHRAE Standard 55, 2010). It reflects the cellular life that results from the consumption of oxygen and release carbon dioxide. In another word, the higher the human physical activity or work, the higher the metabolic rate is. When physical activity is more, relatively the metabolic heat produced is high, meaning that more heat in the body has to be released to the surrounding. Therefore, metabolic rate is a significant factor in affecting thermal comfort. Moreover, others factors like weight, age, gender and fitness need to be taken into consideration as well. Commonly, metabolic rate is expressed in met units where 1 met = 58.2 W/ $m^2$. Figure 2.2 below shows some metabolic values during various human activities.

| Activity | met* |
| --- | --- |
| Sleeping | 0.7 |
| Reading or writing, seated in office | 1.0 |
| Filing, standing in office | 1.4 |
| Walking about in office | 1.7 |
| Walking 2 mph | 2.0 |
| Housecleaning | 2.0 to 3.4 |
| Dancing, social | 2.4 to 4.4 |
| Heavy machine work | 4.0 |

Figure 2.2: Metabolic Rate for Different Activity *(Sources: ASHRAE Standard 55, 2010)*

2.1.2. Thermal Comfort Approaches

1. Rational Approach

It is also known as heat-balance approach which uses data from climate chamber studies to support its theory. This approach is best characterized by the works of Fanger who developed Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) using heat balance equations and empirical studies about skin temperature to define comfort (Fanger, 1970). This approach is acquired in this project in term of defining thermal comfort. Therefore, a little more literatures about PMV and PPD will also be reviewed further.

2. Adaptive Approach

Different from rational approach, the adaptive approach uses data from field studies of people in building to evaluate comfort. The concept of this approach comes from the idea of indoor's comfort could be affected by the climate at the outdoor environment because humans tend to adapt to different temperatures during different times of the year. This approach was derived from the field studies which greatly depend on the behavior of the occupants in the office building and their expectations. The purpose of this approach is to analyze the real acceptability of an indoor thermal environment. Richard (2004) has summarized three categories of thermal adaption which include behavior adaptation, psychological adaptation as well as physiological adaptation. In recent years, this approach encourages field studies should be added to laboratory experiment (the simulation in chamber of rational approach) in order to attain higher reliability of information about the thermal comfort of an actual workplace as well as the interacting parameters. Hence, it can be said that the adaptive approach certainly exploits the rational approach as the basis to conduct field studies in further.

### 2.1.3. Predicted Mean Vote (PMV)

The PMV index is suggested and developed by Fanger to predict the mean response of a large group of people according to the ASHRAE thermal sensation scale. Occupants exposed in a thermal environment are asked to give their opinions according to ASHRAE seven-point scale of thermal sensation. In such thermal environment, the four physical factors and the two human are put together into consideration. The scale is ranging from:

Cold (-3); cool (-2); slightly cool (-1); neutral (0); slightly warm (+1); warm (+2); hot (+3).

A mean vote (MV) is then obtained by finding the mean value of feeling given by the occupants for that particular thermal environment condition.

PMV model is developed by Fanger based on the heat balance equation for human body. Fanger related PMV to the imbalance between the actual heat flows from a human body in a given environment and the heat flow required for optimum comfort at a specified activity by developing the equation:

$$PMV = [0.303\exp(-0.036M) + 0.028]\,L \quad (1)$$

where, L is thermal load on the body and it is expressed as the difference between internal heat production and heat loss of an individual to the environment, M is heat production from metabolic acitivity (W/m$^2$).

This equation can also be expended as:

$$PMV = [0.303\exp(-0.036M) + 0.028] \times \{(M - W) - H - E_c - C_{res} - E_{res} \quad (2)$$

where, H is sensitive heat loss in ($W/m^2$), w is mechanical work in ($W/m^2$), $C_{res}$ is heat exchange in breathing by convection in ($W/m^2$), $E_c$ is heat exchange through evaporation loss in ($W/m^2$), and $E_{res}$ is heat exchange in breathing through evaporation in ($W/m^2$).

The PMV is then incorporated into the Predicted Percentage of Dissatisfied (PPD) index to evaluate thermal comfort.

### 2.1.4. Predicted Percentage of Dissatisfied (PPD)

The PPD is a mathematical function of PMV used to predict the percentage of the occupants who felt more than slightly warm or slightly cold. In another definition, it is the percentage of occupants who tend to complain about the given thermal environment.

Fanger postulated that those who responded $\pm 2$ and $\pm 3$ based on the ASHRAE seven-point scale of thermal sensation ($-3$ to $+3$), are declared as discomfort or dissatisfied. The occupant percentage who give $\pm 2$ and $\pm 3$ are determined for each class of PMV. Such variables are defined as PPD. The relationship between PMV and PPD is described by the equation below:

$$PPD = 100 - 95\exp[-(0.03353\,PMV^4 + 0.2179\,PMV^2)] \quad (3)$$

The merit of this relation is that, it reveals a perfect symmetry with respect to thermal neutrality (PMV = 0). Even if the PMV index is 0, there are still some individual cases of dissatisfaction with the thermal comfort level. It is shown by (Hwang et al, 2009) that even at PMV = 0, a minimum of 5% of dissatisfaction exists as illustrated in the Figure 2.3 below.

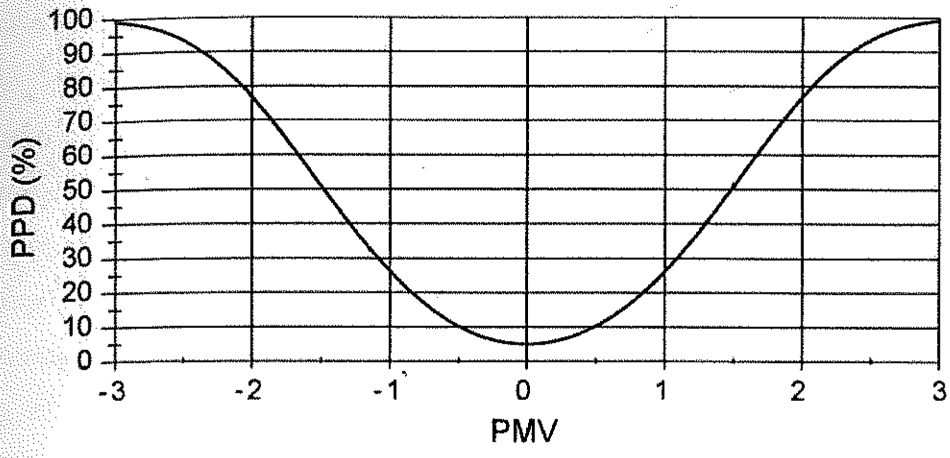


Figure 2.3: Relationship Betwwen PPD and PMV (Source: Thermal Comfort - A Review Paper, 2010)

As a matter of fact, Fanger's PMV-PPD model is no doubt a superb contribution to the theory of thermal comfort and provide better evaluation for indoor thermal environments in a building. This model is still being the only mode which has been widely used and accepted for design and field assessment in term of thermal comfort until today.

## 2.2. Indoor Air Quality (IAQ)

Besides maintaining thermal comfort, another key function of HVAC system is to provide clean, healthy, and odor free indoor environment to the occupants. Indoor air quality (IAQ) is considered acceptable if the air in respective indoor environment has no known contaminants at harmful level and majority of the occupants in the environment have not expressed dissatisfaction (ASHARE Standard 62, 2010). If good IAQ was attained, not only the occupants will feel comfortable but their environment will also be free of unwanted odors and contaminants of harmful concentration.

Thermal comfort that affected by the six factors mentioned above is more towards satisfying the occupants comfort; whereas indoor air quality (IAQ) is associated with health issue of the occupants. Building with an unusual number of occupants having physical problem are described as having sick building syndrome (Sundell, 1996). Sick building syndrome (SBS) symptoms can be certain allergic reactions such as headache, nausea and irritations of eyes or nose. In past few decades, as a result of worldwide energy crisis in 1970s, many buildings were over-emphasizing on the overall energy saving. Fresh air intake by the air conditioning system is reduced to save energy consumption. At the same time, synthetic materials and chemical products were widely used in indoor spaces. The combination of numerous synthetic chemicals with low ventilation rates results in increased concentration of indoor particle pollutants as well as volatile organic compounds (Wang et al, 2004). Therefore, apparently, there is a need to optimize the air-conditioning systems developed in the recent years for a better indoor air quality control for human health.

Maintaining an acceptable IAQ involves keeping indoor pollutants below some acceptable level in the indoor environment. The indoor pollutants are generally classified into particle pollutants and gaseous pollutants. The pollutants may be visible like large particles. It may also only be observable by using instruments. In worst case, it may be discernible by the effect that they have on the occupants. As an optimization study on UFAD, it is important to investigate the pollutants/contaminants that commonly exist in the building and understand the need of contaminants removal as one of the significant functions in UFAD system.

### 2.2.1. Particle Pollutants

The particle pollutants existed in an indoor space could endanger the occupants' health via canal, skin and alimentary canal (Kavouras & Stephanou, 2003). Particle pollutants may enter into human body via respiration canal and it is the most dangerous approach because it may cause human sick. The chemical compositions and characteristic are critical as they indicate the degree and speed of biochemistry processes which particle pollutants undergo and interrupt in human body.

The particle pollutants can be divided into two types of source, which are indoor pollution sources and outdoor pollution sources.

1. Indoor pollution sources:

   For example cooking and smoking. The pollutant particles released are mostly fine particles and ultra-fine particles which are about 80% of the particles in