THE POTENTIAL OF HYBRID TURBINE VENTILATOR TO IMPROVE INDOOR CLIMATIC CONDITIONS IN HOT-HUMID ENVIRONMENT

by

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LIST OF ABBREVIATIONS

AC	- Air-Conditioning
ACH	- Air Change per Hour (Air change rate)
ASHRAE	- American Society of Heating, Refrigerating & Air Conditioning Engineers
ATV	- Attic Turbine Ventilator
BIPV	- Building Integrated Photovoltaic
BSI	- British Standard Institution
CFD	- Computational Fluids Dynamic
CMH	- Cubic/Cm per Hour
DBT	- Dry Bulb Temperature
DC	- Direct Current
EE	- Energy Efficiency
ET*	- New Effective Temperature (°C)
HTV	- Hybrid Turbine Ventilator
HVAC	- Heating, Ventilating and Air-Conditioning
IAQ	- Indoor Air Quality
ISO	- International Standard Organization
LVT	- Long Volume Turbines
MRT	- Mean Radiant Temperature
NPL	- Neutral Pressure Level
NV	- Natural Ventilation
OT	- Operative Temperature
PMV	- Predicted Mean Vote (scale value)
PPD	- Predicted Percent Dissatisfied (%)
PV	- Photovoltaic
PVLV	- Photovoltaic Lightpipe Ventilator
RE	- Renewable Energy
RH	- Relative Humidity
RI	- Relativeness Index
SBS	- Sick Building Syndrome
SET*	- Standard Effective Temperature (°C)
SPEF	- Solar-powered Extractor Fan
SPTV	- Solar-powered Turbine Ventilator
TC	- Thermal Comfort
UBBL	- Uniform Building By-Laws

LIST OF SYMBOLS

Cp	- Pressure coefficient
C_{p1}	- Outdoor Pressure coefficient
C_{p2}	- Indoor Pressure coefficient
ΔT	- Indoor-Outdoor Temperature Difference (°C)
ΔRH	- Indoor-Outdoor Relative Humidity Difference (%RH)
h	- Height (m)
K	- Discharge coefficient
Ø	- Diameter
Θ_i	- Outdoor pressure (temperature)
Θ_e	- Indoor pressure (temperature)
Q	- Air flow rate (l/s) / (m^3/s)
v	- Air velocity (m/s)
t_{out}	- Outdoor DBT temperature
t_i	- Indoor DBT temperature
T_{comf}	- Optimum comfort temperature (ºC)
$T_{a,out}$	- Mean outdoor dry bulb temperature of the month (ºC)
t_a	- Air temperature
t_n	- Neutral temperature / thermal neutrality (ºC)
t_o	- Operative temperature (ºC)
t_r	- Mean radiant temperature (ºC)
U_{ref}	- Reference wind speed
V	- Total volume
N	- Numbers (units)
E	- Exhaust capacity of turbine ventilator (l/s)
V_{ar}	- the relative air velocity (relative to the human body), in m/s

POTENSI PENGALIHUDARAAN TURBIN HIBRID UNTUK MEMPERBAIKI KEADAAN IKLIM DALAMAN DI PERSEKITARAN PANAS-LEMBAP

ABSTRAK

Tesis ini membincangkan hasil kajian empirikal mengenai kemungkinan memperbaiki keadaan iklim dalaman bangunan di persekitaran panas-lembap melalui penggunaan pengalihudaraan turbin hibrid (HTV). Berdasarkan kajian literatur, didapati strategi pengudaraan tingkat berbantukan kipas seperti pengalihudaraan turbin hibrid (HTV) adalah antara strategi yang paling berpotensi untuk digunakan dalam keadaan radiasi solar tinggi dan kelajuan angin rendah seperti yang dialami Malaysia. Melalui satu kajian rintis, konfigurasi optimum HTV telah dikenalpasti, dengan konfigurasi baru yang disertakan saluran ventilasi dalaman dan ruang ventilatisi terbuka yang lebih luas di bahagian atas turbin telah dilihat menunjukkan keupayaan terbaik dalam meningkatkan pergerakan udara dalam bangunan. Kemudian, satu siri kajian lapangan yang dijalankan di bangunan dan di bawah keadaan cuaca sebenar telah mengesahkan kepentingan HTV dalam memperbaiki keadaan iklim dalaman bangunan. Hasil kajian telah menunjukkan strategi mengaplikasikan HTV untuk pengudaraan ruang hunian telah berhasil mengurangkan tahap suhu udara dan kelembapan relatif dalaman bangunan dan juga signifikan dalam meningkatkan pengerakan udara di zon hunian sehingga purata maksimum 0.38m/s dalam kes tingkap dan pintu terbuka. Walaupun kesemua strategi pengaplikasian HTV berjaya mengurangkan tahap Suhu Operatif (OT) dan Suhu Efektif Standard (SET*) berbanding dengan keadaan asal bangunan, namun hasil keseluruhan kajian menunjukkan yang ianya masih belum berupaya untuk menjamin tahap keselesaan terma penghuni dalam kebanyakan masa, apabila OT yang dicapai telah melebihi had maksimum keselesaan terma 30.0°C sebanyak 21% hingga 45% sepanjang waktu kajian. Namun berdasarkan hasilan kajian, satu strategi

yang mungkin berkesan untuk meningkatkan keberkesanan HTV ini ialah dengan mengaplikasikannya untuk kedua-dua ruang atap dan ruang hunian secara serentak dan memastikan bukaan bangunan dibiarkan terbuka.

THE POTENTIAL OF HYBRID TURBINE VENTILATOR TO IMPROVE INDOOR CLIMATIC CONDITIONS IN HOT-HUMID ENVIRONMENT

ABSTRACT

This thesis presents the results of the empirical studies regarding the possibilities of improving indoor climatic conditions in the hot-humid environment with the use of hybrid turbine ventilator (HTV). From the literature, it is found that the fan assisted stack ventilation strategy like the HTV is one of the most potent strategies to be applied in this high solar radiation and low wind velocity region of Malaysia. Through the pilot experiment study, an optimum configuration of the HTV has been determined, which is the new configuration with inner duct and larger free upper outlet area is found to show the best performance in inducing indoor air movement. Then, a series of full-scale field measurement studies conducted in the real building and under real weather conditions confirmed the significance of the device in improving indoor climatic conditions. The study shows that the strategy of applying HTV for occupied space achieved to reduce indoor air temperature and relative humidity (RH) level significantly and succeeded to induce air movement in the occupied level of up to 0.38m/s in the windows and doors are kept opened case. However, although all the HTV application strategies succeeded to reduce the Operative Temperature (OT) and Standard Effective Temperature (SET*) level compared to the existing condition, the overall results revealed that it is still not able to ensure occupants' thermal comfort level at most of the time, when the OT achieved were above the upper comfort limits of 30.0°C for about 21% to 45% during the study period. One possible improvement of the device derived from the results is by applying the HTV for both attic and occupied spaces at the same time and ensure that openings are kept opened.

CHAPTER 1

INTRODUCTION

1.1 Background

Generally, building sector consumes about 30-40% of the world's energy demand and it is expected to increase rapidly in the near future (Santamouris, 2005). In South-East Asian countries, example of the hot and humid tropical region, the average energy consumption of building is 233kWh/m^2/yr of which about 50% is for air-conditioning (Zain-Ahmed, 2008). This scenario of high energy consumption due to the extensive use of air-conditioning system is quite frustrating since various studies indicated that people in hot-humid tropical climate are more tolerable to higher temperature due to the acclimatization factor (Givoni, 1992; Nicol, 2004).

Concerning this issue, various studies have been done in order to find out possible alternatives to air-conditioning system without compromising the environment and people's thermal comfort. One of the most significant strategies which have gained attention from most of the architects, engineers and energy-conscious researchers is the use of natural ventilation as a passive cooling technique in the building. In contrast with air-conditioning system which is usually associated with global warming, acidification and sick building syndrome (SBS) (Seppanen and Fisk, 2002; Liping and Hien, 2007), natural ventilation offers several merits in terms of reducing building energy consumption, improving indoor air quality (IAQ), allowing natural daylighting and providing occupants' thermal comfort (Allard, 1998; Abdul Rahman and Abdul Samad, 2009).

In hot-humid climate region, various studies have clearly shown that natural cross ventilation is much more effective ventilation strategy compared to stack ventilation in order to improve indoor thermal environment. The shortcoming of stack ventilation which is based on thermal force can be referred to several constraints such as this region’s climate conditions (with very low outdoor-indoor temperature differential and outdoor low-wind velocity) (Tantasavasdi et al., 2001) and inappropriate architectural design (insufficient inlet-outlet opening and unsuitable stack ventilation elements) (Brown and DeKay, 2001).

However nowadays, in the conditions of the warmer climate and densely built environment, the conventional concept of natural cross ventilation does not always successfully apply. The need for a compartmentation of spaces in a deep plan building and more compact layout of planning where buildings are laid closely like in the terrace houses have resulted in limited openings for crossflow (Abdul Rahman, 1995; Sadafi et al, 2008). For these situations, the main solution could lie on providing effective outlet area at the top of the building to induce vertical air movement.

These issues and needs are prompting researchers to investigate advanced stack ventilation strategy as an alternative to cross ventilation. These include the research and development in solar induced ventilation, wind assisted stack ventilation and fan assisted stack ventilation strategies.

Solar induced ventilation strategies like solar chimney, solar roof and double façade rely upon the heating of the building fabric by solar radiation resulting into a greater temperature difference to enhance the stack effect (Awbi and Gan, 1992). Although most of the studies regarding these strategies showed that they have significant influence in increasing airflow and ventilation rate, its effectiveness in inducing ample air movement within the occupants’ zone were found to be inadequate to create physiological cooling (Barozzi et al., 1992; Khedari et al., 2000).

On the other hand, many studies revealed that the use of wind-driven ventilation techniques like wind cowl, wind tower, windcatcher, wind jetter and turbine ventilator are very helpful to induce vertical air movement, thus enhancing the stack ventilation significantly (Khan et al., 2008). However, these strategies which can be considered as wind assisted stack ventilation strategy are found to be only effective in moderate to high-wind velocity condition. This constraint limits its function to be effectively used in low-wind velocity region like hot-humid Malaysia.

In an effort to make it more reliable, consistent and efficient, several fan-assisted stack ventilation strategies which maximize the natural energy sources available from both the sun and wind have been developed. This includes the prototype development of some hybrid energy generated stack ventilation devices such as solar-powered windcatcher and solar-powered turbine ventilator. In this context, hybrid energy can be described as *'a complementary operation of multiple renewable energy sources available from the local natural environment to achieve optimum energy generation'* (Lai, 2006). From the previous studies, it has been proven that this stack ventilation strategy, especially hybrid solar-wind driven turbine ventilator (HTV) is very promising and synergetic techniques since the effectiveness of the system to induce airflow increased as solar irradiation increased, which is proportional to the cooling needs of the building.

However, it is realized that the effectiveness of this ventilation strategy in terms of thermal comfort has not been well studied especially when applied for real building in hot-humid region. For country like Malaysia, which is characterized by erratic and outdoor low-wind speed and is blessed with high solar radiation but cloudy sky condition (MMD, 2008), uncertainties of its effectiveness in real building need further investigations. Therefore, a comprehensive empirical study to obtain quantitative data on the performance of such device when it comes to the real application should be done first, before it can be widely accepted by building design community as one of the energy efficient means to ventilate their building.

1.2 Problem Statement and Hypothesis

The use of stack ventilation strategy to induce upward air movement and extracts it out through the upper part of the building is indeed very important for a deep-plan building, like in the case of terrace houses. However, due to the climatic constraints of the hot and humid region possesses i.e. very low indoor-outdoor temperature differential, low outdoor wind velocity and cloudy sky conditions that limits the potential of solar radiation, this type of ventilation strategy is often regarded as insignificant to be used in this type of climate. However, if an appropriate strategy that can maximize both natural sources of wind and solar energy can be developed, it is expected that the performance of stack ventilation in improving indoor thermal environment could be significantly improved.

Therefore, in this study, it is hypothesized that by combining the wind-driven turbine ventilator and solar powered extractor fan, it will produce a more consistent and higher rotation speed of turbine ventilator. Hence, the induced upward air movement will be affected and thus, improving the indoor climatic conditions. As a result, this stack ventilation strategy will provide acceptable indoor thermal comfort level at most of the time in this climate.

1.3 Research Questions

Due to the fact that the hybrid turbine ventilator (HTV) can simultaneously utilize both wind and solar energy to rotate, it would seem logical to consider the device as one of the most possible means to enhance stack ventilation in hot-humid climate. However, since the effectiveness of this strategy is totally dependent on local ambient wind and solar conditions, its practical applicability in Malaysian building need further investigation. Therefore, more specific research questions have been formulated as follows:-

Q1: Is the Hybrid Turbine Ventilator (HTV) possible to be used in Malaysian low-wind and cloudy sky condition?

Q2: What is the appropriate HTV model in inducing maximum vertical air movement?

Q3: Does the proposed HTV model as determined at Q2 effective to improve stack ventilation in the real building and how effective the device would be in comparison with other conventional ventilation strategies?

Q4: What is the most appropriate application strategy of the HTV in Malaysian building in relation with certain architectural parameters like the effects of openings and vented or unvented attic?

Q5: Is the HTV application significant to provide acceptable Malaysian thermal comfort level at most of the time?

Q6: What are the limitations of the proposed HTV model towards improving indoor climatic conditions in hot-humid tropical Malaysia?

1.4 Research Objectives

The main objective of this study is to investigate the applicability and limitations of a hybrid turbine ventilator (HTV) as a stack ventilation strategy in inducing vertical air movement and thus improving indoor climatic conditions and thermal comfort in hot-humid tropical Malaysia.

The specific objectives of this study are:

i) To investigate the reliability of solar radiation based on Malaysian climatic conditions on the consistency and workability of the HTV

ii) To obtain quantitative results of the effectiveness of the HTV in improving indoor climatic conditions in comparison with other conventional ventilation strategies.

iii) To determine the appropriate application strategy of the HTV in hot-humid tropical building, particularly in relation with certain architectural parameters like the effects of openings and vented or unvented attic.

1.5 Research Approach and Methods

In accomplishing the objectives as stated in Section 1.4 and in answering specific research questions as mentioned in Section 1.3, this study has involved some stages of research works, as shown in Figure 1.1.

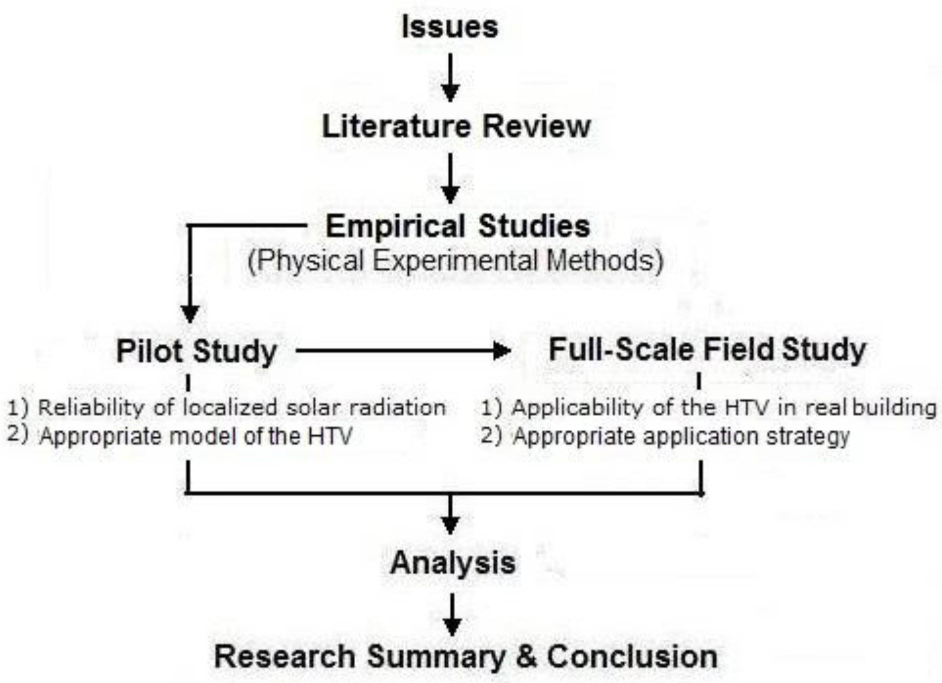


Figure 1.1: Summary of methodology used in investigating the possibilities of using Hybrid Turbine Ventilator (HTV) for enhancing stack ventilation and improving indoor climatic conditions

Firstly, a literature review on the various aspects of stack ventilation concepts and strategies has been done to find out the most potential and suitable stack ventilation strategy to be applied in hot-humid tropical building. The literature surveys led to the conclusion that the fan assisted stack ventilation strategy is the best mean to enhance vertical air movement in the building, especially in the occupied zone. One of the most potent devices is the Hybrid Turbine Ventilator (HTV) which maximizes both free wind and abundant solar energy available in this region.

Then, the real investigations should be carried out to determine the appropriate configuration of the device and to examine its potential in improving indoor climatic conditions in the real building and under the real Malaysian climate conditions. This has been conducted through empirical studies or physical experimental methods, which consist both pilot study and field studies.

Through the pilot study done experimentally in the enclosed space, the reliability of the device in inducing vertical air movement relying only to the outdoor solar intensity without the encouragement of wind force is investigated and its optimum configuration is determined. On the other hand, the applicability of the device to provide an acceptable comfort level for occupants in the real low-rise building is investigated through a series of field studies done in typical Malaysian institutional building. For this purpose, the thermal environments of open plan science laboratory have been studied for the different cases and types of ventilation. Several parameters such as ambient climatic conditions, the effects of the openings, different configurations of the modified turbine ventilators and the influence of different HTV application strategies on improving indoor climatic conditions have been studied. The thermal comfort conditions of each case have been compared and evaluated by measurements of air temperature, mean radiant temperature, relative humidity and air velocity levels in the occupied zone using two thermal comfort indices i.e. the Adaptive Comfort Standard (ACS) and the Standard Effective Temperature (SET*).

1.6 Scope and Limitations

This thesis presents a study on the potential of turbine ventilator driven by hybrid energy to enhance the effectiveness of stack ventilation strategy in improving indoor thermal environment in hot-humid climate region. Although there are many possible combinations of different renewable energy sources e.g. biomass, photovoltaic systems, solar thermal, micro hydro and wind energy, which can be combined to form a hybrid configuration, only a combination of solar energy through polycrystalline photovoltaic (PV) panels and natural wind energy will be studied in this thesis.

In this respect, the concept of simple hybrid energy studied should be differentiated from common understanding of more complex and expensive *'hybrid energy system'*, which usually consists of two or more energy systems, an energy storage system, power conditioning equipment and a controller. The term hybrid energy used in this thesis is also different from the term of *'hybrid ventilation'* which generally has been described as a system providing a comfortable internal environment using different features (modes) of both natural ventilation and mechanical systems at different times of the day or season of the year (Heiselberg, 1999).

With respect to the simplicity of the ventilation strategy and environmental concern, none of the advanced stack ventilation strategies or technologies reviewed in this thesis uses a refrigerant, chemical or too complex system to operate. However it must be recognized that non-availability of the state-of the art stack ventilator based on renewable energy existed in Malaysian market limited the scope of the study. Therefore, only commonly used of lightweight extractor fan powered by the solar energy (through photovoltaic) and conventional turbine ventilator driven by the wind energy will be combined and studied.

As was mentioned earlier, the study will focus on the applicability of the HTV for enhancing stack ventilation in hot-humid region. In this context, a hot-humid climate can be defined as a region which located in a belt extending roughly 15° either side of the equator which the main function of the building is to simply moderate the daytime heating effects of the environment (Givoni, 1998). For this study, special reference was given to Malaysian climate conditions with generally characterized by very low outdoor-indoor temperature differences and windless condition, which make natural stack ventilation almost negligible and make most conventional stack ventilation devices inefficient.

The study will concentrate on the effectiveness of the proposed HTV in improving indoor climatic conditions, thus increase occupants' thermal comfort level. However, possible effects of the device on other important aspects of indoor environmental quality (IEQ) like indoor air quality (IAQ), acoustic comfort, visual comfort and lighting quality as contained in the MS1525:2007 (DSM, 2007) or evaluation of purchased building energy consumed will not be comprehensively covered in this thesis.

1.7 Significance of Research

The study on the effectiveness of the stack ventilation strategies, especially HTV in hot-humid tropical buildings is significant for several reasons:

i) This study responds to Malaysian energy policy i.e. Fifth Fuel Policy (EPU, 2006) and MS1525:2007 (DSM, 2007) that emphasizes to increase the use of renewable energy (RE) and energy-efficiency (EE) in the built environment. With the wide use of the device, it is expected that the HTV could significantly increase the demand for photovoltaic (PV) panels, thus reduce the long-term cost of the technology through product development and competitive manufacturing.

ii) This study produces a new stack ventilation strategy (device) which has several advantages in terms of technical function and aesthetical concern. Therefore, the significance of this product is not only important in terms of ventilation functionality in deep plan building like in the terrace house, but also important for enriching the aesthetical value of the building itself. These advantages therefore could be the added values for the purpose of commercialization.

iii) This study provides general information about natural stack ventilation strategies and detail description on hybrid turbine ventilator (HTV) that is not only useful for architects, researchers and manufacturers but also can help to raise public awareness of environmental friendly cooling techniques. Consequently, this will help to create more sustainable and healthier living environment.

1.8 Organization of Thesis

This thesis comprises 5 chapters, which can be explained as follows:-

Chapter 1 introduces why and how the issues of improving indoor climatic conditions by using the Hybrid Turbine Ventilator (HTV) as a potent stack ventilation strategy is studied and presented in this thesis. It starts by addressing the problem statement, as well as hypothesis, research questions, objectives, research approach, scopes and significance of the research. Then, the outline of the thesis is briefly described in the final part of this chapter.

In **Chapter 2**, fundamental concepts of stack ventilation are described, including the aspects of ventilation functions, principles and some important factors affecting its performance. The real applications of various stack ventilation strategies in the architectural context are also discussed for both passive and active techniques. Based on the previous academic research, the effectiveness of these conventional and advanced stack ventilation strategies are compared with the intention to determine several possible strategies to be applied in hot-humid tropical building. Then, the chapter focuses on some experimental and analytical work that evaluated the effectiveness of turbine ventilator as a stack ventilation strategy. This comprehensive review is done to have a clear understanding of every important aspect of its application, optimum configuration, modifications, limitations and its possible improvements. Then, special focuses were given to the potential usage of the hybrid solar and wind-driven turbine ventilator (HTV) to be applied in the hot-humid tropical region, with special reference given to Malaysian climate conditions.

In **Chapter 3**, the research methodologies implemented in this research work are discussed. The reasons why and how the selected methodologies are used for this study are also described based on the previous literature. The detailed physical research investigations which encompass a pilot study and a series of field studies in the real building are also explained.

Next, the analyzed results of the empirical studies on HTV are discussed and presented in **Chapter 4**. For pilot study which was conducted in an enclosed space with no-wind condition, several different configurations of the HTV were tested and the performances of each configuration to induce vertical air movement relying solely on solar energy are compared. Some conclusions lead to the determination of the appropriate model of the device. Then, the chapter elaborates the outcome of the field study on the effectiveness of the HTV application in the real building and under real climate conditions. Monitoring results of indoor climatic conditions like air temperature, mean radiant temperature, relative humidity and air velocity in a Biological laboratory are shown. In addition, further in-depth analysis regarding the comparative study of the different HTV application strategies is also discussed. Some parameters, which should be taken into consideration when applying HTV in the building like the impact of openings and specific ventilation for the attic, on both ventilation performance and occupants' thermal comfort are examined and the final optimum application strategy is then figured out.

Finally, overall research findings are concluded in **Chapter 5**, which also summarizes the potential and limitations of the HTV in the real building in the hot-humid climate region. The chapter also recommends future research on this ventilation strategy, especially on areas beyond the scope of this study.

CHAPTER 2

PRINCIPLES AND STRATEGIES OF STACK VENTILATION

2.1 Introduction

This chapter presents a review of literature on the topics related to stack ventilation. It starts with the main concepts and functions of natural ventilation, as well as the principles and basic equations used to quantify the airflow induced by the natural stack ventilation. It is followed by a review on the applications of stack ventilation in the real building, covering the aspects of history, main passive techniques and advanced strategies that have been developed and tested. Finally, the chapter presents a comprehensive review on some experimental and analytical work that evaluated the effectiveness of turbine ventilator as a stack ventilation device in different climates, different research methods and variable configurations. Results of these different studies then are discussed based on its possibility to be applied in hot-humid climate of Malaysia.

2.2 Main Concept of Natural Ventilation

2.2.1 Ventilation Functions

From the architectural point of view, ventilation can be described as a process of supplying fresh air to an enclosed space and removing hot and stale air from the interior to the outdoor by natural or mechanical means. Basically, the main functions of the ventilation in building are for health, structural cooling and thermal comfort (Evans, 1980; Givoni, 1981; Allard, 1998; Awbi, 2003). The ventilation process and methods for all these 3 main distinct functions can be briefly described as in Table 2.1 and are in order of increasing air flow requirements:

Table 2.1: Summary of ventilation process and functions

Ventilation Function	Process	Objective
Health	The process by which fresh and clean air is intentionally provided to a space and stale air is removed.	To improve better indoor air quality (IAQ) by providing sufficient air change rate (ACH) and ventilation rate (m^3/s).
Structural Cooling	The process whereby the structure or thermal mass of the building is cooled during dawn or over night when the outdoor air is coolest.	To reduce the cooling load of the building during daytime by cooling the building structure during the night-time (often called the *'night ventilation'* strategy.
Thermal Comfort	The process by which airflow in building can improve occupants' thermal comfort by providing the cooling effect resulted from convection and evaporation of sweat from the skin.	To provide acceptable thermal comfort level (usually associated with the level of air velocity (m/s))

However in hot-humid climate region like Malaysia where the daily diurnal temperature is low, the main purposes of the ventilation are mainly for health and thermal comfort (Szokolay, 1998). As for health requirement, sufficient air change rate (ACH) is needed to ensure the exchange of hot, stale and unpleasant smell of internal air with fresh outdoor air. On the other hand, for the purpose of comfort ventilation, adequate air movement is compulsory to ensure occupant's thermal comfort in the building by means of physiological cooling.

Figure 2.1 summarized these two main ventilation functions as classified by Straaten (1967), who included the function of structural cooling as a part of the comfort ventilation.

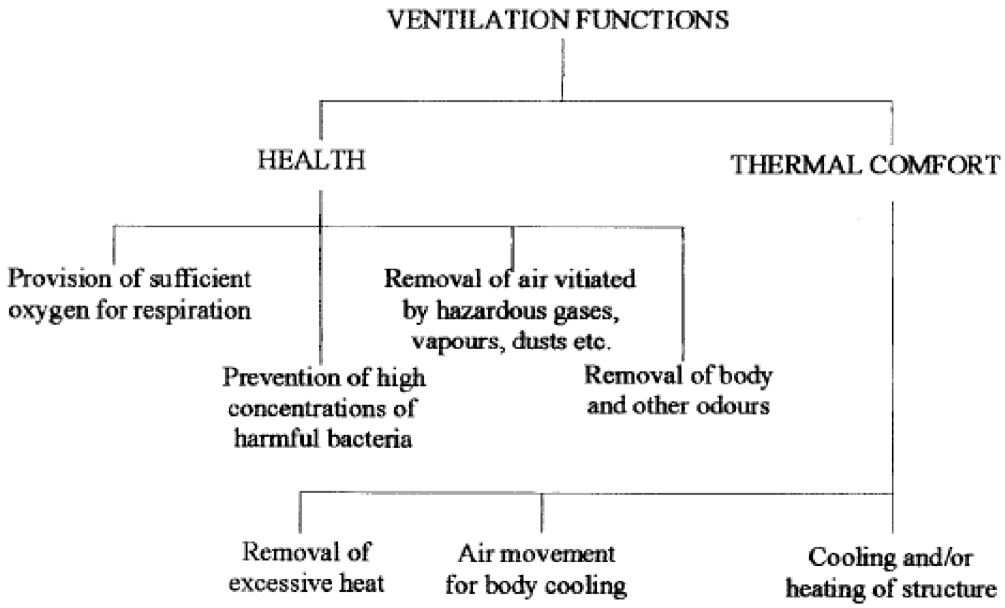


Figure 2.1: Schematic illustration of ventilation functions (Source: Straaten, 1967)

2.2.2 Comfort Ventilation and Air Movement

In hot and humid region, ensuring an indoor environment which meet occupants thermal comfort level is one of the most crucial factors to be considered when designing a building since the outdoor air temperature exceeds 30°C at most of the time and relative humidity is always more than 70%, even during the daytime.

In this context, thermal comfort can be defined as *'the condition of mind which expresses satisfaction with the thermal environment'* (ASHRAE, 1992; ISO 7730, 1994). It also can be explained as the state in which the body adapts itself to the environment by spending the least amount of energy (ASHRAE, 2001), or can be termed as thermal neutrality for a person (Fanger, 1972). The main factors affecting thermal comfort can be divided into two groups which are environmental factors and subjective factors (Fanger, 1972). Environmental factors are air temperature, humidity, air velocity and radiation, which the effect of all these microclimatic elements on human thermal comfort can be visualized in Figure 2.2.

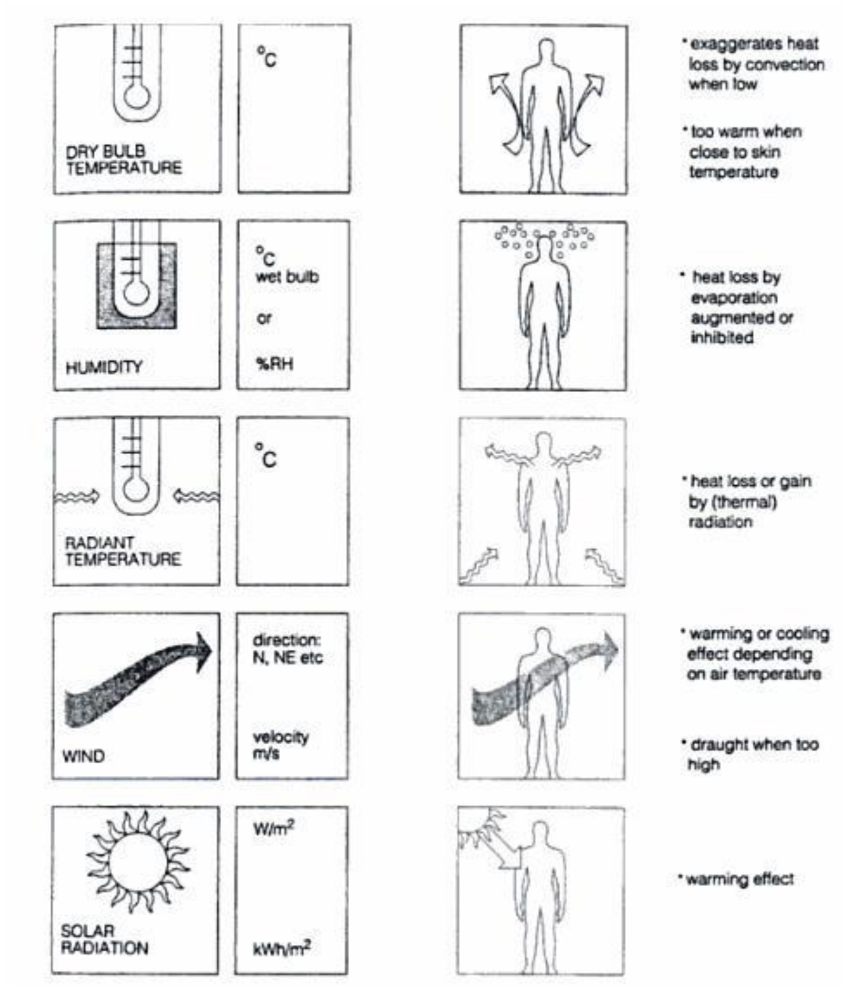


Figure 2.2: Environmental variables and their effects on thermal comfort (Source: Yannas, 1994)

On the other hand, the subjective factors are the activity level, metabolic rate, clothing, dieting habits, sex, age, health condition, skin color, human size and acclimatization. Regarding the acclimatization factor, many researches (Sharma and Ali, 1986; Givoni, 1992; Nicol, 2004) indicated that people who lived in hot-humid tropical climates over long periods generally feel thermally comfortable at higher temperatures than those prescribed by ASHRAE Standard 55 (1992) for summer comfort requirements of temperate climate. This is due to the physiological fact that warm condition sensed mentally in the brain reacts stronger than cold receptor exists in human skin (Mayer, 1993). In South-East Asian countries, examples of hot-humid tropical region, this significant effect of acclimatization factor on thermal comfort has been verified by several field studies, which can be briefly described as follows:

i) De Dear et al. (1991) investigated the thermal comfort level of 583 subjects from naturally ventilated (NV) apartments and 235 subjects from air-conditioned (AC) office buildings in Singapore. The study found that the neutral temperature for NV building and AC building were 28.5°C T_o and 24.2°C T_a, respectively.

ii) Busch (1992) compared the thermal comfort conditions of Thais who work in NV office buildings with those who work in AC office buildings. The study which involved more than 1100 subjects revealed that the neutral temperature for NV buildings was 27.4°C ET* while for the AC building was 24.7°C ET*.

iii) Zain-Ahmed et al. (1997) carried out a thermal comfort study of Malaysian tertiary students aged 21 years old in both NV and AC institutional buildings in Shah Alam, Selangor. The study discovered that the optimum comfort temperature was 26.3°C, with the comfort temperature range was 24.5°C to 28°C with 73%RH.

iv) Abdul Rahman and Kannan (1997) conducted a field survey to determine the comfort condition of Malaysian college students in NV classrooms in Kuala Lumpur. The results showed that the range of comfort temperature was 23.4°C to 31.5°C with the neutral temperature to be 27.4°C. The study also indicated that with the mean air movement of 0.27m/s and average humidity was 65%RH, a mean temperature of 29.8°C was experienced by the subjects.

v) Karyono (1996) carried out a thermal comfort study on 600 office workers from 7 office buildings in Jakarta (1996). The study which covered three types of building i.e. one naturally ventilated, one hybrid and five air-conditioned buildings have discovered that the subjects' comfort temperature was 26.4°C T_a, and 26.7 °C T_o.

vi) Ismail and Barber (2001) studied thermal comfort condition in 11 Malaysian air-conditioned offices in Penang, Malaysia and found that the comfort temperature for Malaysian office workers was 24.7°C with the comfort temperature range between 20.8°C to 28.6°C.

vii) Wong et al. (2002) conducted a field study on occupants' thermal comfort in NV apartment buildings in Singapore and found that the dwellers generally experienced relatively warmer neutral temperature of 28.9 T_o since they have more opportunity to adapt themselves with their environment compared with occupants in AC buildings.

Table 2.2 below summarized the results of these thermal comfort studies done in this region which clearly showed higher neutral temperatures than the value of 24.5°C recommended by ASHRAE (1992) and ISO 7730 (1994) and a wider range of comfort than the range of 23°C to 26°C recommended by MS 1525:2007 (DSM, 2007).

Table 2.2: Summary of previous field studies on indoor thermal comfort in South-East Asian region

Study	Year	Country	Comfort Range (°C)	Comfort Value (°C)	Type of Study
De Dear et. al	1991	Singapore	-	28.5 T_o (NV) 24.2 T_o (AC)	Field Study (NV & AC)
Busch	1992	Thailand	22.0–30.5	27.4 ET* (NV) 24.7 ET* (AC)	Field Study (NV & AC)
Zain-Ahmed et al.	1997	Malaysia	24.5–28.0	26.3	Field Study (NV & AC)
Abdul Rahman & Kannan	1997	Malaysia	23.4–31.5	27.4	Field Study (NV)
Karyono	2000	Indonesia (Jakarta)	-	26.4 T_a 26.7 T_o	Field Study (NV & AC)
Ismail & Barber	2001	Malaysia	20.3–28.9	24.6	Field Study (AC)
Wong et al.	2002	Singapore	-	28.9 T_o (NV)	Field Study (NV)
ASHRAE Std 55	1992		23.0-26.0 T_o	24.5 T_o	Climate Chamber
ISO 7730	1994		23.0-26.0 T_o	24.5 T_o	Climate Chamber
DSM	2007	Malaysia	23.0-26.0 with 55-70%RH	na	For AC non-residential building

T_o = Operative Temperature, ET*=Effective Temperature, NV=Naturally Ventilated, AC=Air Conditioned

From the Table 2.2, it can be observed that thermal comfort studies on the natural ventilated (NV) buildings showed a higher neutral temperature and higher thermal comfort zone than air-conditioned (AC) buildings. These values are in a good agreement with the value estimated with Adaptive Comfort (de Dear and Brager, 2002) approach which recommended a higher comfort temperature for natural ventilated buildings. According to this theory: *'If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort'* (Nicol and Humphreys, 2002). The major effect of this approach is it increases the wider range of the temperatures that occupants feel comfortable, since they have a greater degree of control over their thermal environment, including by opening a window or adjusting its blinds (Humphreys and Nicol, 1998). Therefore, it is obvious that designing a naturally ventilated building is not only advantageous in terms of energy conscious and environmental concerns, but also meets the preferable custom of the people who like to open their windows during daytime, especially in this hot and humid region (Kubota et al., 2009).

Moreover, many researchers found that these upper limits of indoor comfort temperature can be extended by about 4°C to 33.2°C with the aid of ample air movement of 1.0m/s (Abdul Rahman, 1999), since the sufficient air velocity can provide physiological cooling, especially in the very humid conditions (MacFarlene, 1958; Szokolay, 1998). This is due to the fact that when the humidity is high, only higher air velocities can overcome the problem of the high vapor pressure that prevent evaporation and restricting the cooling effect. In this principle, the increased air movement past through the human skin will increase the process of convection and evaporation of sweat from the skin, thus maintain the normal human body temperature to be at 37°C. From the literature, it was reviewed that the optimum air velocity recommended for this climate is between 1.0m/s to 1.5m/s (Salleh, 1989; Auliciems and Szokolay, 1997) while the value of 0.25m/s is found to be the minimum air velocity needed for giving significant cooling effect (Szokolay, 1998), as graphically shown in Figure 2.3.

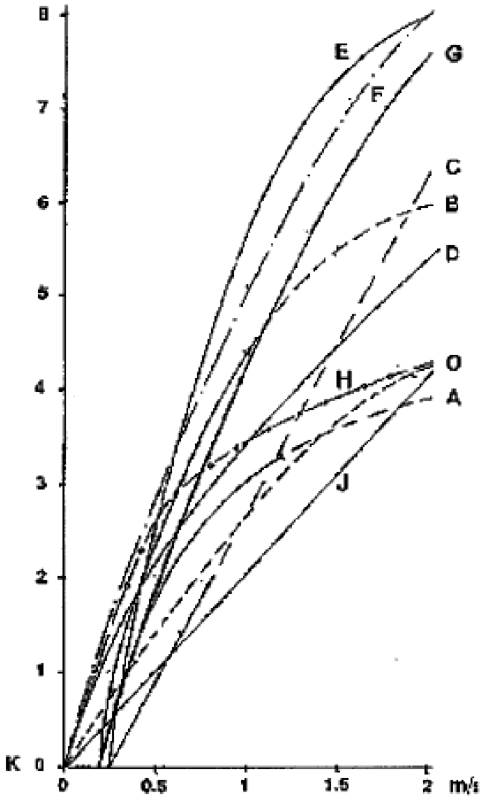
A The ASHRAE comfort standard 55-1992 allows the extension of the comfort zone by air movement up to 1.5 m/s, resulting in some 3.6 K cooling effect (if MRT=DBT, with 1.2 met activity and light clothing of 0.5 clo)

B Is the same as A, but for a situation where MRT=DBT = 10K; this would result in almost 4K apparent cooling at 0.75 m/s velocity.

Both Givoni and Mc Intyre suggested that 2 m/s is the limit of acceptable velocities, with cooling effects of 3.9 and almost 6 m/s respectively shown by the dashed extensions of both lines.

C The ASHRAE Handbook of Fundamentals allows the extension of the comfort zone by 1K for each 0.275 air velocity (above 0.25 m/s), up to 0.8 m/s, which would give 2K perceived cooling.

D This curve is derived from the effective temperature nomogram (basic scale, 25 °C and 50% RH)



E Is based on the revised bioclimatic chart of Arens et. al (1980), which in turn is based on the "2-node" model (at 12 g/kg AH, 1.3 met activity and 0.8 clo) giving up to 8K cooling equivalent)

F is a simple numerical approximation by Szokolay (10 years ago) for students' use: $dT = 6*v-v^2$

G is a revised version of this, allowing for the fact that there is no cooling effect below 0.25 m/s: $dT = 6*(v-0.25) - (v-0.25)^2$.

H Humpreys and Nicole (1995) suggested expression $dT = [\,(7-50) / (4 + 10\ v^{0.5}]$ (if GT = DBT)

J. Rohles et. al. (1974) showed that 0.48 m/s velocity compensates for every 1K overheating (in ET)

O. based on Olgyay's bioclimatic chart (extension of comfort limits at 40% RH).

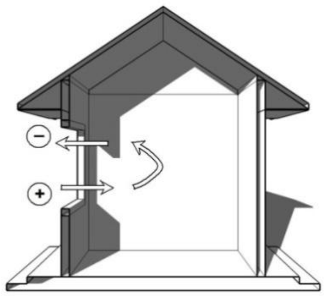
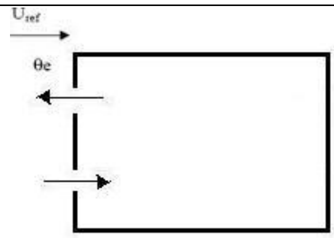
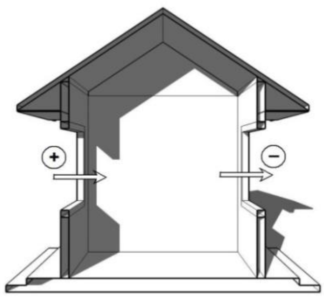
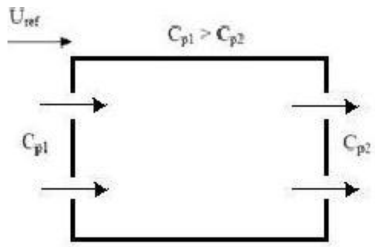
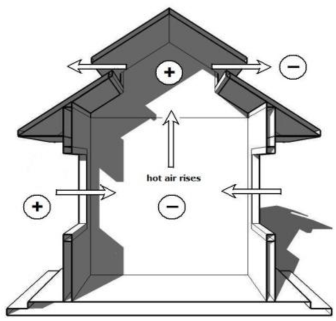
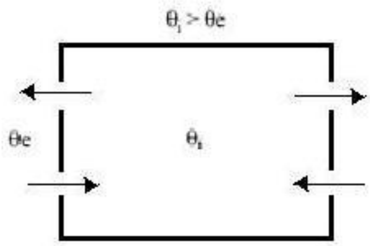
Figure 2.3: Comparative analysis of cooling effect through air movement (Source: Szokolay, 1998)

However, although the importance of ample air movement is obvious, the question now is how to increase air movement in the occupied zone without resorting to mechanical ventilation which absolutely consumes more energy and adversely affect the environment. To answer this question, the strategy of using natural ventilation technique which maximizes natural free energy sources seems to be a good option to explore.

2.2.3 Principles of Natural Ventilation

Since the oil crisis during the 1970's, there was a significantly rising interest among architects and engineers to reinventing natural ventilation as a sustainable strategy to ventilate the building and providing thermal comfort without burning the fossil fuels. In this context, natural ventilation can be defined as *'the movement of air through openings in a building fabric due to wind or to static pressures created by the indoor-outdoor temperature differences (stack effect), or to a combination of these acting together'* (BSI, 1991). From this definition, it is obvious that **wind effect** and/or **stack effect** are the main driving force~~s~~ that will determine the ventilation rate and configure the three major forms of natural ventilation, which can be classified as in Table 2.3:

Table 2.3: Major forms of natural ventilation

Natural Ventilation Strategy	**Typical Sectional Diagram**	**Driving Force** *(cross section)*
Single-sided ventilation		 Wind effect, stack effect (and/or turbulence)
Cross ventilation		 Wind effect
Stack ventilation		 Stack effect

Single sided ventilation occurs when air enters (inlet) and exits (outlet) the indoor space through the same opening. Theoretically, the movement of air by this strategy is driven by small difference in building envelope wind pressure, room scale buoyancy effect and/or turbulence. Due to these factors, this strategy is thought to be only effective for a depth not more than 2.5 times the height of the space (BRE, 1994; Awbi, 2003), thus making it the less effective strategy compared to other types of natural ventilation.

On the other hand, **cross ventilation** which is the most common natural ventilation strategy occurs when air enters the indoor spaces from one side (windward) and exit through the opposite side (leeward). As a rough building design guideline, this strategy is thought to be effective up to 5 times the height of the space (BRE, 1994) and not more than 14m (Awbi, 2003). In theory, the effectiveness of this strategy is a function of the size of the inlets and outlets, outdoor air temperature and outdoor-indoor airflow resistance. Thus, it is clear that the successful cross ventilation requires a building form that provides an adequate inlet and outlet areas with minimal internal obstructions (between inlet and outlet) and maximizes exposure to the prevailing wind direction. These requirements can be major constraints for a deep plan building and building located in the dense built environment (Abdul Rahman, 1995).

Therefore, **stack ventilation** which is thermal buoyancy-based ventilation could be a possible alternative for a more effective ventilation strategy in those particular situations. In this context, stack ventilation can be defined as ‘the upward movement of air through openings in a building fabric due to thermal buoyancy (gravity) and/or negative pressure generated by the wind over the roof’. This principle makes this ventilation strategy less dependent on outdoor wind condition and makes it more significant to improve natural ventilation in a building with limited side openings, like in a terrace house. Due to these advantages, this form or type of natural ventilation was selected to be the main focus of this thesis. In doing so, all of its mechanism, performance factors and architectural features related to this strategy will be further discussed.

2.3 Stack Ventilation Strategies

2.3.1 Mechanism and Factors Affecting Performance

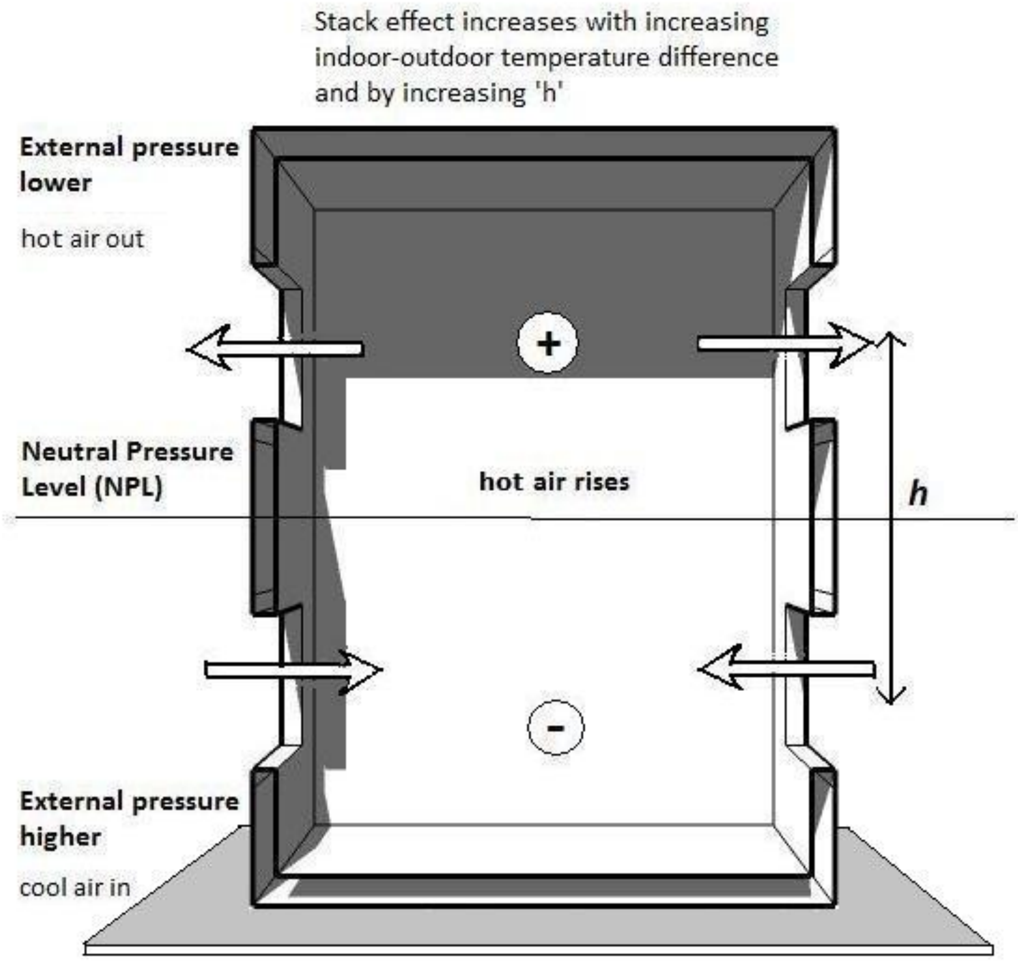


Figure 2.4: Schematic illustration of stack effect principle

In theory, the main mechanism that drives the natural stack ventilation is due to the 'stack effect' principle where the air rises due to thermal force. This principle can be demonstrated by the Figure 2.4 above which shows that warm and lighter air rises vertically and exits through the upper openings above the neutral pressure level (NPL).

As a result, this air is being replaced by cooler and heavier air entering through the lower openings. Specifically, the airflow induced by this mechanism is directly proportional to the outside-inside temperature differential, the effective area of the openings and inlet-outlet height differential (BSI, 1991), as given by Equation 2.1.

$$Q = KA\sqrt{h\,(t_{out} - t_i)} \qquad (2.1)$$

Where,

Q = airflow (m/s)

K = discharge coefficient for the opening (assume K=0.65 for multiple inlet openings)

A = free area of inlets (m²)

h = height from mid-point of the inlets to mid-point of the outlets (m)

t_{out} = average temperature of outdoor air (ºC)

t_i = average temperature of indoor air (ºC)

Due to this principle, it is obvious that the effectiveness of the stack ventilation strategy is mainly dependent on several parameters like the temperature differential between the interior and exterior spaces, the size of inlets and outlets and the height of the space, as described below:-

a) The temperature difference between the exterior and interior spaces

As a simple rule of thumb, it is agreed that natural stack ventilation will only work when outdoor air temperature is cooler than the indoor temperature. According to Brown and DeKay (2001), in order to generate vertical air movement due to the pressure differences, the difference between indoor and outdoor needs to be at least 1.7°C, while a greater temperature difference can provide more effective air movement and