Experimental Evaluation of Zero Energy PG Office Under Natural and Forced Ventilation

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Table of Contents

LIST OF FIGURES

List of Tables

ABSTRACT

With the rapid rise of energy consumption in the world, lowering the energy needs of our houses and buildings can have a significant effect on our future. Up to 66% of our household energy consumption can be reduced by using passive design techniques like natural ventilation discussed in this project. The effectiveness of the natural and forced ventilation systems of the present zero-energy house is to be studied experimentally and discussed in this project. The main aim of such systems is to achieve thermal comfort without using any energy from the grid. In this project, thermal comfort is measured using Fanger's PMV method in accordance with ASHRAE standards. The method depends on air temperature, radiant air temperature, relative humidity, activity level and clothing levels. Data collection is carried out for 4 days under each system and the resulting thermal comfort then calculated. Using the forced ventilation system drops the maximum air temperature by 6^{o}C and improves the thermal comfort by 46%. Although the achieved thermal comfort is not within ASHRAE-55 standards, the results show a considerable improvement in thermal comfort without the use of the grid's energy. Further study into the construction of the office is needed to achieve thermal comfort levels within the accepted levels by ASHRAE-55 standards.

CHAPTER 1 - INTRODUCTION

1.1 Background

The world's energy consumption has been rising steadily in the past forty years. An expected outcome of the ever increasing continual urbanization of third world countries among other factors. While the usage of renewable sources of energy is rising, most of our economies mainly depend on fossil fuels to run. Consequently, we have to deal with the myriad of problems that arise directly from the heavy dependence on fossil fuels. Out of those problems air pollution in the industrialized cities and global climate change impact our lives everyday.

Furthermore, the global energy consumption is expected to rise by 56% in the period from 2010 to 2040 [1]. While the major energy consumption happens in the industrial sector, transportation and household consumptions hold the second and third place respectively as shown by research done by the European Environment Agency. The residential sector accounts for approximately 18% of the global energy usage with an expected annual increase rate of 1.5% [2]. Hence lowering the energy needs of the houses and buildings is vital to decrease the world's energy consumption and increase the dependence on renewable energy sources. It is found that up to 66% energy savings could be achieved in the household annual energy consumption by using net zero-energy building (nZEB) methods to optimize air flow through the usage of passive design techniques[5].

1.2 Problem Statement

In this project the current implementation of a zero energy house is using a natural ventilation system to to achieve temperature comfort needed within the building. There are two types of natural ventilation systems; wind-driven ventilation systems and buoyancy-driven ventilation system. The house studied in this project is using a buoyancy-driven natural ventilation system. Such system depends on the chimney effect where hot air with lower density rises to the top while colder air with higher density drops down. With properly placed openings in the ground floor of the building and a chimney at the top, air circulation occurs.

The problem at hand is to confirm whether the installed ventilation system is sufficient to achieve thermal comfort within the building.

1.3 Objectives

- To carry out monitoring and measurement on zero-energy house prototype.
- To evaluate and compare different ventilation procedure's effectiveness at achieving thermal comfort within the office.

1.4 Scope of study

- The ventilation procedure either natural or forced.
- Monitoring the effect of the ventilation system on the level of thermal comfort within the office.
- Monitoring ΔT and ΔRH between indoors and outdoors.

CHAPTER 2 – LITRETATURE REVIEW AND THEORY

2.1 Classification of low/zero energy criterion

The technical definition and classifications of nZEB is currently actively discussed in the literature. Many definitions have been put forward by researchers to define what exactly is a nZEB and how to measure their performance. A proper technical consistent classification is required for countries and unions to align their ambitions and plans and set KPIs. This is what pushed the Federation of European Heating, Ventilation and Air Conditioning Association (REHVA) to decide on one technical definition to be used all across Europe. The research was led by Kurnitski in 2013 to define a nZEB as "A building that has very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"[3]. It's inherent within this definition that energy exchange between the building and energy grids will take place; deficiency in energy needed to be covered by imported energy from the grid and extra energy to be exported back to the grid. Another aspect needed form the definition is a measuring metric to calculate how close any building is to the mentioned definition. A primary energy indicator (EP_p) expresses the balance between the imported and exported energies per unit meter in the building as follows.

$$EP_P = \frac{E_P}{A_{net}} = \frac{\sum_i \left(E_{del,i} f_{del,i}\right) - \sum_i \left(E_{\exp,i} f_{\exp,i}\right)}{A_{net}}$$

where:

$E_{del,i}$: Energy delivered per energy carrier e.g. natural gas heating, electricity, etc…

$f_{del,i}$: Energy factor applied to delivered energy.

$E_{exp,i}$: Energy exported per energy carrier usually limited to electricity.

$f_{del,i}$: Energy factor applied to exported energy.

A_{net} : Usable are of the building.

It is important to note that any building receives energy from different energy grids. Natural gas grid supplies energy used for cooking or heating, while electricity grid supplies energy for different appliances. Because the building is connected to different grids, the imported energies can not be treated equally. The energy factor, *f*, is multiplied by the energy quantity to get the relevant energy exported or imported through the specific carrier. According to REHVA, a net zero energy building has EP_p of 0 kWh/(m^2 a). That's to say the building doesn't burden the connected grid at all. On the other hand, a nearly zero energy building has $EP_p > 0$ kWh/(m^2 a) yet it can not exceed a national level to be determined by each state in the EU.

The definition adopted by the REHVA is follows an "avoided burden" logic. In this perspective the building is defined as nZEB because it avoids the need for primary energy that would otherwise have been needed to keep the building running. There are many methods by which the energy balance could be calculated within the avoided burden approach. Bourrelle et al. presents four methods for such calculations namely, a) Site balance b) Source energy balance c) Source energy balance with building embodied energy c) Source energy balance with RES embodied energy [4].

A source energy balance is done at the primary energy level and termed ZEB source. This balance method is highly recognised by the international community. Expressed mathematically, the energy source balance is:

$$\Delta E_{source} = \Sigma\left(E_{exp,i} f^{p}_{exp,i}\right) - \Sigma\left(E_{del,i} f^{p}_{del,i}\right) \quad \text{where: } f^{p}_{exp,i} = f^{p}_{imp,i}$$

That is to say that each energy carrier is calculated according to its own weight and the energy exported is subtracted from the energy imported for each carrier. A source ZEB is a building that doesn't burden the energy grids at all during a specific time frame. This approach does not take into account the energy embodied, used, to construct the building or the RES within the building. Figure1 visualizes how the source energy balance is measured.

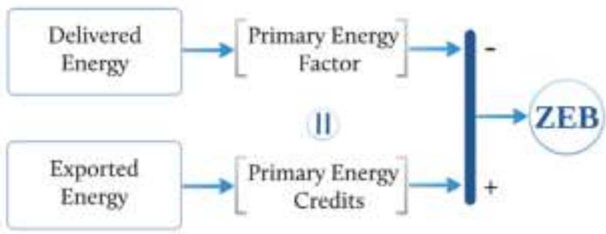

Figure 1 ZEB source energy balance.

A nZEB must be optimized to consume very little energy so that a big part of the energy needed can be generated by the renewable sources installed within. Minimizing the energy usage of the building can be achieved using passive design techniques or energy efficient technologies or a hybrid of both. Passive design techniques mainly focus on using the building design to reduce the energy consumption. Passive design techniques include using the building's envelop, orientation and geometric and ratios to reduce the energy needed to power the building [6]. A major objective of passive design techniques is to use isolation to keep the building temperature stable and to use natural ventilation to provide the thermal comfort needed. On the other hand, using energy efficient technologies lowers the total energy usage by using higher efficiency HVAC systems, appliances and lighting. A hybrid solution aims at using both techniques to lower the energy needs of the building.

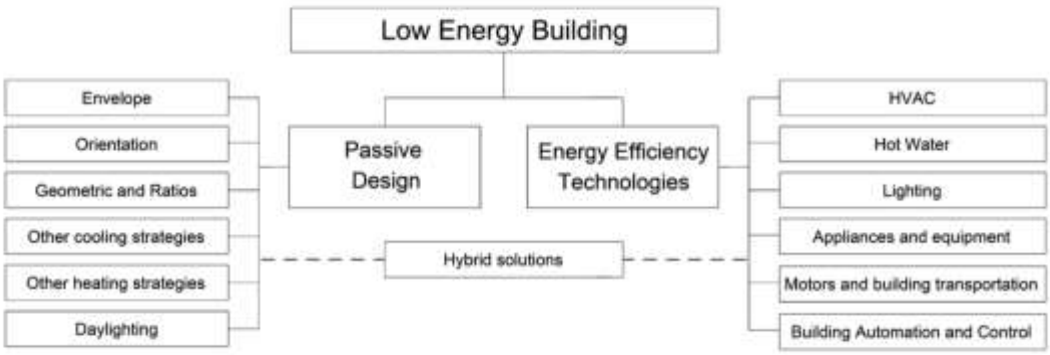

Figure 2 Low energy building techniques. [6]

In the competition zero-energy houses Solar Decathlon Europe, or SDE for short, all the participating houses use hybrid solutions to achieve low energy usage. However, a study on the participating houses shows that the passive design techniques are the basis of the high efficiency performance of most of the houses [7]. Prominent passive design techniques include solar shading, solar direct gain, air tightness, high performance glazing, multifunction façade and natural ventilation.

2.2 Process Identification

A buoyancy-driven natural ventilation system uses the difference in air density resulting from different air temperature to generate airflow. When the building's indoor temperature is higher than the outdoor temperature, the cold, high density, air from outside enters the building at lower floors. At the same time, the hot, low density, air at lower floors, inside the building rises up to higher floors where it exits. Thus the lower floor windows allow air to come in, which then exits from the upper floor creating an airflow within the building; such phenomenon is called the stack effect. The different in pressure between the two sides of the window, resulting from the difference in temperature and thus difference in density, controls whether air enters the building or flow out of it.

The neutral pressure plane is where the pressure difference between outdoor and indoor equals zero. The height of the neutral pressure plane depends on the relative size of lower and upper openings. The natural pressure plane is always closer to the larger opening. In a multi floor building, the top opening is made to be the larger than all the other windows in the building. This design assures that the neutral pressure plane is higher than the top floor, thus there is no recirculation of air within the building. Increasing the window to wall ratio to 0.24 can increase thermal condition indoor [8]. Furthermore, a recommended total area of inlet and outlet apertures is about 40%[9]. The following figure, shows how the stack effect is implemented in a building with an atrium [10].

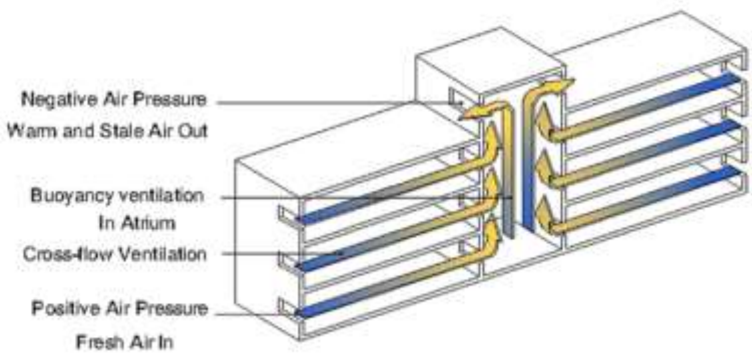

Figure 3 Using the stack effect in natural ventilation with an atrium.[10]

Fig. 3 above shows the airflow of cold air that turns into hot air before exiting the building at the top chimney through the atrium. The design of the building and the implementation of the atrium can be adapted differently to suit the different conditions for different buildings. Designing the building to enhance the natural ventilation and airflow is the best way to reduce the energy usage. Below the different designs of buildings is shown where the atrium is used to achieve a different outcome.

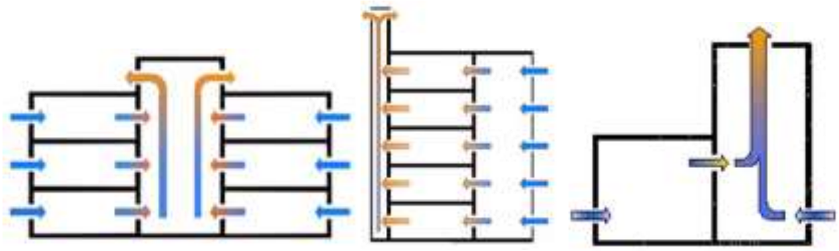

Figure 4 Different implementations of the atrium and stack effect.[10]

In one implementation the atrium receives air from the surroundings and exhaust it. Or atrium to receive air directly and then conduct it to the surrounding rooms. The atrium could also be used to indirectly exhaust the air to outside the building. In all the cases the atrium can significantly improve the natural ventilation of the building. Another passive design strategy is to enable cross ventilation through the building. In cross ventilation, the building is designed to have big apertures in sides across the building usually on the north and south sides. Simulations predict natural ventilation could reduce air-conditioning energy consumption by about 24% [11].

2.3 Thermal comfort within the office

The ultimate objective of using the solar chimney is to achieve thermal comfort within the building while reducing the energy consumption. Although thermal comfort is a very subjective state, the acceptable levels of thermal comfort are specified in ASHRAE building standards. The standard way of measuring the thermal comfort within a building is by conducting a survey whether the condition within the building is comfortable or not. After extensive research and hundreds of conducted surveys, ASHRAE has released a method to calculate the Predicted Mean Vote (PMV). PMV is a standard measurement of thermal comfort within any building and ASHRAE releases standard values of PMV measurement that offices and public buildings must adhere to. Furthermore, the PMV can be calculated based on the temperature of air within the building, the mean radiant temperature the occupants feel, air speed, relative humidity level, metabolic rate and clothing level.

While the PMV model predicts thermal sensation well in buildings with HVAC systems, field studies in warm climates in buildings without air-conditioning have shown that it predicts a warmer thermal sensation than the occupants actually feel.[12] It's for this reason that Fanger, et all. has introduced a way to adjust the PMV values from the standard ASHRAE calculation to be more closer to the measured PMV in warm climates countries where the buildings are without air-conditioning. [13]

In this project the adjusted PMV model developed by Fanger will be adapted. A recommended expectancy factor of 0.7 will be used. The author has specified using an expectancy factor of 0.7 in Singapore and getting a very accurate expectation of PMV. Fanger's adjusted PMV model predicts the thermal comfort response of the occupants in hot weather accurately.

CHAPTER 3 - METHODOLGY

3.1 Method of solution

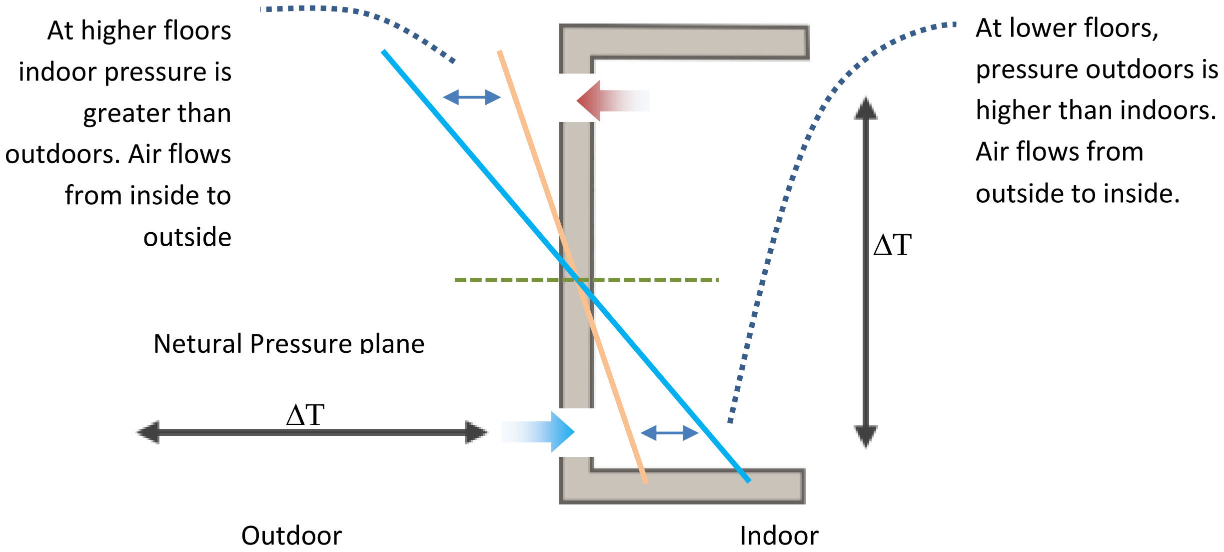

Figure 5 Stack effect in buildings

Fig. 5 shows stack effect works. The outdoor air, blue arrow, has higher pressure at lower floors than the indoor air. Hence the cold outdoor air flows into the building. At top floors, the process is reversed where indoor air, red arrow, has higher pressure than colder outdoor air. The hotter indoor air flows outside the building. The net effect is continuous airflow between indoors and outdoors. This circulation is termed natural ventilation and is responsible for renewing the air inside the building and cooling the building.

This project is concerned with the zero-energy PG office prototype. The house prototype consists of the PG office room, a hallway where cross wind flows and a third room that is of no interest to the project at hand. Fig. 6 shows how natural ventilation happens in the office prototype.

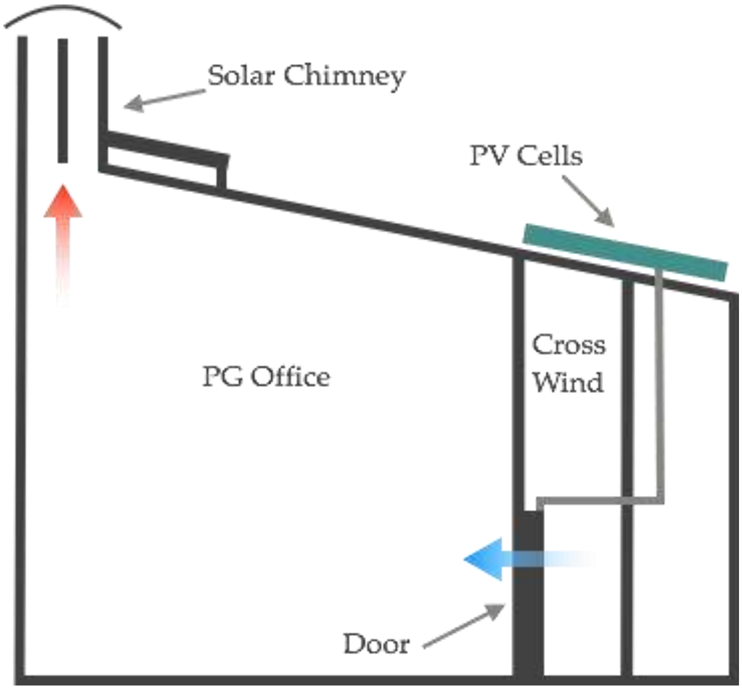

Figure 6 Zero-energy PG office prototype schematic

The cold air enters the office from the open door at the ground floor. The hallway where the cross wind act is the main source of fresh air in this case. The solar chimney at the top helps to heat up the air at the top levels thus acting as an area of low pressure to suck up the stagnant air to outside the building.

The methodology in this project is to experimentally measure the effectiveness of the natural ventilation system. Where the effectiveness is indicated by an increased thermal comfort. The experiments will be designed to track the change in the temperature within the building during the day and during the night. Another factor to be experimentally evaluated is the change in humidity throughout the day. Lastly the airflow rate will be measured. With measurement results at hand, the effectiveness of the system at increasing the thermal comfort could be evaluated. A higher airflow rate between the inside and outside of the building is preferred. The temperature and humidity level in the building should always lie within the comfort levels throughout the day. If the system is not effective enough, a re-evaluation of the design of the natural ventilation system is needed. Such effort could be carried out separately in a different project. Fig. 7 shows the measurement tools installation placement at the site.

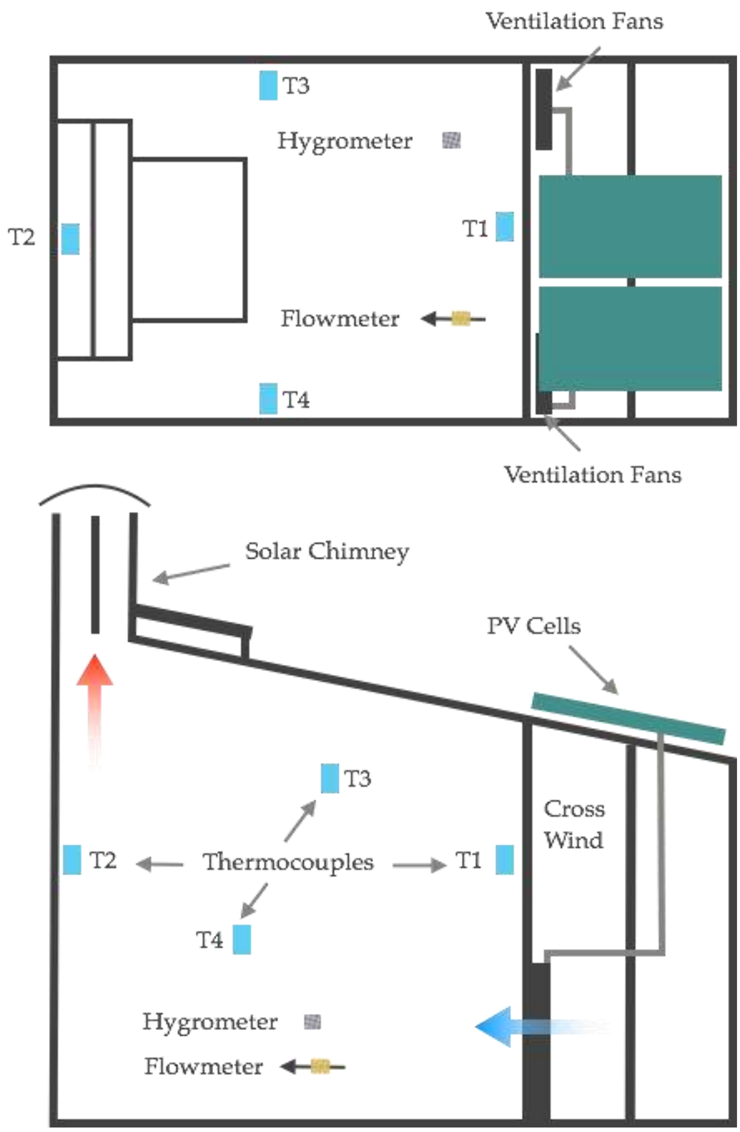

Figure 7 Testing the effectiveness of natural and forced ventilation systems

The placement of the measuring tools is critical in this case since it will influence the quality of the data that we can gather. In order to calculate the thermal comfort, in accordance with Fanger's equation, many variables are needed. Some of these values are assumed according to standards like metabolic rate of the occupants and clothing level. However, the two most critical variables are air temperature inside the office, radiant temperature sensed by the occupant and air flow within the office. Thermocouples T1 and T2 are used to measure the air temperature inside the office. The average of T1 and T2 will be used as the average air temperature within the office. To measure the average radiant temperature of inside the office, the average of T3 and T4 is calculated. Since the width of the office is shorter than the length, the radiant heat from the side panels and walls is the main source of radiant heat within the office.

In Fig. 7 above, the forced ventilation system is also shown. The forced ventilation system is comprised of four fans that are powered by PV cells to be installed later at the top of the building. The fans are used to strengthen the air flow inside to the office. The location will be the same as indicated in the Fig. 7. It’s expected that the forced ventilation system will increase the drop in the temperature difference between outdoors and indoors. The forced flow of air caused by the fans will aid the ventilation system and stack effect. The usage of the forced ventilation system will only happen after measuring the effectiveness of the ventilation under the natural ventilation only. The experiment is to be carried out once without any active ventilation systems. The resulting data will be taken as a benchmark to measure the progress against. Secondly, data will be collected with active natural ventilation system exclusively. Lastly, the experiment is to carried out with both natural and forced ventilation system working in tandem.

In order to determine the effect of the ventilation systems, a benchmark should be established. For this purpose data will be collected with the building locked and sealed. In this case we measure the thermal comfort inside the building while restricting any air motion and any ventilation. The resulting data will serve as a benchmark to measure our system against. Afterwards, the data collection will be repeated with natural ventilation allowed; doors open. The expected increase in thermal comfort achieved then is the result of the natural ventilation system. For the last set of data, the forced ventilation system will be used concurrently with the natural ventilation system to determine the collective effect on the thermal comfort when both systems are operational.

3.3 Flow chart of research activities

To conduct the experiment multiple tools are needed. To track the temperature change throughout the day and night, a thermocouple and data logger are needed to produce the graph of the temperature inside and outside the building. To plot the change in the humidity level inside the building a hygrometer is needed which will also be connected to the data logger. At the same time a solarimeter will be used to evaluate the thermal radiation falling on the building during the day. Lastly, a vane anemometer will be used to track the change of the airflow rate and airflow speed through the building.

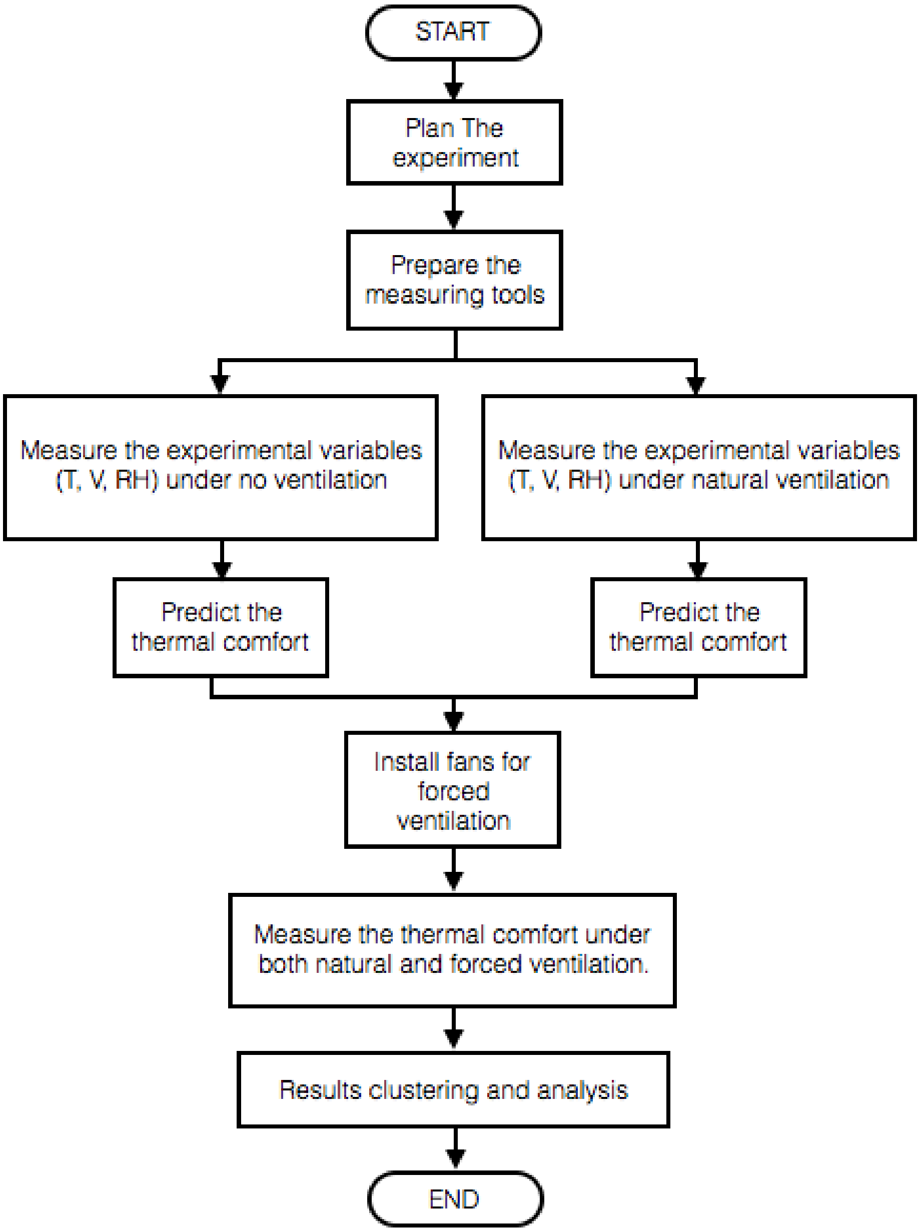

Figure 8 Flowchart of the research activities

3.3 Gantt chart and milestones

Table 1 Project's Gantt Chart

Task / Week	FYP I														FYP II													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Background Study and Literature Review	■	■	■	■	■	■																						
Tools Purchase and Arrangement							■																					
Familiarisation with measuring instrument								■																				
Monitor the system with natural ventilation									■																			
Results Analysis										■ ●																		
Interim Report - Draft 1											■		Final Exams															
Interim Report Final												■ ●																
Install the fans of the forced ventilation system															■	■	■	■										
Monitor the house under both systems																			■ ●									
Final Results Analysis																				■	■	■	■					
Final Report - Draft 1																								■	■			
Final Report																										■ ●		

Planned ■
Milestone ●

CHAPTER 4 – RESULTS AND DISCUSSION

Experiment 1 – No active ventilation system:

In experiment one, the door was closed to deactivate any possible ventilation. The data was collected over the period of 4 days. Thus follows the first set of data collected with a closed door and no ventilation system active for one full day.

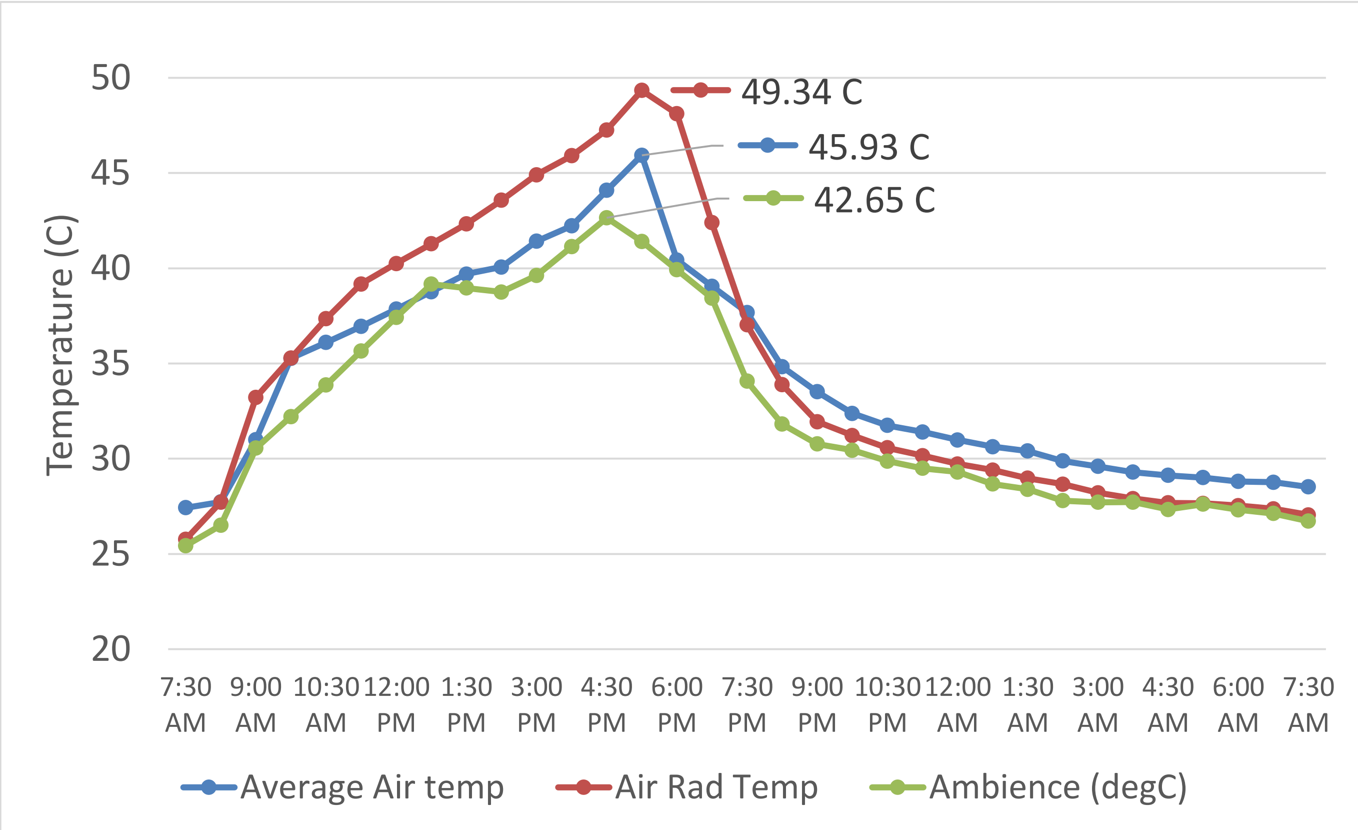

Figure 9 Temperature measurement through 24 hours - Experiment 1

From the graph above, maximum data points have been highlighted. By using the adjusted Fanger's equation, thermal comfort PMV values can be calculated at the maximum temperature and minimum thermal comfort throughout the day.

Table 2 Maximum and minimum thermal comfort level measured during experiment 1

Time	Average Air Temperature (°C)	Average Radiant Temperature (°C)	Adjusted Thermal Comfort PMV
5:15 PM	45.93	49.34	5.65(Too Hot)
7:30 AM	28.47	27.27	0.61(Slightly Warm)

Experiment 2 – Active natural ventilation system:

In this experiment door was open to allow the natural ventilation system to refresh the air within the office. The data was taken for 4 days consecutively as well. Follows up in figure 10 a sample of the data for one full day.

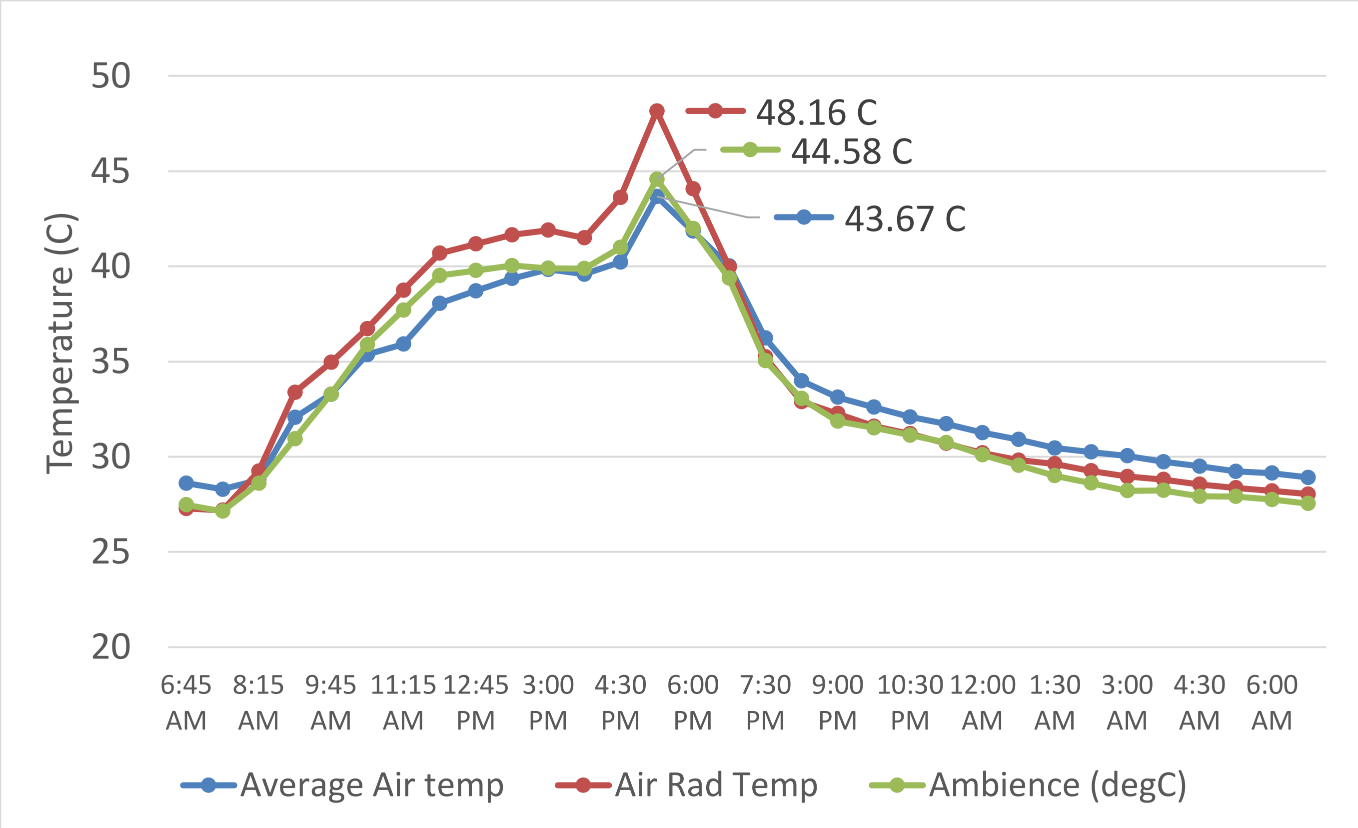

Figure 10 Temperature measurement through 24 hours - Experiment 2

Figure 10 shows the maximum temperature data points achieved with this setup. At the maximum point, the radiant temperature reaches 48.16 C while the air temp. tops at 43.67 C. The following table shows the predicted thermal comfort based on maximum and minimum measurement for this set of data.

Table 3 Maximum and minimum thermal comfort level measured during experiment 2

Time	Average Air Temperature (°C)	Average Radiant Temperature (°C)	Adjusted Thermal Comfort PMV
6:00 PM	41.84	44.06	5.80(Too Hot)
8:15 PM	33.99	32.89	1.9(Slightly Warm)

Experiment 3 – Active natural and forced ventilation systems:

In this last experiment the ventilation fans were turned on. This was the natural ventilation system and the forced ventilation system were both working concurrently. The ventilation fans allow for more airflow within the office and hence lower temperatures are expected.

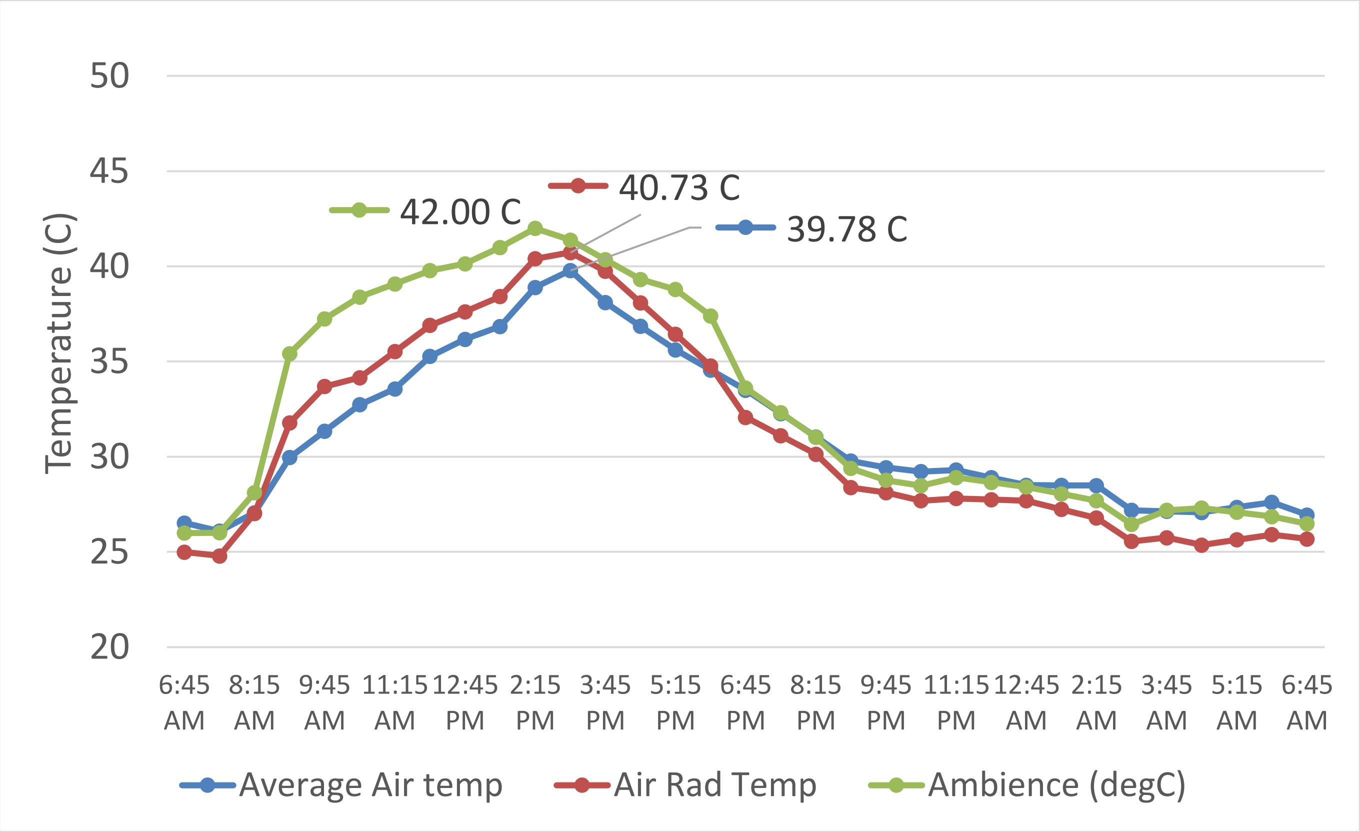

Figure 11 Temperature measurement through 24 hours - Experiment 3

Figure 11 shows the resulting data from the last experiment where the maximum ventilation occurred. The drop in the maximum temperature is noticeable clearly. The thermal comfort throughout the day was also improved. Following are the data for the thermal comfort.

Table 4 Maximum and minimum thermal comfort level measured during experiment 3

Time	Average Air Temperature (°C)	Average Radiant Temperature (°C)	Adjusted Thermal Comfort PMV
2:15 PM	38.89	40.39	3.47(Too Hot)
8:15 PM	31.04	30.13	1.33 (Slightly Warm)

The results previously presented show the progression of the improvement in thermal comfort from one experiment to another. Experiment 1 shows how the space inside the office can heats up to very high temperature without any ventilation system at work. This is the normal state at which the office would be at without any of the ZEB techniques applied to aid in the ventilation of the space. With a maximum radiant temperature of 49^{o}C, the space had a very poor rating of thermal comfort of 5.56 which is considered too hot according to ASHRAE-55 standards. Since the ASHRAE-55 scale extends from -3 to +3, the resulting thermal comfort in this case is off the chart. The space is simply very uncomfortable to stay in at such state.

In experiment 2 the doors were open thus the air was allowed to flow in the house and exit through the solar chimney at the top of the house. This natural ventilation system aids in getting the air to circulate through the office. This ventilation system is purely passive and costs nothing but the initial cost of setup for the solar chimney. Natural ventilation systems are valuable since they can improve thermal comfort, although marginally, without using any mechanical systems. The natural ventilation system dropped the temperature by 2^{o}C and improved the the thermal comfort level by 9%. Although the thermal comfort level is still far away from the recommended range by ASHRAE, the 9% increase at no additional operating cost and with only a solar chimney installed on top of the office is effective.

In experiment 3 the ventilation fans were turned on for 24 hours a day. The ventilation fans run on 12VDC coming from the battery which is connected to the solar panels on top of the office. The four ventilation fans aided the air flow greatly throughout the office and helped improve thermal comfort significantly. Although the ventilation fans don't consume any grid energy, the energy embedded in fabricating the PV panels are considerable. The installation of the PV panels and the ventilation fans might be costly, yet the resulting data are encouraging. With the forced ventilation working side by side with natural ventilation the maximum temperature dropped by 6^{o}C and the thermal comfort improved by 46%. Such improvement in thermal comfort is highly significant. At best the thermal comfort was very close to accepted levels within the ASHRAE-55 standards while at worst, the PMV was slightly overshooting the scale at 3.47.

CHAPTER 5 – CONCLUSION AND RECOMMENDATIONS

This project is concerned with decreasing the energy usage in the residential sector in response to the spike in energy demand and the continual decrease in fossil fuel resources. ZEB building techniques are spreading widely in the architecture space to allow for better buildings that consumes less energy and help provide the usually comfort levels. This project is an experiment to measure the effectiveness of the ZEB techniques implemented in the PG office prototype. The office is equipped with a solar chimney that aids in ventilation along with four ventilation fans powered by the installed PV panels on top. The ultimate aim of any ventilation system is to provide thermal comfort within the building. Hence, the effect of the installed systems on the thermal comfort levels within the building is the focus point of this project. With three experiment conducted under three different settings, the results show a promising improvement in thermal comfort levels.

While using the natural ventilation system exclusively decreased the maximum temperature by 2°C, using the forced ventilation system decreased the maximum temperature by 6°C and consequently improved the thermal comfort by 46%. Nevertheless, the resulting thermal comfort levels are not within the accepted range recommended by ASHRAE-55 standards. This calls for more research to be done on this topic and this office prototype to inspect what can be improved with the office envelope to aid in ventilation. Another suggestion is to install a bigger solar chimney and to try in simulation software different orientation for the building.

As for future recommendations, to improve the thermal comfort within the building two alternative are to be considered. Firstly, installing a green wall made of trees on the south facing side of the office will greatly reduce the radiant air temperature inside the office by blocking the sun rays. This green wall is a very efficient free natural way of decreasing the heat gain by the office's atmosphere. Lowering the radiant air temperature using the green will have a big impact on the thermal comfort within the office.

Another alternative includes changing the design of the office to reduce the solar heat gains. This can be achieved by using solar insulator films on the glass that is located at the walls of the office. The glass parts of the south wall allow so much solar radiation to enter the office and cause the air temperature and air radiant temperature to rise significantly. Using the solar films will reduce the solar heat gain and improve thermal comfort.

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