A PASSIVE SOLAR HEATING EXPERIMENT UTILIZING PLASTIC WATER BOTTLES AS THERMAL MASS

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Abstract

It is a critical concern for architectural educators to increase the awareness of their students about the importance of sustainability in the design of the built environment. This trend is a significant tool that can help the humankind to face many environmental challenges. The passive solar heating design is one of those powerful tools; it relies on specific materials to work as thermal mass or heat sink. Thermal mass can store the solar energy during the day and radiates it to indoor spaces at night in cold seasons, while the reverse process occurs in hot seasons. Due to its high heat storage performance, water is one of the most effective materials for this purpose. This paper aims to introduce a simple and easy process to prepare an experiment that can enhance the understanding and awareness of architectural students to the potential capabilities of water as a thermal mass. The authors asked the students to assign four spaces to carry on the experiment - two identical closed spaces, one semi-closed space, and one open space -; then, the authors directed them to reuse plastic water bottles to build the thermal mass and to constitute small groups that are responsible for monitoring and recording the air temperature within 24 hours. The authors advised the students to use the recorded air temperatures of each space as input data to a web-based thermal comfort tool and to compare the results. A quick survey to measure the students' satisfaction showed that the experiment participated in increasing the awareness of more than 93 % of the students about the positive effect of using water for thermal mass in elevating the indoor space temperature in cold seasons.

Word Count: 4306

Introduction

Many researchers believe that the Greeks were the first who adopted the concept of passive solar heating -heating the indoor spaces without relying on mechanical or electrical systems. They designed and oriented their buildings to collect and store the solar energy during the day, but they could not retain it at night due to the unglazed window openings. The Romans developed the Greek's idea by providing glazed windows. The glass participated in forming a heat trap similar to what we now call the greenhouse effect (Butti, 1980 pp.1-21). The idea vanished with the fall of the Roman Empire, but Walter Gropius adopted it again in the 1920s. Then it took its way across the Atlantic to the Americas and the rest of the world (Grondzik, 2015 pp. 295-296). In passive solar heating design, the main building elements such as floors, walls, and windows do not be only satisfying the architectural and structural requirements but also the energy ones. Glazed windows trap the solar energy in the indoor spaces during the daytime, while the walls, roof, and floor slabs store and radiate the heat at colder times - nighttime and the early morning. Thus, any passive solar heating system consists mainly of three elements:

- Aperture: South-facing glazing - in the northern hemisphere - with no more than 30° of rotation to the east or to the west from the true south.
- Absorber: A hard, darkened and unglazed surface of the storage element.
- Energy Storage Element: Thermal mass such as rock, brick, reinforced concrete or water.

In addition, the designer might incorporate the following elements as well:

- Heat Distribution: Small fans, ducts or blowers in case of the applied system is not strictly passive and relies only on natural heat transfer by conduction, convection or by radiation.

- Control: Overhangs or trees to shade the windows in hot seasons (DOE/EE-0342, 2010).

The relationship between these elements leads to three design systems: Direct Gain, Indirect Gain (Trombe Wall) and Isolated Gain (Solarium / Sun-space). Figures 1-a, 1-b, and 1-c clearly illustrate the major differences between the three systems (Neha Gupta, 2015 pp.305-335).

When compared to different building materials, water is light and has a higher Heat Storage Performance (HSP), which is a function of its thermal capacity and its conductivity (Table 1). Another important issue is that most of the building materials are usually isolated from the indoor environment by floor/wall finishes, suspended ceilings, furnishing... etc. Hence, leads to a significant reduction in the convective and radiant heat transfer between the thermal storage material and the indoor environment. For all these reasons, we can depend on water as one of the favorable materials that we can use as thermal mass when we design passive solar heating or cooling systems for our indoor spaces (Milan Ostry, 2013 pp.837 – 843).

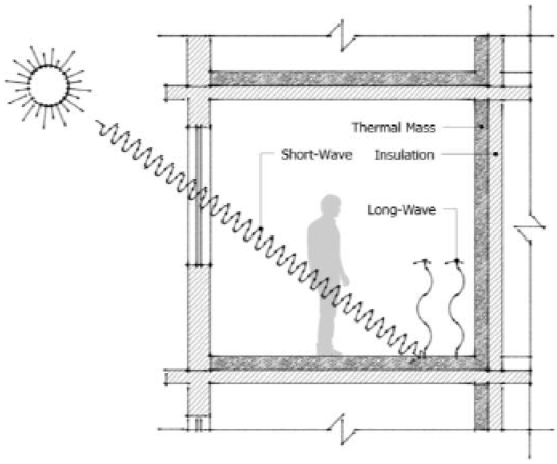

Figure 1-a. Direct gain

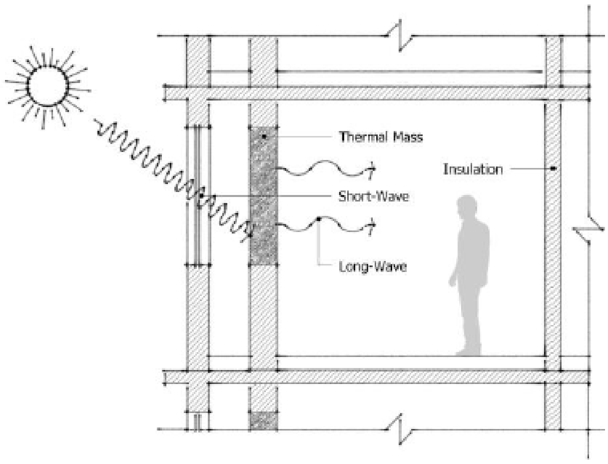

Figure 1-b. Indirect gain (Trombe wall)

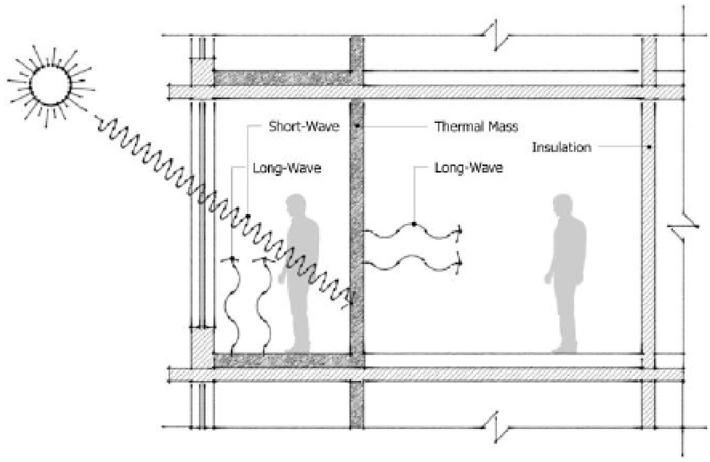

Figure 1-c. Isolated gain (Solarium / Sun-space)

For any thermal mass to be effective, the following conditions should be considered:

- The exposure of thermal mass to the direct solar radiation; therefore, floors are the first favorable choice.
- The combination of directly and indirectly exposed thermal masses when it is difficult to depend only on the directly exposed one. Thus, walls usually become the second favorable choice.
- The isolation of thermal mass from the outdoor environment.
- The surface area of the thermal mass, which is much more important than its thickness.
- The color of thermal mass surface, which should be dark to ensure a high absorption, while the surfaces of non-mass materials should be very light in color to reflect the solar radiation to the darker mass materials.
- The surface area of thermal mass, which is estimated as a percentage of the south glazing area (Table 2). However, this condition really matters, especially in both of the direct and indirect gain systems, while in the isolated gain system; the solarium is designed as a separate space (Lechner, 2015 pp.173-179).
- The relationship between the glazing area and the climate of design location (Table 3). In addition, the rules for estimating the glazing size (Bainbridge, 2011 pp.167).

Material	Water	Steel	RC	Granit	PC	Solid brick	Wood	Gypsum board
Density (kg/m³)	998	7850	2500	2500	2100	1800	400	750
Specific heat (J/kg K)	4182	440	1020	950	1020	900	2510	1060
Thermal capacity (10^6 J/m³ K)	4.17	3.45	2.55	2.38	2.14	1.62	1.00	0.80

Table 1. Characteristics of selected construction materials applicable for heat storage

Thermal mass	Exposure to solar radiation	Thickness & surface area ratio (to glazing area)					
		Direct gain		Indirect gain		Sunspace	
		Thickness	Surface area ratio	Thickness	Surface area ratio	Thickness	Surface area ratio
Concrete or Masonry	Direct	10-15 cm	3 times	25-40 cm	same	20-30 cm	same
	Indirect	5-10 cm		6 times		Not applicable	
Water	Direct	15-30 cm	Half	> 20 cm	same	12 cm	Half

Table 2. Rules for estimating the required thickness and surface area of thermal mass

Climate	Very cold	Cold	Temperate	Tropical	
				Dry	Humid
Thermal load	Heating only	Heating only	Balanced heating & cooling	Cooling & Small heating	Cooling only
Area of glazing as a percentage of flooring area	10-20 %	10-25 %	9-15 %	6-11 %	0 %

Table 3. Rules of estimating the optimum area of south-facing glazing for direct gain and Trombe wall

From the literature survey, the authors noticed that most of the researchers focused on the design guidelines and the field application techniques while less attention was given to the experimental and verification side during the undergraduate studies. Hence, the need for this experiment emerged, posing the major questions for this paper as follows:

- How to introduce a simple and easy experiment that may help architectural students to understand the potential capabilities of using water as a thermal mass in a better way?
- Could we conduct this experiment by utilizing a mobile thermal mass that is made of plastic water bottles without the need to make any changes in the interior design of the campus?
- Is utilizing plastic water bottles will be effective for this purpose?

Choosing the appropriate approach

To answer the first question of this research it was important to make a comprehensive comparison between the three passive solar heating systems to determine the advantages and drawbacks of each. This comparison was necessary to guide the authors in choosing the most appropriate system to conduct the experiment. From the comparison, we could find that:

- The direct gain system will put some restrictions regarding the location of the thermal mass and the way of its direct/indirect exposure to solar radiation, which must be either a floor or walls. In addition, it requires the thermal mass to be an integrated part of the building and this requires for structural modifications.
- Isolated gain system requires the presence of additional space, which is not applicable in the CIC campus.
- The indirect gain is the most appropriate system, as it gives an opportunity to use a movable thermal mass to function as a Trombe wall, where the students can use it only during carrying out the experiment.

To answer the second and third question, the experiment was divided into three main stages:

1. The Preparation Stage: comparing and assigning the suitable spaces to conduct the experiment. In addition, they will prepare the thermal mass and calibrate the measuring tools, which in this case are analog thermometers.
2. The Experiment Stage: During this stage, the students will monitor, periodically record and tabulate the weather data and the Dry Bulb Temperatures (DBTs) for the assigned spaces.
3. The Verification Stage: Studying and analyzing the effect of using water as a thermal mass on elevating the indoor space temperature in cold seasons.

Preparation Stage

It was important to study three main issues during the preparation process; these issues are the basic elements to conduct the experiment, and the way of choosing and/or preparing them has a significant effect on the expected results, these elements are:

• The Indoor Spaces: The students were asked to assign two indoor spaces in the CIC campus to conduct the experiment in a way that the chosen spaces satisfy the following criteria: They should be oriented - or nearly - to the true south and in the same floor level. In addition, the chosen spaces should be identical in the floor area, height, finishing materials, finishes colors, in addition to glazing dimensions and type. The students proposed two rooms B212 & B213 (Figure 2). The two rooms are on the first floor of the school of engineering, facing the true south with a rotation angle of 28° to the east direction (Figure 3). Both of the rooms have a floor area of 11 m² and a height of 2.8 m to the false ceiling level; the walls are painted in ivory white color and the floors are finished with light beige porcelain tiles. Each room has one window opening with the width of 2 m, height of 1.2 m and net glazing area of 2.04 m² of brown tinted glass, which satisfies the required glazing ratio - more than 10 %. In addition to the selected spaces, another two spaces were included during the measuring process in order to enrich the comparison. One of the spaces is a semi-closed one, which is the corridor between classes and staff rooms, while the other one is an outdoor space, which is the campus courtyard.

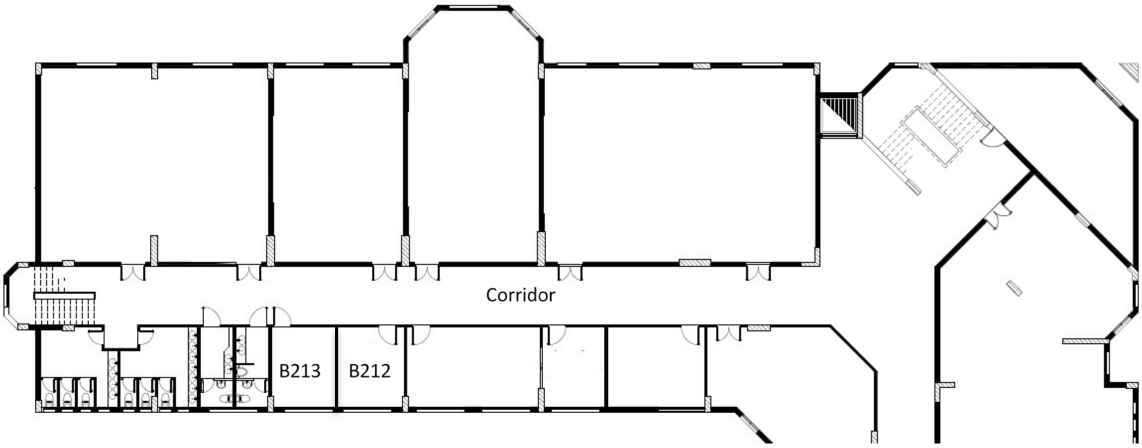

Figure 2. Typical floor plan for the School of Engineering, illustrating the proposed spaces to carry on the experiment, which are B212, B213, Corridor and Campus Courtyard

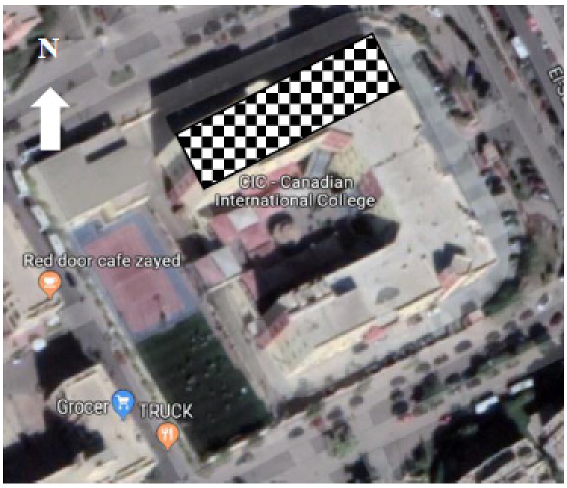

Figure 3. School of Engineering wing, CIC campus

Figure 4. The students preparing the thermal mass

<u>The Thermal Mass (Water Bottles):</u> Regardless the already mentioned advantages of using water as thermal mass, it has some drawbacks such as the extra-added loads on the structure and the need for containers, which may leak or require maintenance. Therefore, it was important to prepare the needed thermal mass - water containers - and use it to conduct the experiment inside the CIC campus without any permanent modifications in the indoor spaces design or the finishing materials. As students use many plastic water bottles during their scholar day, they can present an appropriate alternative in such a case. Another issue was how can these bottles could be used to construct the thermal mass; therefore, authors proposed that students could fix these bottles - after they refill them again with water - on mobile metal stands that they usually use for their architectural project presentations by cable plastic zippers. Since the indirect gain approach necessitates that the exposed surface of the thermal mass to be equivalent to the glazing area, the water bottles were not supported on all over the height of the metal stands but only on the upper part that matches with the windowsill height. To achieve the minimum thickness of the thermal mass, which is 20 cm, double layers of water bottles were supported - back-to-back - on the metal stands

in a staggered way to increase the exposed surface area (Figure 4). To prepare the required thermal mass, three hundred and twenty eight bottles were used; each one has a height of 30 cm, a diameter of 10 cm and contains 1.5 liters of water, with a total volume of 492 liters of water.

The Measuring Tools (Thermometers): four spirit thermometers were installed - one Alcohol thermometer for each space - and fixed to measuring sheets with clear caution signs to record the DBTs. periodically. A calibration process was performed on the used thermometers to ensure that each of them would give an accurate measurement before carrying out the experiment. After the calibration process, each of the measuring sheets was supported in a suitable location in each space to make it easy for any involved student to observe and record the periodical measurements.

The Experiment Stage

To track the effect of using water as a thermal mass on the indoor environment, the experiment period was set to extend for 24 hours over two cold days - the 16th and 17th of December. The students were asked to constitute groups out of two members per group. Each group was responsible for monitoring and recording the DBTs in one of the four mentioned spaces for two hours period - one reading per hour, In addition to recording the official corresponding weather characteristics for the same time of the day. These characteristics such as relative humidity, air pressure, wind speed and the DBTs. are obtained regularly from the nearest certified weather station, which is Cairo International Airport (TWC, 2014). Thus, obtaining 100 records by the end of the experiment.

- The experiment took place on a weekend - from 8:00 am Saturday until 8:00 am Sunday - to eliminate any other thermal effects such as radiation from human bodies, working appliances, lighting fixtures…etc.
- In the morning of the experiment's day - 30 minutes before starting the experiment - the prepared thermal masses were moved to one of the two identical rooms (B213). They placed the metal stands with the fixed on water bottles into their final positions, facing the window directly and 10 cm away from the glazing surface. At the same time, another group of students was responsible for installing the recording sheets with their fixed on thermometers into suitable locations in the four assigned spaces (Appendix A).
- On 8:00 am, the started the monitoring and recording task in two phases:
  - Phase 1: extended from 08:00 am until 03:00 pm, the windows on both rooms - B212 and B213 - were left without thermal insulation to maximize the heat gain.
  - Phase 2: started after 03:00 pm, the students were asked to install polystyrene thermal isolation boards and strips to isolate the windows in both of the indoor spaces. This process was critical when the windows are not exposed to the direct sun to eliminate the heat loss as much as possible.
- By the end of the experiment procedures, the students were asked to tabulate the collected data in a comprehensive way (Appendix B) and to illustrate it in the form of a line chart diagram to demonstrate the temperature changes during the 24 hours in the four spaces compared to the reference weather readings (Figure 5).

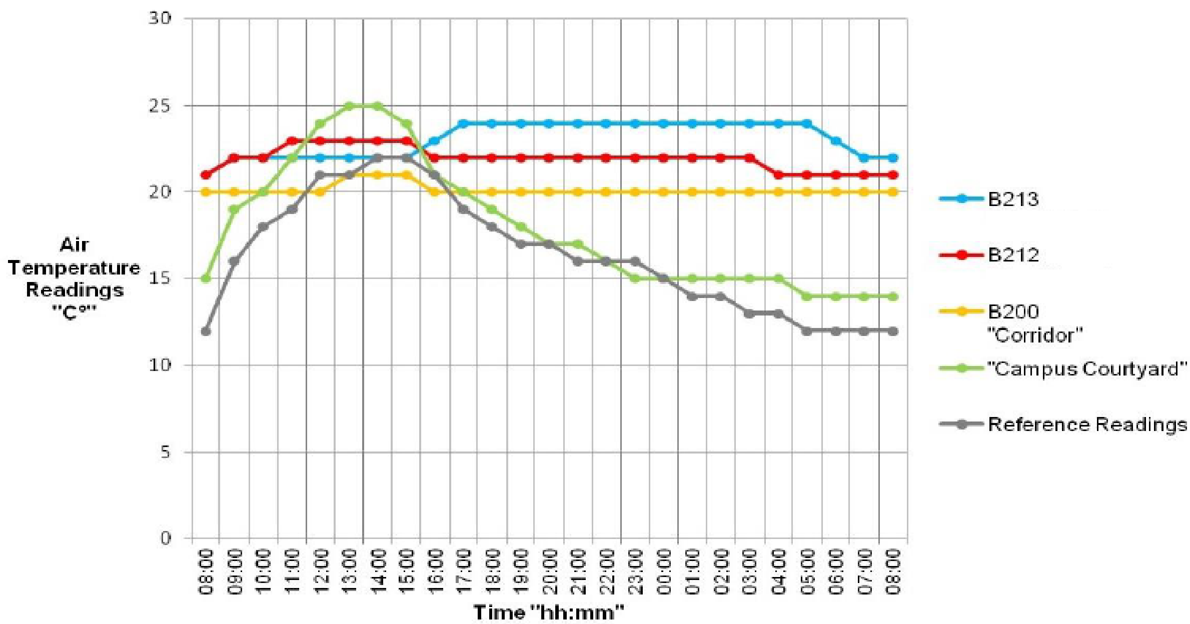

Figure 5. The recorded (DBTs.) of the four spaces compared to the reference (DBTs.) of the same day

Verification Process

To verify the effect of using thermal mass - water bottles - on the feeling of comfort inside the B 213 room, the students were advised to use their recorded air temperatures as input data for a web interface thermal comfort tool developed by the Center for the Built Environment (CBE), University of California Berkeley (Schiavon Stefano, 2014 pp.321-334). After that, the students repeated the same process for the other three spaces and made a comparison between the four spaces.

- The CBE thermal comfort tool enables the user to choose between two methods: the Mean Predictive Vote (MPV) method or the Adaptive method. In addition, either it enables the user to apply the European Standard (EN-15251) or the American Standard for Heating, Refrigerating and Air-conditioning Engineers (ASHRAE-55) to the selected method (CBE, 2017).
- The Adaptive method was the most appropriate choice in our case as it is based on a hypothesis that the outdoor climate influences indoor comfort. Both of ASHRAE-55 and EN-15251 standards apply for the Adaptive method; however, the latter fits more in our case (Figure 6). The ASHRAE standard is only applicable to buildings without any mechanical cooling or heating systems installed, while the EN15251 standard is applicable to mixed-mode buildings, which have mechanical systems but they are not running, as in the case with the CIC campus. In addition, the EN-15251 standard considers the metabolic rates ranging from 1.0 to 1.3 met and the occupants can freely adapt their clothing insulation (CEN, 2007 pp.14).
- Supposing that the measured DBT equals the Mean Radiant Temperature (MRT), and the Airspeed is less than 0.2m/s; then, the Operative Temperature will have the same value of the DBT (ANSI/ASHRAE 2014, pp.16).
- However, it is not the case in the open courtyard; therefore, airspeed was set to 0 m/s for all the spaces, to eliminate the effect of the wind speed on the limits of the comfort zone.
- The last needed input data to the CBE thermal comfort tool is the outdoor running mean temperature. The students referred to the website of the World Meteorological Organization to get this value for the month of December in Cairo - Egypt, which was around 16 C° (WMO, 2017).

Figure 6. The CBE comfort tool interface (adaptive method) according to the EN-15251 standard

The results

According to the predetermined Outdoor Running Mean Temperature, which is 16 C°, the Adaptive method in the European Standard (EN-15251) classifies the comfort zone into three main categories as follows:

- Class I (the Operative Temperature acceptability limits of comfort is between 22.1 and 26.1 C°).
- Class II (the Operative Temperature acceptability limits of comfort is between 21.1 and 27.1 C°).
- Class III (the Operative Temperature acceptability limits of comfort is between 20.1 and 28.1 C°).

For any of the three classes, the CBM comfort tool considers any adaptive temperature higher than the maximum limit to be very warm and anyone lower than the minimum limit to be very cool. When the students entered the recorded data to the CBE thermal comfort tool the results were as follows:

- The corridor recorded the least number of hours that satisfy the thermal comfort and only within Class III, which is too cool for the other two classes and it was as follows:
  - Three hours (12:00 am - 03:00 pm) → (Class III)

  While the rest of the experiment period - 21 Hrs. - were located outside all the comfort zones.
- The courtyard had a longer period that satisfies the thermal comfort as follows:
  - Four hours (12:00 am - 03:00 pm) → (Class I)
  - One hour (11:00 am - 12:00 pm) → (Class II)
  - One Hour (04:00 pm - 05:00 pm) → (Class III)

  While the rest of the experiment period - 18 Hrs. - were located outside all the comfort zones.
- Room B212 (Closed Space without Thermal Mass) was located within the limits of comfort zone during the entire experiment period as follows:
  - Five hours (11:00 pm - 04:00 pm) → (Class I)
  - 14 hours (09:00 am - 11:00 am on day one and 04:00 pm - 04:00 am on day two) → (Class II)
  - Five hours (08:00 am - 09:00 am and 04:00 am - 08:00 am) → (Class III)
- Room B213 (Closed Space with Thermal Mass) was located within the limits of comfort zone during the entire experiment period as follows:
  - 15 hours (04:00 pm - 12:00 am on day one and 12:00 am - 07:00 am on day two) → (Class I)
  - Three Hours (09:00 am - 04:00 pm on day one and 07:00 am - 08:00 am on day two) → (Class II)
  - One hour (08:00 am - 09:00 am) → (Class III)

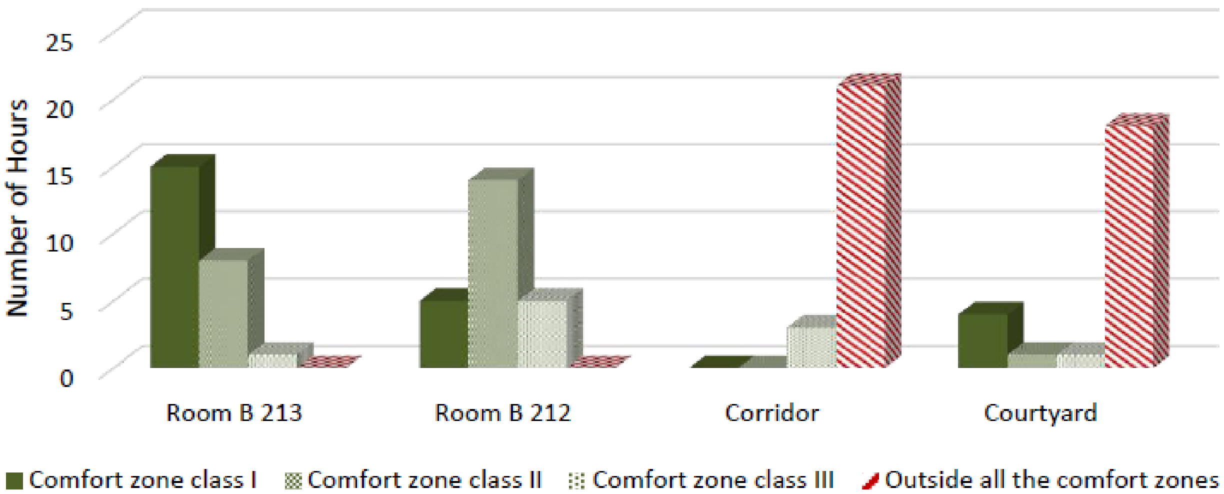

Figure 7 illustrates the summary of the above results in a bar-chart form, while Figure 8 is an example of comparing the state of comfort in the four spaces at 4:00 am (the second day).

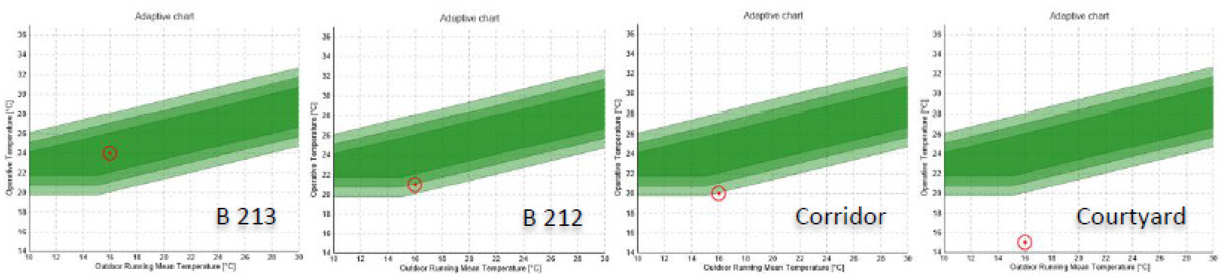

Figure 8. Example of the comparison between the comfort statuses in the four spaces at 4:00 am shows that: B 213 in class I, B 212 in class II, while both of the corridor and courtyard are outside all the comfort zones

Discussion

- Due to the effect of the CIC campus building – U shape – and the context, the recorded DBTs. in the courtyard are higher than the DBTs, collected from the reference station in most of the experiment's time.
- In the morning of the first day, both B212 and B213 had the same DBTs; yet, starting from 10:00 am until 3:00 pm, room B213 had lower DBTs as the thermal mass absorbed more energy. On the other hand, after 3:00 pm, the sun was away from the windows; yet the DBTs in B213 were higher than the DBTs. in B212.

- The effect of the thermal mass was obvious although it was the worst case. As the water was very clear - without adding any dark colors - and the use of individual bottles eliminates the effect of the convection.
- It was important to measure how the experiment could enhance the awareness of the participants in understanding the positive effect of using water as a thermal mass in passive heating systems. The authors' forwarded a quick questionnaire to the students for this purpose and the statistics of the answers showed that more than 93% gave positive feedback.

Conclusion

This paper discussed the applicable systems of passive solar heating design. A quick comparison between the different systems showed that the indirect gain (Trombe wall) is the most appropriate system to depend on when conducting a passive solar heating experiment inside the campus. The authors introduced a simple technique to build a temporary thermal mass by re-using plastic water bottles, which are re-filled with water and fixed on mobile metal stands. This experiment is applicable for execution in many of the academic institutions, as it only requires for two identical South-facing spaces and does not necessitate any temporary or permanent modifications in the interior design. Monitoring, recording and comparing the DBTs in the different spaces assured that utilizing plastic water bottles as a thermal mass is reliable to illustrate the effect of passive heating techniques in elevating the indoor space's temperature in cold seasons. The students play a major role in this experiment during the preparation, recording the air temperatures in the different spaces and while verifying the results. After the validation process, a quick survey showed that more than 93% of the participants were satisfied with the experiment's methodology and results.

Acknowledgment

The authors would like to give special thanks to our diligent students - 46 students who are registered in the Environmental Control, Cohort 2015 - who participated in the different stages of this experiment (Google drive, 2019). In addition, we would like to thank all of CIC academic and administrative members who presented all the possible help to carry on this experiment in such a successful way.

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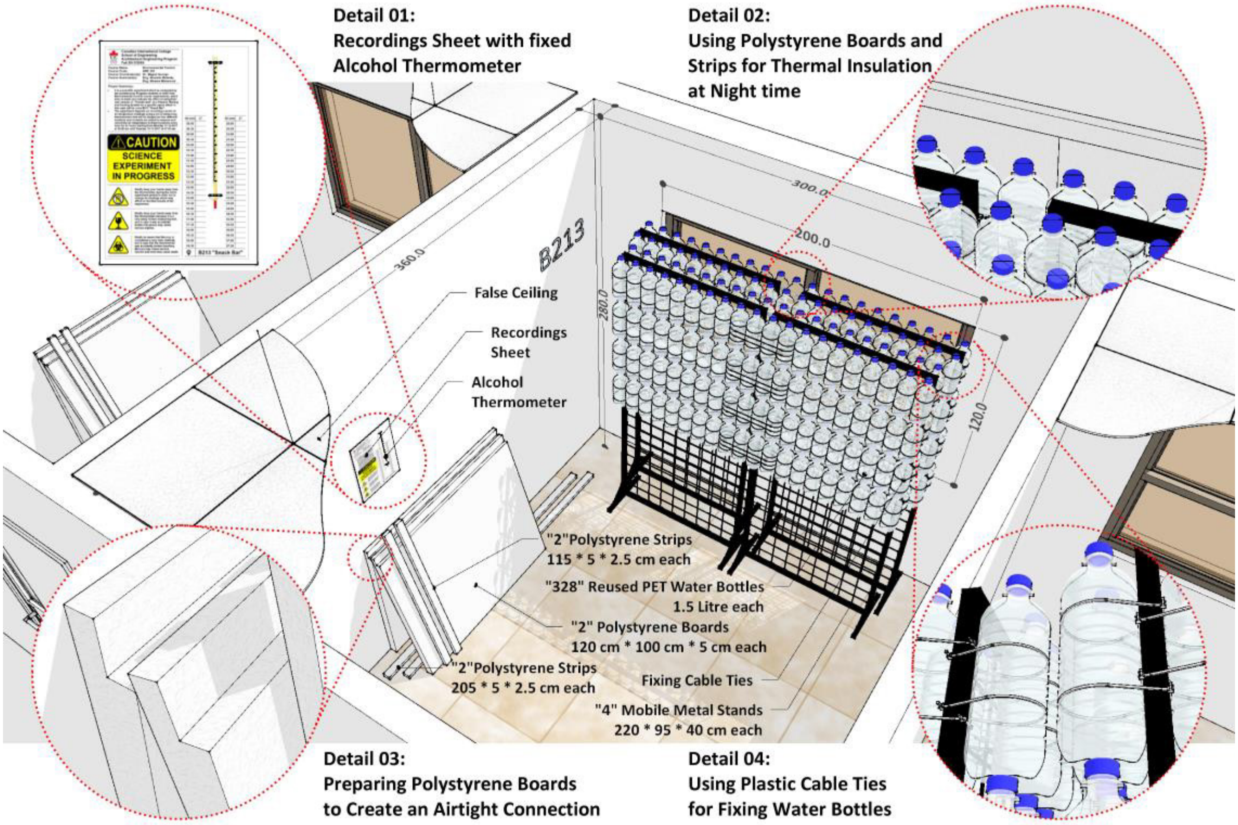
Appendix (A)
Details of the selected spaces and thermal mass



Appendix (B)
Tabulation of the recorded weather data during the experiment period

Day	Time "hh:mm"	Reference Readings				Air Temperature Readings "C°"			
		Relative Humidity "%"	Wind Speed "m/s"	Air Pressure "Pascal"	Air Temperature "C°"	B213 "Snack Bar"	B212 "Staff Room"	B200 "Corridor"	"Campus Courtyard"
Day 01 16-12-17	08:00	85	0.83	101930.00	12	21	21	20	15
	09:00	73	2.22	102240.00	16	22	22	20	19
	10:00	67	3.06	102240.00	18	22	22	20	20
	11:00	57	3.89	102200.00	19	22	23	20	22
	12:00	52	3.61	102130.00	21	22	23	20	24
	13:00	47	3.06	102030.00	21	22	23	21	25
	14:00	44	2.50	102000.00	22	22	23	21	25
	15:00	45	3.61	101930.00	22	22	23	21	24
	16:00	46	3.61	101960.00	21	23	22	20	21
	17:00	50	3.61	102060.00	19	24	22	20	20
	18:00	57	3.06	102000.00	18	24	22	20	19
	19:00	60	2.78	102030.00	17	24	22	20	18
	20:00	62	2.22	102070.00	17	24	22	20	17
	21:00	68	2.22	102000.00	16	24	22	20	17
	22:00	71	2.78	102100.00	16	24	22	20	16
	23:00	71	2.78	102200.00	16	24	22	20	15
	00:00	78	2.78	102030.00	15	24	22	20	15
Day 01 17-12-17	01:00	78	2.22	102000.00	14	24	22	20	15
	02:00	84	1.39	101960.00	14	24	22	20	15
	03:00	88	1.39	101930.00	13	24	22	20	15
	04:00	86	1.67	101930.00	13	24	21	20	15
	05:00	90	0.83	101900.00	12	24	21	20	14
	06:00	92	0.56	101900.00	12	23	21	20	14
	07:00	86	0.56	101930.00	12	22	21	20	14
	08:00	85	0.83	101930.00	12	22	21	20	14