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Analysis of the thermal performance and comfort conditions produced by five different passive solar heating strategies in the United States midwest ☆

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Abstract

This paper presents a summary of the thermal performance of five different passive solar test-cells (Direct Gain, Trombe-wall, Water-wall, Sunspace, and Roofpond) and a control test-cell during the 2002–2003 heating season in Muncie, Indiana. The results discussed in this article correspond to the initial phase of a longer study (data were collected from December of 2002 until August of 2004). The project's original intent was to identify any barriers to achieving thermal comfort within a space when passive solar heating systems are employed in severe winter climates with predominant overcast sky conditions. Because of the original intent of this project, the test-cells were arranged with their smaller facades oriented to the north and south and the longer facades facing east and west. This arrangement permitted to study temperature differences throughout the day (diurnal operative temperature swings) and also simultaneous temperature differences throughout the space (a simultaneous comparison of four points instrumented within each cell to detect variations between the south side and the north side of the test-cells).

The results of this phase of the study show that the Direct Gain strategy had the largest diurnal variations of temperature with an average operative temperature swing of 7.8 °C and a maximum variation during the reported period of 10.3 °C. By contrast, the Roofpond strategy had the smallest diurnal variations of temperature with an average operative temperature swing of 1.2 °C and a maximum variation during the reported period of 1.4 °C. In terms of the simultaneous variations in the operative temperature between the south side and the north side of the test-cells, the Direct Gain strategy showed again the highest variations with an average simultaneous operative temperature difference between the south and north sides of the test-cell of 2.9 °C and a maximum variation during the reported period of 3.7 °C. The Roofpond strategy, on the other hand, had the smallest variations with an average simultaneous operative temperature difference between the south and north sides of the test-cell of 0.1 °C and a maximum variation during the reported period of 0.2 °C. The conclusions of this study demonstrate that diurnal variations of the operative temperature are primarily determined by the type of passive solar strategy utilized (with direct gain producing the highest temperature swings and the indirect gain strategies producing the smallest temperature swings) and by the thermal storage capacity of the system (with a higher thermal storage producing a smaller temperature swing). The simultaneous variations of the operative temperature inside the test-cells during the daytime were mostly influenced by the type of passive solar strategy utilized (with direct gain producing the highest simultaneous differences in temperature between the south and north sides of the test-cell and the indirect gain strategies producing the smallest temperature swings).

Keywords: Passive solar heating; Direct gain; Trombe-wall; Water-wall; Sunspace; Roofpond

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Nomenclature

CC	Control test-cell
DG	Direct gain
TW	Trombe-wall
OT	Operative temperature
MRT	Mean radiant temperature
WW	Water-wall
SS	Sunspace
RP	Roofpond
DBT	Dry-bulb temperature
SSF	Solar savings fraction

1. Introduction

Passive solar heating has been used extensively throughout history with great success (Butti and Perlin, 1980). In the United States, the Southwest Pueblo culture provided superb examples on how the orientation of the dwellings, combined with thermally massive construction materials, can produce comfortable conditions during both winter and summer seasons. Over the past century, the technological advances in the building construction industry prompted the investigation of more creative ways of utilizing the sun for space heating. In 1948, Frank Lloyd Wright demonstrated in the Jacobs House II (also known as the Solar Hemicycle) how an early twentieth century residence could take advantage of the sun to supply part of its heating requirements during the winter season (Lechner, 2001). In 1964, engineer Felix Trombe and architect Jacques Michel used a patent filed by Edward Morse in 1881 (US Patent 246626) to advance the use of solid masonry thermal storage walls (Butti and Perlin, 1980). The Trombe-wall takes advantage of the insulative properties of glass, and by adding vents to the solid masonry wall, it can also be used to circulate and condition the air from the room adjacent to the Trombe-wall. Recognizing water's superior thermal properties, Steve Baer advanced the concept of thermal storage walls with the implementation of a "Water-wall" strategy in the Zomehouse designed in 1971 (Yellott, 1975). In addition to the "Water-wall," the Zomehouse also features the use of a reflector (during the daytime) that can be moved to become nighttime insulation for the large south-facing windows. In 1973, inventor Harold Hay and architect Kenneth Haggard built a "Roofpond" house in Atascadero, California (California Polytechnic State University, 1975). The Roofpond system uses a water pond on top of a flat metal-deck roof. The water is contained inside clear polyethylene bags. During the winter, the water bags are covered with movable insulation panels to avoid heat losses at night (closed mode). During the summertime, the movable insulation operation is reversed (water bags exposed) to take advantage of nighttime radiant cooling (open mode). In 1974, architect David Wright designed his own house in Santa Fe, New Mexico. David Wright's house uses "Direct Gain" as its main passive solar heating strategy and features movable insulation panels that decrease the thermal losses through the large south-facing windows during the nighttime (Yellott, 1975). In 1976, the Unit One – First Village, designed and built by Wayne and Susan Nichols, became one of the most studied examples of the "Sunspace" strategy for passive solar heating (Moore, 1993). The Unit One – First Village features a large green-house with all the living spaces surrounding its thermally massive north wall. In the "Sunspace" strategy, heat is transferred to the adjacent spaces via radiation (from the thermally massive north wall) and convection (by using a series of vents that allow air circulation between the Sunspace and the living spaces).

The passive solar heating strategies described above (i.e. Trombe-wall, Water-wall, Roofpond, Direct Gain, and Sunspace) were systematically studied in the late 1970s and early 1980s at the Los Alamos National Laboratory (Balcomb et al., 1984) and subsequently by the Solar Energy Analysis Laboratory at the Pala passive solar test site near San Diego, California (Clinton, 1982). In spite of the documented energy savings produced by these passive solar heating strategies, and the design guidelines produced to encourage the use of passive solar systems, today the vast majority of all the residential buildings in the United States of America are heated by mechanical systems powered by non-renewable energy sources.

2. Passive solar research in Muncie, Indiana

The research project presented in this paper builds on previous experimental research in passive solar systems (California Polytechnic State University, 1975; Balcomb et al., 1984; Clinton, 1982), and identifies potential barriers to achieving thermal comfort when passive solar heating systems are employed in a severe winter climate characterized by predominant overcast sky conditions during the winter months. The strategies studied in this project were Direct Gain (DG), Trombe-wall (TW), Water-wall (WW), Sunspace (SS), and Roofpond (RP).

2.1. Climate of Muncie, Indiana

Muncie is located 93 km northeast of Indianapolis, Indiana. According to DeKay and Meyers (2001), Muncie would be part of the "Midwestern & Eastern Temperate Climate Zone". This climate zone is characterized by cold winters without reaching the cold temperature extremes found in the North and Northeastern region of the United States of America (AIA Research Corporation, 1980). Muncie oftentimes has very warm summers and does not have a dry period. The design sky condition for Muncie

Table 1
Climate normals for Muncie, Indiana

City													Muncie
State													IN
Lat													40.13N
Long													85.25W
Elevation													286.5 m above seal level
	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Minimum temperature (°C)	−8.8	−7.0	−1.6	4.1	10.7	15.7	17.8	16.6	12.1	5.5	0.3	−5.6	5.0
Maximum temperature (°C)	0.5	3.1	9.1	15.9	22.1	27.2	29.4	28.2	24.6	17.9	10.0	3.4	15.9
Mean temperature (°C)	−4.2	−1.9	3.8	10.0	16.4	21.4	23.6	22.4	18.3	11.7	5.2	−1.1	10.4
Precipitation (cm)	5.2	5.7	7.9	9.1	10.6	10.9	10.1	8.9	7.6	6.7	8.6	7.7	98.9
HDD base 18.3 °C	698	568	452	252	102	12	1	7	47	210	395	602	3346
CDD base 18.3 °C	0	0	0	2	41	106	164	132	47	6	0	0	498

is overcast, and rainfall is distributed quite evenly throughout the year. Table 1 shows the Climate Normals for Muncie, IN (NOAA, 1985).

2.2. Research methods and experiment setup

The research method used in this project was an experimental side-by-side comparison between a control test-cell (CC) and five passive solar test-cells, namely Direct Gain (DG), Trombe-wall (TW), Water-wall (WW), Sunspace (SS), and Roofpond (RP). The equipment used to monitor the test-cells was calibrated prior to the beginning of the experiments in a controlled environment to ensure that all measurements were accurate. In addition, all the test-cells feature the same construction materials and methods (i.e. wood frame construction, the most widely used construction method in residential construction in the United States) and have the same thermal insulation properties. All the test-cells have an interior floor area of 11.9 m^2 (4.88 m by 2.44 m) with the smaller sides facing north and south (see Figs. 1 and 2). From the point of view of passive solar design, it would have been better to have

Fig. 1. South view of the five passive solar test-cells (from the left): Direct Gain (DG), Trombe-wall (TW), Water-wall (WW), Sunspace (SS), and Roofpond (RP).

Fig. 2. Basic floor plan and longitudinal sections of each one of the test-cells.

the larger facades face north and south in order to increase the solar collector area of the test-cells (with a subsequent increase of the thermal storage capacity) and to reduce the overall thermal transmittance of the building envelope using different construction assemblies. However, the main goal of this project is to identify any potential barriers to achieving thermal comfort when passive solar heating systems are employed in severe winter climates with predominant overcast sky conditions. Therefore, given the intent of the project, it made more sense to challenge the passive solar system's performance by designing a less than ideal configuration. During the second phase of this research project, not reported in this article, the test-cells were modified to improve their performance as a result of the observations done during the 2002–2003 heating season. In addition, the design of the test-cells successfully addressed the spatial limitations of the test site (see Fig. 1). Table 2 presents a summary of the passive solar features and thermal properties of each of the strategies studied in this project, and Table 3 shows some basic performance indicators.

The test-cells were instrumented using a four-point grid to detect simultaneous variations of the Operative Temperature across the floor area of the test-cells (see Fig. 3). Each of the four-points instrumented within each of the test-cells had four sensors (two internal and two external) connected to a HOBO H-8 RH/Temperature 2× data logger (see Fig. 4). The two internal sensors were used to measure the air temperature and the relative humidity, respectively, while the two external sensors were used to measure the mean radiant temperature (using a black globe) and the

Table 2
Passive solar features specific to each strategy

	CC	DG	TW	WW	SS	RP	
Floor area (m^2)	11.91	11.91	11.91	11.91	11.91	11.91	
UA total (W/°C)	28.74	35.47	34.93	34.75	45.54	Day 44.09	Night 29.93
Measured ACH	0.68	0.85	0.81	0.86	0.67	0.91	
Solar collector area (m^2)	–	4.28	4.28	4.28	6.05	4.47	
Thermal storage capacity (kJ/°C)	569.57	1786.17	1728.84	4909.57	1517.80	9629.80	

Table 3
performance indicators of each strategy

	CC	DG	TW	WW	SS	RP
Average diurnal swing (°C)	2.26	7.80	3.32	4.99	5.28	1.24
Maximum diurnal swing (°C)	2.41	10.27	3.79	5.94	5.74	1.44
Average simultaneous north–south variation (°C)	0.07	2.89	0.45	0.98	0.32	0.11
Maximum simultaneous north–south variation (°C)	0.15	3.68	0.52	1.22	0.50	0.20

Fig. 3. Four-point grid used to monitor the indoor environmental conditions of the test-cells.

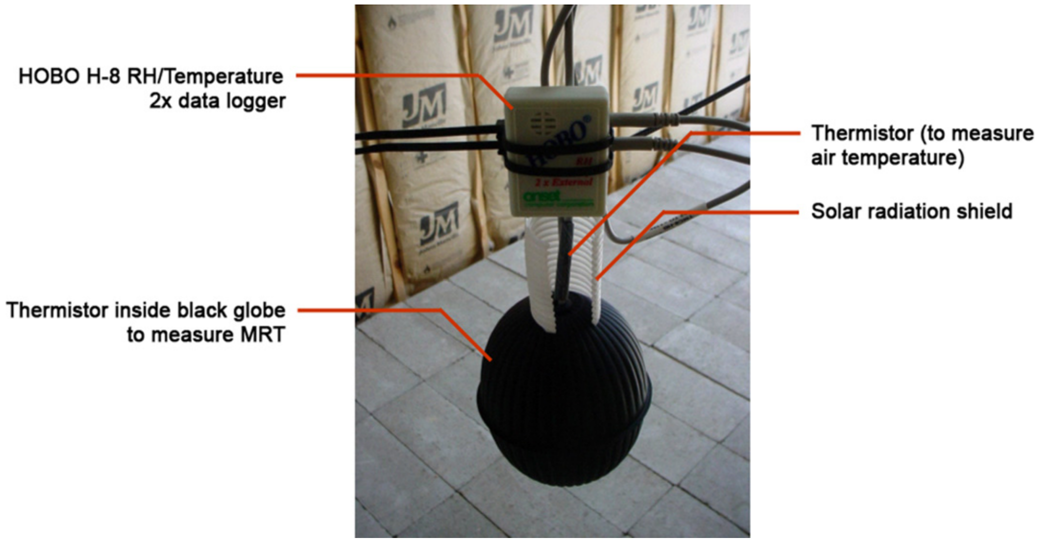

Fig. 4. Equipment bundle placed 1.1 m above the finished floor of each test-cell.

dry-bulb air temperature with a thermistor placed above the globe thermometer and shielded from solar radiation by a white-plastic screen (see Fig. 4). The mean radiant temperature (MRT) and indoor dry-bulb air temperature (DBT) measurements were used to calculate the operative temperature (OT) as described in the ANSI/ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy (ASHRAE, 2004). The OT and its coincident relative humidity were also used to evaluate thermal comfort by comparing the measured indoor conditions against the prescriptive method suggested by the ANSI/ASHRAE Standard 55 (ASHRAE, 2004). The thermal comfort evaluations using this method are presented for the months of January and March in Figs. 6–11. For the purposes of this article, the author has chosen to focus and highlight the variations in OT throughout the day (diurnal operative temperature swings) as well as the simultaneous variations in OT throughout the space, as these two aspects are the indicators that best characterize the challenges to achieving thermal comfort in passive solar-heated buildings.

In addition to the instrumentation of the test-cells, a weather station was installed on the test site to monitor outdoor conditions (i.e. air temperature, wind speed and direction, relative humidity, and solar global radiation). These outdoor conditions were used to record the severity of the outdoor climate and to develop a design guideline that could be extrapolated to other places. A preliminary design guideline to design Roofpond buildings based on the experimental data collected in this project was proposed by the author (Fernández-González, 2004b), and additional guidelines for the other strategies are under development (Fernández-González, 2004a). The comparison between indoor and outdoor environmental conditions was also useful as it provided a better understanding of the ways in which each strategy reacts to the variables that compose the climate (e.g. the WW and RP strategies are able to maintain more comfortable conditions during extreme periods of overcast sky conditions).

3. Results

The results discussed in this article summarize the thermal performance of the test-cells during the 2002–2003 heating season (December 2, 2002 through May 31, 2003). It is important to remember that the test-cells were designed to better understand the ways in which each of the strategies may affect thermal comfort. For that reason, this article emphasizes the results that shed light on the potential challenges to thermal comfort inherent to each of the strategies.

3.1. Control cell (CC)

Since the CC did not have a source of heating nor significant thermal storage, the indoor environmental conditions measured within this test room closely followed the outdoor conditions with the expected attenuation of temperature extremes (see Figs. 5 and 6). The monthly average indoor operative temperature of the CC was approximately 2 °C higher than the monthly average outdoor air temperature. In the case of the CC, three of the four points instrumented inside measured almost the same OT at all times. Point 976 (see Fig. 3) was the exception, as it consistently exhibited slightly lower operative temperatures due to its proximity to the access door – the building component within this test-cell that produced the greatest heat losses (U value = 1.135 W/m^2 °C).

The average and maximum diurnal OT swings in the CC during the reported period were 2.26 °C and 2.41 °C, respectively. The diurnal variations of OT found in the CC are well within the range of variation that would be considered

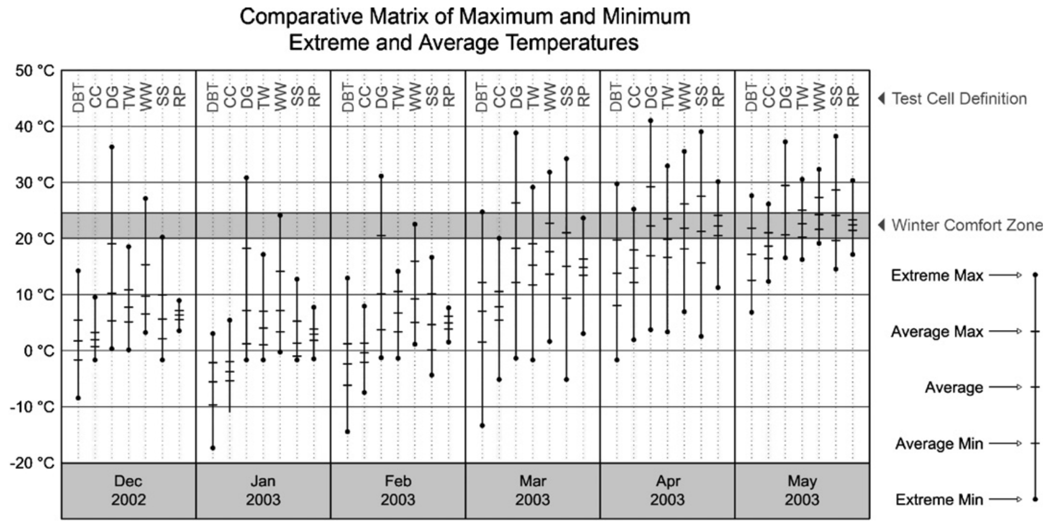

Fig. 5. Maximum and minimum extreme and average outdoor dry-bulb air temperature and operative temperatures inside the passive solar and control test-cells.

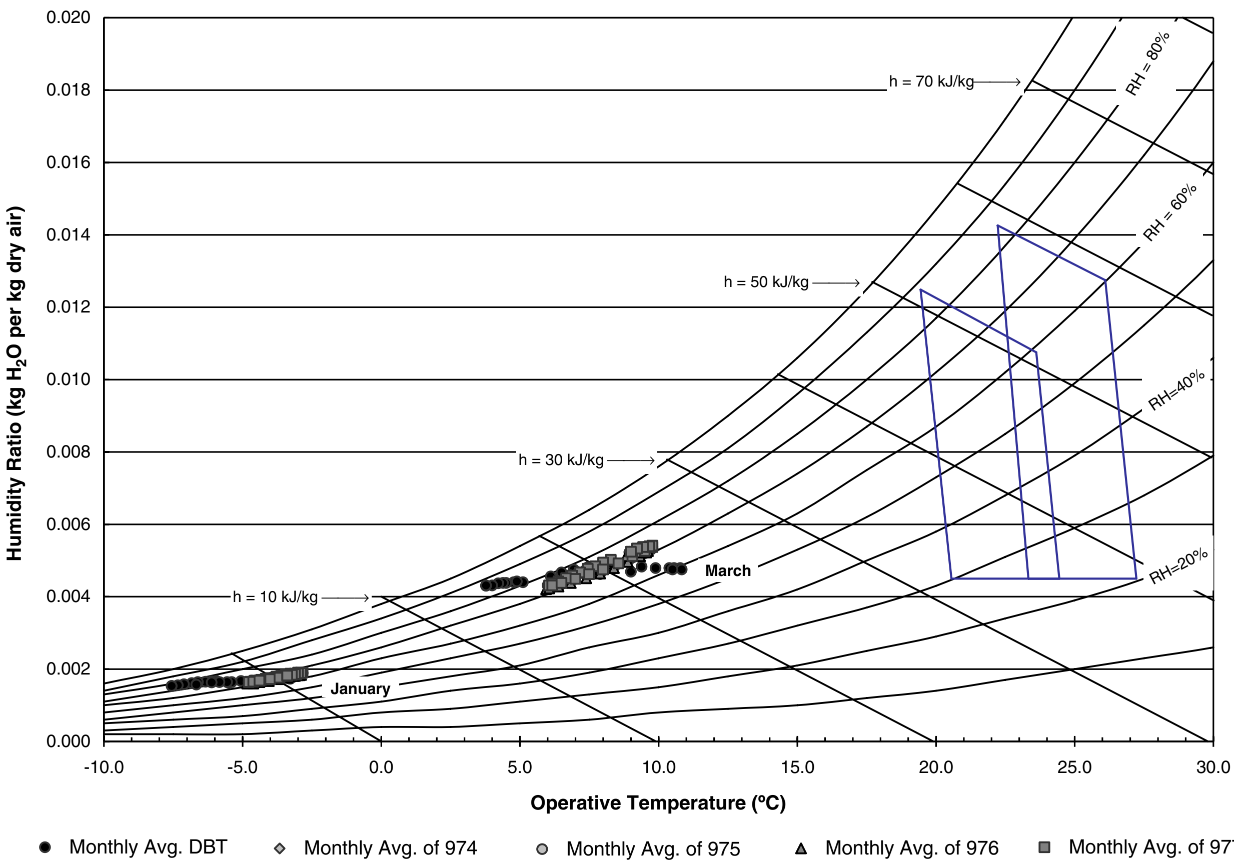

Fig. 6. Hourly average outdoor dry-bulb air temperature and indoor operative temperatures and coincident relative humidity inside the control test-cell (CC) for the months of January and March of 2003.

acceptable for achieving thermal comfort. It is interesting to notice that the Roofpond, an indirect gain strategy having the highest thermal storage capacity, displayed an even smaller diurnal temperature swing (see Figs. 5 and 11).

The simultaneous variations in the operative temperature between the south side and the north side of the CC were almost negligible, with average and maximum variations of 0.07 °C and 0.15 °C, respectively.

3.2. Direct gain (DG)

The DG test-cell had (just like the TW and WW test-cells) a ratio of solar collector area (south-facing vertical fenestration) to floor area of 1:2.78. The thermal storage in this strategy was composed of 115 solid concrete blocks (20 cm by 40 cm and 10 cm thick) laid directly on the floor of the DG test-cell. The ratio of solar collector area to exposed thermal mass was 1:2.15. This solar collector area to exposed thermal mass ratio falls below the minimum of 1:3 recommended by Balcomb et al. (1984) and by Stein et al. (2006), which made the DG test-cell more susceptible to experience midday overheating during clear winter days. In terms of energy savings, the sensitivity curves produced by Balcomb et al. (1984) suggest that the chosen ratio of solar collector area to exposed thermal mass would produce an increase of approximately 5% in the consumption of energy for space heating when compared with the energy consumed by a similar building having the recommended ratio of 1:3.

The DG test-cell featured, like the rest of the passive solar test-cells, a solar collector made of 6 mm clear insulated glass (double glazing with 12.7 mm air space) with an aluminum frame with a thermal brake (whole assembly U value = 3.22 W/m^2 °C). The Solar Heat Gain Coefficient (SHGC) at the center of the glass at normal incidence is 0.70.

With the setup described above, the DG test-cell had the largest diurnal operative temperature swings during the reported period with an average and maximum diurnal swing of 7.8 °C and 10.27 °C, respectively. The results presented in this article demonstrate that Direct Gain, as a passive solar heating strategy, produces the highest indoor operative temperatures (see Figs. 5 and 7). Inherent to its ability to quickly raise the indoor OT, Direct Gain has the potential to produce overheating. During the period reported in this article the DG test-cell produced temperature swings that would adversely affect human comfort (see Figs. 5 and 7). The simultaneous variations in the OT between the south side and the north side of the DG test-cell were in average 2.89 °C with a maximum variation of 3.68 °C during the period reported. These simultaneous temperature differences are caused by the greater exposure of the south side of the test-cell to incoming solar radiation during the day, and to the lower surface temperatures produced by the higher heat losses resulting in a lower surface temperature of the solar collector during the nighttime (see Fig. 3). The latter condition can be addressed by adding nighttime insulation to the solar collector.

The variations of operative temperature in time and throughout the space could be reduced by increasing the ratio of solar collector area to exposed thermal mass (e.g. from 1:2.15 to at least 1:3) or by reducing the solar collec-

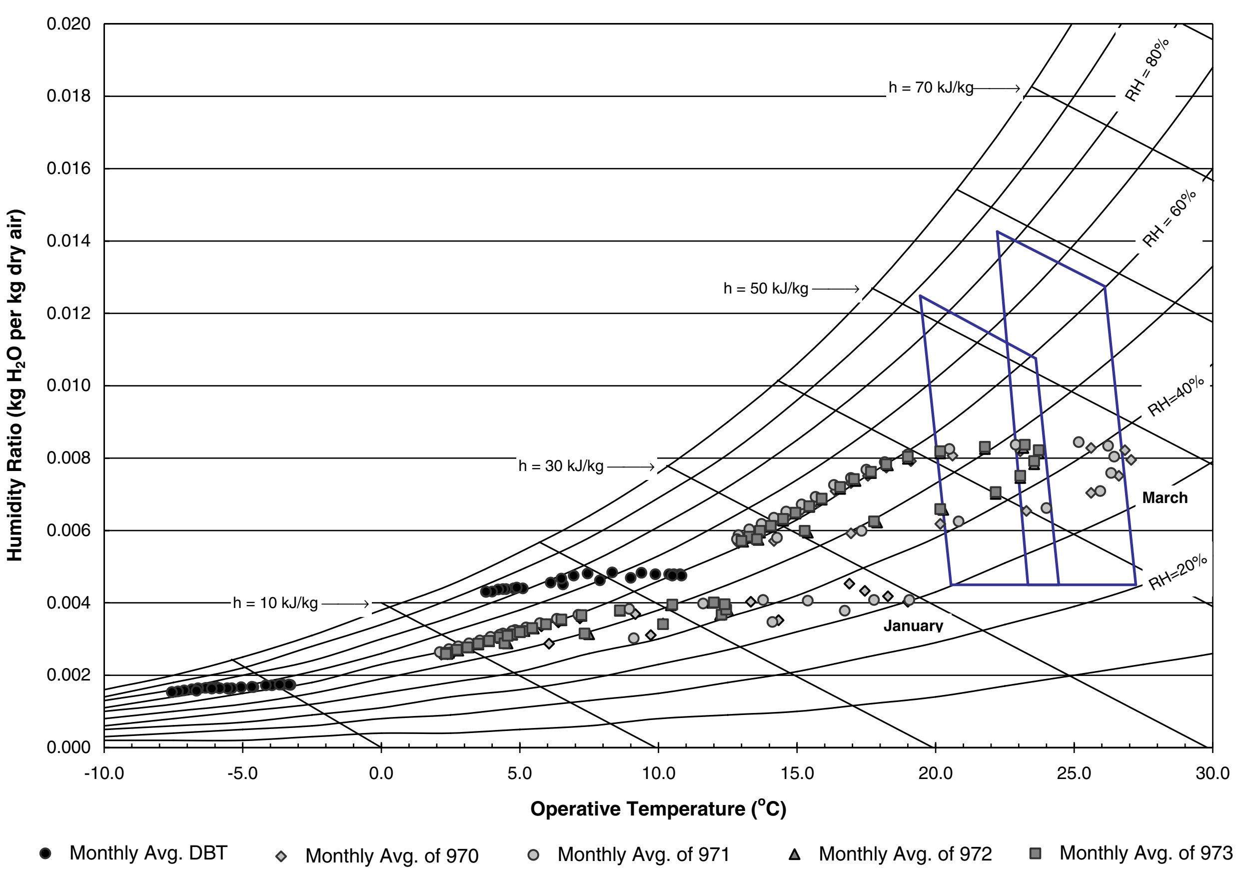

Fig. 7. Hourly average outdoor dry-bulb air temperature and indoor operative temperatures and coincident relative humidity inside the direct gain (DG) test-cell for the months of January and March of 2003.

tor area. The latter approach would reduce the heating energy supplied by the sun and therefore, it would also reduce the Solar Savings Fraction (SSF). The SSF are defined as the dimensionless ratio of the solar savings to the net reference load (Balcomb et al., 1984). Although the definition of SSF implies a ratio that considers the energy supplied by the solar part of a system divided by the total system load, in this experiment the SSF were calculated every hour by dividing the ‘‘heat deficit’’ of any given passive solar strategy by the ‘‘heat deficit’’ of the CC test-cell. The heat deficit in this context is defined as the required energy necessary to raise the indoor operative temperature to 18 °C. Table 4 shows the experimentally derived SSF for all the passive solar heating strategies.

3.3. Trombe-wall (TW)

As mentioned before, the TW test-cell had a ratio of solar collector area (south-facing vertical fenestration) to floor area of 1:2.78. The thermal storage in this strategy was composed of 109 solid concrete blocks that produced a 20 cm thick wall placed directly behind the solar collector area. The thermal storage wall had an area of 4.4 m^2 and included four vents (see Fig. 3), each with an area of 0.1 m^2. The vents of the TW test-cell were left open all the time during the 2002–2003 heating season. The ratio of solar collector area to exposed thermal mass was 1:1.03.

The TW test-cell had a lower thermal storage capacity when compared with the DG test-cell, although both test-cells had the same solar collector area (see Table 2). The results in Figs. 5 and 8 show that, despite its lower thermal storage capacity, the TW test-cell had significantly lower diurnal variations in its indoor operative temperature when compared with the DG test-cell.

The TW test-cell presented relatively small diurnal operative temperature swings during the reported period, with an average and maximum diurnal swing of 3.32 °C and 3.79 °C, respectively. The results presented in this article demonstrate that the Trombe-wall, an indirect gain strategy, produces an extremely stable indoor environment with low variation in the OT. In the view of the author, low diurnal swings should be considered a pre-requisite to achieving thermal comfort. The simultaneous variations in the OT between the south side and the north side of

Table 4
Experimentally derived solar savings fraction

	CC	DG	TW	WW	SS	RP
SSF %	–	50.56	38.95	52.39	29.68	37.91

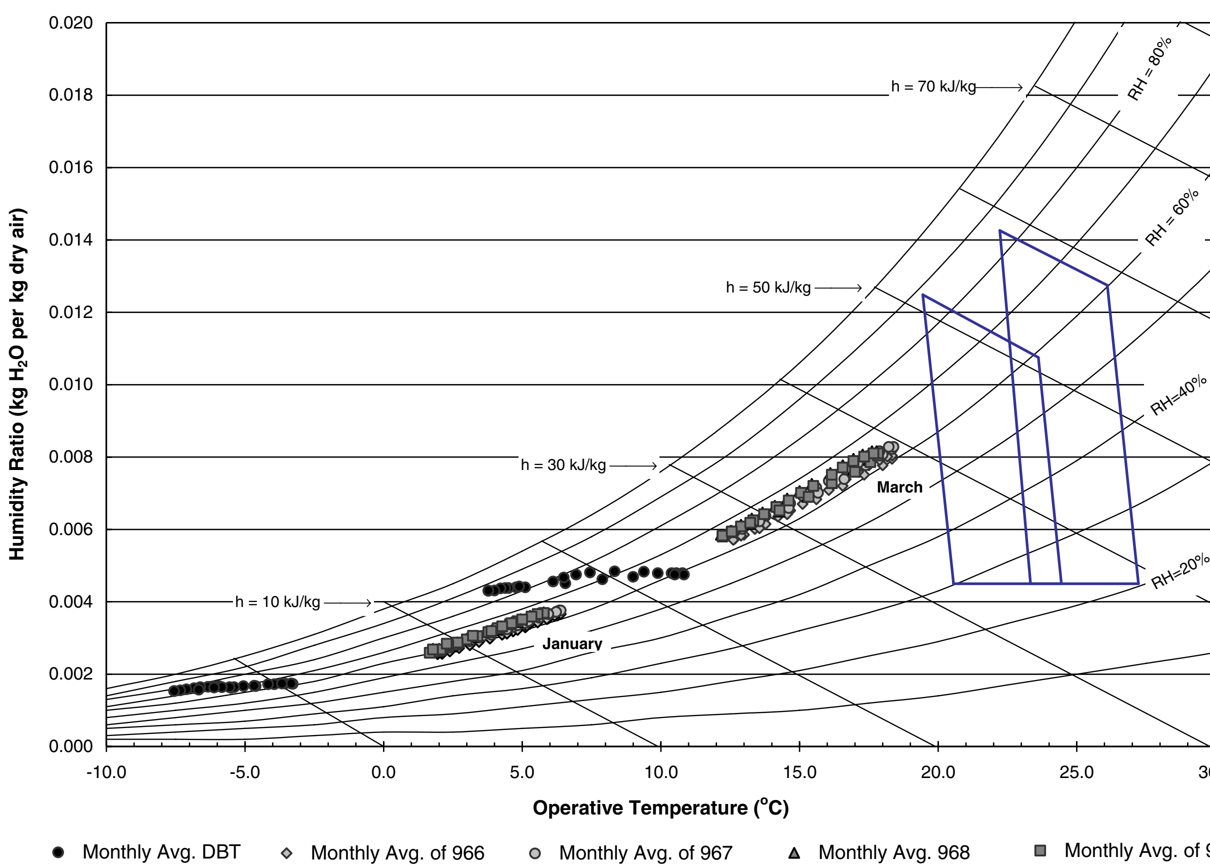

Fig. 8. Hourly average outdoor dry-bulb air temperature and indoor operative temperatures and coincident relative humidity inside the Trombe-wall (TW) test-cell for the months of January and March of 2003.

the TW test-cell were in average 0.45 °C with a maximum variation of 0.52 °C during the period reported. These simultaneous temperature differences are caused by the higher radiant temperature of the Trombe-wall (when compared to the other components of the building envelope).

3.4. Water-wall (WW)

The WW test-cell was a hybrid between a traditional thermal storage wall (indirect gain strategy) and a direct gain strategy due to the fact that the water tanks employed for thermal storage were translucent and had enough separation among them to permit free circulation of the indoor air across the entire space (see Fig. 3). After an evaluation of the results produced by this strategy, it was concluded that the WW test-cell displayed performance characteristics that were more similar to those found in a direct gain strategy. The WW test-cell thermal storage consisted of four translucent Sun-Lite® tubes, each holding 0.25 m^3 of water (250 l) when full (see Fig. 3). Despite its large thermal storage capacity (e.g. 2.84 times the thermal storage capacity of the TW test-cell), the WW test-cell had the second highest maximum diurnal OT swing (the SS test-cell had the second highest average diurnal OT swing), only surpassed by the maximum diurnal OT swing found in the DG test-cell. The average and maximum diurnal OT swings found during the reported period were 4.99 °C and 5.94 °C, respectively. The ratio of solar collector area (south-facing vertical fenestration) to thermal storage capacity (in $m^3$of water) was 1:0.23. According to Brown and DeKay (2000), this ratio of solar collector area to thermal storage capacity would be sufficient to support a SSF of 80%. The average simultaneous variation in the operative temperature between the south side and the north side was 0.98 °C, with a maximum variation of 1.22 °C during the period reported. These simultaneous temperature differences are caused in part by the higher radiant temperature of the Water-wall (when compared to the other components of the building envelope) but also by the solar radiation that freely enters into the south-side of the test-cell. The results presented in Fig. 5 show that the monthly average minimum indoor operative temperature of the WW was always (with the exception of April) above the monthly average maximum outdoor air temperature, which demonstrates the effectiveness of water as a thermal storage medium when compared to masonry and concrete. After a comparison of the hourly average indoor OT and its coincident relative humidity inside the WW test-cell with the outdoor DBT and its coincident relative humidity, one can see that even in the coldest month of January the Water-wall raised the temperature on the south side of the test-cell to almost 15 °C (see Fig. 9).

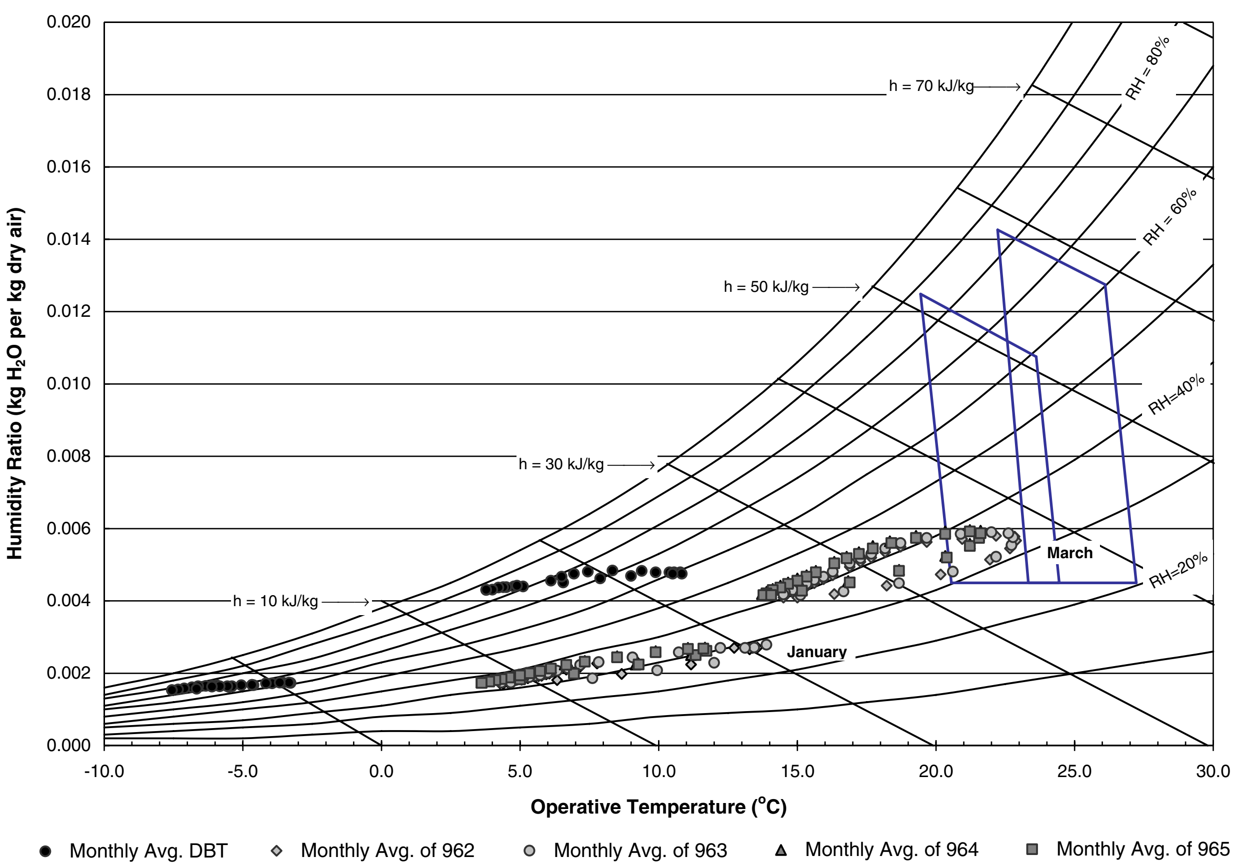

Fig. 9. Hourly Average Outdoor Dry-Bulb Air Temperature and Indoor Operative Temperatures and Coincident Relative Humidity Inside the Water-wall (WW) Test-cell for the Months of January and March of 2003.

3.5. Sunspace (SS)

The SS investigated in this study was attached to a test-cell with a floor area of 11.9 m^2. It featured glazed end walls, a common masonry wall (composed by 84 solid concrete blocks with a wall thickness of 10 cm), and did not include night insulation. According to Balcomb et al. (1984), this system would be best described as *SS-B3*. Consistent with the other test-cells, the glazing used in the SS was clear insulated glass. With the setup described above, the SS test-cell had the second largest average diurnal operative temperature swing during the reported period with an average and maximum diurnal swing of 5.28 °C and 5.74 °C, respectively. The results presented in Figs. 5 and 10 demonstrate that the Sunspace experienced the highest heat losses during the nighttime (and during overcast periods) due in part to the design characteristics of this passive solar heating strategy, but also because the aperture between the Sunspace and the adjacent test-cell was not closed during the nighttime and/or when the temperature in the test-cell exceeded the comfortable range. The larger vertical opening left for access to the glazed part of the sunspace (see Fig. 3) proved to be detrimental to the overall thermal performance of the strategy. The simultaneous variations in the operative temperature between the south side and the north side of the SS test-cell were in average 0.32 °C, with a maximum variation of 0.5 °C during the period reported.

Although the SS strategy displayed the worst performance in this study, it is important to remember that it had the lowest thermal storage capacity of all the test-cells and that the large uncontrolled opening between the sunspace and the test-cell produced higher heat losses (and gains) than those that would be typically found in buildings featuring this passive solar heating strategy. The results presented in Fig. 5 show that the monthly average indoor operative temperature of the SS was approximately 6.7 °C higher than the monthly average outdoor air temperature.

3.6. Roofpond (RP)

The RP test-cell used in this study was based on the Roofpond design used by Larson and Wischman in St. Paul, Minnesota (Marlatt et al., 1984). The system consists of a ‘‘ceiling pond’’ with 20 cm of depth (i.e. a total of 2.38 m^3 of water or 2380 l) under a pitched roof that was conventionally insulated on the north side with clear insulated glass on the south slope. Interior movable insulation was provided by a Thermacore® garage door (R-1.64 m^2 K/W) that moved between the north and south slopes. The movable insulation was automated and during

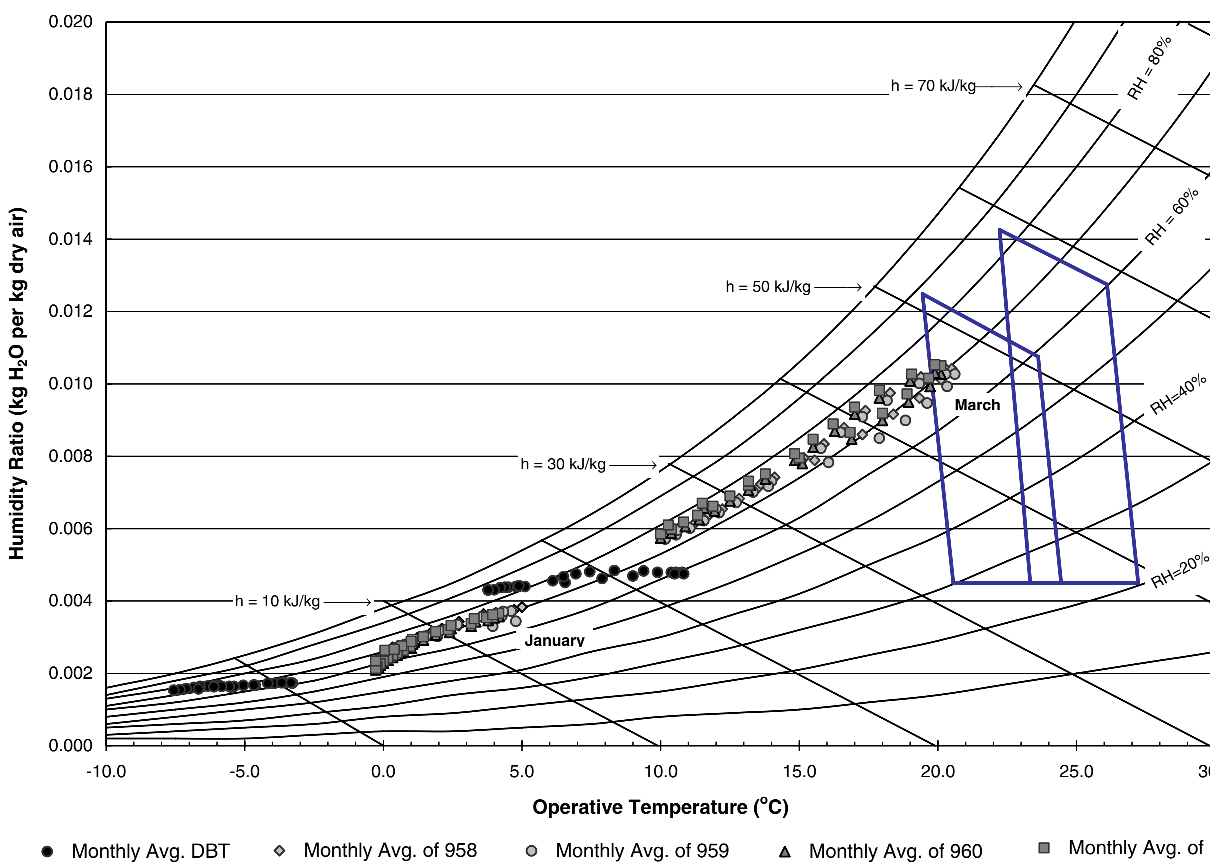

Fig. 10. Hourly average outdoor dry-bulb air temperature and indoor operative temperatures and coincident relative humidity inside the Sunspace (SS) test-cell for the months of January and March of 2003.

the heating season it opened 45 min after sunrise and closed 45 min before sunset. The movable insulation, however, could be programmed to open or close at any desired time. The RP strategy was the only one to feature movable insulation and that clearly gives it an advantage over the other strategies. However, unlike the other strategies, movable insulation panels have always been an intrinsic component of the Roofpond strategy (California Polytechnic State University, 1975; Yellott, 1975; Marlatt et al., 1984). The operable nature of the panels does call into question the Roofpond's traditional classification as a "passive" solar strategy. Nonetheless, Roofponds, including their movable insulation, are considered by most authors a passive solar heating and cooling strategy.

The results in Figs. 5 and 11 show that the RP test-cell had the lowest diurnal variations in its indoor operative temperature when compared to the other passive heating strategies reported in this paper. The thermal stability displayed by the RP test-cell is a consequence of the amount of thermal storage employed (see Table 2) and its placement above the ceiling of the occupied space, which allows it to better collect the energy coming from the sun. The thermal storage in Roofponds is radiatively-coupled to the solar collector area thereby increasing its efficiency to collect solar heat.

The RP test-cell presented the smallest diurnal operative temperature swings when compared to all the other test cells (including the CC), with an average and maximum diurnal swing of 1.24 °C and 1.44 °C, respectively. The results presented in this article demonstrate that Roofponds, as an indirect gain strategy, produce the most stable thermal environments. As stated before, diurnal OT swings of less than 10 °C should be considered a pre-requisite to achieving thermal comfort (Balcomb et al., 1984). In the case of the RP test-cell, there were no significant variations in the OT between the south side and the north side. The average variation was 0.11 °C with a maximum variation of 0.20 °C during the period reported. Given the experimental results obtained in the first phase of this research project, it would be fair to say that the thermal stability of the RP can be compared with that of a mechanically air-conditioned building. It is also important to note that the thermal stability of the RP test-cell was not coupled with sufficiently high indoor operative temperatures (see Fig. 11). The downside of the large thermal storage capacity used in the RP test-cell is that the monthly maximum indoor operative temperature was never able to reach 9 °C during the first three months of the study (see Fig. 5). A way to improve this situation would be to increase the solar gains by adding south facing windows

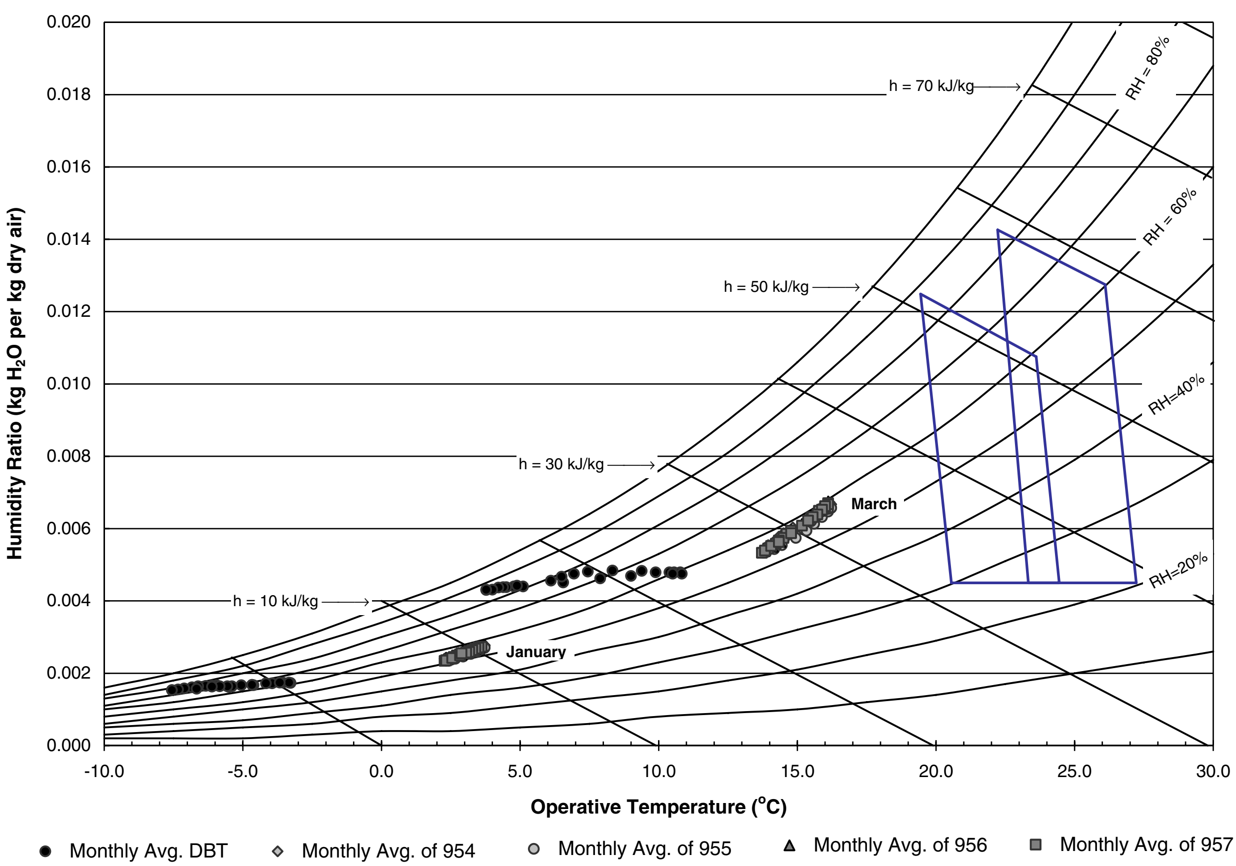

Fig. 11. Hourly average outdoor dry-bulb air temperature and indoor operative temperatures and coincident relative humidity inside the Roofpond (RP) test-cell for the months of January and March of 2003.

to the space below the Roofpond in order to achieve the desirable comfortable temperatures. Due to its large thermal storage capacity, the RP had the best performance during extended periods of overcast sky conditions, which were quite frequent during the 2002–2003 heating season. It is important to highlight that the RP strategy has significant room for performance improvements as it can be easily coupled with any of the other strategies investigated in this project.

4. Conclusions

The main goal of this research project was to identify the limitations of passive solar heating systems to obtain thermal comfort in a challenging climate like that of Muncie, Indiana. With this in mind, and given the spatial limitations of the test site, the test-cells were not configured to be the most efficient, but rather to highlight the potential problems that could arise from the use of these strategies. Therefore, it is important to keep in mind that a building elongated on the east–west axis, with better fenestration and/or night insulation, with internal gains, and, most importantly, with an ability to integrate two different strategies (e.g. Direct Gain and Roofpond), would perform significantly better than the test-cells used in these experiments.

The Solar Savings Fraction (SSF) computed using the experimental results of this study (see Table 4) lead the author to believe that SSF above 80% could be attained with some simple variations of the systems employed in the first phase of this research project. In fact, if one takes the calculated SSF of Direct Gain (approximately 51%) and couples it with those of the RP (approximately 38%), one could end up with an approximate 89% SSF, a similar value to the one reported for the SkyTherm™ North house featuring both a Roofpond and direct gain in St. Paul, Minnesota (Marlatt et al., 1984).

Another important finding of this study is the fact that there could be significant simultaneous operative temperature variations during the daytime between the south and the north side of DG and, to a lesser extent, WW passive solar heating systems. This characteristic of direct gain systems is not desirable for most building typologies. The problem could be accentuated in long spaces, where the distance between the south facade (typically warmer) and the north facade (typically cooler) would lead into radiant asymmetry discomfort issues (ASHRAE, 2004).

A second phase of this research project led to configuration changes of all the test-cells. The results from the first and second phases will reveal via statistical analyses the optimum configurations for each of the studied systems in the Midwestern & Eastern Temperate Climate Zone of the United States.

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