A Simultaneous Modelling Methodology to Analyze Passive Solar Performance of Trombe Walls

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ABSTRACT: In the heating dominated climate of Asheville, North Carolina, maximizing solar gain in a new Visitor Centre for the Blue Ridge Parkway by using segmented Trombe walls along the south façade became the driving force behind the building design. This paper explores the simultaneous use of three analytical methods: hourly 'lumped node' whole building energy analysis (using eQUEST - a DOE 2.2 interface); full-field thermal analysis with RadTherm (heat transfer software) and nPhase (Computational Fluid Dynamics); and hand calculations using the Load Collector Ratio (LCR) correlation tool. These tools were used together to investigate the full impact of the Trombe walls on both energy savings and thermal comfort.
Although we performed CFD simulations for summer and fall conditions, this paper will focus on the winter simulation.

Keywords: energy, comfort CFD, Trombe wall, passive solar

1. INTRODUCTION

Located on the Blue Ridge Parkway, a 439 mile long National Park running from Shenandoah National Park to Great Smokey Mountains National Park, the Blue Ridge Parkway Destination Visitor Centre will provide a host of new visitor services to the Asheville area, including a hi-def theatre, exhibit space reflecting the heritage, history and economy of the region, and other community and visitor services.
The design of the building offers a number of opportunities to take advantage of the moderate climate of Asheville (Figure 3) as well as the spectacular natural landscape into which the building is set. Since the Parkway is primarily experienced by car, creating an intimate experience with the woods, as well as allowing for the famous views, was an important design criterion.

Figure 1: Building main level plan

The building sits nestled into a wooded site oriented 30 degrees east of south, overlooking the Parkway. Sustainable strategies employed include a fully planted roof, daylighting, radiant heated floors, and energy recovery ventilation systems.

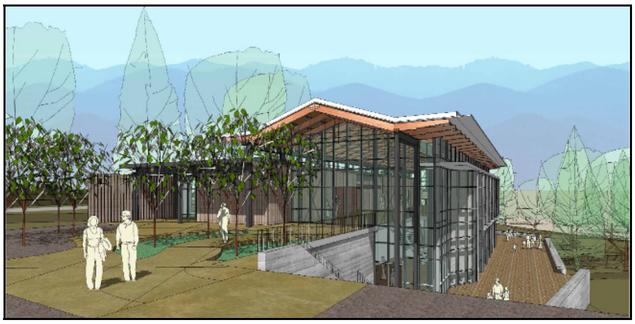

Figure 2: Southwest view of building from plaza

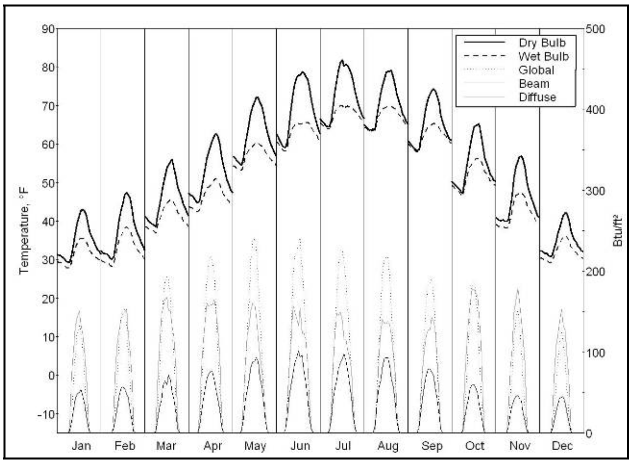

Figure 3: Asheville, NC – Temperature & solar radiation

Figure 3 is a weather summary for Asheville, NC. The summer design temperature is 87˚F and the winter design temperature is 19˚F. It has 4,512 heating degree days, and 748 cooling degree days with fairly strong solar radiation in winter. In this heating dominated climate, the use of passive solar was the primary energy savings strategy. Because the building could not be reasonably rotated on the site to face due south to maximize winter solar gain, the building faces south-east as dictated by the existing site topography. The south façade was partitioned into sections, each facing due south and each becoming its own solar harvester. As shown in Figure 4, each individual Trombe wall was completely integrated into the design of the building, serving as structure, exhibit areas, daylighting elements, air distribution (both for the active HVAC system and the passive Trombe walls), and an intimate space to view the surrounding woods. Each section of wall is about 13' long and they are spaced at about 6' on centre.

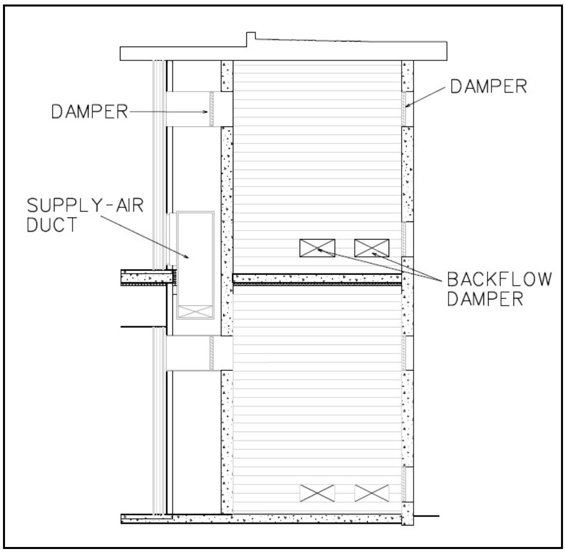

Figure 4: Detail Section of Trombe Walls

As identified in Figure 5 below, Note 1 indicates low dampers into the wall cavity from the building interior. Note 2 indicates a high exhaust vent, with a similar location low on the wall for make-up exterior air. Note 3 indicates a high supply into the building from the cavity as well as a mechanical supply air diffuser immediately below it. An overhang above the walls controls solar exposure in the summer and Note 4 indicates the edge of the brise soleil beyond shading the bottom half of the walls. Dampers at all points will be controlled by the HVAC system, closing or opening the dampers depending on the building's demand. These conditions combine to allow for the walls to heat the building in the winter and vent the skin in the summer.

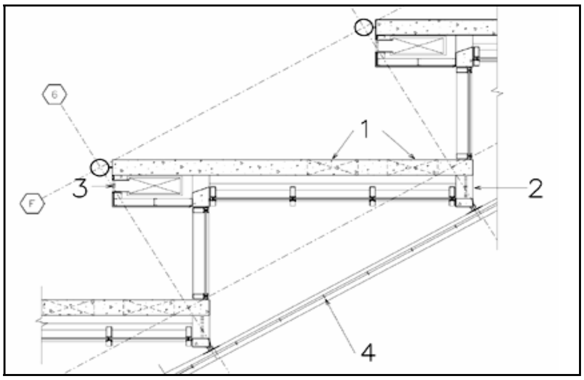

Figure 5: Detail Plan of Trombe Walls

2. NOMENCLATURE

PMV – Predicted mean Vote (Fanger, 1972)
PPD – Predicted Percentage Dissatisfied (Fanger, 1972)
CFD – Computational Fluid Dynamics
MRT – Mean Radiant Temperature.
LEED – Leadership in Energy and Environmental Design (Green building rating system).
LCR – Load Collector Ratio (Balcomb et al, 1983)
Thermal Mannequin – Thermal monitoring node representing human being.

3. SIMULATION METHODS

3.1 Hourly Simulation with eQUEST

Since the project was targeting LEED® Gold certification and energy efficiency was one of the important aspects of the Green building strategy, energy simulation was integrated very early in the design process. A base model (ASHRAE 90.1-1999 compliant) was built in eQUEST to examine the building's energy use profile. Figure 6 shows the base building energy use profile.

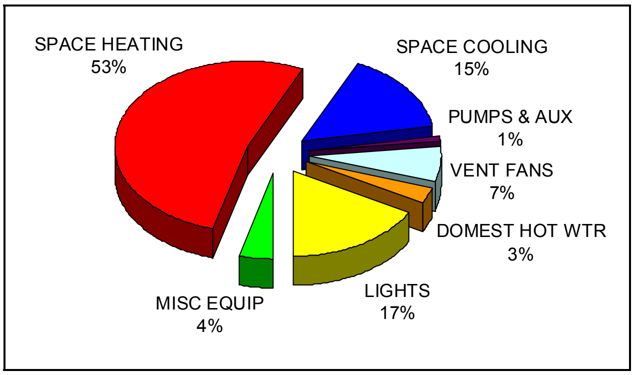

Figure 6: Base building energy use profile

From Figure 6 we see that space heating accounts for 53% of the energy load while lights and space cooling account for 17% and 15% respectively. eQUEST was used to analyze a number of energy efficiency measures, which were compared for cost savings.

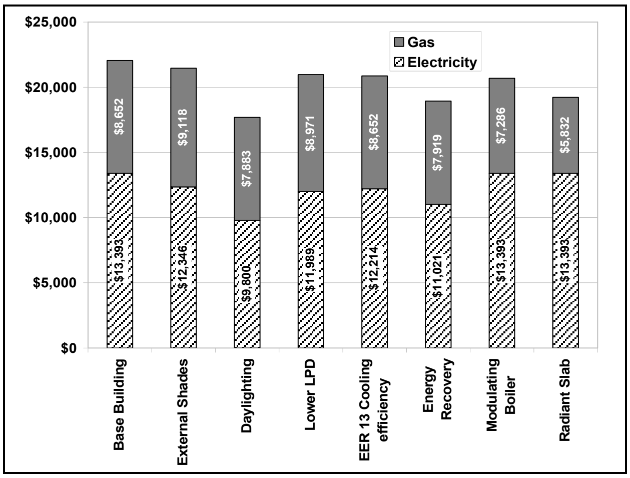

Figure 7: Comparing Energy Efficiency Measures

Figure 7 compares results of the energy efficiency measures examined with eQUEST. The most successful strategies identified were energy recovery, radiant heating in the exhibit hall and classroom, efficient lighting and daylighting.

Since the heating load was the single largest load in the building, passive solar strategies were an integral part of the design strategy, with intelligent orientation, thermal mass and Trombe walls selected. We ran some initial simulations of room temperatures without any HVAC system. Figure 8 shows the results of the simulations taken in January, April and June. We observed that eQUEST was predicting a consistent higher room temperature (around 8˚F) in winter, while both simulations were well over outside dry bulb conditions. In summer, the thermal mass of the buildings actually reduce daytime temperatures below outdoor dry bulb temperatures, and the building with the Trombe walls runs cooler than the one without.

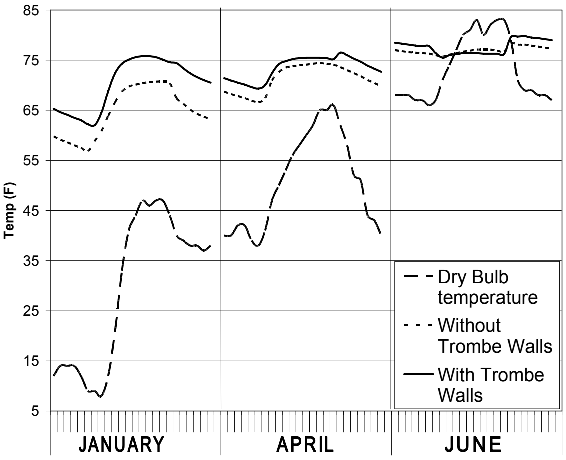

Figure 8: Comparison of interior temperatures

Unfortunately, eQUEST has some shortcomings when it comes to predicting thermal comfort from passive elements, as well as in predicting the overall energy performance of such elements.

3.2 Drawbacks of Conventional Energy Simulation Tools in Modelling Comfort in Passive Buildings

The predicted mean vote (PMV) comfort equation has 6 variables – Air temperature, Mean Radiant Temperature (MRT), Air speed, Relative Humidity, Clothing Level, and Metabolic rate (Fanger, P.O., 1972). Of the six factors, the architect does not control the last two, and in an indoor environment the air movement is fairly small. The first three factors (Air temperature, MRT, and relative humidity) are the most variable in an indoor environment. For most passive solar and hybrid buildings, humidity is not an issue when it is in passive heating mode. Consequently, we did not model humidity for this analysis.

In most mechanically conditioned spaces, a conventional 'lumped node' approach is a reasonable modelling method. Air temperatures are uniform, as are surface temperatures, so comfort conditions will not vary throughout the space. Passively conditioned buildings have greater variations in air temperatures and, more importantly, in surface temperatures. This results in a wider variation of comfort conditions. Conventional hourly simulation packages would not be able to accurately represent these subtle variations in conditions. Furthermore, we needed a simulation method that could model the effects of thermal lag due to thermal mass in the building as well as thermal driven buoyancies.

In order to attain a full-field solution that would be sensitive to subtle differences in MRT, air temperature, and thermal buoyancy, it was determined that computational fluid dynamics (CFD) would be necessary to fully understand the performance of the building in passive mode.

4. CFD SETUP

4.1 The Mesh, CFD and Heat Transfer Model

After exporting the model from a 3D CAD interface (Sketchup) the model was gridded using the gridding tool, GRIDGEN. The grid density varies through the model, getting denser near the points of particular significance to the study (the Trombe walls in this case), and relaxing further from the walls. A total of over 2.1 million unstructured hexahedral elements (427,000 grid points) are included in the mesh. Figure 9 shows the grid mesh through the building and terrain. Note the high density of the mesh around the Trombe walls where the study was focused.

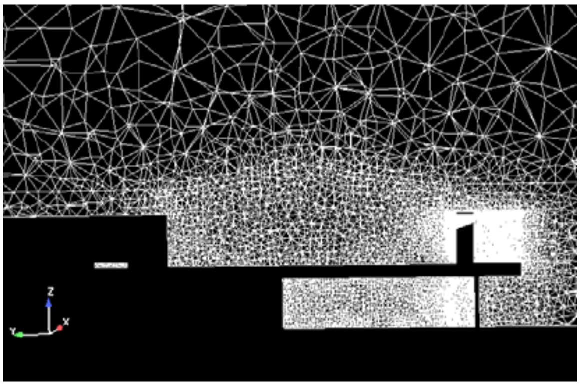

Figure 9: Building grid mesh

The CFD code used for this analysis was NPHASE, which is three-dimensional, unstructured, parallel, and supports an arbitrary number of constituents.

A heat transfer simulation tool, RadTherm (Thermoanalytics 2005), provides the conduction, radiation, and convection portion of the coupled model. Conduction heat transfer is primarily dependent on material properties and geometric thickness. The radiation depends on surface properties and view factors, but RadTherm also includes extensive utilities for modelling environmental factors including the effects of solar radiation as a function of the position of sun and atmospheric conditions provided by an external weather file, full shadowing based on time of day, geometry, reflections, re-radiation between geometric features, glass regions that are transparent to solar radiation but opaque to infrared radiation, and sky radiation.

Table 1 below lists the material property assumptions made for all the simulations.

Table 1: Material Properties used in the CFD and RadTherm simulations.

					Interior		Exterior			
	Thickness (Inches)	**Density (lb/ft3)**	**Specific Heat (BTU/lb°F)**	**Conductivity (BTU/h-ft-°F)**	**Absorptance**	**Emissivity**	**Absorptance**	**Emissivity**	**Transmissivity**	**Reflectivity**
CMU Wall	*8.0*	*123.0*	*0.2*	*0.6*	*0.6*	*0.9*	*0.7*	*1.0*	*n/a*	*n/a*
Insulated Wall Assembly	*8.0*	*12.0*	*0.3*	*0.0*	*0.6*	*0.9*	*1.0*	*0.9*	*n/a*	*n/a*
Interior Wall	*4.0*	*12.0*	*0.3*	*0.3*	*0.6*	*0.9*	*0.6*	*0.9*	*n/a*	*n/a*
Concrete Floor	*6.0*	*144.0*	*0.2*	*0.5*	*0.7*	*0.9*	*0.7*	*0.9*	*n/a*	*n/a*
Concrete Slab on Grade	*6.0*	*144.0*	*0.2*	*0.1*	*0.7*	*0.9*	*n/a*	*n/a*	*n/a*	*n/a*
Exterior Wall	*12.0*	*95.0*	*0.3*	*0.1*	*0.6*	*0.9*	*0.6*	*1.0*	*n/a*	*n/a*
Wood Siding Ext Wall	*8.0*	*12.0*	*0.3*	*0.0*	*0.6*	*0.9*	*0.9*	*0.9*	*n/a*	*n/a*
Green Roof	*9.1*	*52.0*	*0.3*	*0.0*	*0.9*	*0.9*	*0.3*	*.75?*	*n/a*	*n/a*
Trombe Wall Glazing	*0.5*	*140.0*	*0.2*	*0.3*	*0.2*	*0.0*	*0.2*	*0.0*	*0.6*	*0.3*
Trombe Wall Glazing	*0.5*	*140.0*	*0.2*	*0.4*	*0.1*	*0.0*	*0.1*	*0.0*	*0.7*	*0.2*
General Building Glazing	*0.5*	*140.0*	*0.2*	*0.4*	*0.2*	*0.0*	*0.2*	*0.0*	*0.6*	*0.2*

4.2 Thermal Mannequin Setup

A drawback of RadTherm in architectural analyses is that it is set up as a surface modelling tool and cannot provide MRT solutions for the space between the surfaces like a CFD model. In architectural analyses this is crucial for analyzing comfort conditions at different points in a space.

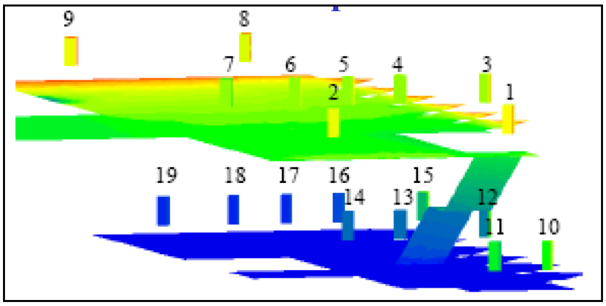

Figure 10: Location of thermal mannequins.

In order to be able to analyze mean radiant temperatures for this building, thermal mannequins were set up throughout the model. The thermal mannequins were six-sided cuboids one foot wide by one foot deep by six feet tall (roughly representative of a human figure). Figure 10 shows the location of the mannequins in an isometric view of the building. The temperatures for each of the mannequins was taken as the average of the six sides, giving it a mean temperature representative of the conditions a person would be exposed to at that location.

4.3 Simulation Assumptions

The simulation was performed with a constant floor temperature of 68˚F to approximate the effect of the radiant floor. The dampers were modelled as closed to the outside (top) and open to the inside (top & bottom) at all times. There were no internal heat gains (people, equipment, etc) modelled and no HVAC system modelled for this condition.

4.4 Weather Conditions

In order to make full use of the limited time and money available for this study, we chose three representative days from the Asheville TMY2 weather data for our analysis:

1. An extreme winter condition: December 21st was chosen as a good design condition representative of an extreme winter day with adequate sunshine to power the Trombe walls.
2. An extreme summer condition: Initially we thought of using the summer solstice, but examining the weather file and initial energy simulation showed July 4th to be a hotter day and the peak cooling condition for the building.
3. A fall condition: We were also concerned that there would be a time of the year in fall when the sun would be low enough in the sky that the Trombe walls would not be shaded, but the outdoor temperature would still be relatively warm.

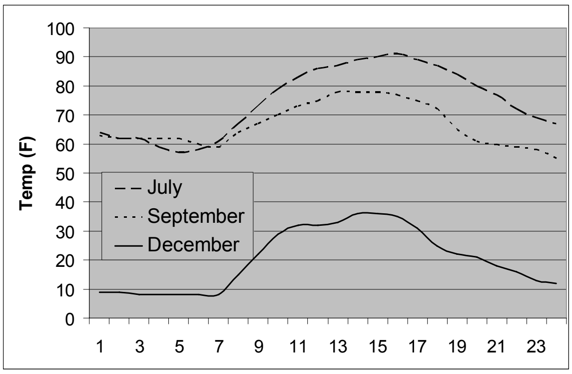

Figure 11: Temperatures for conditions analyzed.

5. CFD RESULTS & ANALYSIS

5.1 Low Mass Considerations

Typical Trombe wall applications use the thermal mass of the wall to stabilize the building temperature over a diurnal cycle, releasing much of their heat at night. Since this building is not operational at night, there were concerns that a heavy mass Trombe wall would be counterproductive, especially early in the morning. We decided to use vented Trombe walls to alleviate some of the early morning thermal lag. We also decided that along with the concrete Trombe walls we would test a low mass, highly insulated Trombe wall and compare their performances. Our hypothesis was that the lower thermal mass would be less of a capacitance, and allow the air cavity to heat up faster, transmitting the heat more efficiently to the interior. We were concerned that the radiant effect would not be present with the low mass option, and that the air cavity could overheat.

After reviewing the results of the high mass simulation, it was clear that it was retaining heat through the night, and stabilizing the temperature over the diurnal cycle, maintaining the building temperature well over outdoor dry bulb temperatures at all times. We concluded that the low mass proposal, in the interest of budget and time, be abandoned.

5.2 Winter CFD Simulation

There is a sizable convective current that develops in the Trombe walls, heating the air in the room to well over 60˚F in the afternoon. It is anticipated that with internal heat gains (people, equipment etc), this will rise a little more. At night the temperature drops down to around 50˚F, but this is still 40˚F above outside conditions.

One of the phenomena we noticed was reverse thermo-siphoning in the Trombe walls at night caused by cold air dropping through the lower dampers (Figure 13). We introduced backflow dampers to prevent this. We will also control the amount the dampers open to allow the air in the Trombe wall cavity to heat up further. Finally, we reduced the Trombe wall cavity air space to 6 inches (from 8 inches modelled) to allow the air to heat up further.

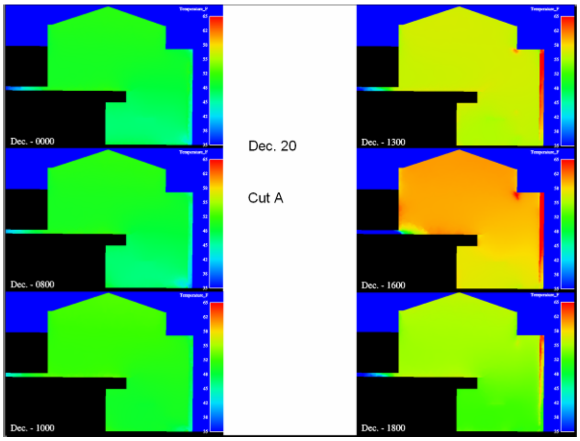

Figure 12: CFD results for Dec 20th – Transverse Section

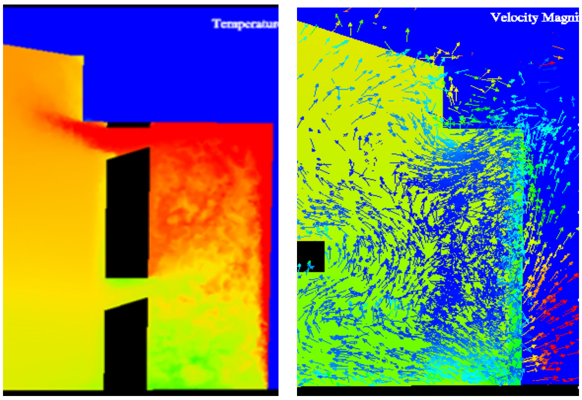

Figure 13: CFD results for Dec 20th – Sections through the Trombe wall

One of the things we noticed in the winter simulations was that the warm air from the Trombe walls was stratifying at the top of the room, with ceiling temperatures around 7-8˚F warmer than floor temperatures. To counter this, we incorporated ceiling fans into the design, to destratify the air, and provide more warmth at the floor level.

The CFD simulations show that the Trombe walls are definitely adding benefit to the building in winter, keeping the building at 30 – 40˚F above the outside temperature even at night. Based on these results, we feel that the building will perform well in winter.

5.3 RadTherm Analysis

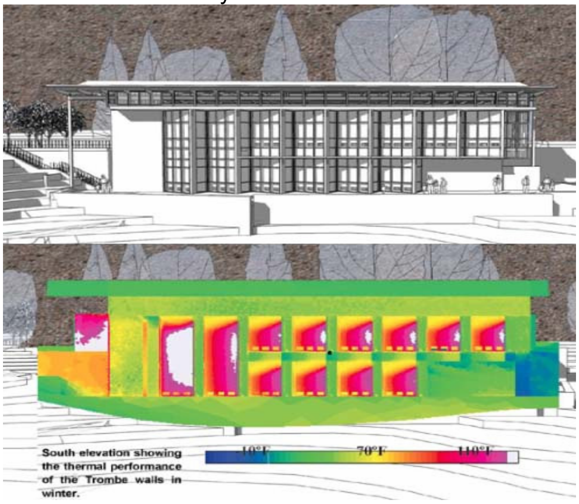

Figure 14: South elevation – comparison of Sketchup shadow study & RadTherm analysis

Figure 14 compares a sun-strike study of the building with the RadTherm thermal study. We see the Trombe wall surfaces attaining temperatures above 115˚F. Figure 15 is a line plot of average interior and exterior surface temperatures for the Trombe walls. There is a thermal lag of around 3 hours between the inside and outside surface, which is less than we see on some other Trombe walls because it is being vented. There is around a 6 hour thermal lag from exterior dry bulb temperatures. The 24 hour analysis for the winter condition has a much colder initial temperature (a preceding cloudy, cold day), causing the thermal lag readings to be slightly skewed.

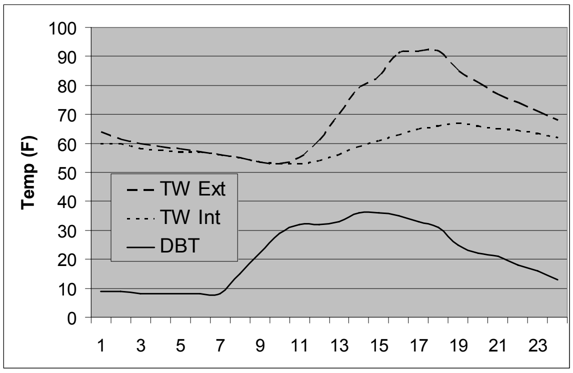

Figure 15: Comparing Trombe wall Interior & Exterior temperatures

We also looked at the MRT values from the thermal mannequins placed in the model (Figure 10). We found that thermal mannequins 8 & 9 were overheating in the morning (because of the eastern curtain wall). We were not concerned about this because of the tree cover on the east. We were more concerned about mannequins 1, 2, 10 & 11 were overheating and the temperatures were even higher in a summer situation.

Based on the MRT analysis, we decided to shade the west curtain wall. We performed a series of light strike studies examining the use of vertical fins to cut off the low sun angles. In the end we concluded that operable shades would be sufficient to cut down heat gain on the west façade.

Concern about the overheating of mannequins 1 and 10 led us to perform light strike animations of the Southwest corner, which showed that it was not getting adequate shading, leading to large amounts of radiation entering through the curtain wall. Based on this information, we removed the curtain wall on the south side of the building, and replaced it with thermally insulated concrete.

6. LCR METHOD

The CFD simulation was performed for 3 select days to gauge occupant comfort and test the Trombe wall mechanics. However, CFD is not a useful tool to judge overall energy saving over a year, since it is best used as a 'snapshot' tool. In order to estimate the annual energy contribution of the Trombe walls, we used the Load Collector Ratio (LCR, Balcomb et al, 1983) correlation method to determine the solar savings fraction of the Trombe Walls. The total energy savings contributed by the Trombe walls is estimated to be 128.5 million BTU/year, which is equivalent to 35% of the buildings space heating load.

7. LIMITATIONS

1. Due to time and budget constraints, we were not able to rerun the summer simulations the way we would have liked. We had to base our analysis on intelligent conjecture from the simulations that were completed.
2. Although the RadTherm simulations were run in 48 time steps of 30 minutes, the CFD simulations were restricted to 6 time steps.
3. We had to restrict the simulations to 3 representative days of the year, and so we had no way of gauging the annual energy saving from the Trombe walls. We ended up hand calculating this from the LCR correlation tool (Balcomb et al, 1983).
4. We could not perform a detailed comfort analysis because of the limitations in the MRT outputs from RadTherm.

8. CONCLUSIONS

8.1 Building performance:

The CFD simulations show that the Trombe walls are providing significant benefit to the building in winter, keeping the building at 30 – 40˚F above the outside temperature even at night. Based on these results, we feel that the building will perform well in winter. The fall simulation showed the building attaining comfort conditions completely passively. The only area of concern was the performance in summer, but we feel that the thermal mass helps in this situation. Furthermore, the heating load on this building is more than triple the cooling load, so the winter performance is more important.

The Trombe walls contribute an annual energy savings of 128.5 million BTUs and 1,500 $.

8.2 Thermal modelling approach:

The simultaneous modelling methodology was useful and informative, with each method making up for the shortcoming of the other 2 methods.

While there were advantages to the coupled model approach, there were some limitations as well. The inability to have a full field CFD type MRT calculation in RadTherm necessitated the use of thermal mannequins and made it infeasible to perform a Fanger PMV/PPD type comfort study.

We could have made better use of the limited time & resources available for this study by experimenting with each simulation with a sparser grid to get preliminary results before going to the finer grids. We recommend this procedure for such studies.

9. ACKNOWLEDGMENTS

We would like to acknowledge the efforts of the Applied Research Laboratory at Penn State especially Dr. Leonard Joel Peltier, Dr Sue Ellen Haupt, Dr Jim Dreyer.

10. REFERENCES

[1] ASHRAE , *Handbook Fundamentals,* 2001

[2] ASHRAE , *Standard 90.1 - Energy Standard for Buildings Except Low-Rise Residential Buildings*, 1999

[3] Fanger, P.O., *Thermal Comfort – Analysis and Applications in Environmental Engineering,* McGraw-Hill, 1972

[4] Haupt, S.E. et al, *Thermal Effects On Dispersion About Structures*, 14th Joint Conference on the Applications of Air Pollution Meteorology , 2006

[5] Moore, F., *Environmental Control Systems – Heating, Cooling, Lighting*, McGraw Hill, 1993

[6] Sami, V, *Modelling Thermal Comfort Delivered By Wind Towers Using Computational Fluid Dynamics*, Arizona Sate University, 2003.

[7] Sami, V, *Applying Computational Fluid Dynamics to Analyze Natural Ventilation & Human Comfort in Buildings*, – ASES 2003

[8] Sami, V, Gassman, J *Examining the Role of Full Field Solutions in Analyzing Passive Solar Architecture*, – ASES 2006