USING ENERGY SIMULATION AND REAL-TIME DATA MONITORING TO INVESTIGATE THERMAL PERFORMANCE OF EXTERIOR CAVITY WALLS

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ABSTRACT

Integrated cavity-wall systems are typically designed to shade the exterior of buildings. They can also eradicate daytime heat absorption by thermal convection. The combined heat loss through the natural nighttime sky radiation, the cavity wall shading effect, and the thermal convective loop results in a significantly improved building envelope performance.

This paper outlines the design, construction, and monitoring of a south-facing cavity wall system integrated into a single-family residence in Southern Arizona. Implemented as a 'heat transfer regulator', the cavity wall functioned as a thermal break between the external and internal thermal forces through the south wall of the building envelope. The outside "Sol-air" surface temperatures of the cavity walls were found to be consistently lower than the standard non-cavity walls during extreme summer conditions. This was due to the combined effect of shading as well as stack-ventilation heat loss triggered by solar radiation received by the south cavity walls. Results from the field data monitoring and computer simulated results yielded a minimized operation of mechanical system, reduction in energy consumption, and optimized human thermal comfort.

INTRODUCTION

In Hot-arid climates, extreme diurnal temperature swing occurs due to longwave radiation exchange to the clear sky conditions of the region. In such heat-dominated regions, intense solar energy absorbed by building envelopes through roof and walls during the day is radiated back through longwave radiation into the clear night sky, thus helping cool the building. Furthermore, integrated 'cavity-wall systems' provide an added opportunity to shade the exterior of a thermal envelope and eradicate day-time heat absorption by thermal convection. Cavity walls consist of two 'skins' separated by a hollow space (cavity). Therefore, the combined effect of 1) heat loss through nighttime blackbody radiation, 2) the wall shading effect, and 3) convective heat loss through the cavity, can improve building envelope thermal performance beyond conventional insulation.

Cavity walls are not new, they have been observed in ancient Greek and Roman structures. Some stonewall of cavity type construction at the Greco Roman town of Pergamum still exists. Cavity walls were first built in the United States late in the 19th century. However, it was not until 1937 that this type of construction gained official acceptance by any building or construction agency in the United States. Since then, interest in and use of cavity walls in this country has increased rapidly. This has resulted in extensive testing to determine cavity wall properties and performance.

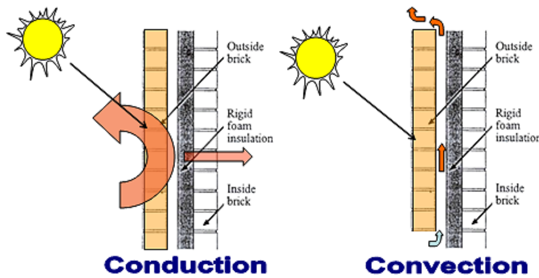

Figure 1 Thermal performance of cavity wall

PROJECT DESCRIPTION

In 2005, the University of Arizona's College of Architecture and Landscape Architecture (CALA) through the Drachman Institute (DI), responded to a City of Tucson's proposal to develop an energy efficient affordable housing demonstration project base on a high-end market-rate housing development at the edge of the City known as the Community of Civano.

Figure 2 Community of CIVANO, Tucson, Arizona

The City of Tucson allocated a site for the project in a neighbourhood called Barrio San Antonio located near a highway and railroad (see Figure below).

The site and proposed residential units will become a community showcase of affordable, energy-efficient housing, demonstrating regional principles of sustainable design in hot-arid regions.

Figure 3 Barrio San Antonio, Tucson, Arizona

The project team proposed to develop the site to include five single-story residences, all vary between 92 m² (1000 ft^2) to 130 m² (1400 ft^2) and built with different construction materials for the purpose of comparing their performance through first data monitoring and then building simulation.

Figure 4 Proposed housing development

Three of the five homes will utilize light-gauge steel framing, concrete masonry units and mud adobe constructions respectively, while the subject home is constructed using conventional wood framing. The compound of the five residences will become a community showcase of affordable, energy-efficient housing, demonstrating regional principles of sustainable design in hot-arid regions.

The house under investigation is called the DDBC2 and is a single story three-bedroom 100 m² (1072 ft^2) built with wood frame. The house long axis is facing south to take advantage of solar orientation.

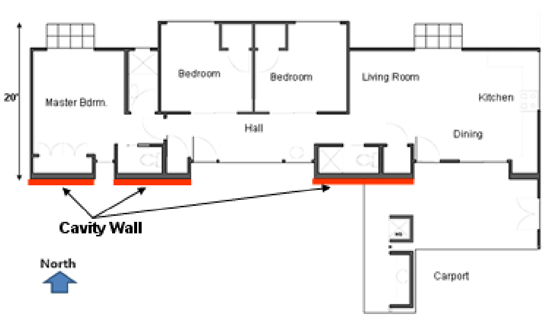

Figure 5 Floor plan of DDBC2 wood frame house

Intended as heat regulator, the vented roof is designed to have a single slope towards the east to facilitate the movement and dissipation of warm air collected on the roof and from the south wall.

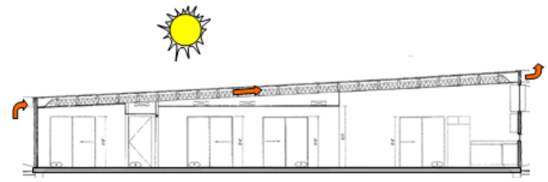

Figure 6 Longitudinal section showing vented roof

The south wall functions as a thermal break and thus has a 9 cm (3.5") air cavity vented towards the top of the wall with inlet vents from the bottom.

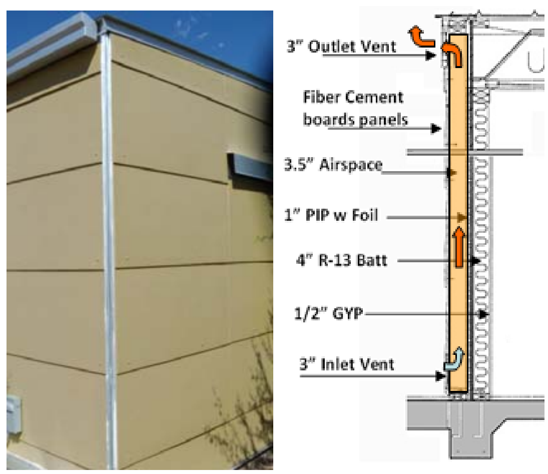

Figure 7 Section through the south-facing cavity wall

Objectives of efforts in this project include the following:

1. Analysis and synthesis of goals and outcomes of Civano energy and water conservation strategies to date, resulting in guidelines for transfer of Civano-based technologies to the lowest cost strata of housing construction.
2. Application of energy efficiency and water conservation technologies outlined in the guidelines to the design of four model home plans and construction of two of these homes for affordable homeownership in Barrio San Antonio in Tucson.
3. Monitoring of energy efficiency and water conservation data for one year for the first two homes built in Barrio San Antonio and modifications to model plan documents based on results.
4. Dissemination of post construction evaluations of efficacy of strategies through public workshops and one-on-one consultation sessions with local builders/developers of affordable housing.

PERFORMANCE MONITORING

After the DDBC2 house was constructed and occupied, the authors began the performance monitoring process. Data acquisition included monitoring and collecting both the site climate and the building surface and air moisture and temperatures. To first monitor the site climate conditions a central weather station was installed on a structure near the house and on the highest and most uninterrupted location. The weather station is a HOBO U30-NRC capable of collecting eight major climate parameters including dry-bulb and wet-bulb temperatures, relative humidity, wind and gust speeds and directions, and global solar radiation.

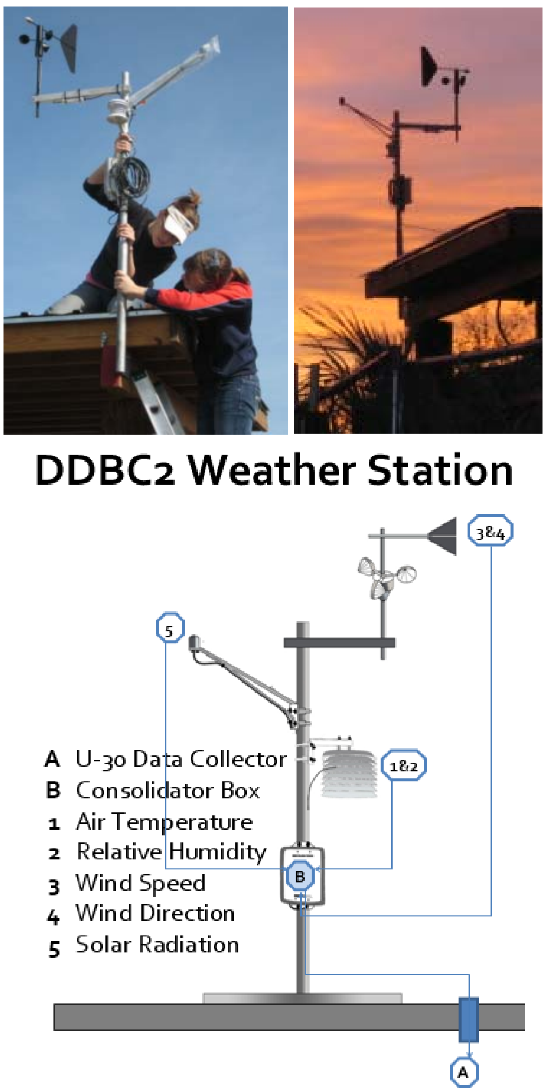

Figure 8 Above: CALA Students installing the station Below: schematic diagram of climate data collection

Indoor data collection was achieved through the installation of a HOBO U30 GSM Cellular Data Logger. It is a remote data logging and monitoring device with built in cellular communications that can be reconfigured and adapted to measure a wide variety of parameters. Up to 15 channels of data can be recorded and monitored remotely via Onset's web-enabled software platform.

Limited by the 15 parameters the U30 is collecting, the author strategically distributed different sensors around the residence to monitor the following:

- Bedroom and living room air and surface temperatures
- Living room mean radiant temperature, air temeperature and relative humidity
- Roof surface temperature
- Cavity wall outside and inside surface temperature
- Cavity inlet and outlet air temperature
- Cavity air-movement

During the monitoring phase, real-time data was instantaneously available for remote viewing by faculty and students with internet access from any location in the world. Twenty two sets of data were retrieved at 3 minute intervals and time-stamped every 15 minutes.

VERIFICATION AND ANALYSIS

Data retrieved from the weather station was first analyzed to verify the accuracy of the installed logger and sensors systems. Solar radiation, temperatures and relative humidity data were found to be displaying responsive thermodynamic properties of moist air. On a diurnal cycle, morning solar radiation causes air temperatures to rise and relative humidity values to drop (see figure below).

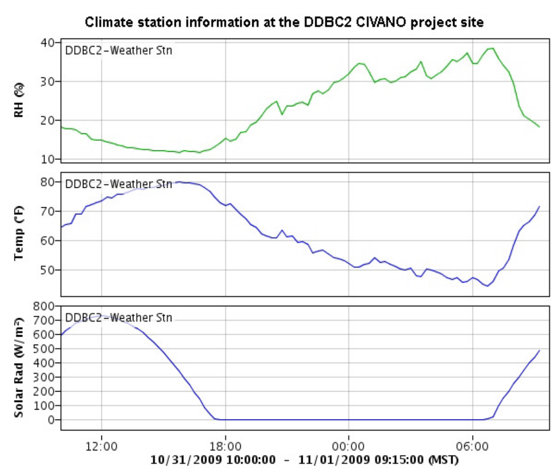

Figure9 Thermodynamics properties of moist air as displayed by the data acquisition system.

Results from the collected cavity wall data demonstrated anticipated results. During the day in the extreme summer months the cavity wall accomplished two primary functions: 1) acting as a shading device, air temperature inside the cavity was reduced by up to 40% compared to the exposed non-shaded portion of that wall. 2) the direct solar radiation raised the Sol-air temperature of the exterior triggering a convective thermal loop resulting in increased heat loss.

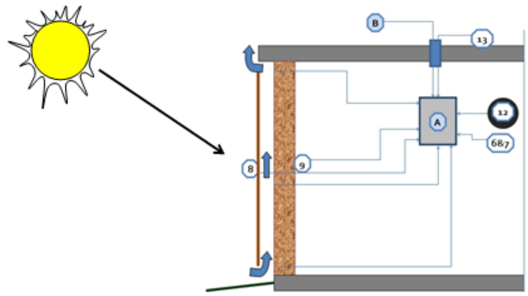

Figure10 Effect of solar radiation warming the outside surface of the cavity wall and activating the convective loop inside the cavity

For example, extreme daytime high surface temperature during August 21st forced air velocity in the cavity to record a high of 1.534 m/s (301.9 fpm) and a low of 0.709 m/s (139.5 fpm). According to the Beaufort Scale (a scale from 0 calm to 7 near gale, that describes the effect of different wind speeds) this air movement is described as "Light Air" where smoke drift shows light air movement and wind vanes don't move, while tree leaves barely move. Additionally, as heat was carried from the wall surface by convection, the daytime temperature of the inlet air at the base of the cavity was cooler than that of the outlet air from the top of the cavity by an average of 6.5 °C (12°F). This observation, when combined with the shading effect and the night-time blackbody heat loss, yielded a significant improvement in thermal performance of the building envelope.

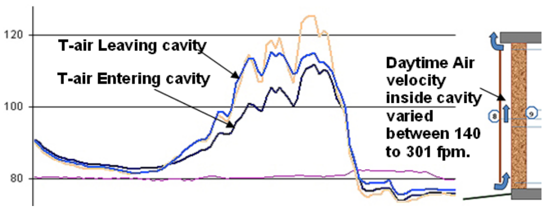

Figure11 Performance of cavity wall

To understand the effect of the rising temperature as the main force on the cavity convective air movement, a plot of the data in August 21st is illustrated in the figure below. As the sun rises about starts to hit the south façade, the temperature inside the cavity is on the rise thus triggering the convective loop. When the sun is setting, the temperature drops and now the air inside the cavity is still.

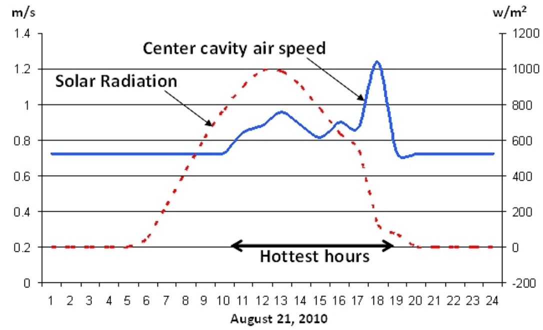

Figure12 Diurnal solar radiation data verses cavity air movement

ENERGY SIMULATION

To estimate the impact of the cavity wall on the thermal performance of the DDBC2 wood frame residence, a computer simulation was used to predict the energy consumption before and after the implementation of the cavity wall. This way, the contribution of the cavity wall to the thermal performance can be assessed.

To simulate the house performance, The Energy-10 V1.8 computer software was used. Energy-10 is a software component of a project to develop design guidelines for low-energy buildings--generally buildings 1000 m² (10,000 ft²) or less--that can be characterized by one or two thermal zones.

The whole house energy performance of the 100 m² (1,072 ft²) DDBC2 wood house was predicted and the total annual cooling and heating consumption without incorporating the cavity wall design were found to be 6,995 kWh (69.95 kWh/m²) (22.3 kBtu/ft²) and 3,123 kWh (31.23 kWh/m²) (9.9 kBtu/ft²) respectively.

To simulate the effect of the cavity wall, two adjustments had to be made to the input file in Energy-10:

1. Since the outside surface of the envelope's south wall is shaded by the 2 cm (¾") fiber cement cavity wall, the solar absorption value had to be minimized to zero compared to the 0.8 absorptance value of the original case.
2. Since the convective loop inside the cavity wall generated an average 1.5 m/s (300 fpm) air movement, the wall cooefficient of heat loss by convection of the outside airfilm is adjusted in the simulation to U=33.33 W/m².°K (U=5.88 Btu/hr.°F.ft²). . The original U=22.7 W/m².°K (U=4.00 Btu/hr.°F.ft²) outside film coefficient value was selected to represents annual average wind speed of 1.34 m/s (264 fpm) in dense urban areas in Tucson.

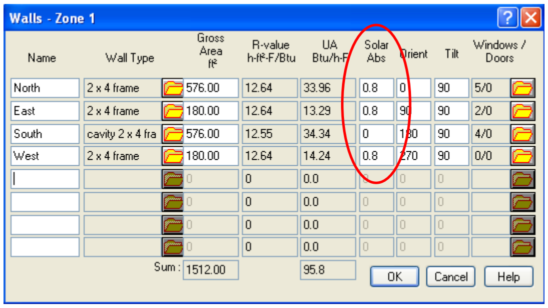

Figure13 Energy-10 input screen showing the solar absorptance value change to zero at cavity locations

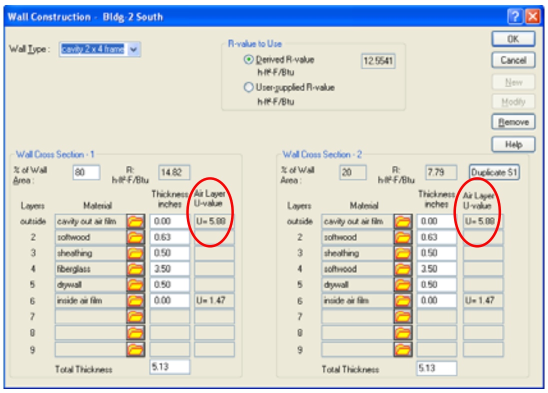

Figure14 Energy-10 input screen showing the new air-layer U value of 5.88

After the south facing cavity walls were simulated using the input changes listed above and shown in the Energy-10 input screens, the total annual cooling and heating consumption values changed to 6,600 kWh (66.0 kWh/m²) (21.0 kBtu/ft²) and 3,273 kWh (32.7 kWh/m²) (10.4 kBtu/ft²) respectively. Although the heating consumption slightly increased, the cooling saving yielded an overall annual 5.8% saving.

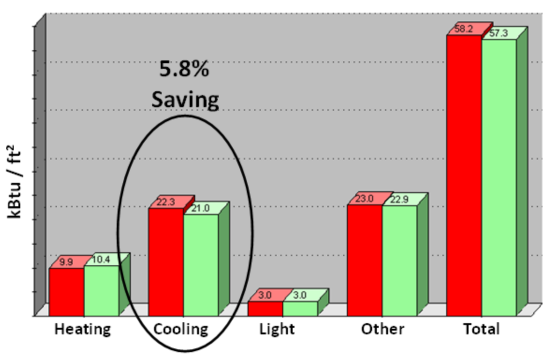

Figure15 Annual cooling energy savings as predicted by the Energy-10 software

FUTURE WORK AND THOUGHTS

Although the above results demonstrated annual cooling energy savings, greater benefits could be achieved from the cavity wall system. First, we could have populated the east and west walls with the same cavity wall and the results would have yielded more energy savings.

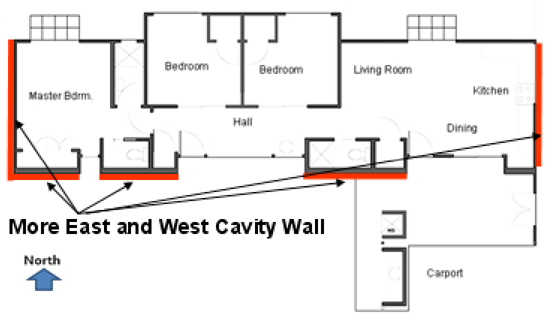

Figure16 The addition of east and west facing cavity walls can greatly increase the cooling energy savings

In addition, we could have created operable or barometric openings that will couple the house air with the cavity air so that we can harvest the rising hot air during winter days or depressurize the house using the updraft chimney of the hot air during summer and bring cooler outside air from the north side. This would have been very analogous to the well known passive solar strategy called Tromb Wall.

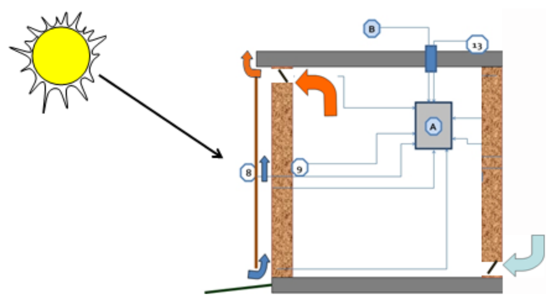

Figure17 New cavity wall summer configuration showing coupling the convective loop with house inside air

CONCLUSION

Cavity wall design has been observed for a long time way back in the Greek and Roman structures. They gained official acceptance and application rapidly and thus underwent extensive testing performance prediction. The research team at the University of Arizona's CALA implemented the cavity wall design as one appropriate energy conservation strategy in the desert southwest. A design/built single family residence demonstrated how a cavity wall system performed as a 'heat transfer regulator', and functioned as a thermal break between the external and internal thermal forces through the south wall of the building envelope. This was due to the combined effect of shading as well as stack-ventilation heat loss triggered by solar radiation received by the south cavity walls.

ACKNOWLEDGEMENT

The author would like to recognize Professor Mary Hardin, director of the DDBC design/build outreach program at CALA for her collaboration and support of the project, Professor Richard Eribes, for the design of the DDBC2 house, Adjunct research professor Stefanie Gurstle who worked very hard with the author on the installation and configuration of the data acquisition systems, and the Homeowners. Last but not least the author recognizes two senior students Heidi Grimwood and Amanda Spear without whos generous efforts and energies this work could have never been completed.

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