

Experimental Validation of the EnergyPlus Low-Temperature Radiant Simulation

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ABSTRACT

The EnergyPlus low temperature radiant model was experimentally validated by comparing measured data with results predicted by the model for radiantly heated and cooled residence. The measured data were obtained from an instrumented house located in Carefree, Arizona, and monitored by Arizona State University.

The study showed that that the low temperature radiant model is sensitive to both the construction parameters, including specification of the thermal mass, and the system parameters. Interaction of the complex thermal processes that result in a given thermal comfort level can be accurately predicted by a carefully tuned EnergyPlus model. On the other hand, a high degree of uncertainty in either the building specification or the system specification can lead to significant errors in the predicted space comfort and energy consumption.

INTRODUCTION

Hydronic radiant systems have become popular as an alternative to conventional forced-air systems due to their potential for energy savings and better thermal comfort (uniform cooling and heating distributions). A number of papers (Athienitis and Shou 1991; Carpenter and Kokko 1998; Olesen 1994; and Simmonds 1994) support system performance claims made by manufacturers of the radiant systems. Nevertheless, there is not a consensus on either the optimal configuration or the range of application of low temperature radiant systems. This is due to a lack of both experimental data sets and experimentally validated design tools for radiant systems.

With the recent release of EnergyPlus (Crawley et al. 2000), designers now have the opportunity to determine whether the radiant systems are viable for a specific building and climate. EnergyPlus includes an integrated radiant system model developed by Strand and Pedersen (1997). Recently several features related to the radiant system models were added to

EnergyPlus. These features include enhancements to allow more than one radiant surface in each zone, improved control algorithms for radiant systems, and coupling of radiant system to the condenser loop.

In order to use the radiant system model in EnergyPlus with confidence, some sort of validation of the EnergyPlus radiant model is essential. In this study, the EnergyPlus program was validated against existing experimental data monitored at the Carefree house (Scheatzle 2000). Essential information including measured data, weather data, house plans, and system schematics were obtained directly from the university research team who supervise, control, and monitor the space conditioning system in the house. In the following sections, the building and system descriptions of the Carefree house are first presented. Comparisons between experimental data and results predicted by EnergyPlus are then discussed. Finally, conclusions and recommendations resulting from the study are provided.

THE CAREFREE HOUSE

The Carefree house is a residential building that utilizes radiant heating/cooling systems to provide indoor environmental control and thermal comfort. The house is located in Carefree, Arizona, with latitude of 33.8° N and longitude of 111.9° W. The house is a single-story building with a total floor area of approximately 2500 ft². Figure 1 shows the floor plan of the house.

Building Construction Descriptions

The exterior walls of the Carefree house are made of 14-inch adobe blocks with 2-inch foam insulation covered with stucco on the outside as shown in Figure 2. The interior wood walls consist of two layers of gypsum board covered by the adobe plaster on both sides. The interior adobe walls are made of 14-inch adobe blocks covered with adobe plaster on both sides.

The floor is constructed of 4-inch concrete (slab-on-grade construction) covered with a 2-inch flagstone finish. The roof is constructed of metal sheeting on wood rafters with batt insulation between the rafters. A continuous vapor barrier is installed below the rafters, then 1-inch Styrofoam insulation, gypsum board, and cement plaster. Figure 3 shows a typical roof section.

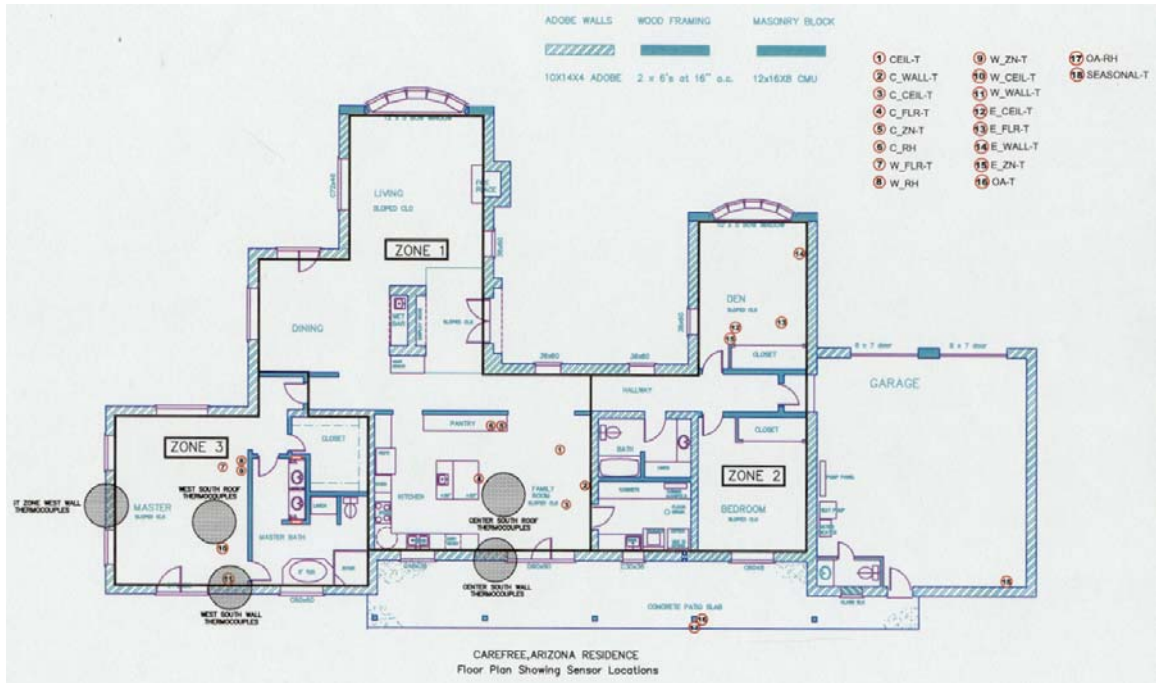


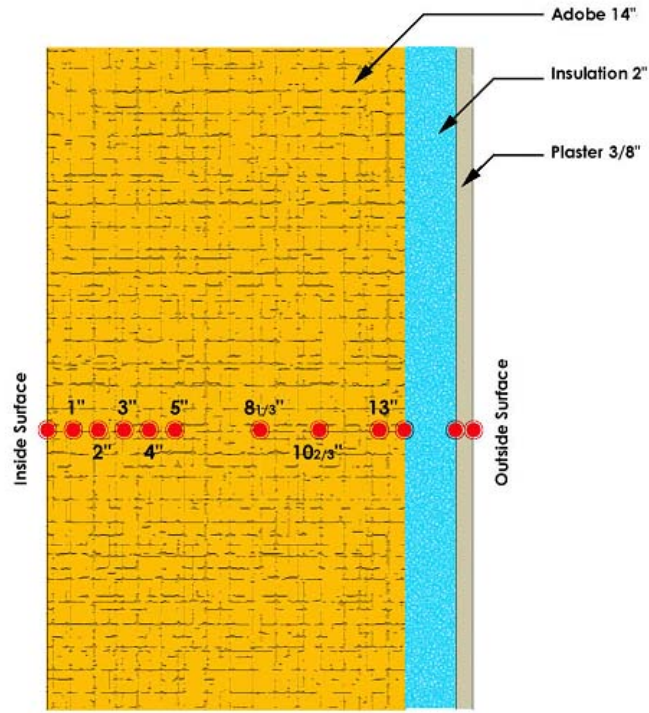
Figure 1

The floor plan of the Carefree house, (Scheatzle 2000)

System Descriptions

To condition the house, a hydronic radiant heating/cooling system is used. The radiant ceiling system is used to cool the house during the summer while the radiant floor system is used to provide heat during the winter. Figure 4 shows a schematic of the hydronic radiant heating/cooling system installed in the house. As shown, a ground-source heat pump and water storage tank are used to provide and store chilled and heated water for the hydronic radiant system.

The radiant floor system consists of 3/8-inch diameter rubber tubing on 9-inch centers. The tubes are embedded in the concrete slab of the floor construction. The radiant ceiling system consists of 1/8-inch diameter capillary tubes on 1/2 inch centers. The tubes are embedded between the dry wall and the cement plaster of the roof construction as shown in Figure 3.



Typical Wall Section

Figure 2

The Exterior Wall Construction (Scheatzle 2000)

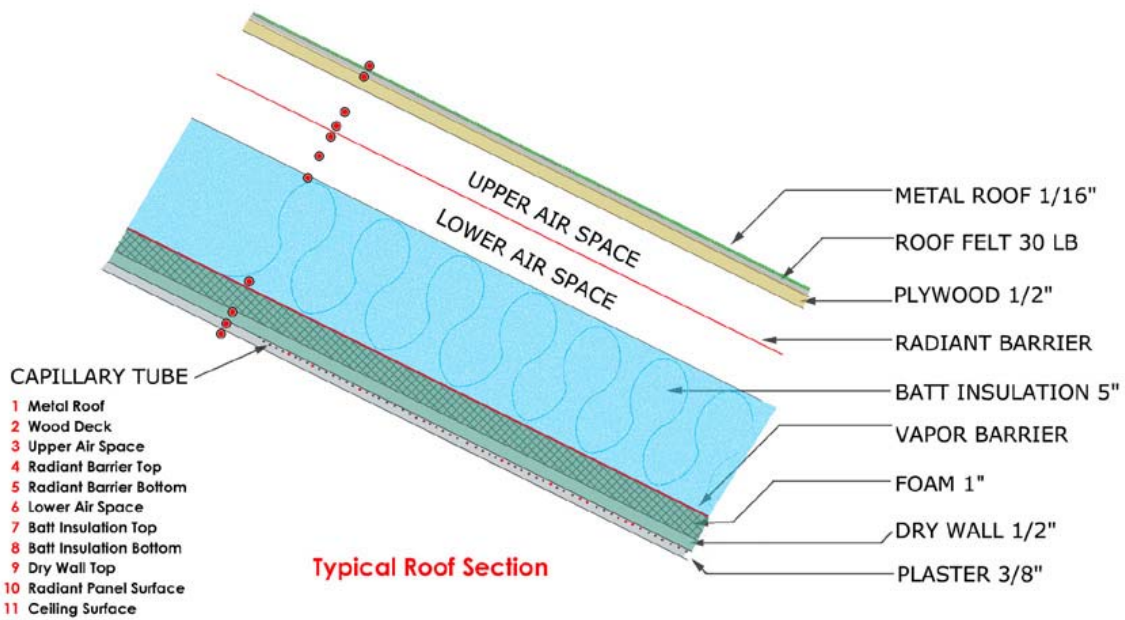


Figure 3

The Roof Construction with Embedded Radiant Panels (Scheatzle 2000)

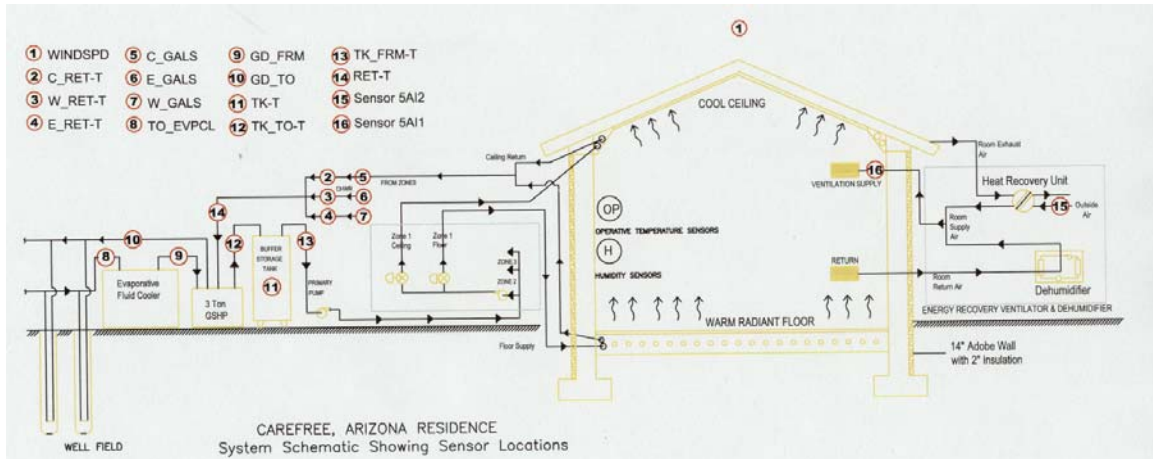


Figure 4

The Schematic Diagram of Hydronic Radiant Cooling/Heating Systems (Scheatzle 2000)

MODELING OF THE CAREFREE HOUSE

A baseline model of the building and systems was developed by Arizona State University researchers. The simulation results shown in the following sections illustrate how the baseline model was “tuned” to the experimental data. The tuning procedure represents a simple, manual “parameter estimation” exercise that results in excellent agreement between the measured and predicted data. The results illustrate the ability of the EnergyPlus models to realistically simulate low temperature radiant systems. As shown in Figure 1, the house was divided into three thermal zones: a central zone (Zone 1), an east zone (Zone 2), and a west zone (Zone 3). In this study, only the west zone, which includes the master bedroom, bathroom, and closet, was simulated. Construction details of the west zone were modeled as shown in Table 1. The material layers are listed from outside to inside. The thermal and physical properties used in the simulation are also given in the table.

On the system side, only the radiant ceiling (cooling) system was investigated in this study. In order to assess the radiant system model, the water loop connecting the ground source heat pump and the storage tank with the radiant system was simulated by scheduling the flow rate and temperature of the chilled water supplied to the radiant ceiling system for the west zone. The radiant cooling system of the west zone was modeled as five radiant ceiling panels. Thus, the total energy consumption of the west zone is the sum of the energy consumed by these five radiant panels.

TABLE 1

Building Constructions, and Thermal and Physical Properties of Building Materials Used in Simulation

Type of Construction	Description of Layers (from Outside to Inside Surfaces)	Thickness	Thermal Conductivity	Density	Specific Heat	Thermal Resistance
		M	W/mK	kg/m ³	J/kgK	m ² K/W
Exterior Walls	A1 – Stucco	0.0254	0.6918	1858	836.8	-
	Adobe – Insulation	0.0506	0.0206	24	836.8	-
	Adobe – 14inch	0.3536	0.8648	1922	836.8	-
	Adobe - Plaster	0.0125	0.8648	2243	836.8	-
Interior Walls - Adobe	Adobe - Plaster	0.0125	0.8648	2243	836.8	-
	Adobe – 14inch	0.3536	0.8648	1922	836.8	-
	Adobe - Plaster	0.0125	0.8648	2243	836.8	-
Interior Walls - Wood	Adobe - Plaster	0.0125	0.8648	2243	836.8	-
	E1 – Plaster or Gyp Board	0.0191	0.7264	1602	836.8	-
	B1 - Air Space	-	-	-	-	0.1604
	E1 – Plaster or Gyp Board	0.0191	0.7264	1602	836.8	-
	Adobe - Plaster	0.0125	0.8648	2243	836.8	-
Roofs with Radiant Panels	Metal - Galvanized Steel	0.0016	45.3149	7833	502.1	-
	E3 - Felt and Membrane	0.0095	0.1903	1121	1673.6	-
	Blbd - Plywood	0.0127	0.1159	545	1213.4	-
	Roof Air Space	-	-	-	-	0.1604
	Batt Insulation – Minwool	0.1558	0.0432	10	836.8	-
	Poly Urethane	0.0254	0.0230	24	1589.9	-
	E6 – Gyp Sheathing Board	0.0127	0.1602	785	836.8	-
	Radiant Surface	-	-	-	-	-
	Cement Plaster	0.0064	0.7207	1858	836.8	-
Floor	Dirt	0.3048	0.1730	1041	836.8	-
	C5 – HW Concrete	0.1015	1.7296	2243	836.8	-
	Flagstone	0.0509	1.8019	2243	836.8	-

Results and Discussions

When designing and/or evaluating performance of space conditioning systems, two factors are of particular concern: energy consumption and thermal comfort. For conventional space conditioning systems, the room air temperature is usually used as a standard thermal comfort parameter. For radiant space conditioning systems, however, both the room air temperature and the mean radiant temperature are important in determining occupant comfort.

The average of the mean radiant and room air temperatures is commonly known as the operative temperature. In this study, in order to validate and illustrate the performance of the EnergyPlus radiant system model, total energy consumption (per day) and operative temperature are compared against measured data.

Figure 5 shows comparisons between results predicted by EnergyPlus using the baseline input data (“Calculated #1”) and the measured data. As shown, EnergyPlus did a reasonable job of predicting energy consumption but significantly under-predicted the operative temperature with the baseline model. Under-prediction of the operative temperature was primarily due to the fact that the temperature set points were specified as 0 °C in the baseline model input file. However, when the input was modified by specifying the control temperature set points to the operative temperatures (one temperature schedule per day), the model accurately predicted the operative temperature but under-predicted the energy consumption as shown by the “Calculated #2” results shown in Figure 5.

The simulated zone was not completely enclosed by the heat-transfer surfaces specified in the original input data. As a result, surfaces outside of the simulated zone actually participate in the radiant exchange. This could have a significant effect on the results, depending on surface temperatures. Also, in the original file, the partitions (interior walls - wood) separating the master bedroom and bathroom and the closet and bathroom (see Figure 1) were modeled as heat-transfer surfaces. From a modeling standpoint, these partitions might be more accurately modeled as thermal storage surfaces, which participate in the radiant exchange, but do not exchange energy with the outside environment or with other thermal zones.

Changes to geometric input and surface descriptions resulted in very little change in the predicted results as shown in Figure 6. Tuning the geometric data did not eliminate under-prediction of the energy consumption when the radiant system was controlled. These results indicate that EnergyPlus under-estimated the heat gains entering and/or occurring in the space. The internal heat gains specified in the input files were in fact quite low (lights were hardly turned on and equipment was rarely used). For a bedroom isolated from the rest of the house, this might be a reasonable assumption, but convective transport between the simulated space and the rest of the house would tend to raise the internal gains in the bedroom to higher than expected levels.

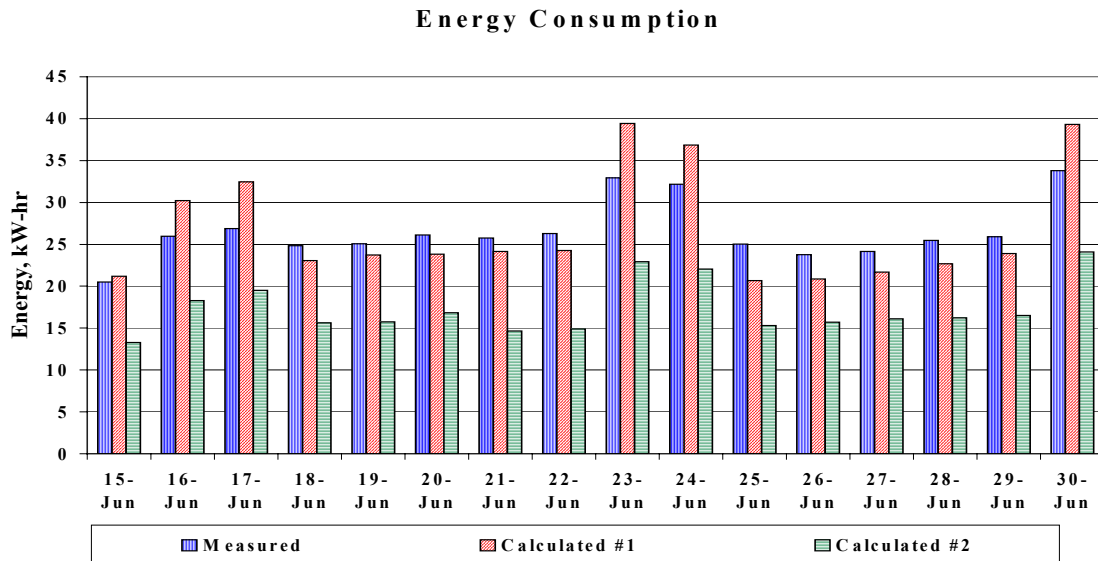
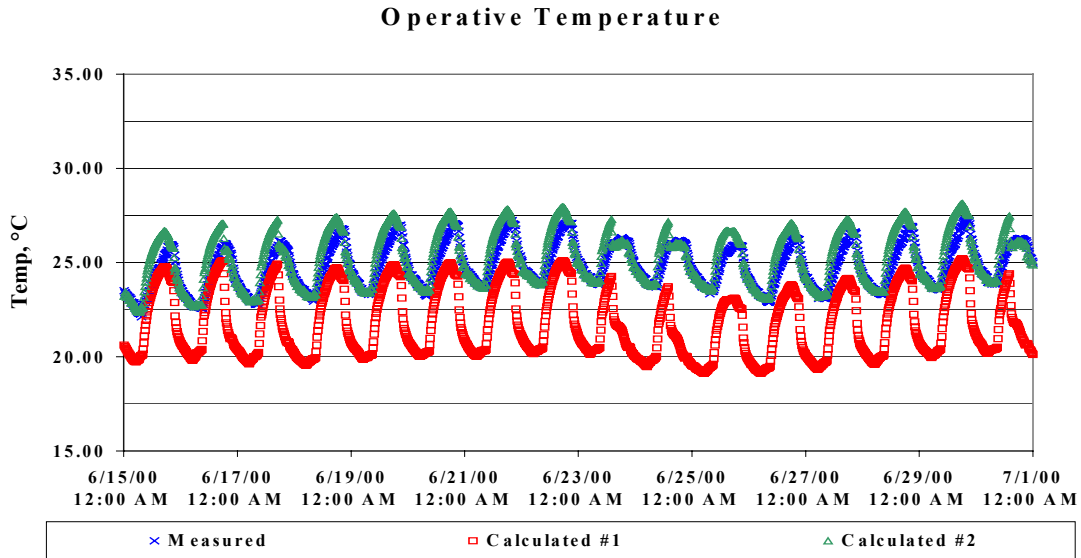


Figure 5

Operative Temperature and Energy Consumption Comparisons

It is expected that the upper limit of heat gains occurring in the bedroom could be represented by the averaged value of internal heat gains occurring in the house. Then, the input file was modified by specifying more appropriate schedules for the occupancy, lights, and electric equipment using the “whole-house” averages. Figure 7 shows the results predicted by the EnergyPlus using the new input file (referred to as “Calculated #4”). Although the modified input file predicted both the operative temperature and the energy consumption quite well, analysis of the calculated data indicated that the operative temperatures predicted by both

“Calculated #3” and “Calculated #4” were higher than the measured data when the radiant system was not available. (The system was only available during the night for weekdays, and it was available during the afternoon and night for weekends). Over-prediction of the operative temperature during the time the space conditioning system was turned off suggests that the thermal mass of the building constructions might be under-specified in the input file.

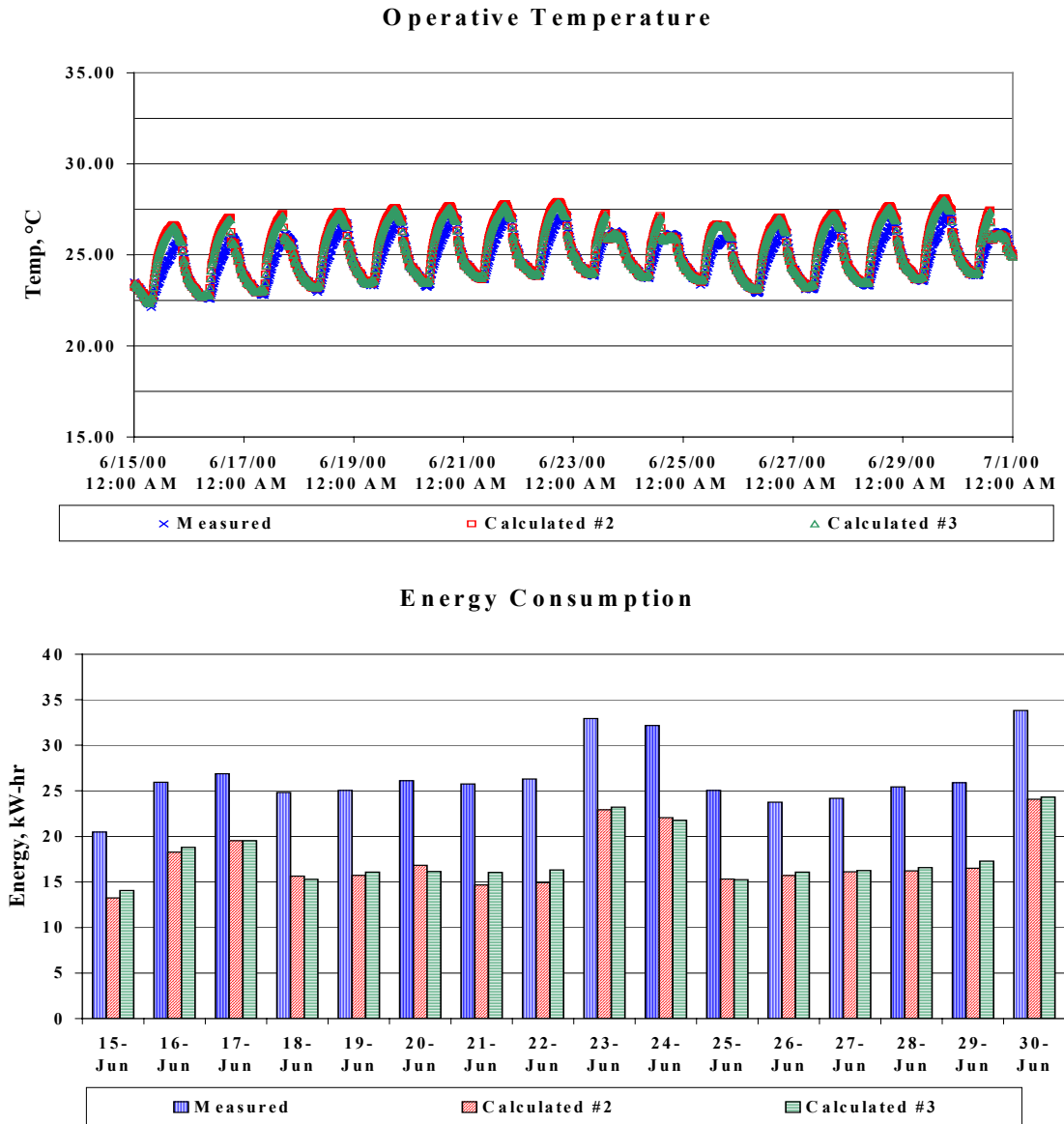


Figure 6

Operative Temperature and Energy Consumption Comparisons

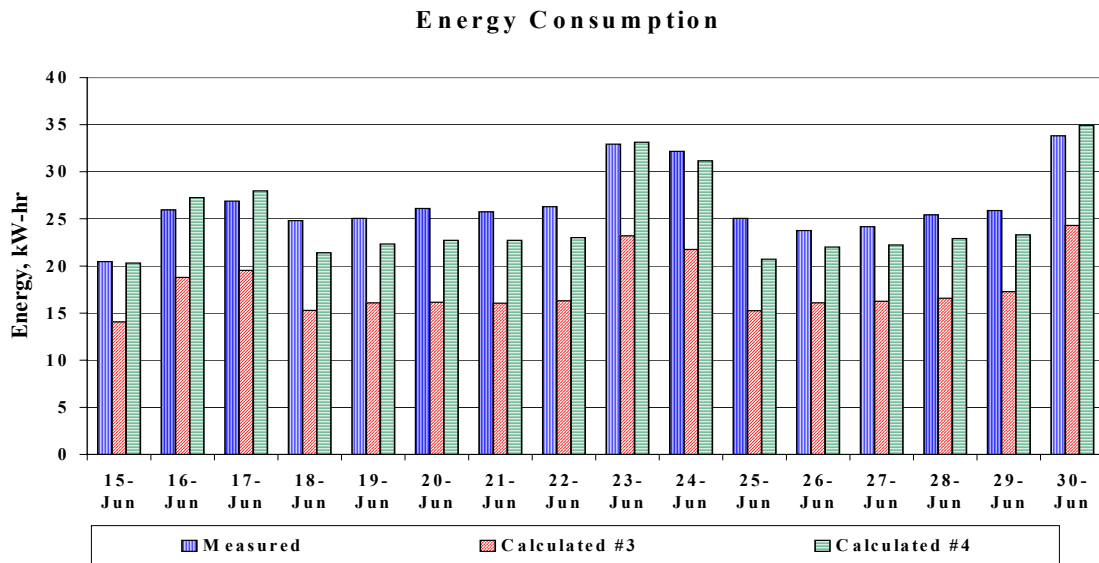
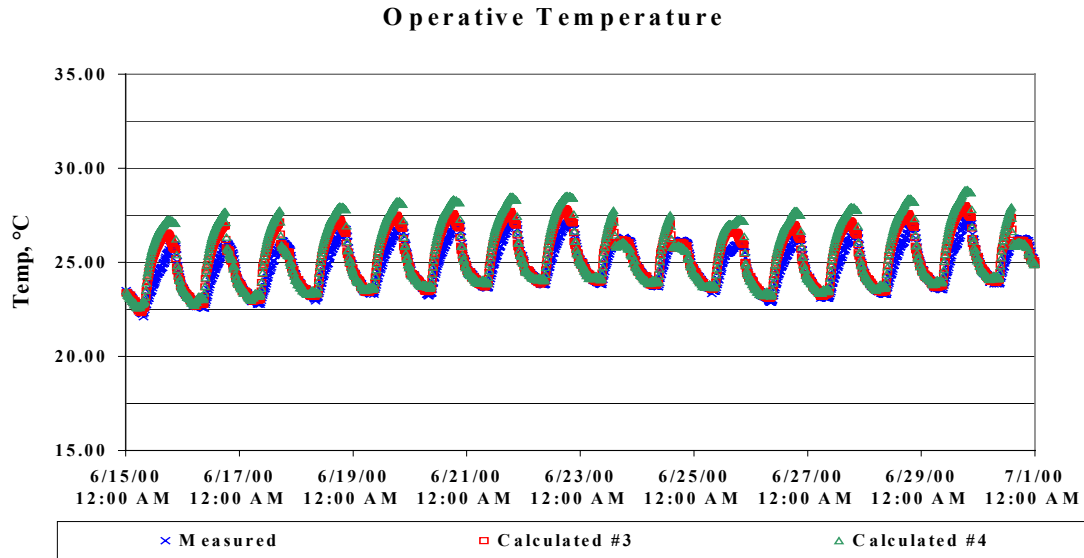


Figure 7

Operative Temperature and Energy Consumption Comparisons

The input file was modified again to specify higher thermal mass for the exterior walls and roofs. For the exterior walls, the density and specific heat of the 14-inch adobe layer were changed to 2400 kg/m³ and 1210 J/kg-K, respectively (see Table 1 for comparison). For the radiant roofs, the density of the batt insulation, polyurethane, and gyp sheathing board layers were also changed to 32, 40, and 1680 kg/m³, respectively. The specific heat of the gyp sheathing board was also changed to 1340 J/kg-K. It should be noted that these values are near the upper limit of a realistic range of these building material properties.

The results predicted by the new file are illustrated in Figure 8. As shown, increasing thermal mass of the exterior wall and roof models resulted in good agreement between the predicted and measured operative temperatures and reasonable agreement between predicted and measured energy consumption.

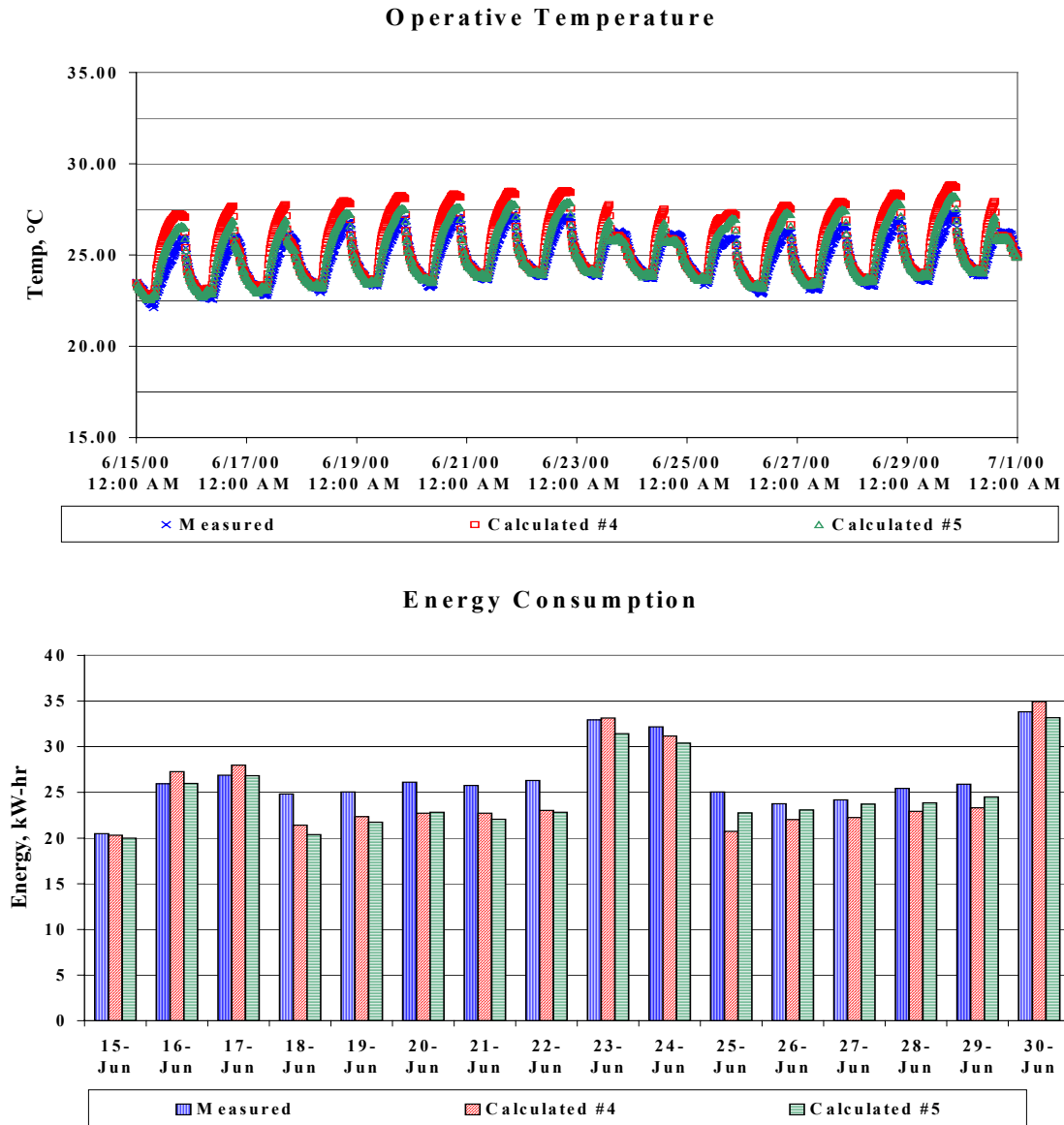


Figure 8

Operative Temperature and Energy Consumption Comparisons

CONCLUSIONS AND RECOMMENDATIONS

Unlike convective air-based systems, low temperature radiant system performance may be significantly affected by the interaction of complex thermal processes. Transient conduction through the building elements, combines with surface convection and the internal surface radiant exchange to produce a given comfort condition in the space. To accurately predict the performance of radiant systems, both the system with its associated controls and the building data must be accurately specified. This study shows that good agreements between predicted and experimental results can be achieved in the EnergyPlus low temperature radiant simulation by adjusting appropriate input parameters that can have an impact on the systems. These input parameters include:

- Scheduling of the radiant system operation.
- Specification of the radiant system set point temperatures.
- Scheduling of internal heat gains.
- Specification of building element thermal properties.

The study also shows that it is essential to compare both energy consumption and thermal comfort parameters in order to evaluate the performance of the systems correctly.

In addition to the input parameters investigated in this study, other model inputs can also have a significant effect on predicted results. These parameters include weather data, optical surface properties, infiltration, and ventilation. Further investigation of these parameters is needed. Also, the hydronic system that supplied the chilled water to the radiant ceiling was modeled by scheduling the flow rate and temperature of the water. It would be better to simulate the actual system that couples the ground source heat pump, the storage tank and the radiant system together. Finally, the west zone actually consists of three separate spaces: the master bedroom, the master bathroom and the closet (see Figure 1). It would have been more interesting to see how EnergyPlus predicted the results if the west zone were modeled as three “slave” thermal zones with the master bedroom conditions controlling the systems. This configuration more accurately reflects actual system operations.

ACKNOWLEDGEMENTS

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