FAST EVALUATION OF SUSTAINABLE HEATING AND COOLING STRATEGIES FOR SOLAR HOMES WITH INTEGRATED ENERGY AND CFD MODELING

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ABSTRACT

This paper demonstrates a simple and practical simulation-based approach for fast identification of appropriate building design strategies at the early stage of a design project. A simplified passive solar house was modeled using an integrated building energy and CFD simulation to examine the feasibility of different sustainable thermal strategies for use in the 2007 Solar Decathlon Competition. The home was modeled in EnergyPlus, and then the surface temperatures at times of interest were used as boundary conditions for CFD modeling in PHOENICS. A number of energy-efficient heating, cooling and ventilation strategies and technologies were tested. The simulation results confirmed some obvious conclusions but also showed that some design strategies that appeared to be promising and met typical design criteria failed to provide desired performance. The outcomes of this study are of great value for decision-making of appropriate architectural and engineering designs for the solar decathlon house. This study illustrates that an engineering-assisted design is feasible and helpful even at very beginning stage of a design project.

BACKGROUND

Designers struggle to incorporate various passive heating and cooling technologies into residential settings. Simple rules relating to passive heating, cooling and ventilation strategies have been developed (e.g., Lechner 2000), but in general they are limited. For instance, they typically include language that favors having windows on two walls in a given room. In addition, simple rules for sizing thermal mass and considering its impact have been developed (e.g., IEA 1997). In some cases, these simple rules fail to capture peculiarities of the geometry in question or interactions between multiple strategies. This may result in passive building designs such as thermal mass or natural ventilation systems not performing as expected.

Building engineering simulation tools such as Computational fluid dynamics (CFD) programs can be used to verify that a design functions as expected (Zhai 2006). CFD programs are particularly useful for evaluating passive building design strategies such as natural ventilation and radiation heating/cooling. CFD can provide detailed thermal comfort and indoor air quality information in the space, which usually can not be obtained from other engineering design tools. In typical applications of CFD, significant time is required to set up a three dimensional simulation model, verify the model is working correctly, and run various parametric cases. Numerical simulations of buoyant flows generally take a longer time to converge. Hence, modeling passive design strategies such as natural ventilation in three dimensional room or house geometries can take hours or tens of hours of computing efforts. The result of all this computing time is that typical CFD is much too expensive to be used during the early phases of design for evaluation of different heating, cooling, and ventilation strategies. Generally, CFD is used after a building has been designed in order to make sure that the design will function, not for making early design decisions.

The power of CFD is not purely quantitative. The graphical depictions of air movement and comfort within a space are a powerful communication tool for engineers, architects, and developers. These vivid depictions of the building operation can speed the acceptance of low-energy, passive design elements and allay the fears of some members of the design team. The communication of the effectiveness of various design strategies could be very helpful during the early stage decision-making process.

In order to improve the utility of CFD for high performance building design teams, a simple methodology with low computing time is required to make CFD an affordable tool during the early stages of design. The authors have worked out a practical approach for simulating these buildings by using an externally integrated building energy and CFD simulation method (Zhai and Chen 2006). The method first simulates the overall thermal performance of a simplified building model with zonal model based building energy simulation tools (e.g., EnergyPlus). The predicted thermal conditions such as surface temperatures will then be used as boundary conditions for a 2-D CFD building model in cross section areas of interest. The CFD model will incorporate the suggested building design technologies and systems and predict the real performance of each. These CFD runs usually take a few minutes each, allowing the designer to look at multiple options of interest in a parametric fashion. This paper uses the design of a house for the Solar Decathlon as an example to demonstrate the application of the method for pre-conceptual design of low-energy buildings. The Solar Decathlon is an international residential solar building contest sponsored by the US Department of Energy. Teams must design an 800 sq. ft. zero-energy house and build and bring the house to Washington, DC for a competition. Teams are judged subjectively on the sustainable architecture and engineering design of their homes. They are also judged objectively on how well their homes perform during the competition in Washington. Houses must maintain temperatures between 71 and 76 degrees F.

CASES OF INTEREST

A number of questions related to the engineering design of the house require detailed answers during the entire design process. What should the capacity of the active cooling system be? What is the optimal thickness of insulation in the ceiling? How big should the thermal storage tank be? But these questions require other inputs from the design process related to the size, shape, and orientation of the building, how much glazing is desired for different parts of the house, and what sort of thermal mass storage might be available. At the early stage of the design process, it is more useful to investigate general options to answer questions of feasibility. Is it possible to cool the house in the evening using passive natural ventilation during the summer? What kind of window geometries work to provide good airflow for this passive cooling? Are there any window geometries that might not work as well as one might suspect? Can the house be cooled with a radiant floor alone or with a radiant floor and some walls or with a radiant ceiling? How long will a hypothetical thermal mass keep the house cool on the design cooling day? How much stratification will occur during heating with a radiant floor? Will the space overheat due to high solar loading during winter? CFD can provide insight into the answers to these questions at an early stage. The following cases allow exploration of passive design strategies suitable for Boulder, Colorado where the house will permanently locate, which include night ventilation cooling, natural ventilation cooling, direct gain solar heating, and radiant heating and cooling. These strategies were identified as both interesting to the designers and easy to explore using this integrated two-dimensional CFD method.

Heating Design Day

On the design day, stratification may be a problem. Cold feet and drafts are common complaints with forced air systems that radiant systems are supposed to fix. Adding a radiant floor to the configuration should resolve this problem, but one should be sure and use CFD to analyze the results. CFD can also be used to see if a given surface temperature on the floor alone is sufficient.

Cooling Design Day with Radiant Surfaces

On the cooling design day, what radiant surfaces are required to cool the space during late afternoon? Radiant surfaces can be added to the base case. Stratification is an obvious problem unless the ceiling is chilled, but if it is possible to get by with common radiant surfaces for heating and cooling, a great deal of cost savings can be realized. Chilled floor, chilled walls and chilled ceiling will be considered. Also, placement of fans will be considered for mixing up room air and reducing stratification with a chilled floor and walls.

Passive Cooling with Ventilation

On a hot summer day in Boulder, it often cools enough for passive ventilation cooling during the evening hours. The case is considered when the surfaces of the space are still warm from heating during the day, but the outside air has cooled to be 5 degrees C cooler than the indoor air. Different window geometries are considered to determine which will provide enough passive airflow when there is no wind. In addition to a steady state analysis, an unsteady case should be run to see how quickly the space cools off when the windows are opened in the evening. All living space should be cooled off quickly.

Passive Cooling with Thermal Mass

How much cooling can thermal mass provide during the design day? In this case, it is assumed that there is a thermal mass that has been chilled during the night down to 15 degrees C. A reasonable thermal mass will be added to the design cooling day base case, along with a chilled floor. The room will have an initial temperature of 18 degrees C, assuming that night cooling has been effective. Surface temperatures corresponding to the design day afternoon are used. An unsteady simulation will show how long the thermal mass is effective in keeping the space comfortable.

Other Cases of Interest

There may be other cases of interest that are more difficult to explore using a 2-D CFD. Achieving comfort through high air velocities with warm dry air in the space requires a detailed three dimensional model effort. Some passive strategies of interest require full integration of hourly energy simulation and CFD to evaluate their utility, because the interactive effects are vital to the operation. These include double-skin facades, sunspaces, and ventilated Trombe walls. The approach used here cannot provide useful information for these cases.

MODELING APPROACH

The modeling is summarized by the following list of steps:

1. Select strategies of interest based on the climate.
2. Determine which of these strategies can be explored with 2-D CFD and simple energy simulation.
3. Determine the weather/building operation cases of interest necessary to evaluate the feasibility of the selected strategies.
4. Create a generic building model for energy simulation.
5. Perform hourly energy simulation of the generic house with an energy simulation program capable of modeling the building and outputting surface temperatures.
6. Capture surface temperatures for each of the building operation cases of interest.
7. Create a 2-D CFD model of the cross section of interest. Use the surface temperatures from the hourly simulation for each case of interest.
8. Model the cases of interest with CFD, manipulating small parts of the model to explore design strategies.
9. Examine CFD output to determine temperature or comfort distribution within the 2-D slice of the building.
10. Determine whether a given strategy can supply adequate comfort. Reject any strategies that do not supply adequate comfort in the 2-D CFD case.

EnergyPlus Model Description

The home modeled in EnergyPlus (USDOE 2006) was an early entry into the effort to design the 2007 University of Colorado Solar Decathlon house, which has since been largely scrapped. However, its generic geometry still can be used to generate useful information, as it is likely that some similar forms will find their way into the final design. The home has generic occupancy and equipment loads based on the typical American home, loosely based on the Building America Benchmark. The heating set point is 21.1 degrees C and the cooling set point is 24.4 degrees C. There is a setback used at night and during the day on weekdays. The home has R-19 insulation in the walls and ceiling and sits on an uninsulated slab. Glazing is double clear. The home is approximately 700 square feet, with a section of space above the living area, and significant amounts of glazing on the north and south sides. There is a small heavily-glazed extension area on the south side. See a rendering in Figure 1.

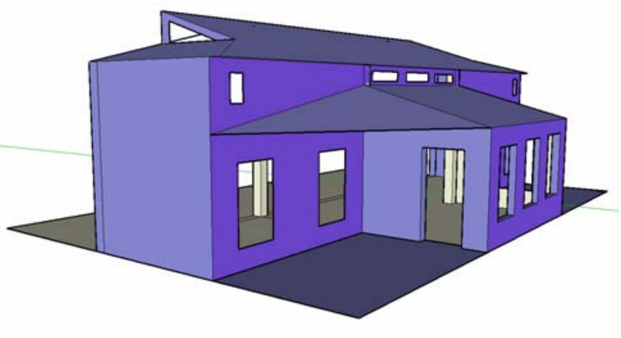

Figure 1: Rendering of Generic Solar House

The house was modeled using TMY2 weather data for Boulder, CO, with typical infiltration based on the Sherman-Grimsrud model with suburban shielding. The EnergyPlus model uses Conduction Transfer Functions (CTF), with detailed interior and exterior convection, short and long wave radiation exchange at surfaces, and minimal shadowing (no self-shading or reflectance) (USDOE 2006).

CFD Modeling

The PHOENICS FLAIR package (CHAM 2005) was used as the CFD simulation engine, with a two dimensional case. A grid density of 50 cells in the vertical (Z) direction and 70 cells in the horizontal (Y) direction was sufficient to capture most turbulence effects and still allow low computing time for use in unsteady calculations. It was determined that the KE-CHEN model (Chen et al. 1987) as implemented in PHOENICS would be a good choice for the room flows in question. This model has been used and verified in multiple cases involving room air flow and is particularly good at modeling different turbulence regimes with differing amounts of shear stress in one model. This is important for use with natural ventilation, buoyancy-driven flows. The KE-CHEN model uses an additional term to account for turbulence production, effectively increasing KE when the mean strain is strong and effectively decreasing KE when the mean strain is weak. An additional term is used to damp out these effects as the Reynolds number gets higher (Monson et al. 1990). The end result is a turbulence model that can handle multiple flow regimes within a given model.

Equations were solved for air pressure (P), air temperature (T), air velocity in the Y-direction (V), air velocity in the Z-direction (W), turbulence kinetic energy (K), and turbulence dissipation rate (E). Radiation was not modeled. Fixed boundary temperatures were used for all surfaces, with the temperatures derived from EnergyPlus modeling results with a forced air cooling system. Inlet temperature was set to the ambient temperature from EnergyPlus.

MODELING RESULTS

CFD modeling produced good results quickly in most cases. Convergence sometimes took a long iteration (1500-2000 iterations), but with a 2-D case and 3500 grid cells, this does not result in long computing time (around 5 minutes for 2000 iterations with a PC). The results of a general case with natural ventilation were proven to be convergent and grid independent.

Passive Cooling with Open Windows

With the surface temperatures from an early evening hour in the summer, different window configurations were considered. The ambient air temperature is 20.6 degrees C, while the floor and most of the walls of the home are at 23 to 26 degrees C.

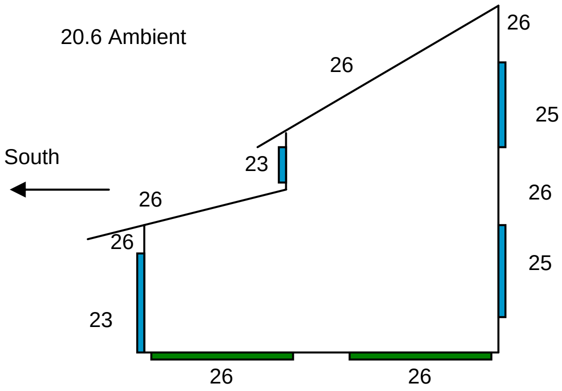

Figure 2: Wall Temperatures (C) for Passive Cooling Cases

Two different grid densities were employed, a fine grid case at 140 x 100, and a medium grid case at 70 x 50, with the basic geometry and a window in the lower right corner and another at the middle clerestory. Both simulations were well convergent in total mass flow rate and have very similar velocity and temperature fields, as the results show.

For the fine grid case, the mass conservation residual was less than 10^{-5}. The monitoring temperature (as pointed by red pen in the figures) and the plane mean temperature were, respectively, 21.3 and 22.8 degree C. For the coarse grid case, the mass conservation residual was less than 10^{-7}. The monitoring temperature and the plane mean temperature were, respectively, 20.7, 22.6 degree C. The error in the air change rate is about 20% for a quadrupling of the number of grid cells. The solution can be considered grid-independent for design purpose.

Passive cooling appears to work well with multiple window configurations (Figure 3: Middle and Bottom Window Passive Cooling). With a window at bottom right and the other at the middle clerestory, or a window at the bottom right and the other at the top right, the space was well-cooled, with the living area at 21 to 22 degrees C. In one case, it was discovered that the air does not mix as well as expected (Figure 4: Middle and Top Window Passive Cooling). With a window at the middle clerestory and a window at the top right, the bottom section does not cool as well as it should, with much of the space remaining at 23 to 24 degrees C. Those two degrees can make a significant difference in the number of hours that passive cooling can be used over active cooling.

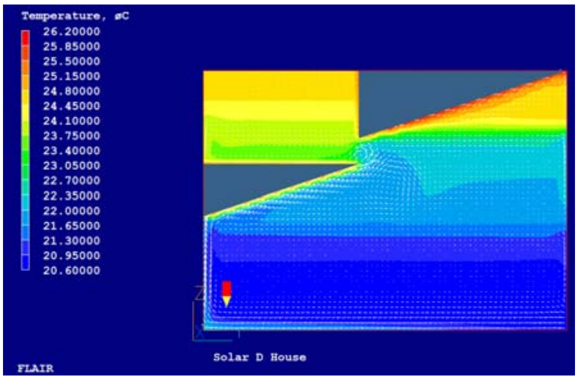

Figure 3: Middle and Bottom Window Passive Cooling

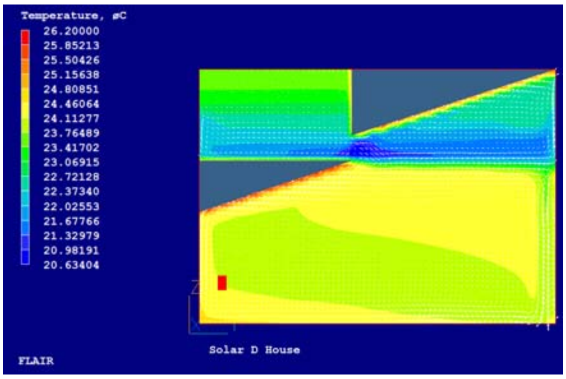

Figure 4: Middle and Top Window Passive Cooling

An unsteady passive cooling case was run with the middle and bottom window design, with a 5 minute increment. The results of this case show that the lower section of the room is less than 23 degrees C within 5 minutes, and that the room is near steady state within 10 minutes. This is very good for passive cooling, since it shows that the house does not lag behind the outdoor temperature as it cools.

Design Day Radiation Heating

A simulation was run to look at stratification with radiant floor heating, which is a problem with forced air systems.

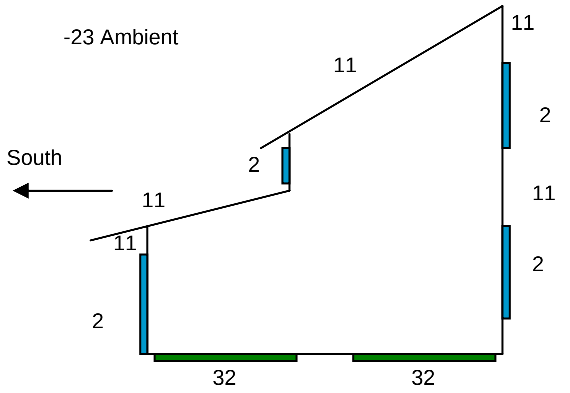

Figure 5: Wall Temperatures (C) for Radiant Heating Cases on Design Day

The wall temperatures from the EnergyPlus model running on the design day with a forced air system were used as boundary conditions in PHOENICS (Figure 5: Wall Temperatures (C) for Radiant Heating Cases on Design ***Day***). The radiant floor provides enough heating to meet the same temperature set point.

There is very little stratification during the heating case. In the area of interest, temperatures range from 15 to 17 degrees C (Figure 6: Temperature Distribution with Radiant Floor Heating on Design Day). As expected, the radiant floor does a good job of providing even heating to the space.

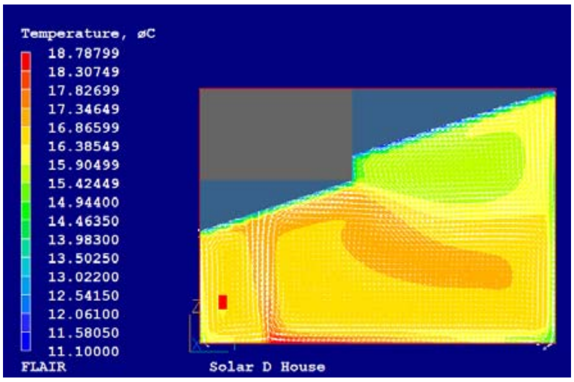

Figure 6: Temperature Distribution with Radiant Floor Heating on Design Day

Design Day Radiant Cooling

Starting with cooling design day wall temperatures from EnergyPlus, radiant floors, radiant walls, radiant ceilings and fans in conjunction with radiant floors were simulated (Figure 7: Wall Temperatures (C) for Radiant Cooling Cases on Design ***Day***
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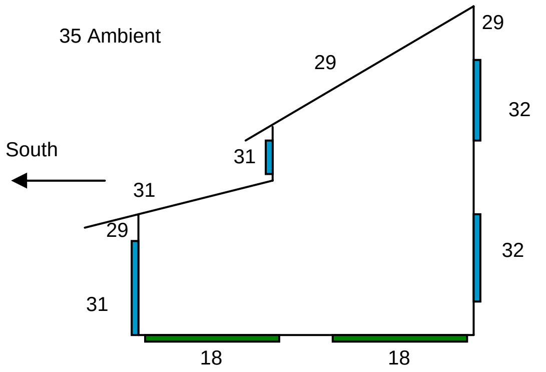

Figure 7: Wall Temperatures (C) for Radiant Cooling Cases on Design Day

The results show that stratification precludes the use of many radiant cooling geometries and prevents the use of a common radiant floor system for primary heating and cooling.

In the radiant floor only case, the space is poorly cooled (Figure 8: Radiant Floor Only Cooling). Only the area immediately proximate to the floor is sufficiently cooled. Stratification is a major problem, with temperatures at head height nearly 10 degrees C warmer than temperatures at foot height. When cooling panels are added at head height, the stratification is still a problem. In Figure 9: Radiant Floor and Wall Panel Cooling, 0.5 m wide panels were added at 18 degree C on the left and right wall at the head height. The stratification level has moved upwards, but not enough to be adequate.

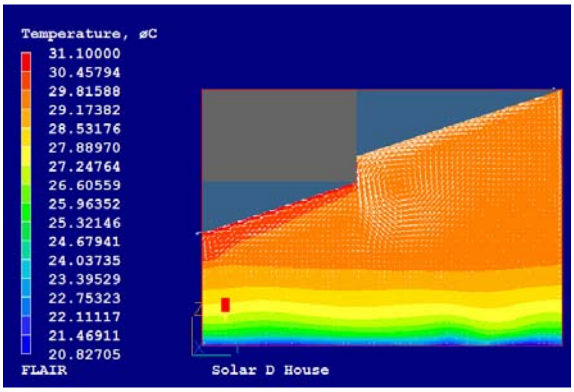

Figure 8: Radiant Floor Only Cooling

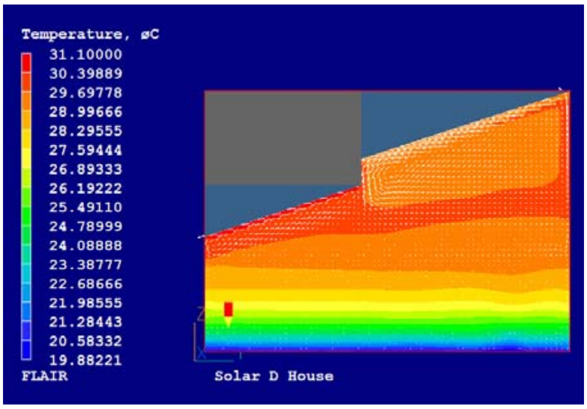

Figure 9: Radiant Floor and Wall Panel Cooling

Adding un-ducted fans does not fix the stratification and distribution problem (Figure 10: Radiant Floor Cooling with Mixing Fan). An internal fan can be seen at the upper left corner of the CFD simulation. The results are worse than the simple radiant case.

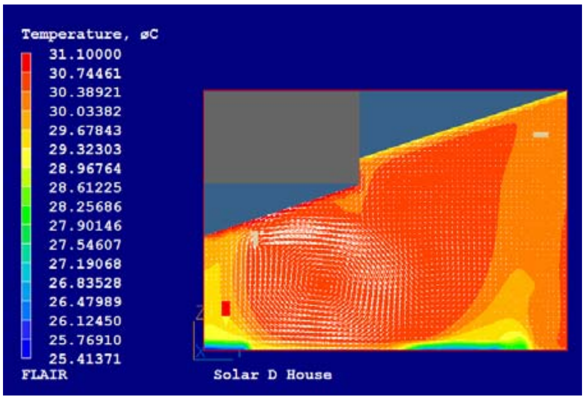

Figure 10: Radiant Floor Cooling with Mixing Fan

When a radiant ceiling panel at 18 degrees C is added to the lower roof, the resulting pattern shows a favorable temperature distribution (Figure 11: Radiant Floor and Ceiling Cooling). The temperature in most the conditioned area is between 23 and 24 degrees C.

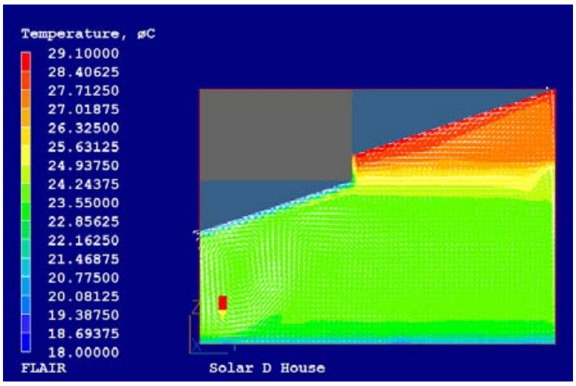

Figure 11: Radiant Floor and Ceiling Cooling

Design Day Cooling with Thermal Storage and Radiant Floor

An unsteady design day cooling case was run to examine how well thermal mass might work for cooling of the space. The floor was conditioned at 18 degrees C, while the air and mass had an initial temperature of 15 degrees C, consistent with night cooling. A slab of concrete 0.3 meters thick and 2 meters long was placed in the model on the right side. The simulation was run with a 5 minute interval and 2 hour run time. After 2 hours, the space was no longer comfortable (Figure 12: Radiant Floor Cooling with Thermal Storage after 1.5 hours). The concrete had not fully warmed at this point. The system provided adequate temperatures up until about 1.5 hours. At that point, the head level temperature was over 25 degrees C, but the rest of the body was sufficiently cool. The space exhibits a high degree of stratification, which may create thermal comfort problems by itself. One may conclude that thermal mass would need to cover a large area of the ceiling, while only a shallow depth is necessary.

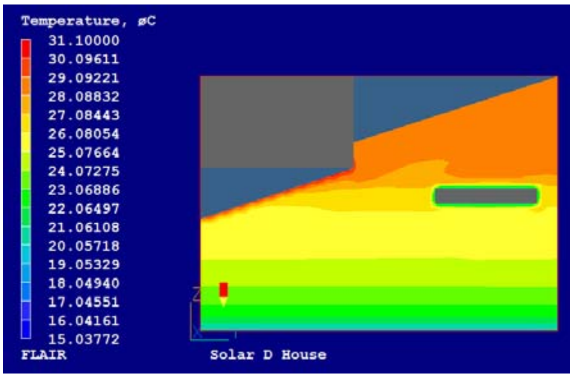

Figure 12: Radiant Floor Cooling with Thermal Storage after 1.5 hours

CONCLUSIONS

Integrated CFD and energy simulations proved to be effective in placing some constraints on the design process and indicating where further attention should be placed in the design of the CU 2007 Solar Decathlon house. Radiant floor heating does a good job of avoiding stratification in the space. That same surface by itself will not do enough cooling to adequately cool the space, due to stratification problems. This stratification problem is not solved with fans or limited wall panels. A radiant ceiling panel is necessary to solve the problem for active cooling.

Natural ventilation can be effective for cooling the space with proper window placement, including one high window and one low window. An unsteady case showed that the space has cooled significantly within 10 minutes of the windows being opened. If both of the windows are high, cooling is much less effective and the lower living space remains warm.

Thermal mass needs to cover a large surface area to be effective. The small surface used for an unsteady case kept the space cool for almost an hour and a half in combination with a radiant floor. The mass did not warm very much at a deep level.

The results of this analysis show how information about passive design can be captured from CFD and energy simulation at the earliest stages of the design process. This information enables designers to make decisions about which passive strategies to pursue further. In this particular analysis, the designers were able to determine that radiant cooling with the floor will not effectively cool the space, even with the addition of fans to mix the air within the space. Additionally, it appears that some window configurations will not work and both a high and low window are probably required for natural ventilation. Large amounts of elevated thin thermal mass are required to store cool energy from night.

The method employed here helped eliminate some strategies from consideration. Since the completion of this work, much further work has been done with three dimensional analysis of the full building envelope in CFD, as changes to the interior design have happened. These further analyses have allowed the design of architecturally integrated heat exchangers to occur.

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