Investigation of a Condenser-Linked Radiant Cooling System using a Heat Balance Based Energy Simulation Program

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ABSTRACT

One of the more powerful benefits of using computer simulation in the process of designing buildings is the ability to try ideas that may not appear feasible on the surface but could potentially have some merit. This is especially true when investigating the energy consumption of buildings—computer simulation allows the architect and engineer to reasonably predict the energy consumption of a particular building and attempt to increase its efficiency or apply a particular technology to the design without actually constructing the building. Thus, ideas can be tried in the computer laboratory and results can fine tune the design and lead to more informed decisions and an integrated design process.

One area where simulation has somewhat lagged available technology is radiant heating and cooling systems. Until recently, a radiant system model within a comprehensive energy analysis program that compares the results on the basis of equivalent thermal comfort with conventional forced air systems has not existed. With the release of the new US Department of Energy building energy analysis program in April 2001, this has been partially resolved. Recent improvements to the program include the ability to link a radiant system directly to a cooling tower rather than a chilled water line. The focus of this study is the discussion of this improvement to the simulation program and a demonstration of how this technology might be used to reduce cooling costs in several climates, including those in which such a strategy would typically be dismissed.

INTRODUCTION

Radiant space conditioning systems have experienced what one might consider a rebirth over the past two decades or so. While interest in these systems is more prevalent outside the US, there is growing interest in these systems nationally and internationally. In addition, there have been numerous research studies of these systems that try to address whether or not radiant systems are more energy efficient than conventional forced air systems. Much of the research has been favorable toward radiant systems, but most of the studies have been limited in scope. As a result, though market penetration for radiant systems has improved, it has not gained widespread acceptance in the US. This is despite the favorable literature reviews and the recent listing of radiant cooling ceilings/chilled beams being listed as one of the top 15 energy saving HVAC technologies by the US Department of Energy (Roth 2002).

The main conditioning strategy employed by radiant systems is to influence thermal comfort in the space by modifying the conditions of the room surface temperatures. The idea is to directly influence a person's thermal comfort by changing the radiant heat gain or loss from the person. This is a more direct approach to achieving thermal comfort than is employed by a conventional forced air system. In forced air systems, the transfer of energy to or from the person to maintain thermal comfort is achieved by first conditioning air which then is used to influence the amount of convection experienced by the person. This indirect approach requires two things that are detrimental to the overall efficiency of conventional systems: the air must be moved from where it is conditioned to where it will achieve comfort and the indirect process may require more extreme temperatures from the boiler and chiller equipment.

The need for more extreme temperatures in conventional systems as opposed to radiant systems applies to both heating and cooling mode and can be related to the area available for the transfer of thermal energy.

In a conventional system, heat transfer occurs at the relatively small area of a heating or cooling coil. In a radiant system, heat transfer takes place at a surface such as the floor or ceiling. The more area there is available for the transfer of heat, the less extreme the temperature differential has to be to achieve the same amount of heat transfer. Lower temperature differentials on the water side lead to the potential use of "lower quality" energy sources for the radiant system. In fact, radiant systems are even limited to what temperature the surfaces can reach by safety and comfort during heating (ASHRAE 2000) and the potential for condensation during cooling.

One potential source of "lower quality" chilled water is water being returned from an evaporative condenser or cooling tower. Normally, these devices serve as the heat rejection path for a chiller. The chiller produces chilled water used by a cooling coil or radiant system. The heat absorbed in the chilled water passed through the cooling coil or radiant system is then transferred across the chiller to the condenser side where it is dumped to the outdoor environment. For evaporative based condensers, the water temperatures approach the wet-bulb temperature of the outdoor environment rather than the dry-bulb temperature. In some climates the wet-bulb temperature can be significantly lower than the dry-bulb temperature though it will not approach a normal chilled water temperature in most cases.

However, the temperature from this "lower quality" energy source, i.e., water being returned from a condenser tower, might be low enough to be used to with a radiant system. This is due in part to the fact that the radiant system has a large surface area over which it can achieve heat transfer. While such a system might not meet the entire cooling load for a space, it has the potential to significantly reduce the amount of cooling that must be provided mechanically via a chiller. One added benefit of this system is that it should nearly eliminate concerns for condensation in most spaces (except those with high latent heat gains) since the water temperature being sent to the radiant system is already above the outside dewpoint temperature and the surface temperatures in such a situation should be even higher, providing an added safeguard against condensation.

The key question that one is immediately confronted with is: this sounds like an interesting concept but how does one know whether or not this can provide enough cooling to meet the thermal demands of the building and under what climatic conditions will this potentially low-energy system simply cannot provide enough effect to be economically feasible?

This paper intends to begin to answer these questions by simulating a relatively simple residential building in various climates using "low-energy cooling" from a cooling tower to supply slightly chilled water to a radiant cooling system. Strand (2001) provided some initial data for such a situation using a model that required significant input data manipulation to mimic the operation of this type of system. The simulation model has been improved (as will be discussed below) to automate the connection between a cooling tower and a radiant slab. This will allow the more efficient analysis of various climates over entire seasons rather than individual design days.

The remainder of this paper gives a brief overview of the simulation program used for this study, specific information about the radiant system model, and further details on controls and how the link between the radiant system and the condenser water was achieved. In addition, it will provide a summary of the building that was used as a case study, the different climates that were analyzed, and the results that were obtained using this low-energy system.

PROGRAM AND RADIANT MODEL OVERVIEW

The simulation program used in this study was based upon the heat balance solution technique described in the ASHRAE Loads Toolkit (Pedersen 2001) and that was used in the BLAST program (Building Systems Laboratory 1997). The basic methodology is to apply the First Law of Thermodynamics at both the inside and outside surface of all building elements as well as on control volumes surrounding the air within the various thermal zones of the building. In each control volume, all of the thermal forces due to conduction, convection, and long and short wavelength radiation that are appropriate for the type of control volume are balanced. This results in equations that can be solved for surface temperatures and either the temperature of the zone air or the amount of heating or cooling that must be provided by the HVAC system to maintain a particular setpoint temperature.

While the scope of this paper does not allow for the complete discussion of the heat balance method as it is applied within this program or the program itself, several of the key assumptions and characteristics are described below.

- Transient conduction is solved using conduction transfer functions that are derived using the state space method
- Uniform surface temperatures (at any given point in time, each building element is characterized by a single temperature at the interior side and a single temperature at the exterior side; larger surfaces may be broken up into multiple surfaces for better temperature differentiation)
- Diffusely radiating surfaces
- Interior and exterior convection correlation that depend on flow conditions and temperature differences
- Well-stirred zone air (air temperature is constant throughout the zone/no stratification)
- Zone time steps are allowed to be less than an hour

One of the key features of the simulation program that is important to the modeling of radiant systems is the fact that the zone, system, and plant simulations are integrated (Taylor 1991). Rather than simulating all of the loads based on an assumed system capacity, the program simulates the thermal envelope and the primary and secondary systems simultaneously. This allows feedback from the plant and the system back to the zone conditions. This is particular critical when modeling a radiant system that serves as both a building envelope element and a space conditioning system.

One of the main goals of the program was to ensure the flexibility and modularity of the new program. Legacy codes (DOE-2 and BLAST) that formed the basis for the program had many of the common drawbacks of monolithic simulations programs. One problem was the lack of flexibility within the models. This meant that it was sometimes difficult to model common situations with the standard systems that were included in the programs. Moreover, small differences from the standard systems meant that either the current model would have to be updated or a new model developed. This generally required a significant amount of expertise in the programs and then a substantial amount of resources. Often, model development lagged well behind industry developments. The flexibility of existing models within the current program and its modularity allow more common situations to be simulated and much faster development time for new models. It is hoped that this will benefit the simulation community in many ways and the users by providing more simulation capabilities within a shorter time frame.

The radiant system model is one example of how the flexibility and modularity of the new program have already paid dividends. The radiant system model is integrated within the HVAC structure of the program but is able to link back to the heat balance since the radiant system can also affect surfaces within the thermal zones. Surfaces are allowed to have embedded heat sources (or sinks) that can either be electrical or hydronic. This addition or subtraction of heat within a building element required the modification of the standard conduction transfer functions (Strand and Pedersen 1994, Strand 1995). The resulting equations were integrating with the standard heat balance formulation and did not require the rewriting of the heat balance equations. In fact, the new conduction transfer function series are calculated alongside the standard series terms and the heat balance equations simply have an addition term to take the heat source/sink into account. The HVAC side of the radiant system model is simply a heat exchanger that is connected to a water loop (Strand and Pedersen 1997). Water is conditioned by boilers, chillers, etc. and circulated through the slab or panel using a pump.

Controls for the radiant system model are flow-based controls that can simulate a variety of thermostat types. The user can decide whether the quantity within a space that is to be controlled is the mean air temperature, the mean radiant temperature, or the "operative" temperature (defined simply as the average of the mean air and radiant temperatures for control purposes). The deviation of conditions within the space from the setpoint will trigger the system to send more or less conditioned water (or electrical current) through the radiant slab or panel. This is defined as a simple linear function where the user has control over both the throttling range and the "gain" (Strand and Pedersen 2002). The user also has the ability to look at the resulting thermal comfort within the space using one of three established thermal comfort models (Lee and Strand 2001).

Previously, the program required users to connect coils, radiant systems, etc. to a "plant water loop" which is separate from the "condenser water loop" as shown in Figure 1. However, with the new link between the condenser loop and the zones, it is possible to directly connect the outlet water from the condenser to the radiant system. The water side of the radiant system is connected to the demand portion of the condenser loop while the radiant floor, ceiling, or wall interacts with the zone simulation. The condenser tower acts upon the supply portion of the condenser loop and produces the slightly cooled water back to the radiant system. An alternate approach to modeling this situation would have been to create a new heat exchanger component that would simply transfer temperatures across from the condenser demand loop to the plant supply loop. While this is a current area of program development, it was deemed to be slightly artificial for a direct connection between the tower water and the radiant system. The new link as shown if Figure 1 is a more direct connection, though in reality a heat exchanger might be necessary to address concerns that an open loop might present to a radiant system.

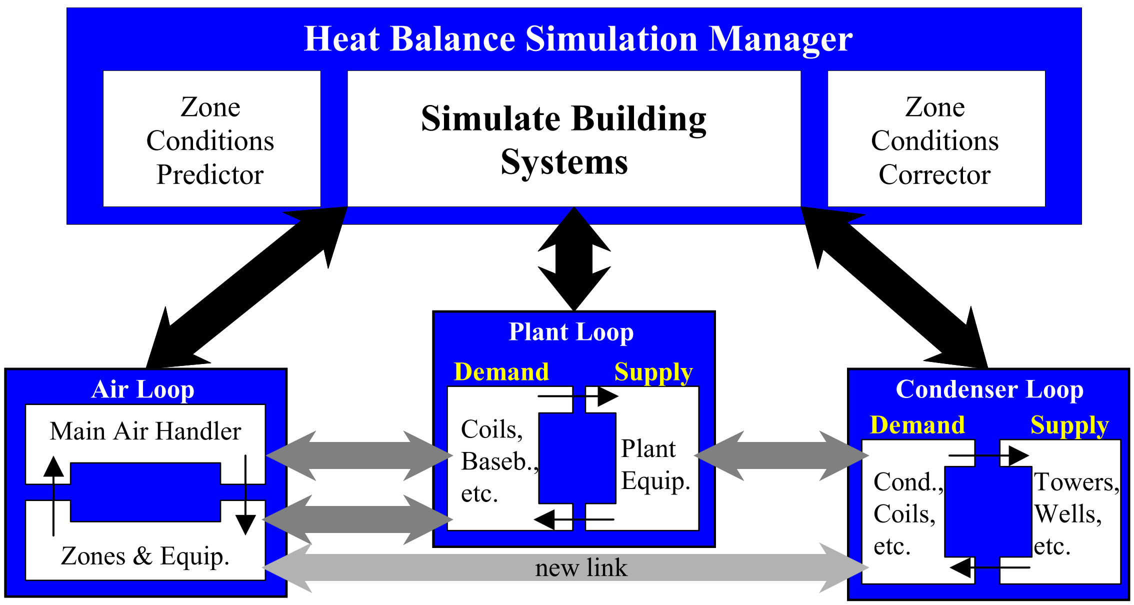

Figure 1. Connections between the Main HVAC Simulation Loops and Sub-Loops.

Many of the other details of the program (Crawley 1997, 2000) and the radiant system model (Strand and Pedersen 2002) are already available in the literature and are not repeated here for the sake of brevity. More in-depth information about the program as well as the program itself is also available free of charge from the program web site sponsored by the US Department of Energy (www.energy.gov).

CASE STUDY DESCRIPTION

The case study is intended to represent a moderately-sized, fairly typical residential building. The home is assumed to have approximately 140m^2 (1500ft^2) of living space (15m/50ft along the east-west axis, 9m/30ft along the north-south axis), an attached garage (37m^2/400ft^2) on the north side of the building, a flat roof above the living space and garage, and a fairly lightweight construction (metal siding). A reasonable amount of double pane windows were placed on all of the exterior walls and an overhang was defined over the entire length of the south wall to cut down on solar gains during the summer. No other attempts were made to make the home more passive or sustainable other than the addition of the low-energy cooling system. The floor was defined as a lightweight heat storage element to eliminate the inherent difficulties associated with modeling ground heat transfer. Combined internal gains for lights and equipment were set at 5.4W/m^2 (0.5W/ft^2), and it was assumed that there were two adults living in the house. Infiltration was kept at 0.25ACH constantly during the entire 24 hours of the day. The living space was assumed to be a single zone controlled to maintain thermally comfortable conditions while the garage area was left unconditioned. The radiant system consisted of a ceiling based system with the radiant tubes embedded in a various thicknesses and types of concrete as will be described later in the paper. The water flow rate through the tubing was approximated as 1.3kg/s(20GPM). A basic plan view of the building is given in Figure 2.

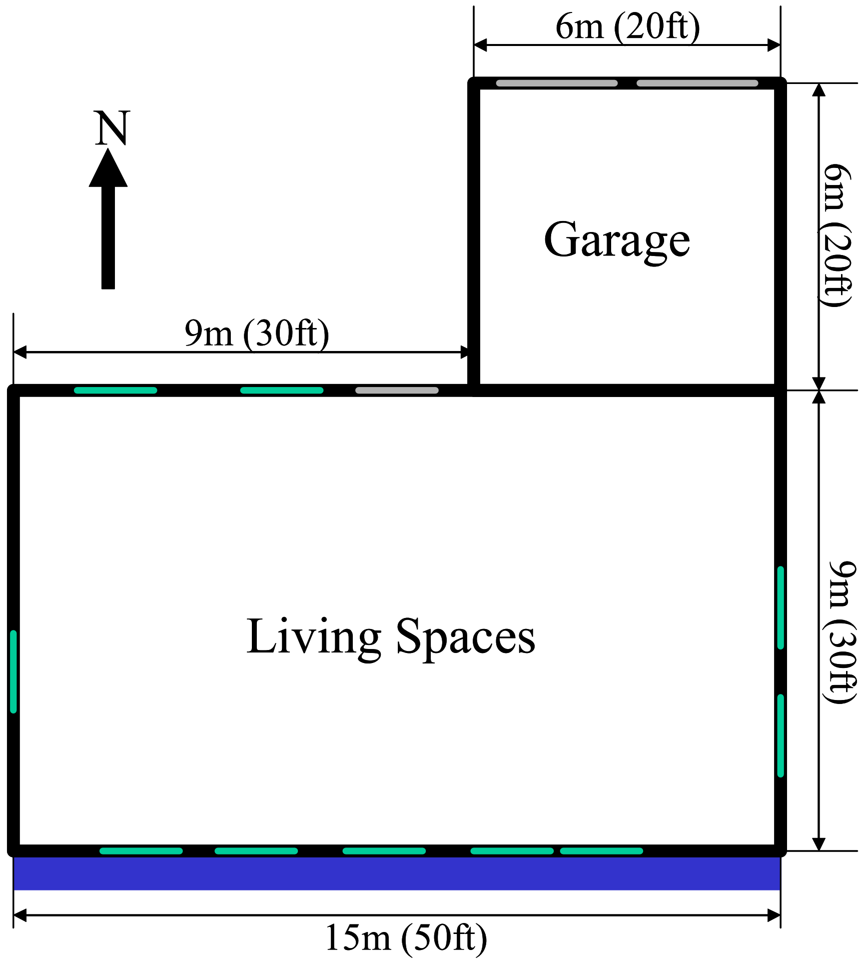

Figure 2. Basic Layout of Test Case Residential Building.

A range of climates was chosen to investigate the feasibility of using a radiant ceiling for cooling the living space under different environmental conditions. The purpose of choosing a variety of climates is to determine if there are limits to the usefulness of the proposed system or if there are conditions where the system simply will not make much impact on the thermal comfort of the occupants. Clearly, the performance of the system will be affected both by how warm the climate is and also the level of humidity. As a result, four site were chosen to reflect the general categories of mild and severe summers as well as dry and moist conditions. A summary of the four sites chosen and some basic weather information about each site (ASHRAE 1995, 2001) is provided in Table 1 below.

TABLE 1
Overview of Summer Climatic Conditions Simulated for Test Case Residential Building

Generic Description	Location	1% DB	1%MWB	CDH23(CDH74)
Mild, Dry	Spokane, WA	31.5°C (88.7°F)	16.3°C (61.3°F)	1918 (3453)
Mild, Wet	Peoria, IL	31.7°C (89.1°F)	23.4°C (74.1°F)	5279 (9503)
Hot, Dry	Phoenix, AZ	42.0°C (107.6°F)	20.9°C (69.6°F)	30224 (54404)
Hot, Wet	Key West, FL	31.9°C (89.4°F)	26.0°C (78.8°F)	27909 (50236)

In addition, two separate operating configurations were chosen to investigate the effect of mode and time of operation. In both cases, the results were compared to a base case that was served solely by a conventional forced air system. The independently operating and the simultaneously operating configurations are described in more detail in the following paragraphs.

In one series of runs, the radiant system and the supplemental conventional forced air system were run independently. The radiant system was allowed to run during the nighttime hours when the wet-bulb temperature would presumably be the lowest. The intent was to have the radiant system "pre-cool" a thermal mass with a resulting reduction in the conditioning needs during the daytime hours. The thermal mass was 8" of heavyweight concrete in the ceiling and the hydronic tubing was centered vertically in the this concrete layer. During the daytime hours, the forced air system was run to meet any loads that were not met by the cold thermal mass, but the radiant system was left in passive mode where any cooling it provided was based on the lowered temperature of the mass as a result of nighttime operation. The radiant system was not allowed to run during the day.

In the independently operated system, the "low-energy cooling" radiant system alone will not necessarily meet all of the cooling loads except in the most mild climates. In this configuration, the radiant system ran from 9PM until 9AM and deviations from the 26°C (78.8°F) cooling setpoint temperature during those hours were allowed. However, due to the presence of thermal mass in the radiant ceiling, some of the benefits from the "low-energy cooling" radiant system were lagged and affected conditions within the space during the daytime when the conventional forced air system was operating (from 9AM until 9PM). In effect, the independently operated system had a temperature setback during the nighttime hours in that its objective was purely to pre-cool the ceiling mass rather than to provide thermal comfort during the nighttime. One drawback of this strategy is that thermal conditions at night could become uncomfortable—either too cold in the combined system or too warm in the base case forced air-only system.

In the second series of runs, both systems were run simultaneously, if necessary, to meet any cooling loads. In this case, the dual system was required to meet the 26°C (78.8°F) cooling setpoint temperature during all 24 hours of the day. In addition, the radiant system configuration replaced the heavyweight concrete with 1.4" (0.035m) of lightweight gypsum concrete to increase the speed with which it responded to changes in the thermal conditions. The conventional forced air system was used as a back-up to meet any load that the radiant cooling system could not meet on its own. Note that while the radiant and conventional systems both served the space conditioning needs of the house, these systems were not linked together, as the radiant system used water from the cooling tower and the forced air system was a direct expansion (DX) system.

The simultaneously operated system is similar to a "deadband" control with no setback. Priority is given to the radiant system in that it attempts to meet as much of the cooling load as possible. If it can meet the entire load, then the forced air system remains dormant. If the radiant system alone running in "low-energy" mode cannot meet the entire space conditioning load, then the forced air system is run in parallel to meet the remaining load and maintain thermally comfortable conditions within the space. In this lightweight system, the space is controlled all 24 hours to the setpoint temperature and there is no attempt to shift the load to the nighttime hours when the wet-bulb temperatures will likely be more beneficial for the low-energy radiant cooling system.

RESULTS AND DISCUSSION

The four weather environments and the two different system configurations resulted in a total of 8 test cases, each with its own base case all-conventional system. These cases were run over the traditional summer months (June 1 through August 31) using TMY2 weather data for each site. Some of these results are shown below. The Fanger Thermal Comfort model was also used to gain an understanding of whether the interior environments created by the various systems would provide acceptable conditions for the residents and also to adjust control setpoints to provide approximately the same level of thermal comfort.

Table 2 shows an overview of results for the cases where the radiant and the conventional systems operated independently. Table 3 shows an overview of the results for the cases where the radiant and conventional systems operated simultaneously. Both tables include simulation results for the period June 1 through August 31. Note that for the combined radiant/forced air system the load that was met by the radiant system that is receiving water conditioned only by the cooling tower is shown in parenthesis for each case. It should also be noted that in Tables 2 and 3 the conventional only results are based on controlling the space to a temperature that would result in approximately equivalent thermal conditions as predicted by the Fanger thermal comfort model. In most cases, this meant that if the radiant system controlled the space to an air temperature of 26°C (78.8°F) that the conventional only system had to control the air temperature of the space to approximately 24°C (75.2°F) in order to maintain similar thermal comfort conditions. A further discussion of thermal comfort is given later following Figure 4. Since there was not an exhaustive effort made to exactly match thermal comfort results between the forced air only system and the combined radiant/forced air system, differences in the loads exist between the two cases. The important point of the tables is the amount of load reduction for the forced air system and thus how much of the cooling load is met by the "low-energy cooling" system.

TABLE 2
Overview of Forced Air Cooling Loads for Independently Operating Systems

Climate/Location	Conventional Only	Radiant/Forced Air (Radiant Load in Parenthesis)
Spokane, WA	1040 kW-hr	4 kW-hr (1950 kW-hr)
Peoria, IL	1870 kW-hr	108 kW-hr (2140 kW-hr)
Phoenix, AZ	6760 kW-hr	1350 kW-hr (7760 kW-hr)
Key West, FL	4280 kW-hr	1540 kW-hr (3200 kW-hr)

TABLE 3
Overview of Forced Air Cooling Loads for Simultaneously Operating Systems

Climate/Location	Conventional Only	Radiant/Forced Air (Radiant Load in Parenthesis)
Spokane, WA	1570 kW-hr	5 kW-hr (1630 kW-hr)
Peoria, IL	2450 kW-hr	300 kW-hr (1930 kW-hr)
Phoenix, AZ	9480 kW-hr	1400 kW-hr (9170 kW-hr)
Key West, FL	6020 kW-hr	3140 kW-hr (3060 kW-hr)

As can be seen in the preceding tables, the requirement of 24 hour comfort in the simultaneously operated cases results in higher cooling requirements as one would expect. The overall trends from Tables 2 and 3 show that the use of a "low-energy cooling" radiant system can significantly reduce the cooling load on the conventional system. In Spokane, both the independently and simultaneously operated radiant/convective system result in a relatively small cooling load on the forced air system. Thus, a homeowner might chose to eliminate the conventional forced air system completely. While Spokane is a mild climate, it does occasionally reach temperatures exceeding 32°C (89.6°F) based on the information from the TMY2 file. Even a home in Peoria, where humidity levels are significantly higher, it may be possible forgo the installation of a conventional system. Even in the extreme climates of Phoenix and Key West, the system appears to hold promise in reducing the amount of energy required for cooling the residence via a forced air system.

Again, it should be noted that the data in Tables 2 and 3 are not intended to provide a direct energy comparison between a conventional forced air system only and the combined radiant/forced air systems. No exhaustive effort was made to exactly match thermal comfort conditions at all hours during the three month period simulated. In some cases, the combined system provided better comfort conditions at the expense of greater total cooling loads (the sum of the forced air system cooling load and the load met by the low-energy radiant cooling system shown in parenthesis in most of the cases is slightly larger than the conventional only system). In fact, for the conventional base cases for the independently operated system where the space was allowed to go into setback during the nighttime hours, the forced air only system resulted in uncomfortable conditions while the combined system met thermal comfort requirements for the most part.

The effect of the extra thermal mass of the roof in the independently operated system can be seen in comparing air temperatures for a typical period from the simulations. Figure 3 shows results for Phoenix from June 17 through June 19. This graph shows the relatively high hot and dry conditions that are typical for Phoenix. It also shows how the two strategies compare to each other.

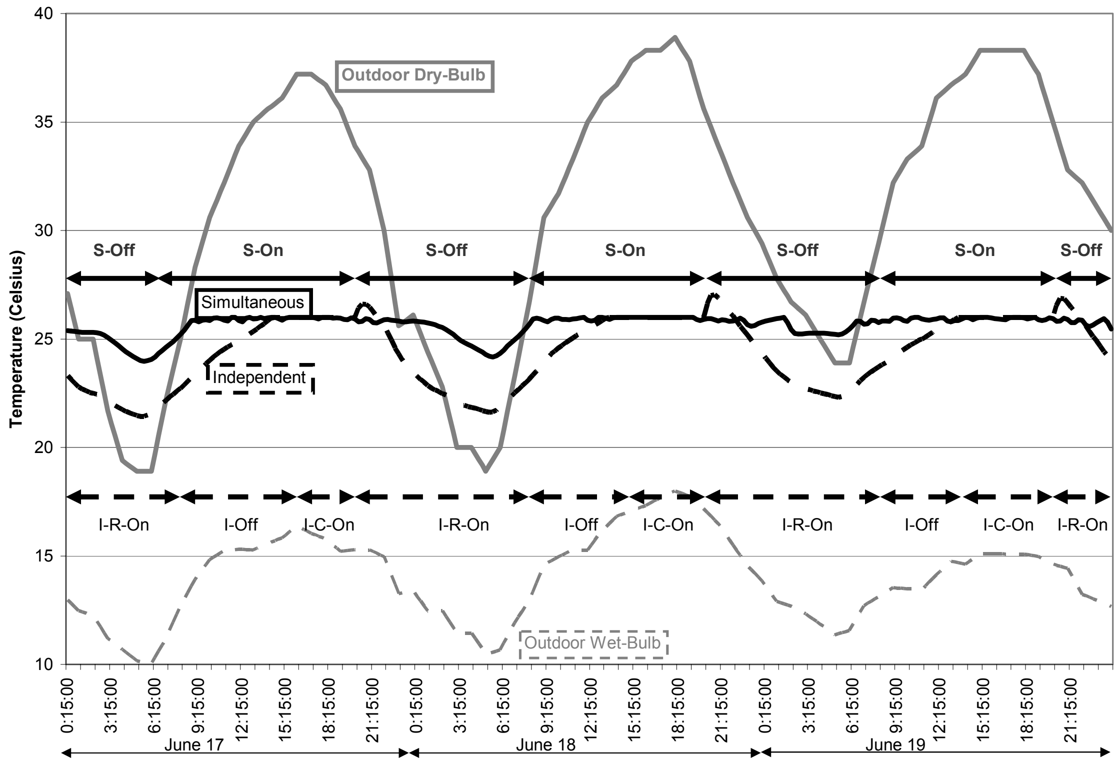

Figure 3. Comparison of Environmental and Interior Mean Air Temperatures and System Operation for Phoenix, June 17 – June 19 for Simultaneously and Independently Operated Combined Systems.

Four temperature plots are shown in Figure 3. The outdoor dry-bulb and outdoor wet-bulb temperatures are shown as the upper and lower plots, respectively, and are based on the TMY2 weather file for Phoenix. The other two plots labeled simultaneous and independent are the resulting mean air temperatures as simulated for the simultaneously operated combined system and the independently operated system. These two temperature plots are also accompanied by system operation information which shows when the two systems are running and when they are off. For the simultaneously operated system, the periods labeled "S-On" denote when both the radiant floor and the conventional forced air system are running. Since for this case, it was required that the zone be kept at 26°C (78.8°F) during the entire 24 hour period, both systems are running most of the time. There are a few cases when the temperature in the space drops below 26°C (78.8°F) due to less extreme outdoor conditions. These periods are labeled with "S-Off". For the independently operated system, periods when the radiant system is on are denoted with "I-R-On", while periods when the forced air system are on are denoted with "I-C-On". When neither system is running, the plot is shown with "I-Off".

Figure 3 shows how the independently operated system allows the building to be "precooled" by running the radiant system during the night. In fact, the system actually overcools the space based on these results. This is possible because when only one system is running it is possible to tell the simulation program to cool the space to a different temperature (in all of the independently operated simulations, this temperature was set low enough to force the radiant system to run). This was helpful in minimizing the amount of cooling required by the convective system. One can see that this precooling actually delays the need for the forced air system until later in the day depending on the severity of the exterior environment. While the independently operated system simulation results seem to suggest much better energy performance than the simultaneously operated system in some of the cases, there is a much greater variation in thermal comfort for the independently operated system that may render it unsatisfactory as a comfort application.

Both Tables 2 and 3 show that the “low-energy cooling” radiant system that relies not on a chiller but simply an evaporative cooling device or cooling tower to produce cold water seems to be effective in reducing the cooling loads on the forced air system in both mild and more extreme climates. Figure 4 shows a comparison of the thermal comfort results for the same environment and time period as Figure 3 for a conventionally cooled case as well as the independently and simultaneously operated combined system.

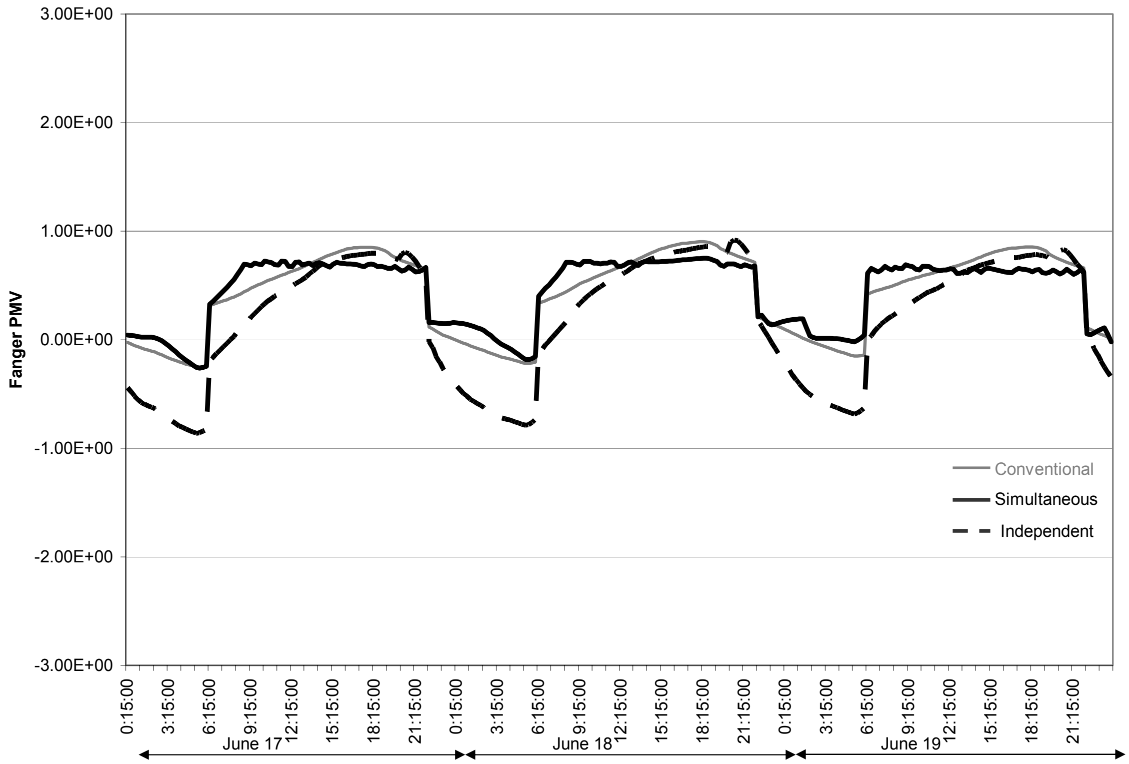

Figure 4. Comparison of Fanger PMV for Phoenix, June 17 – June 19 for Simultaneously and Independently Operated Combined Systems and a Simple Forced Air System.

It should be noted that there is an “artificial” change in the PMV during the nighttime hours due to the fact that activity levels for the residents have been scheduled in such a way that they will be sleeping during certain hours. An effort was made to compensate for this drop in activity level by increasing the clothing level to account for bed sheets and blankets. In reality, occupants would adapt to the thermal environment by modifying their bed coverings.

The trend from Figure 4 is fairly clear. Once the controls were “tuned” to provide nearly the same level of comfort, the conventional and the simultaneously operated system provide the most stable comfort level. The independently operated combined system shows the most variation in PMV during both the daytime and nighttime hours. This is direct result of the operation strategy and the use of extra thermal mass to attempt to “coast” through the daytime hours. It is likely that these significant variations in comfort would lead to dissatisfaction with this system. The amount of thermal mass and the strategy for precooling the mass require further investigation to obtain more consistent comfort levels.

CONCLUDING COMMENTS

This paper has attempted to show the potential benefits of using simulation to test ideas before significant financial and time investments are made in a particular approach or technology. The approach investigated in this paper, the use of cooling tower water to supply cool water to a radiant floor slab, was shown to be surprisingly effective in reducing the cooling load handled by a forced air system required to maintain thermal comfort in a residential space. These results were based on simulations performed with software available from the US Department of Energy. Even in climates such as hot, humid areas that would not normally be seen as a candidate for such an approach shown significant reduction in cooling loads that would need to be met by an additional forced air system.

While the results are certainly interesting and worth further study, it is not appropriate at this point to claim a great advance in the science of cooling buildings. There are many potential problems with the system proposed and caveats on the simulation results. First, the model in its current form still requires more sophisticated controls to better manage when the systems are operating. It would be helpful to be able to run the radiant system using either a different temperature criteria or scheme than the conventional forced air system to see if the precooling that was beneficial to the independently operated scheme could be used in something closer to the simultaneously operated scheme. In addition, more validation of the thermal and system model would need to be performed before the simulation results are accepted. The results of this paper are encouraging, but without better experimental validation, the results may not reflect the physical realities of an actual installation.

The system itself also has potential drawbacks. The use of an open system such as would be required in this case could lead to fouling issues within the radiant system. Typically these are closed loop systems to avoid this issue. In addition, makeup water for the system must also be taken into accounted. The "low-energy cooling" radiant system is not entirely without cost since there is both the added first cost of the system components and the radiant floor slab itself but also the cost of running the circulation pump, any fans associated with the cooling tower, and additional equipment maintenance. All of these factors will increase the financial and energy cost of the system. This paper also does not address any of the potential architectural issues that are posed by the appearance of a cooling tower or evaporative condenser in a residential setting. Finally, this paper did not consider the likely changes in architecture that one might see as a direct result of the differing climates.

While there are many issues yet unresolved and bear further scrutiny, the initial results from the literature and this paper are interesting and warrant further study. This also shows that simulation can be successfully used not only during design but also as a research tool to try new ideas numerically before actually investing in a building project.

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