

Using the Time Delay of Radiant Systems to the Grid's Advantage

Introduction

Building operators and grid operators often find themselves at odds with one another. A building operator's goal is to create a comfortable environment for the occupants and to minimize occupant complaints of thermal discomfort. In order to do so, air conditioning systems are often run at their maximum capacity during the warmest part of the day to maintain a cool environment inside the space while the temperature rises outside. When all offices in a city respond to the rising afternoon temperatures in the same way, it puts a heavy strain on the electrical grid.

For this reason, utilities often charge very high peak rates, and the building operators have sought ways to minimize electrical usage during the warmest part of the day. Some methods for avoiding peak demands include ice storage where the night hours are used to make ice, and cooling during the day is done by having air cooled by passing it over the ice that was formed the night before. Yet, this technique still uses air – a natural insulator – to conduct heat, and requires high fan energy use. A far more effective means of transporting heat is to use water which can be employed in a radiant system.

Radiant HVAC systems have been receiving increased attention in the building community [1]. Radiant systems have been shown to provide better thermal comfort than their air-based counterparts [2]. They are increasingly cost competitive with traditional VAV systems [3]. They are able to use far less energy than air based heating and cooling systems by the nature of their thermal transport property differences. But most importantly, radiant systems reach their peak loads at very different times than conventional air systems do. As a result, having a number of buildings operating with radiant systems can provide a counterbalance to the typical load profiles of buildings with air-based heating and cooling. Because of this, the building operators are no longer pitted against grid operators. A building operator with a radiant system can run a radiant system in such a way as to maximize occupant comfort without worrying about having high peak demand charges from the utility.

Unfortunately, radiant systems are relatively few in comparison with VAV systems, and either through miscommunication or a lack of sophisticated controls, they are sometimes managed as if they are air systems where the controllers call on the system to operate at full capacity during the hottest part of the day, when in fact this is entirely unnecessary. The nature of this research is to determine a more effective control system that maintains thermal comfort while shifting peak consumption to an earlier time.

Understanding Radiant System Operation

There is a fundamental difference in the way that a radiant system keeps a space cool and the way that an air system keeps a space comfortable. In some sense it is a strange phenomenon that most buildings in the U.S. today are heated and cooled by air. Using air as a media to transport heat is thermodynamically inefficient. Water on the other hand is an excellent medium for transporting heat at temperatures suitable for building operation. It is almost a thousand times denser than air (832 times at STP) and has a much higher specific heat. Thus, a cubic centimeter of water can transport heat far more efficiently than a cubic centimeter of air at atmospheric conditions. Radiant systems are much more closely matched to how the human body exchanges heat as well. The human body exchanges its heat through 47% radiant transfer, 28% convective transfer, and 27% through exhalation and other processes [1]. However, many HVAC systems for buildings still marry their ventilation to their heating and cooling, which requires large fans and very large ductwork.

Radiant systems have been installed in the past; there was a brief infatuation with the technology in the 1950's. Even Frank Lloyd Wright was known to design them into his homes, like the Gordon House in Oregon. Unfortunately, these systems were often plagued by poor construction techniques and materials that failed to contain the water that would leak out from the pipes at the soldered joints [1]. As such, radiant systems in the United States fell out of favor in the building industry and all-air systems became the dominant vogue. Today, they are seeing a renaissance as architects seek to design buildings that are more comfortable and use less energy than their neighbors.

One of the advantages of radiant systems is that a space can be considered thermally comfortable even at high indoor temperatures as long as the surrounding surfaces are kept at a cooler temperature and vice-versa. For example, if one leaves their car parked in the sun during the summer, it is a very unpleasant experience getting in and driving home. The driver will spend the first five minutes sweating even though the car's air conditioning is usually turned up to its maximum. Yet even with using lots of energy to blow cold air into the car, all the surfaces are hot to the touch, making it feel uncomfortably warm until the cold air eventually lowers the surface temperatures through convection (a very thermally inefficient process). This is how most buildings work during the peak cooling hours. The building has been sitting in the sun all day, with the radiant gains of the sun pouring in and heating up the walls and the floors. The air conditioning must ramp up to meet these needs at the worst possible time, and even then it may not be enough to provide comfort – people will either be too close to a duct and be too cold, or will be too far away from one, and will be too warm.

Imagine then reversing the scenario, so that on a hot summer day, your car seats had been kept at a very cool temperature – the driver would not feel discomfort, even if the ventilation air blown into the car was not particularly cold. This is how a radiant system works – it should circulate cool water all day to remove the heat from the sun, lights, computers, and occupants before it builds up. With a cool surface, the space can feel comfortable at an operative space temperature of 70 °F even if the air temperature is 85 °F as long as the surface temperatures are kept below 63 °F. Whereas for an air-based HVAC system, an air temperature of 58 °F is required to keep the same operative temperature when the surfaces are at 80 °F [1].

In an attempt to show their skill at energy-savvy design, an architecture firm recently renovated an old steel warehouse and installed a radiant slab for heating and cooling. It is one of the first businesses of its kind to have a radiant system designed to take care of the entire cooling needs of the space in the state of Idaho. Even so, the engineers installed a supplementary Roof Top Unit (RTU) system just in case the thermal comfort parameters in the space could not be met by the slab alone.

One reason for the firm's trepidation for leaving the slab completely in charge of cooling the space is that radiant systems are notoriously difficult to manage. Most HVAC management systems today define thermal comfort in terms of indoor air temperature. In order for a radiant system to affect temperature, the fluid must first conduct enough heat to the surface to a temperature that has enough of a difference from the indoor air with the space that convection can occur. Eventually, the convection from the radiant surface is enough to affect the indoor air temperature. However, this can take hours to occur. For this reason, the time scales at which radiant and air systems see gains are very different. It is as though they communicate in two different languages.

Solar gains are particularly difficult to deal with for HVAC systems of all types. When the sun strikes a surface, a person can feel the gain immediately. If the sun strikes a radiant (or thermally activated) surface, this is also an immediate gain that the system has to handle. However, for a system controlled by a thermostat measuring air temperature, it can take hours for the solar gain to be sensed. This observation was noted in a recent ASHRAE Journal publication by Bauman et al. [3]. In this article, the authors propose that while radiant systems still save significant amounts of energy, they may in fact have higher peak loads which occur earlier in the day than for an all-air system which senses loads based on rises in the indoor air temperature. The authors present an intriguing graph of required cooling rates as computed for a space in an EnergyPlus simulation as shown in Fig. 1:

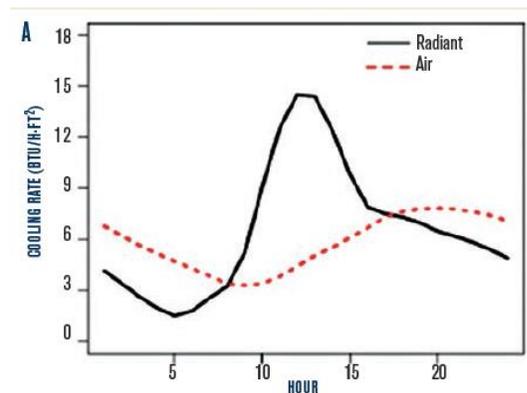


Figure 1: Contrasting Cooling Rates Required of Radiant and Air Systems from [3]

The radiant loads appear to require a higher cooling rate because once again, these are sensing radiant loads in the space from the sun, lights, computers, occupants, etc... These gains take many minutes or even hours to be translated to the air temperature and affect the thermostat and air loads via convection. And, while the cooling rate may be higher, the radiant system will still likely use less energy, because it will cost less to transport that heat with a small amount of water through pumps than a large amount of air through fans.

Identifying a Better Control System

In order to quantify the specific peak load and consumption profiles of the architecture firm for this case study, a research team installed over 70 data loggers throughout the space to monitor performance. These instruments included power and temperature sensors on each of the HVAC components including the RTUs, heat pumps, an Energy Recovery Ventilator (ERV), and cooling tower. The temperature of the slab was also monitored at four different points using thermocouples. The mean radiant temperature of the space was measured by means of a thermocouple embedded in a black hollow sphere [4] and was recorded in three different locations throughout the open office area.

These instruments are providing physical data which can be compared against the suggested load profiles of Bauman et al. [3]. The research team was also granted access to all of the data being processed by the building's Energy Management System (EMS). All of this data will also serve to verify and calibrate the energy model that was the main focus of research for the past months.

As building owners and occupants of fully functioning offices are often loathe to allow researchers to change system operations. These experiments could lead to the stressing of certain pieces of equipment or thermal discomfort for the occupants. Instead of managing the entire building's systems, these experiments will be performed on a virtual energy model of the building. This model was developed in OpenStudio 1.4 which is an interface for the DOE program EnergyPlus 8.1.

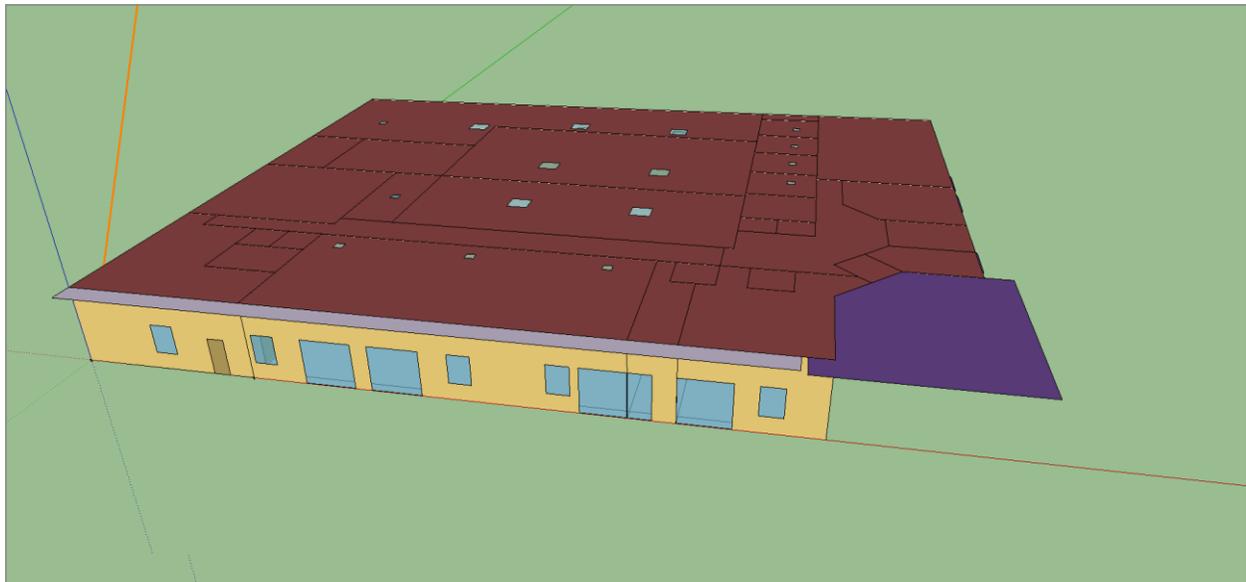


Figure 2: EnergyPlus model of demonstration project as viewed in SketchUp 2013.

EnergyPlus allows users to run the simulations and analyze temperatures throughout the space and even provide estimations of what the occupants' comfort level might be in a metric called the Predicted Mean Vote (PMV). The PMV provides a parameter for various control schemes. The goal of these new

controls will be to regulate the system in such a way as to avoid heavy operation during peak hours and to minimize overall consumption. It was noted that air and radiant systems communicate as if in two different languages. Consequently, they must be controlled differently. Air systems must respond to air temperature control signals, while radiant systems must respond along surface temperature time scales.

While EnergyPlus allows some flexibility in various operational schedules, interfacing with the virtual energy management system within the program can prove to be quite challenging and requires the user to learn a new computer language that is somewhat like the language Perl. In order to avoid this, the research team has decided to instead develop control schemes in Matlab and to apply those schemes to the EnergyPlus model through a couple of programs called Matlab-EnergyPlus (MLE+) and Building Controls Virtual Test Bed (BCVTB). BCVTB was developed by a team at Lawrence Berkeley National Lab as a way to connect EnergyPlus to outside programs. MLE+ was developed at the University of Pennsylvania and used BCVTB as a way to connect Matlab to EnergyPlus. These programs can also be used to link to a BACnet interface so that a controller can be programmed and installed physically based on the commands developed in Matlab and the energy information received inside EnergyPlus.

The energy model of the architecture firm can be linked to the Matlab program so that the radiant system may be managed in new ways. The current arrangement in the physical building is for the slab to pre-cool the space only at night and then shut off before the occupants arrive. The commands sent to the heat-pumps operating the radiant floor system take their cue from a thermostat on the wall.

The proposed scheme is based on Model Predictive Control (MPC). MPC is “an optimization based strategy in which an explicit model is used to predict the behavior of the controlled plant over a receding window into the future” [5]. It is a form of hard control linked to some sort of model inside a program (like EnergyPlus in this case). The model controls rely on historic and real-time data (occupancy profile, current weather and forecasted conditions, a test building’s sub-metered data) to predict control parameters of a building’s heating, cooling and ventilation systems. Linking the simulation to the control system can generate predicted building responses to varying inputs and thermal comfort ranges.

With the rise in computing capabilities, MPC schemes have become increasingly feasible for controlling building HVAC systems. Developing MPCs unique to different HVAC components is an area of ongoing research, but has already proven capable of providing significant savings over conventional energy management systems. An MPC was applied to a district chiller on the campus of UT Austin and was able to save 9% of their energy usage and cost savings of up to 17% by reducing consumption during peak hours [6]. Other MPC systems have shown even more dramatic energy savings of 30-70% [7].

This set-up can be run passively – where the information from the MPC is merely analyzed and compared to the existing controls – or it can be used to actively manage the building’s systems according to the model. This project is based on a passive system to analyze the results. Test implementation and active management of the system remain as areas of future work for this continuing project. Even though the MPC will be implemented passively – without active control over

hardware – the energy consumption profile of the scheme will be compared to the baseline system of packaged air handlers and their peaks and variations with temperature contrasted.

Summary and Future Work

Since radiant systems have such a different time variance and thermal profile from forced-air systems, this should provide insight into how to most effectively manage radiant controls. This research leverages the ability of MPC to manage radiant systems in a sensible manner. Successful implementation and a demonstration of the theoretical savings for a real building in the Pacific Northwest could further encourage the adoption of radiant systems that use far less energy than typical forced-air HVAC systems. This model will also be compared against utility data in short time intervals to minimize consumption during peak demand periods.

Another advantage to MPC is that various systems can be linked together. This currently remains an area for future research in the coming months. For example, in addition to controlling several of the HVAC components, the controller built in EnergyPlus could also govern a dynamic façade. As mentioned previously, radiant slabs that serve to alternately heat and cool a space operate on much longer time-scales than many other HVAC components and are dramatically affected by solar gains through unobstructed windows. This makes radiant slabs and active façades prime candidates for comprehensive governance by an MPC. Other work in this area could include the implementation of indoor comfort modules that monitor the thermal comfort performance of the system in real time and actively manage the control settings. From this, a design guide could be developed for buildings with different types of radiant HVAC systems.

The current state of the research involves calibrating the energy model of the building in order to set the MPC on a verified foundation – so that the virtual building will respond to control signals the same way the actual building might. As the energy consumption data is processed, and the predictive control tuned to this building, the research team aims to identify means of aligning occupant comfort with minimum peak demands. Of course, human's earliest dwellings (caves) were in fact net zero and used no electricity whatsoever. These were not however comfortable working environments. Someday though, it is hoped that many offices can exist with content occupants, relaxed building operators, and less demand on the grid during peak hours. The goal of this research is to facilitate that kind of future.

References

- [1] K. Moe, *Thermally Active Surfaces in Architecture*, 1 edition. New York: Princeton Architectural Press, 2010.
- [2] R. Rumsey and G. Sastry, “VAV vs. Radiant Side-by-side Comparison” *ASHRAE JOURNAL*, vol. 56, no. 5, pp. 18-24, 2013.
- [3] F. Bauman, J. Feng, and S. Schiavon, “Cooling Load Calculations For Radiant Systems,” *ASHRAE JOURNAL*, vol. 55, no. 12, pp. 20–39, 2013.
- [4] E. Berg et al., *ASHRAE Handbook – HVAC Applications*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2011, 54.7.
- [5] Ma, Jingran., Qin, Joe., Salsbury, Timothy., Xu, Peng “Demand Reduction in Building Energy Systems Based on Economic Model Predictive Control.” *Chemical Engineering Science*, 67(2012), 92-100.
- [6] Powell, Kody., Cole, Wesley., Ekarika, Udememfon., Edgar, Thomas. (2012). “Optimal Chiller Loading in a District Cooling System with Thermal Energy Storage.” *Energy*, 50(2013), 445-453.
- [7] Afram, Abdul., Janabi-Sharifi, Farrokh. (2013) “Theory and Applications of HVAC Control Systems – A Review of Model Predictive Control (MPC).” *Building and Environment*, 16(11).