Modeling Radiant Systems in an Integrated Heat Balance Based Energy Simulation Program

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ABSTRACT

For many years, designers have longed for the ability to make fair and accurate performance comparisons between conventional and radiant-based space conditioning systems. All of the past attempts at fulfilling this desired goal have suffered from a lack of sophistication and/or a lack of visibility and availability. With the release of new energy simulation software (EnergyPlus) by the U.S. Department of Energy in April 2001, architects and engineers were finally able to make system performance comparisons using a fundamentally sound tool that will be widely available to the public. In addition to the ability to model configurable forced air systems, the initial release of the new program also included models for low-temperature radiant heating and cooling systems (electric and hydronic), high-temperature radiant heating systems, thermal comfort evaluations using three established comfort algorithms, and the possibility to investigate "hybrid" systems. This paper discusses the capabilities of the new program with respect to radiant systems as well as provides information on the heat balance method itself and the new radiant model usage, development, and limitations.

INTRODUCTION

The last several decades of the 20th century were widely acclaimed as a period of tremendous growth and technological change and development in both the United States and the world in general. The field of heating and air-conditioning also saw significant improvements in areas of efficiency and system innovation. These changes were seen as beneficial to both the industry and the consumer. It is also assumed by many that these developments have also had a net positive impact on the environment since buildings are reported to use approximately one-third of all energy consumed in the U.S. each year.

One aspect of building heating and air-conditioning that did not undergo much change in the last portion of the 20th century is the process by which thermal comfort is maintained within buildings. By and large, the industry within the United States is still dominated by conventional forced air systems with radiant systems being relegated to "special application" status. Whether or not this balance between forced air and radiant systems is justified is not entirely clear.

One can certainly argue that forced air systems operate on a simpler principle and are thus easier to control. In a forced air system, the main goal is to control the air temperature. The knowledge that human beings feel hot when the air temperature is high and cold when the air temperature is low is something that is part of the practical learning experience of our own environment of all human beings. Thus, the logical step is that if air temperature can be conditioned, then thermal comfort can be maintained. Add to this that air temperature is relatively easy to maintain and very simple to measure.

A radiant system has several obstacles it must overcome before it can actually be considered as an alternative to the "simpler," more popular forced air system. Most of these obstacles are related to the way in which a radiant system maintains thermal comfort. The goal of the radiant system is not necessarily to maintain the space conditions but rather to meet the thermal comfort of the occupants directly. This is accomplished by radiant energy transfer from the system directly to the occupants. Unfortunately, the concept of radiation is simply more complex from the perspective of understanding the response of a system, controlling how the system responds, and simulating the effect of radiation.

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In the area of simulation, radiant systems can present several challenges that are not issues in conventional forced air systems. In the case of a high-temperature radiant heating system, the main issues that have to be addressed are the control of the radiant heater and the specification of where the radiant energy from the heater is incident within the space, part of which is presumably incident directly on the occupants of the space. In the case of a low-temperature radiant heating or cooling system, the main concerns are again the control of the system as well as the potential for thermal lag within the system itself. In certain low-temperature radiant systems, such as those embedded in concrete slabs, there can be a significant delay in the response of the system. More information on these challenges and how they were addressed in the new U.S. Department of Energy sponsored energy analysis program is provided in the remaining sections of this paper.

As the next sections will show, overcoming these problems is not a trivial task. Unfortunately, they are not the only issues that have faced previous attempts to model radiant systems. Two other major concerns that have not yet been adequately addressed by radiant system models are widespread availability and simulation comprehensiveness. In most of the models, the lack of a comprehensive simulation environment that includes all environmental effects and the ability to compare a range of system types on the basis of equivalent thermal comfort is a serious detriment to its widespread use. Most applications use simplified physics or are set up to analyze a very narrow range of problems. Even those models that attempt to incorporate the radiant model into an established energy analysis program (Strand and Pedersen 1997) have failed to make a significant impact on the simulation, and, thus, the design, community because of a lack of availability.

While these problems have been noted by the corresponding technical committees within ASHRAE for many years and the availability for a tool to fairly compare radiant and forced air systems has been given a high priority, neither industry nor ASHRAE has succeeded in the development of a comprehensive energy analysis program that is both comprehensive in its ability to model different systems and environmental effects and is widely available. This paper describes a program and modeling approach that is intended to meet both of the main challenges to radiant systems. In April 2001, the U.S. Department of Energy released the initial version of its new national building energy analysis program. This program is fundamentally sound from a thermal physics standpoint and also includes radiant modeling capabilities. The program is readily available to the public and has also gathered a considerable amount of interest both nationally and internationally. This is seen in the fact that over 3,000 people downloaded the initial release version of the program within the first four months of its availability. The remainder of this paper describes some of the technical details of this program, including both the high- and low-temperature radiant system models that were part of the initial program release.

SIMULATION FOUNDATION FOR RADIANT SYSTEM MODELING

Most people would agree that it is not possible to create a successful major Hollywood motion picture by starting with an idea for a character that plays a supporting role. Without preconceived plot lines, thematic elements, locations, dates, etc., which integrate into a seamless cinematic effort, this single supporting character hampers the development of an effective dramatic representation of the ideas of the screenplay writer and results in a highly ineffective movie. The same could be said for an energy simulation that is based on a radiant system model. The development of a radiant system model that is conceived as completely separate from an energy analysis program leads to shallow capabilities within the simulation and the lack of ability to adequately enhance and extend the program.

The following subsections describe some of the foundation of the new energy analysis program. These elements are important not only to the program itself but also to the incorporation of radiant system models.

Heat Balance-Based Simulation

In order to accurately assess the impact of conductive, convective, and radiative effects within a particular space, it is necessary to evaluate these effects at the most fundamental level possible. Advances in computer usage and capabilities have had a significant impact on the field of building energy analysis because they allow the use of more detailed simulation approaches that were not possible before the digital age. The heat balance simulation technique, though fundamental in nature, requires the use of a computer to handle the details that are generally beyond the scope of hand calculations.

The heat balance-based building thermal load simulation is not a new technique. In fact, at its most basic level, it is simply a first law of thermodynamics analysis applied at three key points within a building. These three categories of heat balances include outside surface heat balances, inside surface heat balances, and inside air heat balances. For each building surface (walls, roofs, floors, windows, etc.), the heat balance approach would apply a control volume at an infinitesimally thin layer at both the inside and the outside surface and balance the thermal forces. For each thermal zone within the building, the heat balance approach would apply a control volume around the air contained within this space and balance the thermal forces. In each type of heat balance, the end result is the calculation of a temperature at which all of the thermal forces balance either a surface temperature or the temperature of the air within the control volume. These heat balances are illustrated in Figures 1 through 3.

While the concept behind the heat balance is relatively simple, its implementation is complex. One must deal with many different issues related to the way in which heat is transferred via conduction, convection, and radiation. Each mode of heat transfer presents a different challenge to the simulation environment. Conduction in buildings is almost always a tran-

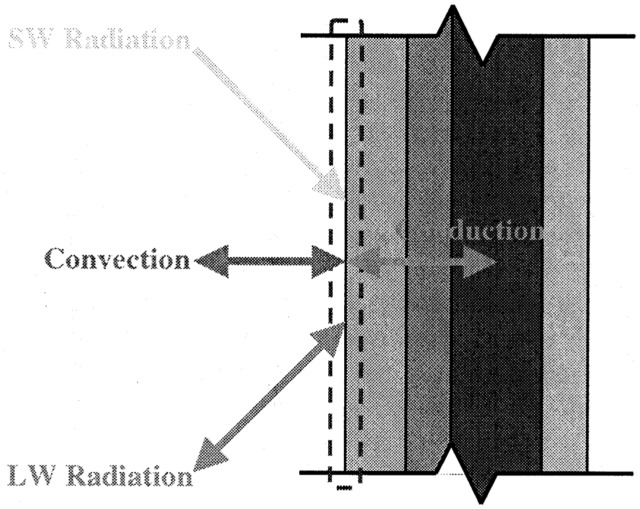

Figure 1 Outside surface heat balance.

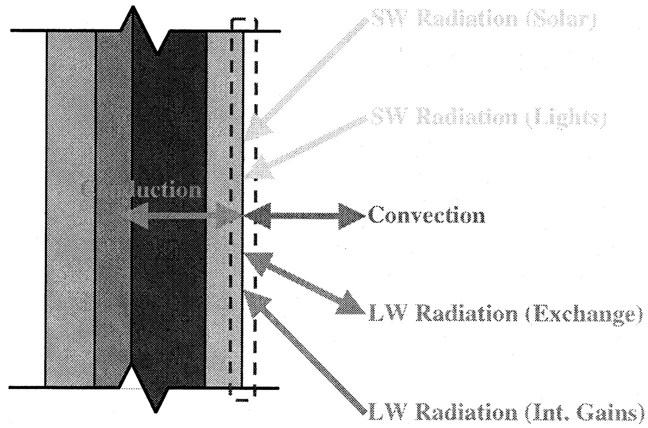

Figure 2 Inside surface heat balance.

sient process and thus cannot be modeled with steady-state equations due to the presence of thermal mass within the building. Convection coefficients can vary with time both at the inside and the outside surface due to changing temperatures and flow conditions. Radiation in itself is a complex process dealing with fourth order equations that are difficult to solve, not to mention solar radiation and the complex shading that can occur in even simple building layouts. Even once these issues are adequately resolved, the algorithm must arrive at a solution—something that is not guaranteed without careful attention to details.

Use of the heat balance method does not guarantee the best solution but rather provides a framework for the best possible solution. How a heat balance solution performs in its goal of accurately predicting the thermal response of a building depends on the accuracy of the solution components. In order to find a reasonably accurate solution in an acceptable amount of time, the solution procedure for the program in question is simplified somewhat by making the following assumptions:

- 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
- well-stirred zone air (air temperature is constant throughout the zone/no stratification)

Most of the other challenges that a heat balance-based solution presents are solved as accurately as possible in the new program. Transient conduction through building walls, floors, roofs, windows, etc., is modeled using a time series

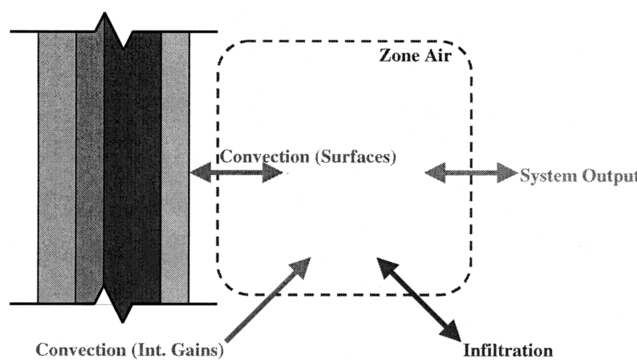

Figure 3 Zone air heat balance.

analysis technique known as conduction transfer functions. This method has been proven over many years of use within simulation programs and can provide an accurate transient solution via an algebraic equation that contains constant coefficients and history terms of surface temperatures and fluxes. Convection can be handled using a variety of models for natural, forced, and mixed convection that vary the convection coefficients based on temperature differential, surface orientation (vertical, horizontal, sloped), and wind conditions. Solar radiation can be projected onto both exterior and interior surfaces using sophisticated geometry and shading algorithms. Exterior long-wavelength radiation is allowed between the surfaces and the surrounding sky, air, and ground. Interior radiant exchange is described in more detail in the following subsection.

Many of the details of the heat balance solution are beyond the scope of this paper and will not be covered in explicit detail. Reference works for the program, as well as the ASHRAE Loads Toolkit, which closely resembles the program in many ways, are provided at the end of this paper. The reader is encouraged to reference these documents for further details on the components of the heat balance simulation.

Interior Radiant Exchange Algorithm

One area in most heat balance-based simulations that has been criticized (fairly or unfairly) has been the handling of interior radiant exchange between zone surfaces. Despite research (Liesen and Pedersen 1997) showing that methods such as the MRT method can be reasonably accurate for most building conditions, concerns about the accuracy and the understandability of simplified interior radiant exchange algorithms caused the research team to improve this aspect of the new program. As a result of this work, the interior radiant exchange model used in the new program is much more fundamentally sound.

The model used is an implementation of what is commonly known as Hottel's Grey Interchange Method (Hottel and Sarofim 1967). This method is an exact formulation of radiant heat transfer within an enclosure of grey diffuse surfaces. Using matrix algebra, the method results in grey interchange factors (or a "Script F" matrix) that can be used to directly calculate the radiant exchange between two surfaces at known temperatures. The input quantities to the Script F routines are the surface emissivities and the matrix of view factors between surfaces within the enclosure.

Currently, the program requires emissivities as input from the user but will calculate approximate view factors for surfaces. These view factors are not exact view factors though there are plans to allow the user to input view factors. Instead, the view factors are area-based with modifications to account for surfaces that cannot see each other and the requirements of completeness and reciprocity. The approximate view factor routine uses the following equation to define the first guess at view factors for surfaces:

$$F_{i,j} = \frac{A_j}{\sum A_j} \qquad (1)$$

Because surfaces that face the same direction cannot see each other and thus cannot exchange radiation, surfaces that face the same direction as surface "i" are excluded from the area summation in the denominator and are assigned a view factor of zero. It should be noted that at this point, these view factors are not exact and do not satisfy completeness or reciprocity as defined by the following equations, respectively:

$$\sum_{j=1}^{\text{Number of Surfaces}} F_{i,j} = 1 \qquad (2)$$

$$A_i F_{i,j} = A_j F_{j,i} \qquad (3)$$

As a result, the matrix of view factors goes through a correction process that uses the area-based view factors as a starting point and manipulates the values until both completeness and reciprocity are met. This typically takes several iterations of the following two steps: average the product of the area vector with view factor matrix (the AF matrix) with its transpose (to ensure reciprocity) and then divide all of the elements within a row of the AF matrix by the sum of all its elements (to ensure completeness). Each of these steps on its own might invalidate the condition of the other step, but the use of iteration eventually results in view factors that satisfy both conditions. These view factors are then used with the surfaces emissivities and Hottel's Grey Interchange Method to produce a Script F matrix. The Script F matrix is then used with surface temperatures to calculate the net radiant flux on a particular surface using the following equation:

$$Q_{lwrad,i} = \sum_{j=1}^{\text{Number of Surfaces}} (\sigma)(\text{Script}F_{i,j})(T_j^4 - T_i^4) \qquad (4)$$

This equation is more accurate than the various MRT-based methods, is easier to understand, and does not significantly increase the computational complexity of the heat balance calculations.

Thermal Comfort Models

Thermal comfort is a critical issue in any building. In most forced air systems, designers will predict satisfaction with the thermal surroundings based on air temperature alone. In a radiant system, such assumptions are not possible and would neglect one of the operating principles of these systems: heating or cooling the room occupants directly using radiant heat transfer. In reality, radiant effects also play a role in conventional forced air system designs.

To accurately account for all of the effects of radiant systems, it was necessary to integrate thermal comfort models into the new program. The Fanger, Pierce Two-Node, and KSU Two-Node thermal comfort models were chosen for implementation in the new program and included in the initial program release. These three established thermal comfort models provide a more accurate view of the thermal surroundings produced by both conventional forced air and radiant systems.

Lee and Strand (2001) provide details on how the models were implemented in the new program as well as how a fictitious person could be placed within a room. The initial release provided two options for locating an individual for thermal comfort study: an "average" location and near a particular surface. The average location was intended to capture a person at the geometric center of a space. This is not the only point of interest within a space, so an additional option that allows the user to place a person very close to a particular surface (window, wall, etc.) was also implemented. These two placement options allow thermal comfort studies without much input from the user, but it is not entirely clear if these are adequate for all thermal comfort studies. A plan to expand these placement options by allowing the user to enter surface angle factors is being investigated.

All of the thermal comfort models also include the effect of direct radiation from a high-temperature radiant heater. This direct radiation incident on a person within a space is taken into account using a version of an equation recommended by Fanger (1970) and has the following form:

$$T_{radiant} = \left[(T_{MRT}^4) + \left(\frac{Q_{heater \to person}}{\sigma A_{person}}\right)\right]^{0.25} \quad (5)$$

where

$T_{radiant}$ = modified mean radiant temperature used in the thermal comfort models,

T_{MRT} = mean radiant temperature either for the average location or near a surface,

$Q_{heater \to person}$ = amount of radiation leaving a high-temperature radiant heater that is incident on a person,

σ = Stefan-Boltzmann constant, and

A_{person} = area of an average person.

Note that the radiation leaving the heater is only for a high-temperature radiant heater and includes the effect of all high-temperature radiant heaters within the zone. Low-temperature radiant systems modify the temperature of individual surfaces and their effect is already included in the T_{MRT} term.

LOW-TEMPERATURE RADIANT SYSTEM MODEL

Low-temperature radiant heating and cooling systems appear, on the surface, to be relatively simple systems. The system circulates hot or cold fluid through tubes embedded in a wall, ceiling, or floor or runs current through electric resistance wires embedded in a surface or a panel. Energy is thus either added to or removed from the space, and zone occupants are conditioned by both radiation exchange with the system and convection from the surrounding air that is also affected by the system.

Despite the relative simplicity of the low-temperature radiant systems, the integration of such a system within an energy analysis program requires one to overcome several challenges. First, for systems with significant thermal mass, the conduction transfer function method for modeling transient conduction must be extended to include embedded heat sources or sinks. Strand (1994, 1995) showed that this was possible and that the standard conduction transfer function equation

$$q_{i,t} = \sum_{m=1}^{M} X_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} Y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} F_m q_{i,t-m} \quad (6)$$

was left intact with the exception of the additional term for heat sources/sinks as shown in the following equation:

$$q_{i,t} = \sum_{m=1}^{M} X_{k,m} T_{i,t-m+1} - \sum_{m=1}^{M} Y_{k,m} T_{o,t-m+1} + \sum_{m=1}^{k} F_m q_{i,t-m} + \sum_{m=1}^{M} W_m q_{int,t-m+1} \quad (7)$$

The use of this equation allows the low-temperature radiant system to be handled like any other surface within the heat balance framework. Heat balances at the inside and outside surfaces take on the same form as other surfaces, and the participation of the radiant system in the radiation balance within the space and thermal comfort models is automatically included. Thus, the radiant system model is fully integrated into the heat balance, and any improvements that are made in areas such as convection coefficients, shading models, etc., are immediately available to the radiant system as part of the overall heat balance solution.

Once the transient nature of the system is accounted for, one must then turn to the next difficult issue: controls. Controls are problematic for almost any simulation program. The problem is not whether something can be simulated because typically a simulation program offers the ability to experiment with many different control strategies. Rather, the problem is typically the diversity of controls that are implemented and keeping the controls that can be simulated up to date. In this area, the new program should be seen as a first attempt at modeling basic low-temperature radiant systems and not as the definition of all radiant systems. Plans call for the addition of other control strategies in future versions of the program.

As a result, controls for low-temperature radiant systems within the new program are fairly simple though there is some flexibility through the use of schedules. The program user is allowed to define a setpoint temperature as well as a throttling range through which the system varies the flow rate of water (or current) to the system from zero to the user-defined maximum flow rate. The flow rate is varied linearly with the flow reaching 50% of the maximum when the controlling temperature reaches the setpoint temperature. Setpoint temperatures can be varied on an hourly basis throughout the year if desired. The controlling temperature can be the mean air temperature, the mean radiant temperature, or the operative temperature of the zone, and this choice is also left to the user's discretion. Since flow rate is varied, there is neither explicit control on the inlet water temperature nor mixing to achieve some inlet water temperature in a hydronic system. However, the user does have the ability to specify on an hourly basis through a schedule the temperature of the water that would be supplied to the radiant system.

Graphical descriptions of the controls for the low-temperature radiant system model in the new program are shown in Figure 4 for a hydronic system. In a system that uses electric resistance heating, the power or heat addition to the system varies in a manner similar to mass flow rate variation shown in Figure 4.

One remaining challenge is the merging of the low-temperature radiant system model with an integrated building simulation program. In the past, most simulation programs have simulated the building envelope, the space conditioning systems, and the central plant equipment in three separate steps. While this had some advantages and was partly due to a lack of computing capacity, the large drawback for this arrangement is that there is no feedback from the space conditioning system or central plant to the building conditions. Thus, if the system or plant was undersized, it was reported as an "unmet load" and did not affect the temperatures experienced within the building. A predecessor (Taylor et al. 1991) to the new program resolved this issue by integrating all three major components of a building simulation, thus allowing feedback between the equipment and the building envelope.

This integration was not a trivial task and required, in some cases, that the systems be simulated at shorter time steps to maintain solution stability. In essence, the system simulation will shorten its time step whenever it senses that conditions are changing too rapidly. While this is effective in maintaining solution stability, it can present problems for a radiant system. The radiant system has either a direct or an indirect impact on the surfaces within a building. So, it must be simulated with the building envelope. Yet, it is also a space conditioning system that must act on the space like any other system and thus must also be simulated at the system time step, which can be less than the building time step and can also vary within the new program.

This issue was handled using a multi-step approach. In the new program, the heat balance is always simulated first. When this happens, the radiant system is temporarily shut off to find how the building would respond if there were no heat source/sink. Then, as the system and plant are simulated at multiple shorter time steps, the radiant system is allowed to operate with the controls specified by the user. Flow rate is allowed to vary at each system time step, and the radiant system model is simulated at each time step as if the current flow rate were being used throughout the entire zone time step. This means that each time the heat source/sink in the radiant system is varied during the system simulation the zone heat balance must be recomputed to see what the reaction of the rest of the zone is to this change in the conditions of one (or more) of the surfaces.

In reality, this is not physically correct because each change in the flow rate throughout the system simulation will have an impact on the system time steps remaining before the heat balance is simulated during the next zone time step. Yet, other approaches to solving the mismatch between the system and the zone response of radiant systems are not feasible. One could force the system to run at the same time step as the zone, but this could result in instabilities in other types of systems that might be present in the simulation. On the other hand, one could try to force the zone to run at the shorter time steps of the system, but this could lead to instability within the heat balance due to limits on the precision of the conduction transfer function coefficients.

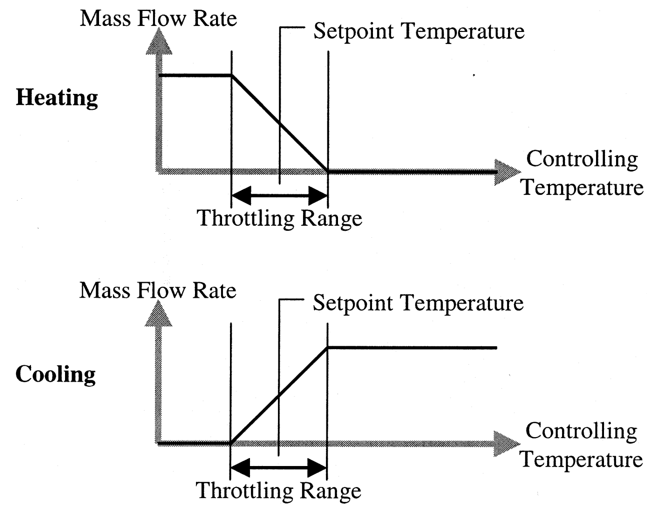

Figure 4 *Low-temperature radiant system controls.*

Despite the fact that the simulation algorithm described above may either over- or underpredict system response depending on how the system has been controlled in previous system time steps, it is reasonable to expect that the effect of these variations will balance out over time even though it might lead to slightly inaccurate results at any particular system time step. The long-term approach is also in view in the final simulation step at each zone time step. After the system has been simulated through enough system time steps to equal a zone time step, the radiant system will rerun the heat balance using the average heat source/sink over all of the system time steps during the past zone time step. This maintains the conservation of energy within the heat balance simulation over the zone time steps and defines more appropriate temperature and flux histories at each surface that are critical to the success of a conduction transfer function based solution. A sketch of this somewhat complex multiple step simulation is shown in Figure 5.

A summary of the major features of the low-temperature radiant system model within the new program is given in Table 1. Most of the other details are similar to those presented by Strand (1995,1997).

HIGH-TEMPERATURE RADIANT HEATER MODEL

The high-temperature radiant heater model is intended to encapsulate an entire class of heating devices that seek to heat the occupants within a zone by direct radiation. This encompasses a wide variety of heaters including both gas-fired and electric. In most cases, the heater appears much like a lamp or a tube that is suspended from the ceiling of a space. The surface temperature of the heater is high enough that it must be some distance away from the occupied portion of the space for safety concerns.

In the new program, the high-temperature radiant heater model allows the user a reasonable amount of flexibility. Rather than specifying an exact location for the radiant heater(s), the user is allowed to specify the percentage of heat leaving the heater as radiation and on which surfaces this radiation is incident. In addition, the user is also allowed the ability to define what fraction of radiation leaving the heater is incident directly on a person within the zone for thermal comfort

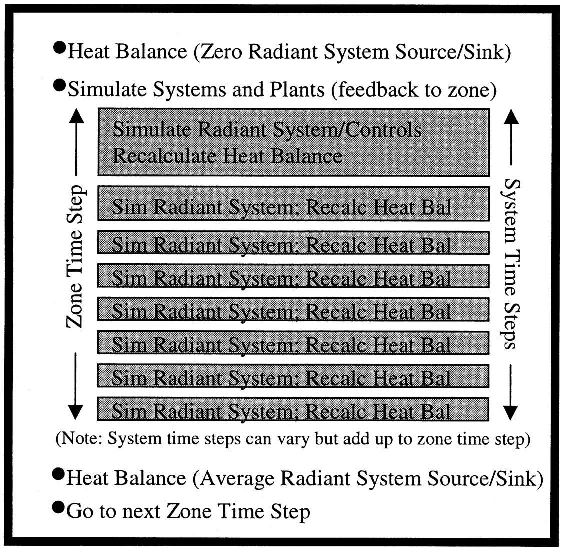

Figure 5 *Resolution of radiant system response at varying time steps.*

purposes. This amount of heat is then used in the thermal comfort models, as shown in Equation 5. The input parameters for the high-temperature radiant heater model are shown in Table 2.

The input for the high-temperature radiant heater has two additive relationships that are assumed. First, the fractions of radiant, convective, latent, and lost heat must sum to unity. The user is required to enter the fractions radiant, latent, and lost with the remainder assumed to be convective energy. The fraction latent is added to the latent energy balance and will affect moisture levels within the zone. The fraction lost is assumed to have no impact on the energy balance of the zone and is assumed to be lost or vented to the exterior environment.

The second additive relationship governs the distribution of the radiant fraction. This energy is distributed to people and to the surfaces within the zone. The sum of all of these distribution fractions (the last six lines of input shown in Table 2) must sum to unity. Note that each high-temperature radiant heater is allowed to distribute energy to up to 20 surfaces and that radiant energy placed on a surface using these distribution fractions is assumed to be completely absorbed. Thus, the distribution fractions should also take into account any differences in long wavelength absorptivity among the surfaces.

Several things should be noted about the fraction of heat that is radiated directly to people. This parameter is somewhat sensitive and will have a direct impact on the thermal comfort models. This is exactly the intent of the high-temperature radiant heaters; however, one must use caution when determining this fraction since overestimation of this number might lead to predictions of satisfactory thermal comfort where in fact it does not exist. In addition, this fraction of radiant energy to

TABLE 1
Major Features of the Low-Temperature Radiant System Model

Features	Notes
Rigorous Model Foundation	• Integrated with a heat balance approach • Takes advantage of existing and tested loads calculation • Improvements to heat balance are immediately available to radiant system model
Transient Conduction	• Accounted for using a modification of standard conduction transfer functions • System can be defined with any material or insulation level
Controls	• Model varies flow rate or electric power to meet conditioning loads • User specifies maximum water flow rate (can be different for heating and cooling) or maximum electric power of system • User specifies setpoint temperature for system (can vary on an hourly basis) • User specifies throttling range for controls • User specifies temperature to which the setpoint is compared (can be MAT, MRT, or operative temperature) • User specifies water temperatures (can vary on an hourly basis)
Simulation Flexibility	• Model can adjust time steps to accurately account for rapidly changing conditions • Zone time step integration of heat source/sink seeks to guarantee that energy is not created or lost • Nearly all of the limits (such as number of zones or number of surfaces) that are found in programs of this type have been eliminated

TABLE 2
Input Description for High-Temperature Radiant Heaters

HIGH TEMP RADIANT SYSTEM,	!	program keyword for high-temp. radiant heaters
Zone 1 Radiant Heater,	!	zone name
Radiant Operation,	!	availability schedule
SHOP ZONE,	!	zone name (name of zone system is serving)
10000,	!	maximum power input (in watts)
GAS,	!	type of heater (either gas or electric)
0.85,	!	combustion efficiency (ignored for elec. heaters)
0.75,	!	fraction radiant
0.05,	!	fraction latent
0.05,	!	fraction lost
OPERATIVE,	!	temperature control type (MAT, MRT also possible)
2.0,	!	heating throttling range (in °C)
Heating Setpoints,	!	schedule of heating setpoint temperatures
0.05,	!	fraction of radiant energy to people
Zn001:Flr001, 0.75,	!	surface/fraction of radiant energy incident on it
Zn001:Wall001, 0.05,	!	surface/fraction of radiant energy incident on it
Zn001:Wall002, 0.05,	!	surface/fraction of radiant energy incident on it
Zn001:Wall003, 0.05,	!	surface/fraction of radiant energy incident on it
Zn001:Wall004, 0.05;	!	surface/fraction of radiant energy incident on it

people does not have a direct impact on any of the surface heat balances. The thermal comfort energy balance is completely separate from and has no bearing on the zone air or the surface heat balances. Thus, in order to not "lose" this amount of energy from the perspective of the zone air or the surface heat balances, the model assumes that any radiation from the high-temperature radiant heater that is incident directly on people is accounted for in the thermal comfort model using Equation 5 but is also assumed to be added to the zone air heat balance via convection from people to the surrounding air. This guarantees that the people within the space feel the direct radiative effect of the heaters and that this quantity of energy is not "lost" within the heat balance routines.

Many of the control and integration aspects of the high-temperature radiant system model in the new program are very similar to the low-temperature radiant system model. The controls are the same as shown in Figure 4, where the amount of heat generated by the radiant heater varies as a function of the difference between the controlling and the setpoint temperatures. As with the low-temperature radiant system, the controlling temperature is allowed to be the mean air, the mean radiant, or the operative temperature, and the setpoint temperature is allowed to vary hourly based on a user-defined schedule. Also, since the high-temperature radiant heater has a direct impact on the surfaces within a zone, the surface heat balances are recalculated to determine an approximate response to the radiation from the heater. A final "average" heat balance calculation is done after all of the system time steps have been simulated to maintain continuity within the surface heat balances.

CONCLUSION

Radiant systems present several challenges to comprehensive energy analysis simulation programs due to the complex nature of their interaction with the building as both a space conditioning system and an element that has a direct impact on heat transfer surfaces within a zone. The model presented in this paper achieves a balance between these two aspects of radiant systems within a simulation program that is readily available to the public. Moreover, the models have been linked to established thermal comfort models, allowing designers the possibility to compare radiant and conventional forced air systems for equivalent comfort.

The meshing of radiant system and thermal comfort models within a building simulation program is not the only benefit of the work described above. Due to the flexibility of the simulation program, users can select multiple systems for a single zone. This allows the user to specify multiple active radiant surfaces/systems and/or combinations of convective and radiant systems. Thus, the model is an ideal starting point for a "hybrid" system model. In fact, the program can, in theory, already model the components of hybrid systems. Due to somewhat flexible connections within the plant simulation, a user can connect a coil and a radiant loop in parallel or in series to model a variety of hybrid system connections. The main obstacle that must be overcome to model systems as they are typically installed in buildings is the integrated control of the radiant and convective system combination. At present, the program assumes that the systems are controlled in series, using a priority list that simulates the systems in a set order based on whether there is still any thermal load remaining.

This initial model is not intended to be the final word on radiant systems but rather a basis for future work. Many basic radiant systems can be simulated using the model within the new program; however, some of the controls may be too simple for some installations. The addition of hybrid controls for radiant and convective system combinations as well as on/off water flow with temperature modulation are some of the improvements that are being considered for future research. Moreover, validation with existing data sets is necessary to provide further credibility for the model. Despite the current shortcomings that will hopefully be addressed in the near future, the new model and program are a significant step forward for the design community, making it possible to determine which system type will be the most efficient in any setting for equivalent thermal comfort.

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