A FUNDAMENTAL APPROACH TO COOLING LOAD CALCULATIONS FOR UFADS AND STRATIFIED SPACES

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ABSTRACT

Spaces with an under floor air distribution system (UFADS) or a stratified atria involve special thermal exchange processes that require special load calculation procedures. This paper introduces an infrared transparent (IRT) surface that enables adjacent zones to exchange thermal radiation while maintaining separate air temperatures. This paper describes the development of the IRT surface and presents a comparison of a UFADS room using the IRT model and a room with conventional air flow configuration. The fundamental principles such as infrared radiation from the zone surfaces to the cool floor, and air preheating within the under floor supply plenum are calculated with a simulation approach using EnergyPlus.

INTRODUCTION

One of the important technical features of EnergyPlus is that the fundamental zone model includes infrared (IR) radiation exchange among all surfaces within the zone. A zone can consist of a single room or space in the building. The other fundamental characteristic of a zone in EnergyPlus is that the air within the zone is assumed to be well-stirred, so it is characterized by a single uniform air temperature. Normally, this corresponds to the desired physical state of the air within a zone. Practically, this is accomplished with the mixing caused by the air distribution system or even with the addition of ceiling fans. However, there are situations where the well-stirred model condition does not fit the physical conditions within a space. For example: large atria spaces, displacement ventilation systems, and under floor air distribution systems. In these cases, the air temperature varies spatially within the zone, but the surfaces in the regions that have different air temperatures still exchange IR radiation with the other surfaces in the zone, even those in regions having a different air temperature.

Historically, several approaches have been taken to model such situations. Some are steady state only (Bauman et. al. 2006). Two other approaches involve unphysical modifications to the fundamental processes in order to represent the heat transfer in the zone. One (Qing Liu. 2006) involves unrealistically modifying the convective heat transfer characteristics within a single zone to produce approximate total heat exchange for the zone while maintaining the zone IR radiation in its basic form. The other approach (Laouadi, et. al. 2003) does the opposite and uses a space divided with fictitious surfaces that separate the thermal radiation between the spaces. The changed radiation is then accounted for by boosting the convection coefficients to make up for the lost radiant exchange.

This paper introduces a similar method in that fictitious surfaces are used to separate zones but, those surfaces are configured to permit the complete IR exchange while keeping all other heat transfer processes basic and unchanged. The separating surface is called an infrared transparent (IRT) surface. With an IRT dividing surface, a space is divided into multiple subzones, each having the basic well-stirred air model, but surfaces in these subzones are able to exchange IR radiation with other surfaces throughout the original space. Any convective air exchange between subzones is handled using the existing flexible capabilities within EnergyPlus. In other words, the subzones are standard EnergyPlus zones but they have been given the capability of allowing IR radiation to be exchanged with surfaces of adjacent zones. IRT surfaces transmit the IR radiation incident on them to the surfaces in adjacent zone. The special surfaces do not participate in the convective exchange because they have zero convective heat transfer coefficients on both sides.

Consider a stratified atrium as an example. The atrium would be divided into stacked vertical zones, with each zone having the special IRT surface between it and the next lower zone. All physical surfaces in the two zones exchange radiation with the IRT surface, but it does not impede the transfer of radiation from one zone to the other. On each side it interacts as a black body surface and any radiation incident on it is absorbed. Since it has no other heat transfer mechanisms, it comes to equilibrium with zero net radiation transfer.

Figure 1(at end of paper) shows it applied between two stacked zones that could be part of an underfloor air distribution system (UFAD). All radiation that is incident on the IRT in the lower and upper zone is completely absorbed by the IRT surface. It is prevented from participating in the zone air heat balance by fixing the heat transfer coefficients on either side at zero. The two upper zones represent the lower occupied (mixed) zone and the upper (stratified) zone. Since the upper zone is being modeled as a mixed EnergyPlus zone, it is not precisely the stratified zone concept, but it provides a model that is capable of being analyzed. However, if a user has concern about having the entire upper (stratified) part of the space at a single average temperature, the space could be modeled with two stacked upper zones. In that case the user would have to supply mixing estimates from external knowledge of the behavior of UFAD systems and plumes. It should be noted, however, that the effect of either a stratified zone with a vertical temperature profile or two mixed zones has little effect on the system load since it is based on the mixed air temperature of the return from the top zone

MODELING IRT SURFACES

The IRT surface behaviour can be modeled by considering three parallel black plates infinite in extent, as shown in Figure 2. The outside plates are held at two different temperatures, and the intermediate plate assumes an equilibrium temperature when the net heat flux goes to zero. All plates have black body surface characteristics

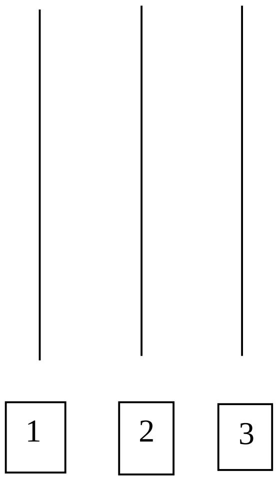

Figure 2, Radiation Exchange Model

The radiant exchange between surface 1 and 2 is:

$$q_{1-2} = \sigma A(T_1^4 - T_2^4) \qquad (1)$$

the exchange between surfaces 2 and 3 is:

$$q_{2-3} = \sigma A\left(T_2^4 - T_3^4\right) \qquad (2)$$

Equating heat fluxes and eliminating T_2 gives:

$$q_{1-3} = \frac{\sigma}{2} A\left(T_1^4 - T_3^4\right) \qquad (3)$$

Where:

q is the heat flux in W/m^2
σ is the Stephan Boltzman constant
A is the plate area, and
T is the absolute temperature [K].

Equation (3) shows that the presence of a black body surface between a source and a sink reduces the heat flux by a factor of two. The same result occurs when the IRT surface is between two zones in EnergyPlus. In order to account for this reduction, the IRT area must be doubled. This can be done without and difficulty in the EnergyPlus radiant exchange routine because the radiation view factors can be determined by an approximate procedure that is based on the areas of the surfaces. Thus doubling the surface area of the IRT surface results in the correct transfer of radiation through the IRT surface. The doubling occurs automatically in the program through the use of the specific material type as described in the input file (IDD object).
It should be noted that, because of the black body behaviour of the IRT surface, any visible or solar short wavelength radiation incident on the surface will be absorbed and included within the long wavelength (IR) exchange with the adjacent zone. No energy will be lost, but zones with IRT surfaces should be used with caution in any lighting analyses. They are not windows to visible radiation.

VERIFICATION OF MODEL BEHAVIOR

The behaviour of multi zones separated with infrared transparent surfaces can be checked with a simple comparison. Begin with a single zone model as shown in Figure 3. This model has a south facing window, and four walls exposed to wind and sun, and a roof exposed to wind and sun.

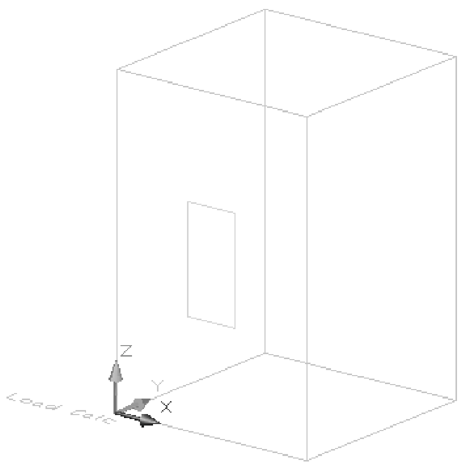

Figure 3, Single Zone Model

The single zone model will be compared with a stacked three zone model that has zones separated by IRT surfaces. This model is shown in Figure 4 with the EnergyPlus IRT surfaces separating the zones.

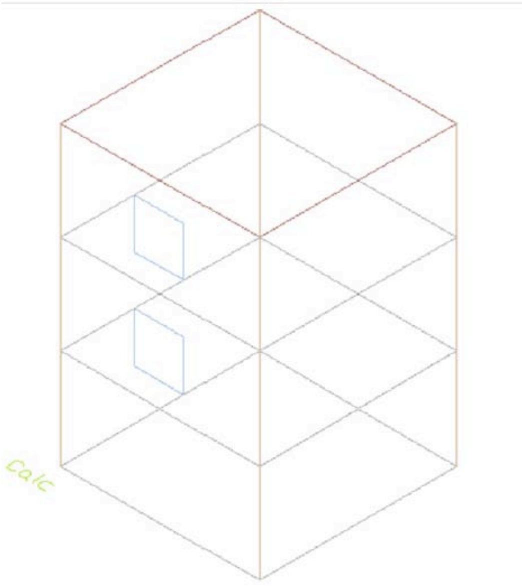

Figure 4, Three Zone Model

The two upper zones have south facing windows whose total area is the same as the window area of the window in the single zone. The top and the sides are again exposed to sun and wind. The separating surfaces are modelled as IRT surfaces. All zones in both models are controlled at the same set point temperature using purchased air.

The sensible heating results are shown in Figure 5. The results show the sum of the sensible cooling load for the three stacked zones and the single zone. It is clear that the IRT surfaces are very effective in transmitting infrared radiation between the zones.

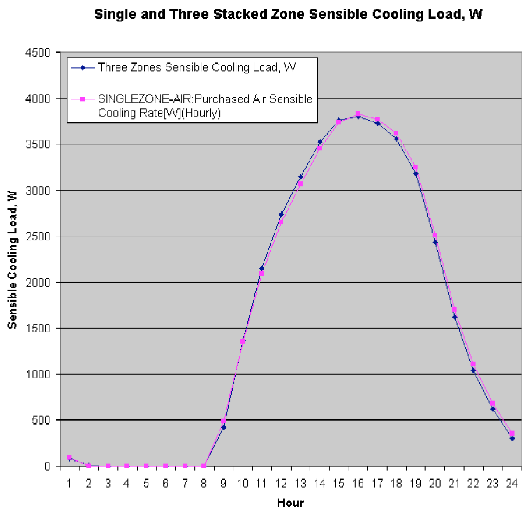

Figure 5, Stacked Zone Comparison

EXAMPLE APPLICATION OF THE MODEL

At the present time there is some question about how UFAD systems are sized. Proponents of the systems make many claims about load and energy reductions, and designers report difficulty determining the appropriate equipment size. ASHRAE Technical Committee 1.4, which is responsible for providing technical information to the members on load calculation procedures, has begun to investigate the load calculation aspect of UFAD systems. The goal is to assist designers with proper sizing of the supply equipment. A base case and two modifications suggested by that committee are shown in table 1. These cases were examined using the IRT surface model. A conventional air system model was also used for comparison.

Application Results

One of the characteristics of a UFAD system is the phenomenon of heat gain in the supply plenum. This affects the actual supply temperature to the zone, and represents a load pickup before the supply air enters the occupied space. Figure 6 shows the total sensible load for the lower occupied zone for the three cases using an example space that has an area of 400 ft^2 (37.16m^2). The sensible load picked up by the air passing through the supply plenum is also shown. For these cases the supply plenum picks up about 40% of the total sensible load. This is due primarily to the thermal radiation to the top of the floor surface from the space above. It shows the importance of having a model that includes all of the radiant exchange. It should be noted that the presence of furniture and other obstructions can affect this transfer, and the entering air temperature can also be affected.

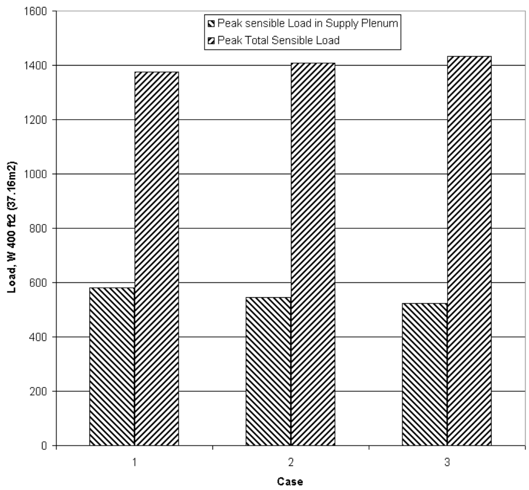

Figure 6. Peak Sensible Loads

Figure 6 also shows how some of the claims of lower loads with UFAD systems can result. For example, since the load in the supply plenum is so large, if only the load in the space above the plenum is considered it would be only 60% of the total load in these examples. So, the claims have to be studied carefully.

The three UFAD examples showed very similar results in figure 6, so they were averaged for a comparison with a conventional air system as shown in Figure 7. It is clear that, from a load calculation standpoint, there is no significant difference between the UFAD system and the conventional air system.

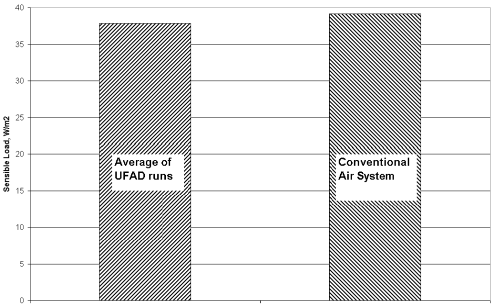

Figure 7, Sensible Loads

Three specific things were learned from the examples:

1. Total sensible loads in UFAD and conventional overhead systems are comparable.

2. Occupied zone RH is significantly higher with UFAD system. This must be accommodated.

3. The supply plenum picks up a significant part of the load.

CONCLUSIONS

The IRT surface concept has been shown to be an important capability when it is desired to perform a fundamental analysis of the heat exchange processes in spaces with stratification. The thermal radiation exchange in such spaces is extremely important, and the IRT surface concept makes it possible to include that exchange without having to resort to unphysical process modifications which usually end up being case specific and not general. A more physical model such as IRT makes it is easy for designers to make understandable limit checks, and obtain information for making good design decisions.

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ACKNOWLEDGEMENT

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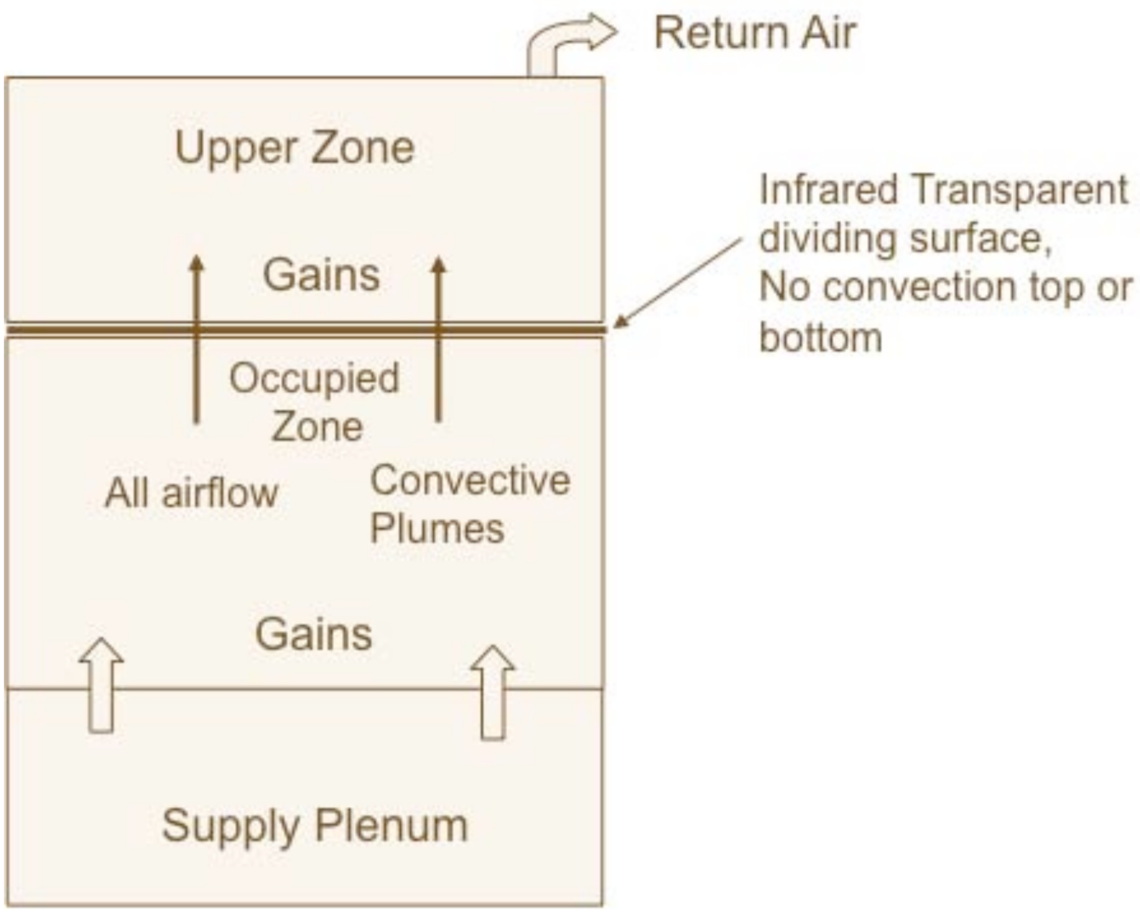

Figure 1, Schematic View of Stacked UFAD Zones

Lighting Gains W/Ft^2 (W/m^2)	People Gains Ft^2(m^2)/person	Equip Gains W/Ft^2 (W/m^2)	Lighting Gains W/Ft^2 (W/m^2)	Lights Fraction to Upper Zone	People Fraction to Upper Zone	Equip Fraction to Upper Zone	Plenum Supply Air Temp F (C)
1.4(15)	150(14)	**1.4(15)**	**1.4(15)**	**1**	**0**	**0.67**	**63(17.22)**
1.4	**150**	**1.4**	**1.4**	**1**	**0**	**0.33**	**63(17.22)**
1.4	**150**	**1.4**	**1.4**	**0.5**	**0.5**	**0.33**	**63(17.22)**

Table 1, TC 4.1 Example Cases