SUSTAINABLE SOLUTION TO BUILDING MECHANICAL SYSTEM – SIMULATION OF THERMO-ACTIVE SLAB WITH THERMAL MASS USING TAS

James Y. P. Lee, BASc, LEED AP
Earth Tech Canada Inc., Global Facility and Infrastructure, Mechanical Engineering
Vancouver, British Columbia
James.lee@earthtech.ca

ABSTRACT

Energy efficient buildings do not require highly technical systems or solutions in order to be effective. The fundamental knowledge of radiant heating and thermal mass system traces back over 2000 years ago, to the Roman Empire. The Thermo-Active Slab system can reduce not only overall construction costs but also annual energy and operation costs. Furthermore, the separation of the heating/cooling function from the ventilation function of the HVAC system allows the designer to match equipment sizes to individual functions. The entire air distribution system infrastructure, therefore, becomes smaller requiring less mechanical and plenum space. This can also lead to the reduction of floor-to-floor heights in the building saving resources.

The main objectives of this presentation are to demonstrate the TAS simulation of Radiant Cooling and Heating with Thermal Mass and to illustrate the advantages of Thermo-Active Slab Construction in line with the latest Sustainable Development Strategies. In addition, thermo-profiles of room sections will be demonstrated using simple Computational Fluid Dynamics (CFD), Ambients, for the visualization of a Thermo-Active Slab. A recent project undertaken by Earth Tech Inc. will be used as a showcase in the presentation. This paper does not discuss the detail cost breakdown or comparison between different mechanical systems.

INTRODUCTION

Radiant heating is a well-known and accepted method of supplying heat in a building. Some of the more popular radiant heating technologies are radiant floor heating and overhead heating panels. Radiant cooling, on the other hand, is less understood, and mis-applications in the past led to a general suspicion toward this type of mechanical cooling, in both residential and commercial buildings. A properly designed and applied radiant heating and cooling system can lead to a significant energy savings in a building.

There are several well-known, widely used, software applications capable of energy simulation. There are, however, few software programs which have the capability of simulating the radiant slab with building thermal mass. TAS is at the forefront of energy simulation software

This report will briefly explain conventional HVAC and Thermo-Active systems and investigate the advantages of the Thermo-Active system introducing TAS energy simulation software.

TAS (Thermal Analysis Software)

TAS has the ability to provide a 3 dimensional analysis and profile of the building incorporating all siting, envelope and interior features. Combined with our sustainable and energy efficient design expertise, we can now expertly explore and simulate Green Design concepts. The program has the unique capability of accurately modeling non-conventional, energy efficient and creative design solutions such as:

- Building Mass and Passive Storage (Load Shifts, Inertial Building Energy),
- External Shading/Overhangs,
- Daylighting (used with Lightscape),
- Advance Building Envelope Designs (Double Façade),
- Shade Analysis,
- Natural Ventilation,
- Displacement Ventilation,
- Thermoactive Floors/Ceilings (Radiant System),
- Underfloor Air Distribution.

Earth Tech is one of the few registered users of this software. TAS is a state-of-art building energy simulation, providing invaluable guidance to architects, engineers and other project participants during early stages of the design.

THERMOACTIVE SLAB

Traditionally, North American HVAC engineers have designed their systems on given architectural layouts that have already been conceptualized. This can impose restrictions on the overall design of efficient and appropriate building system for use in specific projects. In addition, large volumes of conditioned air are required to handle high peak thermal loads with relatively short response times.

The "Thermo-active Slab System" uses the building mass as the main heating/cooling agent, replacing the traditional large air volumes used for air conditioning. Therefore, it separates the heating/cooling function from the ventilation function of the HVAC system.

The most critical component in radiant technology is the building envelope. A well designed high-performance envelope will lead to a low energy use mechanical system; lower lighting energy consumption, if daylighting concepts are incorporated; and significantly reduce transient thermal loads around the perimeter zone, inside the occupied space. Due to the characteristic of this technology which uses the building mass as the enormous thermal storage, the envelope, such as building shape, size, materials, exterior shading devices, high-performance glazing, and etc, plays a significant role in the Thermo-Active Slab System. The premium cost of the high performance building envelope can be easily offset by the savings in mechanical plant size, now that all the heating and cooling is done by a hydronic system rather than masses of air.

Table 1 summarises some of the advantages and disadvantages of the conventional all-air system and thermo-active slab system.

The performance of Thermo-Active Slab cooling is limited by the dewpoint of the air in the building. The lower temperature limit for the Thermo-Active cooling system is approximately 16°C, which prevents any condensation concerns in the Vancouver climate. Due to this limitation, the target is to keep the building cooling load under maximum 100 W/m^2 for the Thermo-Active slab to handle the load effectively. The internal heat generation is quite generous due to the development of office equipment, such as computer and LCD screens with low heat generation.

The typical internal heat generation rates are:

Lights	:	15 W/m^2
People	:	8 W/m^2
Electronic Equipment	:	27 W/m^2
Total	:	50 W/m^2

This leaves approximately 50 W/m for perimeter heat gain through the building envelope.

Type		Content
Conventional All-Air System	Pro	• Unlimited application range. • Occupant perception of fresh air conditions due to high air movement rate.
	Con	• Uneven space comfort of control zones. • High air velocity and noise. • Uncertain indoor air quality due to mixed and re-circulated air.
Themo-Active Slab System	Pro	• Superior space comfort of control zones. • Lower cost due to less building volume. • Lower mechanical equipment costs. • Lower operating costs (up to 60% lower)
	Con	• More collaborations with other engineers and architects.

Table 1: Comparison between Conventional HVAC System and Thermo-Active Slab System

TAS SIMULATION

In order to demonstrate the energy consumptions between the conventional all-air HVAC system and the Thermo-Active Slab System, a project initiated at Earth Tech Inc, the Irving K. Barber Learning Centre at UBC, has been built in the TAS (Figure 1). Although a whole building is built in the TAS, one perimeter zone, approximately 230 m^2, at one the floor is reported for simplicity of the results (shown in red in Figure 1 and section view in Figure 2).

Figure 1: Irving K Barber Learning Centre, UBC, Vancouver, B.C., Canada (Graphics: Courtesy of Downs/Archambault & Partners)

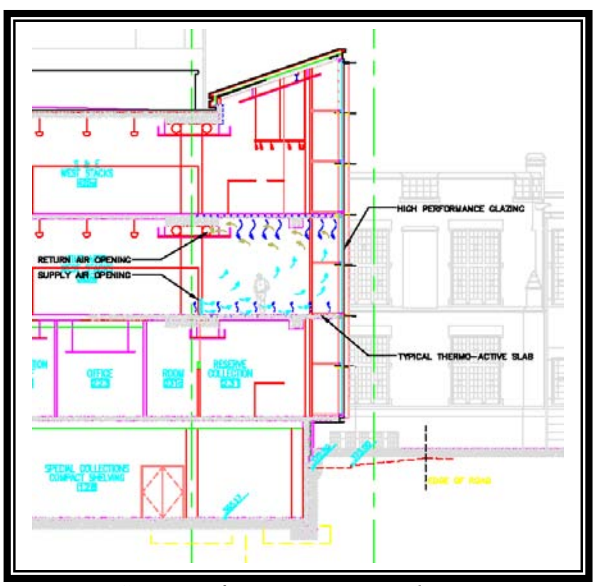

Figure 2: Section of Perimeter Zone shown in Figure 1

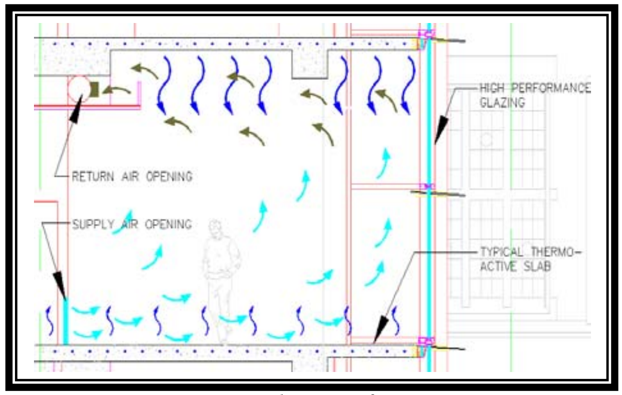

Figure 3: Detail View of Perimeter Zone

Figure 3 demonstrates how the Thermo-Active slab works in the space when it is in cooling mode. Note that approximately 80% of cooling will be supplied by ceiling slab and the rest by floor.

The following table illustrates the materials used in the building. As explained before, the Thermo-Active Slab System should accompany with high performance envelope, such as building shape, size, materials and windows. Note that high performance glazing has been used in the Thermo-Active slab model.

Location	U-Value (Btu/hr-ft2-F)	Construction
Radiant Floor	0.6	200 mm Concrete
Exterior Wall	0.06	250 mm Concrete with R-14 insulation
Interior Wall	0.2	100 mm Concrete with light plaster
Radiant Ceiling	0.6	200 mm Concrete
Exterior Glazing	0.23	Double Glazing with tint with SC = 0.26
Shading Feature	300mm Fin and 300mm Overhang	

Table 2: Building Material used in Thermo-Active Slab System Model

Location	U-Value (Btu/hr-ft2-F)	Construction
Floor	0.6	200 mm Concrete
Exterior Wall	0.06	250 mm Concrete with R-14 insulation
Interior Wall	0.2	100 mm Concrete with light plaster
Ceiling	0.6	200 mm Concrete
Exterior Glazing	0.3	Regular Low E Double Glazing with SC = 0.60
Shading Feature	Not Used	

Table 3: Building Material used in Conventional HVAC System Model

Due to the location of the cooling tubes being centre of the concrete slab in the system and to the characteristic of air, approximately 83% of the heat removed by the circulated cool water are from the room below the slab, while 17% are from the room above. For this simulation, only the ceiling slab is charged with cool water to remove any heat from the space.

The concept of resultant temperature is introduced in the simulation result to demonstrate the radiant effect from the Thermo-Active slab. Resultant temperature is calculated as the mean of air temperature and mean radiant temperature:

$$Tres = \frac{Tar + Tmrt}{2} \bullet (12-3)$$

To construct the Thermo-Active slab, a cavity with 50mm height filled with water is embedded between floors. Due to the limitation of TAS, the space smaller than 50mm cannot be created. In actual Themo-Active slab design in this project, 5/8”∅ pipes are used with 12” spacing. Therefore, the cooling energy will approximately 10%-20% less than the cooling energy with the Thermo-Active slab from TAS. The blue section shown in the figure below, Figure 4, is the cavity with water (indicated as think blue lines), whose temperature is constantly kept between 15°C -16°C. The temperature is set to no less than 16°C to prevent any possible condensation on the radiant pipe system in the concrete slab.

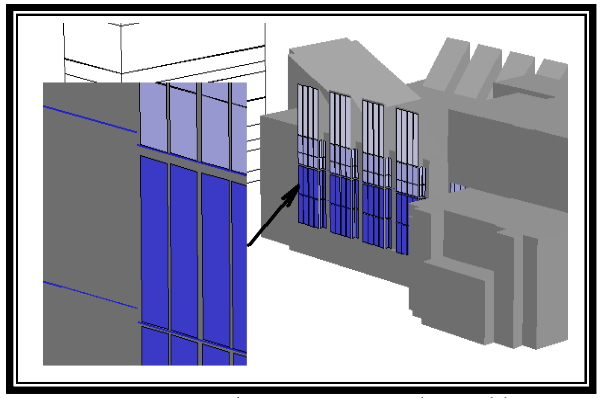

Figure 4: Radiant Cavities in the Building

The space in yellow in Figure 5 and Figure 6 illustrates the plan view of the occupied floor, and the space with brown represents the adjacent building. 5 cm water cavities are located in floor above and below to simulate radiant floor.

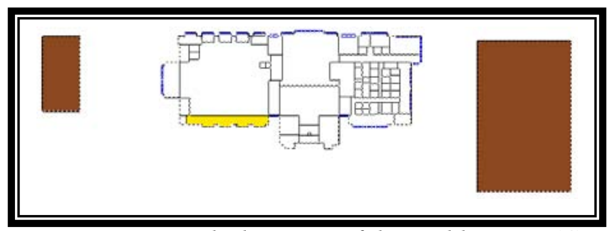

Figure 5: Typical Plan View of the Building in TAS

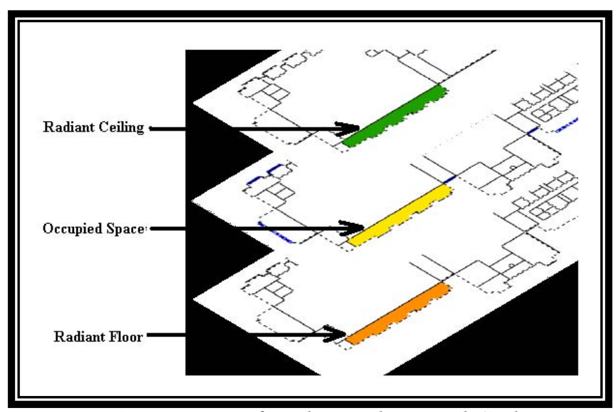

Figure 6: Location of Radiant Floor and Ceiling in TAS

To simulate water in the concrete slab in TAS, the material property and the temperature in radiant floor and ceiling cavities are set to convection factor of 500 W/m^2C and 16°C respectively which result to the floor surface temperature of approximately 19°C-20°C and the ceiling surface temperature of 1°C-2°C higher, due to the air stratification.

One of the drawbacks of TAS is the temperature or operation of the radiant cavity cannot be controlled by the space temperature. The cavity temperature is kept

16°C constant regardless of the instantaneous cooling load requirement at specific times during the day. The operation is controlled only by on/off schedule in equipment schedule section. The target resultant temperature in the space, however, still can be achieved with lower energy consumption using thermo-active slab over conventional all-air system. For simplicity, a simulation was run based on statistics for maximum yearly temperatures. Modelled on one extreme week, daily cooling energy consumption was determined.

ANALYSIS AND RESULTS

The target is to provide the resultant temperature range between 19°C and 24°C in the space with the same or similar cooling or heating load in the spaces with conventional HVAC system or the Thermo-Active Slab system.

To simulate and draw the precise cooling load results, two resultant temperatures, conventional HVAC system and Thermo-Active system, are compared and must be reasonably close, within ±1°C. Both 3D model analysis and CFD model are based on some of the following assumptions:

- The modeled space has uniform surface temperature and one dimensional heat conduction.
- The air between the modeled zone and un-modeled zone does not thermally exchange.
- Thermo-Active pipes are simulated with a 5 mm cavity in the centre of floor/ceiling slab filled with water.
- The weather data used in the model is average weather data for last 20 years at the Vancouver Airport provided by EDSL.
- Occupancy behaviour is assumed maximum at all times during occupancy period in the modeling schedule, based on architectural furniture layout.
- Electronic loads, including lighting and computer, during summer period are assumed full load during occupancy period.

Table 4 shows the result of the simulation. The cooling was simulated during a ten day period from July 9th to July 18th, and the heating was simulated from January 1st to January 9th. Energy consumption was compared between them, with a resultant temperature between 20°C and 22°C.

Day	Thermo-Active Slab Cooling Energy (kWh)	Conventional HVAC Cooling Energy (kWh)
July 9	234	414
July 10	242	428
July 11	286	469
July 12	280	475
July 13	264	465
July 14	252	459
July 15	277	482
July 16	282	487
July 17	210	410
July 18	164	334
Average	**250**	**440**

Table 4: Cooling Simulation Result for Conventional HVAC System Model and Thermo-Active Slab Model

Type	Resultant Temperature	Cooling Load
Conventional HVAC All Air System	22°C - 23°C	440 kWh
Thermo Active Slab System	22°C - 23°C	250 kWh

Table 5: Cooling Simulation Result for Conventional HVAC System Model and Thermo-Active Slab Model

As shown in the Table 5, with the same cooling provided in the space the Thermo-Active slab provides a lower and more comfortable resultant temperature.

Although it was found that peak cooling and heating loads from the Thermo-Active system do not differ from the conventional HVAC system, the savings stem from smaller mechanical equipment. Those features, including high performance glazing and thermal mass, add into the construction cost; but will be offset by the smaller mechanical plant and lower annual energy consumption.

It was also found that once the mechanical cooling system shutsdown, it takes approximately 3 days to return to normal operation in the building. As shown in Figure 7, a spike is observed after a weekend (Saturday and Sunday) shut down, the cooling load stabilized 2-3 days after the system start-up.

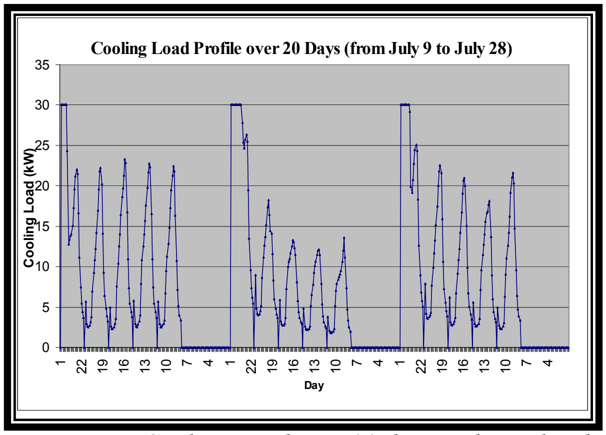

Figure 7: Cooling Load over 20 days with Weekend Shutdown

The following diagram created by Ambients, a part of TAS module, demonstrates the effect of radiant cooling versus conventional air cooling. The 2D sectional resultant temperature profiles, Figure 8 and Figure 9, clearly show that the temperature around the occupant level (usually 2m from the floor) with Thermo-active slab is in the range of evenly comfortable temperatures between 19°C and 22°C (green region). Figure 8 with conventional air cooling system with ceiling diffusers also indicates not only that large amount of air short circuited into the return grille even before the cooled air is fully circulated in the space, but also that 14°C - 15°C drafts are blowing on top of occupants. All the boundary conditions, including surface temperatures, have been found based on 3D building simulation model.

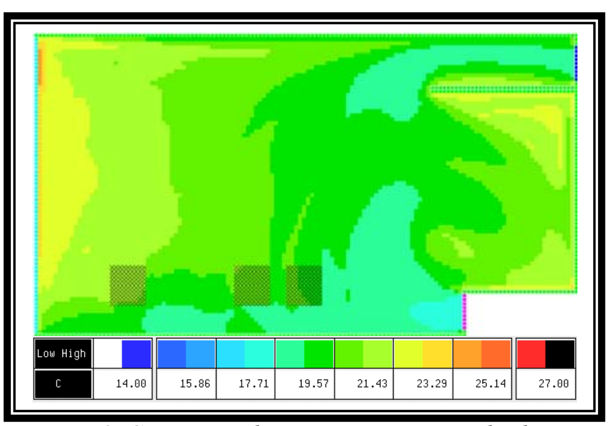

Figure 8: Space Resultant Temperature with Thermo-Active Slab

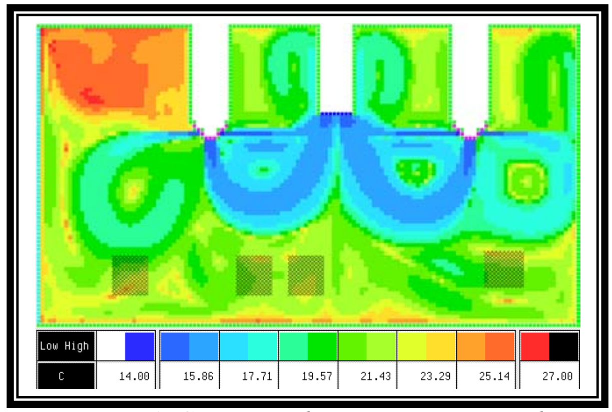

Figure 9: Space Resultant Temperature with Conventional Air Cooling System

CONCLUSIONS

The combined approach, using high performance envelopes and thermo-active slabs, has been used successfully in Western Europe for the last 15 years, with increasing use in the last 5 years due to the rising energy cost, and has been shown to save up to 60% of the energy use compared to conventionally designed and constructed buildings. Despites all the fact, only recently the design tool capable of the variety of creative design solutions becomes available on public. Now this can be proved using the TAS software and be designed effectively in different weather conditions and different building configurations.

There are limitations of TAS and some of them were encountered during this analysis. The following are drawbacks of the TAS system

- Varying Slab Temperature: It is not possible to automatically vary the slab temperature dependant on the space temperature, as you would with the fully functioning system; therefore, currently, there is no method by which to extract annual heating and cooling energy consumption without going through a day-by-day analysis
- Utilizing Resultant Temperature: Having resultant temperature data is an advantageous feature of TAS which indicates the temperature occupants would actually experience. However, this data cannot be used to control the room temperature in the simulation.

ACKNOWLEDGEMENTS

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