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SIMULATING RADIATIVE COOLING/HEATING USING BES-CFD COUPLED SIMULATION

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ABSTRACT
The radiant cooling and heating system like the thermo-active concrete core system (TACS) has long been recognized as an alternative to the conventional all-air system, especially in Europe. The latest developments in simulation tools for radiative cooling/heating focused on the explicit plant definition in the simulation tools , i.e. how to simulate what is behind the radiant surfaces There is less attention on what is going on between radiant surface and the occupied zone. This paper explores the advantages of using the coupled simulation between building energy simulation (BES) and computational fluid dynamics (CFD) simulation in designing space conditioning by radiative cooling/heating. The way the coupled simulation treats the convection coefficient definition can be utilised to improve the prediction of thermal comfort and energy consumption.

INDEX TERMS
Simulation, CFD, Radiant system, Coupled simulation, External coupling

INTRODUCTION
The thermo-active concrete core system
The thermo-active concrete core system (TACS) has long been recognized as an alternative to the conventional all-air system, especially in Europe (see e.g. Olesen et al. 2003). In an all-air system, the heating, cooling and ventilation are all handled by air, where the heating and cooling requirements determine the amount of air needed by the system. Both thermal comfort and indoor air quality criteria are achieved by air flow.

TACS is part of radiant heating and cooling systems where the main heat exchange mechanism for heating and cooling is done by radiation. The idea is to change the medium for main heat transfer mechanism from air to water which has more efficiency. Moreover, the heating and cooling criteria can be met by different mechanism than the ventilation criteria.

The use of radiant panels is one example of radiant heating and cooling system. TACS takes it a bit further to include the thermal mass of the concrete as part of the system by delivering water through pipes embedded in the concrete. In this way, the concrete is acting as heat storage for the system.

Even though the main heat transfer mechanism for this system is radiation, on some cases, the convective heat transfer also plays an important role. In cooling conditions, the TACS is usually combined with a displacement ventilation system to deliver the air to meet the air quality requirements. It is interesting to study how the use of coupled BES-CFD simulation can help to achieve a better design decision.

Problem definition
The latest developments in simulation tools for radiative cooling/heating focused on the explicit plant definition in the simulation tools , i.e. how to simulate what is behind the radiant surfaces (e.g. Stetiu 1998, Strand and Pedersen 1997). There is less attention in what is going on between radiant surface and the occupied zone.

There are enough reasons, however, to focus on the heat exchange between the radiant surface and the occupied

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zone. Firstly, the occupants – the end user who will eventually use the radiant system – are in the occupied zone. Their thermal comfort should be taken into consideration. Secondly, the convective heat source is always present in the occupied zone. This convective heat can be removed by the ventilation system, either by decreasing the supply air temperature, or by local heat removal so that the convective heat would not dissipate through out the occupied zone. Both will potentially result in non-uniform distribution of air temperature in the occupied zone.

This paper explores the advantages of using the coupled simulation between building energy simulation (BES) and computational fluid dynamics (CFD) simulation in designing space conditioning by radiative cooling/heating. With the coupled simulation both the above-mentioned issues can be addressed.

RESEARCH METHODS

This study used the coupled simulation method to simulate a room equipped with a radiant system. The thermo-active concrete core system is used as the case study.

BES-CFD coupled simulation

The coupling of BES and CFD simulation has been studied in various researches in recent years, e.g. Negrao 1995, Srebric et al. 2000, Beausoleil-Morrison 2000, Zhai 2003, Djunaedy 2005. The two simulation programs, as any other simulation programs, have their own limitations. For example, the boundary conditions of CFD are usually assumed with limited consideration for the thermal storage effects of the wall, external conditions and interactions with building services systems. BES, on the other hand, calculates its energy prediction based on a well-mixed assumption so that the definition of the convective heat transfer coefficient (CHTC) cannot capture the dynamics of the flow near the surfaces.

The coupling between the two programs is seen as an alternative to achieve better results because the two can provide boundary conditions to each other. For example, BES can provide internal surface temperatures of the walls to CFD, while CFD can provide more accurate CHTC values for BES. BES can also provide HVAC parameters to CFD (e.g. the supply air temperature and flow rate) by supplying the cooling or heating load.

Further information on coupled simulation can be found in the abovementioned publications. A coupled BES-CFD simulation has an advanced way to model the convective heat transfer coefficient which can capture the effect of non-uniform temperature distribution and the effect of its dynamic fluctuation over time, so that the energy prediction can be more accurate. Furthermore, it can also provide a detailed overview of the airflow distribution so that the local discomfort can immediately be identified. With regards to the simulation of radiant systems, the benefits of the coupled simulation can be categorized into three advantages: (1) more accurate energy prediction due to more accurate CHTC value, and (2) ability to analyze the changes in airflow pattern in CFD due to the dynamic boundary conditions supplied by BES and (3) more accurate comfort calculation as the comfort condition can be defined as local values. These benefits will be discussed and highlighted in the case study below.

Case descriptions

The case (Figure 1) involves an office space where the floor to ceiling height is very high (5.4m). The use of an all-air system is not attractive because of the high volume of unoccupied space in combination with a high glazed area covering one side (west side) of the space. TACS in combination with displacement ventilation is one alternative to be explored. The challenge of the design is to provide a comfortable work area for workstations A and B (see Figure 1) which are located next to the glass wall. In summer condition the west glass wall will have a shading device rolled from the top of the wall down to 2m above the floor. For simplification, the internal shading device is modelled as external shading in the BES model as shown in Figure 1.

Figure 1 also shows a complex control strategy as used by Scheatzle 2003. Operative temperature was used as the main controlled variable. Every time the operative temperature changes significantly, the surface temperature of the concrete is increased or decreased in steps of 1 °C. The control strategy that was used in the simulation, however, was a simplification of the complex control strategy. Only the second control loop (CS2 in Figure 1) was modelled, i.e. the ceiling surface temperature was controlled by injecting/extracting heat to/from the concrete core.

The simulation also used an operational strategy to explore the potential of energy savings practices through system operation. The surface temperature was kept at a certain temperature before occupancy hours (19 °C), and then released to free-float until reaching a certain temperature (24 °C). After occupancy hours, the system was again released to free-float. With this operational strategy, the actual cooling can be done outside office hours with potential savings from off-peak hours charge.

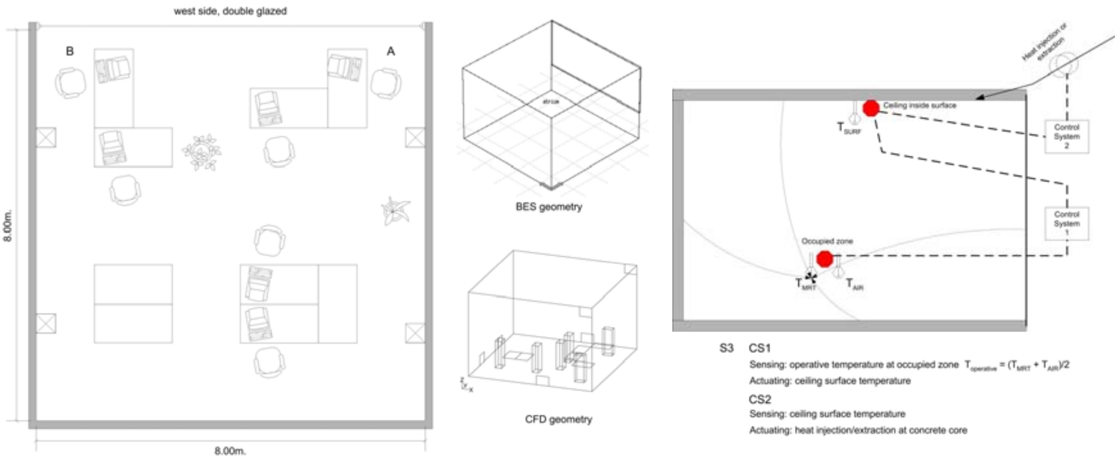


Figure 1. *Room layout, models and control strategy*

Simulation settings

Two simulations were carried out for this study: BES-only, and BES-CFD coupled simulation. For BES-only simulation, the control strategy was activated so there is a cooling condition from both the TACS and the displacement ventilation. For BES-CFD coupled simulation, an external CFD program was called in every time step of BES simulation. The BES sends the wall temperatures and the heat extraction/injection rate to CFD for CFD boundary conditions, and after CFD calculation the CFD sends back the CHTC values for all internal surfaces.

The CFD model (shown in Figure 1) includes the occupants and the desk. The heat flux from humans and equipments are defined by assuming 50% convective part. For the CFD simulations only convective heat transfer is considered, and the radiation model is not activated. For simplicity, all the loads from equipments are defined as plane source at the desks. Only the CHTC of the walls were sent to BES while the CHTC at the human and desk surfaces were not. Four displacement ventilation supplies are located near the floor, one on north and south side, and two on east sides. The two exhausts are located at the north and south wall near the top of the west glass wall.

Both BES-only and BES-CFD coupled simulations have to deliver the ventilation requirements of 6 liter per second per person which is supplied at 19 °C.

RESULTS AND DISCUSSION

BES-only simulation

The result (Figure 2.a) shows that the air temperature reached slightly more than 26 °C. And with the high MRT values, the operative temperature exceeds the maximum value of 26 °C for around 3 hours before noon, and stays within the border for several hours before going down in late afternoon hours. The ceiling surface temperature shows a good indication of controllability, i.e. down to 19 °C before 06:00 and stays below and around 22 °C during occupancy period.

It is important to note that for BES-only there is a discrepancy in the location when calculating the operative temperature. The MRT is usually calculated by defining a "sensor" in a specified location, where the view factors of the sensor is calculated, so that the MRT is a local value. On the other hand the air dry-bulb temperature is uniform throughout the space due to a well-mixed assumption.

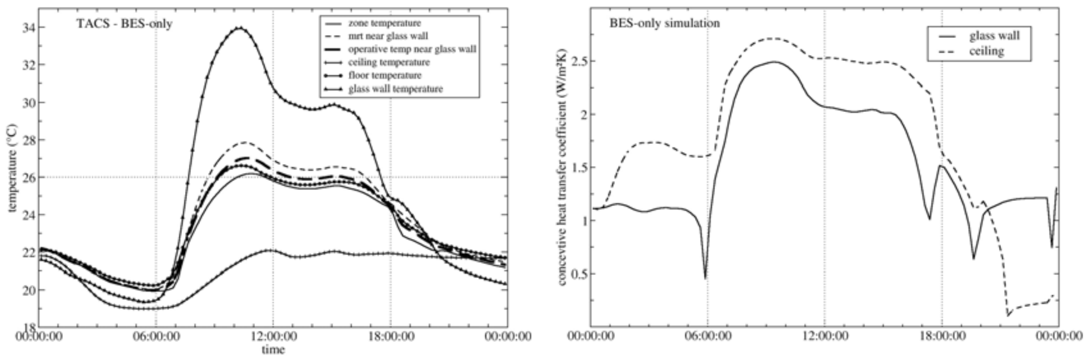
The condition is worse when the displacement ventilation is used because in this system a temperature gradient is expected. The value of the air temperature in the lower parts of the room (where the MRT is measured) should be lower than what is presented in Figure 2.a. This is the point where CFD simulation can improve the comfort prediction, because the local air temperature anywhere in the room can be easily obtained.

Furthermore the CHTC of the ceiling is lower compared to the values reported in the literature. The total heat transfer coefficient for cooled ceiling is between 9 – 11 W/m^2K (Stetiu 1998). The convective part can have the coefficient of 3.5 – 5.5 W/m^{2}K. The values shown in Figure 2.b are considerably lower than that.

The CHTC value on the glass wall needs special attention. The displacement ventilation used in all the scenarios cause temperature stratification, which needs to be considered in the calculation on CHTC. The use of coupled BES-CFD simulation enables the effect of temperature stratification to be considered in the calculation.

The calculation of the correct surface temperature is very important for comfort calculation. It is even more important for a radiant system which relies on surface temperature difference as the main mechanism for heat transfer. The correct calculation of CHTC certainly helps to achieve a more realistic heat balance at the wall and with that can result in, e.g., more realistic comfort conditions.

The use of coupled BES- CFD simulation also enables the non-uniform temperature distribution to be considered in calculating the comfort condition. Comfort condition is a local condition, which should be assessed based on local values.



(a) (b)

Figure 2. *Results of BES-only simulation: (a) temperature predictions (b) CHTC*

BES-CFD coupled simulation

Figure 3.a shows the coupled simulation results for coupled simulation.

BES-only simulation (Figure 2.a) predicted uncomfortable condition during late morning hours where the operative temperature is more than 26 °C. The coupled simulation, however, shows that the system can meet the comfort criteria.

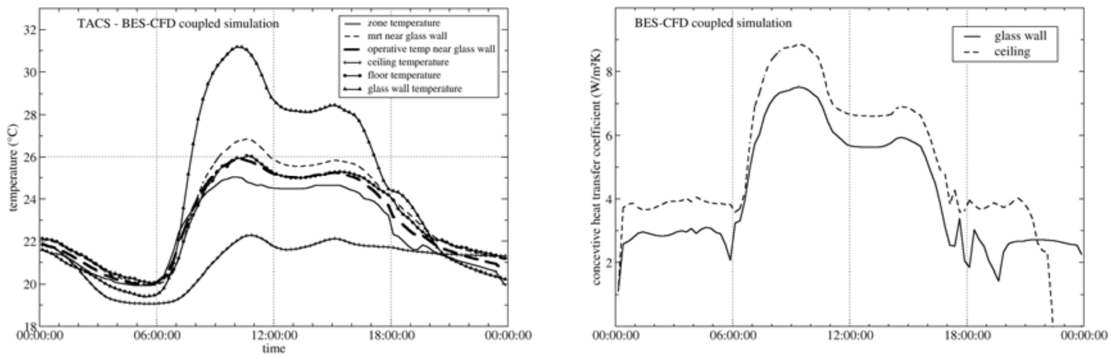
This is the advantage of the coupled simulation where the comfort criteria can be assessed based on local values in the room. Assessment of local values is made possible by the high resolution simulation like CFD.

Figure 3.b shows the CHTC values for BES-CFD coupled simulation. The values are between 6 – 8 W/m^{2}K when the air conditioning system is on, which is significantly higher than the values predicted by the BES-only simulation.

CONCLUSION

This study has shown the application of coupled simulation to a design situation. The main advantage of BES-CFD coupled simulation is the accurate calculation of CHTC. This paper has shown how that main advantage can be utilized to simulate the TACS.

Accurate CHTC value is needed to calculate the correct surface temperature. The performance of TACS system depends on the correct calculation of heat exchange at the surface and in the core of the concrete. The surface temperature affects both the energy and comfort performance of the TACS.



(a) (b)

Figure 3. *Results of coupled simulation: (a) temperature predictions (b) CHTC*

Furthermore, the high resolution of the CFD simulation makes it possible to assess the comfort level in the zone as a local parameter in a part of the room. Of course, CFD-only simulation will be able to do the same. However, with coupled simulation the dynamic of the comfort level throughout the day can be assessed, due to the availability of the surface temperature data.

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