IMPACT OF HEAT TRANSFER THROUGH FLOOR SLAB ON ENERGY PERFORMANCE OF BUILDINGS WITH UFAD SYSTEMS

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ABSTRACT

There are few studies on the impact of thermal storage and heat transfer on the floor slab on energy performance of buildings with Under-floor Air Distribution (UFAD) systems. This investigation used EnergyPlus to conduct energy simulations and analyze energy use of an office building with an UFAD system in Philadelphia. The computed results indicated that the building with the UFAD system would consume more energy than the well-mixed system if the heat transfer through the floor slab was considered. However, in the shoulder seasons, the UFAD system would use less energy than the well-mixed system because the UFAD system can make use of more free cooling. Therefore, the energy performance of the building with the UFAD system could be better or worse than the well-mixed system depending on the climate zones.

INTRODUCTION

For buildings with Under-Floor Air Distribution (UFAD) systems, the air quality is generally better than that with well-mixed ventilation system. Since cool conditioned air is delivered into the floor plenums with UFAD systems before entering the occupied zones, this process leads to the heat transfer from ceiling plenum downstairs to the floor plenum because of air temperature difference between those spaces. Bauman et al. (2006) calculated the cooling load of buildings with UFAD systems by using simplified first-law model and estimated that up to 40% of the total cooling load was transferred into the floor plenum and only about 60% was removed by the return air. Their results indicated that the heat transfer between the ceiling and floor plenums might have significant influence on the energy performance of buildings with UFAD systems.

Many previous studies have compared the energy performance of buildings with UFAD systems and well-mixed systems. Xu et al. (2006) presented a numerical procedure to predict the energy consumption of a typical office building with UFAD systems compared with well-mixed systems. They found that the energy saving of UFAD compared with well-mixed systems was from higher supply air temperature and higher exhaust temperature due to indoor air stratification. Alajmi et al. (2010) examined the performance of the UFAD and well-mixed systems in hot climate (Kuwait). Different supply air temperatures and building heights were studied. The results showed that the amount of total energy saving as well as peak load saving increased with higher building heights. However, the peak load saving was not very sensitive to the supply air temperature.

These investigations introduced the impact of some important factors such as room air stratification on energy performance of buildings with UFAD systems compared with well-mixed systems. But few of them focused on the influence of thermal storage and heat transfer through the floor slab between the ceiling and floor plenums. The energy assessment of UFAD and well-mixed systems could be more rigorous and accurate if this heat transfer process was taken into account. Therefore, this investigation tried to study the influence of heat transfer through the floor slab between the floor plenum and the ceiling plenum downstairs in a building. An office building in Philadelphia was used for the study. This investigation compared the annual energy consumption of the chiller, boiler and fans in the building with a UFAD system and that with a well-mixed system.

RESEARCH METHOD

In order to estimate the impact of the heat transfer through floor slabs on the energy performance of buildings with UFAD systems, it is necessary to conduct annual energy simulations for whole buildings. This investigation selected EnergyPlus since it is capable of simulating thermal load and annual energy use in a building and allows modeling supply and returning plenums as separate zones.

This investigation simulated an office building of 30 m × 40 m × 3.7 m (including ceiling plenum of 0.7 m height) in Philadelphia. To study the heat transfer through the floor slab, the outside boundary condition of the ceiling plenum downstairs was set as that for the floor plenum. To simplify the building model, the space was further divided into two zones: a perimeter of 5 m along the building envelope and a core zone (Karaguzel et al., 2011). This study specified the intensity and schedule of the occupancy, lights and electric equipment as well as building structure information by using the DOE reference model for medium office (NREL, 2011). Figure 1 illustrates the internal load profile for the building. The set points for heating and cooling were 21°C and 24°C, respectively, and the minimum fresh air rate was 0.3 L/(s·m^2) (ASHRAE, 2010). The HVAC system operation schedule was from 6:00 am – 10:00 pm. An economizer was also used for free cooling. The simulations used a time-step of six minutes as recommended for whole-building simulations with HVAC systems (EnergyPlus, 2012).

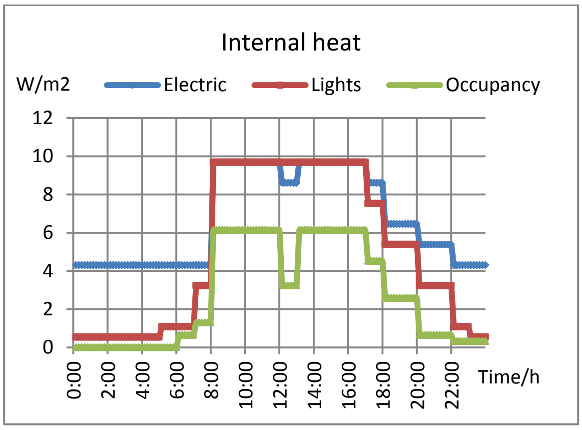
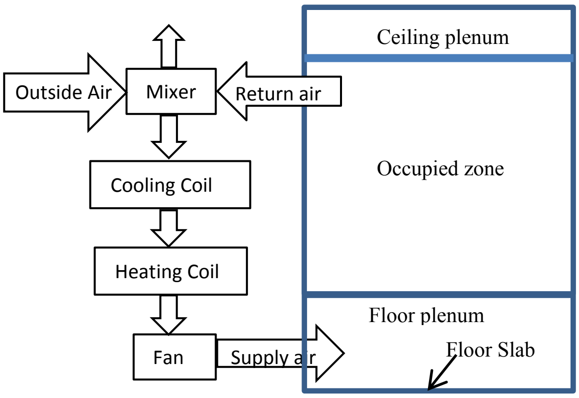


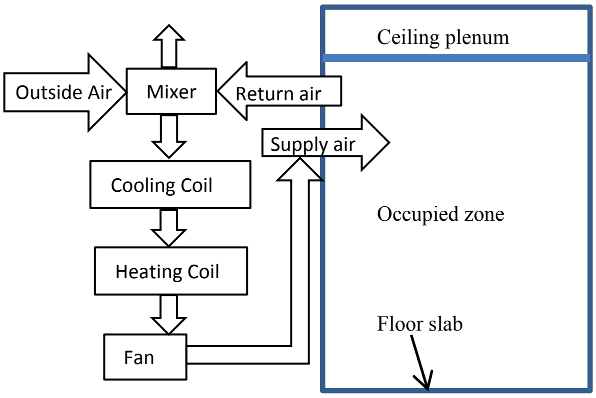
Figure 1 Internal heat load of the office building

Figure 2 shows the building system schematic for the building. Figure 2 (a) is for one with a UFAD system and the room was with a 0.3 m high floor plenum. The under-floor plenum was divided into four perimeter zones and one core zone by partitions. The conditioned air was supplied through ducts encircling the perimeters of all zones. The central cooling system provided conditioned air at 16°C into the floor plenum during cooling mode and air was supplied into the occupied zone through passive diffusers (no fan power) at the raised floor. In heating mode, the air was heated to 32°C before it was supplied into the perimeter zones of the floor plenum. Room air temperature was controlled by Variable Air Volume (VAV) strategy. In order to simulate the air flowing into the occupied zone from the under-floor plenum through the diffusers on the raised floor, the "AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat" modules in EnergyPlus was used to connect the supply plenums and the occupied zones.

Figure 2(b) is for the other with a well-mixed system that delivered directly the conditioned air into the room from the ceiling level and extracted the air through exhausts located at the ceiling level as well. Air was delivered into the room with a temperature of 32°C for heating and 13°C for cooling. In order to realize VAV control, the air unit "AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat" subroutine from EnergyPlus was used for the occupied zones.



(a)



(b)

Figure 2 System schematic: (a) UFAD system; (b) well-mixed system

Since the UFAD system created temperature stratification, correct prediction of the temperature stratification is essential to estimate accurately the energy performance. Because EnergyPlus cannot provide detail information of airflow pattern of zones like a CFD program, the room air model for UFAD systems developed by Lin and Linden (2005) was used to predict the stratified air distribution. Daly (2006) validated the model with measured data obtained on building site and found there was an excellent agreement between the measured data and the room air temperatures predicted by the air model.

Linear bar grilles were chosen as diffusers for the UFAD system and one diffuser was used for every 9.15 m^2 floor area. The "Boiler:HotWater" model in EnergyPlus was used to provide heating with natural gas as its fuel and the "Chiller:Electric:EIR" model was used to provide cooling. Auto size function of EnergyPlus was chosen to calculate the reference capacity of the chiller and nominal capacity of the boiler. The chiller COP was set as 3 and the nominal thermal efficiency was 0.8. The fan efficiency which is the ratio of the power delivered to the fluid to the electrical input power at maximum flow was set as 0.6. On the other hand, the minimum air volumetric flow rate for calculating fan power was specified as 25% of the maximum airflow rate.

RESULTS AND ANALYSIS

Validation of EnergyPlus by experiment

To validate EnergyPlus and the room air model for their ability in predicting energy use in buildings with the UFAD system, this investigation conducted experiment under steady state in an environment chamber at Purdue University. This chamber had a dimension of 4.20 m × 4.80 m × 2.73 m including 0.30 m high floor plenum and 0.03 m thick raised floor panels. Figure 3 depicts the environmental chamber with a raised floor for the UFAD system. The chamber was with several pieces of furniture and some heated boxes that simulated internal loads such as electrical appliances, occupants, etc. Highly insulated materials with the thermal resistance of 5.45 m^2-K/W were used for the walls and ceiling. Insulation was also placed underneath the slab. The raised floor panels have the thermal resistance of 0.16 m^2-K/W (Jiang, et al., 2012). Double glazing windows were installed at the east wall of the chamber and the thermal resistances of them were 0.25 m^2-K/W.

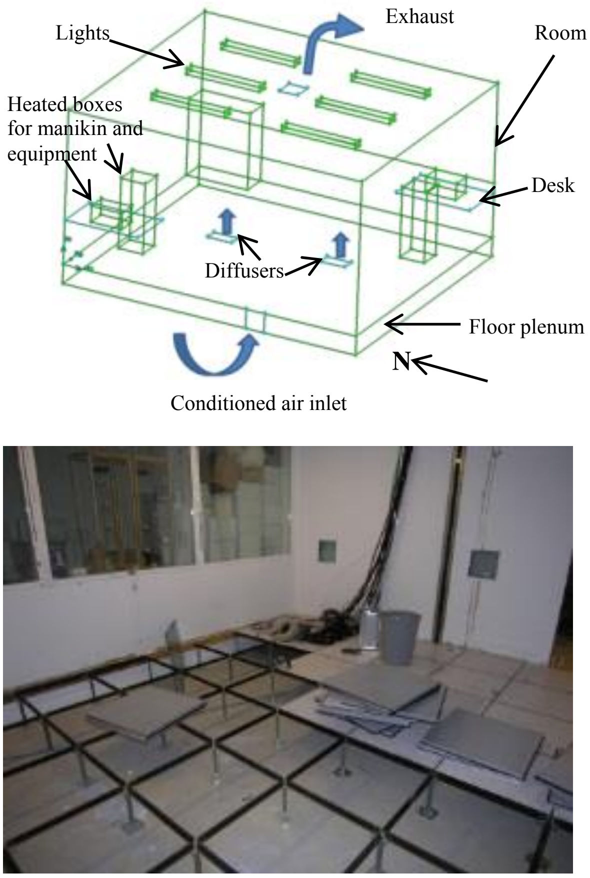


Figure 3 Layout of the environmental chamber

The room air temperature was controlled within ±0.3 K, and the supply air temperature within ±0.6 K. The supply airflow rate was controlled within ±0.01 m^3/s. The inlet temperature was 17.3°C and air change rate was 6 ACH. All the surface temperatures were measured by T-type thermocouples with an accuracy of ±0.5 K (Jiang, et al., 2012). The surface temperature for each wall was measured in upper, middle and lower positions and for the floor slab and ceiling in six places, respectively. The surface temperature for the raised floor was measured in eight places on both sides. The average surface temperatures from the experiment were compared with the simulation results. Anemometer probes were used to measure the air temperature of the conditioned air at the supply inlet to the floor plenum, in the diffusers on the raised floor, and at the exhaust. Table 1 compares the experimental data with the simulated results. The agreement between the data and the simulated surface temperature, average zone air temperature, and exhaust air temperature is pretty good. Therefore, the EnergyPlus with the room air model could be used to predict the energy performance of a building with UFAD systems.

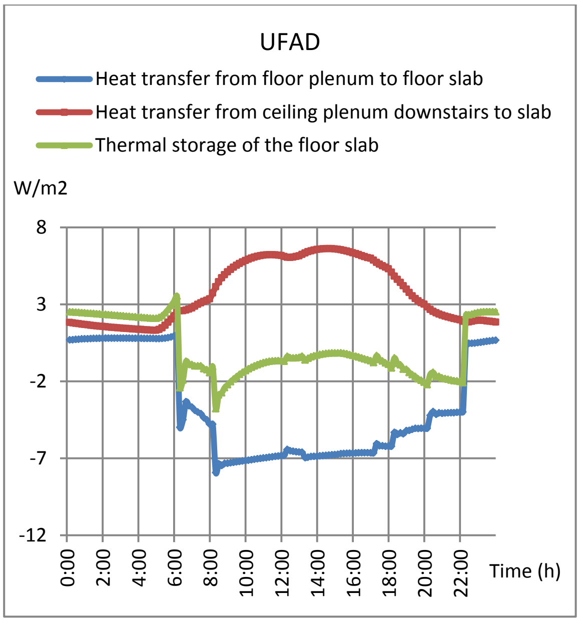
Table 1
Comparison of simulated and measured temperatures in the chamber (°C)

Locations where the temperatures were compared	*Simula-tion*	*Experi-ment*
Supply air to the plenum	17.3	17.3
Air at diffusers	19.9	20.2
Exhaust air	24.4	24.2
Slab surface (facing floor plenum)	23.6	23.7
Ceiling surface	24.7	24.3
North wall in the floor plenum	22.7	23.8
South wall in the floor plenum	22.7	22.7
West wall in the floor plenum	22.7	23.5
East wall in the floor plenum	22.7	22.7
North wall in the room	25.2	25.1
South wall in the room	25.2	24.1
West wall in the room	25.2	24.7
East wall in the room	25.2	25.4

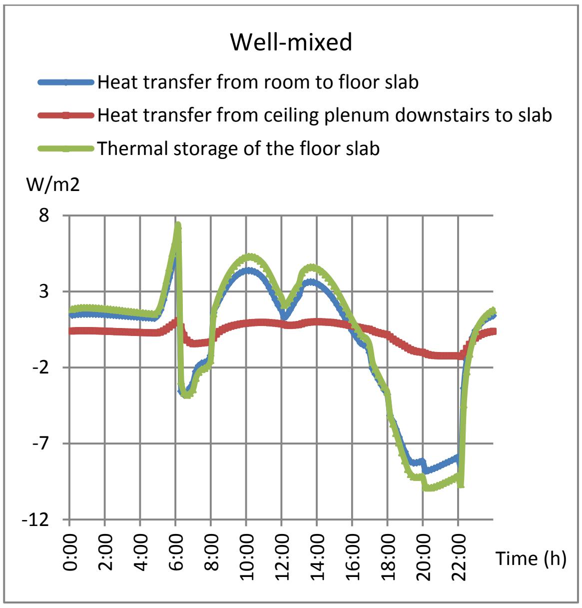
Impact of heat transfer and thermal storage of floor slab on thermal load

The validated EnergyPlus was first used to calculate heat transfer for an office building of 30 m × 40 m × 3.7 m with the UFAD system and the well-mixed system for a summer day and a winter day in Philadelphia. This subsection discusses the results obtained.

Figure 4 shows the heat flux at the two surfaces of the floor slab in the office building on July 21. Positive values mean heat transfer into the slab, negative values implies heat transfer out of the slab, and the algebraic sum of heat transfer at the two surfaces of the slab is equal to the thermal storage.



(a)



(b)

Figure 4 Heat flux at top and bottom surfaces of slabs in summer; (a) UFAD, (b) well-mixed

Figure 4(a) shows the heat transfer on the floor slab for the building with the UFAD system and Figure 4(b) for the well-mixed system. The blue lines show the heat transfer rate from the floor plenum (UFAD system) or the occupied zone (well-mixed system) to the floor slab; the red lines the heat transfer from the ceiling plenum downstairs to the floor slab; the green lines the thermal storage of the floor slab. For the UFAD system, the heat transfer from the floor plenum to the floor slab consisted of convection between the floor slab and the air in the floor plenum, and the radiation between the floor slab and the other surfaces in the floor plenum. During office hours when the HVAC system delivered a lot cool air into the floor plenum, the significant temperature difference between the floor plenum and the ceiling plenum downstairs led to a high heat transfer rate in this period as shown in Figure 4(a).

As for the well-mixed system, the heat transfer rate at the top surface of the floor slab was greatly influenced by the solar radiation and the internal heat sources because there was no raised floor to obstruct the radiation to the floor slab from the sun and internal heat sources. In the early morning and evening, there was heat transferred from the floor slab to the room because of little solar radiation and internal heat load. As the solar radiation and internal heat load became higher in the office hours, there was heat transferred from the occupied zone to the floor slab due to a lot of radiation from the internal heat sources and the sun beam could project directly on the floor slab. If the solar radiation from all the enclosure surfaces from different directions were taken into account, it was found that the solar radiation did not have a peak in the noon. Besides, the internal heat load decreased at noon since some occupants went out for lunch. Therefore, The heat transfer profile had an “M” shape as shown by the blue line in Figure 4(b) for the well-mixed system.

The HVAC systems started working at 6:00 am in the morning and were shut off at 10:00 pm at the night. It is more interesting to look at the heat transfer in this period as the HVAC system operation was linked to building energy consumption. As discussed above, the heat transfer of the floor slab with the well-mixed system was sensitive to the internal heat sources. After 6:00 pm, most of the internal heat sources were gone or switched off. Thus, this subsection would present the results in two periods of time: from 6:00 am to 6:00 pm with significant internal heats and from 6:00 pm to 10:00 pm with little internal heats.

From 6:00 am to 6:00 pm on the summer day when the internal load was high, the slab in the building with the well-mixed system would absorb much heat from the room (as much as 4 W/m^2 at 10:00 am) which helped reduce the cooling load. However, with the UFAD system, the conditioned air led to a low air temperature in the floor plenum and a significant temperature difference between the cool floor plenum and the warm ceiling plenum downstairs. The temperature difference caused a large amount of heat transfer from the ceiling plenum downstairs to the floor slab (7 W/m^2 at 2:00 pm). This heat transfer resulted in a high cooling load during this period for the UFAD system.

From 6:00 pm to 10:00 pm on the day when the internal load decreased significantly, the slab temperature in the building with the well-mixed system was much higher than that with the UFAD system due to the heat stored during the daytime. As a result, more heat rejected into the room air from the floor slab and resulted in a higher room air temperature than that in the building with the UFAD system. Therefore, the cooling load in the evening with the UFAD system was smaller than that with the well-mixed system.

Figure 5 compares the cooling load of the building with the two ventilation systems on the summer day. The red line stands for the cooling load of the building with the UFAD system while the blue one with the well-mixed system. The figure shows that during the office hours from 8:00 am to 6:00 pm, the cooling load of the building with the UFAD system was higher than that with the well-mixed system because there was heat transferred from the ceiling plenum downstairs to the floor plenum with the UFAD system. However, in the evening, the cooling load of the building with the UFAD system was less than that with the well-mixed system because of less heat transfer through the floor slab in the UFAD system. The total cooling load for the whole day with the UFAD system was 5% higher than that with the well-mixed system.

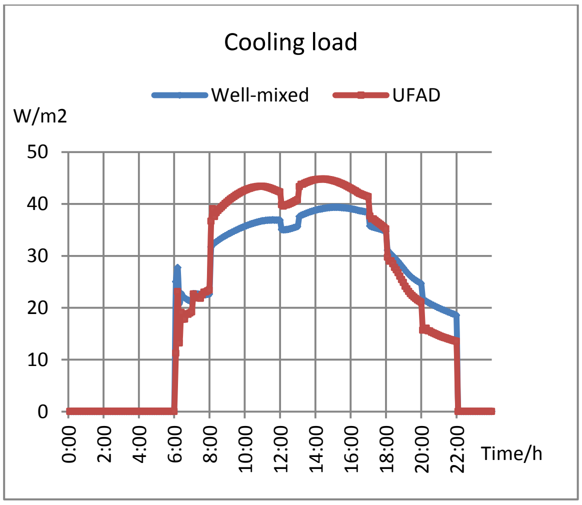
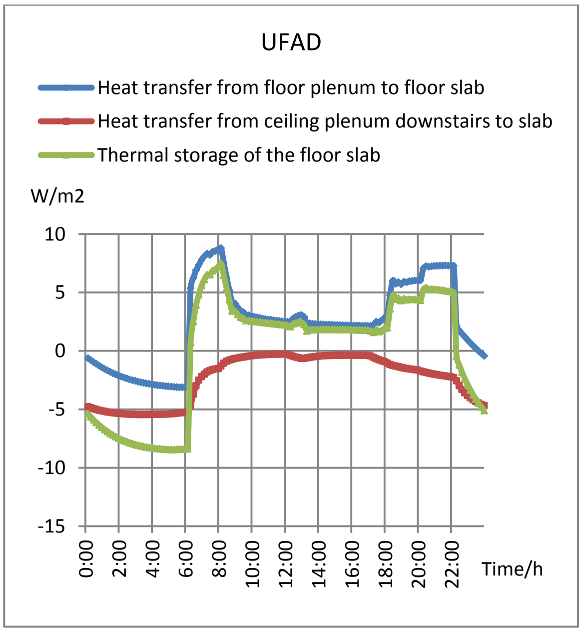
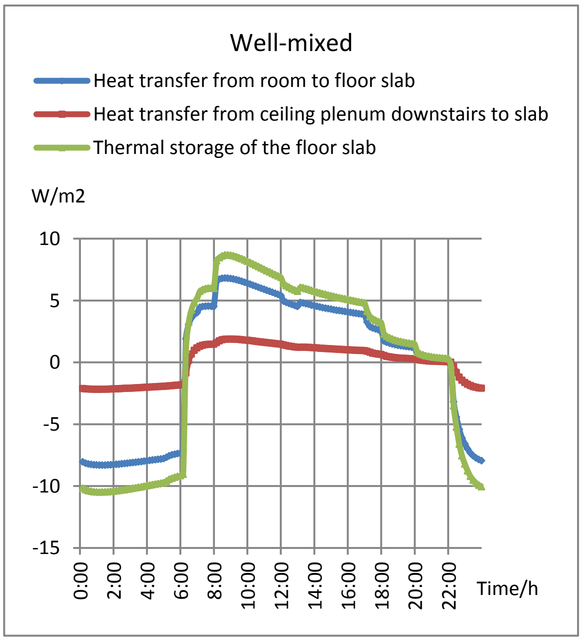


Figure 5 Cooling load

Figure 6 shows the simulated heat transfer through the floor slab for a typical winter day on January 21. For the building with the UFAD system, the high internal heat gains would make the room air temperature pretty high so little warm air was needed from the HVAC system. Hence, the air temperature in the floor plenum was not very high due to the heat transfer to the floor slab during the office hours (from 8:00 am to 6:00 pm) as shown in Figure 6(a). According to the weather data, that day did not have much solar radiation through the windows. The heat transfer on the floor slab with the well-mixed system was not sensitive the solar radiation when compared with the situation on the summer day. The internal heat gains would gradually warm up the floor slab so the heating transfer decreased during the office hour as shown in Figure 6(b). The shape of the blue lines in the two figures was thus different.



(a)



(b)

Figure 6 Heat flux at top and bottom surfaces of slabs in winter; (a) UFAD, (b) well-mixed

In early morning hours, the UFAD system would deliver a lot of heat to the room so the floor plenum was warm and the heat transfer to the floor slab was high as shown in Figure 6(a). The well mixed system did not have a warm floor plenum. The heat transfer between the room air and the floor slab was high as shown in Figure 6(b) but not as high as that for the UFAD system. In the evening, the internal heat gains decreased dramatically, the UFAD system would need to deliver a lot of heat like that in the early morning hours. The heat transfer to the floor slab again became higher as shown in Figure 6(a). However, the floor slab in the well-mixed system was warm in the evening due to the heat absorbed during the office hours. The high temperature of the floor slab would reduce the heat transfer as shown in Figure 6(b).

Figure 7 further compares the heating load of the two systems for the winter day. The heating load during office hours was much lower than that in the early morning and evening since the internal heat sources provided much heat for the occupied zone during this period. The heating load of the building with the UFAD system was lower than that with the well-mixed system because there was little heat transfer from the floor plenum to the slab for the UFAD system during office hours. Compared with the well-mixed system, the heating load of the building with the UFAD system in the early morning and evening was much higher since the heat transfer from the floor plenum to the floor slab was very high.

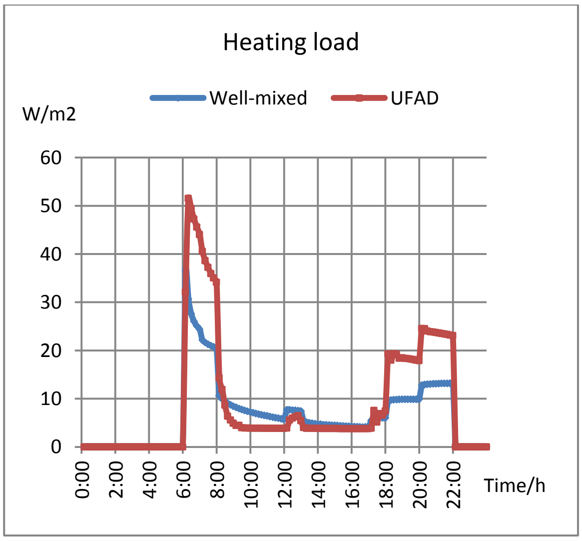


Figure 7 Heating load for the UFAD system vs the well mixed system

Comparison of annual energy consumption

Energy consumption is different from thermal load. The building with the UFAD system may consume less energy on chiller than that with the well-mixed system because of a higher supply air temperature, even though the cooling load with the UFAD system was higher. This is because the system could use more free cooling due to its high supply air temperature and consume less energy by the chiller.

Figure 8 illustrates the monthly energy consumption of the chiller for the two ventilation systems. The building with the well-mixed system used more energy by the chiller during the shoulder seasons, when the outdoor air temperature was suitable for free cooling. Compared with the well-mixed system, the annual energy consumption by chiller of the UFAD system is 6% less by using the energy consumed by the UFAD system as the basis.

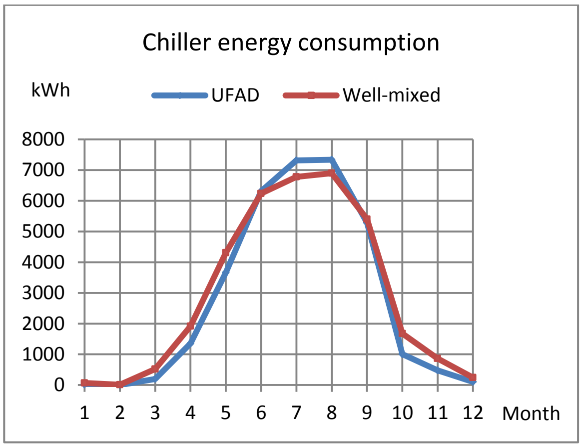


Figure 8 Monthly energy consumptions of the chiller

Figure 9 shows the monthly energy consumption by the boiler. The annual energy consumption by the boiler for the UFAD system was 40% higher than that of the well-mixed system. The reason is that the heat transfer from the floor plenum to the ceiling plenum downstairs led to a higher heating load in the UFAD system as shown in Figure 7.

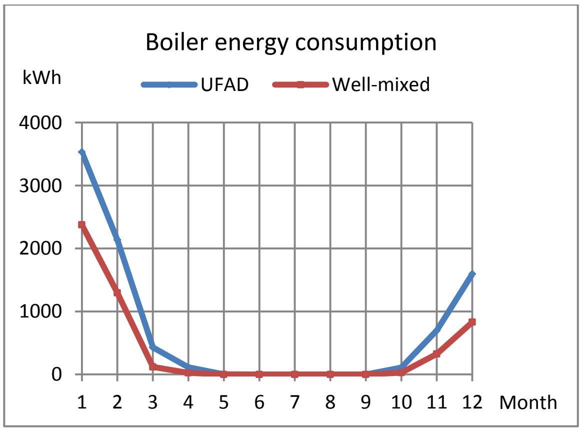


Figure 9 Monthly energy consumptions of the boiler

Figure 10 depicts that the electric energy used by the fan for the building with the UFAD system was 30% higher than that with the well-mixed system. Since the supply air temperature in the UFAD system was 3 K higher than that in the well-mixed system, the airflow rate was higher. The fan energy use is pretty linear to the flow rate of the HVAC system.

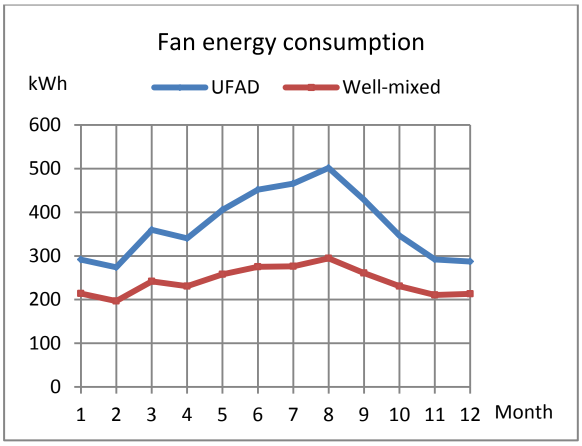


Figure 10 Monthly energy consumptions of the fan

CONCLUSION AND DISCUSSION

The heat transfer through the floor slabs of a multi-story building could play an important role if the building uses an UFAD system. Because of the heat transfer from the ceiling plenum downstairs through the floor slab to the floor plenum, the cooling load of building with the UFAD system could be higher than that with a well-mixed system in a typical summer day. The building with the UFAD system could also have a higher heating load due to the heat transfer from the warm floor plenum through the floor slab to the ceiling plenum downstairs.

Although the cooling load of the building with the UFAD system could be higher than that with the well-mixed system, the UFAD system could use more free cooling due to a higher supply air temperature, compared with a well-mixed system. Our calculation shows that the energy consumption of the chiller for the building with the UFAD system was 6% less than well-mixed system, but 40% more heating energy for the boiler and 30% more electrical energy for the fan, compared to those with the well-mixed system.

It may be possible to reduce the heat transfer through the floor slab by using ducts in the floor plenum or reheating/cooling in the diffusers. The energy performance of the building with the UFAD system could be better or worse than the well-mixed system depending on the climate zones. This investigation was for Philadelphia region. More work is needed for other regions in the United States for achieving more concrete conclusions. However, the major benefits of the UFAD system are for better air quality not energy.

ACKNOWLEDGEMENT

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