Xue, Y. and Chen, Q. 2014. "Influence of floor plenum on energy performance of buildings with UFAD systems," *Energy and Buildings*, 79, 74-83.

Influence of floor plenum on energy performance of buildings with UFAD systems

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Abstract

The heat transfer through the floor slab in buildings with Under-Floor Air Distribution (UFAD) systems may have a negative impact on the energy performance of these buildings, although very few studies have been reported in the literature. By using an energy simulation program, EnergyPlus, this investigation compared the energy use in a Philadelphia office building with a UFAD system to that with a well-mixed ventilation system. When the heat transfer through the floor slab was taken into consideration, the thermal load of the building with the UFAD system was higher than with the well-mixed system. On the other hand, the higher supply air temperature of the UFAD system enables the use of more free-cooling. The annual energy consumption by the chillers in the building with the UFAD system was 16%-27% lower than with the well-mixed system, but energy consumption by the boiler was 12%-30% higher, and the energy consumption by the fan was 22-50% higher, depending on the manner in which the heat was supplied to the floor plenum. When the UFAD system was used with an un-ducted floor plenum and without heating coils under the diffusers, it consumed slightly more energy than the well-mixed system.

1. Introduction

Unlike conventional overhead well-mixed systems, UFAD systems provide directly conditioned air to the occupied zone through diffusers in a raised floor, as shown in Figure 1. Thermal buoyancy causes temperature stratification in the occupied zone, and the air temperature in the lower part of the zone is lower than that in the upper part. Therefore, UFAD systems are believed to use less energy for cooling [1,2]. In addition, the thermal stratification in a room with a UFAD system can create better indoor air quality than in a room with a well-mixed air distribution system [3,4]. A UFAD system also allows individual control of airflow rate in order to meet the thermal comfort requirements of different occupants [5,6] and can thus provide a more comfortable environment than overhead well-mixed systems [7]. However, if the air supply and return in the plenums are un-ducted or un-insulated, the air temperature in the floor plenum is very low during the cooling mode, while the ceiling plenum is very warm. The temperature difference between the floor plenum and downstairs ceiling plenum leads to heat transfer across the floor slab, as shown in Figure 1,which may have an impact on energy use.

Studying the influence of the floor plenum on cooling load and energy use requires that the energy flow between the occupied zone and the floor plenum also be considered, so do the thermal stratification in the occupied zone [8]. Many previous researchers have analyzed the thermal stratification, and various models have been developed to predict the air temperature stratification in rooms with UFAD systems [9-15]. Air flow and heat transfer in the floor plenum contribute further complexity to the simulations. Linden [16] determined that there was a significant air temperature differential and air velocity variation in the floor plenum. These non-uniform air temperature and flow distributions could affect heat transfer in the floor plenum.

In regard to the impact of the floor plenum on the energy performance of a UFAD system, Bauman et al. [17] found that the heat transfer in the floor plenum can be as high as 30%-40% of the room cooling load. However, this conclusion was made on the basis of a simplified first-law model that may not be accurate. Schiavon et al. [8] indicated that the presence of a raised floor changed the cooling load profile greatly, and the peak cooling load could vary in the range of −7 to + 40% as compared to the load without the raised floor. However, their study did not address heating. Lee et al. [18] simulated a three-floor office building with a UFAD system on two design days: a summer day and a winter day. They found that thermal decay in the floor plenum could result in a higher supply airflow rate and greater use of energy by the fans and chiller. However, the non-uniform flow in the floor plenum was not taken into account in their study. The current investigation systematically studied the influence of heat transfer through a floor slab on the energy performance of an office building with a UFAD system. The objective was to accurately simulate the thermal load and energy use as influenced by the floor plenum and to assess the impact of non-uniform flow in the floor plenum on energy modeling.

2. Method

2.1. Load and energy simulations for an office building

To accurately study the impact of the floor plenum on energy performance, this investigation used EnergyPlus [19] as the main tool with the implementation of a room air stratification model. To simplify the study, this investigation simulated a typical middle floor, Floor N, in a multi-floor building, as shown in Figure 2, rather than an entire building. Accurate simulations must take into account (1) the vertical air temperature stratification in the room air and (2) the non-uniform air distribution in the floor plenum.

2.2. Vertical air temperature stratification in the simulated room

Because the EnergyPlus program did not calculate the room air distribution, the air temperature model from Lin et al. [12], implemented into the program by Liu et al. [20], was applied to calculate the vertical air temperature profiles in the room. The model predicts the vertical temperature profiles by simulating the buoyancy plumes from internal heat sources and the jets from air supply diffusers. The buoyancy plumes generate the air stratification and the jets lead to air mixing.

2.3. Non-uniform air distribution in the floor plenum

Along with the air temperature stratification in the room, non-uniform air velocity and air temperature in the floor plenum also contribute additional complexity to the simulation[16]. To simulate the non-uniform flow in the floor plenum, Computational Fluid Dynamics (CFD) can be used in combination with the energy calculation [21,22], but doing so is too computationally demanding. Instead, this investigation used a multizone model [23] to simulate the non-uniform air distribution in the floor plenum for coupling with EnergyPlus. The floor plenum was divided into several subzones according to the temperature distribution determined by CFD simulation. The air velocity and temperature differences among these subzones represented the non-uniform air temperature in the floor plenum. The simulation results of the multizone model were then compared to a single zone model in which the floor plenum had uniform air distribution. The difference between them could indicate the impact of the non-uniform air distribution on the energy modeling.

2.4. Validation of the computer models

The computer models described above use a number of approximations, and coupling them with EnergyPlus can lead to additional errors. The models needed to be validated before they could be used to simulate the cooling load and energy use in the building. This investigation used an environmental chamber as shown in Figure 3 to measure the air and surface temperatures in the floor plenum and the surface temperatures in the room.

This chamber had dimensions of 4.80 m in length, 4.20 m in width, and 2.73 m in height, including a floor plenum with a height of 0.30 m. The room contained several pieces of furniture, lighting fixtures, and heated boxes that were used to simulate internal loads such as electrical appliances, occupants, etc. The supply air duct was connected to the floor plenum, and two linear grille diffusers were installed in the floor. The walls and ceiling were well insulated with a thermal resistance of 5.45 m^2-K/W. The raised floor panels were made of 0.1 m thick lightweight concrete with a thermal resistance of 0.16 m^2-K/W. A double-glazed window with dimensions of

4.65 m in width and 1.55 m in height and a thermal resistance of 0.25 m^2-K/W was installed in the east wall of the chamber. Table 1 shows the power levels of the internal heat sources.

Eight anemometers were placed in the middle of the floor plenum (0.15 m from the slab) for measuring air temperature and velocity in the plenum. Temperatures of the different surfaces of the floor plenum and room were measured by a number of T-type thermocouples. The experiment was conducted under steady-state conditions in summer. The inlet temperature was 17.3°C, and the air change rate was 6 ACH.

3. Validation of the computer models and case setup

3.1. Validation of the computer models

The CFD simulations for this investigation were performed for the floor plenum using a commercial software program FLUENT [24]. The CFD results provided greater understanding of the temperature distribution in the floor plenum, which was the basis of the multizone model. Figures 4 and 5 show the air velocity and temperature profiles, respectively, in two sections of the floor plenum. The air supply was located on the bottom wall under Position 7, as shown in Figure 6, and therefore Positions 3 and 7 were located in the jet region. As a result, the air velocities measured at these positions were high, and the air temperatures were low. The agreement between the CFD results and experimental data for air velocity and temperature is quite good. Figure 6 shows a non-uniform air temperature distribution in the floor plenum.

Our EnergyPlus simulation divided the floor plenum into three subzones, as shown in Figure 6, for studying the impact of the non-uniform air temperature distribution on the load. Figure 5 depicts the air temperature profiles calculated with the multizone model in the two sections of the floor plenum, and again they are in good agreement with the measured data. The results shown in Figures 5 and 6 have validated the computer models for calculating air temperature in the floor plenum.

Table 2 further compares the air temperature from the diffusers, air temperature at the exhaust, and EnergyPlus-simulated surface temperatures with the measured data. The columns of "Error" show the percentage difference between the experimental measurements and simulation results. Once again, agreement between the simulations and measurements is quite good. Therefore, the EnergyPlus program with the multizone air models can be used to predict thermal load and energy use in buildings. In addition, Table 2 shows the results obtained by EnergyPlus with the assumption of uniform air temperature in the floor plenum (one subzone). The air temperature with one subzone differed by only 0.5 K from that with three subzones, which was insignificant, although the air temperature between zones can differ by 2 K, as shown in Figure 6. Thus, the impact of the non-uniform air distribution in the floor plenum on the energy simulation was very limited and our subsequent simulations used only one zone for the floor plenum.

3.2. Case description for a building with UFAD systems in Philadelphia

Using the validated EnergyPlus model, this investigation conducted energy simulations for a mid-level floor of a multi-floor office building in Philadelphia. An office area with dimensions of 30 m × 40 m × 3.7 m, as shown Figure 7, was divided into five thermal zones: a central zone and four perimeter zones, because solar radiation would have a significant impact on the perimeter zones. The perimeter zones had a width of 5.0 m [25]. The construction and material information for the building envelope were taken from the default data for Chicago in EnergyPlus Version 7. Figure 8 shows the internal load profiles for weekdays and Saturdays. This study further assumed that the building was completely closed on Sundays, without an internal heat load.

This investigation simulated three different scenarios for the office building, as shown in Figure 9: a well-mixed ventilation system, a UFAD system without heating coils in the diffusers, and a UFAD system with heating coils in the diffusers [26]. For each of the two UFAD scenarios, three cases were simulated with different floor plenum configurations: completely ducted floor plenums; partially ducted floor plenums (ducted floor plenums in the perimeter zones and an un-ducted core zone); and completely un-ducted floor plenums. The arrangement led to a total of seven simulation cases, as shown in Table 3. All of the cases used the same HVAC system, which incorporated an electric chiller and a gas boiler. The system used variable-air-volume control and an economizer. The thermostat in the occupied zone was set at 21°C during the winter and 24°C during the summer. The minimum fresh air rate was 0.3 $L/(s \cdot m^2)$, in accordance with ASHRAE Standard 62.1-2010 for indoor air quality [27]. For mixed ventilation, the supply air temperature was 13°C for cooling and 32°C for heating [28]. In the UFAD system without heating coils in the diffusers, the supply air temperature was 17°C [1,29] for cooling and 32°C for heating. In the UFAD system with heating coils, the air supply temperature from the HVAC system was 17°C all year round. When heating was called for, the air was heated to 32°C by the heating coils. The HVAC system operated from 6:00 to 22:00.

4. Results

In order to explain the effects of the heat transfer through slabs on the energy performance of buildings, this section will show the heat flux profiles across slabs and analyze their influence on the thermal loads. Then the year-round energy consumption results will be reported.

4.1. Thermal load simulations for the building

Figure 10 shows the heat flux at the two surfaces of the floor slab in the office building on July 21, the summer design day in EnergyPlus. The sum of the heat transfer at the two surfaces is equal to the thermal storage in the slab. For cooling, the heating coils in the diffusers were not activated, and thus the two UFAD scenarios were identical. For the well-mixed system, from 8:00 to16:00, heat was transferred from the occupied zone to the slab, as shown in Case 1 of Figure 10(a, b). In the perimeter zones as shown in Figure 10(a), this heat transfer was caused by the high level of radiation from the direct sunlight on the floor slab and the internal heat sources, With the UFAD systems, however, the radiation from the sun and the internal load had no direct impact on the slab. Thus, the heat transfer profiles in these cases were very different from those with the well-mixed system. In the thermal zones with ducted floor plenums, there was a small amount of heat transfer across the floor slabs. As for the un-ducted UFAD systems, cool air was supplied to the floor plenum, and the downstairs ceiling plenum was warm. The significant temperature difference between the two sides of the floor slab led to a high heat transfer rate from the downstairs ceiling plenum to the floor slab and further to the floor plenum. In the well-mixed system, from 6:00 to 8:00 and 18:00 to 22:00, when the internal load and solar radiation were small, heat was transferred from the floor slab to the room air as a result of the high floor slab temperature. In the UFAD system, however, the total air supply was lower during these two periods than during the occupied hours, and thus the heat transfer from the floor plenum to the slab was smaller.

Despite the drastic difference in heat transfer profiles between the well-mixed ventilation and UFAD, the cooling loads of these systems had similar shapes on the summer design day, as shown in Figure 11.

For the winter heating, the heat transfer between the well-mixed system and UFAD system could be different but the heating load is also very similar as shown in the cooling scenario. Due to limited space in this paper, the detailed results are not presented here.

4.2. Annual energy consumptions of the building

Figures 12 and 13 illustrate the monthly energy consumption by the chiller and boiler, respectively, in the HVAC system in year-round simulations. With the well-mixed ventilation system, more energy was used by the chiller, especially during the shoulder seasons when the outdoor air temperature was suitable for free-cooling. In the two UFAD scenarios, the levels of electricity consumption by the chillers were almost identical. They were lower than that in the well-mixed system by 27% for the ducted cases (Cases 2 and 5), 23% for the partially ducted cases (Cases 3 and 6), and 16% for the un-ducted cases (Cases 4 and 7). The percentage numbers are based on the UFAD systems. However, the natural gas consumption levels by the boiler with the UFAD systems were higher than that with the well-mixed system. Without heating coils under the diffusers, the boiler energy consumption in the UFAD system was higher than that in the well-mixed system by 18% in the completely ducted case (Case 2), 21% in the partially ducted case (Case 3), and 30% in the un-ducted case (Case 4). When there were heating coils under the diffusers, the boiler energy consumption in the UFAD system was higher than that in the well-mixed system by 12% in the completely ducted case (Case 5) and by 18% in the partially ducted (Case 6) and the un-ducted (Case 7) cases.

The levels of electricity consumption by the fans in the building's HVAC system were 22-50% higher with the UFAD systems than with the well-mixed system by using the energy use of the UFAD system as the reference, as shown in Figure 14. This difference occurred because the supply air temperature in the UFAD systems was higher than that in the well-mixed ventilation system, and a higher airflow rate is required in order to remove the same amount of heat.

A comparison of the different cases indicates that the ducting of floor plenums can reduce energy consumption by the chiller and the boiler, and that this effect is more significant in perimeter zones. Furthermore, during the heating mode, supplying warm air directly to the floor plenum without ducts is not recommended because heat flow in the plenum would cause significant energy loss. In addition to ducting of the floor plenums, the use of heating coils under the diffusers is recommended in order to reduce energy use by the boiler.

Using the energy consumption data, this investigation conducted a cost analysis for these cases with EnergyPlus. Table 4 shows the monthly price of natural gas [30]. The cost of electricity [30] was calculated using the block method shown in Table 5. The tax rate was 8%, and the monthly service fee for electricity was $8.81. Table 6 shows the annual electricity costs for the chiller and fans and the gas costs for the boiler. For the same building, the use of electricity by lights and electrical equipment was exactly the same with either the well-mixed ventilation or UFAD. Variations in energy consumption arose from the HVAC systems.

Because only the perimeter zones of the building required heating and natural gas was much cheaper than electricity, the gas costs for the boiler were much lower than the electricity costs for the chiller. As discussed above, energy consumption by the chiller was greater with the well-mixed system than with the UFAD systems. Therefore, as shown in Table 6, chiller operation was more expensive in the well-mixed case (Case 1) than in the UFAD cases (Cases 2-6). Among the UFAD cases, those with un-ducted floor plenums (Cases 4 and 7) had higher electricity costs than the other cases. However, the addition of heating coils under the diffusers did not contribute significantly to the electricity costs.

Although chiller operation was cheaper in the UFAD cases, both the gas costs for the boiler and the electricity costs for the fan were higher with the UFAD systems than with the well-mixed system. These higher costs are consistent with the energy consumption levels shown in Figures 13 and 14. In the UFAD cases, the addition of heating coils under the diffusers (Cases 5-7) reduced the gas cost for the boiler, especially in the cases with un-ducted floor plenums. The total energy cost for a building with a UFAD system could be lower than that with a well-mixed system if the floor plenum was ducted. Unfortunately, ducting of the floor plenum is not a common practice at present.

5. Conclusions

Using validated computer models, this investigation assessed the energy performance of a building in Philadelphia with several different UFAD systems and with a well-mixed ventilation system. The study led to the following major findings:

- The airflow and air temperature distribution in the floor plenum can be highly non-uniform. The non-uniform air temperature distribution can be calculated with the use of a simple subzone model. By comparing the supply air temperature, exhaust air temperature, and enclosure surface temperatures between the multizone model and the single zone model, this study found that the impact of the non-uniform air temperature distribution on the energy modeling is small.
- In cooling situations, the temperature difference between the cold air in the floor plenum and the warm air in the downstairs ceiling plenum can result in significant heat transfer through the floor slab in a building with a UFAD system. This heat transfer leads to a slightly higher cooling load than with a well-mixed ventilation system.
- In heating situations, when a UFAD system is used in the building without heating coils in the air supply diffusers, the presence of warm air in the floor plenum can lead to a higher heating load than that with the well-mixed ventilation system. This increased heat load is again attributed to heat transfer from the plenum air to the floor slab.
- By conducting an annual energy analysis for the building, this investigation found that the chiller used 16%-27% less energy with the UFAD systems than with the well-mixed system because of the use of free cooling during the shoulder seasons. However, the boiler consumed 18%-30% more energy with the UFAD systems because of heat loss in the floor plenum. The use of heating coils in the air supply diffusers and/or the utilization of ducts for supplying air to the floor plenum can reduce energy use by the boiler. Finally, because the UFAD systems had a higher supply air temperature for cooling, the total supply airflow rate was higher than that with the well-mixed ventilation system. As a result, energy consumption by the fans in the UFAD systems was 22-50% higher.
- The total energy cost for a UFAD system with un-ducted floor plenums and without heating coils under the diffusers could be slightly higher than that for a well-mixed system. Either ducting the floor plenums or using the heating coils under the diffusers would reduce the energy cost. However, ducting the floor plenums would increase the

initial investment and maintenance costs. Therefore, although the UFAD system with completely ducted floor plenums and with heating coils (Case 5) had the lowest energy costs, the partially ducted UFAD system with heating coils (Case 6) would be the most favorable one.

Acknowledgement

This research was funded partially by the Energy Efficient Building Hub led by the Pennsylvania State University and funded by the U.S. Department of Energy and other government agencies, where Purdue University was a subcontractor to the grant.

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Table 1.Power inputs of the lights and heated boxes.

	Number	Power [W]
Lighting	1	43.0
	2	44.0
	3	26.5
	4	43.5
Heated boxes for manikins	1	93.3
	2	84.0
Heated boxes for equipment	1	65.0
	2	65.0
	3	65.0

Table 2.Comparison of simulated and measured temperatures for the environmental chamber.

Locations	Experimental measurements	E+ simulation with1-zone floor plenum (uniform air temperature)		E+ simulation with 3-zone floor plenum (non-uniform air temperature)	
	℃	℃	Error (%)	℃	Error (%)
Air at the diffusers	20.2	19.9	1.5	20.4	1.0
Air at the exhaust	24.2	24.4	0.8	24.2	0.0
Slab surface (facing floor plenum)	23.7	23.6	0.4	23.6	0.4
Ceiling surface	24.3	24.7	1.6	25.4	4.5
North wall of floor plenum	23.8	22.7	4.6	23.7	0.4
South wall of floor plenum	22.7	22.7	0.0	23.0	1.3
West wall of floor plenum	23.5	22.7	3.4	23.0	2.0
East wall of floor plenum	22.7	22.7	0.0	23.0	1.3
North wall of room	25.1	25.2	0.4	25.5	1.6
South wall of room	24.1	25.2	4.6	25.5	5.8
West wall of room	24.7	25.2	2.0	26.4	6.9
East wall of room	25.4	25.2	0.8	25.5	0.4

Table 3.Simulated cases.

Case	Ventilation system	Floor plenum configuration	Heating coils under diffusers
1	Well-mixed	N/A	N/A
2	UFAD	Completely ducted	No
3	UFAD	Ducted perimeter zones Un-ducted core zone	No
4	UFAD	Completely un-ducted	No
5	UFAD	Completely ducted	Yes
6	UFAD	Ducted perimeter zones Un-ducted core zone	Yes
7	UFAD	Completely un-ducted	Yes

Table 4. Monthly natural gas price (unit: $/kWh).

Jan	Feb	Mar	Apr	May	Jun
0.344	0.343	0.343	0.346	0.371	0.400
Jul	Aug	Sep	Oct	Nov	Dec
0.391	0.386	0.376	0.375	0.322	0.331

Table 5.Electricity price (unit: $/kWh).

Summer (Jun – Sep)and Winter (Oct - May)			
Charge	Energy [$/kWh]	Transition [$/kWh]	Distribution [$/kWh]
< 80 hrs.	0.1088	0.0669	0.0344
80-160 hrs.	Summer: 0.0592 Winter: 0.0428	Summer:0.0319 Winter: 0.0205	Summer:0.0162 Winter: 0.0103
160-400 hrs.	0.0428	0.0205	0.0103
> 400 hrs.	0.0275	0.0095	0.0046

Table 6. Annual energy cost for the whole building in different cases.

Case	Electricity cost for the chiller ($)	Electricity cost for the fans ($)	Gas cost for the boiler ($)	Total cost as a percentage of Case 1 (%)
1	4275	369	244	100.0
2	3425	481	300	86.1
3	3553	660	320	92.7
4	3797	756	372	100.7
5	3424	481	274	85.7
6	3553	659	290	92.4
7	3814	744	297	99.6

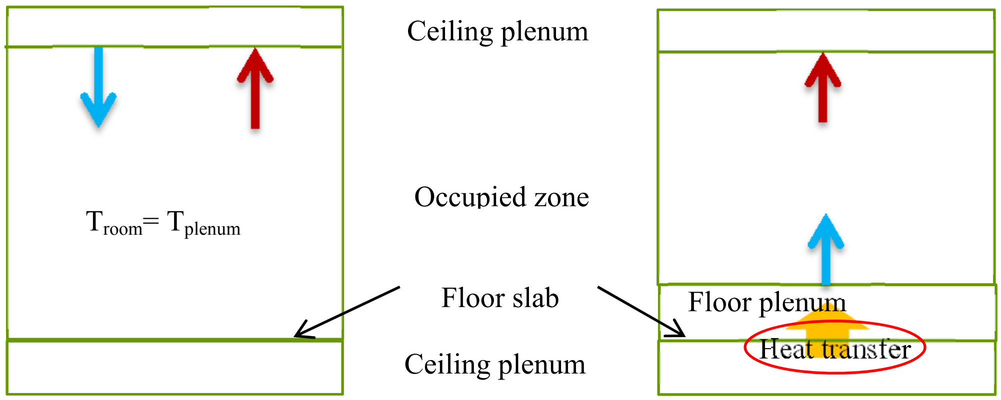


Figure 1.Schematics of well-mixed (left) and UFAD (right) systems.

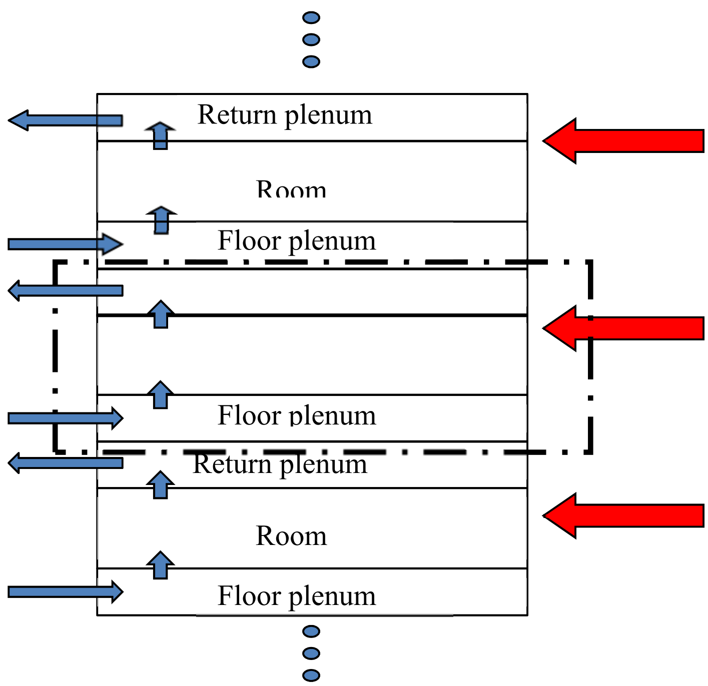


Figure 2. Floor N in a multi-floor building with a UFAD system.

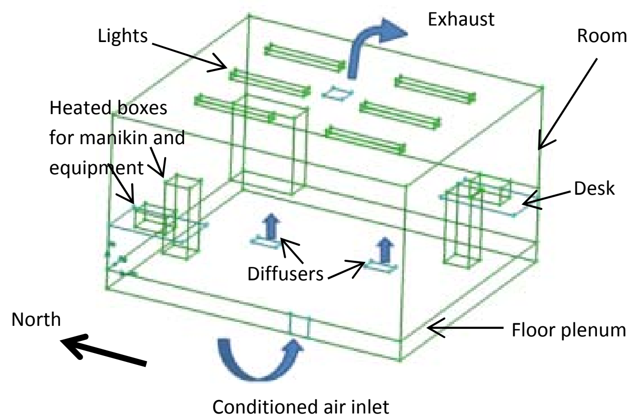


Figure 3.Schematic of the environmental chamber.

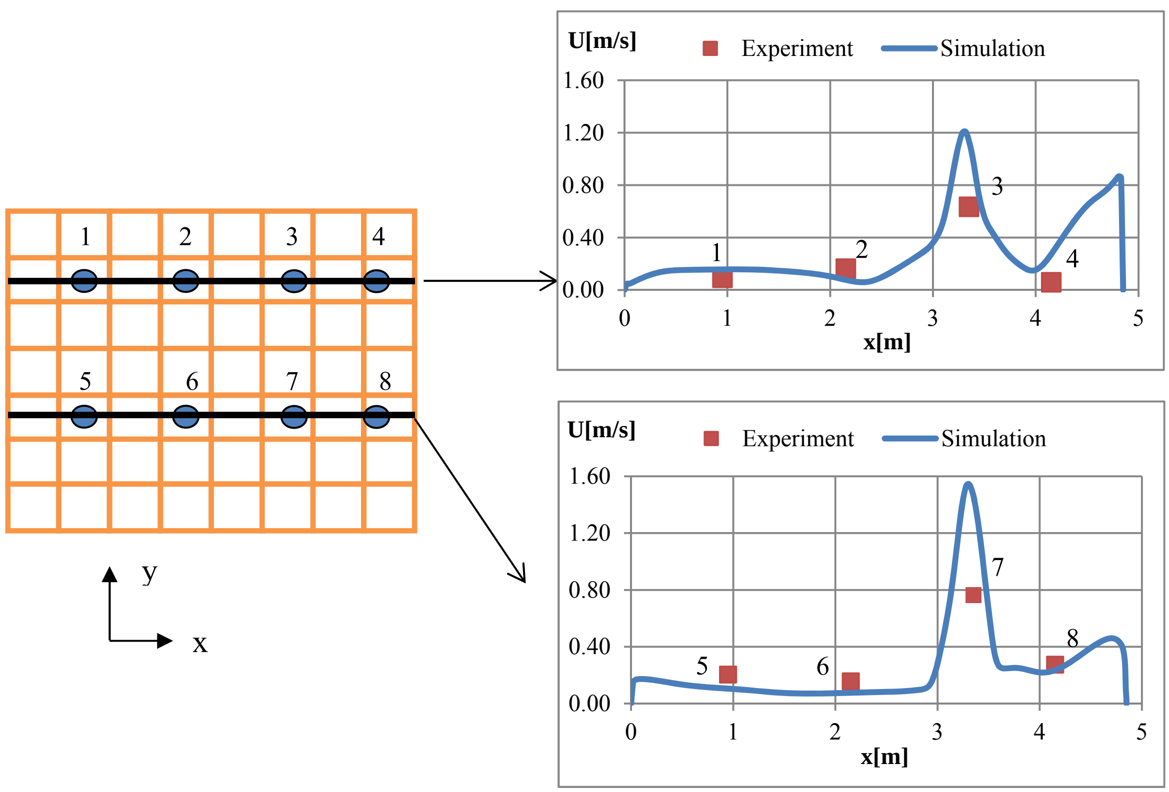


Figure 4. Comparison of CFD results with experimental data for air velocity in two sections of the floor plenum (horizontal cross-section of the plenum at 0.15m above the floor).

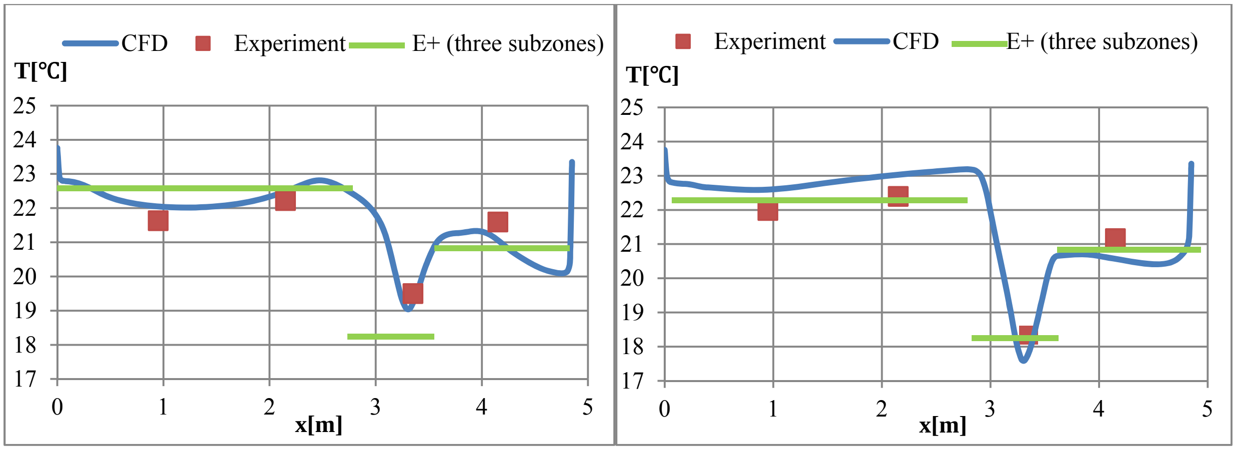


Figure 5. Comparison of measured air temperature with that computed by CFD and by the multizone model in two sections of the floor plenum

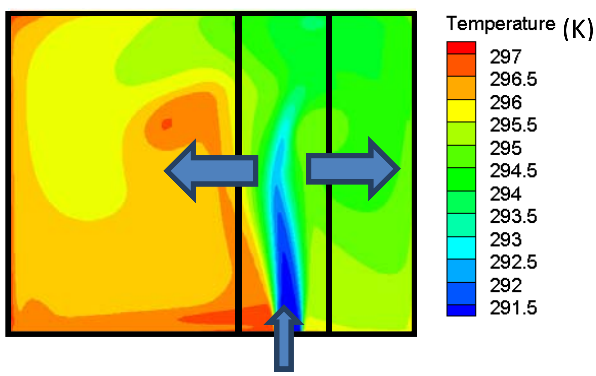
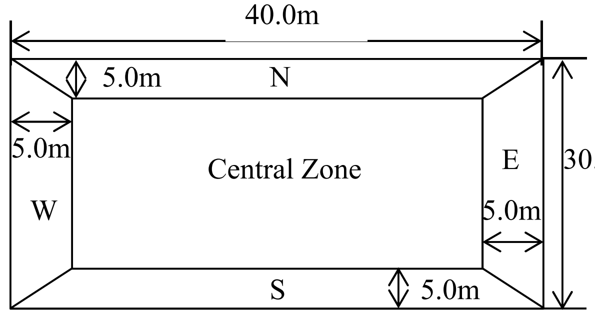
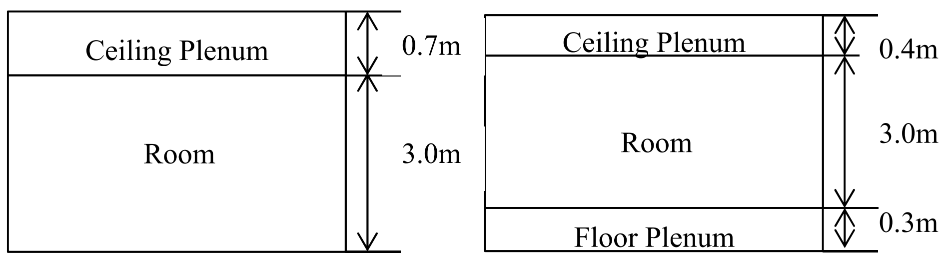


Figure 6.Air temperature distribution at 0.15m above the floor slab as simulated by CFD, and division of the plenum into three subzones.



(a). Top view of thermal zone layout.



(b). Side view of thermal zone layout.

Figure 7.Medium-sized office building in Philadelphia.

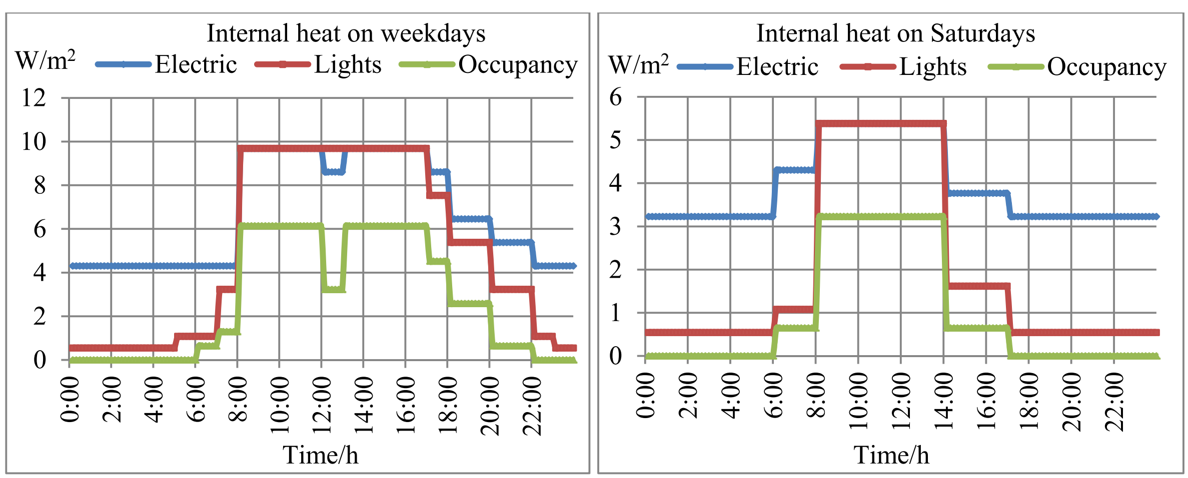
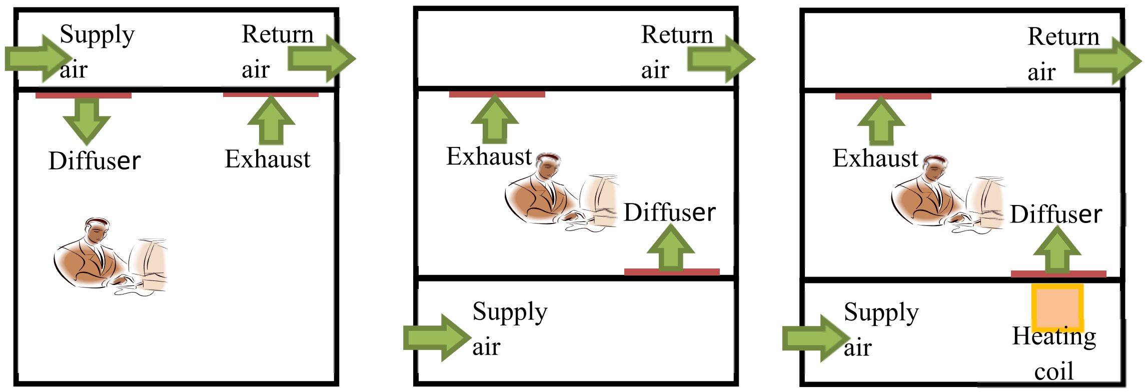
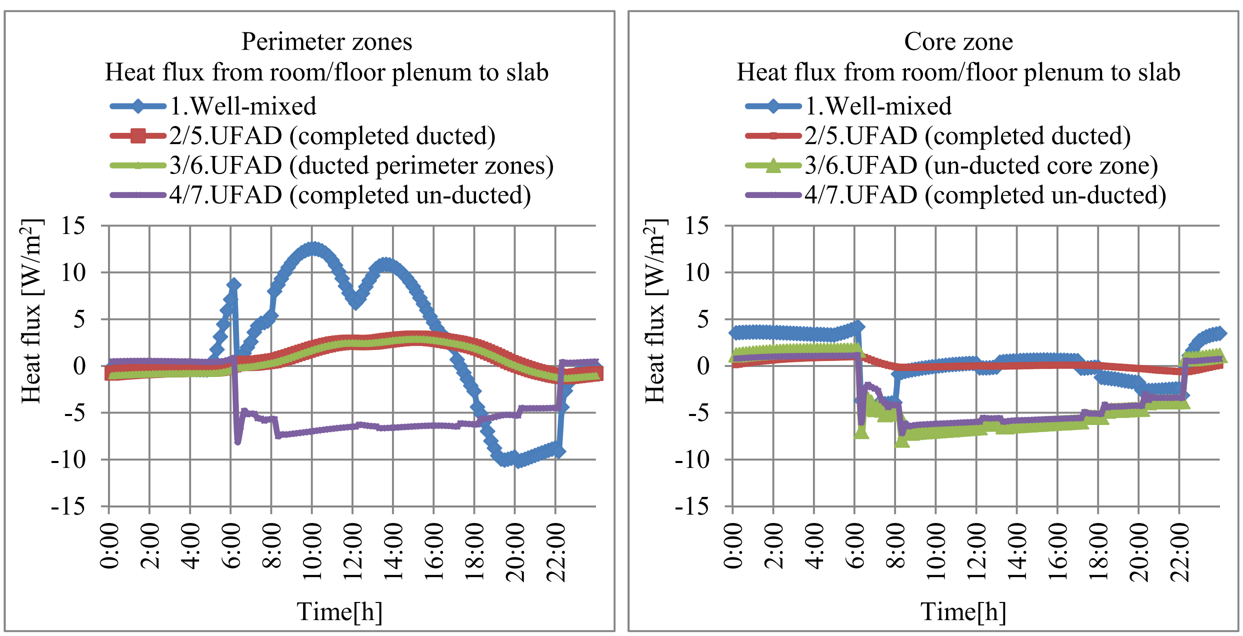


Figure 8.Internal heat load of the office building on weekdays (left) and Saturdays (right).

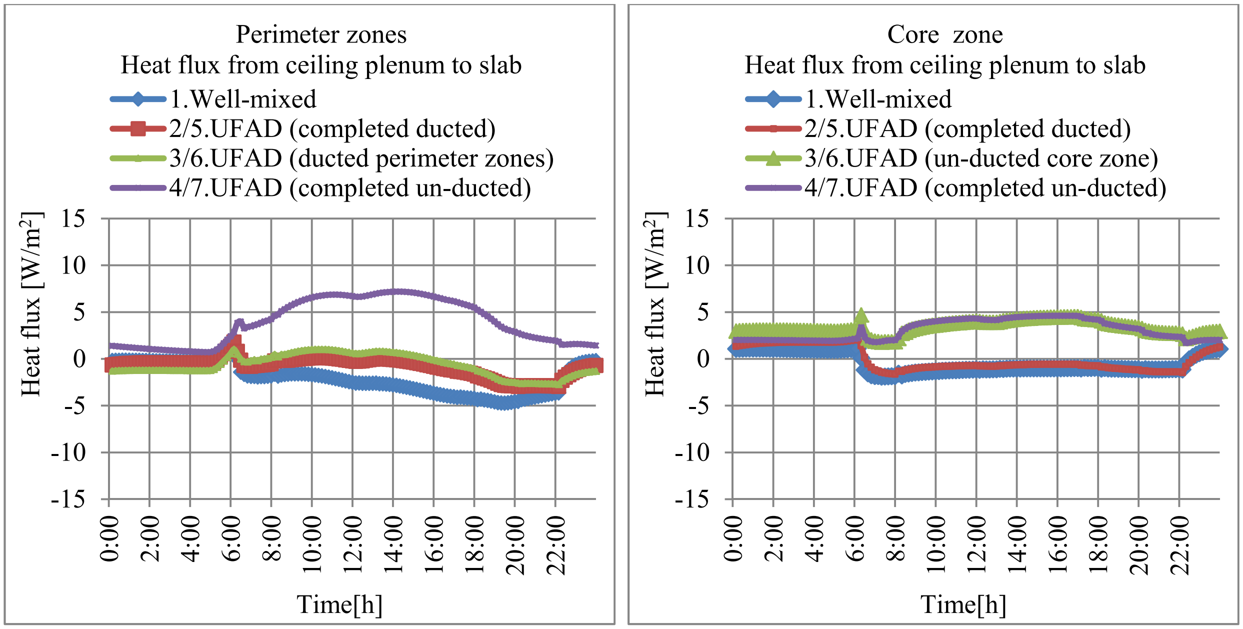


(a) (b) (c)

Figure 9. Simulated scenarios: (1) well-mixed ventilation system, (2) UFAD system without heating coils in the diffusers, and (3) UFAD system with heating coils in the diffusers.

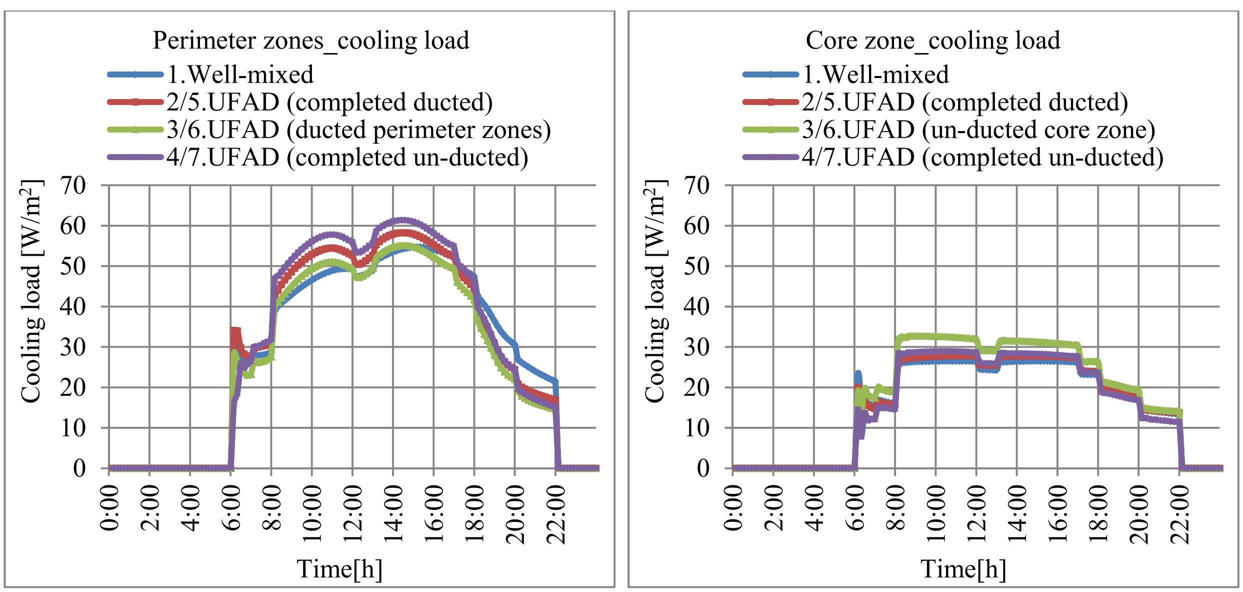


(a) (b)



(c) (d)

Figure 10. Heat transfer across the floor slab of the office building on the summer design day - a weekday. Refer to Table 3 for case descriptions. (a) Heat flux from the room/floor plenum to the floor slab in perimeter zones, (b) Heat flux from the room/floor plenum to the floor slab in the core zone, (c) Heat flux from the downstairs ceiling plenum to the floor slab in perimeter zones, and (d) Heat flux from the downstairs ceiling plenum to the floor slab in core zones (right)



(a) Perimeter zones *(b) Core zone*

Figure 11. Cooling loads on the summer design day for the office building with different ventilation systems. The numbers are for different cases as described in Table 3.

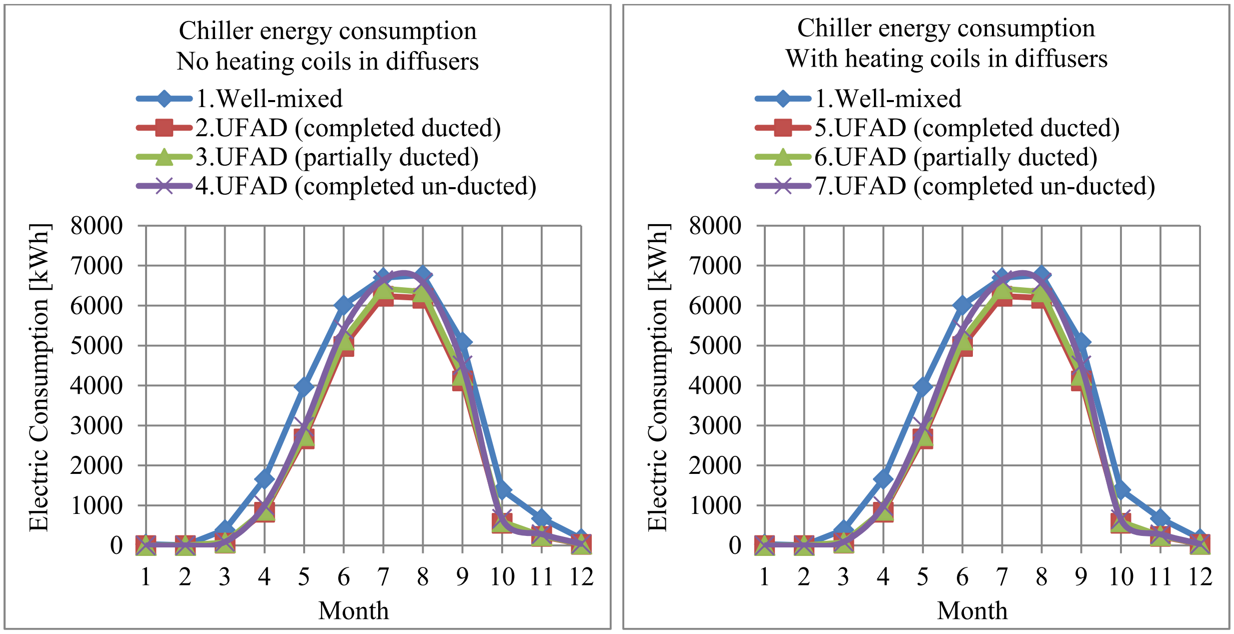


Figure 12.Monthly energy consumption by the chiller in the building's HVAC system.The numbers are for different cases as described in Table 3.

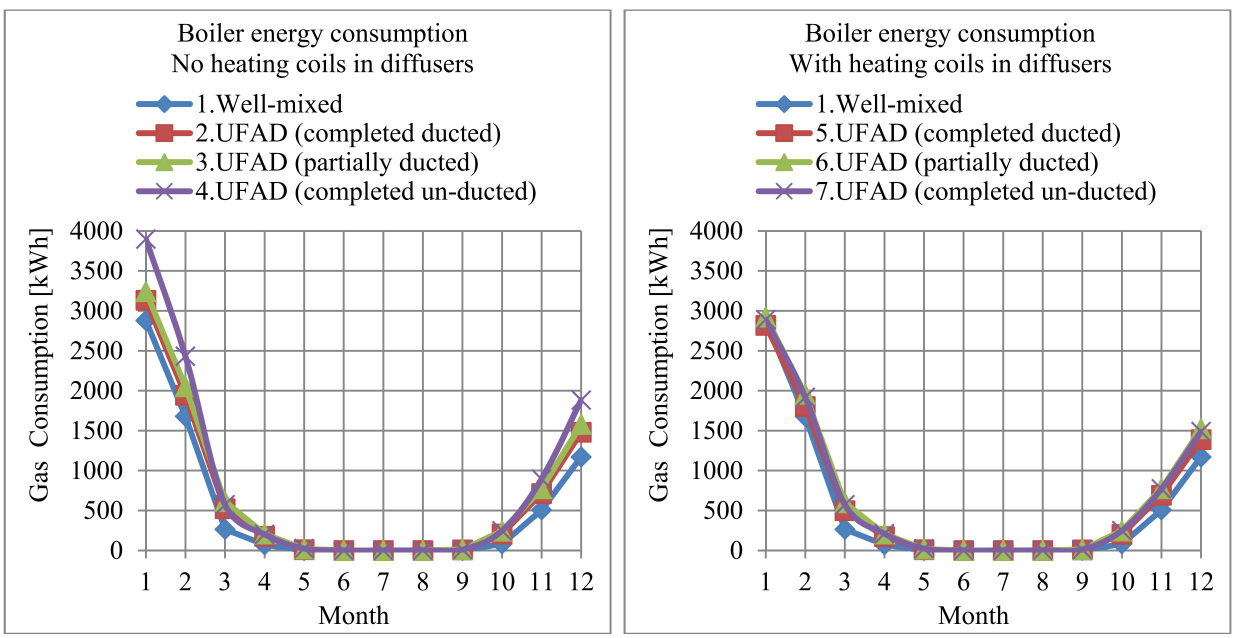


Figure 13.Monthly energy consumption by the boiler in the building's HVAC system. The numbers are for different cases as described in Table 3.

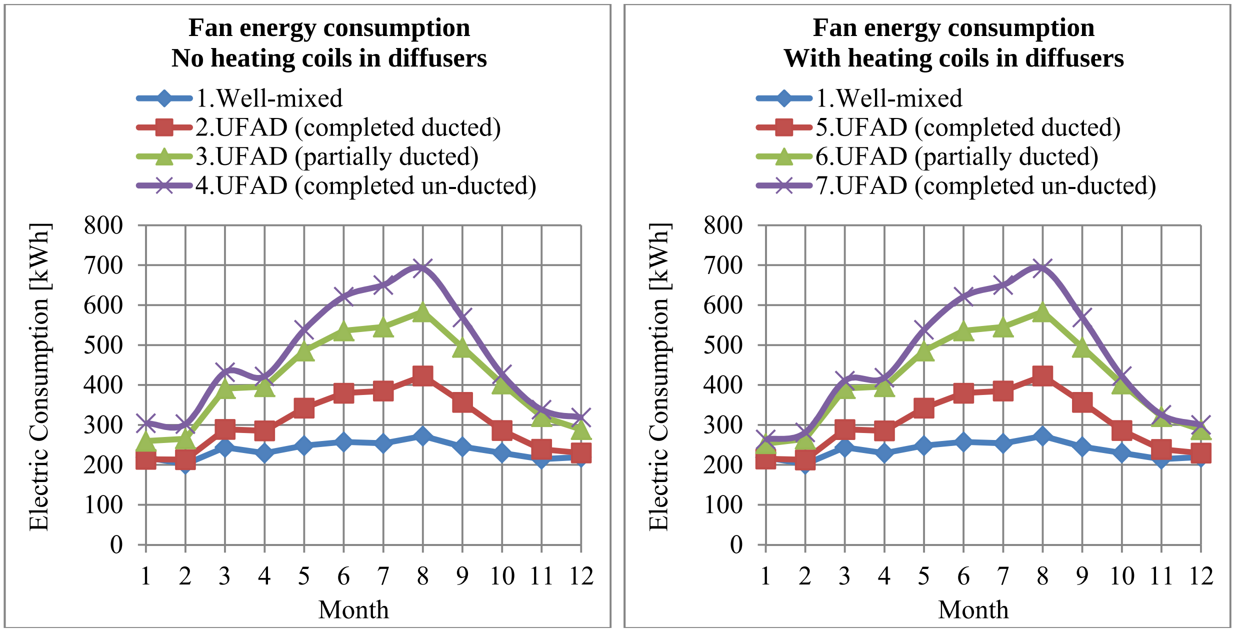


Figure 14.Monthly energy consumption by the fans in the building's HVAC system.The numbers are for different cases as described in Table 3.