Modeling and Simulation of the Mixed Mode Ventilation Strategies with Heat Recovery and Energy Recovery Wheels for Energy Conservation and IAQ Improvement in the Commercial Buildings

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Abstract: -Ventilation systems are used to be heat or cool space in commercial buildings. However, commercial buildings consumed about a fifth of all the energy produced in the U.S. 12% of that energy was being consumed by the commercial building's ventilation system. The U.S. Department of Energy funded an energy innovation hub known as the EEB hub to solve this problem. Morgan State University is among the participating institutions in the hub. The staff at the Center for Advanced Energy Systems and Environmental Control Technologies (CAESECT) has applied an under floor air distribution (UFAD) system along with desiccant wheel and energy recovery wheel system to reduce energy consumption and improving indoor air quality in the buildings.
The Schaefer Engineering library at Morgan State University was selected as a demonstration site for the UFAD. The software, DesignBuilder was used to model the Schafer engineering library and its overhead variable air volume (VAV) system. A comparative analysis of the energy consumption between the overhead VAV system and the UFAD system was performed. First, cooling and heating calculations were performed. Both systems had heating and cooling loads around 50 kBut/h. A design of experiments (DOE) was done using five factors. Annual energy simulations were conducted for both systems. On average, the UFAD system was about 20% more energy efficient than the overhead VAV system. A 2-sample t-test was performed and the results showed that the UFAD system was the more energy efficient system. An ANOVA test was done and one three significant individual factors as well as a 2-way factor interaction significantly affected energy consumption. Desiccant wheel and energy recovery wheel are energy efficient and improving indoor air quality, which can be retrofitted to the existing HVAC system for the commercial buildings.

Key-Words: - Ventilation, Variable Air Volume (VAV), Under Floor Air Distribution (UFAD), Heat and Energy Recovery, Energy Efficient, Indoor Air Quality (IAQ)

1 Introduction

According to the Department of Energy's 2012 Annual Energy Review, commercial buildings consumed 19% of all the energy produced in the U.S. Ventilation systems in commercial buildings consumed 12% of that energy. At a price of $28.92/million Btu, these systems cost $12.6 billion dollars to operate [1].

Ventilation systems depend on the air distribution in rooms that are ventilated. This air distribution has various elements. According to Aiulfi et al, "air distribution in ventilated rooms is a flow process that can be divided into different elements such as supply air jets, exhaust flows, thermal plumes, boundary layer flows, infiltration and gravity currents" [2]. Figure 1 shows the flow element model with its various jets, flow, etc.

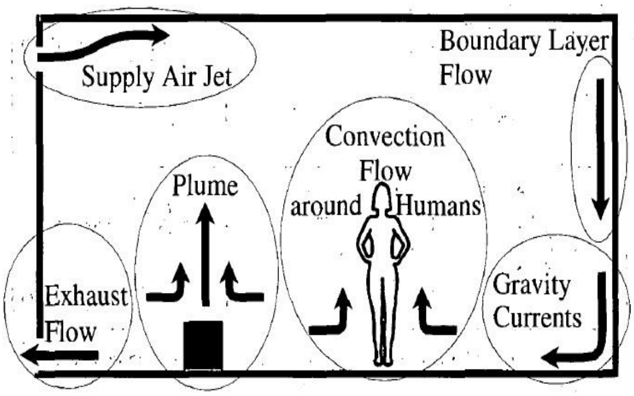

Fig. 1 Flow Element Model

Air distribution systems can be designed using the flow element model. However, this model is appropriate when there is only one flow element in the room or the flow elements that do not interact with one another [2]. In the case of displacement ventilation, such as underfloor air distribution (UFAD) systems, "the supply air from a low level device and the thermal plume from heat sources above the floor are good examples of different flow elements that do not influence each other, and where the design of the air distribution system can be based on the models of these two flow elements" [2].

2 Problem Formulation

There are various types of ventilation systems used in commercial buildings, the most common are conventional air distribution (CAD) systems. An example is an overhead variable air volume (VAV) system. An overhead VAV ventilation system typically consists of an air handler unit (AHU) to provide the conditioned air, duct work to move the conditioned air, VAV box which modulates the conditioned air, and a ceiling diffuser which introduces the conditioned air into the space. Daly describes the system as one that "…supplies conditioned air through ducts at the ceiling and typically takes return air back through a plenum above the ceiling. The diffuser or air outlets to the supply duct system are designed to throw air around the room in such a manner to induce full mixing of the air in the occupied space. For this reason, these systems are called "mixing" systems [3].

Figure 2 shows the overhead air distribution scenario.

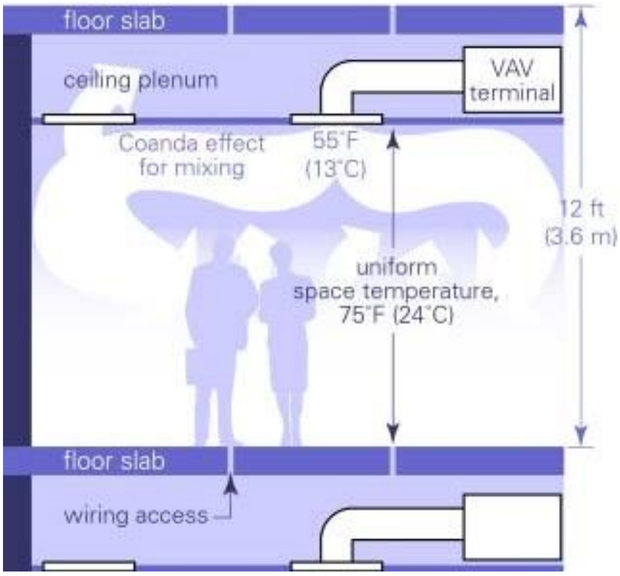

Fig. 2 Overhead Ventilation Scenario

UFAD systems consist of an AHU, VAV box, floor diffusers, duct work, and raised floor panel. The operation of a UFAD system is the opposite of an overhead ventilation system.

Stanke's description of the UFAD system operation is the following:

Floor-mounted diffusers release cool 63°F-to-68°F (17°C-to-20°C) air, which induces local circulation and causes partial mixing and relatively uniform temperatures from the floor to a height of 3 to 6 ft (1 to 2 m). Above that point, the air temperatures stratify. At the return openings near the ceiling, the air temperature ranges from 80°F to 85°F (27°C to 29°C), depending on heat sources, airflow, and ceiling height [4].

Figure 3 shows the UFAD ventilation scenario.

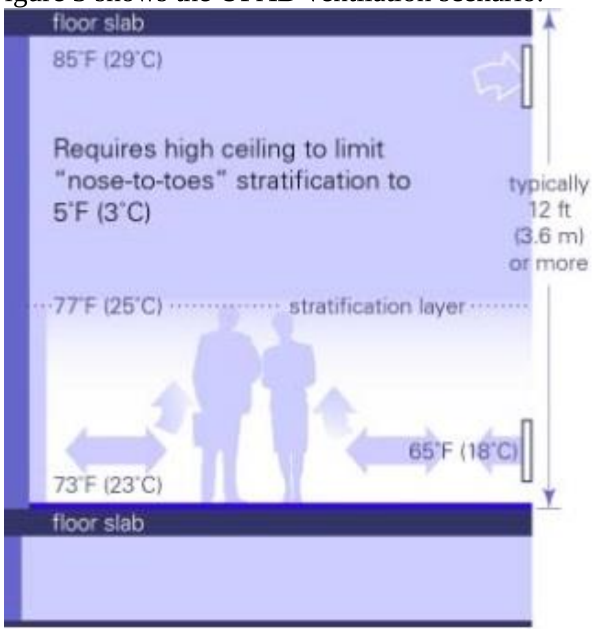

Fig. 3 UFAD Ventilation Scenario

According to York International, UFAD systems offer "20% - 30% total energy savings vs. overhead HVAC system" [5]. This due to many reasons, for example, UFAD operate using low differential static pressure, "0.05" vs. 1.5 – 2.0" typical for overhead supply plenums" [5]. As a result, the "fan horse power" is reduced and consequently, energy consumption. Using EnergyPlus V6., Webster et al was able to create simulations comparing the UFAD vs. the overhead air distribution systems [6]. For example, Figure 4 shows the results of the simulation. Figure 4 shows that UFAD systems produced total heating savings of about ~45 kBtu/sf/yr. Furthermore, the total HVAC savings is between 5% and 25% [6].

Other research has yielded a tool for "cooling airflow design for Displacement Ventilation (DV)" [7]. Researchers at the Center for the Built Environment (CBE) have created a program that allows the user calculate cooling airflow based on input parameters such as the heating load of a space [7].

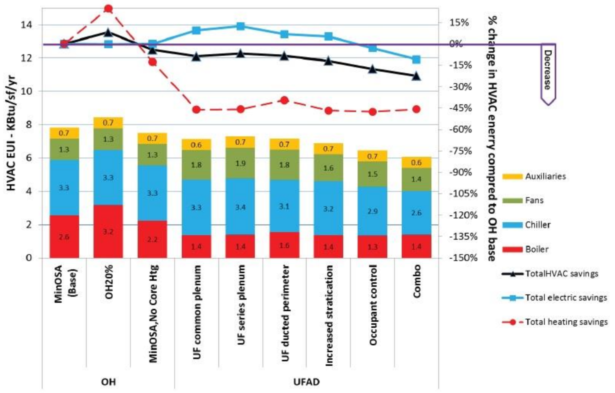

Fig. 4 EnergyPlus Simulation Results

2.1 Methodology

DesignBuilder Software (version 3.0.0.105) is used for creating 3D models of buildings and is also used to perform energy simulations. Minitab 15 is used for collected data and also used for analyzing and displaying data.

Schematics for the Schaefer engineering library were obtained from the Department of Design and Construction Management located in the Montebello complex. The schematics included 1st floor plan view, building sections, wall sections, etc. Figure 5 is the 1st floor plan view of the Schaefer engineering library.

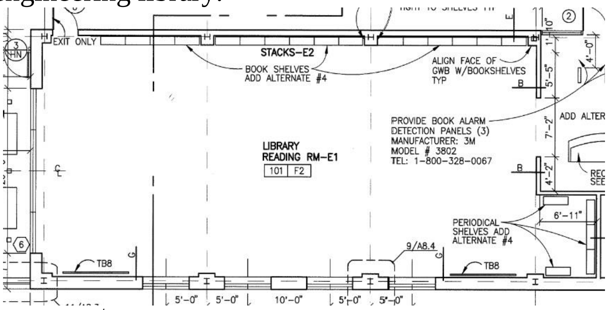

Fig. 5 1st Floor Plan View of Schaefer Engineering Library

Table 1. Schaefer Engineering Library Data

Type	Dimensions
Square Footage	1,839 ft.
Windows (4)	5 ft. 5 in. x 6 ft. 7 in.
Door	3 ft. x 7 ft.
Door opening	7 ft. x 8 ft.
Curtain Wall	19 ft. x 9 ft. 3 in.

Table 1 shows the Schaefer Engineering Library Data.The library has three hot water radiators to heat along the perimeter by the windows. It also has eight ceiling diffusers and three ceiling returns. There are 27 2 ft. x 4 ft. recessed fluorescent light fixtures and 15 down lights.

The Chilled water plant provides the cold water for the cooling coils in the AHU and VAV. Figure 6 is the schematic for AHU #8 that provides the conditioned air to the Schaefer engineering library.

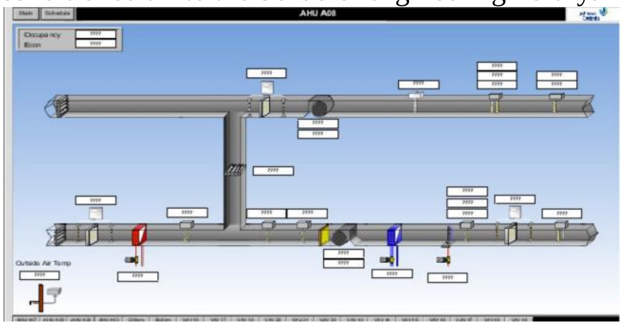

Fig. 6 Schematic Diagram of Air Handling Unit (AHU)

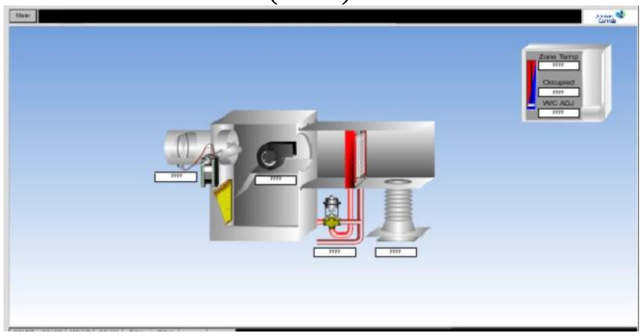

Fig. 7 Schematic Diagram of VAV

Figure 7 is the schematic for the VAV that delivers the conditioned air into the library.

2.1.1 Desiccant Wheel and Energy Recovery Wheel Applications

Desiccant wheel (DW) is a kind of heat recovery system, which is a honeycomb circular matrix for moisture absorption to remove humidity from the air. DW slowly rotated with in a system by a small electric motor and spins the desiccant coating on the wheel absorbs the humidity in the airstream. HVAC systems with DW are more energy efficient, with a low ambient impact, and can be profitable if compared to the traditional system. And also allows a better indoor air quality [9]. It will be used in refrigerated warehouses, schools, hospitals, supermarkets etc.

Energy Recovery wheel or Enthalpy wheel transfers sensible and latent heat between an exhaust and supply air stream on a building [10]. Inside the also have some silica gel or molecular sieve which is same as the desiccant wheel to absorb some moisture. Then indoor air quality will be increased by remove the humidity. It will be used in schools, hospitals, theaters etc.

3 Results and Discussion

The HVAC system is designed to resemble the HVAC system conditioning the Schaefer engineering library. It has a boiler, which supplies the hot water to the heating coils, a chiller which supplies the cold water to the cooling coils, a condenser which condenses the refrigerant back to liquid, an AHU which supplies the conditioned air to the library zone, and a VAV with reheat to control the dry-bulb temperature in the library zone. All of these components are either connected by the hot and cold water supply and return and/or duct Plenum objects in the model serve the function of actual plenums for supply and return air. Data for various parameters obtained from the Morgan State Plant personnel were entered for each component. Figure 8 shows the HVAC system.

According to Douglas Montgomery, a factorial design means "that in each complete trial or replicate of the experiment all possible combinations of the levels of the factors are investigated" [8]. Determining the "main effect" is our goal. The main effect "refers to the primary factors of interest in the experiment" [8]. As mentioned earlier, factors can have multiple levels. An "interaction" occurs when the "difference in response between the levels of one factor is not the same at all levels of the other factors" [8].

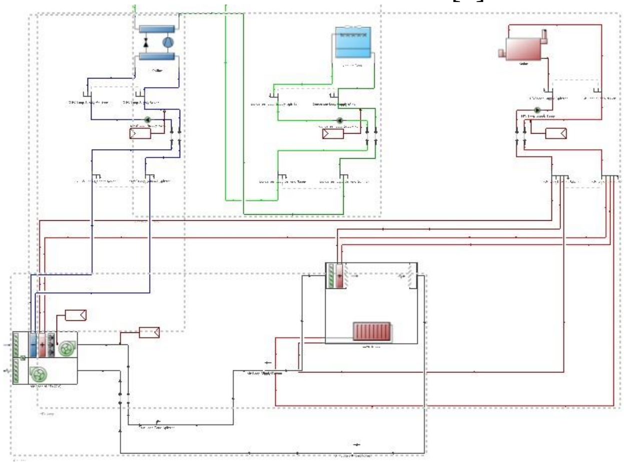

Fig. 8 HVAC System for Overhead VAV 3D model

For the energy simulation experiments, a 2^5 factorial design will be used.

The five factors will be fan efficiency, motor efficiency, setpoint temperature, dehumidification setpoint, and humidification setpoint. Each factor will have two levels, a "high level" and "low level." For fan efficiency, the high level is 70% and the low level is 50%. For motor efficiency the high level is 90% and the low level is 70%. For setpoint temperature, the high level is 72 °F and the low level is 68 °F. For the dehumidification setpoint, the high level is 65% and the low level is 55%. For the humidification setpoint the high level is 30% and the low level is 20%.The following table shows the factors and their combinations:

Table 2. Design of Experiments

Run	Fan Efficiency	Motor Efficiency	Setpoint Temperature	Dehumidification Setpoint	Humdification Setpoint
1	50	70	68	55	20
2	70	70	68	55	20
3	50	90	68	55	20
4	70	90	68	55	20
5	50	70	72	55	20
6	70	70	72	55	20
7	50	90	72	55	20
8	70	90	72	55	20
9	50	70	68	65	20
10	70	70	68	65	20
11	50	90	68	65	20
12	70	90	68	65	20
13	50	70	72	65	20
14	70	70	72	65	20
15	50	90	72	65	20
16	70	90	72	65	20
17	50	70	68	55	30
18	70	70	68	55	30
19	50	90	68	55	30
20	70	90	68	55	30
21	50	70	72	55	30
22	70	70	72	55	30
23	50	90	72	55	30
24	70	90	72	55	30
25	50	70	68	65	30
26	70	70	68	65	30
27	50	90	68	65	30
28	70	90	68	65	30
29	50	70	72	65	30
30	70	70	72	65	30
31	50	90	72	65	30
32	70	90	72	65	30

Following is the procedures of data collection.

1. Look at the combination of factors, i.e. fan efficiency level.
2. Adjust the parameters for the components in the HVAC model according to the combination of factors.
3. Click on the simulation tab and set it for an annual run.
4. Run the annual simulation.
5. Look at the results.
6. Repeat steps 1-5 until all experiments are complete.

3.1 Result and Discussion

Table 3. Heating and Cooling Design Calculations for Overhead VAV System

Design Calculations	Btu/h
Heating	50.820
Cooling	49.40

Table 4. Heating and Cooling Design Calculations for UFAD System

Design Calculations	Btu/h
Heating	51.85
Cooling	58.80

Tables 3 and 4 show summary of heating and cooling design calculation for overhead VAV and UFAD systems respectively.

The mean for the overhead VAV system is: 149,588.75 kBtu. The mean for the UFAD system is: 118,884.38 kBtu. The UFAD system is ~ 20% more energy efficient than the overhead VAV system. The statistical results of two-sample T for OHVAV vs UFAD is summarized in Table 5.

Table 5. Summary of 2-Sample T-Test

	N	Mean	StDev	SE Mean
OHVAV	32	149589	16884	2985
UFAD	32	118884	11021	1948

According to the results from the 2-sampe t-test, since $p < 0.05$, there is a significant difference in the mean and therefore the null hypothesis is rejected. The alternative hypothesis is therefore true.

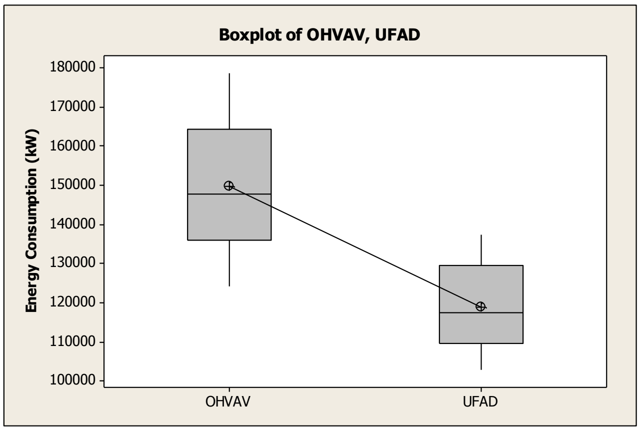

Fig. 9 Boxplot for Energy Consumption

Figure 9 further confirms the previous results as the mean energy consumption of the UFAD system is much lower than that of the Overhead VAV system.

Table 6. Source of Analysis of Variance(ANOVA) for C10 (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	3714620312	3714620312	742924962	562349.01	0
2-way Interact -ions	10	50839839	50893839	50839839	38.27	0
Residu -al Error	16	21138	21138	1321		
Total	31	3765481289				

Table 6 shows different types of ANOVA sources for C10. According to the ANOVA results in Table 7, $p < 0.05$ for the main effects and $p < 0.005$. Therefore, one or more the individual factors has a significant effect on energy consumption. Also, the 2-way interaction indicates that interaction of two factors has a significant effect on energy consumption.

Table 7. Summary of ANOVA Results

sTerm	Coef
Consta nt	704867
A	**-4930.30 (Fan efficiency)**
B	-0.0000
C	**-8152.55 (Setpoint temperature)**
D	-0.0000
E	**886.279 (Humidification setpoint)**
A*B	0.0000000
A*C	**62.9723(Fan efficiency*setpoint temperature)**
A*D	0.000000
A*E	0.607475
B*C	0.000000
B*D	0.000000
B*E	0.000000
C*D	-0.000000
C*E	-4.02187
D*E	-0.000000

Simulation of DW for Schaefer Engineering library at Morgan State University

There are many different types and size for the desiccant wheel. First, the type of desiccant wheel depends on the relative humidity of the outside air or inlet air. Base on the average relative humidity in Baltimore area for summer (June, July, and August) is around 65.5% which is higher than 60%, the High Performance Silica Gel is determined by the following figure 10 of NovelAire brochure .

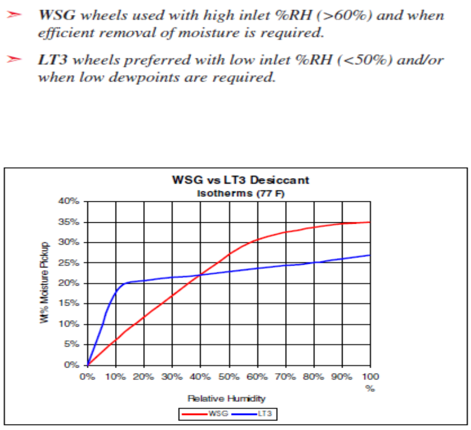

Fig. 10 Desiccant wheel Type

Then, Size of the desiccant wheel is designed by the desiccant wheel simulation software. The Schaefer Engineering library at Morgan State University has two VAV boxes and 8 diffusers which provide near 2163 cfm, and the return air is around 2000cfm which is half of them supposed to be used to regenerate the desiccant wheel. And Average temperature for summer is 74.8°F as shown in Table 8.

Table 8. Summary of DW Input Data for simulation

Outside Average Air Temperature	74.8°F
Outside Average Air Relative Humidity	65.5%
Supply Air Flow Rate	2163cfm
Return Average Air Temperature	72°F
Return Average Air Relative Humidity	60%
Return Air Flow Rate	1022cfm

Simulation Result:
Fig 11 is the simulation result for the Schaefer Engineering library at Morgan State University.

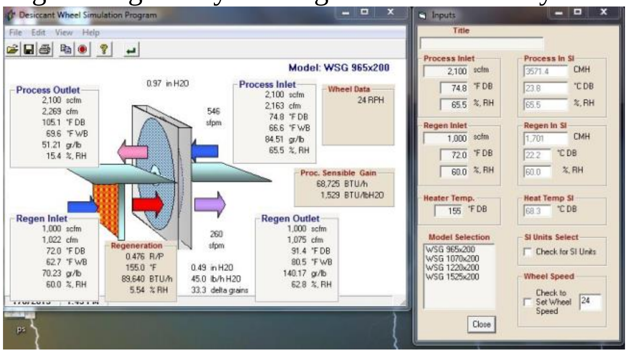

Fig. 11 Simulation Result

It provides the Model, humidity and regeneration energy consumption and more information.
Mode is WSG965*200 and Humidity is 15.4%, the Regeneration heat is 89,640BTU/h. Then from the Table 9 is Engineering detail data for WSG from the following Novel Aire DW brochure. Wheel Diameter is 965mm and the Wheel Depth is 200mm. And then the Drive Motor power is 1/80 Hp.

Engineering Detail

WSG High Performance Silica Gel Desiccant
LT3 Molecular Sieve Desiccant

NovelAire Model No.	Flow Rate (scfm) 75/25	Flow Rate (scfm) 50/50	Wheel Diameter (mm)	Wheel Depth (mm)	Cassette Height/Width A (inches)	Cassette Depth B (inches)	Approx. Total Wt. (pounds)	Drive Motor (Hp)
250	200	150	250	200	21	11.5	90	1/80
370	500	350	370	200	24	12	110	1/80
440	700	500	440	200	26	12	120	1/80
550	1000	750	550	200	29	12	150	1/80
770	2000	1500	770	200	36	12	220	1/80
965	3500	2500	965	200	43	13	290	1/80
1070	4500	3000	1070	200	48	13	330	1/80
1220	6000	4000	1220	200	54	13	410	1/40
1525	8500	6000	1525	200	69	14	790	1/40
1730	11000	7500	1730	200	77	15.5	1020	1/6
1940	14000	10000	1940	200	85	15.5	1370	1/6
2190	18000	12500	2190	200	96	17	1730	1/6
2438	22500	16000	2438	200	106	17	2000	1/6
2743	28000	20000	2743	200	122	18.25	2740	1/6
3050	35000	25000	3050	200	134	18.25	3390	1/6

Table 9. Engineering Data for Desiccant Wheel

According to the simulation results, the wheel diameter, depth is determined. Also DW could remove more than 50% the humidity.

4 Conclusion

UFAD system can offer improved ventilation effectiveness and indoor air quality by delivering fresh air supply through different types of floor diffusers to close occupants.

On average the energy consumption of the UFAD system is ~ 20% more energy efficient than the overhead air distribution system. The data was then entered into Minitab for statistical analysis. The 2-sample t-test results showed that the UFAD system was more energy efficient than the overhead air distribution system. An ANOVA test was performed and individual factors, such as fan efficiency as well as 2-way factor interactions had a significant effect on the energy consumption in the UFAD system.

Based on the simulation results, desiccant wheel will remove the humidity up to 50% which will be increased the IAQ easily. And also it will be save the thermal cooling power. Energy recovery wheel can also significantly reduce ventilation cooling and heating load. And also it will be improve the IAQ in the conditioned space.

Acknowledgements
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