DEVELOPMENT OF A DEDICATED OUTDOOR AIR SYSTEM (DOAS) MODULE FOR A WHOLE BUILDING ANNUAL ENERGY SIMULATION PROGRAM

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ABSTRACT

Dedicated outdoor air systems (DOAS) have been reported to improve indoor air quality and humidity level management, assist radiant cooling systems, and reduce HVAC energy consumption. Although models for HVAC outdoor air handling exists in whole building energy simulation programs, it was necessary to develop a new DOAS model for the whole building energy simulation program, EnergyPlus.

The developed model controls the unit operation not by zone thermal load, but rather by schedules which users set in the input and various control modes. The unit is configured to handle three different control types of outdoor air. It also allows multiple outdoor air units in a single zone that can be tied to unique exhaust fans. In addition, the unit has the flexibility not only to use various coil components and heat recovery systems, but also to configure the components in any order desired. This paper will outline the capabilities of the model and demonstrate them through case studies.

INTRODUCTION

Most building requires outdoor air for acceptable indoor air quality. Generally, the ventilation makeup air is combined with return air from the space, and a conventional forced air system like a constant air volume (CAV) or variable air volume (VAV) system heats or cools this combined air as needed before delivering it into the space.

Because ventilation requirments for individual zones do not always vary with thermal loads, especially under part-load condition, VAV systems do not always achieve good ventilation performance. As a result, VAV systems often require higher total ventilation air flows to provide acceptable zone vetilation (Dickmann, 2007).

CAV systems can encounter difficulties sometimes when trying to control indoor humidity levels when the space has low sensible loads but high latent loads. Under those conditions, the supply air flow remains constant and the system delivers supply air at higher temperatures than at full load. However, this operation condition decreases the dehumidification capacity and can prevent the unit from providing adequate dehumidification (Morris, 2003).

When a radiant panel cooling system is the main HVAC for a building, the ventilation requirement causes potential problems, particulary in hot and humid climate. The hydronic radiant cooling system does not have the ability to control the outdoor air itself. As a result, condensation might occur often on the panel surface when the outdoor air is directly supplied to the zone for ventilation. To avoid the condensation issue, the supply water temperature should be carefully controlled so that the panel surface temperature does not drop below the dew point temperature of the space. Under these conditions, the cooling capacity of the radiant cooling system decreases (Olesen, 1997).

A dedicated outdoor air system (DOAS) overcomes the issues mentioned above, by directly delivering the separately conditioned outdoor air to the each space or delivering it in conjunction with another HVAC system. Meanwhile, the primary HVAC units control sapce temperature by conditioning just recirculated indoor air. Decoupling the outdoor air from the recirculated return air makes it easy to verify sufficient ventilation of outdoor air as required by ANSI/ASHRAE Standard 62 (ASHRAE, 2004).

A DOAS also improves humidity manangement. In most climate areas, the moisture of the outdoor air accounts for the largest portion of latent loads. Consequently, separately conditioning the outdoor air from the internal cooling loads enables efficient removal of most of the outdoor air moisture load. It also enables application of sensible-only-cooling strategies, such as radiant cooling, even in humid climates if the building has a tight envelope and minimal indoor moisure sources (Jeong, et al, 2003, McDonell, 2008). It has been also reported that a DOAS can save energy in various ways for a primary HVAC system such as a VAV or CAV.

Although EnergyPlus is an existing whole building energy simulation program and has numerious system models to predict HVAC performance on an annual basis, it was necessary to develop a new model for the dedicated outdoor air system.

The building energy simulation program offers a outdoor air handler which is a type of subsystem for a central air system, AirLoopHVAC:OutdoorAir-System (DOE, 2009). Even though this model can evaluate most typical outdoor air handling situations, it encounters difficulties when trying to simulate a DOAS that delivers conditioned outdoor air to the zone directly and more than a single DOAS due to the current one-air-system limit in EnergyPlus. The existing model also does not simulate makeup air units for high-exhaust situations such as for kitchens and labortory exhasut hoods. In addition, it has a fatal flaw that it doesn't run if there is no thermal load in the zone.

Therefore, it was necessary to develop a new model to simulate the DOAS as an independent model to the primary HVAC for the whole building energy simulation program, EnergyPlus.

MODULE DEVELOPMENT

A DOAS may have several components such as heating/cooling coils, dehumidification units, heat recovery, and fans. While the system can have simply a single heating and cooling coil with supply fan, it might be composed of several equipment to control the outdoor air for specific control strategies (Bartholomew, 2004). In view of a whole building energy simulation program, the system model should have the flexiblity to respond to users' various needs.

Therefore, the developed DOAS model in EnergyPlus is designed to have flexibility in the type of components that make up the DOAS unit as well as their layout.

Structure of DOAS module in EnergyPlus

Basically, the definition of a DOAS system in EnergyPlus is composed of two inputs, the main system (ZoneHVAC:OutdoorAirUnit) and a equipment list input which has component information. In the system input, several key parameters to control the system such as the zone name, outdoor air (OA) flow rate and schedule, supply fan position (draw or blow through type), OA control type, and several air node identifiers are required. In the equipment list input, the user is asked for a list of components giving both component name and type. This equipment list specifies all the components that will be simulated in the DOAS. The order of components in this list is significant because components are simulated sequentially in the order given in the list. Figure 1 illustrates an overall system diagram of the DOAS system in EnergyPlus.

The component name and type in the list should be identified with the object name and type in EnergyPlus input. For the object input, it has actual performance data and thermal properties for the component. When a user wants to include a water cooling coil in the system, for instance, they will be required to define informantion about the coil such as water nodes, air nodes, and water flow rate conditions in the water coil object.

The components in this list are connected to each other internally by air nodes. The air outlet condition data of one component is transferred to an air inlet node conditon of the next component. For heat recovery, it has four different nodes, two of them are connected with the zone exhaust stream and the rest are placed in supply air path. The structure of the DOAS, which mimics a "Plug in and Play" layout, allows user the flexibility to combine components for any DOAS system.

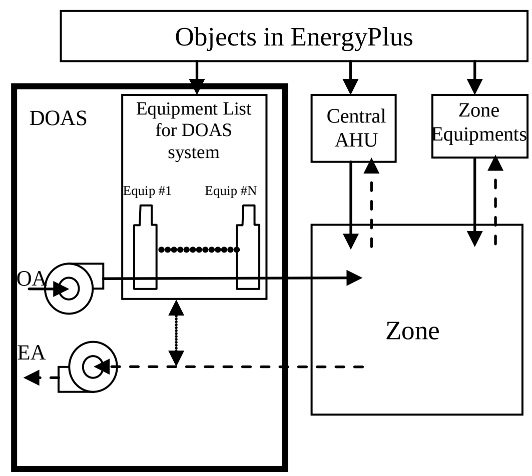

Figure 1 Diagram of a DOAS unit in EnergyPlus

In addition, it allows the user to have multiple coils of the same type. For example, a DOAS system in EnergyPlus may have two water heating coils, one which is linked with a solar water heating system or ground heat pump and the other connected with a conventional water heater system. The second coil will be operated only when the first one is not able to provide enough conditioning to meet the setpoint condition for the outdoor air.

In particular cases such as a kitchen or a laboratory, more than one outdoor air handler may be needed. The new model enables the user to utilize more than one system for a single zone. Each system can have an unique exhaust fan to maintain the air flow balance for the zone ,or it can rely on the zone exhuast fan without a DOAS system exhaust fan.

As with other zone level equipment in EnergyPlus, it can be integrated with not only other zone equipment such as radiant system, unit ventilator, and fan-coil unit, but also central air-conditioning systems like VAV and CAV.

Outdoor air control options

The unit control type determines based on the conditions in the zone being served what the response of the DOAS will be. It is important to note that this only controls the temperature of the air being delivered to the space not whether or not the system will operate. There are three options for this field: Neutral, Uncontrolled, or Temperature. Neutral Mode delivers outdoor air at the temperature of the zone. Uncontrolled Mode delivers outside air without any conditioning. Temperature Mode delivers tempered outdoor air between a high or a low temperature defined by user input.

Neutral control tries to have no energy impact on the zone by delivering air at the temperature of the zone. This allows air to be delivered to the zone without affecting the zone air heat balance and thus provides outside air without impacting any other system providing conditioning to this zone.

The temperature control option will supply air to the zone based on the high and low air control temperature schedules. For temperature control, when the OA temperature is less than the low air control temperature, the system will provide whatever heating is available from its components to achieve the low air temperature value. When the OA temperature is above the high air control temperature, the system unit will provide whatever cooling is available from its components to achieve the high air temperature value. For this control option, the outdoor air is delivered to the zone without conditioning if the OA temperature is floating between high control air and low control air temperature as illustrated in Figure 2.

Component load calculation and flow rate control

Once the design temperature is defined, the coil heating or cooling load is calcualted using Eq. (1)

$$q_{coil} = \dot{M}_{air} \cdot Cp_{air} \cdot \left(T_{coil_{in}} - T_{DGN}\right) \qquad (1)$$

Where, $\dot{M}_{air}$ is the mass flow rate of the outdoor air, Cp_{air} is the specific heat of the air, and $T_{coil\_in} - T_{DGN}$ is the temperature differential between the inlet node of the coil and the design air condition. The temperature of the supply air (T_{DGN}) is re-adjusted to consider the fan heat generation effect for the draw through type supply fan when it is the last equipment in series of the system.

The supply air flow rate is controlled via the maximum outdoor air flow rate and fraction schedule which contains values for modifying the outdoor air flow rate. The supply air flow rate is the product of the outdoor air flow rate and the outdoor air schedule value for the time of interest.The exhaust flow rate can also be controlled via a flow rate control schedule.

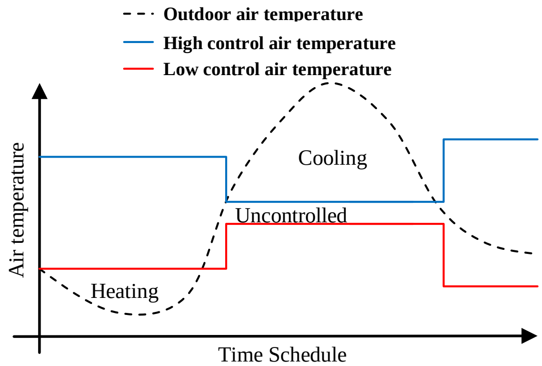

Figure 2 Operation condition by high/low control temperature schedule and outdoor air temperature

CASE STUDY DESCRIPTION

A simple single story office building was selected to verify that the developed model presented in the previous section has been appropriately implemented in the whole building energy simulation program and to investigate the system capability under several configurations.

The building has five different thermal zones as shown in Figure 3 and each zone has a unique DOAS that has different component layouts as shown in Figures 4-8. While zones 1-4 have a single unit to handle outdoor air, zone 5 has two different units to test a multiple unit configuration in a space using sequential control.

In all cases except zone 4, the DOAS systems are the only systems serving these zones. While in most configurations the DOAS system would not act alone, this was done in this case to highlight the performance of the DOAS model.

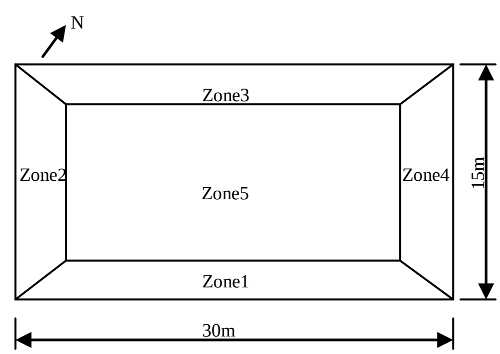

Figure 3 Geometry and horizontal zoning of the sample building

The office occupancy is assumed to be 10m²/person (170ft²/person), and the occupied periods last from 8 a.m. to 5 p.m. During occupied hours, internal heat gain by lighting and equipment is assumed to be 13.5W/m² (1.2 watt/ft²) and 10 W/m² (0.75 watt/ft²), respectively. Infiltration is kept at 0.33 ACH constantly during all 24 hours of the day.

For the ventilation flow rate, ASHRAE Standard 62.1 –2004 provides the minimum ventilation rates and governs the design outdoor air requirements (ASHRAE, 2004). It includes a list of occupancy categories and the required minimum outdoor air rates (V_{bz}) per person and per floor area for the zones that can be calculated using the following equation (2).

$$V_{bz} = R_p P_z + R_a A_z \qquad (2)$$

Where R_p is the outdoor air flow rate per person, P_z is the zone occupant population, R_a is the outdoor airflow rate per unit area, and A_z is the zone floor area. Table 1 illustrates the unit control options and ventilation rate of each zone.

Table 1 OA control options and outdoor air flow rates

Case (zone)	**Control option**	**Control Temp.**	**OA flow rate [CMM]**
1	Neutral	Zone mean air temperature	3.22*
2	Temp.	Unoccupied : 27 °C Occupied : 24 °C/ 20 °C	5.92
3	Temp.	Occupied : 15 °C (for dehumidification)	3.22*
4	Neutral	Zone mean air temperature	1.48*
5-1	Temp.	Occupied : 20 °C	5.92
5-2	Neutral	Zone mean air temperature	2.96*

*minimum ventilation rate by the Eq(2).

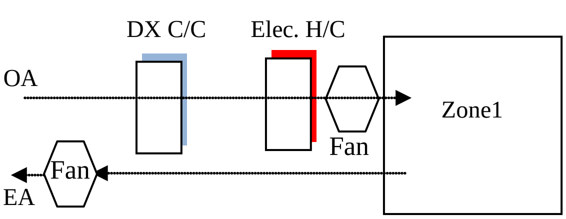

Figure 4 System configurations (CASE1)

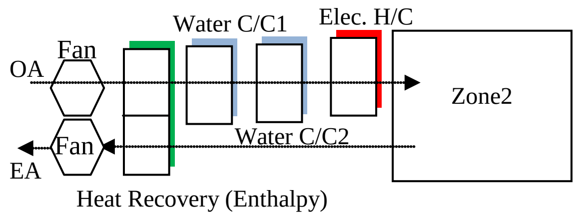

Figure 5 System configurations (CASE2)

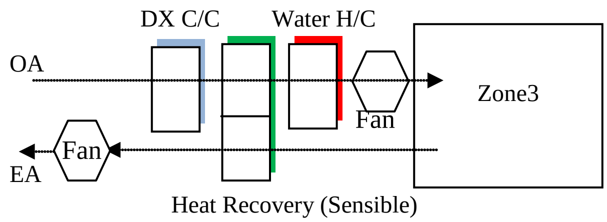

Figure 6 System configurations (CASE3)

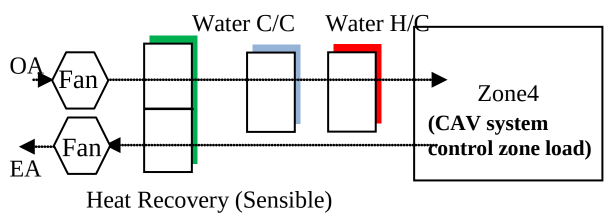

Figure 7 System configurations (CASE4)

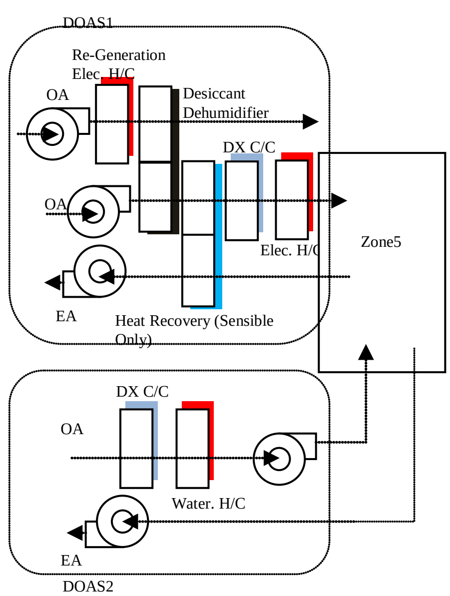

Figure 8 System configurations (CASE5)

RESULTS

System operation control

For case 1, the DOAS has a simple DX cooling and electric heating coil, and the outdoor air is controlled by the zone mean air temperature during occupied hours. Because case 1 is only served by a DOAS, the space air temperature is mostly higher than the outdoor air temperature for the cooling design day, so the outdoor air actually needs heating as shown in Figure 9. This means that unit control for the developed model is independent of the zone thermal load condition, and it is only controlled by the set point conditions as presented in the previous section.

Multiple coils with the same type for different control air temperature

Case 2 has two water cooling coils and an electric heating coil incorporated with total heat recovery. It has been assumed that the zone requires high ventilation rates (4 ACH) all day long with different control air temperatures during occupied time as illustrated in Figure 11.

The high control air temperature is set as 27°C for unoccupied hours, 24°C for 08:00~12:00, and 20°C for 12:00~17:00, respectively. From 0:00 to 07:00, the outdoor air was below the high control air temperature (27°C), so the outdoor air is delivered directly to the zone without conditioning. When the first water cooling coil failed to condition the outside air to the set point control temperature in occupied hours, the second water cooling coil started to take over the remaining load. Although even load sharing is not allowed in this model, each water coil can be manipulated by controlling its water flow rate. The total coil cooling rates for each water coil is illustrated in Figure 12.

Dehumidification control

In a hot and humid climate, there are times when the air outlet temperature of the dedicated outdoor air unit would be lower than the space temperature so as to remove moisture from the outdoor air. In this case, the conditioned air often must be reheated to avoid occupant discomfort and overcooling (Murphy, 2006).

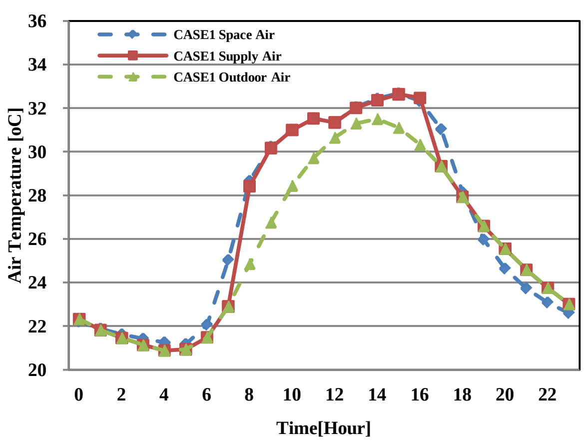

Figure 9 Hourly air temperature profiles for cooling design day (CASE1)

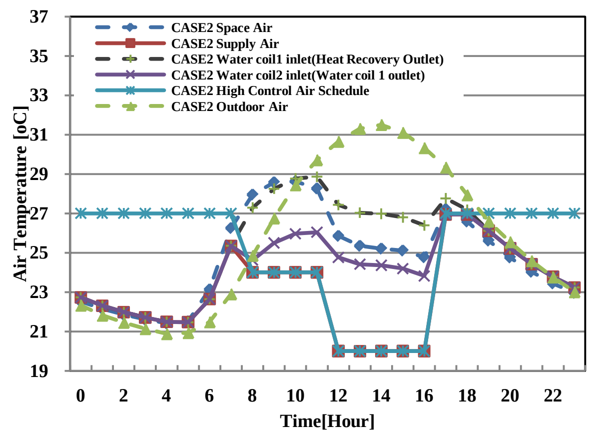

Figure 11 Hourly air temperature profiles for cooling design day (CASE2)

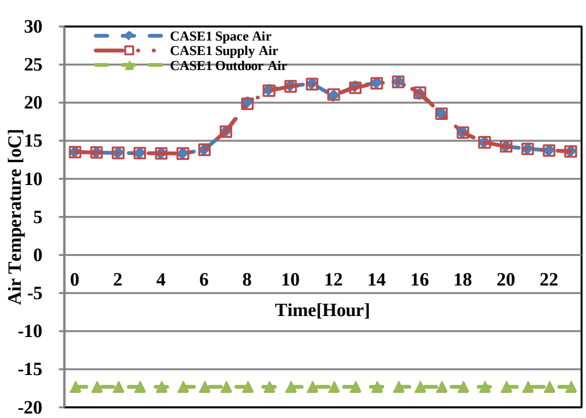

Figure 10 Hourly air temperature profiles for heating design day (CASE1)

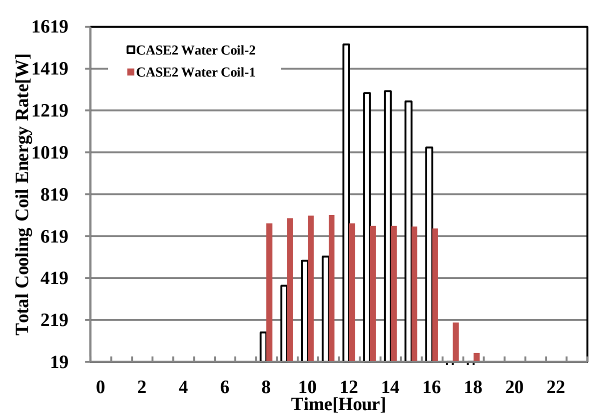

Figure 12 Hourly cooling coil energy rate of each water coil for cooling design day (CASE2)

Case 3 has a single DX cooling coil, water heating coil, and heat recovery. A sensible heat recovery with 0.65 for nominal efficiency is placed between the cooling and heating coil to recover heat from the exhaust to the supply air stream.

The outdoor air control temperature is set as 15°C to control humidity level. The temperature and humidity ratio of the outdoor air are reduced passing through the DX cooling coil. The dehumidified outdoor air is reheated back somewhat by the sensible heat recovery to close to the space air temperature. Although the supply air temperature is different than the set point condition due to the sensible heat recovery, the system delivers the conditioned outdoor air without additional treatment, once the outdoor air temperature set point condition is met by the heating or cooling coil. As illustrated in Figure 13 and 14, the zone mean air temperature and relative humidity ratio ranged from 25.2-29.3°C and 50-60%, respectively during occupied hours.

The DX cooling coil outlet temperature is not stable at the set point, but ranged from 13.23°C to 16.21°C. The DX cooling coil model in EnergyPlus is based on the rated total cooling capacity, the rated sensible heat ratio (SHR), the rated COP, and the rated air volume flow rate. The rated air volume flow rate should be between 0.4027E-4 m^3/s and 0.6041E-4m^3/s per Watt of rated total cooling capacity (DOE, 2009). For this case, as it did not fall within these bounds, the coil outlet temperature could not be controlled exactly as desired due to the low flow rate. For real world applications, the actual parameters of the installed DX coil system should be used.

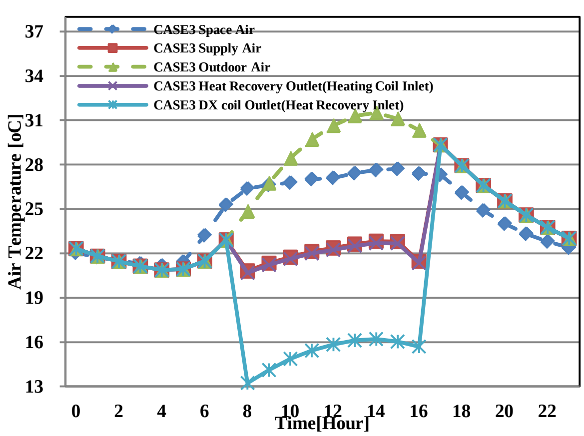

Figure 13 Hourly air temperature profiles for cooling design day (CASE3)

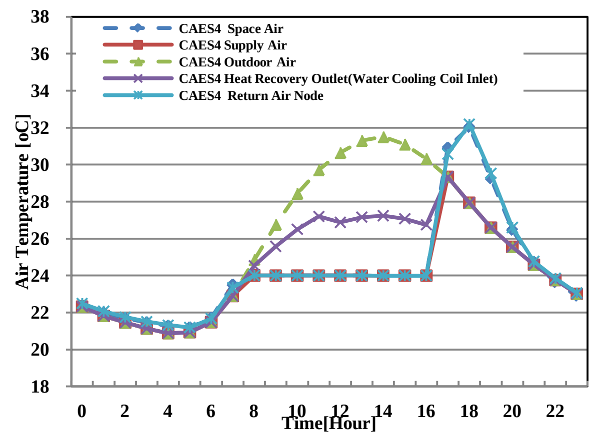

Figure 15 Hourly air temperature profiles for cooling design day (CASE4)

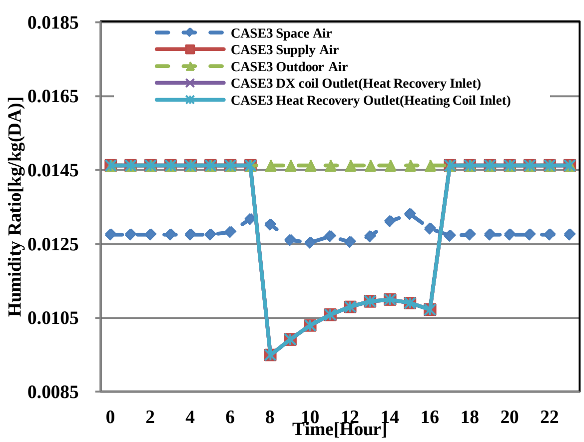

Figure 14 Hourly humidity ratio profiles for cooling design day (CASE3)

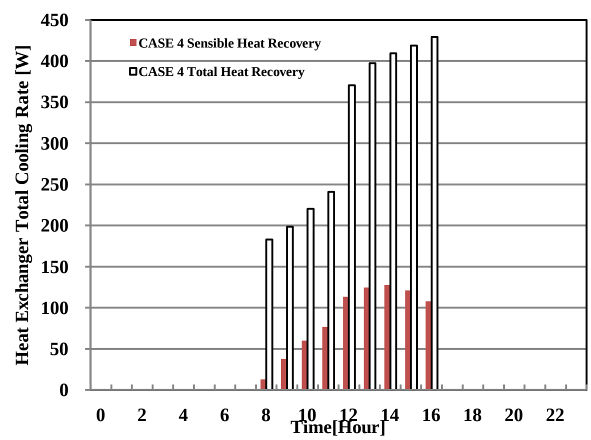

Figure 16 Hourly cooling rates by each heat recovery type for cooling design day (CASE4)

Incorporation with other HVAC equipment

Case 4 has a typical unitary system with a constant air volume (CAV) system for controlling zone thermal loads. The CAV system works in conjunction with a dedicated outdoor air unit that has a water heating coil, a cooling coil, and heat recovery. According to the equipment list order in EnergyPlus, the CAV system is running prior to the DOAS in a particular time step. During occupied hours as shown in Figure 15, the CAV system responds to the zone thermostat (24°C), and the DOAS supplies the minimum ventilation requirement at the zone temperature. Figure 16 also shows that the total heat recovery has better performance than the sensible type when the temperature and moisture has a large differential between the outdoor air and space air.

Multiple units in a single zone

For a typical case like kitchen or laboratory conditioning, it may be necessary to utilize multiple outdoor air handlers. Case 5 has two different DOAS units with sequential control. The first system is composed of a desiccant dehumidifier, sensible heat recovery, a DX cooling coil, and an electric heating coil. The dehumidifier with no fan option, a compound object in EnergyPlus, is a solid desiccant dehumidifier that has two companion components, a gas heating coil for re-generation and a supply air fan.

The outdoor air is heated up and dried by the dehumidifier, and sensible heat recovery decreases the air temperature without humidity transmission. After that, the DX cooling coil takes over the remaining cooling requirement. The outdoor air has additional dehumidification by DX coil as shown in Figure 18 and 19. The second system has a simple configuration: a DX cooling coil and a water heating coil only. The system is controlled by the neutral control option for outdoor air, and the results can be seen in Figure 20.

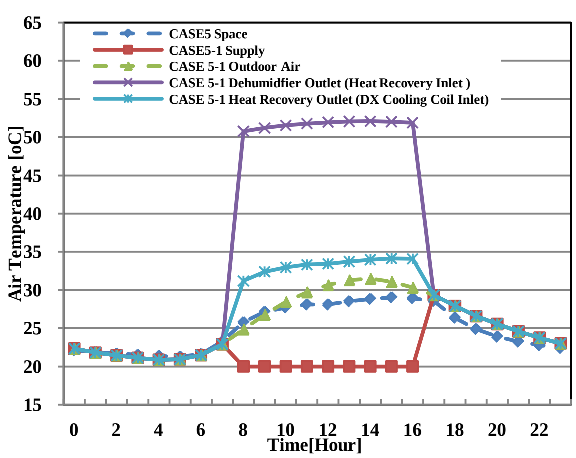

Figure 17 Hourly air temperature profiles for cooling design day (CASE5-1)

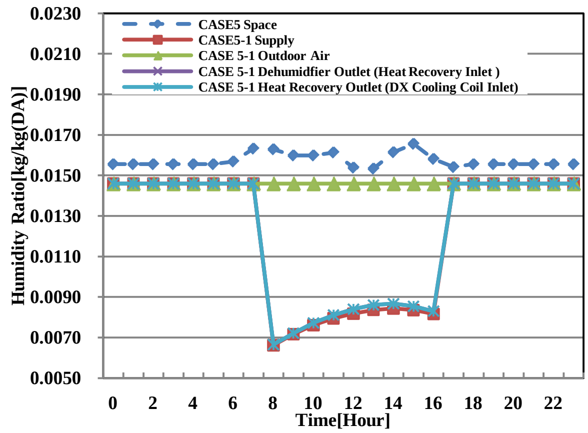

Figure 18 Hourly humidity ratio profiles for cooling design day (CASE5-1)

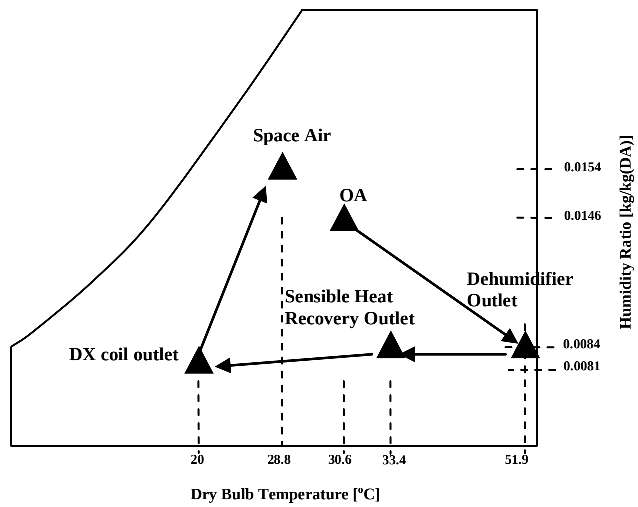

Figure 19 Outdoor air properties changing at 13:00 for cooling design day (CASE5-1)

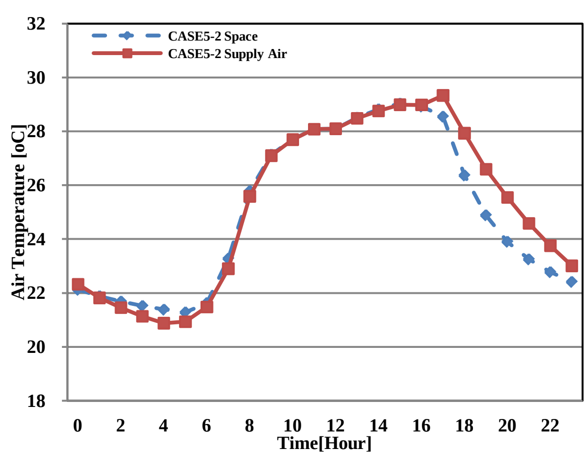

Figure 20 Hourly air temperature profiles for cooling design day (CASE 5-2)

CONCLUSION

This introductory paper has described a new simulation model for a dedicated outdoor air system for a whole building energy simulation program and has tested its implementation into the program as well as the capabilities of the model for various configurations.

The developed model is designed to:

- deliver conditioned outdoor air to the zone directly
- control the DOAS by a defined schedule input, not by zone load
- enable the user to control the outdoor air to zone air temperature or a control air temperature schedule defined by input
- allow the user the flexiblity to select various heating and cooling components
- enable the user to set the supply and exhaust air flow rate
- allow the incorporation with other local HVAC systems or equipments
- control the operation of mutiple units using sequential control for a single zone

The implementation of this new model into a whole building energy simulation program was investigated via simple case studies in which the developed model controlled the system and the outdoor air by schedules defined in the simulation input file. In addition, it was also demonstrated that the new model can be used in conjunction with other HVAC systems in EnergyPlus.

While the sample test cases presented in this paper are only for design days in a simple climate, it is possible to use the model for any length of time including an entire year, for any climate, and in any configuration of vaild components beyond the five configurations shown in this paper.

Future work with this model will include investigations into the use of DOAS systems with radiant heating and cooling systems, analysis of the overall energy impact over an entire year, and optimization of the system configuration for minimum energy use. Finally, future model improvements include using the model to control for strictly sensible or latent loads or potentially for total load performance.

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REFERENCES

ASHRAE, 2004, ANSI/ASHRAE Standard 90.1-2004, Energy standard for buildings except low-rise residential buildings, American Society of Heating Refrigerating and Air-Conditioning Engineers INC, atlanta, USA

Bartholomew, P., 2004. Saving Energy In Labs, ASHRAE Journal, 46(2):35-40

Dickmann, J., Roth, K.,Brodiric, J., 2007. Dedicated outdoor air systems revisited, ASHARE Journal, 49(12):127-129

DOE, 2009, EnergyPlus:Input Output reference, Version 4.0, Department of Energy

Jeong, Mumman, and Bahnfletch. 2003, Energy conservation benefits of a dedicated outdoor air system with parallel snesible cooling by ceiling radiant panels, ASHRAE Transactions 109(2):627-636

McDonell, G., 2008, Is Radiant Cooling an option?, ASHRAE Journal, 50(4):46-52

Murphy, J., 2006. Smart dedicated outdoor air systems, ASHRAE Journal.

Morris, W. 2003. The ABCs of DOAS:dedicated outdoor air systems, ASHRAE Journal, 45(5):24-29

Olesen, 1997, Possiblities and limitations of radiant floor cooling, ASHRAE Transactions, 103(1):42-48