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Energy efficiency and indoor climate benefits of demand-based ventilation in simulated office rooms

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Abstract. The demand for high energy efficiency of office buildings with an increasing focus on safety and good indoor air climate has increased the use of demand-based HVAC systems. The varying occupancy of office spaces can lead to unnecessarily high ventilation airflow rates and cooling of the room when there are no occupants. To achieve the same level of indoor climate with a more traditional ventilation system causes high energy consumption and inefficient operation of the HVAC system. A comparison of three active chilled beam systems was made with energy simulation software for finding the best performing room configuration in realistic operating conditions. Office room and meeting room cases) were simulated with 1) traditional CAV (Constant Air Volume) ventilation system, 2) BCV (Boost Controlled Ventilation) system with 2 automatic operating modes and 3) DCV (Demand-Controlled Ventilation) system with 3 automatic operating modes. For BCV and DCV systems same active chilled beam unit was used for office and meeting room cases to highlight the possibility of office layout changes without additional modifications to the ventilation system. CAV ventilation system required change between two different chilled beam units for office and meeting room cases to maintain the same level of indoor climate. Energy consumption, indoor climate conditions, and cooling system operation were simulated. The office building was located in a middle European temperate climate and had generic building materials and energy-efficient window characteristics Operation of demand-based ventilation system control logic for controlling airflow rates was studied between CO2 control and CO2 control with added presence control. The most energy-efficient solution was DCV system having 3 operating modes as the energy savings based on the ventilation airflow rates required at minimum operating mode is large compared to normal or maximum operating mode. With BCV active chilled beam ventilation system having 2 operating modes, energy efficiency can be increased notably compared to CAV active chilled beam ventilation system. BCV ventilation system could have performed with lower energy consumption for office room case if the active chilled beam was designed to be used for only office room operation, and not for meeting room operation as well.

Keywords. Demand-based ventilation, chilled beam, energy efficiency, office building
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1. Introduction

The demand for high energy efficiency of office buildings with an increasing focus on safety and good indoor air climate has increased the use of demand-controlled ventilation (DCV) systems [1,2]. Demand-based ventilation systems' energy saving potential for offices is highly dependent on occupancy, which can vary between 15% to 80% for average day time office [3,4]. This paper presents an energy simulation study between three different active chilled beam (ACB) systems for simplified office and meeting room cases. It compares cooling load, HVAC energy consumption, and indoor environmental quality (CO_2, air age, and temperature) for finding a safe and most energy-efficient system.

2. Methods

2.1 Simulation model

IDA Indoor Climate and Energy 4.8 (IDA-ICE) simulation tool was used in the study for assessment of indoor climate and energy performance.

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Performance of three different active chilled beam systems was compared: 1) Traditional CAV (constant air volume) ventilation system manually adjusted and designed to office or meeting room situation 2) BCV (boost-controlled ventilation) system with two operating modes where boost airflow rate is automatically controlled based on room CO_2-level and temperature 3) DCV (demand-controlled ventilation) system with three operating modes automatically controlled based on occupancy, room CO_2-level and temperature.

The simulation model in the study consisted of a single room used as a two-person office room (10.9 m^2/person) or as an eight-person meeting room (2.7 m^2/person). The model had one external wall with two windows that was directed to south, and all other surfaces were internal. The net heat transmission through internal surfaces was ignored. The office building located in middle European temperate climate and had generic building materials and energy-efficient window characteristics with solar shading. The geometry of the simulated room is presented in Fig. 1. Energy performance and indoor climate conditions were studied during the cooling season from May to September. The building construction data used in different simulation cases are presented in Table 1.

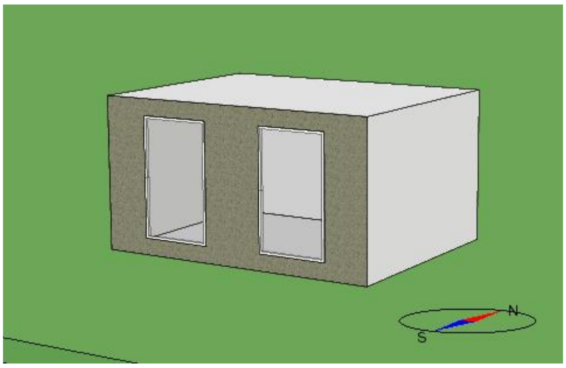

Fig. 1 – Geometry of simulated room

Tab. 1 – Building construction details

Building construction details	
Main building data	Paris weather data, 1 office room with orientation to south
Room data	5.3 m wide, 4.1 m long, floor area 21.7 m^2, 2.8 m high, one external wall (other internal)
Window size	two 1.3 m wide, 2.2 m high windows located 0.3 m from the floor (38.5 % of external wall area)
Window performance	U=1.1 W/(m^2, K), g=0.37, T_{vis}=0.7 Frame with U=2.0 W/(m^2, K)
Solar shading	Blind between panes, multipliers for U=0.87, g=0.39, T=0.12
External wall heat conductivity and material layers from inside	0.54 W/(K, m^2), render 0.01 m, concrete 0.25 m, render 0.01 m
Internal wall conductivity and material layers from inside	0.62 W/(K, m^2), gypsum 0.026 m, air gap 0.032 m, light insulation 0.03 m, air gap 0.032 m, gypsum 0.026 m
Internal floor material layers from inside	coating 0.005 m, concrete 0.25 m
Infiltration	Wind-driven 0.5 ACH at 50 Pa

Internal heat loads during office hours consisted of occupants, equipment, and lighting. Heat loads were simulated for office and meeting room cases based on the number of occupants. The occupancy schedule for office and meeting room cases was based on EN16798-1 standard's occupancy schedules for energy calculation [5]. Smoothing of ± 12 minutes was used for all schedules. Operating data used in different cases for internal heat loads and occupancy schedules are presented in Table 2.

Tab. 2 – Operating data of internal heat loads

	Office	**Meeting room**
Occupancy schedule during office hours Mo-Fri 6.00-20.00	Weekdays: 6-9 0.0 9-13 1.0, 13-14 0.0, 14-17 1.0 17-20 0.0	Weekdays: 6-9 0.0 9-10 0.5, 10-11 0.8, 11-12 0.9, 12-13 0.8, 13-14 0.0, 14-15 0.7, 15-17 0.8, 17-18 0.7 18-20 0.0
Heat loads	Number of occupants 2 (1.0 MET)	Number of occupants 8 (1.0 MET)
	Equipment load 13.8 W/m^2 (during occupancy)	Equipment load 27.6-49.8 W/m^2 (based on occupancy load)
	Lighting load 9.2 W/m^2 (during occupancy)	Lighting load 9.2 W/m^2 (during occupancy)

2.2 Active chilled beam systems

Modern active chilled beam systems with mixing ventilation were designed with manufacturer's design tool into office and meeting room cases with realistic performance data [6,7]. Traditional CAV ventilation system was designed with two different active chilled beam units for office room and meeting room cases to achieve good indoor climate conditions. For this ventilation system airflow rate was controlled based on AHU (air handling unit) operating schedule, maintaining designed office room and meeting room airflow rates.

BCV system with two operating modes was designed with a single chilled beam unit for both office and meeting room cases. The additional boost airflow controlled based on room CO_2-level and temperature was introduced for this system without boost airflow passing through the active chilled beam cooling coil. With the boost airflow, additional boost air cooling could be utilized when airflow rates were increased above normal operation. Airflow rates for BCV system was operated in two operating modes: 1) Normal airflow rate operation based on AHU operating schedule if room CO_2-level or temperature isn't above set limits 2) If room temperature with water cooling fully in use, or CO_2-level is above set limits, airflow rate is increased between normal and maximum airflow rate to maintain the desired room temperature and CO_2-levels.

DCV system with three operating modes was designed with a single chilled beam unit for both office and meeting room cases. For this system the additional air was introduced with supply air increasing room airflow circulation through the active chilled beam cooling coil, leading that water cooling is increased with additional air cooling. Airflow rates were controlled in three operating modes: 1) When no occupancy is detected in the room, airflow rate is decreased to the minimum level and room temperature setpoint is increased by 1°C 2) If occupancy is detected in the room and the room CO_2-level or temperature isn't above set limits, airflow rate is increased to normal operation 3) If temperature with water cooling fully in use, or CO_2-levels increase above set limits air flow rate is increased between normal and maximum airflow rates to maintain the desired room temperature and CO_2-levels.

Ventilation airflow rates for different simulation cases fulfilled airflow rate requirements in standard EN-16798-1 category 2 for low-polluting building. Due to SARS-CoV-2 recommendations room CO_2-levels were maintained at lower level than required in the standard [1]. Maximum room CO_2-level was limited to 800 ppm with studied occupancy schedule, and outdoor air CO_2-level of 400 ppm was used in simulation cases. With studied occupancy schedule this corresponds to maximum airflow rates of 1.4 l/s, m^2_{floor} for office room case and 3.7 l/s, m^2_{floor} for meeting room case. The operating parameters and cooling design of different HVAC systems are presented in Table 3.

Tab. 3 – Operating parameters and cooling design of HVAC system in office (O) and meeting room (M) cases

	Active chilled beam (CAV)	**Active chilled beam (BCV)**	**Active chilled beam (DCV)**
Cooling set-point (room air temperature)	25 °C		Occupied 25 °C Unoccupied 26 °C
Operating data of ventilation system (AHU)	Weekdays 6-20, 16 °C supply air		
Cooling water circulation	Only during AHU operating hours		
Supply air sensible cooling in design operation	(O) 15.1 W/m^2_{floor} (M) 40.6 W/m^2_{floor}	(O) 15.2 W/m^2_{floor} (M) 40.5 W/m^2_{floor}	*6.2 W/m^2_{floor} (O) 15.2 W/m^2_{floor} (M) 41.7 W/m^2_{floor}
Water coil cooling capacity in design operation	(O) 43.4 W/m^2_{floor} (M) 57.1 W/m^2_{floor}	53.2 W/m^2_{floor}	*28.1 W/m^2_{floor} (O) 43.1 W/m^2_{floor} (M) 58.9 W/m^2_{floor}

*DCV system minimum airflow operation.

3. Results

Energy performances of different ACB systems during cooling season (May to September) for office and meeting room cases are presented in table 4. DCV system showed the lowest energy consumption, most stable temperature conditions, and highest utilization of room water cooling (zone cooling).

AHU fan energy consumption in the office room case for the DCV system was 25% lower compared to the CAV ventilation system and 28% lower compared to the BCV system. BCV system had higher fan energy consumption than CAV system for office room case because airflow rates were increased during office hours briefly above normal operation to maintain the room temperature and CO_2-levels at setpoint values.

AHU fan energy consumption in meeting room case for DCV system was 53% lower compared to CAV ventilation system and 7% lower compared to BCV system. CAV system had noticeably higher energy consumption for meeting room case compared to BCV and DCV systems because airflow rates were at a constant maximum level compared to BCV and DCV systems which were able to decrease the airflow rates during unoccupied hours.

Differences for pump energy consumptions in office and meeting room cases were minor. DCV system had the lowest pump energy consumption for office room and meeting room cases.

Tab. 4 – Energy performances for different ACB systems in office (O) and meeting room (M) cases

	Active chilled beam (CAV)	**Active chilled beam (BCV)**	**Active chilled beam (DCV)**
Fan energy O	37.1 kWh	38.4 kWh	27.7 kWh
Fan energy M	201.2 kWh	101.6 kWh	94.3 kWh
Pump energy O	1.3 kWh	1.3 kWh	1.1 kWh
Pump energy M	3.4 kWh	3.1 kWh	3.0 kWh
*Electric cooling energy O	166.7 kWh	169.3 kWh	152.8 kWh
*Electric cooling energy M	434.8 kWh	429.9 kWh	424.2 kWh
Total electric energy O	205.1 kWh (100 %)	209 kWh (102 %)	181.6 kWh (89 %)
Total electric energy M	639.4 kWh (100 %)	534.6 kWh (84 %)	521.5 kWh (82 %)
Cooling energy (sensible and latent) O	Zone cooling: 102.4 kWh AHU cooling: 397.8 kWh	Zone cooling: 95.6 kWh AHU cooling: 412.3 kWh	Zone cooling: 149.0 kWh AHU cooling: 309.5 kWh
Cooling energy (sensible and latent) M	Zone cooling: 247.0 kWh AHU cooling: 1057.4 kWh	Zone cooling: 562.1 kWh AHU cooling: 727.6 kWh	Zone cooling: 611.4 kWh AHU cooling: 661.3 kWh

*COP (Coefficient of Performance) value of 3 was used.

Room air temperature stability curves for cooling season during office hours for different ACB systems in office room cases are presented in fig. 2 and for meeting room cases in fig. 3. X-axis in the fig. 2 and fig. 3 represents hours when the office is in use (office hours). Temperature didn't exceed the 25 °C room temperature setpoint in any ACB systems during office hours, in exception of DCV system which was controlled so that temperature could rise by 1 °C during office hours in unoccupied periods. DCV system showed the best temperature stability for office and meeting room cases. In the office room case DCV system temperature was below 25 °C setpoint for 400 h, compared to CAV and BCV systems which were below 25 °C setpoint for 600 h. In the office room case, CAV and BCV systems had similar temperature stability curves as the airflow rates during unoccupied hours were higher in both systems, leading to unnecessary cooling of the room.

The CAV ventilation system in the meeting room case had a temperature below 25 °C setpoint for 500 h, compared to the BCV system with 250 h and the DCV system with 150 h. In the meeting room case, BCV system performed better than in the office room case with a more stable temperature curve due to the possibility of airflow rate variation between normal and maximum airflow rates.

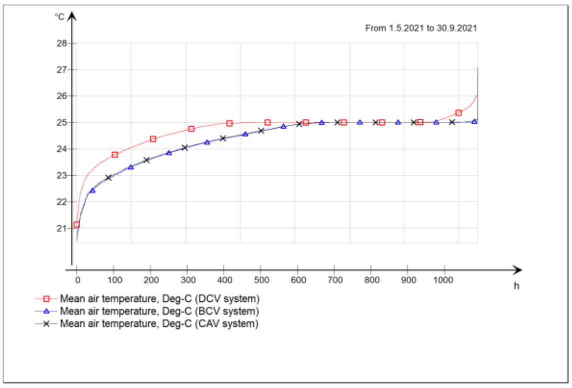

Fig. 2 – Temperature stability curves between different ACB systems during office hours for office room case

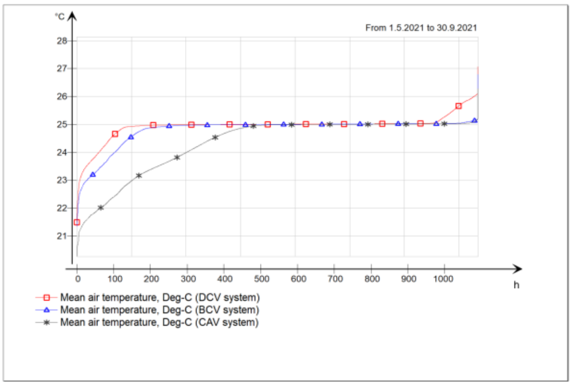

Fig. 3 – Temperature stability curves between different ACB systems during office hours for meeting room case

Ventilation airflow rates during design day for different ACB systems for office room cases are presented in fig 4. and for meeting room cases in fig 5. Ventilation airflow rates in office room cases show the minimum airflow rate operation for DCV system during unoccupied periods when both CAV and BCV systems stay on higher airflow rates. In the meeting room case, airflow rate trends for DCV and BCV systems are closer to each other, compared to the CAV ventilation system which has a constant maximum airflow rate. For meeting room case difference between DCV and BCV can be seen during unoccupied hours and after people leave the office, as the ventilation airflow rates can be lower in the DCV system.

CO_2-level setpoint for BCV and DCV systems in office and meeting room cases was 800 ppm. In all office and meeting room cases, CO_2-levels were maintained at setpoint levels. For office room cases CO_2-levels in all cases were at a maximum of 700 ppm, and for meeting room cases at a maximum of 800 ppm. For the DCV system morning flush operation was used where air flow rate was increased to normal operation for 2 h when AHU started to maintain better indoor air quality and lower age of room air. CAV ventilation system and BCV system showed similar air age for office room cases. CAV ventilation system had the lowest air age for meeting room case which was close to 0 h when occupants entered the room. DCV system had the highest air age for meeting room case which was close to 1 h when occupants entered the room.

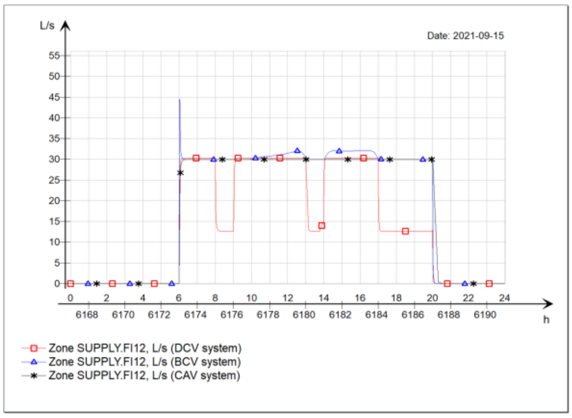

Fig. 4 – Ventilation air flows between different ACB systems during design day for office room case

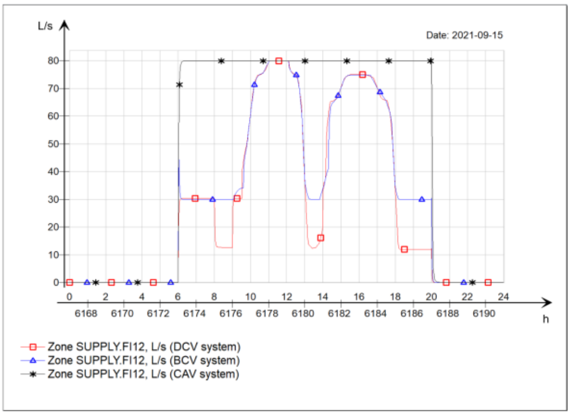

Fig. 5 – Ventilation air flows between different ACB systems during design day for meeting room case

4. Conclusions

The demand-controlled ventilation (DCV) system showed the best energy performance while maintaining good indoor climate conditions. Boost-controlled ventilation (BCV) system had similar fan energy consumption than CAV ventilation system for office room case but had only 7% higher energy consumption than DCV system for meeting room case. BCV system could have performed better in office room case if the ACB design was made only for office room operation, so the maximum (boosted) air flow rate would be the office room airflow rate. This highlights additional benefits of the 3 operating modes in the DCV system compared to the BCV system when the DCV system could operate with the lowest energy consumption in both cases while maintaining good indoor climate conditions. Constant air volume (CAV) ventilation system had highest fan energy consumption in meeting room case with 53% higher energy consumption than in DCV system and 50% higher than in BCV system.

Additional benefits of the DCV and BCV systems in the study were the use of the same chilled beam unit for both cases when the CAV ventilation system required different chilled beam units for office and meeting room cases. This highlights the adaptability of chilled beams for possible room layout changes without making additional adjustments to the active chilled beams or ventilation system. For CAV ventilation system chilled beams would require manual work to adjust the chilled beam to operate in either office room operation or meeting room operation and this could also pose problems with too low-pressure level for required airflow rate in meeting room operation.

The benefits of the DCV system could be realized better with real-life occupancy profiles of office spaces. In the study, occupancy profiles were based on occupancy schedules for energy calculation presented in EN16798-1 standard, where the occupancy profile is the same for all workdays. With a high occupancy rate, the energy-saving benefits of the DCV systems are lower but with low or highly varying occupancy rates the energy-saving benefits of the system can be utilized the most. With the increase of remote work in offices due to SARS-CoV-2 occupancy rates can vary highly and energy benefits of the DCV system could be utilized, by also maintaining a safe indoor environment.

5. Acknowledgment

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6. References

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DATA ACCESS STATEMENT

The datasets generated during and/or analysed during the current study are not available due to the simulation file sizes but the authors will make every reasonable effort to publish them in near future.