

SIMULATION OF STATIC PRESSURE RESET CONTROL IN COMFORT VENTILATION

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ABSTRACT

Variable air volume (VAV) ventilation systems reduce fan power consumption compared to constant air volume (CAV) systems because they supply air according to the airflow demand. However VAV ventilation systems do not take fully into account the potential energy savings as the control strategy operates the terminal boxes and the air handling unit (AHU) independently without pressure integration. The pressure in the main duct is maintained at a constant static pressure (CSP) which corresponds to the pressure required under the design full load condition. Under part load conditions, the fan provides excessive static pressure which is dissipated via throttling at the terminal boxes. As a result significant fan power is wasted in mechanical energy losses. The development of sophisticated direct digital controls (DDC) creates possibilities to integrate feedback from the dampers into the building management system. In this way the operation of central plant equipment is adjusted in real time according to the actual pressure demand; this control scheme can be implemented by the static pressure reset (SPR) method. The SPR control method ensures that at least one damper remains fully opened; thus the fan generates only enough pressure to satisfy the airflow demand in the most critical zone. Consequently the airflow resistance of the ductwork is maintained at a minimum and the fan operation is optimized. There are various approaches to implement the control scheme of the SPR method; the state of the art is represented by the method of trim and respond based on pressure alarms.

This study investigates the operation of the SPR control method of trim and respond based on pressure alarms in a CO₂ demand application where large air volumes are provided to three classrooms. The investigation was based on simulations performed with a fully dynamic model of a VAV ventilation system that was developed in the Simulink programming tool which is add-on software to MATLAB mathematical programming language. The Simulink model was developed in previous research work and was built based on the International Building Physics Toolbox (IBPT), which is a library of blocks constructed for the thermal analysis in building physics. For the purpose of the current investigation the IBPT toolbox was remodelled to integrate the calculation of the airflow demand based on the CO₂ concentration occurring in the zone. The performance of the Simulink model was in previous work evaluated based on the experimental setup of a ventilation system. The investigation of the SPR control algorithm of trim and respond based on pressure alarms disclosed some issues that need to be addressed and optimized before the algorithm can effectively establish the pressure conditions that satisfy the pressure demand under high airflows. In short the algorithm must be tuned to the application beforehand or, preferably, actively learn to perform from continuous feedback before it presents a real plug-and-play solution.

KEYWORDS

CO₂ demand control ventilation, static pressure reset, modelling, Simulink, energy savings.

1 INTRODUCTION

The potential energy savings in a VAV ventilation system can be boosted by integrating the control of terminal boxes into the building management system (Hartman, 1995). In this case it is possible to implement the SPR control method, instead of operating the fan with a CSP set point which corresponds to the pressure required under the design full load condition (Wei et al, 2004). The SPR control method operates the fan with a variable pressure set point which is established based on the dynamics of the actual pressure demand occurring in the system. Since 1999 the SPR control method has been a requirement for ventilation systems equipped with terminal boxes with DDC (Taylor, 2007). In accordance with ASHRAE Standard 90.1 (ASHRAE 90.1, 2004), the fan pressure set point shall be reset based on the critical zone request. A similar requirement is included in California’s Title 24 Energy Standards (Title 24, 2005). There are various approaches able to implement the control scheme of the SPR method; the state of the art is represented by the method of trim and respond based on pressure alarms as it is stable, flexible and it minimizes the impact of rogue zones (Taylor, 2007).

The objective of this paper is to investigate the operation of the SPR control method of trim and respond based on pressure alarms when the airflow demand changes in different zones in the ventilation system. The investigation is carried out by simulating the pressure and airflow conditions occurring in a system that provides air in three classrooms. The simulations are conducted with a fully dynamic model of a VAV ventilation system that was developed in Simulink (Simulink, 2013) during previous research work. The Simulink model was in previous work documented based on the experimental setup of a ventilation system that it is able to perform accurate calculations.

2 THE SIMULINK MODEL

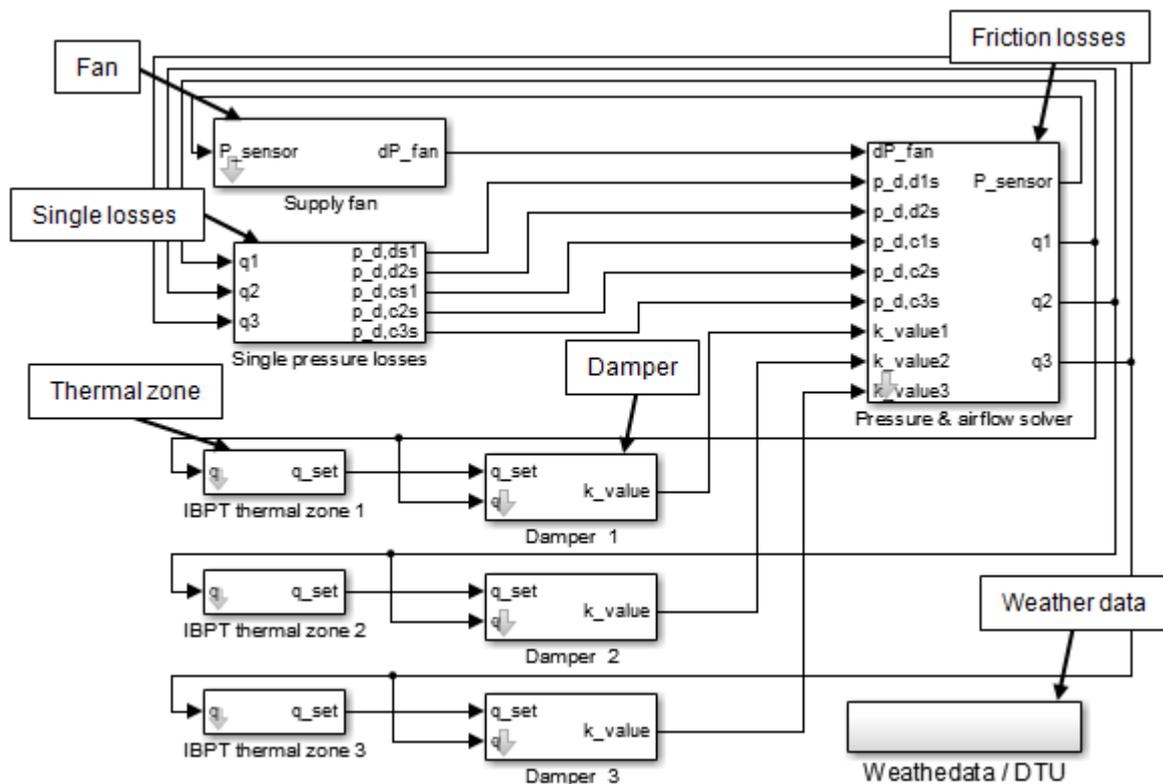


Figure 1: The Simulink model of the VAV ventilation system.

The model of the VAV ventilation system was created in the graphical environment of Simulink in Matlab (Matlab, 2013). Figure 1 illustrates the Simulink model which was built based on the blocks of the international building physics toolbox (IBPT). IBPT is library of blocks constructed for the thermal analysis in building physics (IBPT, 2012). The default IBPT blocks for the internal gains and the ventilation system were rebuilt to comply with the modelling of the VAV ventilation system (Koulani et al, 2014). A detailed validation of the model can be found in Koulani et al (Koulani et al, 2014).

2.1 The ventilation system

The IBPT ventilation system block was configured to calculate dynamically the airflow demand based on the CO₂ concentration occurring in the zone. The CO₂ concentration is approximated by equation (1) (Bekö et al, 2010) and the corresponding airflow demand is calculated dynamically by the ramp functions shown in Figure 2. The user defined data are the minimum ($q_{set,min}$) and maximum ($q_{set,max}$) airflow set point required in order to maintain a comfortable range of CO₂ concentration ($CO_{2, set,min}$, $CO_{2, set,max}$) in the zone.

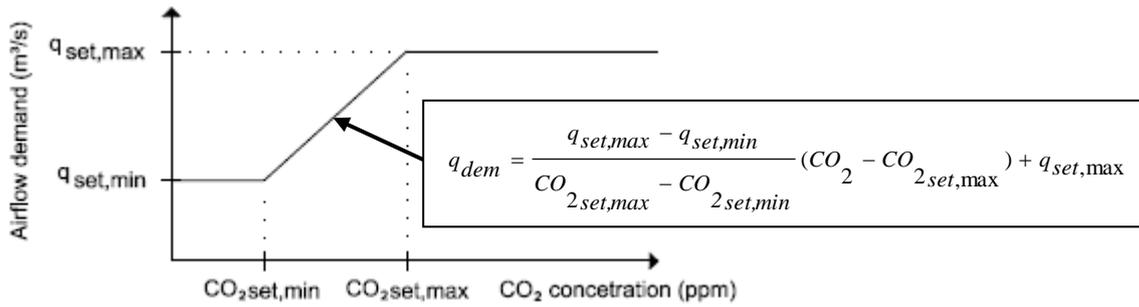


Figure 2: The dynamic calculation of the airflow demand based on the zone CO₂ concentration.

$$c = (c_0 - c_i) \cdot (1 - e^{-nt}) + \frac{G}{n \cdot V} \cdot (1 - e^{-nt}) + c_i \quad (1)$$

Where c_0 carbon dioxide concentration in the room at start, $t = 0$ (m^3/m^3)
 c_i carbon dioxide concentration in the inlet ventilation air (m^3/m^3)
 G carbon dioxide supplied to the room (m^3/h)
 n air change rate (1/h)
 V the volume of the zone (m^3)
 t time (h)

2.2 The fan

The mathematical model of the fan represents the operation characteristics of a typical fan box ventilator. The details regarding the control of the fan are given in Koulani et al (Koulani et al, 2014). Field measurements were performed on a typical box fan with large capacity (Exhausto BESB250-4-1) in order to model a similar response. The measurements were conducted in open loop, i.e. with no feedback and aimed at identifying the built up of the fan pressure when different steps were given to the input signal (see Figure 3).

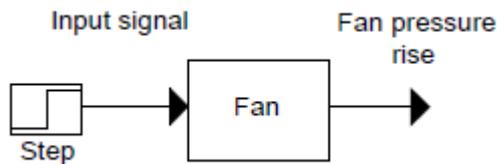


Figure 3: Setup for performing the field measurements.

The field measurements indicated that the second-order linear time-invariant (LTI) system is appropriate for modelling a fan able to provide the pressure rise required at the design full load condition. The second-order LTI system is implemented by using the state space method; the state space equations (see equation 3 & 4) calculate the derivative of the system response with respect to time (Rowell, 2002).

$$\dot{x}_1 = x_2 \quad (3)$$

$$\dot{x}_2 = \ddot{y} = \omega_n^2 \cdot u - \omega_n^2 \cdot x_1 - 2 \cdot \zeta \cdot \omega_n \cdot x_2 \quad (4)$$

Where x_1, x_2 the state vectors represent values from inside the system that can change over time

u the input vector to the system, voltage signal (V)

y the output vector from the system, fan speed (rpm)

ω_n the natural frequency is relevant to the speed response of the system (rad/s)

ζ the damping ratio is relevant to the oscillation mode of the system (-)

The modelling is performed by using the state space representation because in this way it is possible to express the operation of the fan with a variable run up time (t_s). The run up time is defined as the time required for the fan to adjust the angular speed to the current input signal, thus the run up time changes according to the input signal to the fan. This behaviour can be modelled by applying equation (5) (Herring, 2005) where the damping ratio is calculated as a function of the run up time.

$$\zeta = \frac{t_s \cdot \omega_n + 1.6}{6.6} \quad (5)$$

The data for the run up time were obtained by performing open loop measurements on a typical box fan (Exhausto BESB250-4-1) when the input signal to the fan changed per 1 V within a range of 0 V to 10 V. Based on the measurement points a trend line was drawn to correlate the damping ratio with the input signal (see equation 6). The given equation was incorporated in equation (4) and thus the damping ratio became variable of the input signal. In this way the fan model is built with a variable run up time.

$$\zeta = 0.0222 \cdot V^2 - 0.4442 \cdot V + 3.5965 \quad (6)$$

Where V the input signal to the fan (Volts)

Equation (5) establishes a stable response for values of damping ratio above 0.7, for lower values oscillations occur (Herring, 2005). In this case the natural frequency can be adjusted accordingly.

The pressure rise of the fan is calculated according to the fan speed which is output of the state space system (see equation 4). The correlation between the two fan parameters is determined by collecting measurement points in open loop from a typical box fan (Exhausto BESB250-4-1). The measurements were conducted when the input signal changed per 1 V within a range of 0 V to 10 V; equation (7) was obtained based on the relevant measurement data.

$$\Delta P_{fan} = 0.0002 \cdot speed^2 - 0.0082 \cdot speed + 5.7401 \quad (7)$$

Where ΔP_{fan} the pressure rise that the fan provides (Pa)

$speed$ the angular speed that the fan rotates (rpm)

2.3 The damper

The mathematical model implementing the operation of a typical damper (D) is built according to equation (8) which corresponds to the second-order LTI system expressed in the Laplace domain (Franklin et al 1993). The details regarding the control of the damper can be found in Koulani et al (Koulani et al, 2014).

$$D(s) = \frac{k_d \cdot \omega_n}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2} \quad (8)$$

Where k_d the process gain correlates the system output with the system input ($\text{m}^3/\text{s}/\text{Pa}\%$)

In the damper model the system input refers to the opening position of the damper while the system output to the corresponding resistance coefficient. The correlation between the two parameters is obtained from table values for a typical damper. The two fundamental factors that describe the response of the second-order LTI system, the damping ratio and natural frequency, are determined by trial and error. The damping ratio is set to 1 as the damper returns to equilibrium as quickly as possible without oscillating while the natural frequency is established at 50 rad/s.

2.4 The pressure and airflow solver

The friction and single pressure losses blocks illustrated in Figure 1 implement the hydraulic calculation of the VAV ventilation system according to the duct design shown in Figure 4. The unknown pressure and airflow conditions are determined by setting up a system of equations expressing the pressure losses occurring in every component of the system. The equations used for calculating the frictional and single pressure losses are described in detail by Koulani et al (Koulani et al, 2014). The hydraulic calculation determines the pressure demand (P) at the beginning and end of every component as well as the airflows (q) delivered to the different zones (see Figure 4). The system of equations derived cannot be solved analytically; therefore the Newton-Raphson numerical method is used instead.

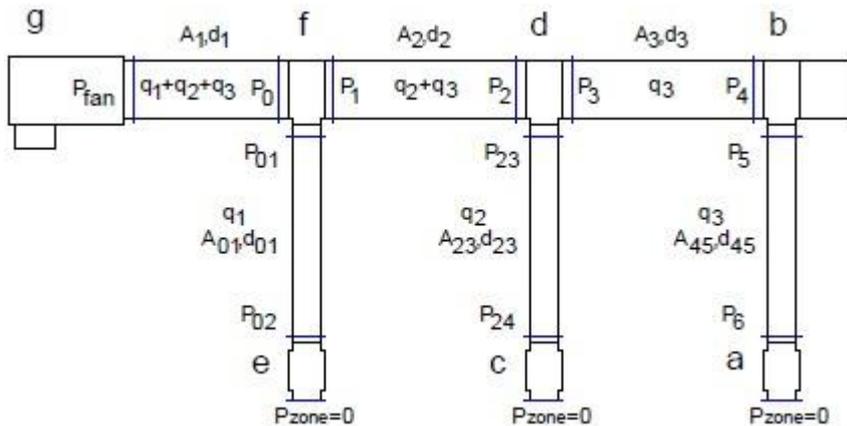


Figure 4: The duct design in the pressure and airflow solver block.

2.5 The static pressure reset algorithm

The operation principle of the SPR control method of trim and respond based on pressure alarms is presented in Figure 5. Every damper of the VAV system transmits an alarm signal when its position exceeds 85 % opening that indicates that the available pressure is critically low but still sufficient for providing the airflow demand. The zone keeps generating a pressure

alarm until the damper closes to a position of 80 % opening. The alarms from all zones are summed and when at least two zones request higher pressure the operation set point of the fan is reset 10 % upwards; in the opposite case it is reset 5 % downwards. The SPR algorithm is performed within a specific pressure range; the upper limit is set equal to the CSP set point which corresponds to the pressure required under the design full load condition. The lower SPR limit is determined according to the minimum pressure demand that ensures the precise operation of the dampers. The SPR loop is iterated every 90 sec and the fan adjusts to the new pressure set point.

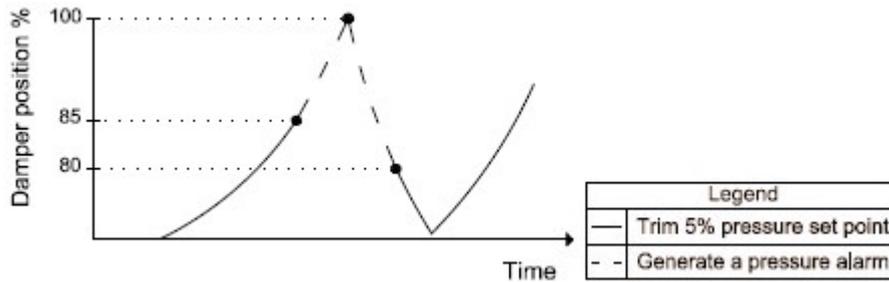


Figure 5: The control logic of the trim and respond static pressure reset method.

3 THE SIMULATION SETUP

The simulations investigate the operation of a VAV ventilation system which provides air in three classrooms, where each classroom can accommodate 20 students and has an area of 50 m². When no students are present in the classroom the CO₂ concentration is equal to 400 ppm (CO_{2 set,min}) that corresponds to the outdoor CO₂ level. The minimum airflow demand is set to 10 l/s (q_{set,min}) to comply with the ventilation rate of 0.2 l/s, m² which is recommended during unoccupied periods in non-residential buildings (see annex B.4, EN15251, 2007). At the design full load condition a ventilation rate of 185 l/s (q_{set,max}) is provided to maintain the CO₂ concentration to 1000 ppm (CO_{2 set,max}) that corresponds to a typical CO₂ level used in comfort ventilation. The occupancy in the three classrooms was configured as shown in Table 1.

Table 1: The occupancy profile in the three ventilated zones.

Time (min)	No of students zone 1	No of students zone 2	No of students zone 3
0 - 12	20	20	20
12 - 24	20	5	3
24 - 36	20	10	20

A simulation was performed based on the occupancy profiles given in Table 1 when the VAV ventilation system was controlled with the SPR control method. The SPR pressure set points were adjusted by trial and error to fit to the case study simulated. Table 2 summarizes the selected pressure range, within which the operation set point of the fan is reset.

Table 2: The pressure range of the SPR control method

Lower SPR pressure set point	15 Pa
Upper SPR pressure set point	145 Pa

4 RESULTS

4.1 System operation

Figure 6 and Figure 7 present the results of the simulation according to the occupancy profiles given in Table 1 when the VAV ventilation system operates with the SPR control method. The

two graphs given in Figure 6 illustrate the CO₂ concentration in the three zones and the adjustment of the operation set point of the fan, respectively. The distribution of the airflows and the operation of the dampers in the three ventilated zones are shown in the graphs given in Figure 7.

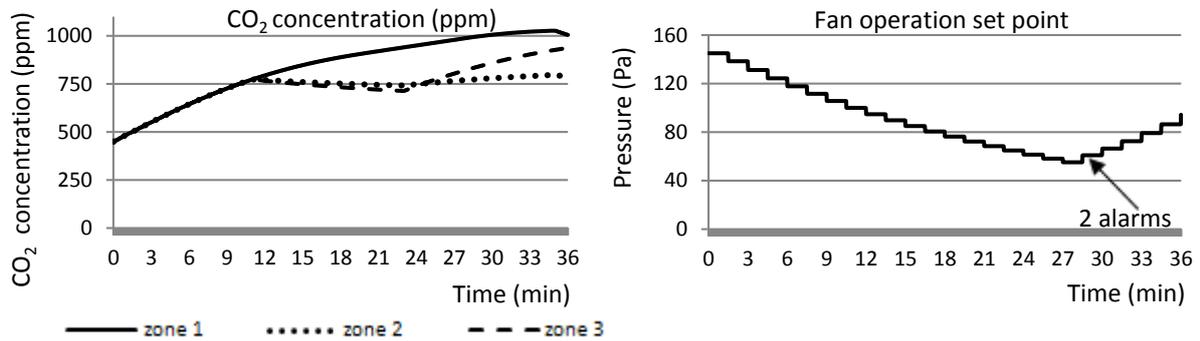


Figure 6: CO₂ concentration in the three ventilated zones and adjustment of the fan operation set point, respectively.

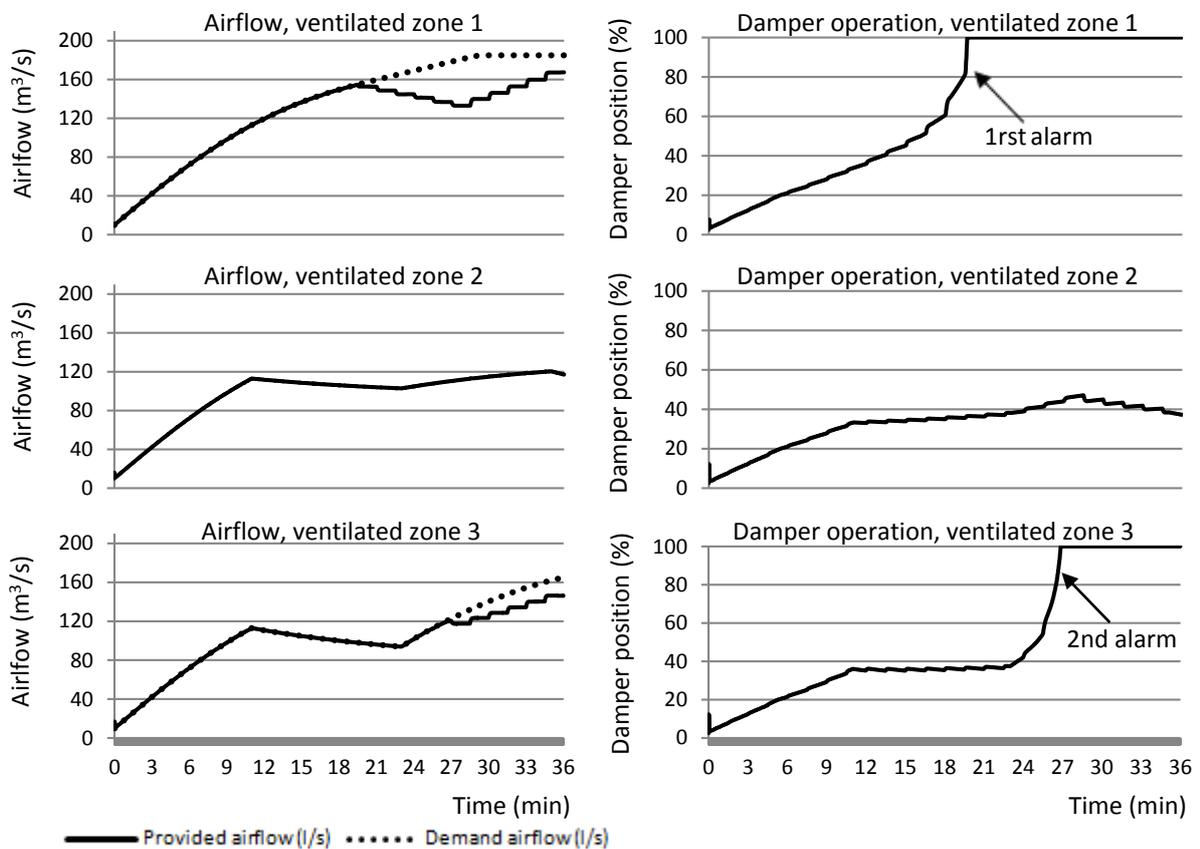


Figure 7: Airflow distribution and damper operation in the three ventilated zones.

The results are analyzed according to the different occupancy periods (see Table 1).

0 min to 12 min: When the system is set to operation the design full load is occurring in the three zones; thus the zone airflows increase and the dampers follow an upward trend. The position of the dampers is still below 85%; therefore no alarm is generated. Consequently the operation set point of the fan is decreased by 5% when the SPR control loop is iterated.

12 min to 24 min: The maximum occupancy load is maintained in zone 1 whereas in zone 2 and zone 3 the load is decreased approximately to 1/4 of the maximum. As the position of the dampers is not open enough to generate an alarm, the SPR control algorithm keeps trimming the operation set point of the fan. The pressure that is available in the system is constantly

decreased and the dampers continue to open to wider positions. The rate that the damper position opens depends on the amount of airflow demanded in the zone. In zone 1, where the design full load is occurring, the position opens fast and as soon as it exceeds 85% opening an alarm is generated. Despite that the alarm indicates that the provided pressure is insufficient to satisfy the airflow demand in the zone, the fan operation set point is decreased even more. This is because the SPR control algorithm is designed to reset upwards when at least two zones are in alarm. As a result the damper saturates at 100% opening.

24 min to 36 min: Both in zone 1 and zone 3 the design full load is occurring while in zone 2 half of the maximum load is present. At the moment that the occupancy profile changes, the fan operation set point is lower than the pressure demand that satisfies the design airflow in zone 1. Therefore, once the occupancy in zone 3 becomes critical and the design airflow is requested also in this zone, the damper position rises and almost immediately saturates at 100% opening. In this case there are two zones in alarm; thus at the next iteration of the SPR control loop the operation set point of the fan is reset upwards. The pressure that is available in the system becomes higher and the airflow provided in both critical zones increases. However the increment is not enough to satisfy the pressure demand occurring in the system. This is because the SPR control algorithm is designed with a pressure increment of 10%, which is not sufficient to establish in good time the pressure conditions able to provide the design airflow in both critical zones.

5 CONCLUSIONS

The selected values for the parameters of the SPR control method of trim and respond based on pressure alarms were proven inappropriate to establish the pressure conditions that satisfy the pressure demand occurring under high airflows. The SPR control algorithm underperformed because the following parameters did not fit to the case study examined:

- The threshold number of alarms above which the fan operation set point is reset upwards
- The trim percentage used for resetting downwards the fan operation set point
- The respond percentage used for resetting upwards the fan operation set point

The parameters need to be adjusted and optimized in order to build up an algorithm able to control efficiently a VAV ventilation system where large fluctuations in the airflow demand occur. The parameters were configured based on preselected values established in previous research work where the SPR pressure range was narrow and complied with a difference of 9 Pa between the lower and the upper limit. Therefore a respond percentage of 10 % was able to reset the fan operation set point to satisfy in good time the pressure demand of the occurring airflow. In the case study examined the system is designed for providing high airflows; thus the reset is performed within a wide range. The parameters of the SPR algorithm should be adjusted to achieve an optimized solution where the system can handle efficiently large fluctuations in the airflow demand while avoiding intense dynamics and at the same time maximizing energy savings.

It is not recommended to apply a significantly high respond percentage for resetting upwards the fan operation set point because the dampers would be imposed to adjust to pressure steps that can establish unstable operation conditions in the system. The intention is to maintain a high trim percentage for resetting downwards the fan operation set point as energy savings are increased. A compromise should be found between the respond and trim percentage used for resetting the fan operation set point upwards and downwards, respectively. The higher the trimming rate, the higher the potential for energy savings as the available pressure in the system is reduced fast. However a higher value for the respond rate should also be implemented as the SPR algorithm should be able to increase in good time the fan operation

set point in case that high airflow demand occurs. Thus by building up a SPR algorithm with main focus on higher energy savings may compromise stability in the system. The adjustment of the threshold number of alarms above which the fan operation set point is reset upwards is a parameter that can improve the response of the SPR algorithm to handle large fluctuations in the airflow demand without causing unstable operation conditions in the system. In the future, the algorithm, preferably, can be developed to actively learn from continuous feedback, the necessary trim and respond increments and in the end present a real plug-and-play solution.

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