Energy Research Journal

Original Research Paper

Optimal Control Strategy for Parallel Fan-Powered VAV Systems

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Article history
Received: 23-03-2022
Revised: 19-04-2022
Accepted: 21-04-2022

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Abstract: ASHRAE Guideline 36 recommends resetting the Supply Air Temperature (SAT) for Variable Air Volume (VAV) systems to balance fan power, heating and cooling loads and zone reheat requirements. This is achieved by employing a trim and response algorithm in conjunction with using the outside air temperature and readings from zone cooling loops. However, resetting the SAT for the VAV systems with parallel fan-powered terminal units according to Guideline 36 recommendations may not produce the best performance. Reducing the reheat requirement in parallel fan-powered terminal units can be done by increasing the air recirculating at the zone level rather than at the system level. This will allow keeping the system level SAT as cold as possible to reduce fan airflow for the zones in cooling with no or little effect on heating requirement for the zones in heating. Therefore, this study evaluates SAT control strategies and fan-powered terminal airflow rates to maximize total energy efficiency. Multiple airflow rate designs and operational variables such as the size of the fan-powered terminal unit and minimum airflow rate set point are included in this study. The simulation results for a typical small commercial building in various locations show that the new resetting method with local zone air recirculation enhancement can significantly reduce fan energy use with little effect on the heating requirement. The result may significantly improve the guideline related to the sequence of operation in a parallel fan-powered terminal unit.

Keywords: Building Energy Performance, VAV System, Supply Air Temperature Reset, Optimization, Energy Efficiency

Introduction

Buildings account for approximately 40% of the United States' total energy demand, greater than the amount consumed by either industry (32%) or transportation (29%) (US EIA, 2020). In addition,70% of the electricity produced in the US is used in the building sector leading to a substantial amount of energy bills each year. When building end-use is considered, Heating, Ventilation, and Air Conditioning (HVAC) systems consume about 50% of the total energy use, significantly more than any other end-use (Pérez-Lombard *et al*., 2008). Therefore, improving the operation of the HVAC system is crucial to achieving maximum building energy efficiency and reducing the total building energy cost (ASHRAE, 2019; Nassif, 2014, Pease *et al.*, 2021; Tahmasebi *et al.,* 2019). One of the common strategies for better system energy efficiency is different temperature set points reset. Among the temperature set points, resetting the Supply Air Temperature (SAT) is widely implemented in HVAC systems. This reset strategy can maximize the use of economizers and lower the reheat energy required (Okochi and Yao, 2016). There have been different studies on the SAT resetting strategies for the Variable Air Volume (VAV) system, but some general trends can be observed in all of them. Murphy (2011) suggested varying the SAT according to the Outdoor Air Temperature (OAT) and keeping it cold (55°F or 13°C) when the ambient temperature is warm (higher than 65°F or 18°C). SAT should be reset according to the worst zone in cooling during colder months. In another study, (Park *et al*., 2020) investigated the energy consumption of office buildings by simulating SAT reset as a function of outdoor air temperature. To compare the energy savings, (Nassif and Ridwana, 2022) also evaluated two SAT reset strategies, one of which varies according to the outdoor air temperature in a single duct VAV and dual VAV system. In addition, (Wang and Song, 2012) proposed optimized SAT reset strategies during economizer cycles by developing an energy cost model and steady-state analysis. (Raftery *et al*., 2018) developed an SAT reset strategy for multi-zone VAV systems that is simple enough to be implemented in existing energy management systems. This strategy showed opportunities for energy cost reduction with optimal SAT without the need for complex controls. Furthermore, (Ke *et al*., 1997) investigated eight different control strategies for the VAV systems and concluded that SAT reset is one of the best parameters to optimize, leading to significant energy savings.

As many different approaches have been studied over the year for HVAC system control and optimization strategies, ASHRAE Guideline 36-High-Performance Sequence of Operation (ASHRAE, 2018) was published in 2018 to create standardized optimal controls for HVAC systems. Guideline 36 introduces the best-in-class control and sequences of operation for HVAC systems to maximize energy efficiency. Moreover, it provides the sequences for VAV controllers for better thermal comfort and energy savings (ASHRAE, 2018; Taylor, 2018). As a part of the control strategies, the guideline recommends a trim-and-response method to reset the Supply Air Temperature (SAT) set point for a multi-zone VAV system based on readings from zone cooling loops. This SAT reset strategy fits a typical VAV system configuration serving multiple zones well. However, this recommended reset strategy may not produce the best performance for the VAV system with parallel fan-powered terminal units. The heating requirement of the zone depends on the temperature of the air entering the reheat coil. When the economizer is enabled, resetting the SAT set point to a higher value will introduce a higher amount of return air at the system level. This increases the air temperature entering the reheat coil and consequently reduces the reheating requirement. But this resetting strategy will hurt the zones operating in cooling as this will result in increasing fan airflow rates and energy use. Alternatively, for the VAV systems with parallel fan-powered terminal units, the reheat coil's temperature can be raised by increasing the terminal secondary air at zone level instead of system level. This will allow keeping the system level SAT as cold as possible to reduce the required airflow for the zones in cooling with no or little effect on the heating requirement for the zones in heating. The guideline also recommends resetting the SAT linearly as a function of Outside Air Temperature (OAT). When the building has zones mostly in cooling, especially the interior zones, resetting the SAT based on OAT as proposed by the Guideline may not be the best approach to reduce energy consumption. Therefore, this study proposes a new SAT reset strategy for the VAV systems with fan-powered terminal units and evaluates the proposed control by simulating and comparing it with the guideline-recommended strategy to maximize the total system efficiency.

Proposed Fan-Powered Control and SAT Resetting Algorithm

VAV systems are sometimes equipped with local fan-regulated terminal units called Fan-Powered Terminal Units (FPTUs). VAV systems with parallel fan-powered terminal units have small local return fans placed at the plenum level that draws the return air and mixes it with the supply air from the central Air Handling Unit (AHU). This induced return air can reclaim the heat from zones and therefore, reduce the required heating energy (Sardoueinasab, 2019). FPTUs have a few advantages over the typical single duct VAV system like lower operating pressure of the central supply duct and reduced fan energy consumption, better temperature control, etc., (Yin, 2014). Figure 1 shows a schematic of a typical parallel fan-powered VAV system. The system has the following major control loops: Space control loops, duct static pressure control loop, and supply air temperature control loop. The latter is the focus of this study. The supply air temperature control is to maintain the SAT at its set point by modulating chilled or hot water valve for chilled water VAV system or direct expansion DX refrigeration coil capacity for packaged VAV system.

The Guideline 36 resetting algorithm resets the SAT Set Point (SP) linearly between a fixed minimum value $SP_{\min}$ (e.g., 55°F) to an adjusted maximum value $SP^*_{\max}$ as a function of OAT. The resetting algorithm is based on the predefined maximum change-point outside air temperature $To_{\max}$ and the minimum change-point outside air temperature $To_{\min}$ (e.g., 65°F). The active maximum value $SP^*_{\max}$ is dynamically adjusted using the trim and response algorithm to ensure that the SAT is low enough to meet the required cooling load in the critical zone (s) by keeping the cooling control signal less than a predetermined value (e.g., less than 95%).

Even when it is cold, there may be several zones in cooling, and the SAT resetting based on OAT as proposed by the Guideline may not produce the best performance. Thus, the proposed strategy uses both the zone cooling or heating control loops instead of OAT to count the number of zones in cooling or heating at any time. If the zone is in cooling or Deoband, the zone value ZV is assigned to be one; otherwise, it is zero. The SAT resetting cooling signal RCS is then calculated as follows:

$$RCS = \sum_{i=1}^{n} a_i ZV_i \tag{1}$$

The n is the number of zones. The term a_i is a factor in giving a weight for zone i. The a_i can be determined from the design airflow rate or actual readings. In this study, the a_i is calculated by the design zone flow rate ratio to the sum of design zone flow rates. The sum of a_i should be one. The RCS should then vary from 0 to 1 (0 to 100%).

DOI: 10.3844/erjsp.2022.1.9

If there is no zone in cooling, the RCS is zero. If all the zones are in cooling, it becomes 1 (100%). The SAT will be reset based on RCS, as shown in Fig. 2b. The maximum value of the SAT Set Point SP^*_{max} is dynamically adjusted using the same trim and response algorithm recommended in the Guideline to ensure that the SAT is cold enough to meet the cooling load in critical zone(s).

Another improvement proposed in this study is related to fan-powered terminal unit control. The constant-speed fan can be sized to deliver larger airflow to reduce the reheat. But this may increase the annual fan energy use as the fan may run at elevated airflow when there is no real benefit from recirculating air from the plenum. Therefore, it is recommended to use a variable speed fan in the terminal unit and reset the secondary air flow rate (air recirculated from the plenum by the terminal fan) in the following manner: In heating mode, the discharge air temperature is reset to maintain the space temperature at its set point. The fan speed maintains the set point until the speed reaches the maximum value (e.g., 80% of the design maximum fan speed). The fan speed will control the discharge set point as long as the secondary air temperature is higher than the discharge temperature set point by a certain value (e.g., 3°F). If the secondary air temperature is not higher than the discharge temperature set point by a certain value or fan speed reaches the maximum value, the discharge temperature set point will be maintained by the reheat coil. When the discharge air temperature set point becomes 90°F or higher, the fan speed shall increase to the maximum design value. Figure 3 shows the proposed control logic of the variable speed fan-powered terminal units.

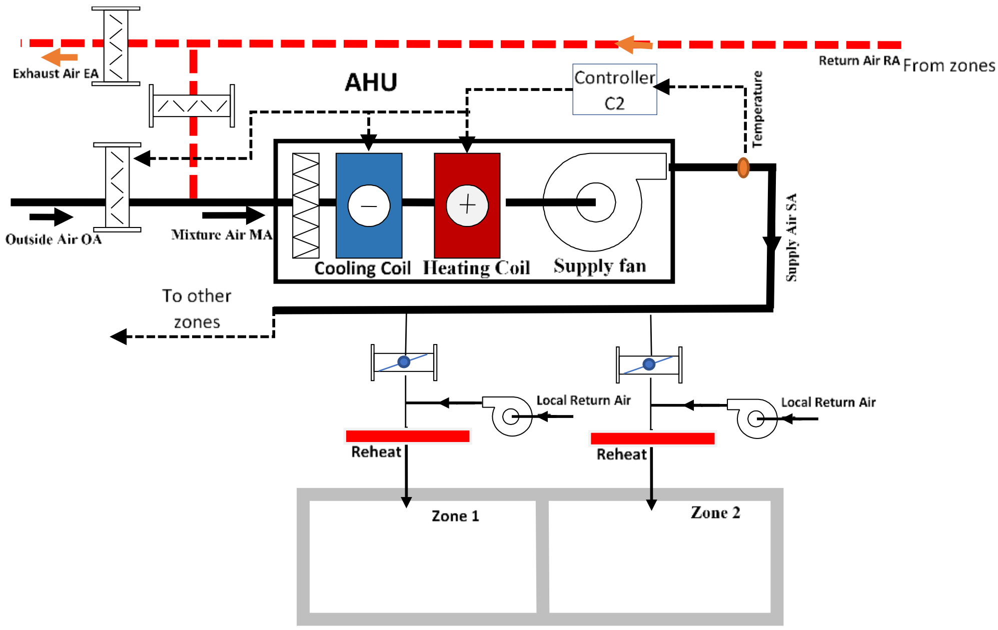

Fig. 1: Schematic of a VAV system with parallel fan-powered terminal units

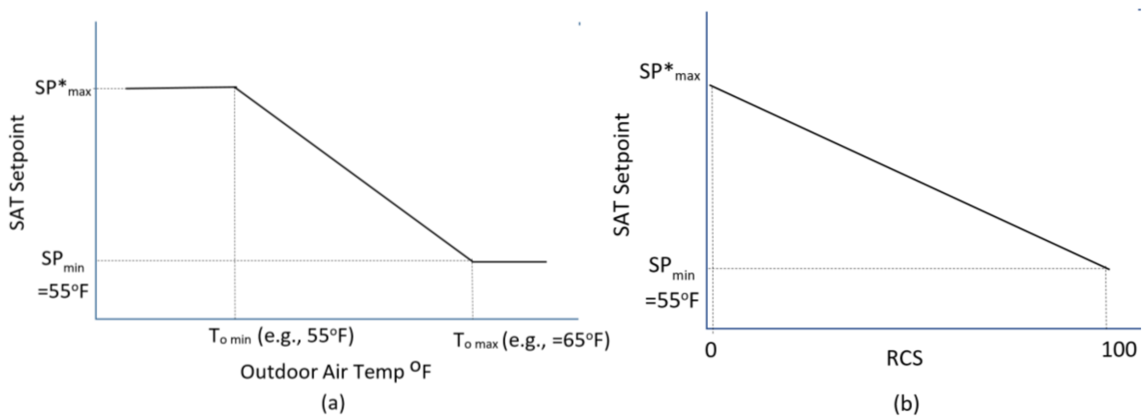

Fig. 2: SAT Set Point (SP) resetting algorithms (a) Guideline 36 and (b) Proposed algorithm

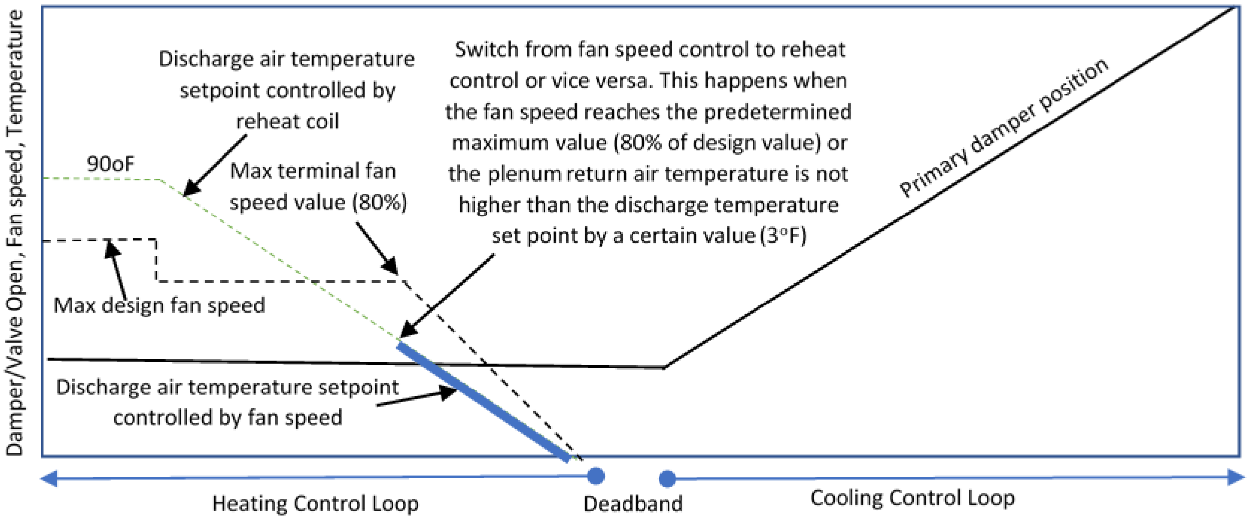

Fig. 3: Proposed variable-speed fan-power terminal unit control logic

Variable Interactions in a Two-Zone Building

A simple two-zone building example is introduced to show the interaction between the secondary air flow rate and primary supply air temperature SAT on both heating requirement and fan power under various OATs. The example assumes two zones with a design zone airflow rate of 1000 cfm each; the design fan-powered airflow (secondary air flow rate) is 500 cfm. The design static pressure for the terminal unit fan is 0.5 in WG and for the AHU fan is 5 in wg. The duct static pressure set point is assumed to be constant at 1.5 in WG. Using the quadric flow-pressure equation applied between the set point and design static pressure, the actual fan static pressure and fan power can be calculated, assuming a constant fan efficiency of 0.75. The reheat requirement, load, or airflow rates are calculated using the sensible heat equation (e.g., sensible load = specific heat × airflow rate × temperature difference). Eight cases are introduced in this example. The first four cases (Case 1, Case 2, Case 3, Case 4) are when both zones are in heating but with various OA temperatures and secondary air flow rates, while the second four cases are when one zone is in cooling and the other in heating (Case 5, Case 6, Case 7 and Case 8).

Figure 4a shows Case 1 when both zones are in heating with a heating load of-11 kbtu/h and when the OAT is 5°F and Fig. 4b shows Case 2, similar to Case 1, but when the OAT is 52°F instead. For both cases, the SAT is reset linearly based on OAT as recommended by Guideline, the SATs are then 65°F at the OAT of 5°F (Fig. 4a) and 63.6°F at the OAT of 52°F (Fig. 4b). Figure 4c and 4d show Case 3 and Case 4, similar to Case 1 and Case 2, respectively, but maintain constant SAT at 55°F. The calculated system and local heating requirements, fan power, temperatures, and airflow rates are all presented in the figures.

In Case 1 and Case 3, when the OAT is 5°F, the system heating is activated to maintain the SAT at 65°F for Case 1 and 55°F for Case 3. Both cases require the same amount of total heating of 35.618 kbtu/h (system heating + local reheat) and, there is no benefit from resetting the SAT from 55 to 65°F. Indeed, resetting the SAT from 55 to 65°F will simply shift heating from the terminal unit to the AHU heating system. In those cases, if some zones may require cooling, resetting SAT based on OAT would increase the fan power with no effect on the heating requirement. However, when the OAT is 52°F, in Case 2 and Case 4, the SAT is maintained by recirculating the return air at the system level, and then the total heating requirement increases from 24.244 kbtu/h to 27.280 kbtu/h by keeping the SAT at 55°F (Case 4) instead of 63.67°F (Case 2). This requirement can be reduced by increasing the amount of air recirculated from the plenum (secondary air flow rate) and/or resetting SAT all the way to 65°F independently of OAT as long as there is no zone in cooling. Resetting SAT as a function of OAT does not provide the best performance in those cases.

This section discusses the second four cases when one zone is in cooling, the other is in heating and the OAT is 52°F. The heating and cooling loads are assumed to be-11 kbtu/h and 11 kbtu/h. Fig. 5a shows Case 5 when the SAT is 63.6°F based on the OAT resetting algorithm. Fig. 5b shows Case 6 when the SAT is kept at 55°F. Fig. 5c shows Case 7 when the SAT is kept at 55°F but increases the secondary air from 500 cfm to 1000 cfm. Figure 5d shows Case 8 when the proposed algorithm determines the SAT (Fig. 2b). In Case 8, the SAT is 60ºF instead of 63.6ºF.

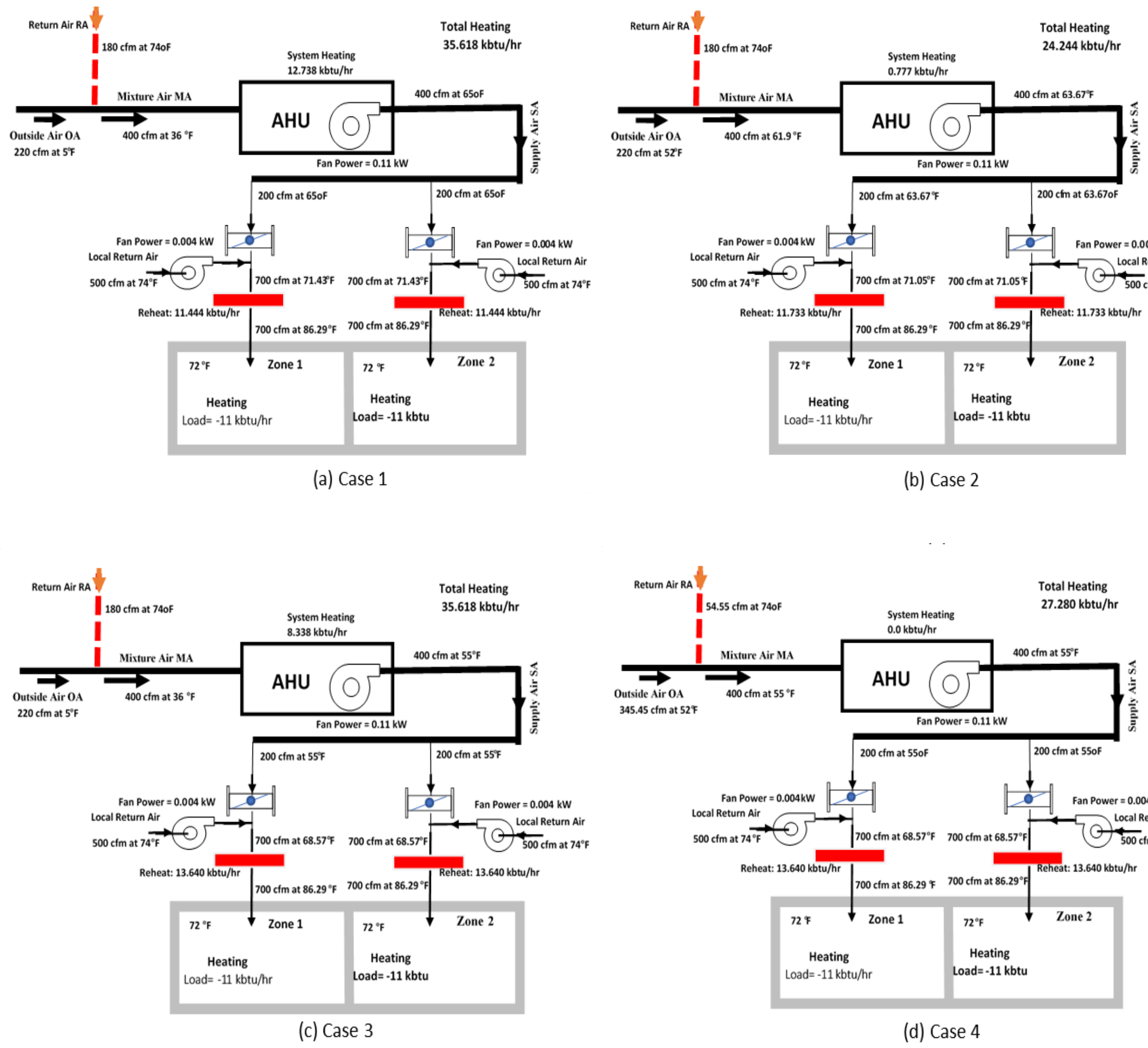

Fig. 4: Two-zone example when both zones in heating

When there are some zones in cooling (in this example, it is just one zone) and the SAT is maintained at 55°F instead of resetting to 63.67°F (Case 6 instead of Case 5), the fan power reduces from 0.4 kW to 0.21 kW, but the reheat increases from 11.733 kbtu/h to 13.640 kbtu/h. Instead of recirculating the return air at the system level, more air can be recirculated at zone level from the plenum. For instance, by increasing the secondary air flow rate from 500 cfm to 1000 cfm (Case 7 instead of Case 6), the reheat will reduce from 13.640 kbtu/h to 12,540 btu/h. Furthermore, resetting the SAT by the proposed algorithm, the SAT becomes 60°F instead of 63.67°F, and the reheat drops to 11,440 kbtu/h, even lower than the one for Case 5 at 63.67°F due to increased secondary airflow. The fan power becomes 0.21 kW which is still less than 0.4 kW at the SAT of 63.67°F. This example shows that using the OAT to reset SAT cannot produce a near-optimal performance as there may still be zones in cooling. For instance, when some zones require cooling, the SAT temperature may not need to reset to 63.6°F as in case 5, compared to 60°F as in Case 8 using the proposed algorithm and the reheat requirement could be reduced by increasing the secondary air flow rate as recommended by the proposed algorithm shown in Fig. 3.

DOI: 10.3844/erjsp.2022.1.9

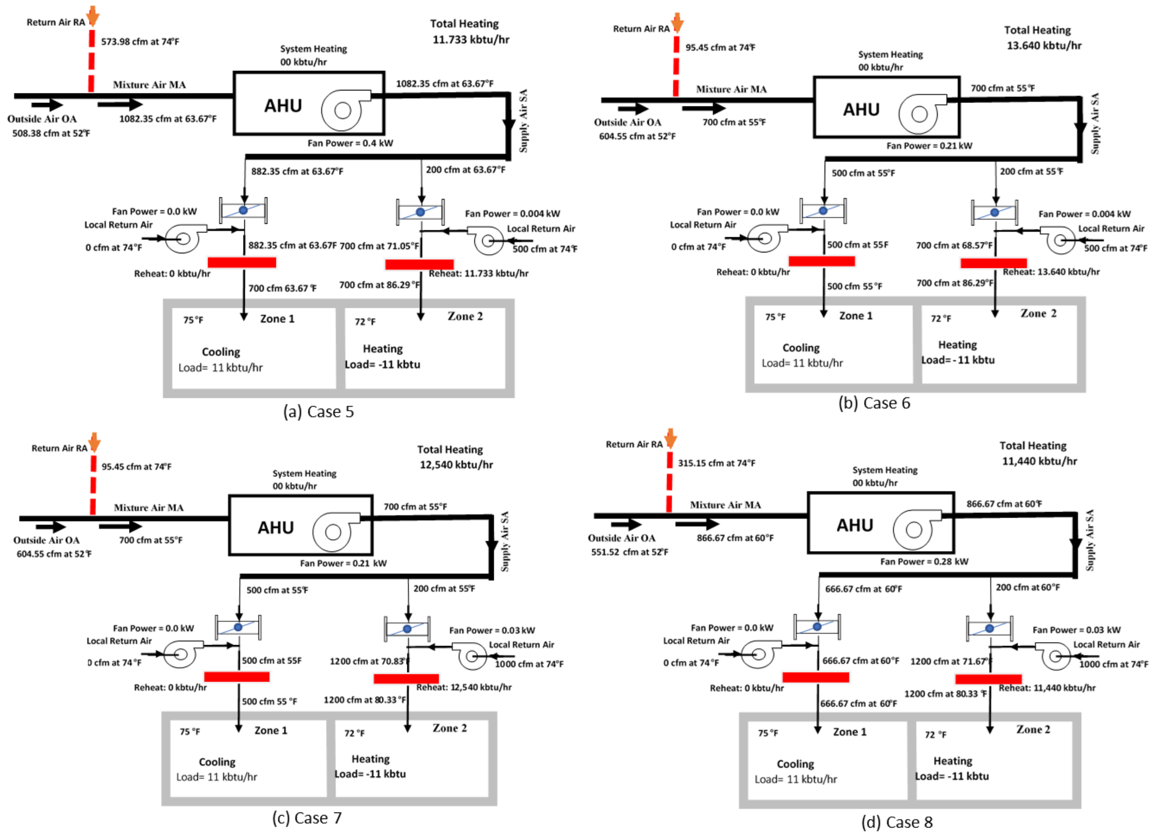

Fig. 5: Two-zone example when one in heating and the other in cooling

Results and Discussion

A five-zone 25,000 ft^2 office building is used to evaluate the proposed algorithms. Fig. 6 shows the floor plan and the design information of the case study building. The building is modeled in the building energy simulation software Energy Plus (EP, 2020). Four control strategies are investigated:

Strategy I (S1): This strategy is the one in Guideline 36, SAT is reset based on OAT from a minimum value of 55ºF to a maximum active value. The maximum active value is adjusted from 55 to 65°F using the trim and response algorithm to ensure there is no cooling control signal in any zone greater than 95%

Strategy II (S2): This is the simplest strategy, keeping the SAT constant at 55ºF to save fan energy power

Strategy III (S3): This strategy is the same as S2 but doubles the secondary airflow rates from the previous strategies (3000, 3000, 6000, 3000, and 2000 cfm)

Strategy IV (S4): This is the proposed strategy, resetting the SAT based on the proposed algorithm discussed in Fig. 2b from the minimum value of 55ºF to the maximum active value. The maximum active value is calculated using the trim and response algorithm as recommended by the guideline to keep the cooling control signal in any zone no greater than 95%. The terminal unit fan varies the secondary airflow from zero to the maximum design flow rates (3000, 3000, 6000, 3000, and 2000 cfm). The fan speed is controlled by the recommended strategy shown in Fig. 3

The four strategies are modeled in the EMS of Energy Plus. The total design pressure for AHU is 5in WG and for the terminal unit is 0.5 in WG. The duct static pressure set point is assumed to be constant at 1.5 in WG. Four cases containing different OATs and sensible zone heating and cooling loads are selected from the annual energy simulation results for discussion as shown in Table 1. The negative sign is for the heating load. Table 2 shows the zone level results. It includes zone reheat, secondary airflow (Sec flow), and primary flow (Prim flow). Table 3 shows the

DOI: 10.3844/erjsp.2022.1.9

system-level results. It includes total primary AHU airflow (Prim flow), total secondary airflow (Sec flow) (sum of zone secondary airflow rates), total airflow (Tot flow) (sum of local and system airflow rates), required outside airflow rate (Required OA) calculated based ASHRAE 62.1 ventilation procedure (ASHRAE, 2020), actual economizer OA Airflow (OA Provided), mix air temperature (Mix Air), Supply Air temperature (SA), total sensible cooling and heating loads, AHU and all local terminal fan powers and total fan power (sum of the AHU and local terminal fan powers).

For case-1 (OAT = 26ºF) and case-2 (OAT = 53ºF), S1 provides the lowest heating requirement but the highest fan energy use. On the other hand, S2 provides the lowest fan energy use but the highest heating requirement. In S3 when the secondary zone airflow rates are doubled, the reheat is dropped and total fan energy use is slightly increased from 2.3 to 2.46 kW due to the increase of terminal fan power but still less than the first strategy S1(3.76 kW). The proposed strategy S4 somewhat compromises fan energy and heating requirements. For instance, S4 raises the SAT to 61.5°F, but not to 65°F even if it is too cold outside as there is a large zone in cooling (Zone 3). The terminal unit fan does not have to run at full speed as in S3. The total heating system in S4 is somewhat close to S1 but the fan energy use is less than in S1. This example represents the worst-case scenario for S4, as for certain conditions, S4 can achieve even lower annual reheat requirement and fan energy use, as shown in the annual energy analysis below. Looking at case 3, no heating is required. The fan power drops significantly, but the cooling load is increased, as more mechanical cooling at OAT of 60°F should be provided to maintain the SAT at 55°F, compared to S1 when the SAT is 58.3°F.

The next section discusses the annual energy uses. Table 4 shows the baseline annual heating and reheat loads, fan energy use, and sensible cooling load for five locations, representing different climate zones. The baseline is when S1 is applied. Table 5 shows the percentage increase or decrease in energy or load from the baseline if other strategies (S2, S3, and S4) are applied. Applying S2 reduces fan power significantly, but the total heating system increases. For instance, in Cincinnati, the total heating load increases by 35% and the fan energy drops by-29.71% (negative sign is "decrease"). S3 can significantly reduce the total heating requirement but is still higher than the baseline S1 (e.g., 9.38% in Cincinnati). S4 reduces the fan energy and the total heating in most locations. There is a slight increase in cooling load in S2 and S3 and S4, as more mechanical cooling is needed to maintain lower SAT. This increase may be avoided by resetting the SAT to a higher value only when OAT is in the range of 55 and 65°F.

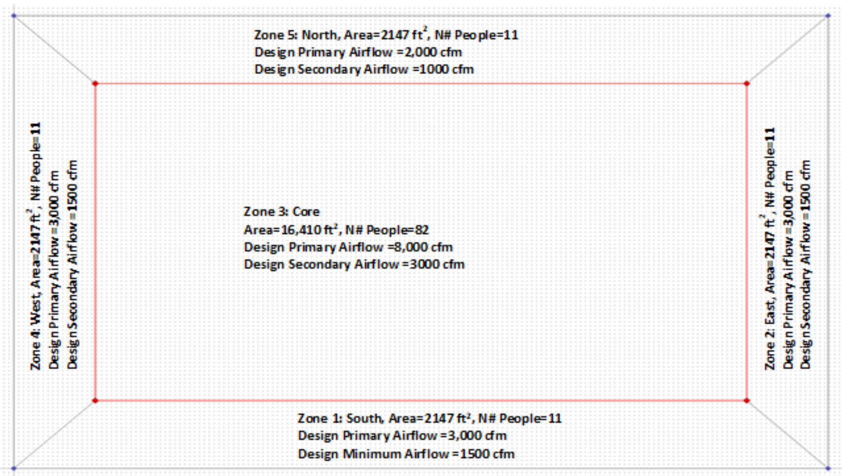

Fig. 6: Floor plan for the example 25,000 ft^2 (2323 m^2) office building

Table 1: Four different cases showing the OAT and cooling and heating loads (negative sign for heating)

Cases	OAT	Sensible heating and cooling loads BTU/hr				
	°F	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Case-1	26	-1,932.0	-5,555.8	82,136.5	-5,488.3	-4,137.7
Case-2	53	13,424.8	34,820.7	89,344.9	7,555.8	8,441.3
Case-3	60	36,390.6	23,275.1	127,528.0	53,759.0	21,898.1
Case-4	67	40,114.9	45,255.8	102,882.0	18,205.1	18,750.2

Table 2: Zone-level results

Strategy	Case	South zone 1			East zone 2			Core zone 3			West zone 4			North zone 5		
		Prim flow CFM	Sec flow CFM	Reheat Btu/hr	Prim flow CFM	Sec flow CFM	Reheat Btu/hr	Prim flow CFM	Sec flow CFM	Reheat Btu/hr	Prim flow CFM	Sec flow CFM	Reheat Btu/hr	Prim flow CFM	Sec flow CFM	Reheat Btu/hr
S1	1	600.0	1,500.0	-3,252.0	600.0	1,500.0	-6,875.8	7,467.0	0	0	600.0	1,500.0	-6,808.3	400.0	1,000.0	-5,017.7
	2	1,017.0	0.0	0.0	2,637.9	0.0	0.0	6,768.6	0	0	600.0	0.0	0.0	639.5	0.0	0.0
	3	1,984.9	0.0	0.0	1,269.6	0.0	0.0	6,956.1	0	0	2,932.3	0.0	0.0	1,194.4	0.0	0.0
	4	1,823.4	0.0	0.0	2,057.1	0.0	0.0	4,676.5	0	0	827.5	0.0	0.0	852.3	0.0	0.0
S2	1	600.0	1,500.0	-9,852.0	600.0	1,500.0	-13,475.8	3,733.5	0	0	600.0	1,500.0	-13,408.3	400.0	1,000.0	-9,417.7
	2	610.2	0.0	0.0	1,582.8	0.0	0.0	4,061.1	0	0	600.0	1,500.0	-364.2	400.0	0.0	0.0
	3	1,654.1	0.0	0.0	1,058.0	0.0	0.0	5,796.7	0	0	2,443.6	0.0	0.0	995.4	0.0	0.0
	4	1,823.4	0.0	0.0	2,057.1	0.0	0.0	4,676.5	0	0	827.5	0.0	0.0	852.3	0.0	0.0
S3	1	600.0	3,000.0	-6,552.0	600.0	3,000.0	-10,175.8	3,733.5	0	0	600.0	3,000.0	-10,108.3	400.0	2,000.0	-7,217.7
	2	610.2	0.0	0.0	1,582.8	0.0	0.0	4,061.1	0	0	600.0	3,000.0	-364.2	400.0	0.0	0.0
	3	1,654.1	0.0	0.0	1,058.0	0.0	0.0	5,796.7	0	0	2,443.6	0.0	0.0	995.4	0.0	0.0
	4	1,823.4	0.0	0.0	2,057.1	0.0	0.0	4,676.5	0	0	827.5	0.0	0.0	852.3	0.0	0.0
S4	1	600.0	2,407.1	-3,585.9	600.0	2,407.1	-7,209.6	5,519.1	0	0	600.0	2,407.1	-7,142.1	400.0	2,000.0	1,604.7
	2	669.3	0.0	0.0	1,735.9	0.0	0.0	4,454.1	0	0	600.0	1,268.5	0.0	420.8	0.0	0.0
	3	1,654.1	0.0	0.0	1,058.0	0	0.0	5,796.7	0	0	2,443.6	0.0	0.0	995.4	0.0	0.0
	4	1,823.4	0.0	0.0	2,057.1	0	0.0	4,676.5	0	0	827.5	0.0	0.0	852.3	0.0	0.0

Table 3: System-level results

Strategy	Case	Supply air flow			Outside air flow		Air temp			Cooling and heating loads				Fan power	
		Tot flow CFM	Prim flow CFM	Sec flow CFM	Required CFM	Provided CFM	Mix air oF	SA oF	Cooling Btu/hr	AHU heating Btu/hr	Total reheat Btu/hr	Tot heating Btu/hr	AHU fan kW	Local fan kW	Total kW
S1	1	15,167.0	9,667.00000	5,500.0	2,233.4	2,233.40000	62.9	65.0	-22,219.4	-21,953.7	-44,173.1	3.71		0.05	3.76
	2	11,663.0	11,663.00000	-00.0	2,430.7	6,109.20000	63.0	63.0	0.0	0.0	0.0	5.19	-0.00	5.19	
	3	14,337.3	14,337.30000	-00.0	2,246.5	14,337.30000	60.0	58.3	26,285.1	0.0	0.0	0.00	7.82	-0.00	7.82
	4	10,236.7	10,236.70000	-00.0	2,340.9	10,236.70000	67.0	55.0	135,124.8	0.0	0.0	0.00	4.10	- 0.00	4.10
S2	1	11,433.5	5,933.50000	5,500.0	2,620.6	2,620.60000	52.8	55.0	-14,358.0	-46,153.7	-60,511.7	1.78	0.05	1.83	
	2	8,754.1	7254.10909	1,500.0	2,717.5	6563.24156	55.0	55.0	0.0	-364.2	-364.2	2.36	0.01	2.37	
	3	11,947.8	11947.76360	0.0	2,271.4	11947.76360	60.0	55.0	65,712.7	0.0	0.0	0.00	5.43	-0.00	5.43
	4	10,236.7	10236.72730	0.0	2,340.9	10236.72730	67.0	55.0	135,124.8	0.0	0.0	0.00	4.10	-0.00	4.10
S3	1	16,933.5	5,933.50000	11,000.0	2,831.4	2,831.40000	51.1	55.0	-25,487.4	-34,053.7	-59,541.1	1.78	0.37	2.15	
	2	10,254.1	7254.10909	3,000.0	2,839.8	6563.24156	55.0	55.0	0.0	0.0	0.0	2.36	0.10	2.46	
	3	11,947.8	11947.76360	0.0	2,271.4	11947.76360	60.0	55.0	65,712.7	0.0	0.0	0.00	5.43	-0.00	5.43
	4	10,236.7	10236.72730	0.0	2,340.9	10236.72730	67.0	55.0	135,124.8	0.0	0.0	0.00	4.10	-0.00	4.10
S4	1	16,544.9	7,719.10000	8,825.9	2,431.2	2,431.20000	58.9	61.5	-21,983.0	-23,177.9	-45,161.0	2.59	0.19	2.78	
	2	9,148.7	7880.17273	1,268.5	2,675.7	6467.48070	56.8	56.8	0.0	0.0	0.0	2.67	0.01	2.68	
	3	11,947.8	11947.76360	0.0	2,271.4	11947.76360	60.0	55.0	65,712.7	0.0	0.0	0.00	5.43	-0.00	5.43
	4	10,236.7	10236.72730	0.0	2,340.9	10236.72730	67.0	55.0	135,124.8	0.0	0.0	0.00	4.10	-0.00	4.10

Table 4: Baseline annual total heating and reheat loads, fan energy use, and sensible cooling load for five different locations when S1 is applied

	Cincinnati	Charlotte	Seattle	Boston	Fargo
Cooling load kbtu	311,810.4	438,455.5	144,349.7	243,036.1	227,986.7
Total heating kbtu	27,840.7	5,770.2	14,791.6	29,003.1	100,436.7
Reheat kbtu	13,697.4	2,566.7	8,070.8	14,067.0	43,170.8
System heating kbtu	14,143.3	5,770.2	6,720.8	14,936.1	57,265.9
Fan kW	12,214.1	14,745.5	12,403.0	13,144.7	11,587.0

Table 5: Annual percentage energy and load changes from the baseline when S2, S3, and S4 are applied

	Cincinnati			Charlotte			Seattle			Boston			Fargo		
	S2	S3	S4	S2	S3	S4	S2	S3	S4	S2	S3	S4	S2	S3	S4
Cooling load %	2.27	2.27	0.44	1.92	1.92	1.50	8.51	8.51	7.16	3.62	3.62	2.18	2.30	2.30	1.41
Total heating %	35.46	9.38	-8.78	51.60	5.59	-9.21	64.97	7.86	-5.10	30.91	4.14	-2.48	16.29	6.93	4.65
Fan %	-29.71	-27.33	-32.26	-26.19	-25.32	-23.69	-37.67	-35.11	-33.86	-36.93	-34.58	-36.23	-34.19	-31.01	-33.53
Reheat %	105.01	44.53	-15.83	174.57	64.09	-7.54	170.38	65.67	5.85	106.82	45.48	5.39	51.09	23.81	2.70
System heating %	-31.90	-24.67	-1.96	51.60	5.59	-10.54	-61.62	-61.57	-18.25	-40.58	-34.79	-9.89	-9.94	-5.79	6.13

Conclusion

The SAT resetting algorithm in Guideline 36 as a function of OAT may not provide a near-optimal performance. The proposed algorithm using a strategy to count the number of zones in cooling or heating and using this count to reset the SAT instead of only relying on OAT can maintain a better balance between fan power and heating requirement. Using a variable speed fan in the terminal unit with appropriate control can further reduce the reheat requirement while minimizing the negative effect on the total fan power. This will allow to recirculate the warm air from the plenum at zone level rather than AHU level and maintain the SAT slightly colder to meet the cooling loads if some zones are in cooling. The annual results show that the proposed strategies can achieve the same heating requirement or even slightly less than the strategy recommended in the Guideline and significantly reduce fan power in the range of 25-35% depending on the location. Therefore, this study shows a significant improvement from the guideline strategy, and it can be implemented for the VAV systems with parallel fan-powered terminal units to ensure balance and achieve better energy efficiency.

Author's Contributions

Nabil Nassif: Provided the research topic, created the research plan, performed computational simulation and data analysis, and reviewed the manuscript.

Iffat Ridwana: Assisted with conceptualization, conducted data analysis, and prepared visualizations, and the original manuscript.

Mostafa Tahmasebi and Pejman Ebrahimi: Helped with the visualizations and manuscript review.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved.

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