Energy efficient duct design and control of VAV systems: where is the fan energy savings?

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ABSTRACT

Energy efficient operation of variable speed fans in Variable Air Volume (VAV) systems is highly dependent on both the type of duct design as well as the type of control strategy that has been implemented in association with the volume flow demand profiles of each individual zone in the building. The quantification of energy savings due to duct design and the effects of fan control have generally been poorly understood, even with very simplistic types of control strategies, e.g. static pressure *P* + *I* control which have often been employed. The introduction of networked Building Energy Management Systems (BEMS) has offered the possibility to implement more advanced control methods using terminal unit feedback (commonly known as box polling), which can be employed to improve the optimal usage of fan power in VAV systems. The distribution pattern of volume airflow in a multi-zone VAV system with a duct loop is also analysed under various volume flow demand conditions. This paper quantified some of the key issues pertaining to radial and duct loop designs as well as the contribution of various fan control methods to the overall fan energy savings in a VAV system.

INDEX TERMS

Air conditioning; Air distribution; Control; Energy efficiency; HVAC design

INTRODUCTION

Variable Air Volume (VAV) systems are known to be used in large commercial buildings primarily to save fan energy usage during part load conditions by varying the flow of conditioned air to its individual zones. The amount of fan power required to distribute conditioned air to its respective zones as determined by simple Static Pressure (SP) fan control is governed by Eqn (1) (Khoo *et al.*, 1996a; Wang and Burnett, 1998):

$$W_{\text{fanairpower}} = \Delta P_{T(\text{fan})} V_{\text{Total}} = \left(\Delta P_{T(\text{Control})} + \sum (R_{\text{else}} V_{\text{else}}{}^2) \right) V_{\text{Total}} \qquad (1)$$

where $W_{\text{fanairpower}}$ is the supply fan air power (W), $\Delta P_{T(\text{fan})}$ is the total pressure across the fan (Pa), V_{Total} is the total volume flow rate through the fan (m^3/s), $\Delta P_{T(\text{Control})}$ is the total pressure across the duct network due to fan controller's SP set point (Pa). $\sum (R_{\text{else}} V_{\text{else}}{}^2)$ are the sum of the pressure drops as a product of flow resistance and its volume flow rate of each VAV components including duct sections, filters, coils, etc., before the SP sensor (Pa).

The location of the SP sensor and the associated SP at full load conditions is usually used to determine the SP set point of the controller. This normally fixed setting of SP and its associated velocity pressure dictates the value of $\Delta P_{T(\text{Control})}$ (Wang and Burnett, 1998) has highlighted that maximum fan savings of a VAV system under partial load is achieved only when the airflow rate demand of all zones are met by reducing the SP and maintaining the VAV system flow resistance to a minimum. This is achieved by keeping the index Terminal

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Unit (TU) dampers fully opened. The index TU is often defined as the TU which requires the highest pressure across the supply fan to attain its demanded volume flow rate. However, the index TU in a VAV system does not necessarily mean the furthest box requiring the highest pressure requirement from the fan during full load conditions, as normally assumed by Constant Air Volume (CAV) systems. The index TU may shift from TU to TU during different part-load operating conditions especially when the index TU (at full load conditions) throttles down while other TUs (having slightly less pressure requirements at full load) remain having high airflow demands. In this case, the next TU requiring the highest pressure needs becomes the new index TU for that particular part-load operating condition.

Apart from a good fan control strategy, duct design and layout can also contribute significantly to the overall fan energy consumption of a VAV system depending on the load demand profile of different TUs. The duct design and layout is one of the key factors which would determine the base duct resistance of the VAV system's duct network. Hence it is often equally important to design a duct network with low duct system resistance. However, low resistance duct networks often relates to the need for larger sized ducts in which the difference in capital cost must be significantly outweighed by the difference in fan energy savings the larger duct size will make. The most common duct design layout has often been radial, where the main duct run is branched off to smaller ducts along the duct distribution circuit from the supply fan to the most distant TUs. However, duct loops are becoming a more popular duct layout approach as it offers a lower system duct resistance and a higher energy saving potential than radial circuits under diverse asymmetric loading condition (Khoo *et al.*, 1996b). Figure 1 shows the typical VAV duct layouts used in our HVAC test experiments which includes a radial layout, branch layout and a duct loop layout.

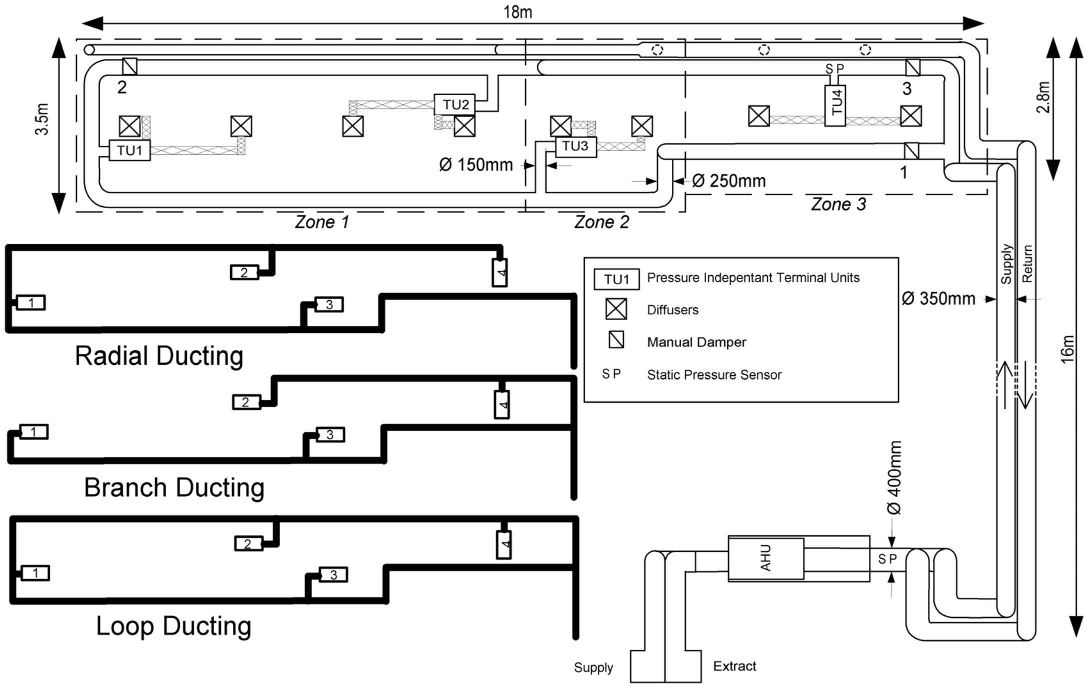

Figure 1 Diagram of the HVAC rig used for experiments.

APPARATUS

A schematic layout of the HVAC rig shown in Figure 1 supplies conditioned air to three occupied zones by four pressure independent TUs (rated to 125 l/s each) from a central Air Handling Unit (AHU) situated in a plant room. The AHU comprises of a three damper economizer, a frost protection electrical heater bank (9 kW), a panel filter, cooling coil connected to an 18 kW chiller, a main electrical heater bank (15 kW), variable speed backward curved centrifugal fan supply fan and a return fan (with a return duct network).

METHODOLOGY

The duct network of the multi-zone VAV test rig is reconfigurable to offer three different types of duct layouts by the opening and closing of manual dampers as shown in Figure 1:

- Radial Duct Layout—This uses a single supply duct to distribute the conditioned air to all zones.
- Branch Duct Layout—This uses two main supply duct branches to distribute the conditioned air to all zones.
- Loop Duct Layout—This uses an equally sized main supply duct constructed in a loop arrangement to distribute the conditioned air to all zones.

The following three fan control strategies have also be implemented on the above duct layouts to establish the fan power required for air distribution in the VAV system.

- Conventional SP Control with SP sensor near the supply fan (SPC).
- Static Pressure Reset Control (SPRC) (Warren and Norford, 1993). All TUs are polled every 60 s to check if any of the TUs in the VAV system are starved (i.e. airflow rate supplying less than 95% of the airflow rate demanded).
  The SP set point is reset up by 5% of its full load SP value, if three or more TUs are starved of conditioned air; the SP set point remains at its present value, when two TUs are starved of conditioned air; the SP set point is reset down by 5% of its full load SP value, if one or less TU is starved of conditioned air.
- Terminal Regulated Air Volume (TRAV) Control (Hartman, 1993). The TRAV controller monitors the actual flow rate and demanded flow rate from all TUs. If any TU is starved by more than 15 l/s below its demanded volume flow rate, a logic signal is sent to the controller which will raise the speed of the fan directly. If any TU is starved by less than 5 l/s below its demanded volume flow rate, a logic signal is sent to the controller to lower the speed of the fan directly. The fan controller which takes a logic signal to either raise or lower the fan speed is essentially an integral controller. The controller has been tuned with an integral time of approximately 900 s to avoid interaction with the TUs damper actuator, which takes approximately 90 s to fully open and close its dampers. At the optimum operating point, a TRAV controller requires the TU to be starved by 10 l/s (between a deadband of 5 l/s and 15 l/s starvation), the demanded volume flow rates used in our TRAV experiments were raised by 10 l/s to counter the offset inherent in the TRAV strategy.

The volume flow rates of the TUs were loaded based on two main load profiles as shown in Tables 1 and 2 to establish the fan power consumption under various duct layouts and control strategies. The TUs were expected to operate between 20 to 100 l/s.

Table 1 Symmetric load profile (where all TUs has got the same demands)

Option	Terminal unit (l/s)				System (l/s)
	TU1	TU2	TU3	TU4	
1	100s	100	100	100	400
2	80	80	80	80	320
3	60	60	60	60	240
4	40	40	40	40	160
5	20	20	20	20	80

Table 2 Asymmetric load profile (where some TUs had high and other TUs low demands)

Loading profile	Terminal unit (l/s)				System (l/s)
	TU1	TU2	TU3	TU4	
1	100	100	100	20	320
2	100	100	20	100	320
3	100	100	20	20	240
4	100	20	100	100	320
5	100	20	100	20	240
6	100	20	20	100	240
7	100	20	20	20	160
8	20	100	100	100	320
9	20	100	100	20	240
10	20	100	20	100	240
11	20	100	20	20	160
12	20	20	100	100	240
13	20	20	100	20	160
14	20	20	20	100	160

RESULTS

From the symmetric load test results shown in Figure 2, the TRAV and SPRC strategy offered very similar part-load performance characteristics as compared to SPC with its SP sensor close to the supply fan, savings of up to 29–32% of full-load fan power were seen possible using the box polling methods (TRAV and SPRC). By placing the SP sensor close to the supply fan, the fan power follows close to a linear law in relation to system volume flow rate. This is due to the fact that the SP set point at the fan is often fixed at a high level to meet the full-load pressure requirement. The SP often dominates over velocity pressure for the duct section close to the fan; variability of fan total pressure during part-load is hence often not large. Duct design, on the other hand, contributed to fan power savings of 13–17% at full load conditions moving from radial to duct loop layout, and a fan power savings of 19–22% was observed moving from radial to a branch duct layout. The significance of fan power savings due to different duct layouts diminishes as the demands of airflow reduces. It is important to note that the radial and branch duct designs were based on an equally sized main duct and not based on a constant pressure drop duct sizing approach which would mean, progressively reducing duct sections. Hence, the fan power consumption in this paper, offered by the radial and branch layouts, is expected to be lower than standard radial or branch designs by approximately 4–2.5%.

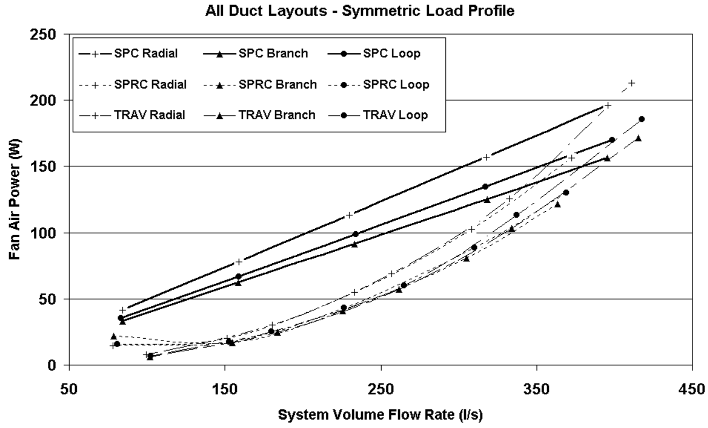

Figure 2 Fan air power for all duct layouts with symmetric load profile.

In the asymmetric load tests, shown in Figure 3, very similar performance characteristics and savings were observed between SPC and box polling methods. However, due to the nature of the branch network, a significantly higher fan power was required if one branch has much higher flow rates than the other. This causes a much higher fan pressure requirement to satisfy the pressure demands of the higher volume flow branch. In such cases the duct loop layout performed better under these diverse conditions, as the airflow would come from the two limbs of the loop. Thus, reducing the overall pressure was required from the supply fan. But on average, the branch duct and loop duct layouts had very similar overall fan power characteristics when having the same type of control method.

SPC dynamically offered the best response to airflow demands as full load SP is constantly available. The TRAV control method was also relatively responsive to changes in airflow demands.

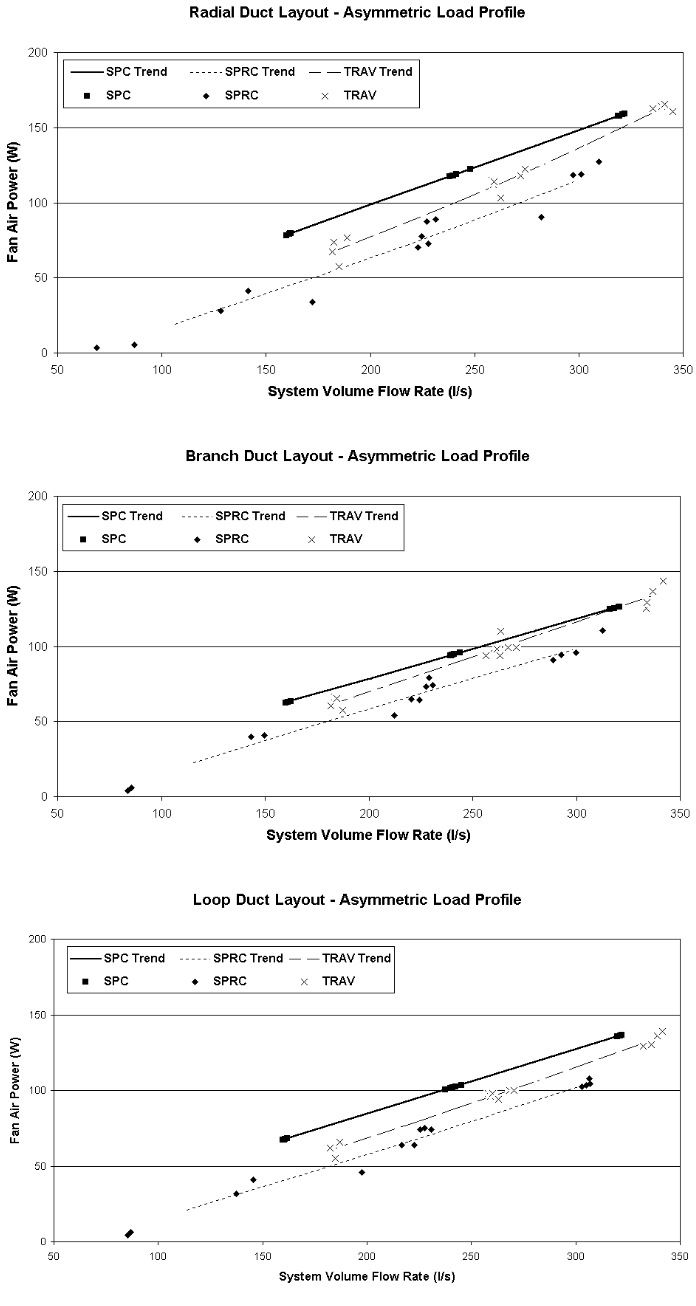

Figure 3 Fan air power for all duct layouts with asymmetric load profile.

Due to the nature of the SPRC algorithm requiring a 60 s polling period, SPRC offered the most sluggish system response to changes in volume flow demands. The dynamic SP response at the supply fan for the three types of control under a symmetric load profile is shown in Figure 4. The SPRC technique could also cause significant starvation issues due to the nature of its algorithm as shown in Figure 3.

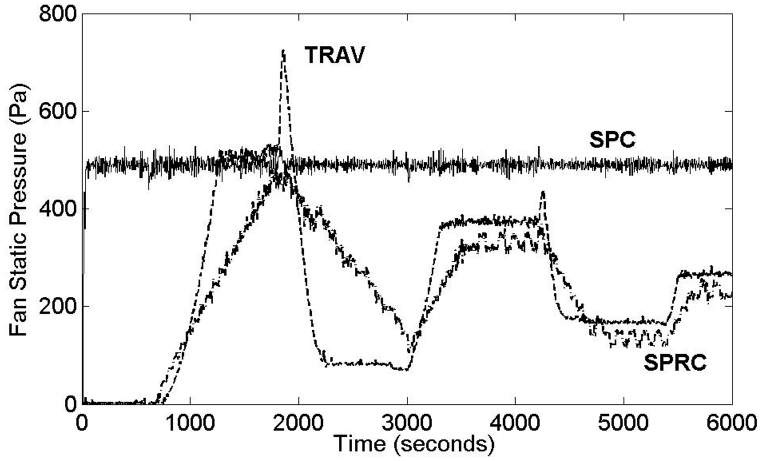

Figure 4 Dynamic response of fan SP with symmetric load profile on a radial duct layout.

CONCLUSION

This paper has shown that box polling methods offer a closer to ideal fan saving in VAV systems than conventional SPC. Although we acknowledge that the recommendations by CIBSE to place the static pressure sensor half to two-thirds down the index run (CIBSE, 1985) offers a good balance of fan energy savings and simplicity of fixed SP control, the fixed SP control technique has its limitation to offer optimum fan energy savings, which has been highlighted in this paper. This paper has highlighted through practical implementation some of the limitations of using box polling methods. TRAV, in this paper, has shown to offer the best balance of fan energy saving and reliability in meeting airflow demands.

ACKNOWLEDGEMENTS

The authors would like to thank The University of Reading through the Research Endowment Trust Fund (RETF), the School of Construction Management and Engineering and EPSRC under Project GR/R33489/01 for their financial support towards this project.

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