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Summary A field experimental study on the performance of a VAV system having a variable speed drive for fan motor under reduced static pressure control has been carried out. Direct-digital-control VAV boxes and network communication technology were applied in the study. The supply fan speed was adjusted to its lowest possible level using summation of airflow passing each VAV box as the control signal. The results confirmed that more fan energy can be saved if duct static pressure is allowed to be reduced as compared to the requirements of fixed static pressure control algorithms, and when a VAV system is operated in lighter load condition under reduced static pressure control.

Variable-air-volume air-conditioning system under reduced static pressure control

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1 Introduction

Variable-air-volume (VAV) air-conditioning systems are widely applied in many buildings because this is the only commonly used design that reduces fan energy consumption significantly as the cooling load is reduced[1]. Instead of varying supply air temperature, the total amount of supply air is decreased at constant temperature. Thus the fan energy consumption is significantly decreased at reduced load conditions.

Traditionally, in a VAV air conditioning system, supply fan control is based on a duct static pressure sensor located at about two-thirds of the main supply air duct run downstream of the supply fan. When the cooling load is reduced, VAV boxes reduce the flow rate of supply air to the areas they serve; thus the static pressure inside the air duct is increased. The static pressure sensor sends a signal to a supply fan controller, normally of the PI type, to reduce the airflow rate by, for example, lowering the fan speed. The desired duct static pressure (setpoint) is maintained. Fan energy consumption is therefore reduced at part load because the fan is running slower.

The fixed static pressure (FSP) setpoint is normally commissioned on the basis of the maximum cooling load condition when the maximum airflow is delivered. However, under part load the duct static pressure setpoint might be unnecessarily high, wasting energy. The duct static pressure for a VAV system can be reduced further under part load without starving any VAV terminal. This is due to the development of direct-digital-control (DDC) and network communication technology. Fans can be expected to consume up to 40% less energy[2].

This paper reports a field study of the performance of VAV air conditioning under reduced duct static pressure control. The summation of airflow rate passing each VAV box is used as the control signal. The control algorithms are discussed and the experimental set-up is described. The field measurement results are presented, confirming that fan energy consumption can be further reduced using reduced static pressure (RSP) control.

2 Background

Previous work included retrofit for a VAV system from variable inlet vanes (VIV) to variable speed drive (VSD).This motivated the search for a static pressure minimisation control technique[3]. In the project, the static pressure in the duct was reduced manually from 0.62 kPa to 0.37 kPa after the retrofit. The required minimum inlet pressure for each VAV box was between 0.042 and 0.14 kPa. The reduction in static pressure resulted in a clear fan energy reduction; 69% for one air handling unit (AHU) and 46% for another. The work concluded that if, in conjunction with variable speed drives, the constraint on duct static pressure is relaxed, fan motors may use as much as 50% less energy relative to conventional control (i.e. using inlet vanes and a FSP setpoint). But lowering static pressure in a VAV system with VIV has little benefit. It was also recognised that resetting duct static pressure manually, a low-cost measure, is not feasible if this must be done frequently.

On the basis of the results obtained in the retrofit, the same researchers proposed two methods of controlling a supply fan to minimise duct static pressure without sacrificing occupant comfort or adequate ventilation[4]. Both methods (the modified PI and heuristic approaches) used a feedback airflow rate signal from local zone flow control loops. This has recently become possible with the introduction of DDC terminal boxes. A public-domain dynamic simulation program HVACSIM+ was used to evaluate the two control approaches on the basis of measured data from the retrofit. Preliminary evaluation of the proposed static pressure minimisation control algorithms using mathematical simulation was encouraging. It confirmed that energy can be saved through duct static pressure minimisation in a VAV system equipped with VSD.

Duct static pressure has also been minimised using duct static pressure reset algorithms[2]. Each DDC terminal box has a low airflow alarm setting, which can be communicated to a microprocessor-based fan controller via a network. If the controller found that several of its terminal units (typically three) gave a low airflow alarm, it generally indicated that the static pressure provided by the fan was too low. The static pressure was then reset upward by 5% every 60 seconds until the alarm ceased. If only a minimum (typically one) of its terminal units gave a low airflow alarm, the duct static pressure was reset downward. Field measurement showed that on average up to 40% of fan energy could be saved.

It has been recognised that saving more energy due to lower required fan power results from decreasing the pressure drop across terminal boxes. These open wider for a given flow rate. With the air damper inside a VAV box at its minimum position, decreasing the inlet pressure will result in less flow through the box. However, if there is an airflow sensor in the box which monitors airflow so as to open the damper wider to allow more air to flow into the terminal unit if its inlet pressure is lowered, then duct static pressure can be reduced to the minimum without starving any terminal units.

It has been also recognised that precise duct static pressure control cannot be achieved without adding an electronic control system. This allows communication with each of the terminal boxes to ensure that none of them has insufficient inlet pressure or lower airflow rate(3). This is not a problem with the introduction of DDC VAV terminal box and network technology. With further development of this, it is now possible to adopt new control approaches to minimising duct static pressure. These save more energy as against fixed static pressure control. An example is the control algorithm reported here, which uses the summation of airflow rate from each DDC VAV box to adjust the supply fan using a VSD.

3 Experimental setup

3.1 Building DDC VAV system

A new office building was used to study a VAV system under RSP control. The gross floor area of a typical floor is about 23 000 ft^2. There are two AHUs on each floor, each handling the cooling load of half of the floor. Two typical floors (the third and fourth) were used for the measurements. A traditional FSP controlled VAV system was installed on the third floor and a RSP controlled VAV system on the fourth. Supply fan speed can be varied through VSDs on both floors. The office floor was not occupied during the experiment, so four 15 kW electric heaters were placed on each floor to simulate the cooling load. This arrangement would ensure that the results of traditional FSP control and RSP control could be compared accurately. The cooling loads for two adjacent floors of the same building with the same orientation, envelope structure and electrical heating output will be identical.

The RSP control in this study is based on summing the airflow passing through each pressure-independent DDC VAV box at the air stream inlet. The DDC VAV box can also calculate the airflow required for cooling according to the difference between the actual space air temperature and the desired space air temperature (set point). All VAV boxes served by a supply fan are linked through the network. It is therefore possible to sum the total required airflow and total actual airflow from all the boxes. The difference between the two sums is used as an error signal for controlling the fan speed. A proportional-plus-integral (PI) controller sets the supply fan to the lowest static pressure output delivering just the right airflow.

A microprocessor-based data concentrator taps the network to access data from each VAV box. It also has analogue output for fan speed control. The data concentrator polls data from up to 128 individual boxes at a given sampling interval. A summation loop is then followed giving the total required flow rate to be delivered to the ductwork. An error signal is derived and used for fan speed control by the PI controller, which can be represented as follows:

$$M = K_p[e + (\Delta t/K_i)\int e\,dt \qquad (1)$$

where M is the controller output, e is the error signal between the total actual airflow and total required airflow, Δt is the sampling interval, K_p is the proportional gain, K_i is the period of integration.

The PI controller is incorporated in the data concentrator; its output is sent to the VSD via the analogue output channel.

A predefined dead band is introduced into the control algorithms by the data concentrator. Once the errors fall within this band, a reset algorithm takes over the PI control. A timer is reset once the reset algorithm is triggered. Should the error still be within the deadband after the reset timer, the fan speed will be lowered by a user defined percentage and the timer is reset. If however the error exceeds the band, the PI control is activated. The supply fan speed is controlled continuously between the PI control and the reset algorithm. The purpose of the reset algorithm is to ensure that the fan will deliver the right airflow to the ductwork with the fan speed (or the duct static pressure) reduced to the lowest possible. The control algorithms for the data concentrator are shown in Figures 1 and 2.

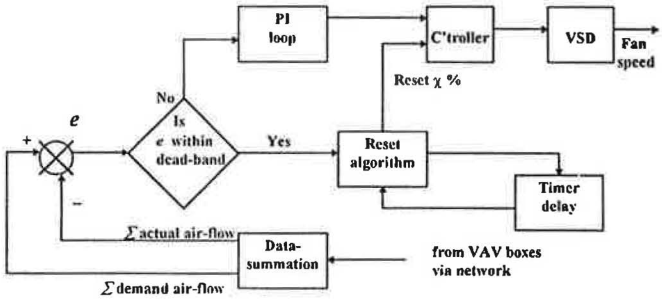

Figure 1 Airflow control algorithm of data concentrator

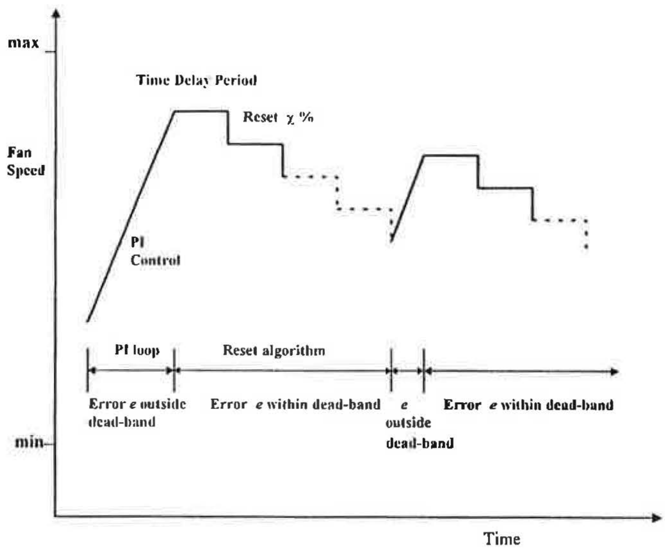

Figure 2 Fan speed control algorithm of data concentrator

The complete schematic of experimental setup for RSP control algorithms is shown in Figure 3.

For FSP control, a static pressure sensor located in air duct is used for fan speed control via a PI controller. This is typical of common use and the details are not repeated here.

The following parameters were measured and recorded for FSP and RSP control simultaneously:

- actual airflow rate (l s^{-1})
- demanded airflow rate (l s^{-1})
- fan speed (rpm)
- fan motor running current (Ampere)

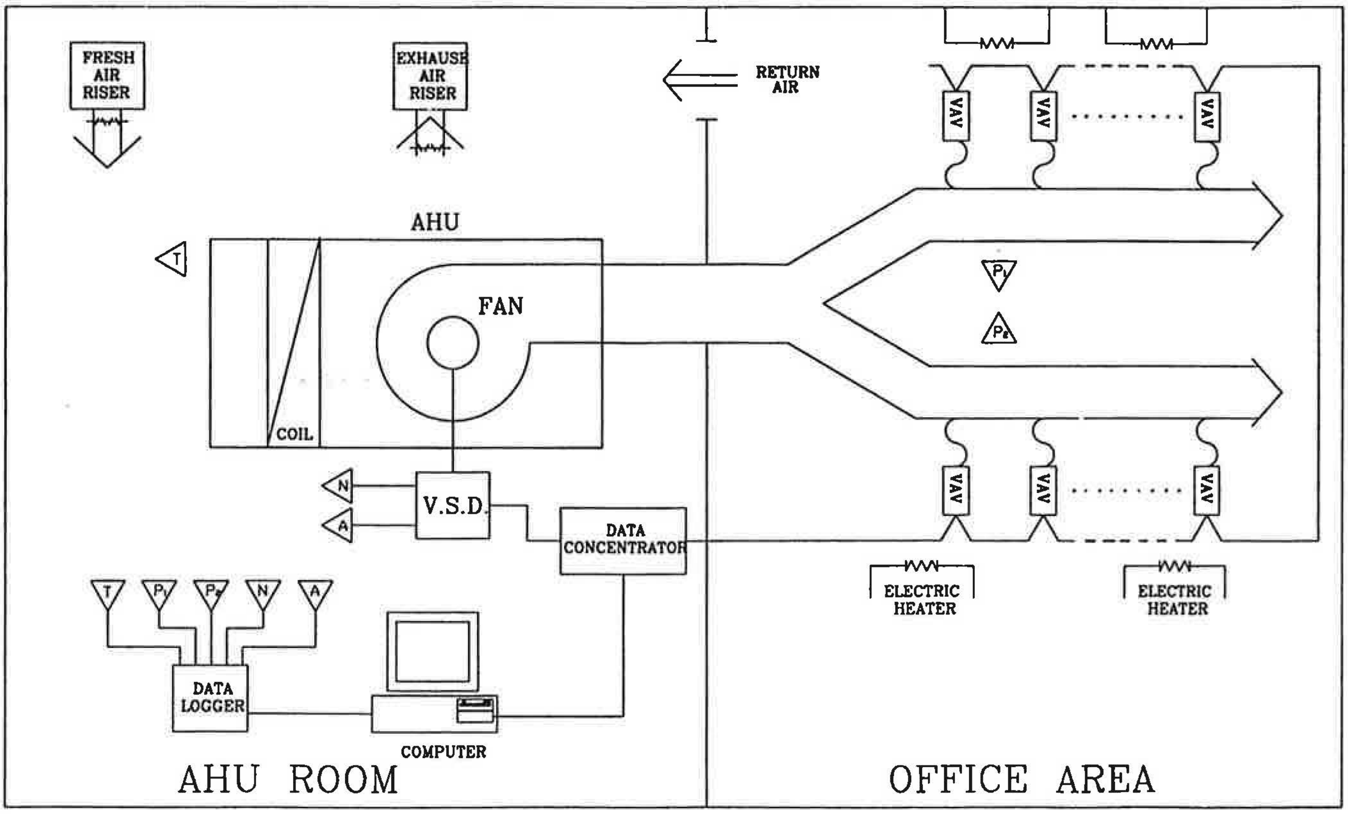

Figure 3 Complete air-conditioning schematic for VAV system under RSP control ($p1$ and $p2$ duct static pressure; T return air temperature; N fan speed; A fan motor current)

— air duct static pressure (Pa)

— AHU return temperature (°C)

Due to the limitation of computer software, the space temperatures under VAV boxes can only be displayed but not recorded for analysis. AHU return temperatures were therefore used in the comparison between FSP and RSP control.

3.2 Experimental procedures

The experimental work was divided into three parts:

— determination of proportional gain K_p and integral time K_i for the PI controller used in RSP control, based on the method developed by Zeigler and Nichols[5]

— study of the system performance through simulated supply airflow rate under both FSP and RSP control algorithms

— study of the system performance through simulated cooling load from electric heaters placed in the spaces under both FSP and RSP control algorithms.

4 Results and discussion

4.1 Determining settings for PI controller used in RSP control

The proportional gain K_p and integral time K_i for the PI controller used in RSP control were determined according to the method of Zeigler and Nichols[5]. The best settings were found to be:

$$K_p = 0.0227 \quad (2)$$

$$K_i = 60 \text{ s} \quad (3)$$

4.2 Performance assessment through simulated supply airflow

In this study, the fan energy consumption and duct static pressures were measured and compared as between the RSP control and the FSP control. The supply airflow of all VAV boxes in both floors was set manually at the same value. Since there are the same number of VAV boxes on both floors, the total airflow rate from the supply fans will be identical. The purpose of this study is to compare the system energy performance when same amount of airflow was delivered to air conditioned spaces by supply fans under the RSP and FSP control algorithms. Thermostats on both floors were disabled. The airflow rate for each VAV box was gradually changed from the maximum of 120 l s^{-1} (100% load airflow) to the minimum of 80 l s^{-1} (66% peak load airflow). The results are shown in Figure 4 for fan speed and static pressure, and Figure 5 for fan motor running current. It is seen from Figure 4 that duct static pressure was maintained relatively constant under FSP control. It reduced gradually as the flow rate was decreased under RSP control, and therefore the fan was running slower. The motor running current under RSP control as shown in Figure 5 is lower than under FSP control. On average, a 30% reduction in energy consumption was achieved.

It is also seen from the diagrams that under the RSP control, at full airflow (120 l s^{-1}), an energy saving of 10% was obtained because the duct static pressure was allowed to be lowered as compared with that under FSP control. This saving gradually increased to about 32% at reduced flow condition (80 l s^{-1}). This is significant because it indicates that energy reduction is greater when the supply airflow is smaller at part load, given that an air-conditioning system operates most of the time under reduced load.

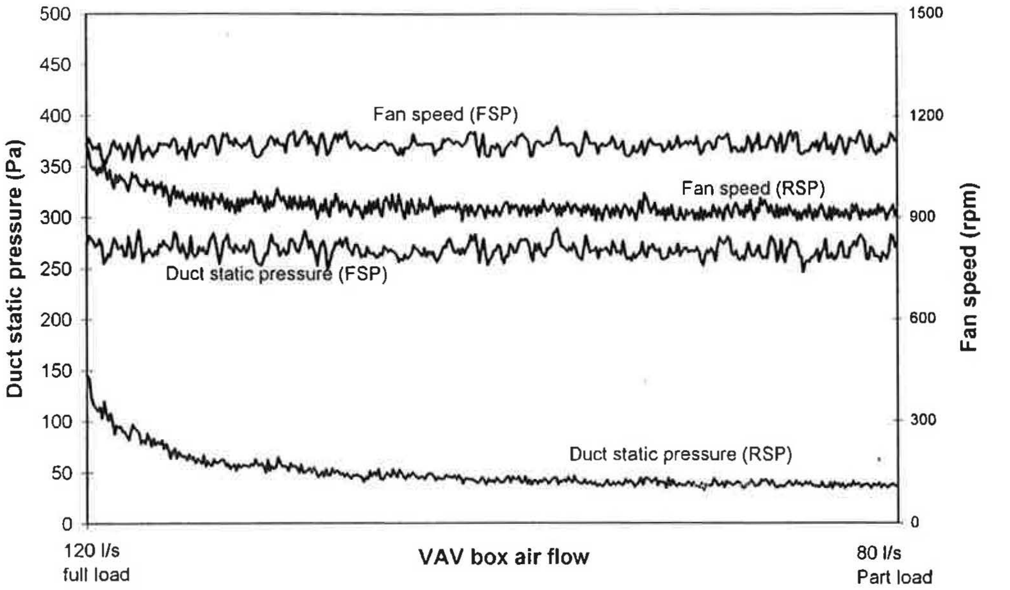

Figure 4 Duct static pressure and supply fan speed under RSP and FSP control in simulated airflow test

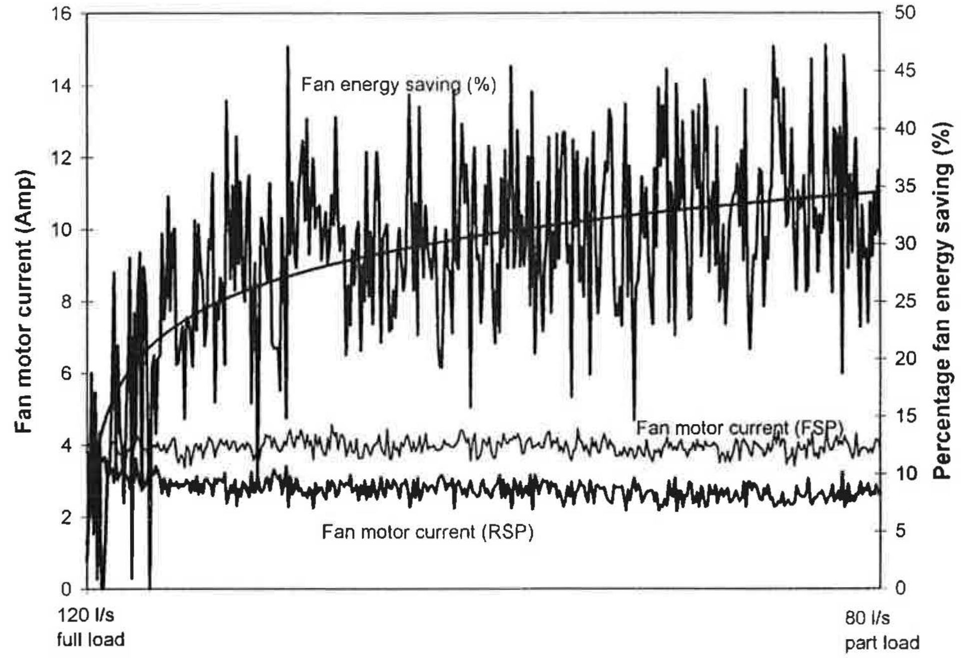

Figure 5 Supply fan motor current under RSP and FSP control and percentage fan energy saving in simulated airflow test

4.3 Performance assessment through simulation of cooling load by electric heaters

This is to compare the energy performance of VAV systems under FSP and RSP control in a real building. At the time of measurement the building was unoccupied and electric heaters were used to simulate the cooling load. On each floor there were four 15 kW electric heaters, giving a total load of 60 kW.

During the experiment all operating parameters (room temperature settings, amount of fresh air supply, etc.) for VAV systems on the two floors were set identically.

Operating parameters were measured for VAV systems under RSP and FSP controls. These included AHU return air temperature, duct static pressure and fan speed and fan motor running current. Examples are shown in Figures 6–11. Figures 6–8 show the results when the room temperature was set at 25°C. In the diagram, AHU return temperatures are shown instead of actual room temperatures. The return temperatures were however several degrees lower than the space air temperature because they were measured after the return air had mixed with the fresh air supply from the primary air handling units (PAUs). From the diagrams, the AHU return air temperatures for both floors were almost the same, but the duct static pressure under RSP control was much lower than that under FSP control. The fan speed and thus the fan motor running current under RSP control were lower than under FSP control. The average energy reduction was at around 30%. The results with the room air temperature set at 23 °C are shown in Figures 9–11. At the start, since the systems on both floors were operating under almost full load to cool the building envelope first, fan speeds and duct static pressures were almost the same. However, when the building cooled later, differences in static pressure and fan speed between the floors became obvious. Results similar to those at 25 °C were obtained, but the percentage energy reduction was smaller at about 20% on average. The diagram also shows that when the heaters on both floors were turned off about 430 minutes after starting the experiment, room air temperatures experienced a small decrease and gradually reverted to their original values. The duct static pressure level under FSP control was main-

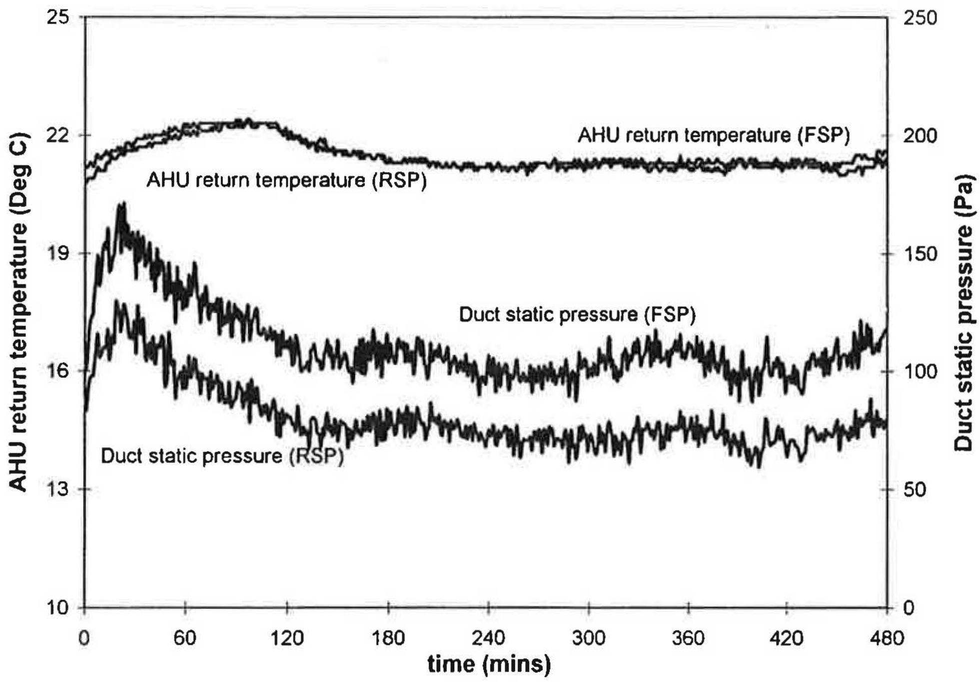

Figure 6 Comparison of AHU return temperature and duct static pressure under RSP and FSP (25°C room setting)

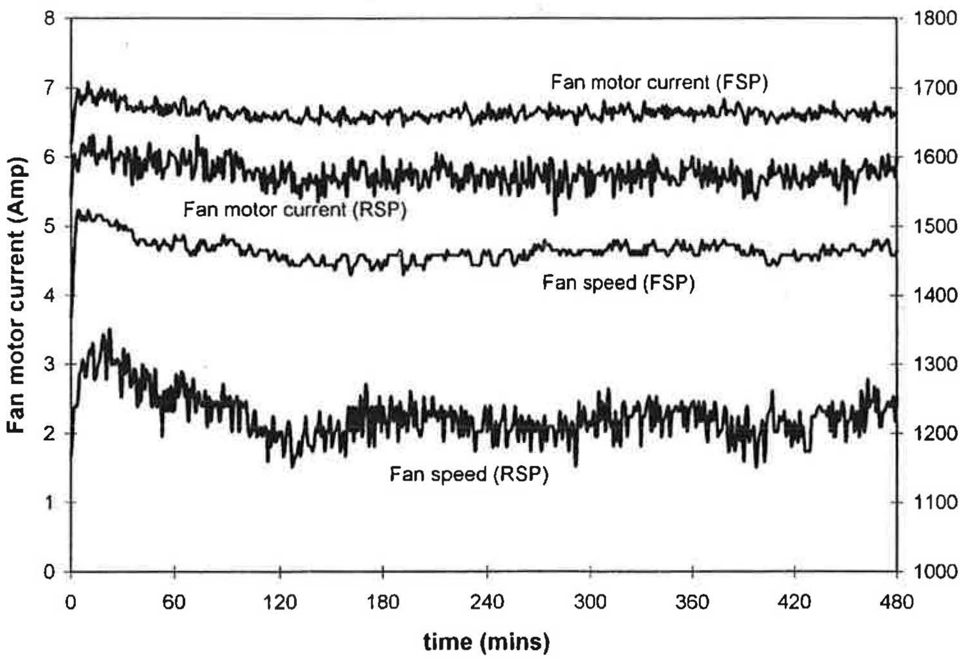

Figure 7 Comparison of fan speed and motor current under RSP and FSP (25°C room setting)

tained, but that under RSP control reduced significantly. Energy consumption was reduced over this period by as much as 40%.

It might be assumed that when the room air temperature was set higher, the VAV system operated under lighter load. Comparing the two sets of results, it is not difficult to show that under RSP control fan energy reduction at 25 °C room temperature setting was greater than at 23°C. This may be interpreted as greater fan energy reduction under part-load conditions.This agrees with conclusions from the simulated airflow study.

4.4 Discussion

The study has shown that when a VAV air conditioning is under RSP control, fan energy can be reduced more than under FSP control. This is because when duct static pressure is allowed to be lowered there will be less throttling in VAV boxes. The fixed duct static pressure is normally based on maximum supply airflow condition. When the airflow is reduced at part load this pressure setting might be unnecessary high.

In the reset algorithm, either increasing the reset ratio or reducing the reset timer can quickly force duct static pressure to decrease. However, the reset ratio must not be so large as to cause system oscillation, nor the reset time so short that the system becomes more sensitive to load change. The best values for these parameters should be determined through field testing and commissioning. Here they were determined as 2% and 40 seconds respectively.

Precise duct static pressure control requires an advanced electronic system communicating with each VAV box. With the recent introduction of DDC VAV boxes, a VAV system under RSP becomes cost-effective over the life cycle of new construction. The capital cost is higher. In this project reported in this paper, a payback period of 2.5 years according to the net present value method indicated that this is attractive.

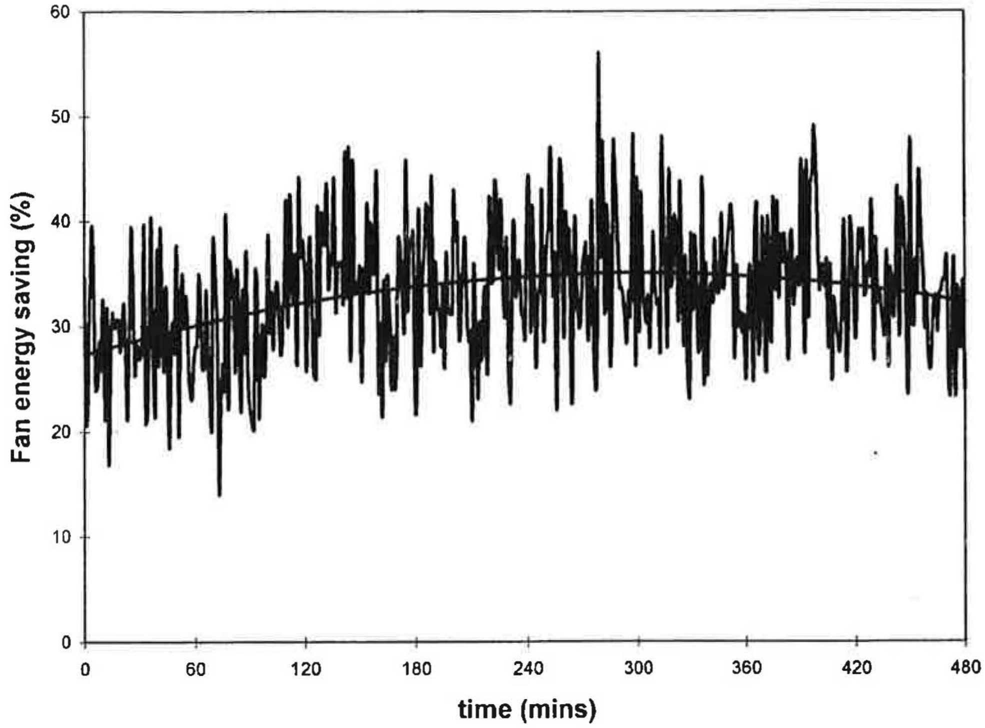

Figure 8 Fan energy saving of RSP control over FSP control (25°C room setting)

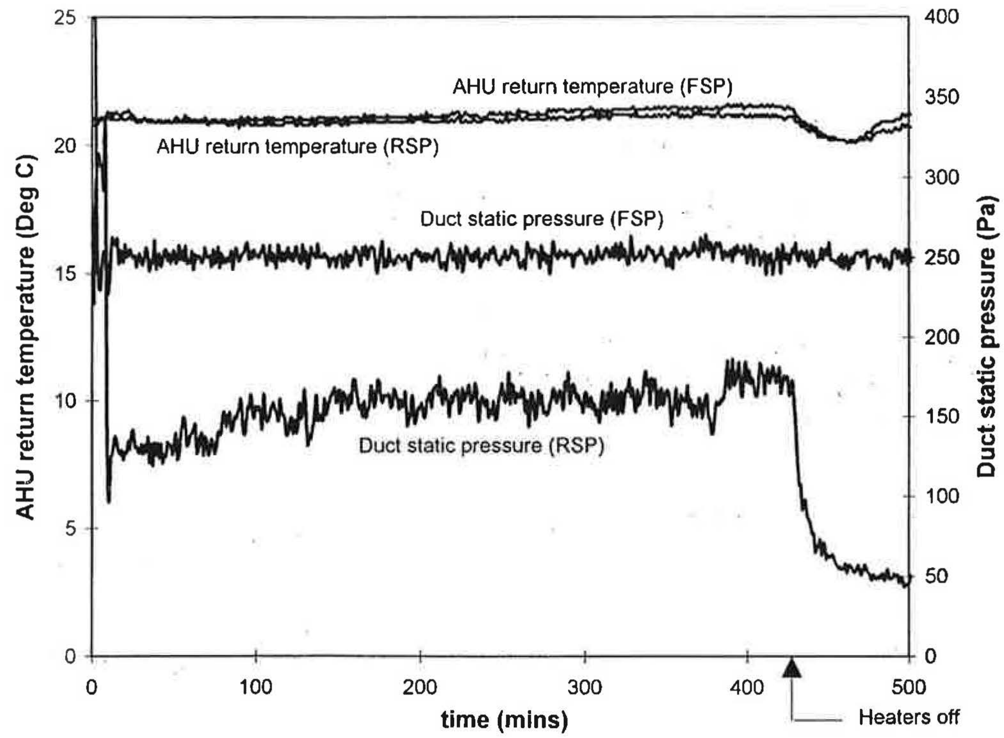

Figure 9 Comparison of AHU return temperature and duct static pressure under RSP and FSP (23°C room setting)

Reducing static pressure in a VAV air conditioning system offers additional fan energy saving over a VAV system under FSP, makes the VAV system quieter and smoother in operation and reduces maintenance of the VAV boxes.

5 Conclusions

Measurements confirm that additional saving in fan energy consumption can be achieved when a VAV system is under RSP control in comparison with that under FSP control.

This study also revealed that greater fan energy saving resulted under lighter load under RSP control. Given that air conditioning operates under part load for most of the time, the results are important if such a control strategy were widely applied. VAV air conditioning system is already advantageous in energy conservation. RSP control will make it more so.

This work used the summation of airflow rate as the control signal. Different approaches might be applied in RSP control for a VAV system, but perhaps with varying degrees of energy reduction. As long as the duct static pressure in a VAV system is no longer fixed, but is allowed to be reduced, additional fan energy reduction is achievable.

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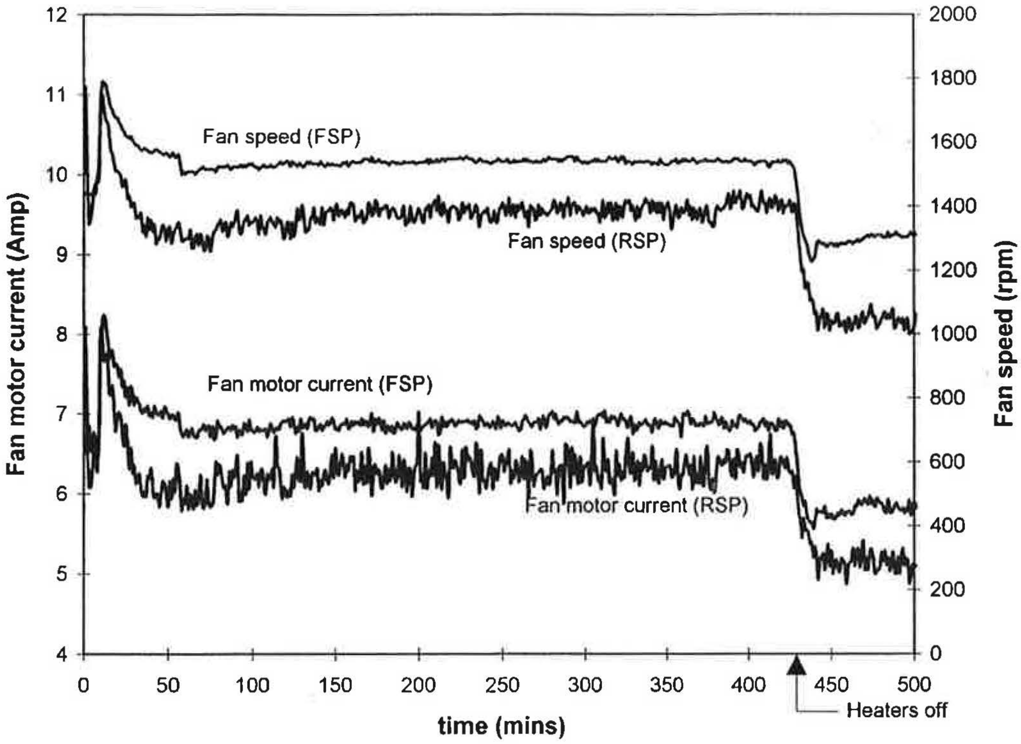

Figure 10 Comparison of fan speed and motor current under RSP and FSP (23°C room setting)

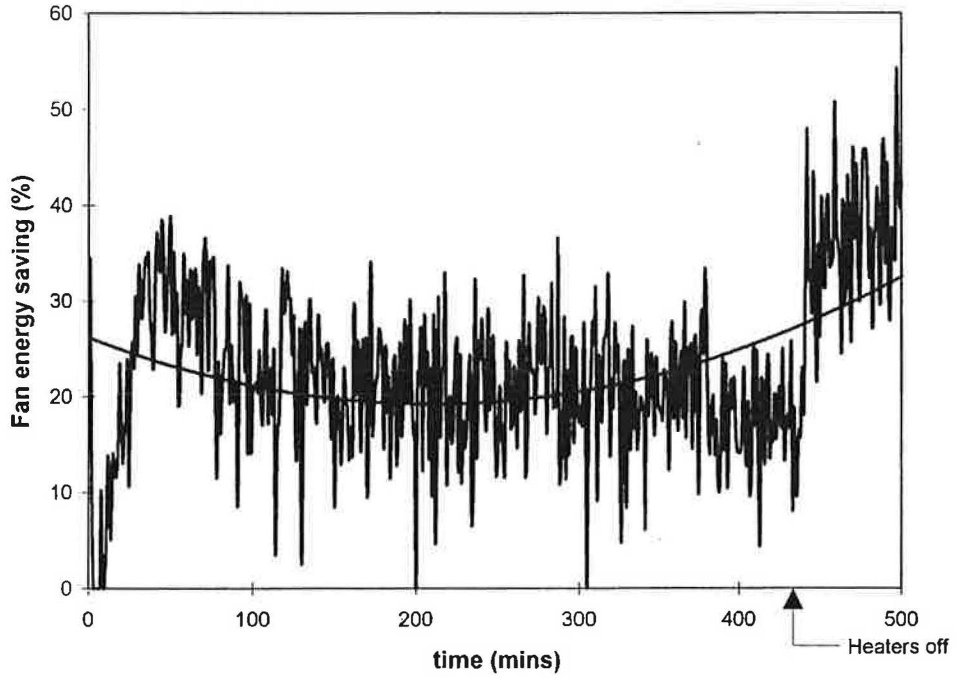

Figure 11 Fan energy saving of RSP over FSP control (23°C room setting)

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