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Experimental and Analytical Evaluation of VAV Air-Conditioning System in An Office Building

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Abstract

The flow-pressure characteristics of the AHU/VAV air-conditioning system in an open-plan office building is assessed by site experiments under various conditions. The effects of VAV supply pressure setting, return fan pressure setting and damper operation on energy consumption, fresh air intake and ex-infiltration flow rate are evaluated analytically on the basis of the VAV/AHU system and component characteristics.

Introduction

Energy and health are the main issues concerned in buildings recently besides comfort. Proper operation or control of the air-conditioning system is essential to maintain a comfort and healthy environment with minimum energy input besides the system design and efficiency of components. Concerning operation and control of a air system, the energy consumption associated to air-conditioning in a building is affected by the air flow rate, fan pressure settings, fresh air intake and infiltration. The amount of fresh air intake is one the main factors determining the health of indoor environment or indoor air quality.

The use of VAV system provides significant energy saving in partial load by reducing the air flow rate supplied to the occupied zones. However, the conventional VAV system control reduces the supply air flow rate by increasing the flow resistance while keeping constant AHU fan supply static pressure. An even more energy efficient operation for reducing VAV system supply air flow rate intends to keep minimum flow resistance of VAV dampers (i.e. keep VAV dampers fully open) [1,2,3]. In this case, the AHU fan supply pressure needs to be reduced until it is just high enough and not more than enough for those critical zones, concerning the fact that the load is not evenly distributed in practice.

The fresh air intake often gives contrary effects on the energy and health issues except the cases when free cooling is applicable or partially applicable [4,5]. Normally, more fresh intake provides better indoor air quality but also increases the cooling load of the cooling coils. To properly balance the effects of fresh air intake on energy and health, the use of economizer (or enthalpy control) should be combined with low limit of fresh air intake or demanded ventilation [6,7].

In order to evaluate the potentials of energy saving by resetting supply fan and return fan pressures and the controllability of fresh intake, site experiments and analytical tests are conducted prior to upgrading the air system control from pneumatic controllers to integrated DDC in the building. It also presents the possibility of using the existing fire damper to increase the fresh air intake, the possibility of controlling the fresh air ratio by resetting the return fan outlet pressure on the existing A/C system and the effect of pressure drop across the filter on the energy consumption.

Air System and Experiments

The building is 46 stories office building with an atrium at the center of the floors. The floor under investigation is an open plan office of about 2300 square meters usable floor area. Two central air handling units (AHU) serve the floor. Each of them serves half of the floor. One AHU consists of a VAV system and a CAV system which serves the perimeter zones only. There are about 40 VAV dampers and over 100 air diffusers associated with one AHU. The design air flow rates of the VAV system and CAV system are 6 m3/s and 1.4 m3/s respectively. The design VAV supply fan pressure at the location of pressure sensor (about two third of main duct length from AHU) is 650 Pa. Both the VAV supply fan and the return fan are variable pitch angle fans. There are no damper moderating actuators on the existing air handling units. A schematics of the AHU and the locations of pressure measurement are shown in Figure-1.

The supply flow rate, return flow rate, and fresh air flow rate and the pressure drops across the dampers, filter, coil, air ducts and VAV dampers are measured under various flow rates by manually changing the supply and return fan pitch angle. The flow resistance of VAV dampers at "regular" operation conditions is monitored. The flow resistance of VAV dampers at damper fully open position and minimum position are tested by manual control of existing pneumatic controllers. The fan performance curves from manufacturer's catalogue are verified with a few site tests and used in the analytical evaluation.

The evaluation of the system performance under various operating conditions was performed by simulating the A/C system controlled by DDC. Simulation is performed using TRNSYS (A Transient System Simulation Program) as the platform using the models developed to representing the pressure-flow characteristics and energy performance of components, flow-pressure balance of air-conditioning system and operation of DDC. In the test cases, one PID controller controls the AHU supply static pressure by regulating the VAV supply fan pitch angle, and the return fan outlet pressure is controlled by another PID controller. The corresponding office area is divided into eight zones. One VAV terminal from each zone is selected and controlled by a PID controller to represent the VAV terminals in the zone. The air flow of an entire floor area is obtained by multiplying the flow rates of the selected VAV terminal by suitable factors.

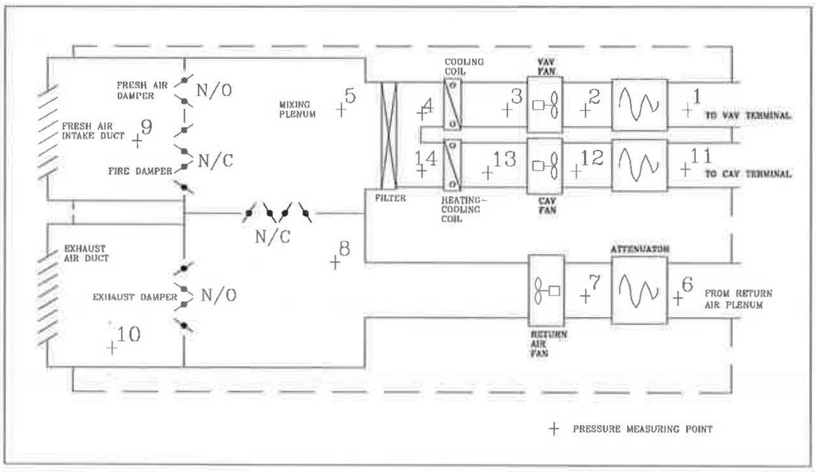


Figure-1 Schematics of AHU and pressure measurement points

System and Component Characteristics

Figure-2a&2b present the pressure-flow characteristics of fresh air damper with fire damper open and fire damper closed respectively. It can be observed that the fresh air intake with open fire damper is close to five times that with closed fire damper at same pressure head. The fresh air ratio can be increased significantly when the fire damper is opened. Figure-2c&d show the pressure-flow characteristics of exhaust and recycle air dampers. The flow resistance of the exhaust damper is much high than that of the recycle damper. It shows that the main proportion of return air will be reused under normal operation. Since the dampers are very close to the fans, the pressure is not very stable. Significant measurement errors appeared as indicated in the figures.

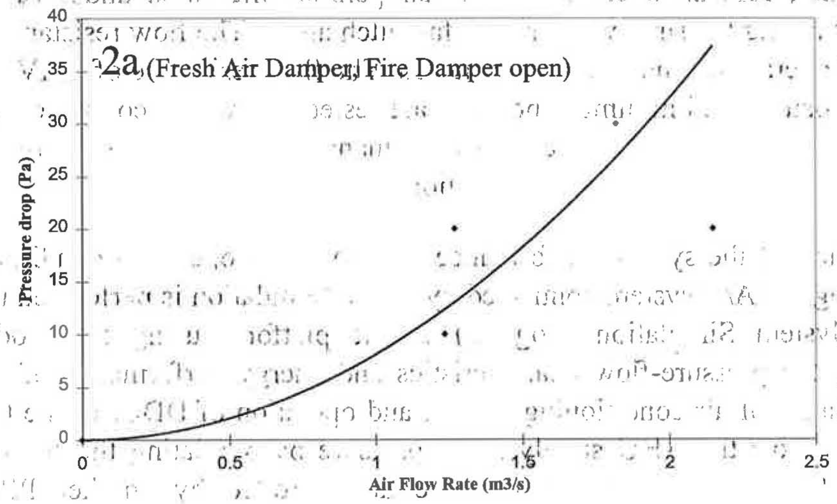


Figure-2a Pressure-flow characteristics of fresh air damper (fire damper open)

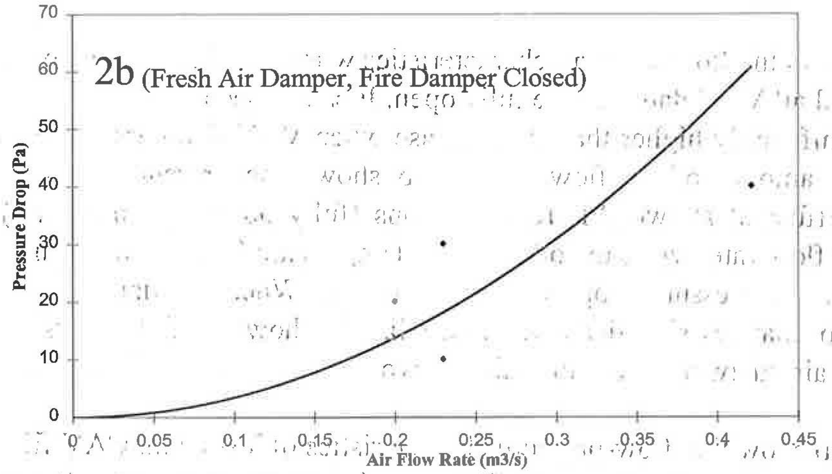


Figure-2b Pressure-flow characteristics of fresh air damper (fire damper closed)

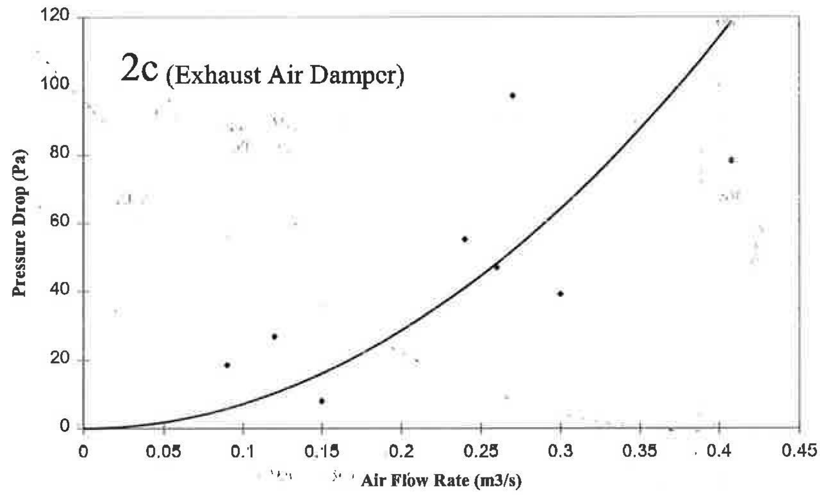


Figure-2c Pressure-flow characteristics of exhaust air damper

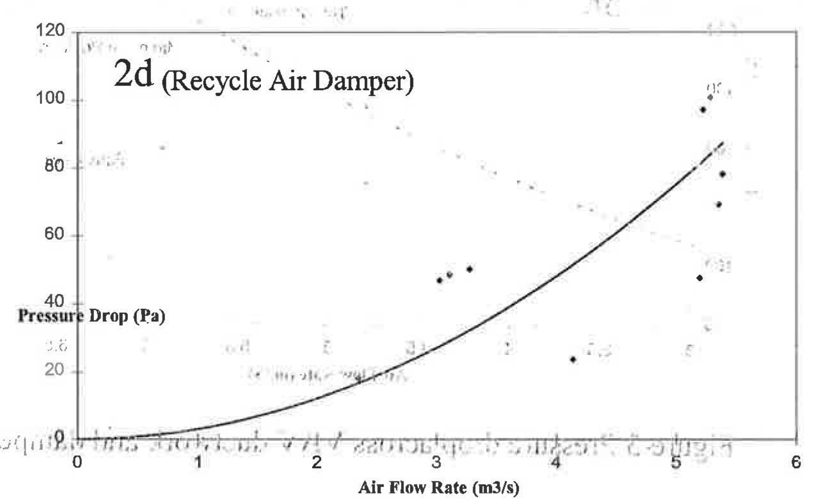


Figure-2d Pressure-flow characteristics of recycle air damper

Figure-3a shows the flow-pressure characteristics when VAV dampers are in "regular operation positions" and all VAV dampers are fully open. It can be seen that the pressure drop in "regular cases" is significantly higher than that in case when VAV dampers are fully open in order to supply same amount of air flow. Figure-3b shows the pressure drop on a VAV damper (including diffusers) at two different positions (fully open and minimum) at different total VAV supply flow rate, while the other VAV dampers are fully open. It can be seen that a main proportion of the pressure drop is on the dampers. When the damper position changes, the pressure drop changes significantly. Figure-4a&4b show the flow-pressure characteristics of CAV supply air ductwork and return air ductwork.

Figure-5a&5b show the flow-pressure characteristics of VAV and CAV filters and coils. It can be observed that the pressure on the filter contributes the major part. It can be also found by comparing Figure-5 with Figure-3 that filters contribute significant proportion to the required fan delivery head.

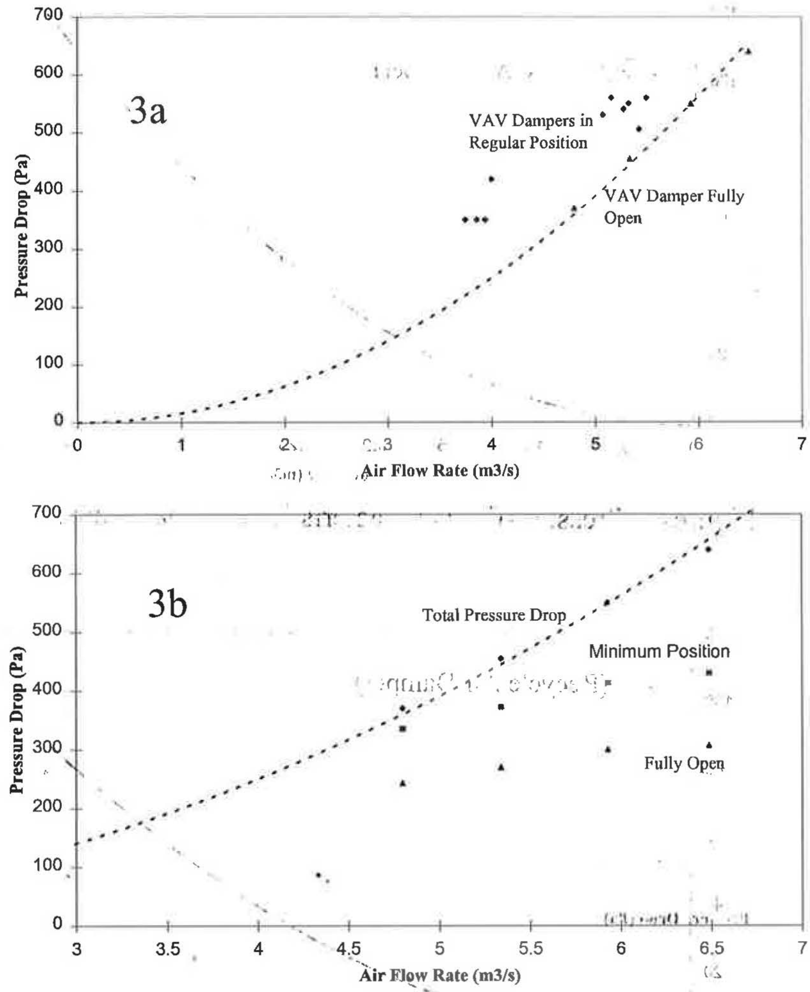


Figure-3 Pressure drop across VAV ductwork and dampers

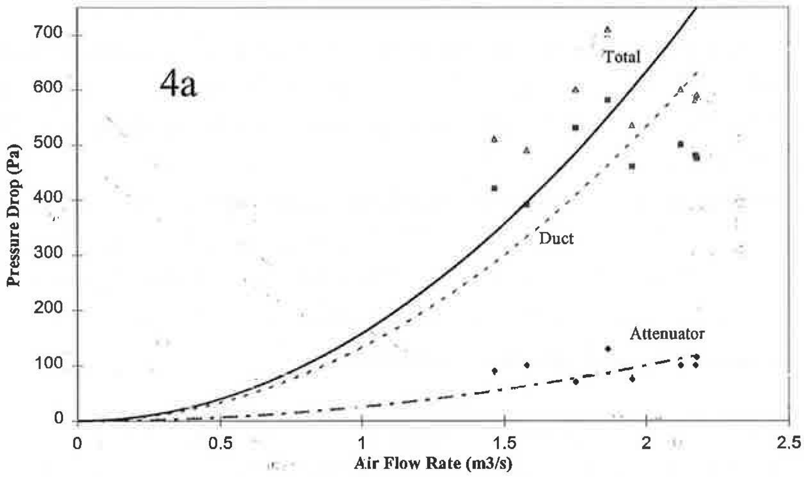


Figure-4a Pressure-flow characteristics of CAV ductwork

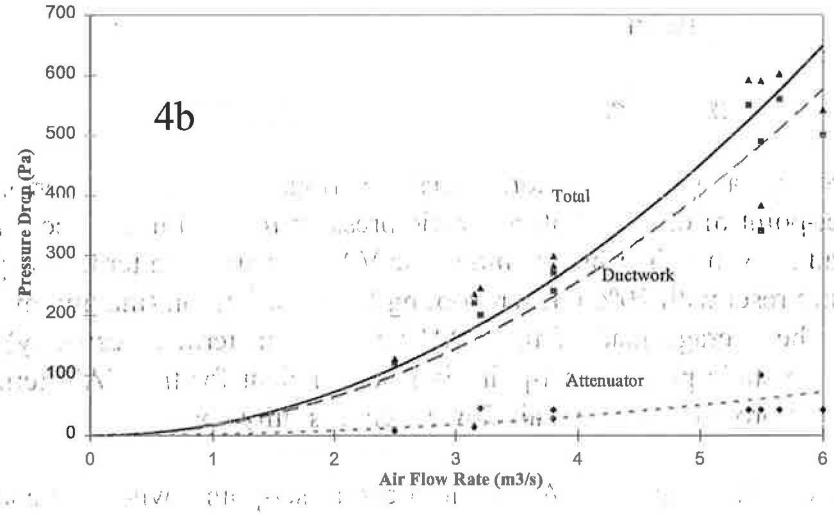
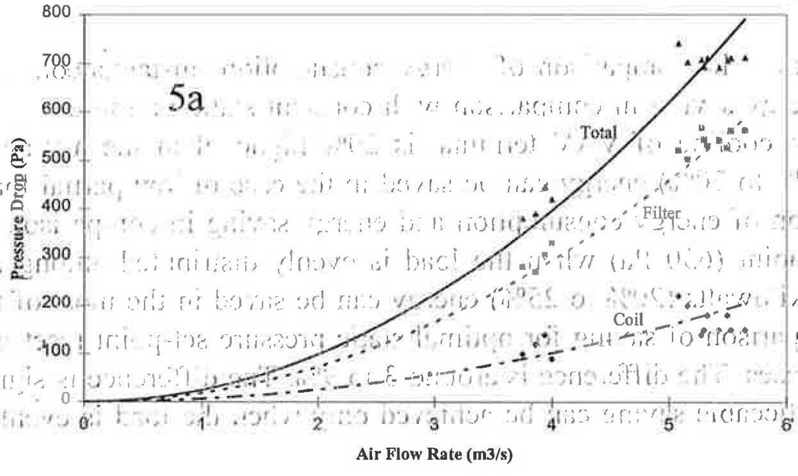


Figure-4b Pressure-flow characteristics of return ductwork



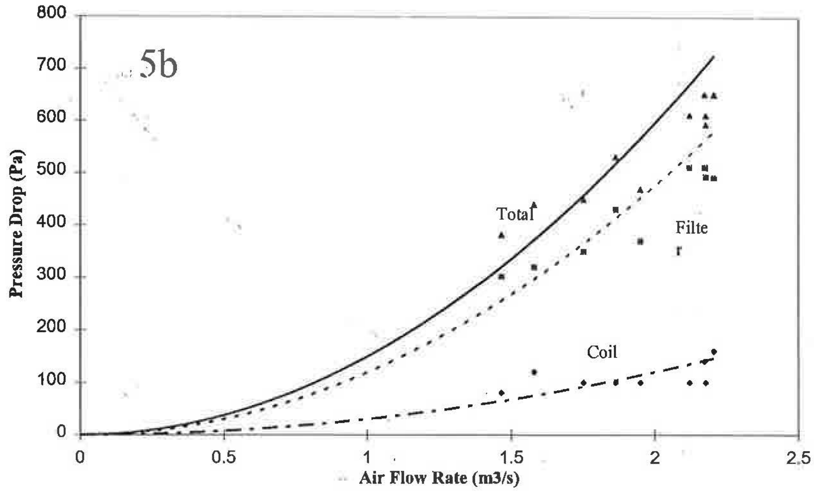


Figure-5 Pressure-flow characteristics of CAV and VAV filters and coils

Analytical Evaluation

Effects of Static Pressure Reset

Tests on pressure and energy performances at various flow rates are performed in three cases, i.e. fixed set-point of 650 Pa, optimal static pressure reset with even cooling load distribution (cooling load is evenly distributed among the VAV terminals in term of capacity), and optimal static pressure reset with 20% uneven cooling load distribution (maximum cooling load is 20% higher than the average load of the VAV terminals in term of capacity). The optimal reset means that the static pressure set-point is just sufficient for the VAV terminal for maximum cooling load to provide sufficient air flow when it is fully open.

Figure-6a shows the required VAV static pressure set-points when the cooling load is evenly distributed and when the maximum load is 20% higher than the average load. It can be seen that the required pressure set-point can be significantly less than the constant set-point of 650 Pa in cases when the demanded flow rate is low. When the cooling load is evenly distributed among VAV terminals, the minimum static pressure set-point is significantly lower than that of the uneven distribution case.

Figure-6b shows the comparison of energy consumption (instantaneous power of the fans is used) and energy saving in comparison with constant static pressure set-point (650 Pa) when the maximum cooling of VAV terminal is 20% higher than the average load. One to two kilowatts (10% to 20%) energy can be saved in the case of low partial load. Figure-6c shows the comparison of energy consumption and energy saving in comparison with constant static pressure set-point (650 Pa) when the load is evenly distributed among the VAV terminals. Around two kilowatts (20% to 25%) energy can be saved in the most of the cases. Figure-6d shows a comparison of saving for optimal static pressure set-point reset in two different load distribution cases. The difference is around 3 to 9%. The difference is significant at high flow rate, since noticeable saving can be achieved only when the load is evenly distributed in this case.

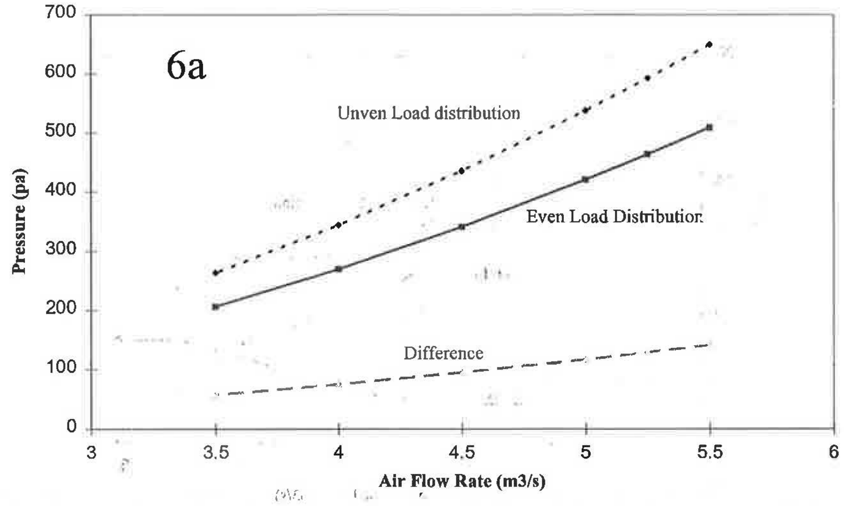


Figure-6a Minimum (optimal) static pressure set-point

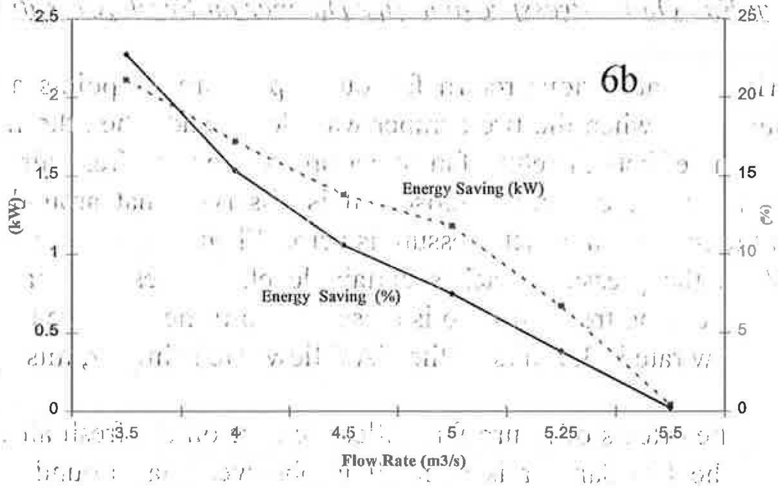


Figure-6b Energy saving of static pressure set-point reset (20% load difference)

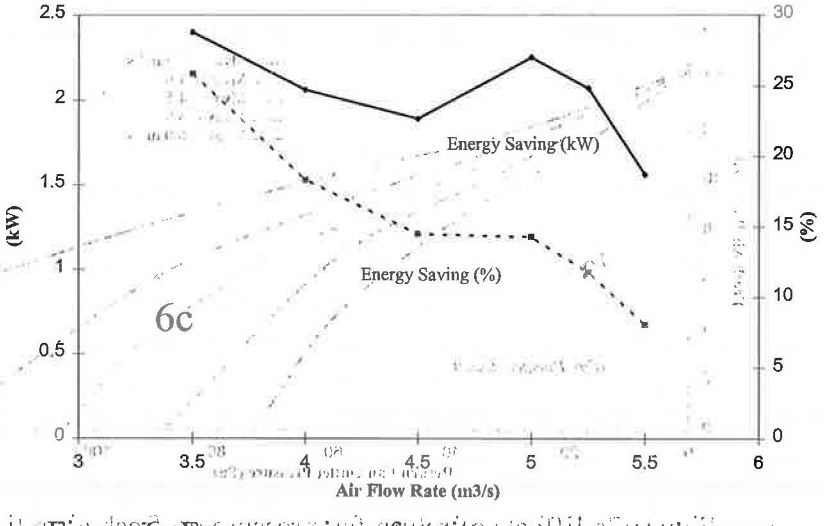


Figure-6c Energy saving of static pressure set-point reset (even load distribution)

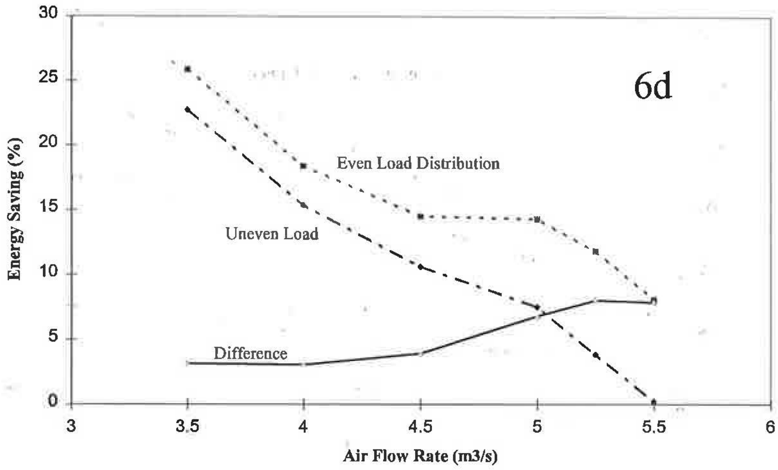


Figure-6d Comparison between energy savings in different cases

Effects of Return Fan Outlet Pressure and Fire Damper on Fresh Air Ratio

Tests were performed at various return fan outlet pressure set-points and at different VAV supply flow rates, both when the fire damper was closed and when the fire damper was open. Figure-7a shows the effects of return fan outlet pressure on the fresh air ratio at various VAV flow rates, when the fire damper is closed. It is observed that around 14% of fresh air is provided when the return fan outlet pressure is zero. When the pressure increases, the fresh air ratio drops. When the pressure reaches certain level, no fresh air can be provided to the building. For instance, the fresh air ratio is close to zero if the pressure reaches 70 Pa when the VAV supply air flow rate is 3.5 m^3/s. If the VAV flow rate is higher, this upper limit is higher.

Figure-7b shows the effects of return fan outlet pressure on the fresh air ratio at various VAV flow rates when the fire damper is open. It is observed that around 38% of fresh air can provided when the return fan outlet pressure is zero. When the pressure increases, the fresh air ratio drops. When the pressure reaches certain level, no more fresh air can be provided to the building. The upper limit of pressure for zero fresh ratio is nearly the same as that when the fire damper is closed.

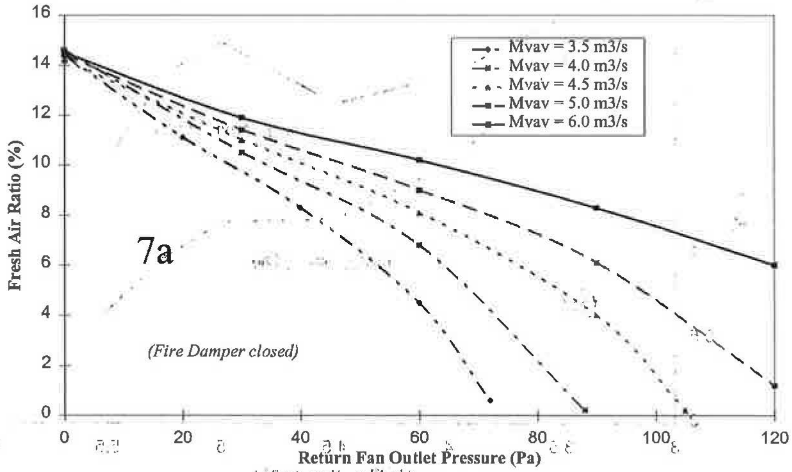


Figure-7a Effects of return fan pressure on fresh air ratio (fire damper closed)

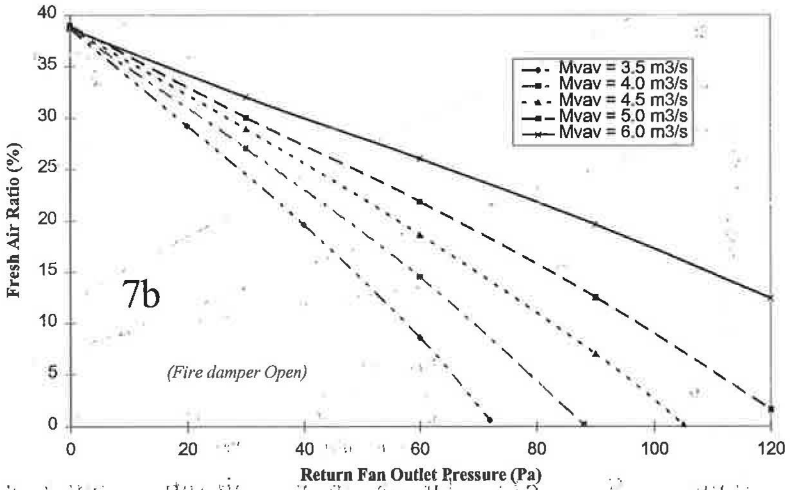


Figure-7b Effects of return fan pressure on fresh air ratio
(fire damper open)

Figure-7c&7d show the comparisons of the fresh air ratio between two fire damper positions at two VAV supply flow rates. It is shown that the fresh air ratio can be controlled by proper setting of the return fan outlet pressure. The results also show that three times the fresh air can be provided if the position of fire damper is turn from close to open position. It provides the possibilities to (partially) implement enthalpy control to reduce the load of cooling coil in winter season.

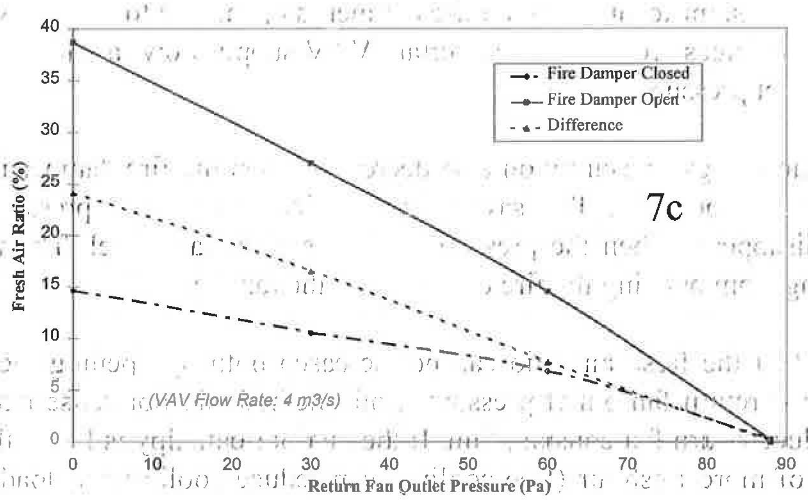


Figure-7c Effect of air damper on fresh air ratio (flow rate: $4m^3/s$)

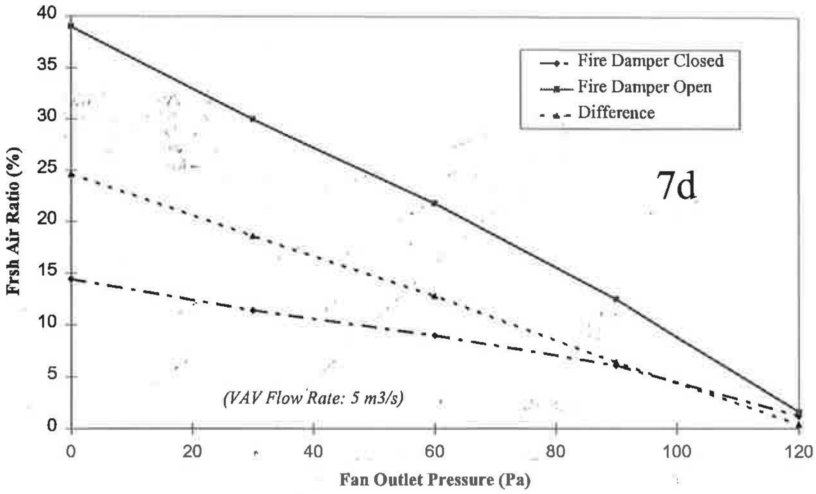


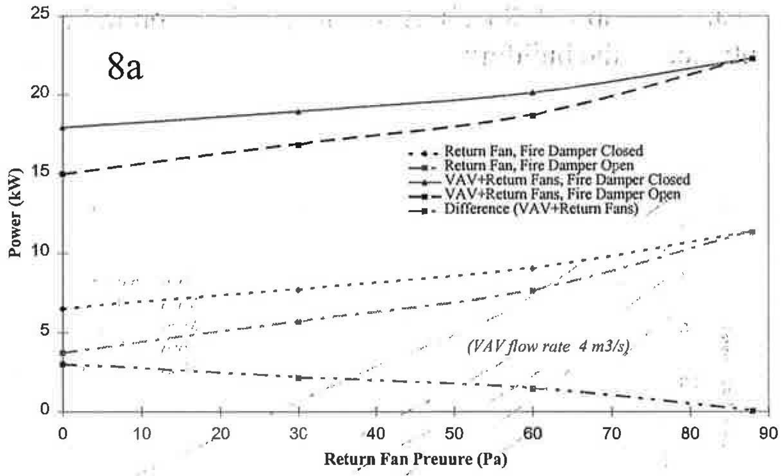
Figure-7d Effect of air damper on fresh air ratio (flow rate: $5m^3/s$)

Effects of Return Fan Outlet Pressure and Fire Damper on Fan Power Consumption

Figure-8 shows the effect of the return fan outlet pressure on the fan energy consumption at two VAV air flow rates. The return fan consumption increases when the outlet pressure set-point increases, both when the fire damper is open and when the fire damper is closed. The increase is more significant when the fire damper is open. five to ten kilowatts of the return fan consumption changes are observed at certain VAV supply flow rate in the test range, when the return fan outlet pressure increases.

The return fan energy consumption also decreases when the fire damper is turned from closed position to open position. The saving is significant when the pressure is not high. This difference disappears when the pressure increases to certain level. The maximum return fan energy saving from opening the fire damper is in the range between 3 and 5 kilowatts.

This shows that the fresh air ratio can be increased both by opening the fire damper and by controlling the return fan outlet pressure. Both methods do not cause extra fan consumption, but even reduce return fan consumption. If the outdoor enthalpy is lower than that of the return air, the use of more fresh air (free cooling) can reduce cooling coil load and save return fan energy.



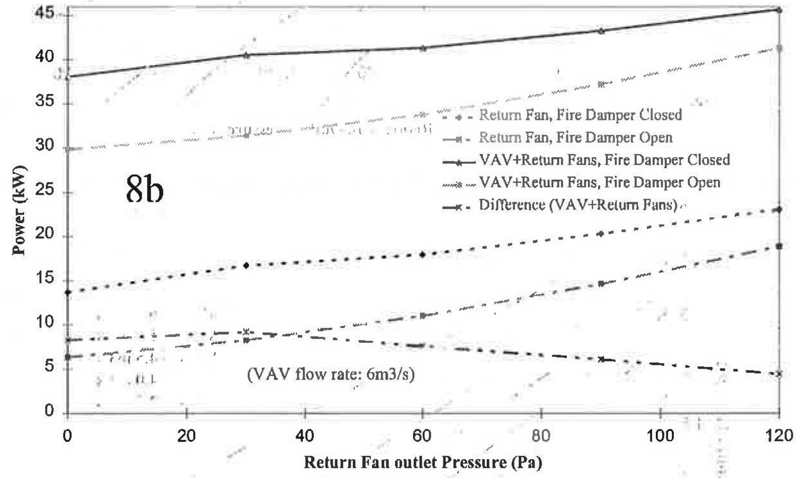


Figure-8 Effect of return fan pressure on energy consumption

Effects of Return Fan Outlet Pressure and Fire Damper on Exfiltration Rate

The exfitration rate is also an important fact of which we should be aware. Figure-9 shows the exfiltration flow rate, which is actually the difference of the supply (including VAV and CAV) air flow rate and return air flow rate.

It can be seen that the exfiltration rate reduces when the return fan outlet pressure increases. The upper limit of return fan outlet pressure for preventing infiltration varies from 63 Pa to 140 Pa when the VAV flow rate increase from 3.5 to 6 m^3/s with fire damper open. The upper limit varies from 60 Pa to 120 Pa when the VAV flow rate increase from 3.5 to 6 m^3/s with fire damper closed.

To ensure positive exfiltration (positive building pressure), the return fan outlet pressure set-point should not be too high. On the other hand, one should be aware of the effects that might be caused by a high exfiltration rate. As high fresh air intake (free cooling) is beneficial in term of energy in winter season in Hong Kong, one may expect the demanded VAV air flow rate to be around 3.5 to 4 m^3/s when implementing free cooling. When the fire damper is open, the exfiltration rate can reach 2 kg/s in winter situation. When the fire damper is closed, the exfiltration rate can reach up to 0.8 kg/s. A too high exfiltration in building might cause strong air flow at the entrance of the building.

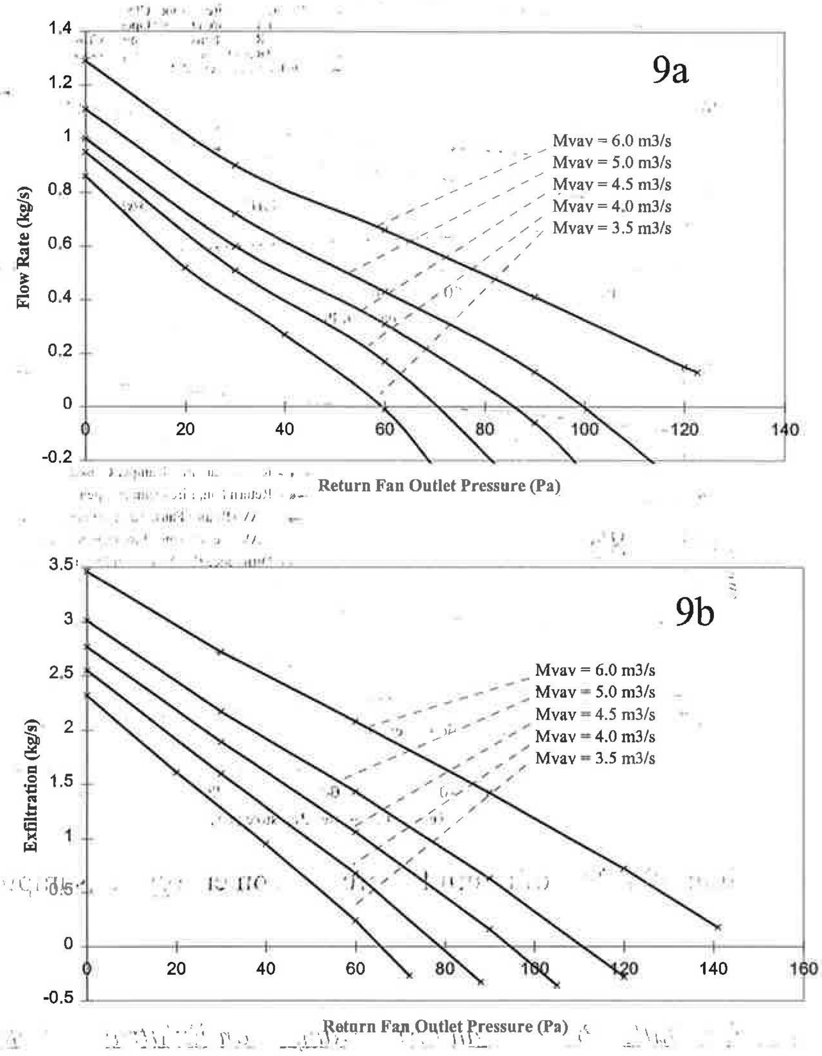


Figure-9 Effect of return fan pressure on extrifiltration flow rate

Energy Effect of Filter Flow Resistance

The pressure drop on filters contributes up to 40% of the VAV fan delivery head in the system. The filter flow resistance is affected very much by maintenance (replacement or cleanliness). Therefore, attention should be paid on the influence of filter flow resistance on energy consumption.

Figure-10a&10b show energy consumption and energy saving when reducing the pressure drop on the VAV filter at various flow rates. The energy saving by reducing pressure drop on the filter increases as the flow rate increases. When the pressure drop on the filter reduces by 30%, a 0.25 kilowatt (3%) fan power can be saved at low VAV flow rate. This increases to 1 kilowatt (5%) at high VAV flow rate.

Concerning energy efficiency, the filter should be replaced regularly to maintain low pressure drop across it. The frequency of replacement in summer should be higher than that in winter, since the effect at high air flow rate is more significant than that at low air flow rate.

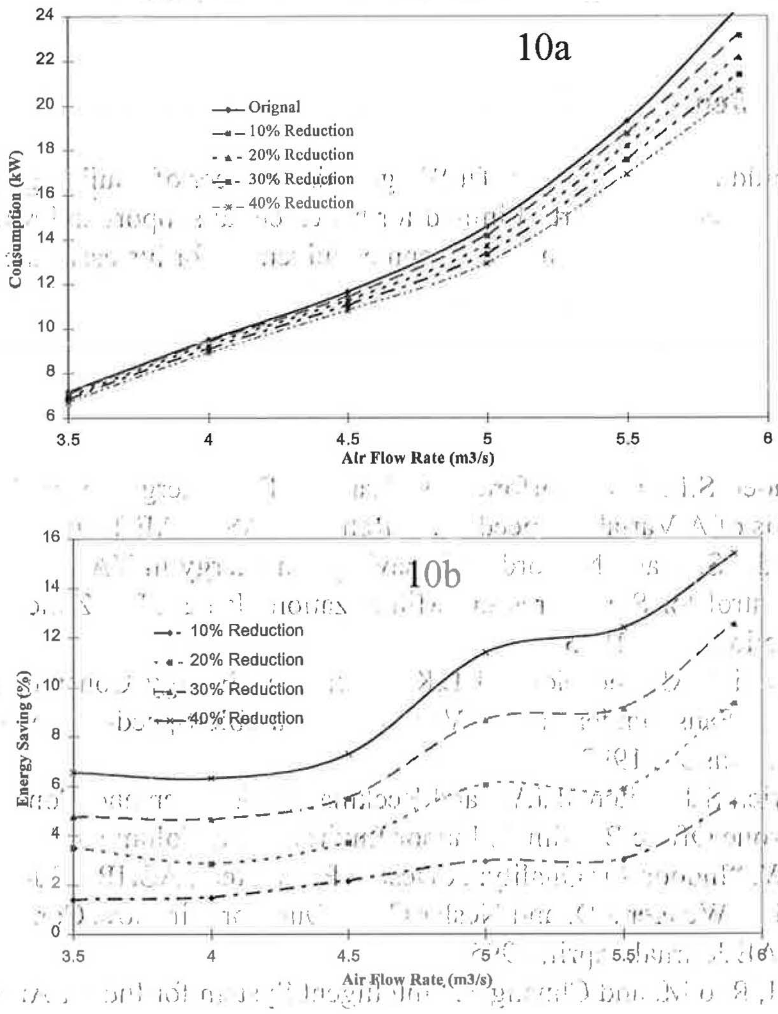


Figure-10 Effect of filter pressure drop on VAV fan energy consumption

Discussion and Conclusions

Significant energy saving (reducing fan consumption and cooling coil load) can be achieved by proper settings of the A/C system and implementing integrated DDC control, without significant modification on the mechanic system.

Enthalpy control can be applied to the existing A/C system when it is beneficial. Fresh air intake can be increased by opening the existing fire damper and reducing the return fan outlet pressure set-point. The cooling load of the coil can be reduced and the energy consumption of the return fan can be also reduced. Positive pressure (positive exfiltration) and adequate fresh air intake can be also ensured for air quality issues. But a too high exfiltration flow rate might affect the air distribution and air balance of the building envelope.

Supply fan static pressure set-point can be significantly reduced in partial load to save supply fan energy. Supply air should be evenly distributed among loads to maximize the possibility of resetting (i.e. reducing) AHU supply pressure to achieve high energy efficiency and ensure that the entire office area is provided with sufficient cooling in the mean time. The upgrading of integrated DDC VAV terminal control will be beneficial both in providing an even distributed air supply, optimal reset of fan static pressure and necessary indoor air quality.

Acknowledgment

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