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Performance evaluation of an innovative fan-coil unit: Low-temperature differential variable air volume FCU

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Abstract

An innovative low temperature differential variable air volume fan-coil unit (LTD-VAV FCU) was developed to improve the defects of variable air volume (VAV) and cold air distribution energy-saving technologies. A test bench and procedures according to its unique air supply features were established to investigate the energy-saving and IAQ improving potential experimentally.

The experimental results of the prototype indicated the supply air volume can be continuously varied between 0.09 m^3/s (200 CFM) and 0.38 m^3/s (813 CFM), controlled by the bypass damper giving an air supply/air return temperature difference from only 2.30 to 8.09 °C. The effect of reducing the supply/return air temperature differential not only makes people feel comfortable, but also improves the cold draft and condensing at the outlet generated by ordinary air supply method. In addition, continuous capacity variations range from 0.45 kW (383 kcal/h) to 5.29 kW (4550 kcal/h) rendering to achieve the effect of comfort at a stable indoor thermal condition. Moreover, the temperature difference of chilled water ranges from 0.42 to 5.05 °C, the chiller plant not only can be unloaded at a low temperature difference to enhance energy-saving, but also complement other areas for multi-area application.

Keywords: LTD-VAV FCU; Energy-saving; Cold air distribution; IAQ; Cold draft

1. Introduction

Energy consumption and huge emission of waste heat have already caused serious global problems like the global warming and hot island effects and therefore become urgent issues in the international community. Since HVAC has become an indispensable facility in human life, energy economy and environmental friendly air conditioning will be the trend in the future to accomplish the goal of sustainable existence with the ecology and the earth.

The VAV supply system has become quite popular on the market, thanks to its improvements in critical defects of a typical constant air volume (CAV) one. The air conditioning capacity of both VAV and CAV systems are both controlled by the supply air volume. When the air circulation rate or air age is inconsistent with the load needed in an occupied room, certain problems occur. Five major problems are:

(1) bad mixing of the circulating air and the indoor air,
(2) insufficient outdoor air circulation,
(3) dumping happens when air volume is inadequate leading to local air circulation only,
(4) the ventilation rate reduces as the load decreases,
(5) the air supply temperature reduces abruptly when the load decreases. A greater inlet and outlet air temperature difference makes human bodies become uncomfortable extremely (cold draft effect).

Accordingly, an innovative concept of a new generation air conditioner, LTD-VAV FCU, is proposed in this research. The applications of VAV technology are introduced in detail in ASHRAE handbook [2]. Hung et al. [4] studied the effect of flow controllers on VAV system performance by simulations and field measurements. They concluded that the flow controllers can modulate the supply air to provide a stable air temperature. Zaheer-Uddin and Zheng [6] found that there is an optimal air supply temperature with and return air used in a climate where the relative humidity is high. Engdahl and Johansson [3] optimized the air supply temperature of a VAV

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system theoretically by minimize the system energy use. Ke [5] proposed a variable-power VAV FCU and established a test bench and experimental method to evaluate and rate its energy-saving potential. Beside this research currently there are few published literatures or reports about VAV FCU. Not to mention on the present LTD-VAV FCU. Therefore, this study proposed a standard test procedure in according with the unique features of LTD-VAV FCU and performed detailed ratings of its operation capability and energy-saving efficiency.

2. LTD-VAV FCU

The design principle of the LTD-VAV FCU is shown in Fig. 1. There are two air return ways inside the unit. One is the primary air, Q_A, which the return air passes by the cooling coil for heat exchange. The other is the bypass air, Q_B, which the return air is drawn through the variable opening bypass damper and goes into the mixing chamber directly. These two air sources are mixed evenly in the mixing chamber by the supply fan to become the mixed air, Q_T ($Q_T = Q_A + Q_B$), and provide air supply required in an occupied space.

As the traditional VAV system may cause discomfort for the people indoors while running at a low load, the variable speed fan and the variable opening damper of the LTD-VAV FCU may adjust the primary air volume Q_A automatically under low load running. Thus, cooling capacity and load tend to be balanced and the bypass air volume Q_B is increased simultaneously to maintain the air supply volume Q_T as desired. Accordingly, the mixing rate of the indoor air and air distribution can be maintained. Furthermore, the return air of the room temperature is brought in by the bypass damper and enforced to mix with the cold air passing by the dry cooling coil to increase the air supply temperature and to minimize the temperature difference between air supply and indoor air, which prevents the cold draft effect and discomfort resulted from a tremendous supply air temperature drop as well as larger supply/return air temperature differential by a low air volume supply at a low load running. Not being limited to air supply or ventilation volume, the total air circulating rate and the ventilation rate of the LTD-VAV FCU can be controlled by the variable speed fan and the variable opening damper independently in compliance with air-conditioning requirements. The capacity is automatically adjusted by the primary air in accordance with the cooling load. Consequently, the demand for indoor air circulation or ventilation can be met. Besides, better dehumidifying effect will be achieved as the FCU is running at a low load, the inlet and outlet temperature difference of the cooling water reduces significantly and the apparatus dew point (ADP) lowers when the setting temperature is reached. Air supply and return temperature difference is therefore lowered and the energy consumed satisfies the cooling load exactly; i.e., the most healthy and comfortable environment is created at the lowest energy consumption.

The LTD-VAV FCU system presented in this research is based on a new concept of ‘‘low temperature differential air supply’’, which not only copes with the requirements for comfort and health, but also saves energy and achieves the goal of environmental friendliness.

3. Experimentation and measurement instruments

Currently, there is no testing standard published regarding the VAV fan-coil units. Various kinds of testing standards regarding the fan-coil units including ASHRAE’s standard were established based on the CAV FCU. At the present time, ANSI/ASHRAE 79-2002 is the most popular and widely accepted testing standard [1]. This research established experimentation including equipment considerations, testing platform, laboratory requirements according to the requirements with this standard and the VAV testing method [5] as reference.

An environmental control room and experiment platform was therefore established as shown in Fig. 2. Required environmental conditions at a constant temperature and humidity for testing are maintained to conduct a series of parametric experiments.

Strict requirements for measurement instruments specified by ASHRAE are complied. A set of nozzle and differential pressure measurement system is applied to measure the air volume as well as air temperature and humidity. Various instruments and apparatuses adopted in this testing experiment are listed in Table 1.

All of the measurement data will be collected in the computer by the data acquisition system simultaneously for follow-up reduction and analysis.

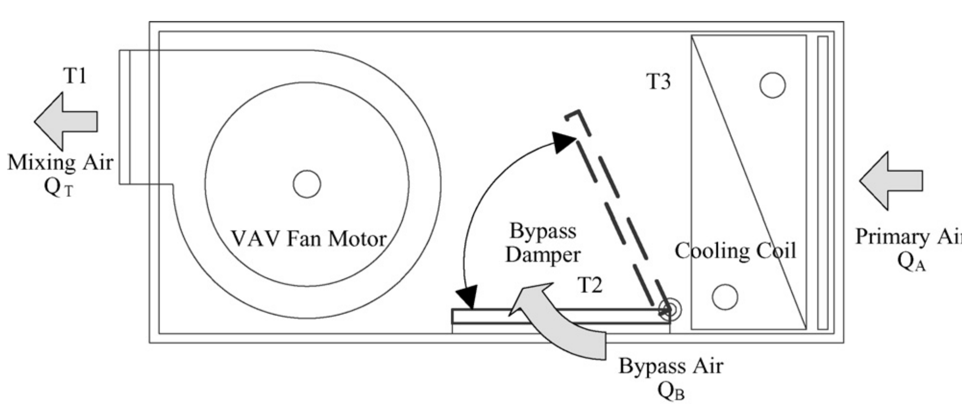

Fig. 1. Schematic diagram of LTD-VAV FCU.

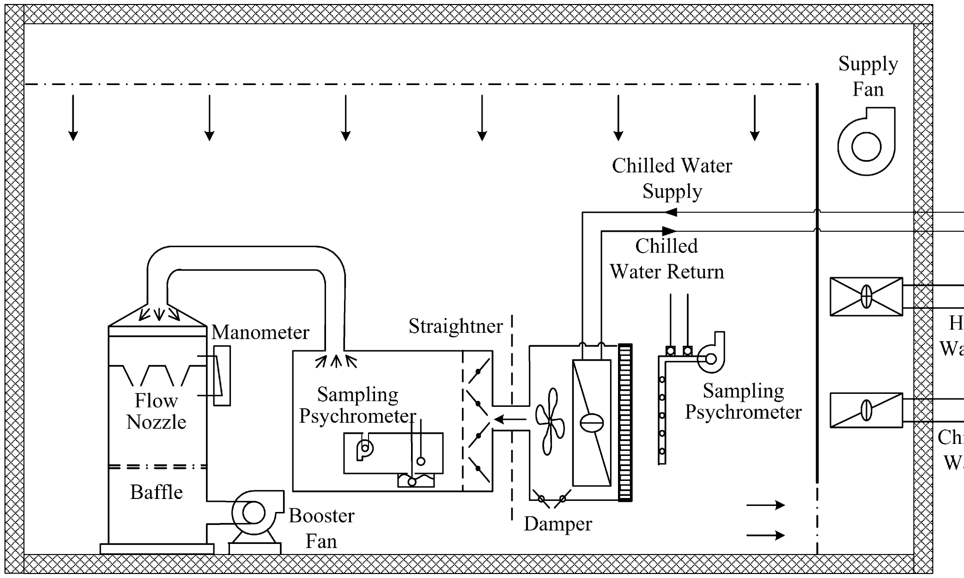

Fig. 2. Layout of environmental control room and experiment platform.

4. Experimental procedure

First, the test environment in the laboratory is to maintain the dry-bulb temperature (DB) at $27.0 \pm 0.2\,^{\circ}\mathrm{C}$ and the wet-bulb temperature (WB) at $19.5 \pm 0.2\,^{\circ}\mathrm{C}$. The chilled water circulating pump is actuated to control the inlet chilled water at a temperature of $7.0 \pm 0.2\,^{\circ}\mathrm{C}$ and a flow rate of $2.5 \times 10^{-4} \pm 1.67 \times 10^{-5}\,\mathrm{m^3/s}$. Meanwhile, the standard wind tunnel experiment equipment is adjusted to maintain an external static pressure of 0 ± 0.05 Pa.

Upon stabilizing all testing requirements, the bypass damper of the LTD-VAV FCU is opened at 0°, 30°, 60° and 90° separately before adjusting speed of the fan motor from minimum to maximum in order. When air supply of the LTD-VAV FCU becomes steady, data of air supply volume, power consumption, temperature/humidity at the air inlet/outlet, chilled water flow and the chilled water temperature at the inlet and outlet of the LTD-VAV FCU with different opening angles of the bypass damper and fan speed were measured and recorded in the computer. The experiment flowchart is indicated in Fig. 3.

5. Results and discussion

5.1. Bypass damper opening at 0°

Performance test of the LTD-VAV FCU with the bypass damper opened at 0° is mainly to simulate air supply fully provided by air return that passes by the cooling coil when the bypass damper is shut with $Q_B = 0$ and $Q_A = Q_T$. At this time the supply air volume is controlled by the continuously variable speed fan motor. The experimental results are shown in Figs. 4 and 5. When the maximum air volume is $0.36\,\mathrm{m^3/s}$ (788 CFM) with an input power as 173 W, the cooling capacity is 5.29 kW at an air supply temperature of 15.3 °C. The chilled water leaving temperature is 12.05 °C and the temperature difference between the inlet and the outlet of chilled water is 5.05 °C. When the air volume is minimized to $0.09\,\mathrm{m^3/s}$ (200 CFM),

Table 1
Instruments and accuracy used in present study

Measuring item	Instrument (brand)	Approximate accuracy	Remark
Velocity	Hot-wire anemometer (TESTO)	±(0.03 m/s ± 4% of mv)	
	Pitot tube (TESTO)	±(0.3 Pa ± 0.5% of mv)	
Flow rate	Nozzle and differential pressure measurement system	±0.5–2.0%	Air side
	Magnetic flowmeter (YOKOGAWA)	±1%	Water side
Pressure	Precision pressure probe (TESTO)	±(0.3 Pa ± 0.5% of mv)	
	Inclined manometer (Dwyer)	–	
Temperature	Liquid-in-glass thermometers	±0.05 °C	
	Resistance thermometers (TESTO)	±0.3 °C	
Humidity	Compact transducer (capacitive humidity sensor)	±2%RH	
Power	(HIOKI)	±0.3%	
Stroboscope	(SHIMPO)	±0.2 rpm (200–4000 rpm)	

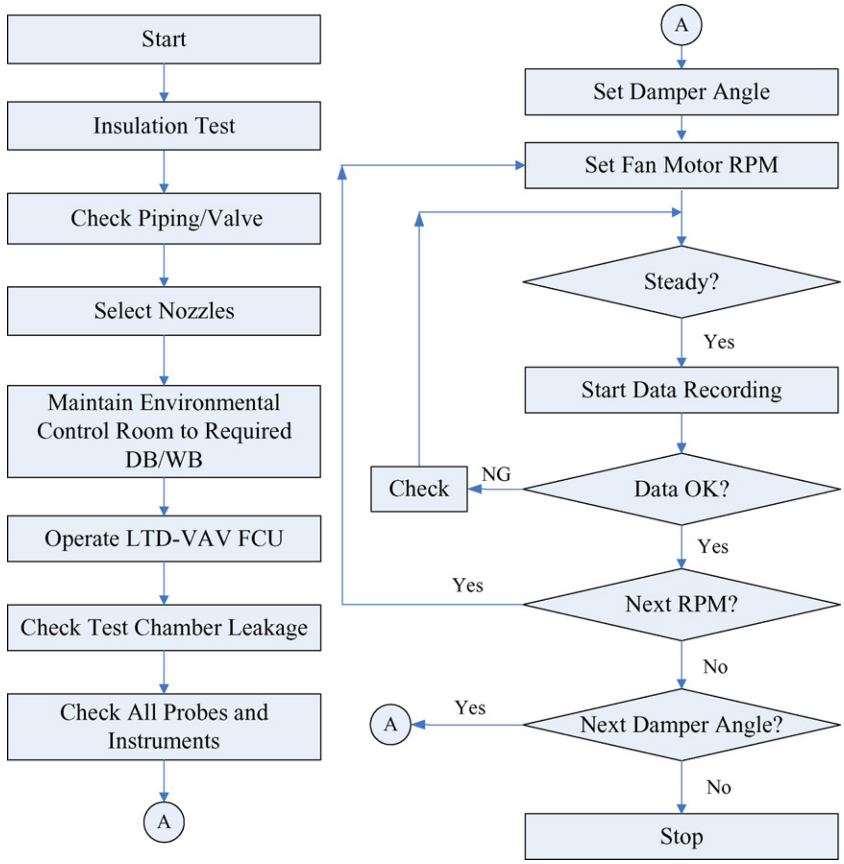

Fig. 3. Test procedures for rating LTD-VAV FCU.

power consumed is 37 W, cooling capacity is down to 0.56 kW and the supply air temperature is 12.4 °C. The chilled water leaving temperature is 9.2 °C and the temperature difference between the inlet and the outlet of chilled water is reduced to 2.2 °C. These experimental data indicate the performance features of the LTD-VAV FCU equal those of the VAV-FCU when the damper opening is at 0°. The capacity adjustment feature helps the VAV system supply the air volume in compliance with the required capacity; i.e., the cooling capacity and the load are balanced automatically for energy economy. However, as the capacity is still confined to the air supply volume, the cold draft effect and dumping may occur possibly when running at a low load.

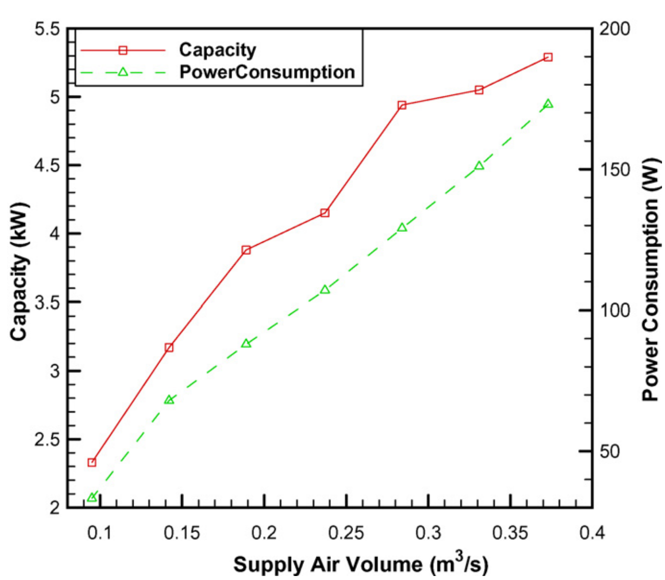

Fig. 4. Performances of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 0°).

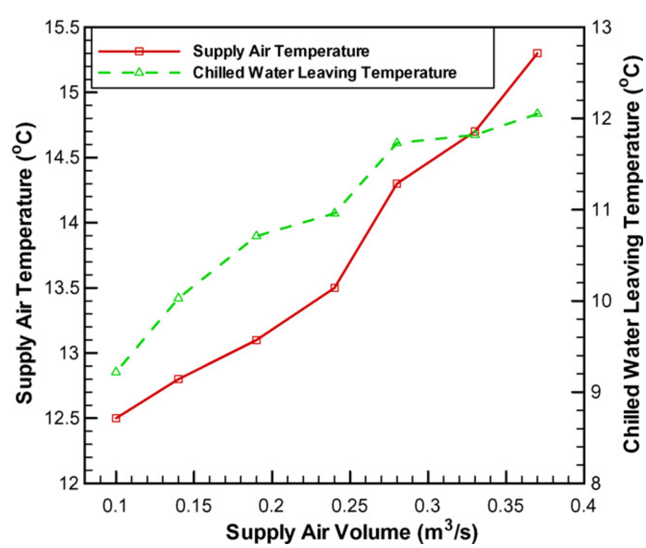

Fig. 5. Temperature variations of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 0°).

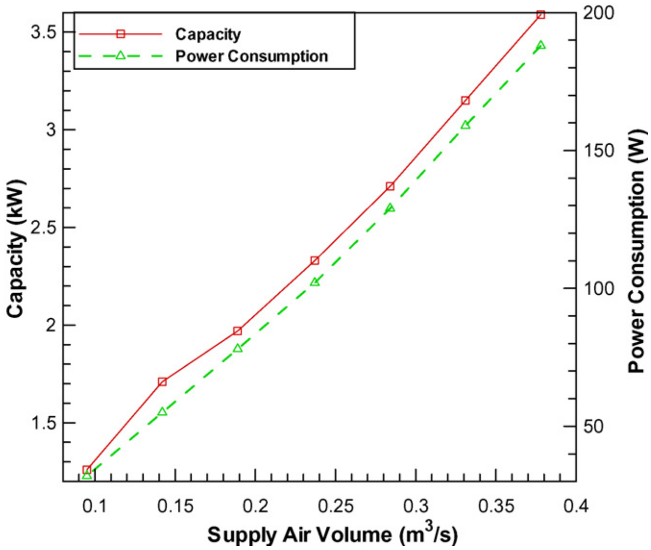

Fig. 6. Performances of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 30°).

5.2. Bypass damper opening at 30°

Results of the performance test with the bypass damper opening at 30° are shown in Figs. 6 and 7. As the damper opened, airflow resistance increases. When the maximum air volume was 0.36 m^3/s (788 CFM) at this time, fan power consumption increased to 188 W and the air supply capacity, due to the bypass effect, reduced to 3.59 kW, which was 67.8% of the capacity with the damper opened at 0°. It is obvious to see that the cooling capacity is no longer limited to the air supply volume like a traditional air supply system. Moreover, the air supply temperature rises to 18 °C, the chilled water leaving temperature is 10.1 °C and the chilled water temperature difference to 3.1 °C, which helps save energy on the chilled waterside.

When the supply air volume reduced to 0.09 m^3/s (200 CFM), fan power consumption was 32 W. As the bypass effect was enhanced causing airflow resistance reduced, power consumed was less than that having the bypass damper opened at 0°. Nevertheless, the cooling capacity was reduced to 1.26 kW, which accounted for only 24.2% of full capacity. The air supply temperature was 20.1 °C and the air supply temperature difference reduced to be 6.9 °C, which was significantly lower than 14.6 °C when the damper was opened at 0°. Apparently, control of the bypass damper indeed may put the ideal of low temperature differential air supply into practice, which not only improves the defects like the cold draft effect and condensing/dewing at the outlet, but also modulates the chilled water temperature difference between 1.2 and 3.1 °C alleviating the chilled water loads and achieving the benefit of energy economy.

5.3. Bypass damper opening at 60°

Experimental results of the performance test with the damper opening at 60° are shown in Figs. 8 and 9. When the LTD-VAV FCU was running at the maximum air volume of 0.38 m^3/s (810 CFM) at this time, fan power consumption was 188 W and the cooling capacity was 2.93 kW. The supply air temperature was 23.2 °C, the chilled water leaving temperature was 9.8 °C and the chilled water temperature difference was 2.8 °C. When the air volume was reduced to the minimum of 0.09 m^3/s (200 CFM), fan power consumption was 32 W and the cooling capacity was 0.56 kW. At this time the supply air temperature became 24.3 °C and the chilled water temperature difference was reduced to 0.54 °C. Accordingly, the performance with the damper opened at 60° is similar to that with the damper opened at 30°. The bypass effect increases significantly as the damper is opened wider. The cooling capacity at the maximum air volume was 53.8% of the full capacity and was only 10.8% of the capacity when the air volume was at

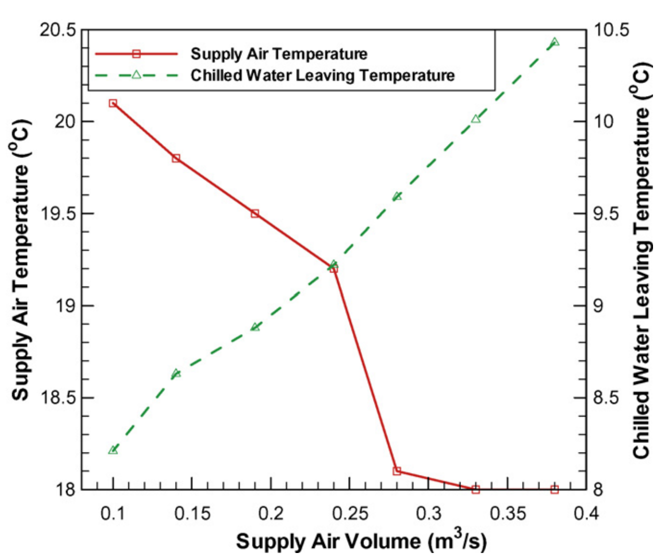

Fig. 7. Temperature variations of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 30°).

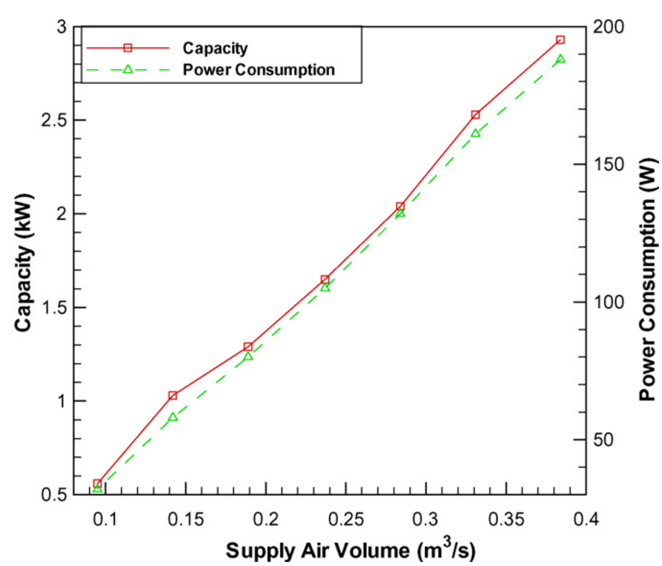

Fig. 8. Performances of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 60°).

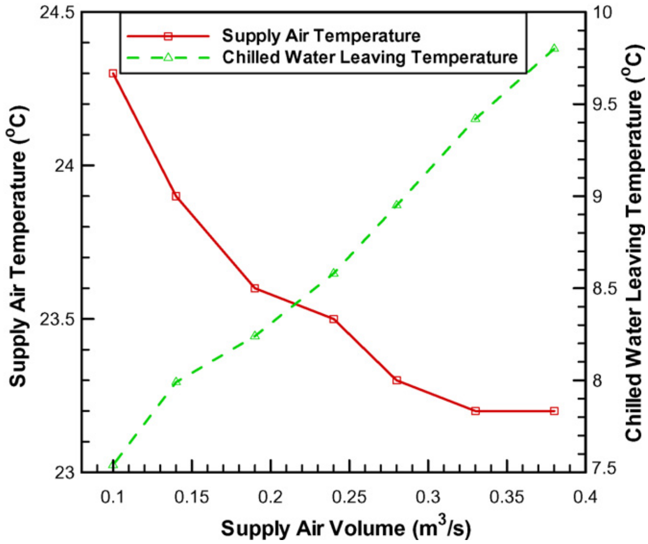

Fig. 9. Temperature variations of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 60°).

minimum. The air supplied and returned temperature difference ranges from 2.7 to 3.8 °C. The effect of low temperature differential air supply was enhanced significantly as well. These experimental results indicate plenty of problems caused by a typical VAV-FCU running at a low load at the outlet can be improved by the LTD-VAV FCU presented here. The chilled water temperature difference can be reduced to 0.54 °C due to reduction of the cooling capacity, which is quite suitable for multi-area central chilled water occasions since the loads of the chilled water plant can be relieved and complementary capacity among areas with different loads may be balanced.

5.4. Bypass damper opening at 90°

Results of the performance test with the damper opened at 90° (vertical) are illustrated in Figs. 10 and 11. When the LTD-

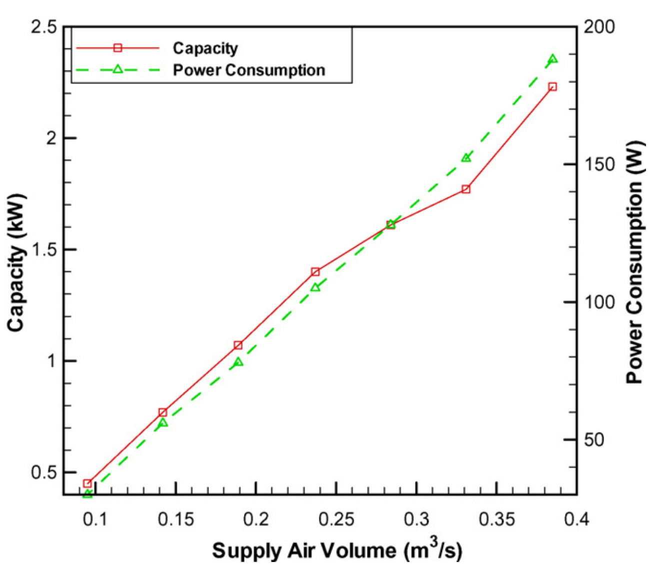

Fig. 10. Performances of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 90°).

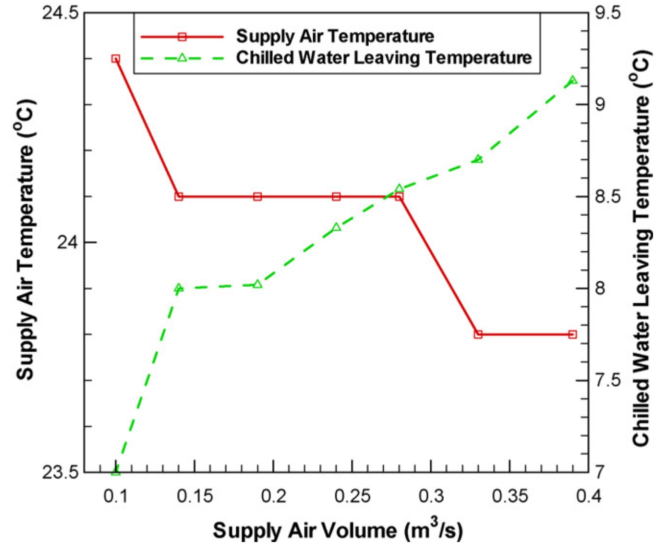

Fig. 11. Temperature variations of present LTD-VAV FCU under various supply air volumes (bypass damper opening at 90°).

VAV FCU was running at the maximum air volume of 0.38 m^3/s (813 CFM) at this time, power consumption was 188 W and the air cooling capacity was reduced to 2.23 kW, which was 42.6% of the standard capacity only. The air supply temperature was 23.8 °C and the chilled water outlet temperature was 9.13 °C with a temperature difference of 2.13 °C. When the air volume was reduced to the minimum 0.09 m^3/s (200 CFM), power consumed was 40 W and the air cooling capacity was 0.45 kW, which merely accounted for 8.5% of the standard capacity. The outlet air temperature was increased to 24.5 °C and the chilled water outlet temperature was reduced to 7.42 °C with a reduced temperature difference of 0.42 °C. Accordingly, the air supplied and returned temperature difference at a damper angle of 90° was between 2.5 and 3.2 °C and the cooling capacity was modulated from 8.5 to 42.6% of the standard capacity. It is obvious to see that the cooling capacity and the air supply volume can be controlled separately, which not only improves the limitation to the air (or ventilation) volume for a typical CAV system, but also achieves the energy economy benefit of the VAV system, thanks to its modulation feature by over 90%.

6. Conclusion

To correct the defects of energy saving and indoor comfort found in traditional air supply system, an LTD-VAV FCU prototype was developed and an experimental platform for detail performance rating was designed and evaluated in this research. The parametric experimental results indicate the air supply and return temperature difference can be ranged from 2.5 to 11.7 °C by controlling the bypass damper and the fan motor, causing "the low temperature differential effect" to improve the cold draft effect at a low air supply volume and condensing/dewing at the outlet when air is supplied at a low temperature found in a typical VAV or cold air distribution system. The cooling capacity and the air volume can be adjusted between 0.45 and 5.29 kW with a variable air volume of 0.09–0.38 m^3/s (200–813 CFM). The inlet and outlet temperature difference of chilled water ranges from

0.42 to 5.05 °C. When the temperature difference is lowered, the load of the chilled water plant can be reduced to promote energy economy and capacities in multiple areas may be complemented. Besides, the energy consumed by the fan motor ranges from 30 to 188 W, which can be modulated to develop the energy-saving effect. These experimental results prove that in addition to the energy-saving feature found in a typical VAV system, the LTD-VAV FCU proposed in this research may control the cooling capacity and the air supply (or ventilation) volume independently via the variable opening bypass damper and the variable speed fan motor to improve the shortcomings found in a traditional CAV system. Moreover, the ventilation volume can be adjusted spontaneously according to the zone requirements and load changes to provide a most healthy and comfortable environment for human bodies at the lowest energy required.

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