2006

Field Performance Measurements of a VRV AC/HP System

Tolga Nurettin Aynur
University of Maryland

Yunho Hwang
University of Maryland

Reinhard Radermacher
University of Maryland

FIELD PERFORMANCE MEASUREMENTS OF A VRV AC/HP SYSTEM

Tolga Nurettin AYNUR, Yunho HWANG*, Reinhard RADERMACHER

Center for Environmental Energy Engineering,
University of Maryland, 3163 Glenn L. Martin Hall, College Park, MD, 20742, USA
Tel: (301) 4055247, Fax: (301) 4052025, e-mail: yhhwang@eng.umd.edu

*Indicates Corresponding Author

ABSTRACT

The performance potential of a variable refrigerant volume (VRV) air conditioning and heat pump system was investigated experimentally during field tests and compared to the performance of the existing variable air volume (VAV) cooling system. Two different control modes; individual control and master control are applied to the VRV system. The master control using only one thermostat at the same location as that of the original VAV system is intended to simulate the existing system's control mode, thus the effects of the control modes on energy consumption and thermal comfort can be evaluated. It is found that cooling performance factor (CPF) of the VRV system in the individual control mode is from 3 to 15% higher than that of the VRV system in master control mode. Similar to the VAV system, the VRV system in master control mode is not sufficient to provide thermal comfort for multiple rooms. Whereas, the VRV system in individual control mode provides the desired set temperature and the corresponding comfort level throughout the season.

1. INTRODUCTION

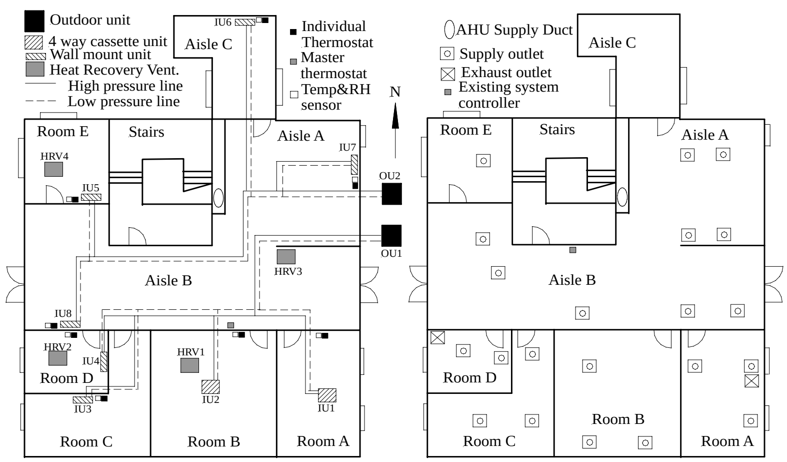
Variable refrigerant volume (VRV) air conditioning systems have been widely used for residential and commercial buildings. These systems have several indoor units connected to one outdoor unit with an inverter driven compressor which supplies the variable refrigerant volume to the system based on the desired cooling load of the building. Besides, each indoor unit has its own electronic expansion valve (EEV) and an air temperature sensor, which compares the set temperature and the indoor air temperature, to adjust the refrigerant flow through the unit. Thus, based on the set temperature and the indoor air temperature, each indoor unit is operated individually. Some of them can be turned off, while others are in operation. With the help of the inverter driven compressor and individual operation of the indoor units, VRV systems have energy saving potentials as compared to the conventional air conditioning systems primarily because of better zoning. In addition, these systems may provide better thermal comfort.

VRV systems have been studied by some researchers as summarized next. Park *et al.* (2001) developed a model for a multi evaporator air conditioning unit with two evaporators, a variable speed compressor and EEV. Performance analyses were conducted with variation of the compressor frequency, opening of EEV and the loads of the conditioned rooms. They found that the COP of the system decreases with an increase of the load ratio between the rooms due to the increased compressor frequency as the load difference between the evaporators. Masuda *et al.* (1991) studied a multi-evaporator air conditioner with a new control method. In this study, an outdoor unit connected to two indoor units was investigated experimentally in environmental chambers. They measured the refrigerant mass flow rates of indoor units by operating the individual expansion valves manually and found a correlation between them and obtained a relationship between mass flow rate and compressor frequency. By applying this relation to the microprocessor, they controlled the mass flow rate of individual indoor units based on the heating or cooling load, and maintained the set temperature accurately. Wu *et al.* (2005) studied a multi-evaporator air conditioner, and proposed a control strategy. In this strategy, they took the suction pressure as the control variable to modulate the compressor speed and room air temperatures were taken to regulate the openings of the individual EEVs. After executing the thermodynamic model, they checked several cases and found that their control strategy with a fuzzy control algorithm could achieve the desired control parameters; such as room air temperature, accurately. Shi *et al.* (2003) developed a fluid network model to simulate the steady-state performance of a heat recovery VRV system. In this study, a heat recovery VRV refrigeration system with two indoor units is taken into account. The model can predict the energy efficiency ratio (EER) of different operating modes; cooling only, cooling mainly (most of the units are used for cooling, while the rest is used for heating), heat recovery, heating mainly (most of the units are used for heating, while the rest is used for cooling) and heating only. They found that the EER in the heat recovery mode is about two times higher than the cooling only or heating only mode. As summarized, because of the complexity of VRV systems, almost all of the open literature relies on either the steady state experimental results or the steady state modeling, and do not provide insights on their performance and operating characteristics under actual operating condition over the entire cooling and heating seasons. In order to provide real time operational characteristics of the VRV system, a field test was conducted with two different control modes in this study. The performance of the existing variable air volume (VAV) cooling system was measured for comparison purposes.

2. EXPERIMENTAL SYSTEMS

Two VRV systems, charged with R410A, were installed in an office suite. Each outdoor unit; equipped with two compressors; one inverter driven and one fixed speed, was connected to four indoor units and each indoor unit was installed into a room or an open-space such as an aisle or reception area. In addition to the new cooling system, four heat recovery units (HRV) to ensure ventilation of the office suite were installed into the ceiling. On the other hand, the existing cooling system based on a VAV system and connected to a centrally located air handling unit (AHU) was preinstalled. The AHU consists of a fan, cooling coil and a duct system. The fan draws the return air from the entire building and the ventilation air from outside. The mixed return and ventilation air is, then sent to the cooling coil. The chilled water flowing inside the cooling coil cools the mixed air. This conditioned air is supplied through a branch duct and then distributed throughout the office suite with 21 supply outlets provided in Figure 1.

VRV outdoor unit 1 is connected to two four-way cassette type and two wall mount type indoor units, on the other hand the second unit is connected to four wall mount type indoor units. In this study, the set temperature for the systems is chosen as 25.0°C. Regarding the thermostat temperature bands (TTB), the four-way cassette units are turned on and off at 26.0°C and 24.0°C, respectively. On the other hand, the wall mount units are turned on and off at 25.5°C and 24.5°C, respectively. This discrepancy is a consequence of the manufacturer's default settings. The layout of the office suite for the new and the existing system is provided in Figure 1.



(a) VRV System **(b) VAV System**

Figure 1: Layout of two test systems

2.1 Control Modes

Existing VAV cooling system has only one thermostat which is located almost in the center of the office suite. Two different control modes; individual control and master control, were used for the VRV system. In the individual control mode, all the indoor units are controlled by their own individual thermostats located into each room. Each thermostat is equipped with a temperature sensor. Based on the control algorithm, the set temperature and the thermostat temperature are compared and based on the difference; the refrigerant mass flow rate through the indoor unit is adjusted to provide the set temperature accurately. If no cooling is needed at all, the expansion valve is closed, while the fan keeps running. In the master control mode, all eight indoor units are controlled by only one thermostat which is located close to the existing system's thermostat. With this mode, conventional existing system's control mode was simulated, and the differences between the individual control and master control were observed.

2.2 Measurement System

All indoor, outdoor and duct air temperatures were measured by T type thermocouples. For refrigerant temperature measurements, thermocouples were attached to the pipe surfaces, and several layers of insulation were applied in order to increase the accuracy of the reading. Relative humidity (RH) sensors with an accuracy of 3% were used to measure the RH of indoor, outdoor and duct airs. For the power consumption of the outdoor units, two watt meters with an accuracy of ±0.5% were used. One watt meter with an accuracy of ±0.2% is used to measure the power consumption of the eight indoor units and four HRV units. All data were collected with 20 seconds intervals.

2.3 Schedule of the Field Test

In order to observe the differences between systems and control modes more clearly, parametric experiments were conducted based on the test schedule provided in Table 1. Each experiment for the new system was started at 7:00 and finished at 24:00. The existing system was always turned off at 19:00 due to preexisting controls.

Table 1: Test schedule

Day	Operating system
Monday	VRV system in individual control mode with HRV units
Tuesday	VRV system in individual control mode with HRV units
Thursday	VRV system in master control mode with HRV units
Friday	Existing VAV cooling system
Saturday	VRV system in master control mode with HRV units

3. EVALUATION METHODOLOGY

3.1 Performance Evaluation of VRV System

Total refrigerant mass flow rate supplied from the outdoor unit was calculated based on the compressor performance map provided by the manufacturer. Furthermore, a correlation given in Equation (1) was used to calculate the refrigerant mass flow rate of the individual indoor units. This correlation is based on EEV and taken from Baumann (1996). A similar correlation is also used in Park *et al.* (2001) study.

$$\dot{V} = 0.865 \cdot C_V \cdot \sqrt{\Delta P / G_f} \tag{1}$$

Each indoor unit's cooling capacity is calculated by equation (2),

$$\dot{Q}_j = \dot{m}_j \cdot \left(h_i - h_o\right)_j \tag{2}$$

In order to calculate the refrigerant enthalpies; one thermocouple was installed in the inlet part of the indoor unit before the EEV, and another thermocouple was installed at the outlet of the indoor unit. Refrigerant pressures were measured from the compressor discharge and suction ports. The location of the instrumentation is illustrated in Figure 2, where T and P denote thermocouple and pressure sensor locations, respectively.

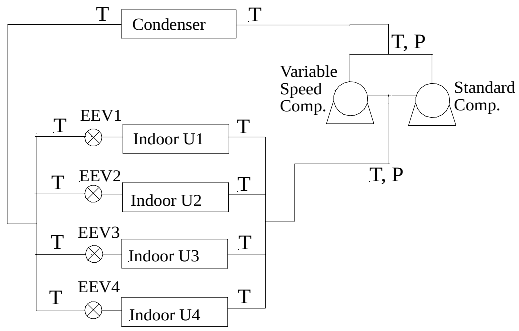


Figure 2: Schematic diagram of a VRV system

VRV system performance is calculated by using Equation (3) as the cooling performance factor (CPF).

$$CPF = \left(\sum \left(\sum_j \dot{Q}_j \right) \cdot \Delta t \right) \Big/ \sum \dot{W} \cdot \Delta t \tag{3}$$

3.2 Thermal Comfort

ASHRAE thermal sensation scale was used for evaluating the indoor room thermal comfort conditions. In this scale; +3, +2, +1, 0, -1, -2 and -3 correspond to hot, warm, slightly warm, neutral, slightly cool, cool and cold, respectively. Rohles (1971) studied thermal sensation in chamber tests and used 1 to 7 scale instead of the above one. In their study, they took account of a wide range of temperature and relative humidity; 15.5°C to 36.6°C with 1.1°C increment and 15% to 85% with 10% increment with a clothing factor of 0.6. At the end of the study, they obtained correlations based on the exposure time, and gender as male, female or combined. In this study, three hours exposure time with combination of men and women was chosen. According to that, Equation (4) given in ASHRAE 97 Handbook for conversion to -3 to +3 scale was used for the thermal comfort evolution.

$$TSS = 0.243 \cdot T + 0.278 \cdot p - 6.802 \tag{4}$$

4. RESULTS AND DISCUSSION

4.1 Performance Evaluation

The main difference between VRV system in the individual control mode and master control mode is the number of the thermostats and their locations. In master control mode, only one thermostat located in the center of the office suite controls the system, on the other hand in individual control mode, four different thermostats located four different rooms control the system. Because of this control difference and based on the outdoor and indoor temperatures, VRV system in the individual control mode operates continuously, while the master control mode has cyclic operations throughout the day. These cyclic operations may have some drawbacks. In order to evaluate this situation, several days with essentially the same outdoor temperature values and variations were chosen and comparisons were done according to the unit 2 due to the same indoor temperature thermostat bands.

In Table 2, comparison of the VRV system in the individual and master control mode is provided. The supplied cooling energy is calculated throughout the day. The total power consumption of the indoor units is added to the power consumption of the outdoor unit in the evaluation. CPF of the VRV system in the individual control mode is from 3 to 15% higher than that of the VRV system in the master control mode.

Table 2: Daily basis comparison of the VRV system in the individual and master control mode

	Individual	Master	Individual	Master	Individual	Master
Cooling Energy (kWh)	152.17	150.73	171.87	125.63	142.93	123.52
Energy Consumption (kWh)	34.62	39.56	43.59	33.55	34.58	30.9
CPF	4.40	3.81	3.94	3.75	4.13	4.00

In Figure 3, power consumption of the outdoor unit of the VRV system in individual control mode and in master control mode and the outdoor air temperature variation for the corresponding days is provided. These graphs correspond the first comparison provided in Table 2. As can be seen, between the periods of 750-970 minutes, VRV system in master control mode has similar cyclic operations while the individual control mode works continuously. The variation of the discharge and suction pressures for the same period is provided in Figure 4. As can be seen, the discharge pressure of the VRV system in the individual control mode is around 2.0 MPa, however when the VRV system in master control mode turns on, the discharge pressure becomes higher than that of the individual control mode, and reaches up to 2.7 MPa. The suction pressures of the VRV system in master control mode and the individual control mode are almost same.

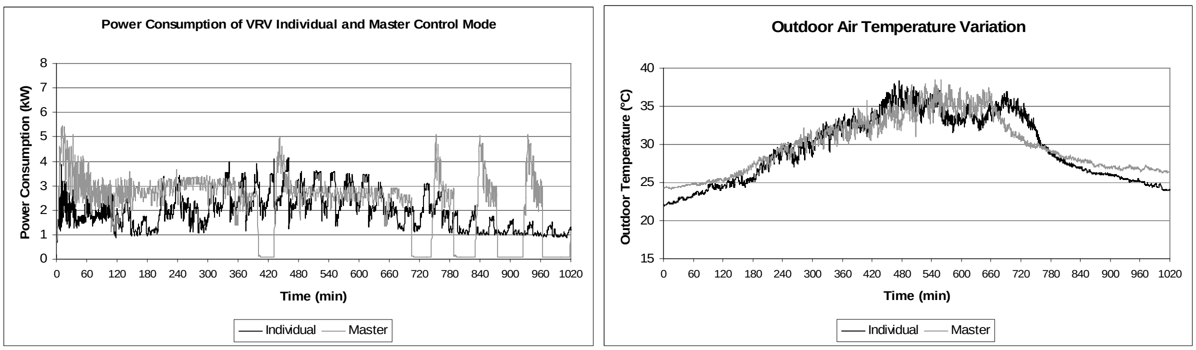


Figure 3: Power consumption and outdoor air temperature variations

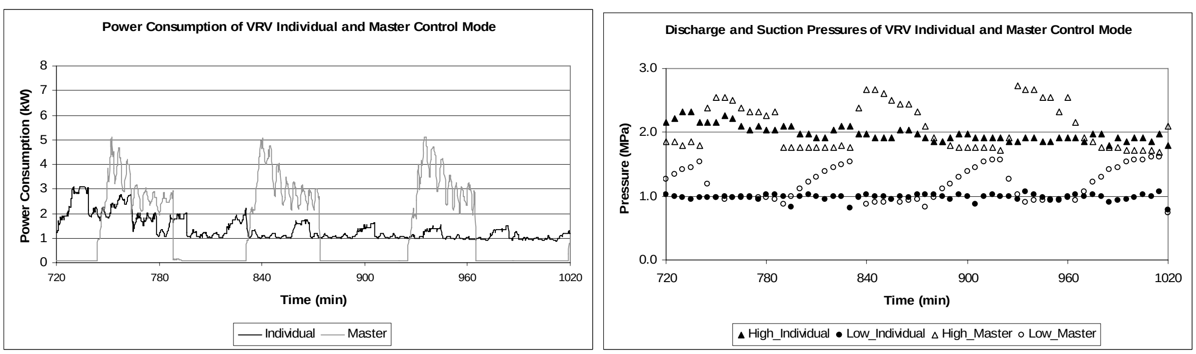


Figure 4: Power consumption, discharge and suction pressure variations

In Figure 5, power consumption of the outdoor unit of the VRV system in the individual and master control mode and the outdoor air temperature variation for the corresponding days is provided. Graphs provided in Figure 5 correspond the second comparison in Table 2. As can be seen, similar to the Figure 3, VRV system in master control mode has cyclic operation. The period of 160-820 minutes has similar cyclic operations. The corresponding power consumption of the outdoor unit and the discharge and suction pressures for this period is provided in Figure 6. As can be seen, when the VRV system in master control mode turns on, the power consumption becomes higher and reaches up to 5 kW, while the VRV system in individual control mode has a power consumption of around 3.5 kW. Similar to Figure 4, when the VRV system in master control mode turns on, the discharge pressure becomes higher than that of the individual control mode.

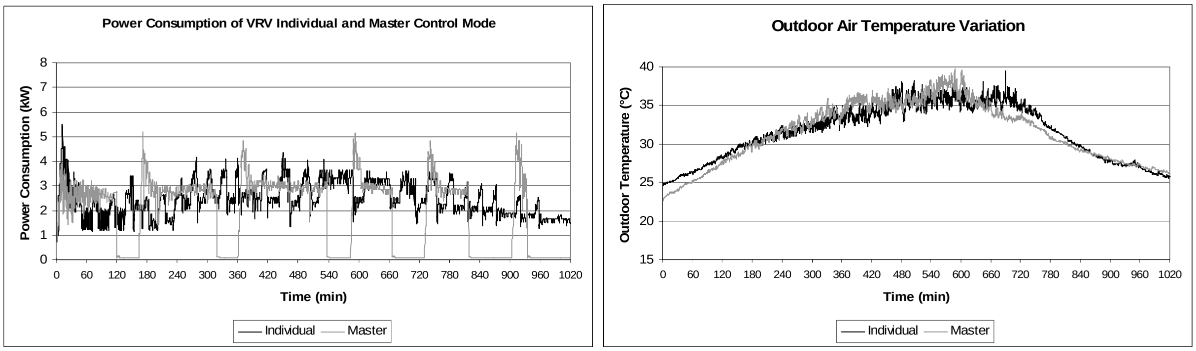


Figure 5: Power consumption and outdoor air temperature variations

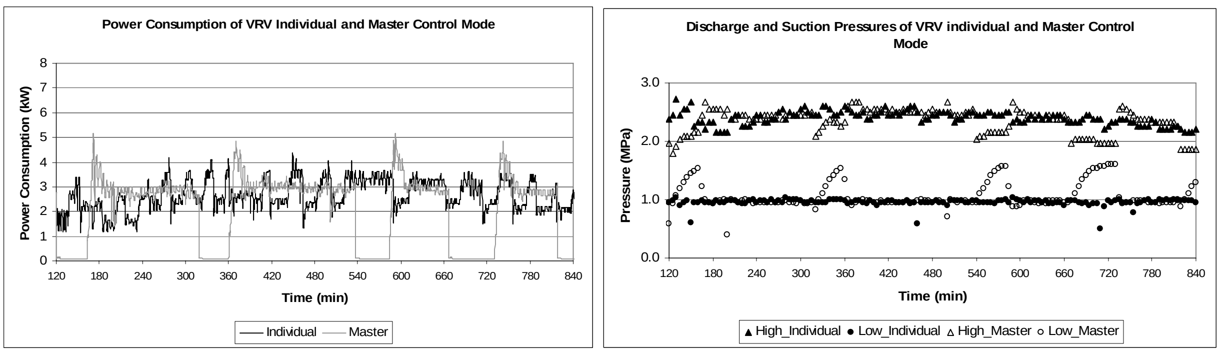


Figure 6: Power consumption, discharge and suction pressure variations

Hourly averaged CPF variation of the VRV system in individual and in master control mode with respect to outdoor air temperature is shown in Figure 7. As can be seen, even though for the lower outdoor temperatures, individual control mode operates continuously with an average CPF of 4.01; however; the master control mode has cyclic operations. The off periods of the cyclic operation for the VRV system in master control mode correspond zero in Figure 7.

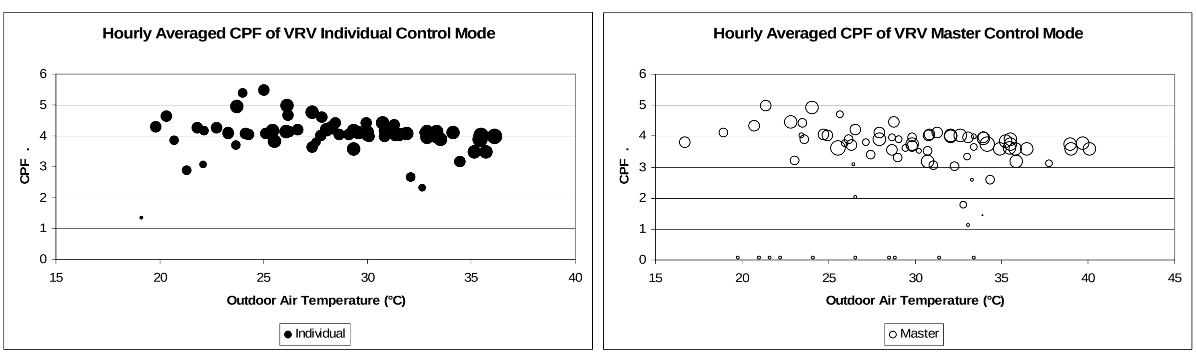


Figure 7: Hourly averaged CPF for VRV system in individual and in master control mode

Throughout the cooling season, the measured CPF of the VRV individual control mode is 8.6% higher than that of the VRV master control mode.

4.2 Thermal Comfort

In Figure 8; hourly thermal sensation scale (TSS) and hourly averaged temperature variation are shown for unit 1 and 2 with the individual control mode. Hourly TSS is calculated from hourly averaged temperature and relative humidity. Y_RA, Y_RB, Y_RC and Y_RD show TSS of room A, room B, room C and room D, respectively for unit 1, and Y_RE, Y_AiA, Y_AiB and Y_AiC show thermal sensation scale of room E, aisle A, B and C, respectively for unit 2. As can be seen, the individual control mode provides the desired comfort level, and maintains it throughout the day within +0.1 and -0.5 for unit 1 and within -0.1 and -0.5 for unit 2. On the other hand, RAT, RBT, RCT and RDT denote room A, room B, room C and room D air temperatures, respectively for unit 1 and RET, AiAT, AiBT and AiCT denote room E, aisle A, B and C air temperatures, respectively for unit 2. As can be seen, the set temperature of 25°C can be maintained; and the deviation throughout the day is around ±1.1°C. From those two figures, it can be concluded that temperature variation mostly affects TSS variation.

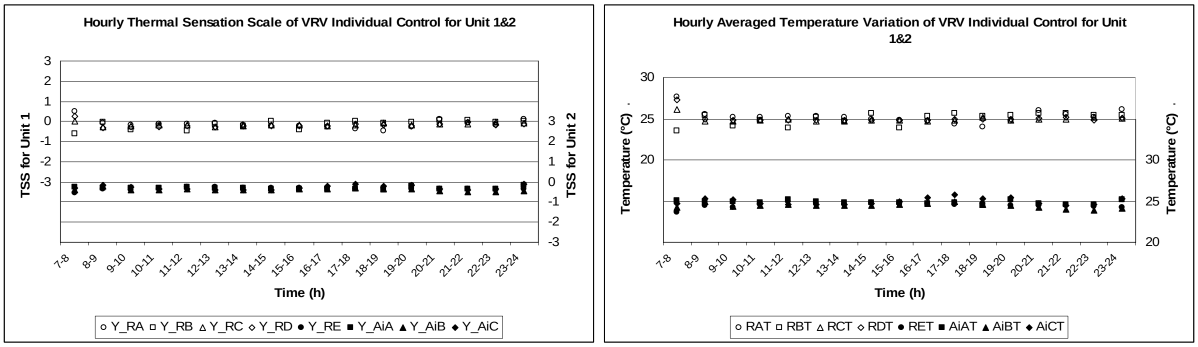


Figure 8: Hourly TSS and temperature variation of VRV system in individual control mode

Hourly TSS for unit 1 and 2 for VRV in master control mode and the existing system's control mode is shown in Figure 9. As can be seen, thermal sensation scale of master control mode is inside the neutral and cool region (+0.04 and -1.53) for unit 1 and mostly inside the slightly cool and slightly warm region (+0.80 and -1.22) for unit 2, while the TSS of the existing system is inside the slightly warm and slightly cool region (+0.52 and -0.96) for the rooms corresponding to the unit 1 for the VRV system and inside the warm and slightly cool region (+1.30 and -0.56) for the room and aisles corresponding to the unit 2 for the VRV system. VRV system in master control mode and the existing system have similar bands except room E, however TSS of the master control mode is shifted around 0.50 scale downwards. TSS of the room E for the existing system starts increasing after 12:00, and reaches to slightly warm level; which means that the existing system can not cool down the room because of the solar radiation.

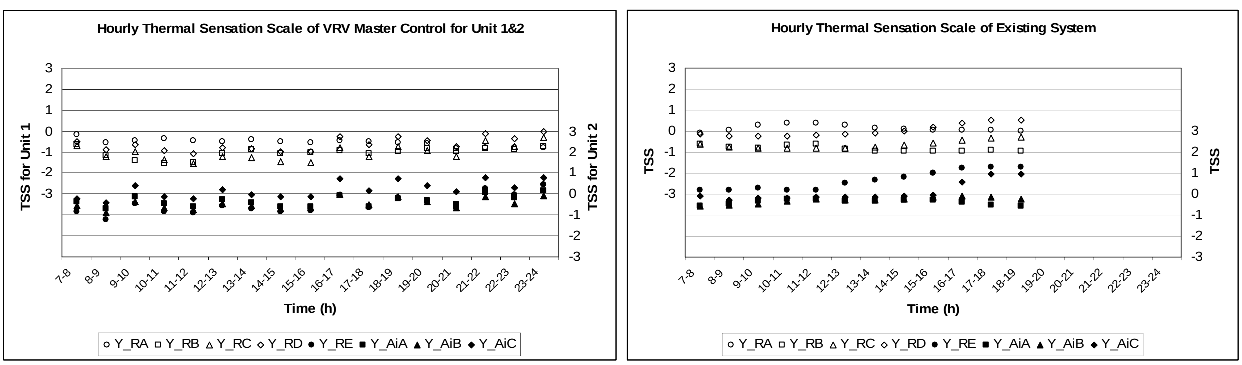


Figure 9: Hourly TSS variation of VRV system in master control mode and the existing system

Comparison of Figures 8 and 9 shows that VRV system in individual control mode provides better thermal comfort than that of the VRV system in master control mode or the existing cooling system. The existing system turns off at 19:00 due to preexisting controls, that's why data after 19:00 is not taken into account.

5. CONCLUSIONS

The performance potential of a variable refrigerant volume (VRV) air conditioning and heat pump system was experimentally investigated during field tests and compared to the existing variable air volume (VAV) cooling system. Two different control modes, individual and master controls were applied to VRV system. Existing system's control mode is similar to VRV system in master control mode. From the experiments, the following conclusions are deduced.

- VRV system in individual control mode operates continuously, however VRV system in master control mode has cyclic operation throughout the day.
- CPF of the VRV system in the individual control mode is from 3 to 15% higher than that of the master control mode.
- Throughout the cooling season, the measured CPF of the VRV individual control mode is 8.6% higher than that of the VRV master control mode.
- VRV system in individual control mode provides the desired set temperature and the corresponding comfort level and maintains it throughout the day. On the other hand, either the VRV system in master control mode or existing system can not provide or maintain the desired thermal sensation scale level. Therefore, it is concluded that using only one thermostat to control multiple numbers of zones is not sufficient to provide thermal comfort for all zones.

Overall, the VRV system in the individual control mode provides better thermal comfort for multiple rooms with higher efficiency.

NOMENCLATURE

c_V	EEV coefficient	$\dot{Q}$	Cooling capacity (kW)
CPF	Cooling performance factor	t	time (h)
G_f	EEV inlet refrigerant density (kg/m^3)	T	Dry bulb temperature (°C)
h	Refrigerant enthalpy (kJ/kg)	TSS	Thermal sensation scale
$\dot{m}$	Refrigerant mass flow rate (kg/s)	$\dot{V}$	Refrigerant volumetric flow rate (m^3/h)
p	Vapor pressure (kPa)	$\dot{W}$	Total power consumption of the outdoor and indoor units (kW)
ΔP	EEV Pressure drop (Pa)		

Subscripts

i	inlet	j	1,2,3,4
o	outlet		

REFERENCES

Baumann, H.D., 1996, Easy valve design, *Control valve primer*, Instrument Society of America, pp. 21-47.

Masuda, M., Wakahara, K., and Matsuki, K., 1991, Development of a multi-system air conditioner for residential use, *ASHRAE Transactions*, Vol. 97, no. 1, pp. 127-131.

Park, Y.C., Kim, Y.C., and Min, M.K., 2001, Performance analysis on a multi-type inverter air conditioner, *Energy Conversion and Management*, Vol. 42, no. 13, pp. 1607-1621.

Rohles, F.H., 1971, Thermal sensations of sedentary man in moderate temperatures, *Human Factors*, Vol. 13, no. 6: pp. 553-560.

Shi, W., Shao, S., Li, X., Peng, X., and Yang, X., 2003, A network model to simulate performance of variable refrigerant volume refrigeration systems, *ASHRAE Transactions*, Vol. 109, no. 2, pp. 61-68.

Wu, C., Xingxi, Z., and Shiming, D., 2005, Development of control method and dynamic model for multi-evaporator air conditioners (MEAC), *Energy and Conversion Management*, Vol. 46, no. 3, pp. 451-465.

ACKNOWLEDGEMENT

The support of this effort through Daikin, the Center for Environmental Energy Engineering and the University of Maryland, Department of Facilities is gratefully acknowledged.