2016

Review of Temperature and Humidity Control Technology for Heat Pump and Air Conditioning Systems

Xiaojie Lin
University Of Maryland, United States of America, xiaojie@umd.edu

Yunho Hwang
University Of Maryland, United States of America, yhhwang@umd.edu

Reinhard Radermacher
University Of Maryland, United States of America, raderm@umd.edu

Saikee Oh
University Of Maryland, United States of America, purdueherrickconf16@gmail.com

Review of Temperature and Humidity Control Technology for Heat Pump and Air Conditioning Systems

Xiaojie LIN[1], Yunho HWANG[1*], Reinhard RADERMACHER[1], Saikee OH[2]

[1]Center for Environmental Energy Engineering, University of Maryland,
4164 Glenn L. Martin Hall Bldg., College Park, MD 20742, USA
[2]System Air Conditioning Laboratory, LG Electronics, 327-23,
Gasan-Dong, Geumcheon-gu, Seoul, 153-802, Republic of Korea
*: Corresponding Author, Tel: (301) 405-5247, E-mail: yhhwang@umd.edu

ABSTRACT

Indoor temperature and humidity are the two most significant factors to occupants' thermal comfort. In residential and commercial buildings, split-type air conditioning systems have been widely used for its compactness and installation flexibility. However, the current split-type systems could not effectively control the thermal comfort of the occupants due to its insufficiency in humidity control. For the single-unit split-type system, the controller design is based on the concept of sensible heat factor (SHF) matching between the air conditioner side and the room side. The experimental and simulation studies are reviewed. It is concluded that this method is only applicable in a narrow operation range. This study also covers variable refrigerant flow (VRF) system, which is a typical multiple-unit split-type system. Existing temperature and humidity control in VRF systems is realized by introducing a solid desiccant heat pump (SDHP) unit. SDHP in the integrated system will cover part of latent and sensible cooling load of system. Both field tests and simulation work show that the integrated system has a better coefficient of performance (COP) than the original VRF system. In cooling season, the COP improvement is 25.7%. After the review of both the single-unit and multiple-unit studies, we further discuss the research progress of VRF system temperature controller design. Finally, based on the review and discussion, we proposed the necessary modifications required to apply single-unit temperature and humidity concept to VRF systems.

1. INTRODUCTION

Building technology is an essential part of modern life. According to the building data book published by Department of Energy (DOE), the building section consumed 41.1% of the primary energy in 2011 (Department of Energy, 2012), followed by the transportation industry sector. A key part of the building technology is the building air conditioning systems. In the selection of building air conditioning systems, split-type systems are popular in both residential and commercial buildings for its compactness and flexibility. A typical split-type system, as the name indicates, includes an outdoor unit (OU) and an indoor unit (IU) which are split in two different locations of the building. The OU, which usually includes a compressor, a fan and an outdoor heat exchanger, could be installed as one unit outside of the building. The IU, which is made up of a fan, an expansion valve, an air-to-refrigerant heat exchanger and a condensate pump, is installed indoor. The split-type systems provide cooling or heating to the indoor space by delivering air of a designed supply air temperature. This is realized by the air-to-refrigerant heat exchanger in the indoor side. Since the air is cooled by the refrigerant in the IU, such a system is also called a split-type direct expansion (DX) system. In the cooling season, the return air from the room is cooled down and the condensate is removed by the pump. The dry and cool air is thereafter provided to the room to remove the moisture and reduce the room temperature.

Along with the technological advancement, the concept of air conditioning also evolves. For example, instead of providing cooling in each zone individually, the modern air conditioning systems should provide comprehensive cooling solutions for the entire building. In buildings where multiple rooms need air conditioning, it is economically infeasible to have individuals DX systems in all the rooms. Therefore, in 1980s, the variable refrigerant flow (VRF) systems were developed by Japanese manufacturers. The VRF system also has OUs and IUs. The outdoor part of VRF systems usually includes a variable speed compressor, several outdoor exchangers, refrigerant receivers and other components such as suction line heat exchangers. High capacity VRF systems could have a combination of a fix speed compressor and a variable speed compressor to improve its load regulation capability during the peak period. VRF systems also include refrigerant flow distribution units and IUs that are typical DX units. In addition to cooling and heat pump only operation, VRF systems are able to provide space cooling and space heating simultaneously. Some VRF systems are also able to provide service hot water to the occupants. In the room side, the conventional DX systems only use the room temperature as the set point for the IUs. Therefore, the IUs are not able to control the room humidity independent to temperature. However, the thermal comfort of the occupants is affected by both the temperature and humidity. Since 1990s, a variety of studies have been carried out to realize the humidity and temperature control of DX units. Similarly, in the VRF system research, a lot of effort has also been contributed for the humidity control of individual zones. This study first reviews the humidity control studies of DX system. Since most VRF systems use DX IU in the room side, the humidity control of VRF system is reviewed. After that, the studies of both DX and VRF systems are compared and the future research are suggested.

2. SPLIT-TYPE DX COOLING SYSTEM

The reviewed temp and humidity control studies in split-type DX cooling system are summarized in Table 1.

To realize temperature and humidity control, some researchers modified the DX IU by employing additional evaporators and radiation panels (Han and Zhang, 2011). In Han and Zhang's study, one evaporator was air-cooled and another was water-cooled. The basic idea of this approach is to generate a chilled water of 18 °C in the additional evaporator. The chilled water could be used to remove the sensible load of the room via the radiation panel. In the latent part, dry air at a temperature of 16°C could be provided to the room to remove the moisture. In this approach, the sensible and latent load are covered separately.

Instead of separating sensible and latent part, it is also possible to consider coupled temperature and humidity simultaneously. For example, Chu et al. (2005) and Chu and Jong (2008) used effective temperature instead of room temperature. The target effective room temperature was set as 24.5°C. However, even with the same room effective temperature, there are multiple pairs of temperature and humidity. For a given effective temperature, the pair of room temperature and humidity ratio that yields a least enthalpy change was found by using Equation (1). The goal was to find a pair of temperature and humidity that could generate the same effective temperature but had the least enthalpy change from the current moist air state.

$$E = 1.006\left|t_B - t_A\right| + 1.805\left|t_B W_B - t_A W_A\right| + 2501\left|W_B - W_A\right| \tag{1}$$

where E is the enthalpy difference between state A and state B, kJ/kg; t_A and t_B are the dry bulb temperature of the moist air, °C. W_A and W_B are the humidity ratio, kg/kg.

When the pair of temperature and humidity had been determined, the controller further utilized a fuzzy control logic to adjust the fan speed. The objective of fuzzy control was to minimize difference between the room air state and the state generated by the least enthalpy change method by controlling the fan speed according to their decision tables.

Another widely used index is the sensible heat factor (SHF). In 1990s, Krakow et al. (1995) proposed a control algorithm which enhanced the moisture removal capability of split-type systems by using PID controllers to adjust the evaporator fan speed and compressor speed. In this approach, the controller is designed to match the SHF delivered by the unit with the SHF of the room. Different control strategies have been developed by researchers based on this concept. Since mismatch between the equipment SHF and room SHF causes thermal discomfort, some researchers investigated the sensible load change of the room (Li et al., 2014; Li et al., 2006; Xu et al., 2008). The goal of these studies was to find the change of SHF of the room so that the unit could respond to the change. It is also quantified in these studies that in the summer, the room SHF in Hong Kong is usually between 0.55 and 0.72 during daytime. In the nighttime, the SHF would range from 0.6 to 0.85. However, the typical equipment SHF is between 0.7 and 0.8, which further justified the necessity of SHF matching. Li and Deng (2007a, 2007b) proposed a direct digital control concept algorithm where the real time operation parameters were measured and collected to find the proper compressor speed and fan speed. This method controls the supply air condition to match with the SHF of the room. The challenge of such controller is the time required to estimate the SHF change of the room and the action time the controllers requires. Moreover, such a controller needs to be made based on the specification of the system and could not be easily applied to other equipment. Sekhar and Tan (2009) also proposed a SHF matching algorithm by manipulating the effective rows in the evaporator to adjust the moisture removal capability of the coils, therefore adjusting the SHF of the unit to match the room SHF. This method is specifically designed for oversized coils. Some researchers also introduced the optimization concept (Huh and Brandemuehl, 2008). The basic idea is to optimize the energy consumption with thermal comfort as constraints. The design variables are the compressor speed, fan speed, bypass air amount and indoor set points for temperature and humidity.

In the controller selection part, despite the conventional PID controllers, some novel controls are also investigated. Xu et al.(2008) introduced a high-low compressor control to replace the widely adopted on/off control for split-type DX system. The basic idea is to find the set of fan speed and compressor that could provide proper air matching the SHF of the room based on the performance of the DX coil. Qi and Deng (2008, 2009) investigated the possibility of multiple-inputs-multiple-outputs (MIMO) controllers in temperature and humidity control of the DX unit. The study is based on linearization of a validated DX unit transient model. The MIMO controller could control compressor speed and fan speed simultaneously.

Deng et al. (2009) discussed effectiveness of SHF matching methods and concluded that the controls aiming at matching the equipment SHF with the room SHF is effective within a certain normal range of SHF. Their study showed that the SHF match method would lead to thermal comfort when the SHF of the room was to 0.72. When the room had SHF as higher as 0.96 or as lower as 0.62, even with a variable speed compressor and variable speed fans, the effectiveness of SHF matching method would be restricted.

The drawback of SHF matching method is that room SHF needs to be either predicted by simulation or estimated by real-time measurements. In addition, the change of room SHF is less sensitive as compared with apparatus SHF. Moreover, as the previous studies indicated, the concept of SHF matching is only applicable in a certain narrow operation range of the IUs and could not fully represent the thermal comfort of the room.

Table 1: DX Unit Humidity Control

Author (Year)	**Location**	**Cooling Capacity (kW)**	**Concept**
Krakow et al. (1995)	N/A	N/A	Proposed PID control of compressor and evaporator fan to meet the room load.
Chu et al.(2005), Chu and Jong (2008)	Taipei	14	Used least enthalpy estimator based on effective temperature. Use fuzzy control.
Han and Zhang (2011)	Shanghai	12	Utilized two evaporator and one radiation panel
Li et al. (2006)	Hong Kong	N/A	Investigated building sensible heat ratio change.
Li and Deng (2007a,2007b)	Hong Kong	10	Changed supply air condition to match the apparatus SHF with the room SHF.
Sekhar and Tan (2009)	Singapore	100 (Building)	Manipulated the effective coil rows to match the SHF of room. Specially designed for oversized coils.
Li and Deng (2007c), Xu eta al. (2009), Li et al. (2014)	Hong Kong	10	Investigated the SHF change of the DX AC unit.
Deng et al. (2009)	Hong Kong	10	Discussed the effect of SHF matching control. Found that thermal comfort would be troublesome.
Huh and Brandemuehl (2008)	Miami	106 (Building)	Optimized energy consumption with thermal comfort constraints based on compressor control, fan control
Xu et al. (2008)	Hong Kong	4	Used “High-Low” speed control instead of on/off control
Qi and Deng (2008)	Hong Kong	10	Built and linearized a control oriented dynamic model.
Qi and Deng (2009)	Hong Kong	10	Used MIMO simultaneous control of compressor speed and evaporator fan speed.

3. VARIABLE REFRIGERANT FLOW SYSTEM

A typical VRF system has one outdoor unit (OU) and a series of IUs. The OU has air-cooled heat exchangers, fans and variable speed compressors. In the commercial application, the OU could use water-cooled heat exchangers. The IUs, regardless of types (wall-mounted type, ceiling type), include air-to-refrigerant heat exchangers. Some researchers proposed an integrated system to separate the control of temperature and humidity in the VRF systems by introducing desiccant heat pumps (SDHP) (Jiang et al., 2013; Aynur et al., 2008). The basic idea is to have a separate parallel system which could provide low humidity air to the room that the VRF system only needs to cover the sensible load. Therefore, the integrated system could respond to the change of room SHF. SDHP is a heat pump system where the condenser and evaporator are both desiccant-coated heat exchangers. By switching the operation mode of the system, i.e., the roles of evaporator and condenser, the system is able to periodically regenerate the desiccant material while keeping a continuous dehumidification or humidification of intake air. The detail of SDHP could be found in Aynur et al.'s work(Aynur et al., 2008). Aynur et al. (2008) found that with SDHP, the VRF system could provide a better thermal comfort to the building while reducing the energy consumption by 26.3% when compared to conventional heat recovery ventilators. Studies based on SDHP concept are summarized in Table 2.

Table 2: VRF with Humidity Control Capability

Authors (Year)	Type	# of IUs	OU Cooling Capacity (kW)	Operation Modes	Note	Highlights
Aynur et al. (2010a)	HP	8	28	Cooling Only	Field test	Temperature and humidity control with solid desiccant
Aynur et al. (2010b)	HP	8	28	Heating Only	Field test	
Jiang et al. (2014a)	HP	6	28	Cooling Only	Field test	
Jiang et al. (2014b)	HP	6	28	Heating Only	Field test	
Jiang et al. (2013, 2014)	HP	6	28	Cooling and Heating	Simulation	

Aynur et al. (2010a, 2010b) investigated the performance of an integrated system made up of a heat pump VRF system and a SDHP (IDVS) during cooling and heating season through field testing. In the cooling season, three cooling operation modes were considered: non-ventilated, SDHP ventilation assisted and SDHP dehumidification assisted mode. Similarly, in heating season, three heating operation modes were compared: non-ventilated, SDHP ventilation assisted and SDHP humidification mode. In cooling season, during the SDHP dehumidification assisted mode, the VRF system provided 78.9% of the accumulated cooling capacity delivered by the integrated system. The SDHP system covered the rest cooling capacity, including both sensible and latent part. Similarly, in the heating season, the VRF system provided 46.8% of the total heating capacity delivered. Regarding the thermal comfort, in the cooling season, it was observed that 99.8% of the indoor room condition fell in the ASHRAE thermal comfort zone in the SDHP dehumidification assisted mode. In non-ventilated operation mode, this ratio reduced to 95.4%. In the aspect of seasonable system performance, the SDHP assisted mode consumed 40.6% higher than the non-ventilated mode due to the fact that the additional ventilation lead to a higher cooling demand. However, the cooling season performance was increased by 7.2%. In the heating season, it was also found that the energy consumption of SDHP assisted humidification and ventilation operation lead to a 67.2% energy consumption increase when compared with the non-ventilated mode. It was also observed that the SDHP assisted ventilation and humidification operation mode could maintain a better performance factor under a low ambient temperature (~7°C). When the ambient temperature was closer to 7°C, the non-ventilated VRF system had a performance factor of 2.2 while the integrated system had a performance factor of 4.4.

Jiang et al. (2013) simulated the performance of IDVS in EnergyPlus. Since there were no modules available for SDHP in EnergyPlus, a correlation based module was developed. The module used the air temperature and humidity of the outdoor and return air as variables to develop a performance map of the SDHP under ventilation, humidification and dehumidification modes. SDHP would first remove the moisture of the air, and the VRF system would mainly deal with the remained (mainly sensible) load of the zones. The module was validated against the manufacturer's data with a relative error less than 15%. It was found that the humidity and the part load ratio had a significant impact on the system performance. When the SHF was less than 0.5, the VRF system rarely worked. When the SHF was higher than 0.5, the VRF system took most of the cooling demand. However, the performance of the system would decrease along with an increase of part load ratio. IDVS was compared with a conventional hybrid system of VRF and heat recovery ventilator. It was found that the IDVS system could save 18.7% of energy annually while yielding a better thermal comfort. Jiang et al. (2014) also investigated the performance of IDVS with another two ventilation options in EnergyPlus: heat recovery ventilator and standalone ventilation system. The simulation results were validated against experimental data, which showed a deviation of 15% in energy consumption. The coefficient of performance (COP) deviation was within 30%. It was found that the desiccant system consumed less energy than the other two systems. The simulation results also showed that the IDVS yielded a COP of 5.3 and 4.6 in summer and winter, respectively. Jiang et al. (2014a, 2014b) also experimentally studied the performance of IDVS in cooling and heating season. To show the energy saving potential of IDVS, a joint heat recovery ventilation and VRF system (JHVS) was also built. The two systems were compared to see the energy saving and performance improvement of the IDVS. It was found that IDVS could increase the COP by 25.7% and 45.2% in cooling and heating season, respectively.

4. DISCUSSION

Compared with the studies reviewed in the DX humidity control, the novelty of VRF systems with humidity control capability lays upon the additional system introduced into the integrated system but not the VRF systems itself. Therefore, the VRF system still provides sensible and latent cooling. Instead of using the SHF matching concept adopted by the DX coil units, IDVS actually distributes the load between the VRF system and the dehumidification system, which slightly changed the SHF of the VRF system. The benefit of this concept is that such novel systems could improve the humidity of the room in both cooling and heating season. For example, in cooling season, the outdoor air processing unit generates dry air to remove the moisture of the room. In the heating season, the SDHP system could humidify the supply air of the room. With this approach, in order to cover only the sensible load, the VRF systems should be designed to have an evaporating temperature higher than the dew point of the room. For example, when the room is 25°C with a RH of 60%, the evaporating temperature of the VRF system should be higher than 16.7°C. However, the current VRF systems in the market need to handle both the sensible and latent loads of the target building space. The evaporating temperature of current VRF system is lower than the dew point of the return air. Moreover, since most of IUs in VRF system are wall-mounted units, the evaporating temperature is designed even lower to meet the room load with limited heat transfer area. Therefore, the highest evaporating temperature the current VRF systems could reach is around 10°C. Therefore, to get a higher evaporating temperature, the VRF part in the IDVS system needs to be redesigned. Because the VRF system is working as the secondary system to the main dehumidification system, another drawback is that the IDVS is not able to effectively response to the possible disturbance such as the increase of indoor load. The transient behavior of such integrated system, which is critical in the temperature and humidity control of the room air conditions, is still unknown.

In the cooling operation, the VRF systems have a number of DX units in the evaporating side of the system. When compared with single split-type DX unit, the VRF systems has a series of IUs. The conventional compressor speed and fan speed control applied in DX unit could not be directly applied because the system needs to consider the capacities of individual IUs and rooms. VRF systems widely use the electronic expansion valves (EEVs), which could provide the precise control on the refrigerant flow rate to IUs. Therefore, to apply similar temperature and humidity control method to VRF systems, the refrigerant distribution caused by the EEVs needs to be taken into account in addition to compressor speed and fan speed. Moreover, a VRF system has a higher order of model complexity by nature when compared to split-type DX cooling system, due to the plurality of IUs.

Before applying the aforementioned temperature and humidity control concept to VRF systems, it is necessary to inspect the existing VRF temperature control studies. The flow chart of existing VRF temperature control these studies is shown in Figure 1 (Lin et al., 2015). In Figure 1, it should be noted that the transient VRF model is the kernel in VRF controller design. Various transient VRF models could be found in open literature. As Lin et al. (2015) summarized, most of current transient VRF models are based on simplified physical models that date back to the work done by Gordon et al. (1999) in 1990s. An alternative to physical model is a black box model that neglects the thermodynamic details of VRF system, as shown in the studies carried out by Lin and Yeh (2007). As shown in Figure 1, once the transient model has been created and validated, the remained work is to design a controller that could generate control variables that could transfer the output variables to desired state (set points). In the open literature, compressor speed and EEV openings are widely used as the control variables. Even though the control logic of commercial VRF systems is often confidential, there are still several studies (Elliott and Rasmussen, 2009, 2013; He and Asada, 2003; He et al., 1998; Shah et al., 2004; Shao et al., 2002; Wu et al., 2005; Lin and Yeh, 2007) focusing on the control of VRF systems. Based on the amount of output and control variables, controllers could be sorted into two categories: single-input-single-output (SISO) and multiple-inputs-multiple-outputs (MIMO). Currently, the widely used output variables are room temperature or superheat. If only room temperature or superheat of a single DX unit needs to be considered, a SISO controller is enough. However, in the VRF system, the researchers need to consider multiple IUs simultaneously. In such case, a MIMO controller is preferred. In order to regulate the room temperature or system superheat of VRF system, researchers have developed several types of controllers:

- Feedback controller (Lin and Yeh, 2007)
- Linear quadratic regulator (Shah et al., 2004)
- Fuzzy controller (Wu et al., 2005)
- PID controller with nonlinearity feedback (SISO controller focusing on evaporating temperature) (He and Asada, 2003)
- Model predictive controller (Elliott and Rasmussen, 2009, 2013)

Conventional controllers could not be directly applied to realize the temperature and humidity control unless the coupling terms are included in the control architecture. For example, Shah et al. (2004) discussed the performance of a two PID controllers in a dual-evaporator system. It was found that PID controllers could not maintain the superheat while tracking the reference evaporating pressure. Shah et al. (2004) also concluded that the MIMO controllers worked better than multiple SISO controllers in complex system. Therefore, to realize temperature and humidity control in VRF systems, it is necessary to consider the coupling between room temperature and humidity. Moreover, another challenge in VRF system is the coupling effect between individual IUs. For example, when the number of IUs in operation is reduced due to operation stop of some IUs, the number of state variables (temperature, pressure, and enthalpy) included in the equations also decreases. Therefore, the order of the model decreases. In such case, if the controller and observer are designed for a higher order system, the performance of designed controller could deteriorate due to the decrease in the order of the model as pointed out by He and Asada (1995).

Therefore, several necessary modifications need to be made in order to apply split-type DX system temperature and humidity control concept to the current VRF controllers. These possible modifications are as follows:

- Room model modification that considers both the sensible and latent load generation within the room and the mixing of the supply air, infiltration air and ventilation air.
- Output variable modification that uses an index similar to SHF to reduce the difficulty of controller design. For example, effective temperature could be a good alternative that combines both the humidity and temperature of the room. In this sense, the temperature and humidity control is reduced to a single variable.
- Controller modifications which could deal with the compressor speed, multiple EEV opening and multiple fan speed, as shown in split-type DX system.

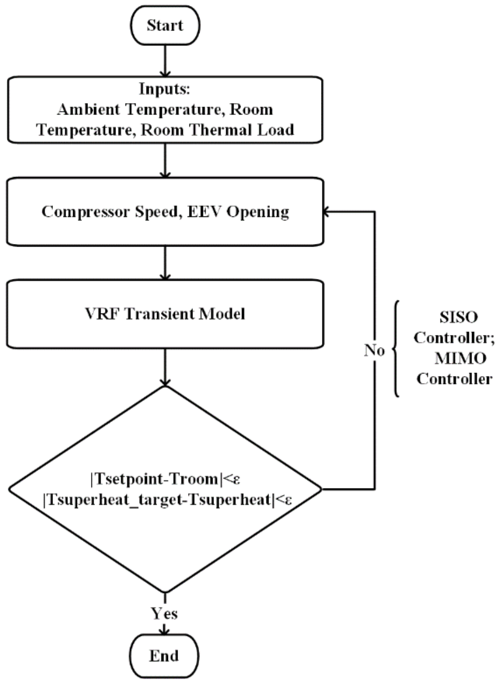

Figure 1: Transient Study Flowchart

5. CONCLUSIONS

In this study, the temperature and humidity control studies for both the split-type DX system and VRF systems are reviewed. Most of the humidity control studies of DX units focus on the SHF matching between the room side and the unit side. This approach mainly depends on the compressor speed and fan speed control. The drawback is the dependency on the real-time measurement and the narrow applicable range. The temperature and humidity control studies in VRF systems are also reviewed. It is found that the current studies focus on the integrated system (IDVS) made up by VRF system and a parallel system (SDHP). The parallel system is able to control the room humidity while the VRF system will cover the remained sensible and latent loads. Based on the literature review, it is suggested that the VRF system could also control the temperature and humidity during the cooling season in a manner similar to the DX systems. This could be realized by making necessary changes to the current VRF transient models.

NOMENCLATURE

COP	coefficient of performance
DX	direct expansion
EEV	electronic expansion valve
IDVS	integrated solid desiccant heat pump and VRF system
IU	indoor unit
IHVS	integrated heat recovery ventilation and VRF system
OU	outdoor unit
RH	relative humidity
SDHP	solid desiccant heat pump
SHF	sensible heat factor
VRF	variable refrigerant flow

REFERENCES

Aynur, T. N., Hwang, Y. H., and Radermacher, R. (2008). Field performance measurements of a heat pump desiccant unit in dehumidification mode, *40*, 2141–2147. doi:10.1016/j.enbuild.2008.06.003.

Aynur, T. N., Hwang, Y., and Radermacher, R. (2010). Integration of variable refrigerant flow and heat pump desiccant systems for the cooling season. *Applied Thermal Engineering*, *30*(8-9), 917–927.

doi:10.1016/j.applthermaleng.2010.01.002.
Aynur, T. N., Hwang, Y., and Radermacher, R. (2010). Integration of variable refrigerant flow and heat pump desiccant systems for the heating season. *Energy and Buildings*, *42*(4), 468–476. doi:10.1016/j.enbuild.2009.10.016.
Chu, C.-M., and Jong, T.-L. (2008). A Novel Direct Air-Conditioning Load Control Method. *IEEE Transactions on Power Systems*, *23*(3), 1356–1363. doi:10.1109/TPWRS.2008.926432.
Chu, C.-M., Jong, T.-L., and Huang, Y.-W. (2005). Thermal comfort control on multi-room fan coil unit system using LEE-based fuzzy logic. *Energy Conversion and Management*, *46*(9–10), 1579–1593. doi:10.1016/j.enconman.2004.08.002.
Department of Energy. (2012). *2011 Buildings Energy Data Book*. Retrieved from http://buildingsdatabook.eren.doe.gov/ChapterIntro1.aspx.
Elliott, M. S., and Rasmussen, B. P. (2009). A model-based predictive supervisory controller for multi-evaporator HVAC systems. *2009 American Control Conference*, 3669–3674. doi:10.1109/ACC.2009.5160498.
Elliott, M. S., and Rasmussen, B. P. (2013). Decentralized model predictive control of a multi-evaporator air conditioning system. *Control Engineering Practice*, *21*(12), 1665–1677. doi:10.1016/j.conengprac.2013.08.010.
Gordon, B. W., Liu, S., and Asada, H. H. (1999). Dynamic Modeling of Multiple-Zone Vapor Compression Cycies using Variable Order Representations. In *Proceedings of the 1999 American Control Conference* (pp. 3765–3769).
Han, X., and Zhang, X. (2011). Experimental study on a residential temperature–humidity separate control air-conditioner. *Energy and Buildings*, *43*(12), 3584–3591. doi:10.1016/j.enbuild.2011.09.029.
He, X., and Asada, H. H. (2003). A new feedback linearization approach to advanced control of multi-unit HVAC systems. *Proceedings of the 2003 American Control Conference, 2003.*, *3*, 2311–2316. doi:10.1109/ACC.2003.1243419.
He, X. D., Liu, S., Asada, H., and Itoh, H. (1998). Multivariable Control of Vapor Compression Systems. *HVACandR Research*, *4*(3), 205–230. doi:10.1080/10789669.1998.10391401.
Huh, J.-H., and Brandemuehl, M. J. (2008). Optimization of air-conditioning system operating strategies for hot and humid climates. *Energy and Buildings*, *40*(7), 1202–1213. doi:10.1016/j.enbuild.2007.10.018.
Jiang, Y., Ge, T. S., Wang, R. Z., and Huang, Y. (2014a). Experimental investigation on a novel temperature and humidity independent control air conditioning system – Part I: Cooling condition. *Applied Thermal Engineering*, *73*(1), 782–791. doi:10.1016/j.applthermaleng.2014.08.028.
Jiang, Y., Ge, T. S., Wang, R. Z., and Huang, Y. (2014b). Experimental investigation on a novel temperature and humidity independent control air conditioning system – Part II: Heating condition. *Applied Thermal Engineering*, *73*(1), 773–781. doi:10.1016/j.applthermaleng.2014.08.030.
Jiang, Y., Ge, T., and Wang, R. (2013). Performance simulation of a joint solid desiccant heat pump and variable refrigerant flow air conditioning system in EnergyPlus. *Energy and Buildings*, *65*, 220–230. doi:10.1016/j.enbuild.2013.06.005.
Jiang, Y., Ge, T., and Wang, R. (2014). Comparison study of a novel solid desiccant heat pump system with EnergyPlus. *Building Simulation*, *7*(5), 467–476. doi:10.1007/s12273-014-0166-7.
Krakow, K. I., Lin, S., and Zeng, Z. S. (1995). Temperature and Humidity Control During Cooling and Dehumidifying by Compressor and Evaporator Fan Speed Variation. *ASHRAE Transactions*, *101*(1), 292–304. Retrieved from http://www.osti.gov/scitech/biblio/87400.
Li, Z., Chen, W., Deng, S., and Lin, Z. (2006). The characteristics of space cooling load and indoor humidity control for residences in the subtropics. *Building and Environment*, *41*(9), 1137–1147. doi:10.1016/j.buildenv.2005.05.016.
Li, Z., and Deng, S. (2007a). A DDC-based capacity controller of a direct expansion (DX) air conditioning (A/C) unit for simultaneous indoor air temperature and humidity control – Part I: Control algorithms and preliminary controllability tests. *International Journal of Refrigeration*, *30*(1), 113–123. doi:10.1016/j.ijrefrig.2006.06.007.
Li, Z., and Deng, S. (2007b). A DDC-based capacity controller of a direct expansion (DX) air conditioning (A/C) unit for simultaneous indoor air temperature and humidity control – Part II: Further development of the controller to improve control sensitivity. *International Journal of Refrigeration*, *30*(1), 124–133. doi:10.1016/j.ijrefrig.2006.06.003.
Li, Z., Xu, X., Deng, S., and Pan, D. (2014). Further study on the inherent operating characteristics of a variable speed direct expansion air conditioning system. *Applied Thermal Engineering*, *66*(1–2), 206–215. doi:10.1016/j.applthermaleng.2014.02.019.

Lin, J.-L., and Yeh, T.-J. (2007). Identification and control of multi-evaporator air-conditioning systems. *International Journal of Refrigeration*, *30*(8), 1374–1385. doi:10.1016/j.ijrefrig.2007.04.003.

Lin, X., Lee, H., Hwang, Y., and Radermacher, R. (2015). A Review of Recent Development in Variable Refrigerant Flow Systems. *Science and Technology for the Built Environment*, 1–13. doi:10.1080/23744731.2015.1071987.

Qi, Q., and Deng, S. (2008). Multivariable control-oriented modeling of a direct expansion (DX) air conditioning (A/C) system. *International Journal of Refrigeration*, *31*(5), 841–849. doi:10.1016/j.ijrefrig.2007.10.009.

Qi, Q., and Deng, S. (2009). Multivariable control of indoor air temperature and humidity in a direct expansion ({DX}) air conditioning ({A}/{C}) system. *Building and Environment*, *44*(8), 1659–1667. doi:10.1016/j.buildenv.2008.11.001.

Sekhar, S. C., and Tan, L. T. (2009). Optimization of cooling coil performance during operation stages for improved humidity control. *Energy and Buildings*, *41*(2), 229–233. doi:10.1016/j.enbuild.2008.09.005.

Shah, R., Alleyne, A. G., and Bullard, C. W. (2004). Dynamic Modeling and Control of Multi-Evaporator Air-Conditioning Systems. *ASHRAE Transactions*.

Shao, S., Shi, W., Li, X., and Yan, Q. (2002). Performance of Multi-System Air Conditioner With Variable Frequency Control Based On Units. In *International Refrigeration and Air Conditioning Conference*.

Shiming, D., Zheng, L., and Minglu, Q. (2009). Indoor thermal comfort characteristics under the control of a direct expansion air conditioning unit having a variable-speed compressor and a supply air fan. *Applied Thermal Engineering*, *29*(11–12), 2187–2193. doi:10.1016/j.applthermaleng.2008.10.011.

Wu, C., Xingxi, Z., and Shiming, D. (2005). Development of control method and dynamic model for multi-evaporator air conditioners (MEAC). *Energy Conversion and Management*, *46*(3), 451–465. doi:10.1016/j.enconman.2004.03.004.

Xu, X., Deng, S., and Chan, M. (2008). A new control algorithm for direct expansion air conditioning systems for improved indoor humidity control and energy efficiency. *Energy Conversion and Management*, *49*(4), 578–586. doi:10.1016/j.enconman.2007.07.040.

ACKNOWLEDGEMENT

We gratefully acknowledge the support of Energy Efficiency and Heat Pumps Consortium of the Center for Environmental Energy Engineering (CEEE) at the University of Maryland, and System Air Conditioning Laboratory at LG Electronics Inc.