A New Control Strategy for Variable Refrigerant Flow Systems

Xiaojie Lin – University of Maryland – xiaojie@umd.edu
Yunho Hwang – University of Maryland – yhhwang@umd.edu
Reinhard Radermacher – University of Maryland – raderm@umd.edu
Byungsoon Kim– CAC R&D Lab., LG Electronics – bs.kim@lge.com

Abstract

In the US, more than 45 % of the building primary energy is used for space cooling, space heating, and water heating. Advanced HVAC systems are key to building energy consumption reduction. A variable refrigerant flow (VRF) system is a promising solution to this problem, because it can precisely provide space cooling and/or space heating for different zones. A literature review of previous VRF modeling studies shows that the use of existing simulation tools, such as EnergyPlus, can result in more than 20 % deviation in both capacity and energy consumption. In this study, a new VRF model is proposed to improve the accuracy over conventional models. Simulation results show that the proposed model agrees with experimental field test data within a 10 % deviation in hourly capacity and 5 % in hourly energy consumption. After the validation of the VRF system model, a new VRF control strategy was proposed based upon evaporating/condensing temperature controls. The seasonal performance of VRF system with the new control strategy was simulated for the same building design in four different climates representing these US cities: Miami, Houston, Baltimore, and Chicago.

1. Introduction

The variable refrigerant flow (VRF) system is an air conditioning solution introduced by Japanese manufacturers in mid-1980s. It is well known for its excellent systematic modularity and installation flexibility as compared to ducted air conditioners. Among various VRF types, two types of VRF systems, the heat pump type (HPVRF) and the heat recovery type (HRVRF), are of interest. The differences and similarities between HPVRF and HRVRF are illustrated in Fig.s 1 and 2. In Fig. 1, the HPVRF system works in a cooling mode while HRVRF works in a cooling main mode where the system provides more cooling than heating to the building. Both systems have four indoor units (IUs) and one outdoor unit (OU).

In addition, HRVRF has one extra component, which is a heat recovery unit (HRU). In the OU of HPVRF system (Fig. 1), the discharged refrigerant from the compressor rejects heat to the ambient air and is cooled down to subcooled state. The subcooled refrigerant bypasses the main electronic expansion valve (EEV) via the check valve, and flows into the IU side where it is distributed among different IUs. As shown in Fig. 1, a typical IU is made of one crossflow fan, direct expansion coils and one EEV. The subcooled refrigerant expands through the EEV and cools down room air by forced convection. Then, the refrigerant is sent back to the suction port of the compressor.

In the heating season, the four-way valve is reversed and refrigerant flow direction is alternated so that the system is working in the heat pump mode where the room air is heated. Fig. 2 shows the cooling main operation of the HRVRF. Therefore, in order to meet the demands of the rooms, a HRU has three pipes of refrigerant: low pressure vapor, high pressure vapor, and high pressure liquid. HRU distributes the refrigerant based on demands of the IUs. For example, in Fig. 2, part of the high-pressure refrigerant vapor is delivered to the IU via the HRU, instead of it being sent to the OU, when one or more rooms need heating. For the rest of the rooms, the HRU also delivers the subcooled liquid to these IUs. Finally, HRU also sends the superheated vapor back to the suction port of the

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2018. Building simulation applications BSA 2017. bu,press.
https://doi.org/10.13124/9788860461360

compressor. As can be seen in Fig.s 1 and 2, HRVRF is preferred over HPVRF where the cooling and heating loads from different parts of the building need to be satisfied at the same time, such as hospitals and office buildings.

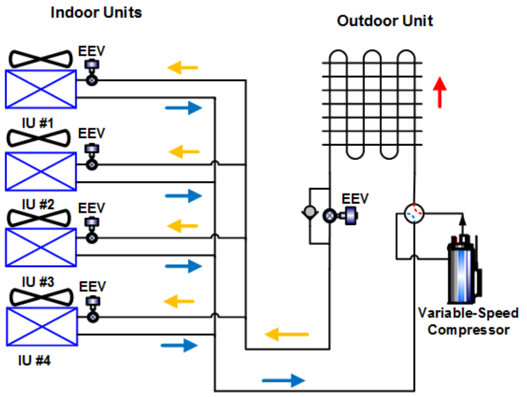

Fig. 1 – HPVRF operated in cooling mode

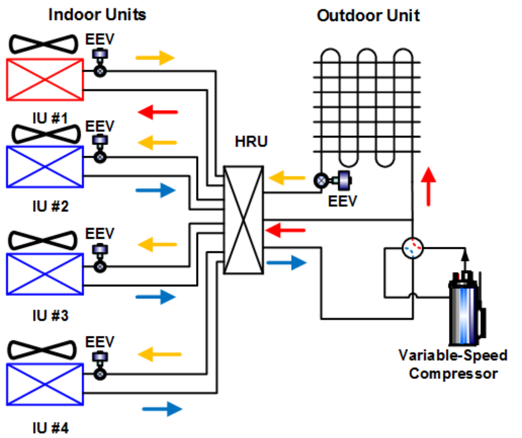

Fig. 2 – HRVRF operated in cooling main mode

However, in the buildings, the occupants could actually have more demands than space cooling or heating. For example, occupants also need ventilation and hot water. As a comprehensive and flexible building HVAC solution, VRF systems could also provide other functionality than cooling or heating. Zhu et al. (2015; 2014a; 2014b) proposed a VRF system incorporated with a dedicated outdoor cooling system. Simulation results showed that the proposed system could provide a better indoor thermal comfort with a 12.2 % higher coefficient of performance (COP) in cooling season than conventional AC systems.

Similarly, Aynur et al. (2010a; 2010b; 2008) and Aynur (2008) tested an integrated system made of HPVRF system and a solid desiccant heat pump unit. They found that the CO_2 concentration of the room could be kept within 450-500 ppm. In addition, another perspective in building VRF research is to use the simulation tools to evaluate the performance of the system. For example, eQuest and EnergyPlus are the two most popular tools used in open literature.

Most of the existing VRF models in building simulation tools are based on performance mapping method. This method is effective only with a carefully tuned model with accurate onsite parameters and schedules, as found by Lin et al. (2015a). For example, the performance mapping model developed by Zhou et al. (2008; 2007) and Zhou and Wang (2006) could yield weekly cooling energy and power consumption errors of 25.2 % and 28.3 %, respectively when applied to a real building. Researchers also observed that the model could lead to a higher uncertainty when the focus of the study switched from weekly data to hourly data. Moreover, another disadvantage of performance mapping method is the insufficiency in adopting new control strategies when focusing on hourly performance. Lin et al. (2015b) suggested and developed a first-principle based VRF model. In this paper, the development of the model is explained before the extended modeling work with the new control. After the model was validated, a new ambient temperature based evaporating/condensing temperature control strategy was applied to the model and the seasonal energy saving potential was demonstrated.

2. VRF Model

2.1 Model Flow Chart

Performance mapping model was firstly developed by Zhou et al. (2007a; 2007b; 2008) and Zhou and Wang (2006). A model of similar concept was later incorporated into EnergyPlus 6.0 as part of the official engine developed by Raustad and Sharma (2013); Nigusse and Raustad (2013); and Sharma and Raustad (2013). The basic idea is illustrated in

Fig. 3. The first step is to process the building geometry file and weather data specified by the user. The model then calculates the required space cooling and heating loads of the rooms. In the earlier versions of building model, the VRF model does not have its own IU module. Therefore, some researchers would use the window AC module instead of VRF IU module. Based on the room load, the required IU (or window AC) cooling or heating capacity is calculated. Once the engine has obtained all the information from the IU and building side, the OU module of the VRF model is called. This module reads two maps as the lookup tables. The first one is the system capacity map based on indoor and outdoor temperatures. The second map is the energy consumption map. The OU module searches the operation point in the cooling capacity map. The ideal operation point should deliver the required IU load to the building. Once the operation point is found, the energy consumption of the system is calculated accordingly.

Lin et al. (2015b) analyzed the uncertainty of performance mapping method and concluded that a thermodynamic model could be a proper way to reduce the model uncertainty. The flow chart of the new model is shown in Fig. 4. As compared to Fig. 3, the model still begins with the estimation of room load and IU load. After that, the model calls a thermodynamic OU module to find the energy consumption of the system. The required inputs for the OU module are the polynomial equations of the compressor performance and user-specified control parameters such as the degree of superheating. In order to quantify the accuracy of the new model, the normalized mean bias error (NMBE) concept (Eq. 1) from ASHRAE guideline (ASHRAE, 2002) was used. The target NMBE value was less than 5 %.

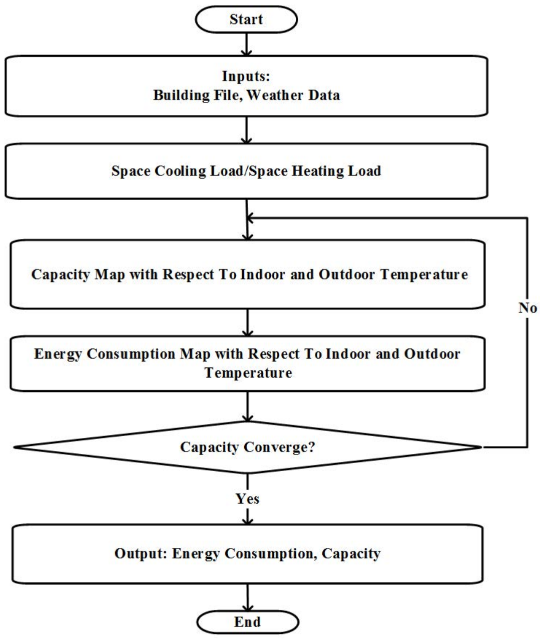

Fig. 3 – Flow chart of performance mapping method

$$NMBE = 100 * \frac{\sqrt{\sum_{i=1}^{n}(y_i - \hat{y_i})}}{(n-1)*\bar{y}} \quad (1)$$

where y_i is the simulation result, $\hat{y_i}$ is the experimental result, n is the amount of points, and $\bar{y}$ is the mean of experimental results.

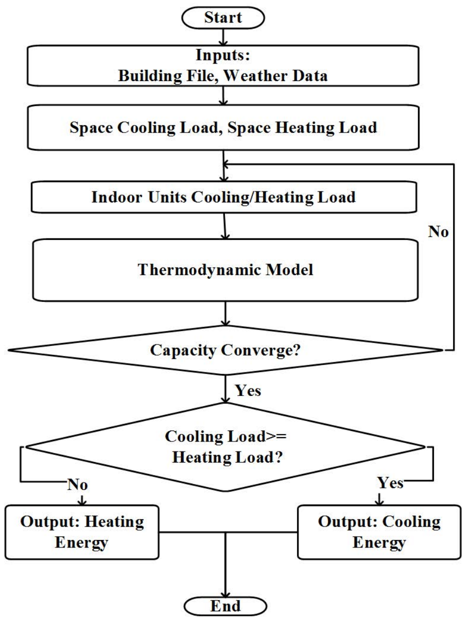

Fig. 4 – Flow chart of the new method

The model was validated in the cooling season while focusing on hourly operation data with a VRF system having seven IUs. The system has a rated cooling capacity of 28.1 kW. The hourly energy consumption validation result is shown in Fig. 5. The obtained NMBE value was 3.7 %, which means the hourly model uncertainty is less than 5 %. The details of the model could be found in Lin et al.'s study (2015b).

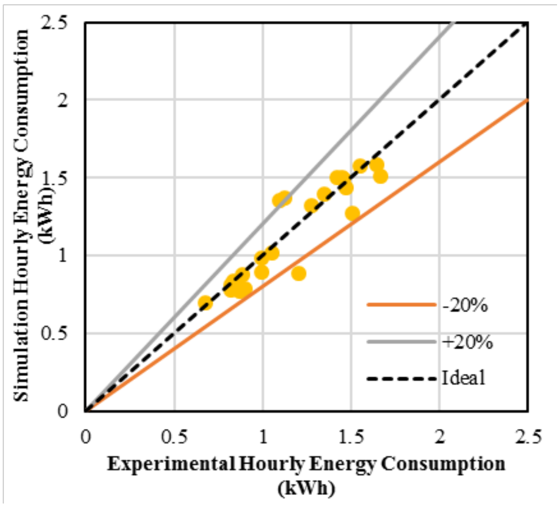

Fig. 5 – Hourly energy consumption validation

2.2 New Control Strategy

As mentioned by Chen et al. (2005), the control mechanism of VRF system is less discussed in existing literature as compared to the field tests or simulation studies due to commercial confidentiality. Even though the details of control mechanism are not available and vary with products, manufacturers generally use lookup tables to control compressors (LG Electronics 2015), as mentioned by Tu et al. (2010).

The controller estimates the building load based on ambient condition. Then it references a table to find out the proper compressor frequency meeting the estimated building load. The map is generated by laboratory testing. For example, during the cooling operation, the evaporating temperature is designed based upon the rated condition where the ambient temperature is 35 °C. When the ambient temperature decreases, the cooling demand also decreases. In a conventional fix-speed air conditioning system, the evaporating temperature decreases with ambient temperature. However, in the VRF system the evaporating temperature can be maintained by reducing the compressor frequency. The energy consumption of the system is thereby reduced. Therefore, increasing the evaporating temperature can achieve energy saving. As shown by the experimental work from Anyur et al. (2008) and Shao et al. (2004), the compressor could operate under a further lower frequency with a higher evaporating temperature, but still delivers sufficient amount of refrigerant to the IUs, which reduces the energy consumption. Zhao et al. (2015) found that by increasing the evaporating temperature from 8 °C to 12 °C, 15 % energy saving could be achieved. Typically, the latent cooling load in the room is lower at a lower ambient temperature. When a higher evaporating temperature is used, the latent cooling capacity is decreased. Therefore, using a higher evaporating temperature at lower ambient temperature can save energy while delivering a proper sensible cooling. This means that the control of evaporating temperature is critical to energy saving in the cooling season. Similarly, in the heating operation, the condensing temperature of the system could be a key design parameter for energy saving. Therefore, in this study, a new control strategy was proposed. Instead of using single linear map based on single evaporating/condensing temperature, this new control strategy determines the compressor frequency under a varying evaporating/condensing temperature. The control strategy follows two simple rules:

- The evaporating temperature of the system is adjusted linearly from 11 °C to 4.2 °C when the ambient air temperature increases from 20 °C to 35 °C.
- The condensing temperature of the system is adjusted linearly from 50 °C to 40 °C when the ambient air temperature increases from -10 °C to 5 °C.

3. Results and Discussion

The specifications of the VRF system used in this study are listed in Table 1. The floor map of the building where the system was installed is shown in Fig. 6. The test VRF system has seven IUs and a rated OU cooling capacity of 28.1 kW. The IU #1 was installed in Room A. IU #2 and #3 were installed in Room B. IU #4 and IU #5 were installed in Room C. IU #6 was installed in Room D. IU #7 was installed in Room E. For the cooling operation, the running period was set from July 1 to September 1. The set point of the rooms was 25 °C in cooling season. The TMY3 weather data in Baltimore, MD was used. Fig. 7 shows the daily energy consumption reduction when compared to the default VRF control strategy in the cooling season. Overall, in the cooling season, the seasonal energy consumption is reduced from 1,938 kWh to 1,764 kWh with energy savings of 8.9 %. For heating operation, the running period was set from February 1 to April 1. The set point of the rooms was 22 °C. Similarly, Fig. 8 shows the daily energy consumption reduction of the new control strategy. In heating season, the energy consumption is reduced from 2,753 kWh to 2,329 kWh with energy savings of 15.4 %.

Table 4 – VRF system specifications

Component	Cooling (kW)	Heating (kW)
OU	28.1	31.6
IU #1	2.2	2.5
IU #2	3.6	4.0
IU #3	3.6	4.0
IU #4	5.6	6.0
IU #5	5.6	6.0
IU #6	2.2	2.5
IU #7	2.2	2.5

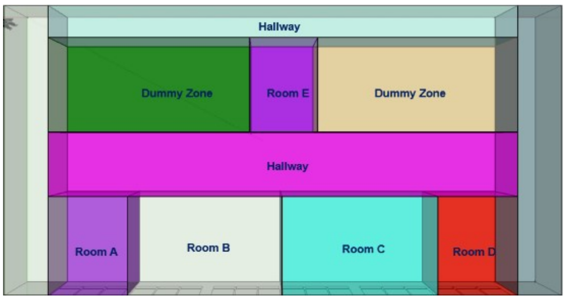

Fig. 6 – Building floor map

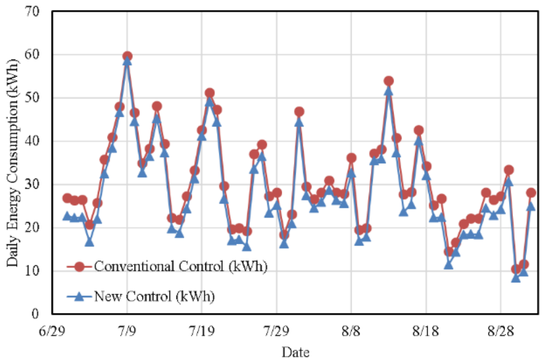

Fig. 7 – Cooling seasonal energy savings by new control strategy in Baltimore, MD

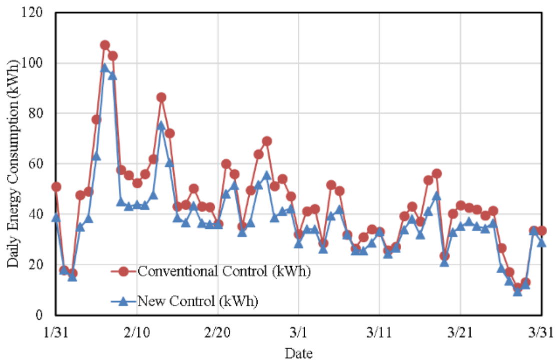

Fig. 8 – Heating seasonal energy savings by new control strategy in Baltimore, MD

The same building and VRF system were also simulated in Miami, Houston, and Chicago, which are the representative cities of the respective climate zones. The seasonal performance in different climates is listed in Table 2. Energy saving potential of the new control strategy is reduced when it is applied to Miami. That is because the key of the new control strategy is the applicable temperature range. In this case, the applicable range is selected based on the climate of Baltimore, MD. Therefore, the applicable range is relatively narrow as compared to the weather conditions in Miami, which leads to a degradation of the performance.

Table 5 – Cooling and heating energy savings in different climates

City	Cooling Season Energy Savings (%)	Heating Season Energy Savings (%)
Miami, FL	6.8 %	10.5 %
Houston, TX	5.2 %	11.2 %
Baltimore, MD	8.9 %	15.4 %
Chicago, IL	10.8 %	14.1 %

4. Conclusion

In this study, a new control strategy based on evaporating/condensing temperature control was proposed and embedded on a validated VRF model. The seasonal performance of the new control strategy was simulated in a seven-IU VRF system with a rated cooling capacity of 28.1 kW. The simulation results show that the VRF system with the new control strategy could save 8.9 % and 15.4 % of energy during the cooling and heating seasons in Baltimore, MD.

Acknowledgements

This work was supported by LG Electronics Inc. and the sponsors of the Energy Efficiency and Heat Pumps Consortium, the Center for Environmental Energy Engineering (CEEE) at the University of Maryland, College Park, MD, USA.

Nomenclature

Symbols

COP	Coefficient of performance
EEV	Electronic expansion valve
HRU	Heat recovery unit
HPVRF	Heat pump variable refrigerant flow
HRVRF	Heat recovery variable refrigerant flow
IU	Indoor unit
NMBE	Normalized mean bias error
OU	Outdoor unit
VRF	Variable refrigerant flow

References

ASHRAE. 2002. *ASHRAE Guideline 14-Measurement of Energy and Demand Savings*. Atlanta, U.S.A.: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Aynur, T., Y. Hwang, R. Radermacher. 2008. "Experimental Evaluation of the Ventilation Effect on the Performance of a VRV System in Cooling Mode—Part I: Experimental Evaluation". *HVAC&R Research* 14(4): 615–30. doi:10.1080/10789669.2008.10391029.

Aynur, T.N., Y. Hwang, R. Radermacher. 2010a. "Integration of Variable Refrigerant Flow and Heat Pump Desiccant Systems for the Cooling Season". *Applied Thermal Engineering* 30(4): 917–27. doi:10.1016/j.applthermaleng.2010.01.002.

Aynur, T.N., Y. Hwang, R. Radermacher. 2010b. "Integration of Variable Refrigerant Flow and Heat Pump Desiccant Systems for the Heating Season". *Energy and Buildings* 42(4): 468–76. doi:10.1016/j.enbuild.2009.10.016.

Aynur, T.N. 2008. *Experimental and Simulation Evaluation of a Multi-Split Type Air Conditioning System Under Steady-State and Transient Conditions*. College Park, U.S.A.: University of Maryland.

Chen, W., X. Zhou, S. Deng. 2005. "Development of Control Method and Dynamic Model for Multi-Evaporator Air Conditioners (MEAC)". *Energy Conversion and Management* 46(3): 451–65. doi:10.1016/j.enconman.2004.03.004.

LG Electronics. 2015. *Multi V IV Service Manual*.

Lin, X., H. Lee, Y. Hwang, R. Radermacher. 2015a. "A Review of Recent Development in Variable Refrigerant Flow Systems". *Science and Technology for the Built Environment* 21(7): 1–13. doi:10.1080/23744731.2015.1071987.

Lin, X., H. Lee, Y. Hwang, R. Radermacher, B. Kim. 2015b. "A New Variable Refrigerant Flow System Simulation Approach in EnergyPlus". *International Journal of Air-Conditioning and Refrigeration* 24(1). doi:10.1142/S2010132516500012

Nigusse, B., R. Raustad. 2013. “Verification of a VRF Heat Pump Computer Model in EnergyPlus”. In: *Proceedings of ASHRAE Annual Conference*. Denver, U.S.A.

Raustad, R. 2013. “A Variable Refrigerant Flow Heat Pump Computer Model in EnergyPlus”. *ASHRAE Transactions* 119: 299–308.

Shao, S., W. Shi, X. Li, H. Chen. 2004. “Performance Representation of Variable-Speed Compressor for Inverter Air Conditioners Based on Experimental Data”. *International Journal of Refrigeration* 27(8): 805–815. doi:10.1016/j.ijrefrig.2004.02.008.

Sharma, C., R. Raustad. 2013. “Compare Energy Use in Variable Refrigerant Flow Heat Pumps Field Demostration and Computer Model”. In: *Proceedings of ASHRAE Annual Conference*. Denver, U.S.A.

Tu, Q., Z. Feng, S. Mao, K. Dong, R. Xiao, W. Song. 2010. “Heating Control Strategy for Variable Refrigerant Flow Air Conditioning System with Multi-Module Outdoor Units”. *Energy and Buildings* 42(11): 2021–27. doi:10.1016/j.enbuild.2010.06.010.

Zhao, D., X. Zhang, M. Zhong. 2015. “Variable Evaporating Temperature Control Strategy for VRV System under Part Load Conditions in Cooling Mode”. *Energy and Buildings* 91: 180–86. doi:10.1016/j.enbuild.2015.01.039.

Zhou, Y., R. Wang. 2006. “Module Development and Simulation of the Variable Refrigerant Flow Air Conditioning System under Cooling Conditions in EnergyPlus”. In: *Proceedings of the International Conference for Enhanced Building Operations*. Shenzhen, China.

Zhou, Y., J. Wu, R. Wang. 2007a. “Definition Identification of Two Kinds of Part Load Ratio (PLR)”. *Refrigeration And Air Conditioning*: 5–7.

Zhou, Y., J. Wu, R. Wang, S. Shiochi. 2007b. “Energy Simulation in the Variable Refrigerant Flow Air-Conditioning System under Cooling Conditions”. *Energy and Buildings* 39(2): 212–20. doi:10.1016/j.enbuild.2006.06.005.

Zhou, Y.P., J.Y. Wu, R. Wang, S. Shiochi, Y.M. Li. 2008. “Simulation and Experimental Validation of the Variable-Refrigerant-Volume (VRV) Air-Conditioning System in EnergyPlus”. *Energy and Buildings* 40(6): 1041–47. doi:10.1016/j.enbuild.2007.04.025.

Zhu, Y., X. Jin, Z. Du, B. Fan, X. Fang. 2014a. “Simulation of Variable Refrigerant Flow Air Conditioning System in Heating Mode Combined with Outdoor Air Processing Unit”. *Energy and Buildings* 68(1–2): 385–95. doi:10.1016/j.enbuild.2013.09.042.

Zhu, Y., X. Jin, X. Fang, Z. Du. 2014b. “Optimal Control of Combined Air Conditioning System with Variable Refrigerant Flow and Variable Air Volume for Energy Saving”. *International Journal of Refrigeration* 42: 14–25. doi:10.1016/j.ijrefrig.2014.02.006.

Zhu, Y., X. Jin, Z. Du, X. Fang. 2015. “Online Optimal Control of Variable Refrigerant Flow and Variable Air Volume Combined Air Conditioning System for Energy Saving”. *Applied Thermal Engineering* 80: 87–96. doi:10.1016/j.applthermaleng.2015.01.030.