Journal of Southeast University (English Edition) Vol. 26, No. 2, pp. 197 - 200 June 2010 ISSN 1003—7985

Application of water loop variable refrigerant flow air-conditioning system in large-scale buildings in northern China

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Abstract: A water loop variable refrigerant flow (WLVRF) air-conditioning system is designed to be applied in large-scale buildings in northern China. The system is energy saving and it is an integrated system consisting of a variable refrigerant flow (VRF) air-conditioning unit, a water loop and an air source heat pump. The water loop transports energy among different regions in the buildings instead of refrigerant pipes, decreasing the scale of the VRF air-conditioning unit and improving the performance. Previous models for refrigerants and building loads are cited in this investigation. Mathematical models of major equipment and other elements of the system are established using the lumped parameter method based on the DATAFIT software and the MATLAB software. The performance of the WLVRF system is simulated. The initial investments and the running costs are calculated based on the results of market research. Finally, a contrast is carried out between the WLVRF system and the traditional VRF system. The results show that the WLVRF system has a better working condition and lower running costs than the traditional VRF system.

Key words: variable refrigerant flow; air-conditioning system; water loop; large-scale building

Previous researches show that if applied properly, a variable refrigerant flow(VRF) air-conditioning system can operate flexibly, occupy small space, and consume low energy, and it is widely used in residential buildings, villas, as well as small and medium public buildings. Recently, the VRF systems have become a hot issue among HVAC researchers. The most enormously complex task is to apply the VRF systems to large-scale construction in northern China. Lots of previous studies have focused on the extent of the effective regions of the VRF air-conditioning systems. The effective region of a VRF system was proposed by Shi et al[1]. Wu[2] concluded that the COP increases when the capacity decreases. A few attempts have been made to design highly efficient VRF air-conditioning systems, which can be used in northern China. For instance, the lubricating oil level sensor technology[3], the enhanced vapour injection technology[4] and the double-stage compression technology are used in the VRF air-conditioning systems to make the large-scale systems technically feasible and economically acceptable in northern China. However, for large-scale construction in northern China, whether the VRF air-conditioning system has a better energy efficiency than a traditional central air-conditioning system is still controversial. Water source VRF (WSVRF) air-conditioning systems have been introduced in recent years. The water source outdoor units of the WSVRF systems speed up the start-up phase even if the outdoor temperature is very low. The WSVRF air-conditioning systems have already been applied in practical projects[5]. But in previous investigations, the energy consumption and the performance of the WSVRF air-conditioning systems have not been analyzed in detail. Moreover, the WSVRF air-conditioning systems obtain heat from electric boilers. It is not an advisable choice to spend high quality energy on heating low-temperature water.

This paper introduces an improved VRF air-conditioning system, a WLVRF air-conditioning system, which can be applied in large-scale construction in northern China with considerable energy efficiency. The system uses an air source heat pump as the heat supplementing equipment. An office building is taken as an example, and the performance of this system is analyzed. A comparison is also made between the traditional VRF air-conditioning system and the WLVRF air-conditioning system.

1 Description

The WLVRF air-conditioning system consists of a WSVRF air-conditioning unit, an air source heat pump, a water loop, a cooling tower and an assistant heater. Among these elements, the assistant heater is used in comparatively colder regions (Shenyang for example) and can be ignored if not necessary (for instance in Jinan and Beijing). The WLVRF system retains the advantages of three subordinate systems, the VRF air-conditioning unit, the water loop and the air-source heat pump unit, and it is proven to be suitable for large-scale construction in northern China. Fig. 1 shows the principle of the WLVRF air-conditioning system.

The running conditions of the system are as follows: 1) In summer, every WSVRF unit in the entire building is generally under refrigeration conditions. The cooling tower and the water pumps work while the air source heat pump unit and the assistant heater are left unused. Valves d, e, g, h in Fig. 1 are closed while valves b, c, f, i, j are open. Valve a is used to regulate the water flow rate. 2) In a transitional season, some WSVRF air-conditioning units function as heaters while others function as refrigerators. When the energy released by heating units equals that received by refrigerating units, the cooling tower, the air source heat pump and the assistant heater stop working. If the majority of the units work as chillers, the energy released to the water loop exceeds that extracted from it. Subsequently, the air source heat pump is off duty and the cooling tower runs. 3) In winter, the majority units heat the space. The energy released to the water loop is not as much as that extracted from it. The air source heat

Received 2009-11-12.
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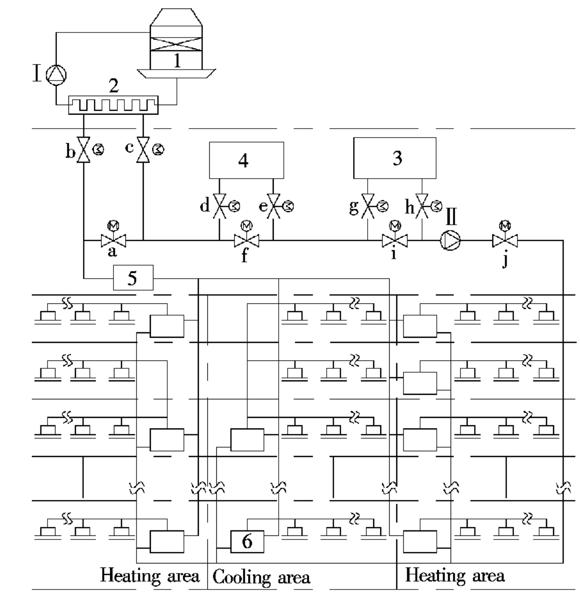
Citation: Sun Tingting, Ni Long, Yao Yang, et al. Application of water loop variable refrigerant flow air-conditioning system in large-scale buildings in northern China[J]. Journal of Southeast University (English Edition), 2010, 26(2): 197 - 200.



1—Cooling tower; 2—Heat exchanger; 3—Air source heat pump; 4—Assistant heater; 5—Water tank; 6—WSVRF air-conditioning unit; Ⅰ, Ⅱ—Water pumps; a to j—Valves

Fig. 1 Principle of WLVRF air-conditioning system

pump works. Lukewarm water with a temperature of 10 to 20 ℃ is prepared by the air source heat pump and performs as a low-grade heat source for the WSVRF air-conditioning units. If the outdoor temperature continues falling and the air source heat pump cannot supply the system with enough energy, the assistant heater starts to play a critical role in the system.

The WLVRF system is a double stage coupling heat pump system. It consists of an air/water heat pump (air-source heat pump) and a water/air heat pump (WSVRF air-conditioning unit). The air-source heat pump in this system works more stably and efficiently than the traditional ones, because the outlet water temperature set-point of the air source heat pump is 10 to 20 ℃ which is different from the customary value of 45 ℃. The small difference between the evaporation and condensation temperatures results in steadiness and high efficiency. The outdoor unit of the WLVRF system is supported by a water-cooled heat exchanger. The outdoor unit of the traditional air-source VRF air-conditioning system can only be positioned in a well ventilated place while that of the WSVRF system can be located anywhere near the indoor units. Instead of refrigerant pipelines, the water loop undertakes the responsibility of transferring energy among different regions of the building. Moreover, household heat metering can be easily carried out in this system.

The WLVRF air-conditioning system can simultaneously supply space heating and cooling throughout the whole year. The automation level of the control system is high, which can meet the requirements of intelligent construction. Therefore, the WSVRF system is suitable for the buildings which work at alternative times and have a large amount of waste heat as well as variable heating and cooling loads.

2 Methods

The simulation is based on a case of an office building with 19 stories. The total construction area is 43 340 m^2; the building area is 4 146 m^2; the construction area of the inner zone is 14 063 m^2; the construction area of the peripheral zone is 29 277 m^2. The indoor design temperature is 20 ℃ in winter, and 26 ℃ in summer. The indoor design relative humidity in summer is 60%. The heating system continuously runs in winter while the cooling system and the fresh air system only operate during the usage time. The air-conditioning cooling loads are calculated by using the cooling-load-factor method[6] and the heating loads are counted based on the heating load coefficient[7]. The thermodynamic properties of the refrigerant is formulated according to Ref. [8]. The mathematical models of the main equipment are established by using the lumped parameter method because this method is relatively simple and offers enough precision for this study. The integration time step is set to be 6 min according to Ref. [9]. The meteorological data are chosen from Ref. [10]. The running conditions of the system in Beijing, Jinan and Shenyang are simulated respectively.

The type of the air/water heat pump unit is YE-AS300RC50B charged with R22. The type of the WSVRF units is RWEYQ30MY1 charged with R410A. The mathematical models are established by using the DATAFIT software.

The equations for the air/water heat pump unit YE-AS300RC50B are as follows:

$$Q_a = a + bt_a + ct_{w1} + dt_a^2 + et_{w1}^2 + ft_a t_{w1} + gt_a^3 + ht_{w1}^3 + it_a t_{w1}^2 + jt_a^2 t_{w1} \quad (1)$$

$$W = a_1 + b_1 t_a + c_1 t_{w1} + d_1 t_{w1}^2 \quad (2)$$

where Q_a is the heating capacity; t_{w1} is the outlet water temperature; W is the input power; t_a is the outdoor temperature. The correlation coefficients of Eqs. (1) and (2) are 0.996 and 0.992, respectively.

The equations for the WSVRF air-conditioning unit YE-AS300RC50B in cooling conditions are expressed as

$$\mathrm{COP} = a + bt_{w2}^2 + \frac{c}{t_{w2}^2} \quad (3)$$

$$t_{\mathrm{COP}} = a_0 k^3 + b_0 k^2 + c_0 k + d_0 \quad (4)$$

$$Q_c = a_c t_{w2} + b_c t_{w2}^{1.5} \quad (5)$$

where t_{w2} is the inlet water temperature; k_{COP} is the ratio of the COP in the partial load to the COP in the full load; k is the partial load ratio; Q_c is the refrigeration output.

The equations for the WSVRF air-conditioning unit YE-AS300RC50B in heating conditions are expressed as

$$\varepsilon_h = a_1 + b_1 t_{w2}^{1.5} + \frac{c_1}{t_{w2}^{0.5}} \quad (6)$$

$$k_\varepsilon = a_{10} k^3 + b_{10} k^2 + c_{10} k + d_{10} \quad (7)$$

where ε_h is the coefficient of the performance; k_ε is the ratio of ε_h in the partial load to ε_h in the full load. The correlation coefficients of Eqs. (3) to (7) are 0.994, 0.993, 0.998, 0.993, and 0.992, respectively.

According to the stylebook, the heating capacity rarely varies with the change in the water temperature within a specific range.

A dynamic simulation is carried out based on the mathematical models by using MATLAB. The major parameters, such as the consumed energy, the output heat energy and the cold heat energy, are computed. The initial investment of the equipment and the running costs are contrasted between the WLVRF air-conditioning system and the traditional VRF air-conditioning system by market research. The electricity price at the end of 2008 is 0. 762 5 yuan/(kW·h) in Beijing. The operation cost is calculated based on the temperature correction coefficient, the pipe length correction coefficient, the height correction coefficient and the defrosting loss.

3 Results and Discussion

The results of the dynamic simulation show that the WLVRF air-conditioning system can operate normally and effectively in large-scale construction in northern China. The peak exhaust temperature of the air source heat pump is 65 ℃, which is much lower than the upper limit 150 ℃. The highest condenser pressure is 1. 23 MPa, which is far below the design pressure 3. 1 MPa. The maximum values of the daily average compression ratios in three cities vary from 2. 5 to 7. 7. A screw compressor has excellent cubage efficiency in this range. The daily average coefficient of the heating performance of the air source heat pump is 3. 1 to 4. 5. Tab. 1 provides crucial information on heat recovery in winter based on different cities. In the table, C_i is the design cooling load of the inner zone; Q_p is the design heating load of the peripheral zone; Q_a is the total quantity of the heat from the air source heat pump; W_a is the total quantity of the consumed power by the air source heat pump; Q_v is the total quantity of heat energy from the WSVRF air-conditioning unit; W_{vh} is the total quantity of the consumed power by the WSVRF air-conditioning unit under the heating conditions; C_v is the total quantity of cold energy from the WSVRF air-conditioning unit in winter; W_{vc} is the total quantity of the consumed power by the WSVRF air-conditioning unit under the cooling conditions in winter; Q_m is the quantity of the-heat released by the WSVRF air-conditioning unit in the inner zone in winter; Q'_m is the quantity of the heat received by the WSVRF air-conditioning unit in the peripheral zone; Q_L is the heat released by the cool tower under the winter running condition; W is the total power consumed by the whole system in winter; t_h is the heating time; t_c is the cooling time in winter.

Tab. 1 Information on heat recovery in winter based on different cities

City	Beijing	Shenyang	Jinan
C_i/kW	1 036	1 036	1 036
Q_p/kW	2 700	2 540	3 440
Q_a/GJ	3 675	7 088	2 399
W_a/GJ	1 081.3	2 158	676
Q_v/GJ	11 531	17 787	8 789
W_{vh}/GJ	1 900	3 106	1 420
C_v/GJ	5 590	6 919	4 582
W_{vc}/GJ	859.9	977.5	729
Q_m/GJ	6 450. 2	7 897	5 311
Q'_m/GJ	5 955. 5	7 593	4 969
W/GJ	4 086	6 242	2 826
Q_L/GJ	494. 7	304. 0	342. 0
Q_v/W	2. 82	2. 85	3. 11
C_v/W	1. 37	1. 11	1. 62
t_h/h	2 928	3 624	2 400
t_c/h	1 464	1 812	1 200

Tab. 1 reveals that more than half of the heat energy from the peripheral zone is transferred from the inner zone in Beijing and Jinan. The proportion in Shenyang is 43% . The data in Tab. 1 indicate that the sufficient and perennial scrap heat energy is a critical condition of the system. If the scrap heat energy is not available in the building, the system cannot fully play a role in enhancing the building energy efficiency. We can conclude that when the system consumes 1 J electric power, about 3 J heat energy is supplied for the peripheral zone and more than 1 J energy is extracted from the inner zone.

Take a building in Beijing as an example. The costs of the traditional VRF and WLVRF air-conditioning systems are calculated and a contrast between them is made. Tabs. 2 and 3 show the initial investments for the traditional VRF and WLVRF air-conditioning systems in Beijing.

Tab. 2 Initial investment of traditional VRF air-conditioning system

Model	Unit price/ 10^3 yuan	Number	Total investment/ 10^3 yuan
RHXYQ14PY1	56. 68	75	4 251
RHXYQ10PY1	41. 73	60	2 503. 8
FXFP45KMVC	8. 047	50	462. 3
FXFP90KMVC	9. 945	470	4 674. 1
Else			350
Total			12 241. 2

Tab. 3 Initial investment of WLVRF air-conditioning system

Model	Unit price/ 10^3 yuan	Number	Total investment/ 10^3 yuan
RWEYQ30MY1	120. 12	55	6 606. 6
FXFP45KMVC	8. 047	50	462. 3
FXFP90KMVC	9. 945	470	4 674. 1
YEAS300RC50B	400	3	1 200
NC8329D-1	220	2	440
KDSB250-200-360A	59. 4	3	178. 2
BR2. 0-1. 0-650-N-I	442	1	442
Else			200
Total			14 200

As shown in Tabs. 2 and 3, the initial investment of the WLVRF air-conditioning system is about 16% more than that of the traditional VRF air-conditioning system. However, the WLVRF air-conditioning system costs less than the traditional VRF air-conditioning system in the running costs. The WLVRF air-conditioning system consumes 4. 734 $\times 10^6$(kW·h)/year while the traditional VRF air-conditioning system consumes 4. 086 $\times 10^6$ (kW · h)/year. 1 kW·h power costs 0. 762 5 yuan. That is, the WLVRF air-conditioning system can save 494 $\times 10^3$ yuan/year. Thus, the payback period is about four years.

It can be concluded that the WLVRF air-conditioning system runs safely and effectively, and it can be applied in large-scale construction in northern China. The WLVRF system can be widely used in the future because of its essential characteristics. But it is a common bias that the VRF air-conditioning system is an utterly energy-saving system. The investigation implies that the precondition of this proposition is the existence of enough waste heat in the building. Otherwise, it would be an unadvisable choice. This study provides HVAC designers with theoretical support and direction.

4 Conclusions

1) The scale of the WLVRF air-conditioning system is extended by introducing a water loop into the system. The water loop also leads to favorable working conditions for the air source heat pump and the VRF air-conditioning unit. The WLVRF air-conditioning system is suitable for large-scale buildings in northern China.

2) The WLVRF air-conditioning system is more economic and secure than the traditional VRF air-conditioning system.

3) The WLVRF air-conditioning system saves energy only when it is used in buildings with abundant waste heat.

References

[1] Shi W X, Shao S Q, Yan Q S. Effective region of multi-connected air-conditioning (heat pump) system [J]. *Journal of Refrigeration*, 2007, **28**(2): 8 − 12. (in Chinese)

[2] Wu S J. Discussions a few problems in VRF air condition system design[J]. *Fujian Architecture & Construction*, 2006, **97**(1): 164 − 165. (in Chinese)

[3] Yan Q S, Li X T, Shi W X. Status of small variable capacity air-conditioner controlling in Japan [J]. *Science and technology of Household Electric Appliances*, 2000, **20**(9): 55 − 58. (in Chinese)

[4] Liu Q, Fan S C, He S. Application of enhanced vapor injection technology in ASHPWH [J]. *Fluid Machinery*, 2008, **36**(9): 68 − 72. (in Chinese)

[5] Zhang C Y, Liao Z T. A typical application with the water cooled digital variable multiunit [J]. *China Construction Heating & Refrigeration*, 2009, **9**(3): 46 − 49. (in Chinese)

[6] Lu Y J, Ma Z L, Zou P H. *Heating, ventilation and air conditioning* [M]. Beijing: China Architecture & Building Press, 2002. (in Chinese)

[7] Jiang Y Q. Study on heating optimal energy balance point of the water heater/chiller units of air source heat pump [D]. Harbin: School of Municipal and Environmental Engineering of Harbin University of Civil Engineering and Architecture, 1999. (in Chinese)

[8] Wu Y Z. *Designing guidance of small refrigeration appliances* [M]. Beijing: China Architecture & Building Press, 2001. (in Chinese)

[9] Wang Q F. *System dynamics*[M]. Beijing: Tsinghua University Press, 1994. (in Chinese)

[10] School of Building Technology Science of Tsinghua University. *Meteorological data set of typical meteorological year for building thermal environment analysis in China*[M]. Beijing: China Architecture & Building Press, 2005. (in Chinese)

水环多联集成空调系统在北方大型建筑中的应用

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摘要:首先,设计了一种水环多联式集成空调(WLVRF)系统.该系统节能环保,是多联机、水环路和空气源热泵的集成产物,适用于北方大型建筑中.其中,水环路替代制冷剂管路承担了建筑各区域间能量转移的任务,从而减小了单台多联机的规模,提高了机组效率.然后,应用现有的制冷剂和建筑负荷模型,以 DATAFIT 和 MATLAB 软件为工具,建立了该系统中各主要组成设备及其他组件的集总参数法数学模型,并模拟了系统性能.通过市场调查,计算出系统的初始投资和运行费.最后,将 WLVRF 系统和传统多联机(VRF)系统进行比较,结果显示 WLVRF 系统具有更优良的运行工况,运行费用更低.

关键词:变制冷剂流量;空调系统;水环路;大型建筑

中图分类号:TU831