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Variable refrigerant flow systems: A review

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ABSTRACT

This review study presents a detailed overview of the configurations of the outdoor and indoor units of a multi-split variable refrigerant flow (VRF) system, and its operations, applications, marketing and cost. Besides, a detailed review about the experimental and numerical studies associated with the VRF systems is provided. The aim is to put together all the diversified information about the VRF systems in a single source. According to detailed review, it is observed that the compressor frequency and the electronic expansion valve opening should be controlled simultaneously for the control strategies, and it is concluded that VRF system not only consumes less energy than the common air conditioning systems such as variable air volume, fan-coil plus fresh air under the same conditions, but also provides better indoor thermal comfort as long as it is operated in the individual control mode. It is found that even though the main drawback of the VRF system is the high initial cost compared to the common air conditioning systems, due to the energy saving potential of the VRF system, the estimated payback period of the VRF system compared to an air cooled chiller system in a generic commercial building could be about 1.5 year.

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1. Introduction

Air conditioning for residential and commercial buildings is the necessities of life due to the large demand for thermal comfort and healthy environment of the living space in modern society. The conception of the air conditioning has gradually developed from one unit for one house to independent units for separate zones in the same house [1].

A multi-split air conditioning system, featuring variable refrigerant flow (VRF) or variable refrigerant volume (VRV) technology, so-called the multi-split VRF/VRV system can satisfy the same needs for the installation of several individual units with less space, because this system consists of one outdoor and multiple indoor units [2,3]. (VRV is a trademark of a leading VRF manufacturer, and VRF is a generic term used by all of the VRF manufacturers [4].)

Basically, a multi-split VRF system is a refrigerant system that varies the refrigerant flow rate with the help of the variable speed compressor and the electronic expansion valves (EEVs) located in each indoor unit to match the space cooling or heating load in order to maintain the zone air temperature at the indoor set temperature.

The aim of this review paper is to put together all the diversified information about the multi-split VRF systems in a single source.

2. General overview

A typical multi-split VRF system having four indoor units is provided in Fig. 1 [5]. As can be seen from Fig. 1, the indoor units (located in each zone) are connected to the outdoor unit in parallel with the refrigerant pipes. By adjusting the four-way valve located in the outdoor unit, the refrigerant path can be reversed, so that the multi-split VRF system can be used for both air conditioning (cooling mode) and heat pumping (heating mode) according to the season.

In the cooling mode, the discharged refrigerant from the compressors enters the outdoor unit heat exchanger (used as a condenser) through the four-way valve. The high pressure, low temperature refrigerant, is then throttled to a low pressure by the EEV and enters the indoor unit heat exchanger (used as an evaporator). Thus, the indoor unit absorbs heat from the indoor air and cools it down. Then, the low pressure superheated refrigerant returns back to the compressors, and finishes the cycle.

In the heating mode, the four-way valve, shown in Fig. 1, reverses the refrigerant path. The discharged refrigerant from the compressors enters the indoor unit heat exchanger (used as a condenser). Thus, the indoor unit rejects heat to the indoor air and

Abbreviations: COP, coefficient of performance; EER, energy efficiency ratio; EEV, electronic expansion valve; VRF, variable refrigerant flow; VRV, variable refrigerant volume.

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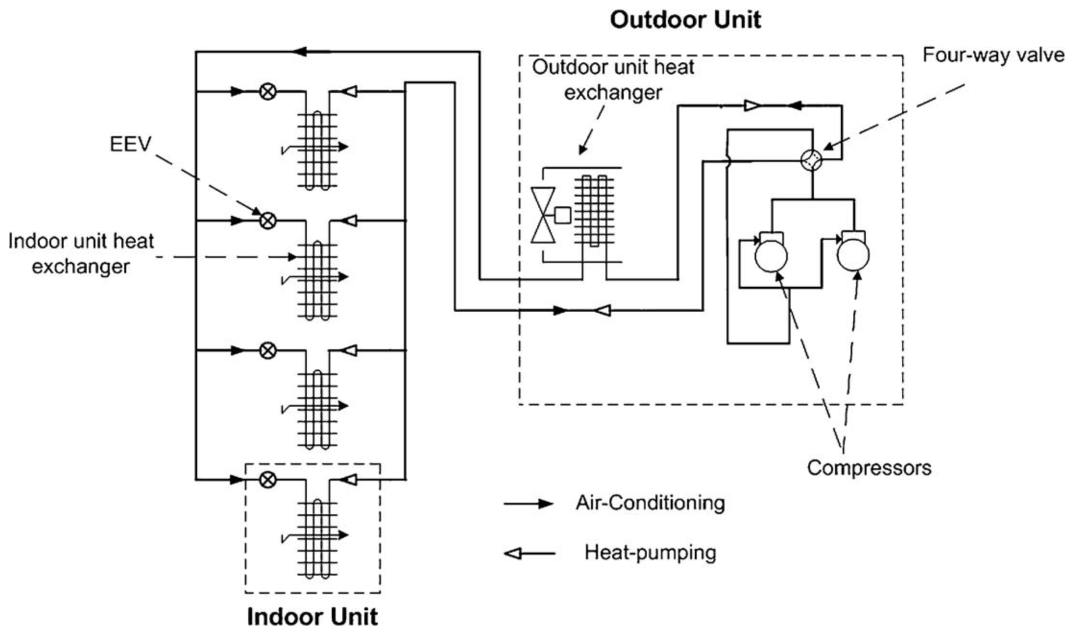

Fig. 1. Schematic diagram of a multi-split VRF system having four indoor units.

heats it up. Then, the high pressure, low temperature refrigerant is throttled to a low pressure by the EEV. The low pressure, low temperature refrigerant enters the outdoor unit heat exchanger (used as an evaporator). The low pressure superheated refrigerant returns back to the compressors, and finishes the cycle.

Following sub-chapters give a general overview related to the configurations of the outdoor and indoor units, operations, applications, marketing and the cost of the multi-split VRF systems.

2.1. Configurations of the outdoor and indoor units

2.1.1. Outdoor unit configuration

The outdoor unit of a multi-split VRF system consists of generally two or three compressors, one of which is variable speed. The inverter driven variable speed compressors enable wide capacity modulation with high part-load efficiency for the multi-split VRF systems [6]. The inverter frequency generally varies from 20–30 to 105–120 Hz [2,7,8]. By varying the inverter frequency, the outdoor unit changes its capacity by varying the discharged refrigerant mass flow rate in order to match the required total cooling or heating loads of the zones. Thus, the multi-split VRF system can actively respond to fluctuations in space load conditions [9]. Currently, the outdoor units are available in sizes up to 70 kW [10].

Until 2000, all of the multi-split VRV/VRF systems had been air-cooled, but the introduction of water-cooled versions extended the application potential [4].

According to the definition, the air-cooled multi-split VRF systems are cooled by the ambient air, while the water-cooled VRF systems are cooled by water. Unlike the air-cooled multi-split VRF systems which have generally fin-and-tube outdoor unit heat exchangers, the water-cooled multi-split VRF systems have plate type heat exchangers. Similar to the air-cooled multi-split VRF systems, one outdoor unit of water-cooled multi-split VRF system can be connected with several indoor units. Different from the air-cooled multi-split VRF system, the outdoor unit of water-cooled multi-split VRF system needs to be linked to a cooling tower, and it can be placed indoors. There is no restriction on the length of water pipe for the water-cooled multi-split VRF system, and the plate heat exchangers provide the connection between the refrigerant circuits and the water loop [11]. The water temperature supplied to the plate heat exchanger from a cooling tower/dry cooler is generally between 10 and 45 °C. Similar to the air-cooled VRF systems, the liquid/gas refrigerant lines connect the outdoor unit with the indoor units. Since the water piping is not located in the conditioned space, there are no leakage problems [4].

2.1.2. Indoor unit configuration

The indoor unit of a multi-split VRF system generally consists of a heat exchanger, an EEV, a temperature sensor and a fan. Several indoor units can be connected to one single outdoor unit in the multi-split VRF technology. The progression has been from a few indoor units operating with a single outdoor unit to 4–8 units in the late 1980s, then to 16 units in the early 1990s, 32 units by 1999, and 40 units by 2003. Current the multi-split VRF technology allows as many as 60 or more indoor units to operate with one outdoor unit [10].

The indoor units can be found with different capacities and configurations. The traditional configuration is the wall-mounted type indoor unit. In addition, ceiling mounted cassette, ceiling mounted built-in, ceiling mounted duct, and floor standing type indoor units can be found in the applications. The indoor units can have cooling and heating capacities from 1.4 to 17.5 kW.

The air temperature sensor located in the indoor unit is used for the comparison of the actual air temperature and the thermostat set temperature. According to the temperature difference, the refrigerant flow rate through the indoor unit heat exchanger is regulated by adjusting the EEV. Thus, based on the thermostat indoor set temperature and the actual indoor air temperature, each indoor unit can be operated individually, namely some of them can be turned off, while the others are in operation [12]. Thus, many zones are possible with individual set temperatures [6].

The outdoor and indoor units are connected to each other with the refrigerant pipes. Currently, with the advanced oil circuitry, returns and controls [10], the total system piping length is increased up to 1000 m [4].

2.2. Operations

Generally, the multi-split VRF systems have either two-pipe or three-pipe configurations and they are operated with or without ice thermal storage tanks.

The two-pipe (a high pressure gas pipe, a low pressure liquid pipe) multi-split VRF systems are the general ones that can be used for cooling or heating depending on the season.

On the other hand, the three-pipe (a high pressure gas pipe, a low pressure gas pipe, and a low pressure liquid pipe) VRF systems work best, when there is a need for some of the spaces to be cooled and some of them to be heated during the same season. This generally occurs in the winter season in medium-sized to large-sized commercial buildings with a substantial core such as computer rooms [10].

The three-pipe multi-split VRF systems use branch selector boxes (located before each indoor unit) and they can be operated in five different modes:

a. Cooling-only mode: All indoor units are in cooling operation.
b. Heating-only mode: All indoor units are in heating operation.
c. Cooling-principal mode: Cooling is the principal mode in the concurrent heating and cooling operation.
d. Heating-principal mode: Heating in the principal mode in the concurrent heating and cooling operation.
e. Heat recovery mode: Heat is balanced between indoor units while the outdoor unit heat exchanger is closed [6,13–15,7].

Heat recovery can be accomplished by transferring heat between the cooling and heating indoor units. One way is to use heat exchangers to extract the superheat from the units in the cooling mode and direct it into refrigerant entering a heated zone. One manufacturer first sends the refrigerant to the indoor units that require heating, allows the refrigerant to condense, collects it at a central point, and then sends it to the indoor unit heat exchangers to do the cooling. Most of the manufacturers have a proprietary design for heat recovery plumbing and operation with special valving arrangements, heat exchangers, controls, receivers, and distribution boxes [10].

Even though the three-pipe multi-split VRF systems are known for providing simultaneous heating and cooling as well as heat recovery operations, one manufacturer has a two-pipe system than can also provide simultaneous heating and cooling as well as heat recovery operations [10].

There are several different ways to store the thermal energy including ice. The demand for electricity is seldom constant over time, and the excess generation available during low demand periods can be used to produce ice for use during high demand periods [16]. The multi-split VRF systems operated in conjunction with the ice thermal storage tanks can reduce the peak electric demand by charging (making) ice during the off-peak time (during the night time), and discharging (using) it during the on-peak time (during the day time). During the ice charging period, the ice storage tank is used as an indoor unit (the actual indoor units are turned off during the ice making period) with a significantly lower evaporating temperature compared to the actual cooling mode, and during the ice discharging period, an additional subcooling is provided to the outlet refrigerant of the outdoor unit heat exchanger [17,18]. Thus, the power consumption of the compressors can significantly be reduced during the on-peak time period resulting in lower electric bills.

The ice storage tanks can also be used during the heating season. In the heat charging mode, the water in the tank is heated up to 50 °C to store the energy during the off-peak time, and during the heat discharging time, the refrigerant flows through the tank which increases the evaporating temperature resulting in a reduction in the power consumption of the compressors [18].

2.3. Applications

Applications well-suited to the multi-split VRF systems include anywhere there is an advantage to delivering individualized comfort conditioning, such as office buildings, schools, hotels and motels [6,10]. Hospitals and nursing homes can also be good candidates for the multi-split VRF systems, since they avoid zone-to-zone air mixing. Banks have favored the system for security because the egress paths into the bank are minimized due to the minimal smaller diameter ductwork. The multi-split VRF systems can also be used in luxury single-family homes as well as in condos and multi-family residential buildings [10]. In addition, the historical buildings have benefited from the minimum alterations needed for the addition of a multi-split VRF system. Retrofit situations can also be good applications for the ductless systems since additional ductwork can be minimized with the multi-split VRF systems compared to ducted systems [10].

On the other hand, the water-cooled multi-split VRF systems are suited to both new and existing high-rise commercial buildings lacking roof or external space for regular air-cooled outdoor units. They can also be installed to buildings where strict noise regulations apply [4].

2.4. Marketing

The first multi-split VRF systems were introduced in Japan around 25 years ago, and after that they have become popular in many countries, especially, in Asia and Europe. In Japan, the multi-split VRF systems are being used in approximately 50% of the medium-sized commercial buildings (up to 6500 m^2) and one-third of the large commercial buildings (more than 6500 m^2) [6]. However, they are relatively unknown in the U.S. [2,6,10]. Ductless products entered the U.S. market in the early 1980s, but market penetration was minimal because of the lack of Japanese manufacturer support, and unfamiliarity with the technology [6,10]. Besides, ozone depletion issues became an increasing concern at that time and the issue of a high refrigerant charge of multi-split systems was likely a strong negative [10].

During the fiscal year of 2003, one of the leading VRF manufacturers sold totally 85,500 VRF products all around the world: 69% in Asia (46.8% in Japan and 22.2% in China), 21.9% in Europe, 6.3% in Oceania and only 2.8% in the rest of the world [19], which also shows the limited market in the U.S. However, refrigerant developments, advances in charge management, controls, and inverter technology have transformed the technology. Thus, Asian manufacturers have re-entered the U.S. market individually or in partnership with the U.S.-based manufacturers in the past few years. Afterwards, the multi-split VRF system technology has gradually expanded its market in the U.S. In 2007, less than 10,000 VRF systems were sold in the U.S. [10].

2.5. Cost

The cost of the multi-split VRF systems is one of the main disadvantages of these systems. Even though the installation costs are highly dependent on the application, construction, and layout of the building and whether the installation is new or retrofit, lack of familiarity with the technology in the U.S. will add to the multi-split VRF system costs [6,10]. Besides, the multi-split VRF systems do not have any ventilation capability, that's why additional ventilation systems are necessary, which also increases the cost [2,6].

There are several available cost comparisons:

- The total costs of the multi-split VRF system were likely to be about 5% to 20% higher than the chilled water systems of similar capacity [10].
- The cost of the multi-split VRF system was about 30% to 50% more than equivalent capacity single package ducted system with SEER of 13 to 14, and more than twice as much as packaged terminal units [10].
- Data from a VRF manufacturer compared the installation and operating costs for a set of 14 buildings in Italy, where the chiller/boiler systems were installed in seven of the buildings and the multi-split VRF systems were installed in the other seven buildings in 1998. For the humid subtropical climate conditions, it was found that the multi-split VRF systems used 35% less energy and had 40% lower maintenance costs for the period studied. Even though, the equipment costs for the multi-split VRF systems were higher than the equipment costs for the chiller-based systems but this was offset by lower installation costs for the multi-split VRF systems [10].
- For a 200-ton cooling system in a generic commercial building, multi-split VRF systems could save up to 30–40% of the energy used by a chiller-based system. However, the installation cost of a multi-split VRF system would be about 8% more than a water-cooled chiller and 16% more than an air-cooled chiller. Combining these energy use and installation cost provided an estimated payback period of about 1.5 years for the multi-split VRF systems compared to an air cooled chiller and about 8 months compared to a water cooled chiller [10].
- Cassidy and Sweet [20] compared the whole-life costs of four common air-conditioning systems (variable air volume with perimeter heating, four-pipe fan-coil units, multi-split VRF, chilled ceilings and passive beams with radiant panel perimeter heating) used in a modern new-build three-storey commercial office building with a gross internal floor area of 6500 m^2 for a 25-year operating period. The whole-life cost analysis showed that, a system with four-pipe fan-coil units was 53% more expensive than the chilled ceilings option, the variable air volume system was 74% more expensive, and the multi-split VRF was 111% more expensive.
- For a case study of a 17 floor, about 9290 m^2 office building in Brazil, the installed cost premium of the multi-split VRF system was found to be about 15–22% relative to chiller options. However, a full year, hourly simulation, comparison of a 538-ton multi-split VRF system to both screw and centrifugal chillers (2×240 tons) of the most recent designs showed an energy savings potential of 30% in summer for the multi-split VRF system [21].

3. Studies on the multi-split VRF systems

The first multi-split VRF systems were introduced around 25 years ago in Japan. Due to the long history, this technology has been widely studied experimentally and numerically.

The experimental and numerical studies are provided in the following sections in the chronological order.

3.1. Experimental studies

Masuda et al. [8] developed a control method for a multi-split VRF system with two indoor units. The new control method showed that, the refrigerant flow rate for the indoor unit installed to a room with higher cooling load was much more than the other indoor unit. It was obtained that the compressor frequency decreased when each room temperature reached to the setting temperature, and increased in the opposite case. It was concluded that the new control method could control the refrigerant flow rate of the indoor units individually and respond to the cooling loads.

Xia et al. [7] applied a testing methodology to a multi-split three-pipe VRF system having five indoor units. The tests were performed in six calorimeters; the outdoor and indoor units were placed in each calorimeter. The coefficient of performance (COP) of the system was defined as the ratio of the total thermal load to the total electric consumption of the system. All the tests were performed in "cooling all" mode and without any latent load. It was found that the COP of the system did not vary too much according to the part load ratio. This was explained by the use of two compressors in "tandem", which yielded good part load performance. The COP of the system was obtained within 1.9–2.4 for the "cooling all" mode.

Choi and Kim [22] studied the performance of a multi-split VRF system having two indoor units with individual EEVs by varying the indoor loads, the EEV opening and the compressor speed. It was suggested that the superheats for both indoor units had to be maintained around 4 °C by adjusting the EEVs, and consequently, the compressor speed should be adjusted to provide enough cooling capacity for each indoor unit.

Hu and Yang [23] developed a cost effective, energy efficient, multi-split VRF system having five indoor units. A variable refrigerant volume scroll compressor was used instead of an inverter aided one. The capacity control of the compressor was performed by an "ON/OFF" switching of the solenoid valves which changed the position of a static scroll to provide variable refrigerant flow. The system determined the required load of the indoor units from the difference between the room and set temperatures, and regulated the degrees of each EEV opening to control the refrigerant flow and the evaporation temperature of each indoor unit. Meantime, the outdoor unit determined the running cycle and the output time of the refrigerant in the compressor according to the requirement of the indoor units to control the "ON/OFF" cycle time of the solenoid valves, which controlled the refrigerant volume of the compressor. It was found that the developed system could adjust the capacity within 17–100% with a power input of 1.3–4.8 kW, on the other hand, the inverter system adjusted the capacity within 48–104% with a power input of 2.5–6.1 kW.

Hai et al. [13] studied a multi-split three-pipe VRF system with a nominal capacity of 30 kW. The system was charged with R22 and consisted of five indoor units with different capacities. The experiments were performed under steady state conditions with different cooling and heating configurations, and it was found that the COP of the system increased in the "cooling-principal" and the "heating-principal" modes, because both condensing and evaporating capacities were used.

Hai et al. [18] designed and researched a multi-split VRF system having an ice storage tank. It was mentioned that with the ice storage tank, an additional 30 °C subcooling could be achieved which increased the energy efficiency ratio (EER) about 25%. According to the economic evaluation based on the electric price of Shanghai, the payback period of the multi-split VRF system with the ice storage tank was found to be less than 3 years.

Aynur et al. [12] conducted a field-performance test with a multi-split VRF system in an actual office suite in order to provide real time operational characteristics of the system. Two different control modes (individual and master) were applied to the system. In the individual control mode, all indoor units were controlled by their own individual thermostats located into each zone. In the master control mode, all indoor units were controlled by only one thermostat which was located in the center of the office suite. First time in the open literature, a thermal comfort evaluation for a multi-split VRF system was performed with the ASHRAE thermal sensation scale (+3, +2, +1, 0, −1, −2 and −3 correspond to hot, warm, slightly warm, neutral, slightly cool, cool and cold, respectively). It was concluded that the multi-split VRF system in the individual control mode provided better thermal comfort for multiple rooms with higher efficiency compared to the master control mode.

Aynur et al. [24] investigated the effect of ventilation on the indoor temperature control, thermal comfort, outdoor unit energy consumption and the efficiency of a multi-split VRV system integrated with a heat recovery ventilation system in a field performance test under varying outdoor conditions. It was observed that ventilation did not affect the indoor temperature control; instead it increased the indoor humidity ratio resulting in a less comfortable indoor environment according to the ASHRAE summer thermal comfort zone. It was also found that even though the ventilation increased the outdoor unit energy consumption due to the ventilation load (ventilation-assisted multi-split VRV system consumed 27.8% more energy than the non-ventilated one), it did not have a considerable effect on the efficiency of the multi-split VRV system.

Aynur et al. [25] investigated the integration of a multi-split VRV system with a ventilation unit, a self-regenerating heat pump desiccant unit, in a field performance test. It was found that the heat pump desiccant unit provided better indoor thermal comfort than a heat recovery ventilation unit due to the better indoor humidity control. It was also concluded that since the heat pump desiccant unit took care of some portion of the cooling load, the outdoor unit of the multi-split VRV system consumed 26.3% less energy for the operation in conjunction with the heat pump desiccant unit as compared to the operation in conjunction with the heat recovery ventilation unit. Three different operating modes; non-ventilated, heat pump desiccant ventilation assisted and heat pump desiccant ventilation-dehumidification assisted VRF systems were investigated in the study of Aynur et al. [26], which is an extension study of Ref. [25]. It was found that the VRF systems provided an average of 97.6% of the total cooling energy of the heat pump desiccant ventilation assisted mode. The remainder was the recovered cool by the heat pump desiccant units during the ventilation. On the other hand, the VRF systems provided an average of 78.9% of the total cooling energy of the heat pump desiccant ventilation-dehumidification assisted mode. The remainder was covered by the heat pump desiccant units which provided additional sensible and latent cooling.

Aynur et al. [5] investigated the effects of the ventilation and the control mode on the performance of a multi-split VRV system integrated with a heat recovery ventilation system for the heating mode in an office suite. It was found that the heat recovery ventilation system decreased the indoor humidity ratio by introducing the low outdoor air humidity ratio to the indoors, resulting in a dry indoor environment. It was also found that due to the additional ventilation load; the ventilation-assisted multi-split VRV system consumed 35.2% more energy than the non-ventilated one.

Aynur et al. [27] investigated the integration of a multi-split VRF system with a heat pump desiccant unit in a field performance test for a heating season. The heat pump desiccant units use only the moisture in the outdoor air and return air to humidify the indoors during ventilation in the heating season, which eliminates the drawbacks of the heat recovery units, such as providing dry indoor environment and introducing additional ventilation loads [5]. Three different operating modes; non-ventilated, heat pump desiccant ventilation assisted and heat pump desiccant ventilation-humidification assisted VRF systems were investigated. It was found that the VRF systems provided an average of 93.5% of the total heating energy of the heat pump desiccant ventilation assisted mode. The remainder was the recovered heat by the heat pump desiccant units during the ventilation. On the other hand, the VRF systems provided an average of 46.8% of the total heating energy of the heat pump desiccant ventilation-humidification assisted mode. The remainder was covered by the heat pump desiccant units which provided additional sensible and latent heating.

3.2. Modeling studies

Park et al. [1] studied the system performance of a multi-split VRF system having two indoor units based on the compressor frequency, total cooling load, and the cooling load fraction between two zones (defined as the ratio of the cooling load of the first zone to the total cooling load). It was found that the compressor power increased with a second-order of the compressor frequency with a reduction in the COP. By fixing the total cooling load of the system at 6 kW, it was obtained that the power consumption increased with an increase of the load difference between each zone with a reduction in the COP. The reason of the increase in the power consumption was due to the increase in the compressor operating frequency. It was observed that when the load ratio was changed from 50 to 100%, the compressor frequency changed only 30%, but the EEV opening changed about 92%. It was concluded that the major control parameter was the EEV opening in a multi-split VRF system rather than the compressor operating frequency when the load ratio was changed.

Xia et al. [7] studied the performance of a multi-split three-pipe VRF system. Instead of "ON/OFF" operation of each indoor unit, a continuous adaptation of the heat transfer coefficient method was applied to maintain the same superheating in "ON" periods. In this control strategy, each EEV was adjusted individually to distribute the suitable refrigerant mass flow rate to each indoor unit in order to maintain the constant indoor room temperature.

Shi et al. [14] developed a fluid network model to simulate the performance of a multi-split three-pipe VRF system having two indoor units. It was found that the EER of the system in heat recovery mode was about two times higher than the EER in "cooling-only" or "heating-only" modes, due to the usage of both cooling and heating capacities.

Xia et al. [28] studied the operating characteristics of a multi-split VRF system having three indoor units. It was found that the greater the EEV opening, the greater the mass flow rate through the indoor unit. It was obtained that for the same compressor speed, when the EEV opening of one indoor unit increased while the other two kept unchanged, the cooling capacity of the first indoor unit increased, while the cooling capacities of the rest decreased because of the distribution of the refrigerant mass flow rate. It was concluded that by adjusting the compressor rotation speed while keeping the suction pressure unchanged, the cooling capacity of the individual evaporators could be changed without affecting others.

Shah et al. [29] developed a new methodology for the dynamic modeling of a multi-split VRF system. The expansion valve was modeled as an isenthalpic orifice, and the compressor was defined as a function of the compressor speed, volume of the compressor and the pressure ratio. It was found that the compressor could be used as a control actuator for a multi-split VRF system because of its direct influence on refrigerant flow rate. The EEV of the first evaporator changed, while the second one was kept constant, and it was found that the pressure in the second evaporator also changed due to the coupled system dynamics. It was concluded that a control algorithm should also include the EEV in order to maintain the pressure of the second evaporator at the desired value.

Wu et al. [30] proposed a control strategy for a multi-split VRF system having three indoor units. The suction pressure and the room air temperature were taken as the control parameters to modulate the compressor speed and the EEV opening, respectively. A self tuning fuzzy control algorithm with a modifying factor was also input in the controller. The parametric tests showed that the proposed control strategy with the fuzzy control algorithm could achieve the desired control accuracy of the controlled parameters.

Zhou et al. [31] investigated the performance of a multi-split VRF system with the EnergyPlus dynamic building energy simulation program. A module for the multi-split VRF system was developed and imported into EnergyPlus. The module (validated with the experimental results by Zhou et al. [32,33]) could give the power and energy consumptions of the indoor and outdoor units, as well as the COP and the part load ratio. It was found that the COP of the multi-split VRF system increased when the system worked in part load conditions due to the high part load efficiency. Besides, the developed model was used for a comparison study performed in a 10-story office building in Shanghai. It was obtained that the multi-split VRF system saved more than 20% energy compared to a variable air volume system and more than 10% compared to a fan-coil plus fresh air system.

Lin and Yeh [34] studied a three-evaporator air conditioner for a feedback controller design. For the proposed control structure, the three evaporating temperatures were controlled by the EEV openings in order to keep the indoor temperatures at the set points with no steady-state errors. Besides, the compressor speed was used to control the three superheat temperatures associated with the three evaporators. The proposed control method was experimentally validated.

Aynur [2] investigated the performance of two VRF systems integrated with heat recovery ventilation units numerically with DOE's building simulation package in an existing office suite which had a total area of 167.3 m^2 during the cooling season of 2007. Simulations were performed under four different U.S. climate conditions. The locations were selected to cover the entire range of weather conditions ranging from cold to hot temperatures and dry to humid weather: cold and moderate humid climate (Los Angeles, CA), mild climate (College Park, MD), hot and humid climate (Houston, TX), and hot and dry climate (Phoenix, AZ). For the period of June–August 2007, Los Angeles was found to be the coldest location with the monthly average outdoor temperatures of 17.7 °C (June), 20.5 °C (July) and 21.2 °C (August), and Phoenix was found to be the hottest location with the monthly average outdoor temperatures of 34.2 °C (June), 35.4 °C (July) and 35.5 °C (August). On the other hand, Houston was the most humid location with the monthly average outdoor humidity ratios of 0.0171 kg/kg (June), 0.0176 kg/kg (July) and 0.0182 kg/kg (August), and Phoenix was the driest location with the monthly average outdoor humidity ratios of 0.0041 kg/kg (June), 0.0103 kg/kg (July) and 0.0116 kg/kg (August). Overall, a wide range of outdoor temperature (from 10.6 to 45.6 °C) and a wide range of humidity ratio (from 0.0015 to 0.0216 kg/kg) were covered with the selected locations. The VRF systems integrated with the heat recovery ventilation units were operated 24 h a day, 7 days a week during the period of June-August 2007. In CA for an indoor set temperature of 27 °C, the seasonal total energy consumption of the whole system was found to be 3200.5 kWh, and it increased by 12.9% and 27%, when the set temperature decreased from 27 to 25 °C and 23 °C, respectively. On the other hand, for the set temperature of 25 °C, the seasonal total energy consumptions in MD, TX and AZ were found to be 46%, 2.08 times and 2.45 times higher than in CA.

Aynur et al. [35] investigated the effect of ventilation on the indoor temperature control, thermal comfort, outdoor unit energy consumption, the efficiency of a multi-split VRV system and energy saving options. The multi-split VRV module obtained from Zhou et al. [31] was used. A control strategy for the multi-split VRV system integrated with the heat recovery ventilation units, "synchronized indoor fan operation with economizer", was proposed, which promised 17–28% energy savings when compared with the "continuous indoor fan operation without economizer."

Aynur et al. [36] compared the performance of two widely used air conditioning systems, variable air volume and multi-split VRF, in an existing office building environment under the same indoor and outdoor conditions for an entire cooling season. It was found that the secondary components (indoor and ventilation units) of the multi-split VRF system promised 38.0–83.4% energy-saving potential depending on the system configuration, indoor and outdoor conditions, when compared to the secondary components (heaters and the supply fan) of the variable air volume system. Overall, it was found that the multi-split VRF system promised 27.1–57.9% energy-saving potentials depending on the system configuration, indoor and outdoor conditions, when compared to the variable air volume system.

Li et al. [11] developed an EnergyPlus module for a water-cooled multi-split VRF system. After modeling and testing the new model, on the basis of a typical office building in Shanghai, the monthly and seasonal cooling energy consumption and the breakdown of the total power consumption were analyzed. The simulation results showed that, during the whole cooling period under the humid subtropical climate condition, the fan-coil plus fresh air system consumed about 20% more power than the water-cooled VRF system.

Liu and Hong [37] presented a preliminary simulation comparison of the energy efficiency between an air-source heat recovery multi-split VRF system and a ground source heat pump system. A small office building with a conditioned floor area of 360 m^2 was selected, and the building required simultaneous heating and cooling year round. Two cities were selected to represent the hot and cold climates of the US; Miami and Chicago. It was found that the ground source heat pump system saved 9.4% and 24.1% electricity compared to the multi-split VRF system for the same office building located in Miami and Chicago, respectively. It was concluded that electricity savings goes up with the increasing heating demands.

4. Conclusions and recommendations

This review study gives a detailed overview of the configurations, operations, applications, marketing and cost comparisons of the multi-split variable refrigerant flow (VRF) systems. Besides, experimental and numerical studies associated with the multi-split VRF systems are provided.

The VRF technology refers to the ability of a system to control the refrigerant mass flow rate according to the cooling and/or heating load, enabling the use of as many as 60 or more indoor units of differing capacities and configurations with one single outdoor unit, individualized comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another.

This detailed review indicates that the researchers focus on three main subjects: (a) Control strategies of the variable speed compressors and the electronic expansion valves (EEVs), (b) field-performance testing and integration with the ventilation systems, (c) comparisons of the energy consumption and thermal comfort with other common air conditioning systems.

It is observed that the compressor frequency and the EEV opening should be controlled simultaneously for the control strategies. Considerable focus should be oriented towards the integration with the ventilation systems, because poor integration causes not only worse indoor thermal comfort, but also more energy consumption due to the additional ventilation load. For the system performance comparisons, for the cooling season, based on the available studies, it can be concluded that the multi-split VRF system not only consumes less energy than the common air conditioning systems such as variable air volume (from 20 to 57.9% under the humid subtropical climate), fan-coil plus fresh air (10% under the humid subtropical climate condition), chiller/boiler system (35% under the humid subtropical climate condition), chiller system (30% under the tropical climate condition), but also provides better indoor thermal comfort as long as it is operated in the individual control mode. On the other hand, for the heating season, based on the available study, it can be said that the ground source heat pump system consumes 24.1% less energy than a heat recovery multi-split VRF system under the cold climate condition.

The detailed review reveals that even though the main drawback of the multi-split VRF system is the high initial cost compared to the common air conditioning systems, due to the energy saving potential of the multi-split VRF system, the estimated payback period of the multi-split VRF system compared to an air cooled chiller system in a generic commercial building could be about 1.5 year. However, there is still a necessity to develop cheap multi-split VRF technology in order to increase the market potential and the energy saving advantage.

References

[1] Y.C. Park, Y.C. Kim, M.K. Min, Performance analysis on a multi-type inverter air conditioner, Energy Conversion and Management 42 (13) (2001) 1607–1621.

[2] T.N. Aynur, Evaluation of a multi-split type air conditioning system under steady-state and transient conditions, Ph.D. thesis. Department of Mechanical Engineering, Istanbul Technical University, 2008 (in English).

[3] C. Wu, Z. Xingxi, D. Shiming, Development of control method and dynamic model for multi-evaporator air conditioners (MEAC), Energy Conversion and Management 46 (3) (2005) 451–465.

[4] M. Dyer, Approaching 20 years of VRF in the UK, Modern Building Services, June 2006 (http://www.modbs.co.uk/news/fullstory.php/aid/2127/Approaching_20_-years_ of_VRF_in_the_UK.html).

[5] T.N. Aynur, Y. Hwang, R. Radermacher, The effect of the ventilation and the control mode on the performance of a VRV system in cooling and heating modes, in: 12th International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, (2008), pp. 1–8.

[6] W. Goetzler, Variable refrigerant flow systems, ASHRAE Journal 49 (4) (2007) 24–31.

[7] J. Xia, E. Winandy, B. Georges, J. Lebrun, Testing methodology for VRF systems, in: 9th International Refrigeration and Air Conditioning Conference, Purdue, IN, USA, (2002), pp. 1–8.

[8] M. Masuda, K. Wakahara, K. Matsui, Development of a multi-split system air conditioner for residential use, ASHRAE Transactions 97 (2) (1991) 127–131.

[9] R. Afify, Designing VRF systems, ASHRAE Journal 50 (6) (2008) 52–55.

[10] A. Amarnath, M. Blatt, Variable refrigerant flow: where, why, and how, Engineered Systems 25 (2) (2008) 54–60.

[11] Y. Li, J. Wu, S. Shiochi, Modeling and energy simulation of the variable refrigerant flow air conditioning system with water-cooled condenser under cooling conditions, Energy and Buildings 41 (9) (2009) 949–957.

[12] T.N. Aynur, Y. Hwang, R. Radermacher, Field performance measurements of a VRV AC/HP system, in: 11th International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, (2006), pp. 1–8.

[13] X.H. Hai, S. Jun, Z.Y. Hand, T.C. Bin, Design and research of the digital VRV multi-connected units with three pipes type heat recovery system, in: 11th International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, (2006), pp. 1–6.

[14] W. Shi, S. Shao, X. Li, X. Peng, X. Yang, A network model to simulate performance of variable refrigerant volume refrigerant systems, ASHRAE Transactions 109 (2) (2003) 61–68.

[15] J. Xia, E. Winandy, B. Georges, J. Lebrun, Experimental analysis of the performances of variable refrigerant flow systems, Building Services Engineering Research and Technology 25 (1) (2004) 17–23.

[16] R. Best, G. De Valence, Design and Construction: Building in Value, Butterworth-Heinemann, 2002.

[17] Electric Power Research Institute, EPRI, Use of variable refrigerant flow in conjunction with ice thermal storage and dehumidification for space conditioning, 2009, pp. 1–2.

[18] X.H. Hai, Z. Tao, F.H. Yun, S. Jun, Design and research of the commercial digital VRV multi-connected units with sub-cooled ice storage system, in: 11th International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, (2006), pp. 1–5.

[19] Daikin Ind., VRV product and technology introduction, Daikin U.S. presentation, TX, USA, 2005.

[20] T. Cassidy, C. Sweet, Services whole-life costs: air conditioning, Building 265 (5) (2000) 50–53.

[21] K.W. Roth, D. Westphalen, J. Dieckmann, S.D. Hamilton, W. Goetzler, Energy consumption characteristics of commercial building HVAC systems Volume III: Energy saving potential, Reference No: 68370-00, 2001, TIAX LLC, Cambridge, MA, USA.

[22] J.M. Choi, Y.C. Kim, Capacity modulation of an inverter-driven multi-air conditioner using electronic expansion valves, Energy 28 (2) (2003) 141–155.

[23] S.C. Hu, R.H. Yang, Development and testing of a multi-type air conditioner without using AC inverters, Energy Conversion and Management 46 (3) (2005) 373–383.

[24] T.N. Aynur, Y. Hwang, R. Radermacher, 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) (2008) 615–630.

[25] T.N. Aynur, Y. Hwang, R. Radermacher, Field performance measurements of a heat pump desiccant unit in dehumidification mode, Energy and Buildings 40 (12) (2008) 2141–2147.

[26] T.N. Aynur, Y. Hwang, R. Radermacher, Integration of variable refrigerant flow and heat pump desiccant systems for the cooling season, Applied Thermal Engineering (2010), doi:10.1016/j.applthermaleng.2010.01.002.

[27] T.N. Aynur, Y. Hwang, R. Radermacher, Integration of variable refrigerant flow and heat pump desiccant systems for the heating season, Energy and Buildings (2009), doi:10.1016/j.enbuild.2009.10.016.

[28] J. Xia, X. Zhou, X. Jin, Y. Wu, Simulation study on operating characteristics of multi-evaporator VRV air conditioner, in: 21st IIR International Congress of Refrigeration, Washington, DC, US, (2003), pp. 1–7.

[29] R. Shah, A.G. Alleyne, C.W. Bullard, Dynamic modeling and control of multi-evaporator air conditioning systems, ASHRAE Transactions 110 (1) (2004) 109–119.

[30] C. Wu, Z. Xingxi, D. Shiming, Development of control method and dynamic model for multi-evaporator air conditioners (MEAC), Energy and Conversion 46 (3) (2005) 451–465.

[31] Y.P. Zhou, J.Y. Wu, R.Z. Wang, S. Shiochi, Energy simulation in the variable refrigerant flow air-conditioning system under cooling conditions, Energy and Buildings 39 (2) (2007) 212–220.

[32] Y.P. Zhou, J.Y. Wu, R.Z. Wang, Y.M. Li, S. Shiochi, Development and experimental investigation of the variable-refrigerant-flow (VRF) air conditioning system in EnergyPlus, in: International Congress of Refrigeration, Beijing, China, 2007.

[33] Y.P. Zhou, J.Y. Wu, R.Z. Wang, S. Shiochi, Y.M. Li, Simulation and experimental validation of the variable-refrigerant-volume (VRV) air-conditioning system in EnergyPlus, Energy and Buildings 40 (6) (2008) 1041–1047.

[34] J.L. Lin, T.J. Yeh, Identification and control of multi-evaporator air conditioning systems, International Journal of Refrigeration 30 (8) (2007) 1374–1385.

[35] T.N. Aynur, Y. Hwang, R. Radermacher, Simulation evaluation of the ventilation effect on the performance of a VRV system in cooling mode—Part II: Simulation evaluation, HVAC&R Research 14 (5) (2008) 783–795.

[36] T.N. Aynur, Y. Hwang, R. Radermacher, Simulation comparison of VAV and VRF air conditioning systems in an existing building for the cooling season, Energy and Buildings 41 (11) (2009) 1143–1150.

[37] X. Liu, T. Hong, Comparison of energy efficiency between variable refrigerant flow systems and ground source heat pump systems, Energy Buildings (2009), doi:10.1016/j.enbuild.2009.10.028.