EFFECTS OF SUBCOOLER ON COOLING PERFORMANCE OF INVERTER VARIABLE REFRIGERANT FLOW (IVRF) TYPE AIR CONDITIONING SYSTEM: A REVIEW

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ABSTRACT

Inverter Variable Refrigerant Flow system has emerged as one of the promising candidate for the near future, in the heating, ventilation and air conditioning (HVAC) area. This review study presents a detailed overview of the configurations of the outdoor and indoor units of a variable refrigerant flow (VRF) system, and its operations, applications and cost. Besides, a detailed review about the effects of subcooler on cooling performance of inverter variable refrigerant flow (IVRF) type air conditioning system. 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 but also provides better indoor thermal comfort as long as it is operated in the individual control mode. In detailed review it is also observed that subcooling technique with inverter variable refrigerant flow (IVRF) air conditioning (AC) system helps in improving the energy efficiency, reliability and stability of the system.

Keywords: *Inverter variable refrigerant flow, Air conditioning, Electronic expansion valve, Accumulator, Subcooling.*

1. Introduction

The VRF technology/system was developed and designed by Daikin Industries, Japan who named and protected the term variable refrigerant volume (VRV) system so other manufacturers use the term VRF "variable refrigerant flow". In essence both are same. Variable refrigerant flow (VRF) is an air-condition system configuration where there is one outdoor condensing unit and multiple indoor units. The term variable refrigerant flow refers to the ability of the system to control the amount of refrigerant flowing to the multiple evaporators (indoor units), enabling the use of many evaporators of differing capacities and configurations connected to a single condensing unit. The arrangement provides an individualized comfort control, and simultaneous heating and cooling in different zones. With a higher efficiency and increased controllability, the VRF systemcan help achieve a sustainable design [1].

The term VRF refers to the ability of the system to control the amount of refrigerant flowing to each of the evaporators, enabling the use of many evaporators of differing capacities and configurations, individualized comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another. VRF systems operate on the direct expansion (DX) principle meaning that heat is transferred to or from the space directly by circulating refrigerant to evaporators located near or within the conditioned space. Refrigerant flow control is the key to many advantages as well as the major technical challenge of VRF systems.

2. Refrigerant Modulation in a VRF System

VRF technology is based on the simple vapor compression cycle (same as conventional split air conditioning systems) but gives you the ability to continuously control and adjust the flow of refrigerant to different internal units, depending on the heating and cooling needs of each area of the building. The refrigerant flow to each evaporator is adjusted precisely through a pulse wave electronic expansion valve in conjunction with an inverter and multiple compressors of varying capacity, in response to changes in the cooling or heating requirement within the air conditioned space [1].

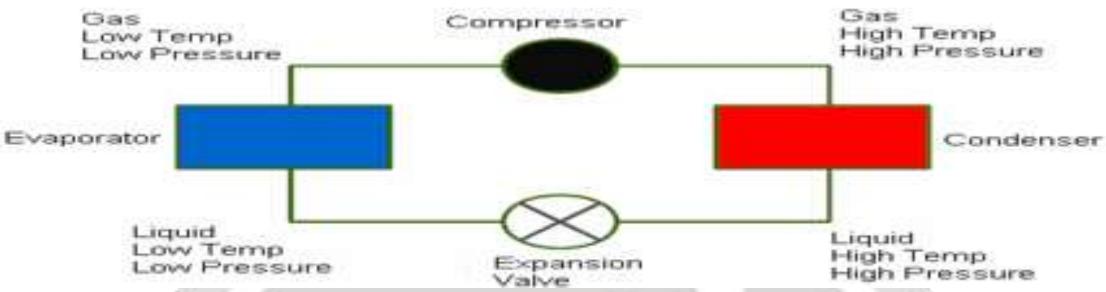

Figure 1: Simple Vapor Compression Cycle [1]

The fundamental of an air conditioning system is the use of a refrigerant to absorb heat from the indoor environment and transfer it to the external environment. In the cooling mode, indoor units are supplied with liquid refrigerant. The amount of refrigerant flowing through the unit is controlled via an expansion valve located inside the unit. When the refrigerant enters the coil, it undergoes a phase change (evaporation) that extracts heat from the space, thereby cooling the room. The heat extracted from the space is exhausted to the ambient air.

Refrigeration systems can operate on reverse cycle mode with an inclusion of special 4-way reversing valve, enabling the absorption of heat from the external environment and using this heat to raise the internal temperature. When in the heating mode, indoor units are supplied with a hot gas refrigerant. Again, the amount of hot gas flowing through the unit is controlled via the same electronic expansion valve. As with the liquid refrigerant, the hot gas undergoes a phase change (condensation), which releases heat energy into the space. These are called heat pump systems. Heat pumps provide both heating and cooling from the same unit and due to added heat of compression, the efficiency of a heat pump in the heating mode is higher compared to the cooling cycle.

3. Electronic expansion valve

With an electronic expansion valve (EXV), you can tell the system what superheat you want and it will set it up. EXV in a VRF system functions to maintain the pressure differential and also distribute the precise amount of refrigerant to each indoor unit [2].

Figure 2: Electronic Expansion Valve [2]

Figure 2 shows that the EXV communicate with thermistor connected to the indoor unit through communication cable and regulates the refrigerant flow accordingly. Step motor of EXV can run at 200 steps per second and can return to their exact position very quickly.

4. Inverter Technology

An Air Conditioner bearing inverter tag uses a variable-frequency drive to control the speed of the motor and thus the compressor. It consumes at least 30% less (it can go to 50% or more) electricity depending on various factors like the outside temperature ,purpose for which the AC is used, Hence it uses less amount of electricity [3].

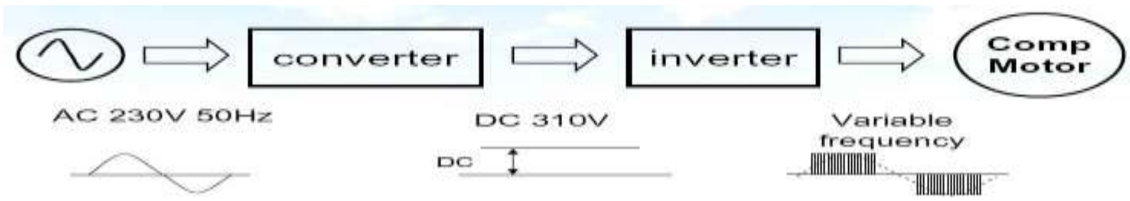

Figure 3: Variable Frequency Drive [3]

Inverter is a device which supplies variable frequency of power supply on equipments. Thanks to this function, motor revolution speed can be controlled and it leads to reduce energy consumption. Use of inverter technology can maintain precise temperature control, generally within ±1°C.Figure 3 shows that the inverter technology converts the incoming AC supply to DC voltage and then modulate it by changing the voltage, current and frequency of the power to the compressor.

5. Types of VRF Systems

The VRF systems available on the market today differ according the mode of cooling or heating like: cooling only, only heating or cooling and both simultaneous heating and cooling [1].

5.1 Cooling type VRF System

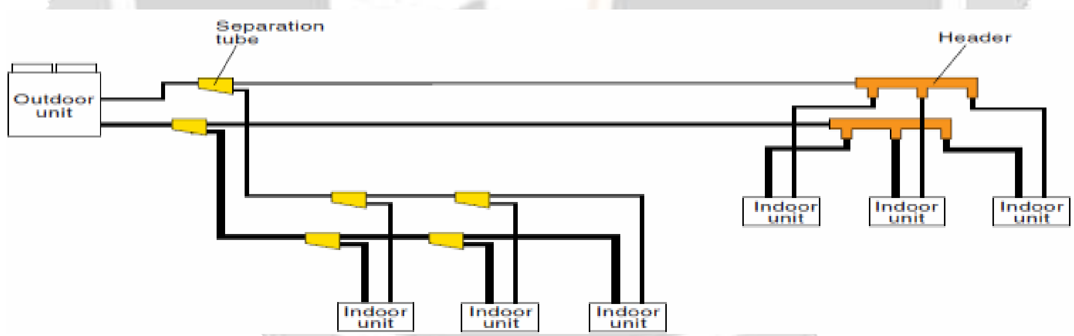

Figure 4: Cooling type VRF system [1]

This type of VRF system can be used for cooling only. It is the simplest version of VRF system. This is considered as most advanced version of multi split air conditioning system. Each indoor unit connected to single outdoor unit provides cooling only. This system typically used in warmer climate. In this each indoor and outdoor unit connected to two pipes.

The compressor placed inside the outdoor unit pushes the high temperature, high pressure super heated vapor refrigerant into the heat exchanger which is acting as a condenser. The fan in the outdoor unit which sucks the air inside the condenser and heat transfer with the refrigerant inside the condenser coil takes place. So, the refrigerant leaving the condenser is now high pressure, medium temperature liquid. This refrigerant now flows through pipe work and supplied to each indoor unit. Each indoor unit consists of electronic expansion valve, which limits the refrigerant flowing to evaporator to match the exact cooling requirement and also reduce the pressure and temperature of refrigerant. This low temperature and low pressure refrigerant absorbs the heat from the air inside the evaporator and provides the cooling to the conditioned space.

5.2 Heat Pump type VRF System

VRF heat pump system permit heating or cooling in all of the indoor units, but NOT Simultaneous heating and cooling. When the indoor units are in the cooling mode, they act as evaporators; when they are in the heating mode, they act as condensers. These are also known as two-pipe systems.

VRF heat pump systems are effectively applied in open plan areas, retail stores, cellular offices and any other area that require cooling or heating during the same operational periods.

5.3 Heat Recovery type VRF System

Variable refrigerant flow systems with heat recovery (VRF-HR) capability can operate simultaneously in heating and/or cooling mode, enabling heat to be used rather than rejected as it would be in traditional heat pump systems. VRF-HR systems are equipped with enhanced features like inverter drives, pulse modulating electronic expansion valves and distributed controls that allow system to operate in net heating or net cooling mode, as demanded by the space.

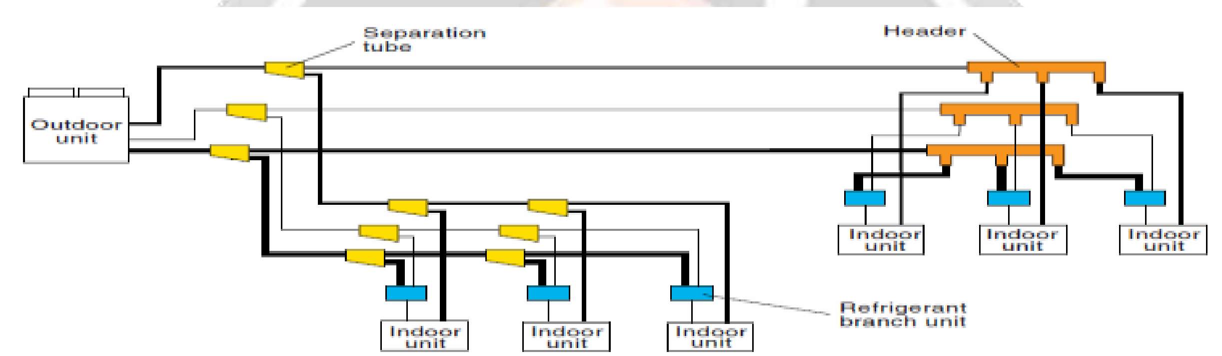

Figure 5: Heat Recovery type VRF system [1]

Each manufacturer has its own proprietary design (2-pipe or 3-pipe system), but most uses a three-pipe system (liquid line, a hot gas line and a suction line) and special valving arrangements. Each indoor unit is branched off from the 3 pipes using solenoid valves. An indoor unit requiring cooling will open its liquid line and suction line valves and act as an evaporator. An indoor unit requiring heating will open its hot gas and liquid line valves and will act as a condenser.

This 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 period. This often occurs in the winter in buildings with a substantial core or in the areas on the north and south sides of a building.

6. Subcooling with Air Conditioning System

Subcooling in air conditioning implies cooling the refrigerant in liquid state, at uniform pressure, to a temperature that is less than the saturation temperature, which corresponds to condenser pressure. Subcooling is normally used so that when the cycling refrigerant reaches the expansion valve; its totality is in its liquid form, if gas reaches the expansion valve, in a refrigeration system, a series of usually unwanted phenomena may occur. The magnitude of subcooling is usually kept from 8℃ to 10℃. If there is too much subcooling, then the work input increases considerably, thus offsetting the gains from the subcooling of the refrigerant [4].

As a complicated multi-input and multi-output system, the key technology is to achieve energy saving, make low noise, gain good cooling effect, and obtain stable and reliable operation. Thus it is necessary to attempt to adopt the sub-cooling technology to improve the performance of IVRF AC system. Generally the subcooling can be provided by improving and carrying out modifications in condensers so that subcooling arrangement is included or by installing internal/external heat exchangers to provide subcooling.

7. Effects of various subcooling techniques on air conditioning systems

It is necessary to attempt to adopt the subcooling technology to improve the cooling capacity and energy efficiency ratio (EER), decrease noise, and prevent the compressor overheating. Here cooling capacity and EER are respectively defined as the total amount of heat removed from a confined space, or room during the cooling operation of the air conditioning system, and the ratio of cooling capacity to the power consumption.

Qiu et al. [5] investigated the effects of external plate type heat exchanger as a subcooler on 11.2 TR (40KW) capacity variable refrigerant flow type air conditioning (VRF AC) system. The system was consisted of one outdoor unit (ODU) with four indoor units (IDUs), each IDU with capacity of 10 KW. The system was charged with 16 KG Refrigerant R410A.The electronic expansion valve (EXV) had a full opening of 480 PLS. The ambient temperatures of the outdoor room and indoor room were adjusted to be 35℃ and 27℃ respectively. The influence of the subcooler with the different EXV openings is investigated on cooling capacity, electrical power consumption, energy efficiency ratio (EER) and subcooling degree. It is observed that optimum regions of EER and cooling capacity were obtained at 75-100 PLS, 100-125 PLS and 125-150 PLS EXV openings respectively. The relative subcooling degrees were respectively 17.3-26.1, 21.5-27.6 and 20.1-23.5 ℃. The EER was respectively 3.3%, 3.1% and 3.0% higher than that of without the subcooler.

Hoon et al. [6] investigated the effects of an accumulator heat exchanger as a subcooler on heat transfer rate and subcooling difference of 2.85 TR capacity Variable Flow Refrigeration (VRF) refrigeration system. The heat transfer rate and subcooling difference in an accumulator heat exchanger were measured under various operating and geometric conditions. The effect of the operating conditions on the performance of the accumulator heat exchanger was analyzed for R22, R134a, and R410A. Experimental results indicated that the heat transfer rate increased with an increase in the refrigerant flow rate. The heat transfer rates under R410A and R134a were on average higher by 40% and 23%, respectively, than that under R22. It was also observed that the heat transfer rate decreased with an increase in the d/h of the accumulator due to a decrease in the velocity of the vaporous refrigerant flowing around the IHX. As the tube length and tube diameter of the IHX increased, the heat transfer rate increased significantly.

Gustavo et al. [7] developed simulation model to investigate the effect of condenser subcooling on the performance of vapor-compression systems. The simulation model was used to evaluate the effect of subcooling on the overall systemperformance for different refrigerants. The capacity of systemwas 1 TR.

and over sizing of condenser was done by increasing the number of tubes and tube passes for providing subcooling. The effect of subcooling was investigated on different refrigerants like R123yf, R410A, R134a and R717. The operating condition like condenser and evaporate inlet temperature were maintained at 35 ℃ and 27 ℃ respectively. It was observed that the COP maximizing subcooling is roughly 9 ℃ for all four refrigerants. Simulation results indicated that refrigerants with large latent heat of vaporization, such as R717, tend to benefit the least from condenser subcooling. For a typical AC system, simulation results indicated that R1234yf would benefit the most from condenser subcooling in comparison to R410A, R134a and R717 due to its smaller latent heat of vaporization.

Ming et al. [8] experimentally investigates the thermal performance of a heat pump system with an ice storage subcooler. The system included a compressor, two greenhouses (that supplied heating and cooling demand, condenser, two expansion valves, and an ice storage tank. The capacity of heat pump system was 2.13 TR. The system was charged with 5.5 kg of refrigerant R22. The system was designed for simultaneous heating and cooling. It was investigated that the ice storage tank charges for storing ice, when the cooling load is less than the nominal cooling capacity. While the cooling load is larger than the nominal cooling capacity, the ice storage tank discharges for subcooling. Experiment showed that at the charge mode, Tw drops from initial temperature from 305K to 274 K. During the prior 70 min, Tw does not close to the frozen point, so ice fraction keeps at 0%. After 70 min, ice fraction increases from 0% to 34% when the charge mode is over. Under the discharge mode, Tw rises and ice fraction reduces as the ice storage tank receives the heat from the subcooled refrigerant. At the ending of the discharge mode, Tw increases from 274 K to 278 K; ice fraction drops from 34% to 7%. The results indicated that the ice storage tank can improve more than 12% COP of heating and 15% COP of cooling in the charge and discharge mode respectively.

Vijayan et al. [9] experimentally investigated the performance of 1 TR capacity window air conditioning system for both with and without an internal heat exchanger (IHX) condition, along with performance comparison of R22 and R407C in same AC. An IHX of shell and coil type configuration was designed and fabricated for analysis. Experiment was carried out initially with R22 without IHX. The system was allowed to reach steady state and then reading was taken by keeping condenser temperature at 50°C and evaporator temperatures at 6°C, 8°C, 10°C and 12°C respectively. Once the baseline experiment has carried out, IHX was included by adjusting valves. After completion of all tests with R22, AC was retrofitted with R407C and experiments were repeated with and without IHX for R407C. Experimental results indicated that inclusion of IHX improved refrigerating performance to 5.44% with R22 and 6.13% with R407C.

Qureshi et al. [10] experimentally investigated the effects of employing a dedicated mechanical subcooling cycle with a residential 1.5 ton simple vapor compression refrigeration system. Dedicated mechanical type subcooler is where a separate condenser exists for both the main and the subcooler cycle. The experimental outcomes indicated that the load carrying capacity of the evaporator increased by approximately 0.5 kW when R22 was subcooled, in the main cycle, by 5°C to 8 °C. Furthermore, the general trend indicated that this percentage increase is inversely proportional to the ambient temperature variation. The amount of subcooling is consistently larger in value when the outside ambient temperature is lower.

8. Advantages of VRF System

The main advantage of a variable refrigerant flow system is its ability to respond individually to fluctuations in space load conditions [1]. The advantages of this system are as follows:

8.1 Comfort:

Figure 6: Comfort condition with VRF system [1]

The user can set the ambient temperature of each room as per his/her requirements and the system will automatically adjust the refrigerant flow to suit the requirement. VRF systems are capable of simultaneous cooling and heating. Each individual indoor unit can be controlled by a programmable thermostat.

8.2 Design Flexibility:

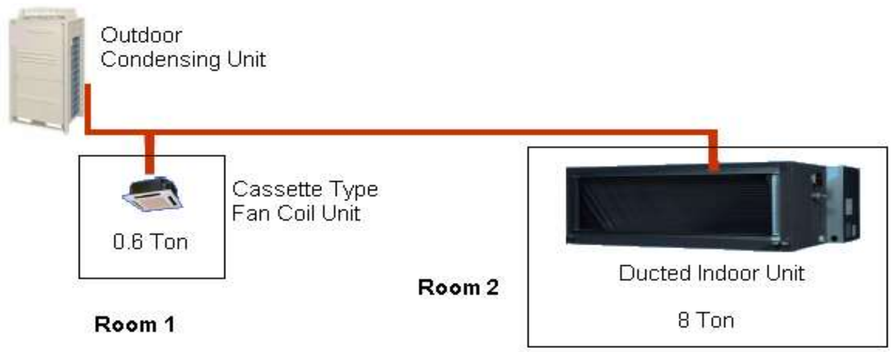

Figure 7: Design Flexibility with VRF system [1]

A single condensing unit can be connected to wide range of indoor units of varying capacity (e.g., 0.5 to 4 tons ducted or ductless configurations such as ceiling recessed, wall-mounted and floor console). Current products enable up to 60 indoor units to be supplied by a single condensing unit.

8.3 Flexible Installation:

VRF systems enable floor by floor installation and commissioning. These systems are lightweight; require less outdoor plant space and offer space-saving features. When compared to the single split system, a VRF system reduces installation cost by about 30%. A VRF systemprovides reduction in coppertubing and wiring costs.

8.4 Energy Efficiency:

VRF systems benefits from the advantages of linear step control in conjunction with inverter and constant speed compressor combination, which allows more precise control of the necessary refrigerant circulation amount required according to the system load. The inverter technology reacts to indoor and outdoor temperature fluctuations by varying power consumption and adjusting compressor speed to its optimal energy usage. Inverter provides superior energy efficiency performance and also allows for a comfortable environment by use of smooth capacity control. Field testing has indicated that this technology can reduce the energy consumption by as much as 30 to 40% a year compared to traditional rotary or reciprocating type compressors.

8.5 Reduced Noise Levels:

Indoor and outdoor units are so quiet that they can be placed just about anywhere, providing more flexibility on how to use indoor and outdoor space. Indoor ductless operating sound levels are as low as 27dB and ducted units sound levels are as low as 29dB. When compared to the single split system, a VRF system reduces outside noise levels by almost 5 dB@1m.

8.6 Reliability:

Each indoor unit is controlled individually on the system network. This allows all indoor units continue to run unaffected even if trouble should occur at any indoor unit in one system.

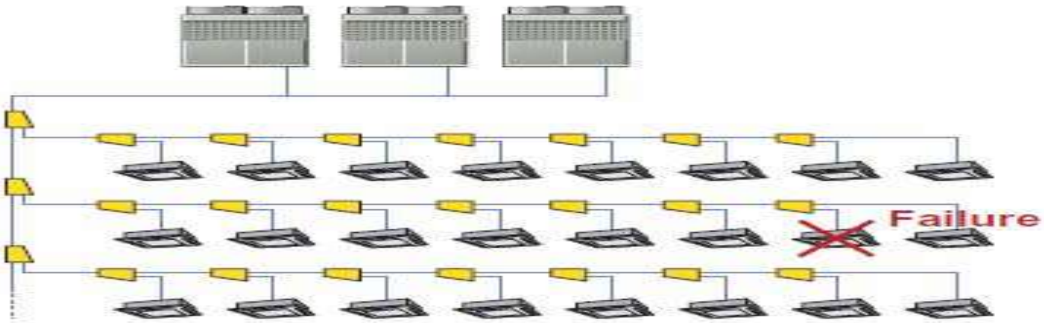

Figure 8: Failure of indoor unit in VRF system [1]

Continuous operation is possible even in the event of compressor failure. There is no immediate system shutdown if trouble occurs in any compressor. The other compressors can continue to operate on an emergency basis.

8.7 Maintenance and Commissioning:

VRF systems with their standardized configurations and sophisticated electronic controls are aiming toward near plug-and-play commissioning. Normal maintenance for a VRF system is similar to that of any DX system and consists mainly of changing filters and cleaning coils. Because there are no water pumps to maintain or air ducts to be cleaned, less maintenance is required compared to other technologies.

8.8 Aesthetics:

Figure 9: Indoor units with VRF system [1]

Indoor units are available in different capacities and multiple configurations such as wall-mounted, ceiling-mounted cassette suspended, and concealed ducted types. It is possible to provide an assorted arrangement that combine multiple types of indoor sections with a single outdoor section. These provide extreme versatility to the aesthetic requirements of different building types. Outdoor units can be located on roof or hidden space.

9. Limitations with VRF System

VRF systems are not suitable for all applications [1]. The key limitations are:

1. VRF HVAC systems may cost more than traditional central air systems up front. But this cost can be offset by lower energy bills and repair expenses over time.

2. A VRF system being the split installation is restricted by distance criteria between the condensing unit and the evaporator. The maximum length of refrigerant pipework for a VRF or any other split system is determined by the compressors ability to overcome the pressure drop and for the system to maintain proper oil return.

3. VRF systems raise the specter of refrigerant leaks which can be difficult to find and repair; particularly in inaccessible spaces. The refrigerant leak, especially if the system serves small rooms, can cause oxygen depletion. So you need to limit the system size within reasonable limits based on the smallest room area served.

4. As the system has a larger spread, the refrigerant pipes traverse long lengths; hence their pressure testing and protection becomes critical. Long refrigerant piping loops also raise concerns about oil return. Typically, each compressor has its own oil separator which is optimized for the VRF system. Periodically, the VRF goes into oil retrieval mode during which time the thermostatic expansion valve opens, and the compressor cycles at high pressure to flush oil out of any location where it has accumulated.

5. Ozone depletion issues have become a global concern and the issue of a high refrigerant charge associated with long refrigerant lines of VRF systems is a strong negative for the system. But with new refrigerant developments, advances in charge management and controls have transformed the technology to some extent. HFC refrigerants, typically R410A and R407C, are commonly used.

10. Applications of VRF System

Followings are the common areas where VRF system can be easily implemented:

1. Campuses and school buildings are tough; they almost always mean a variety of different rooms with different needs, not to mention retrofits and the possibility of future expansion. A VRF system is a solution that delivers flexibility and a lot of efficiency. One VRF system can cover everything from your structure's smallest workspace to its most vast spaces, like lobbies and auditoriums.

2. For hospitality purpose VRF is comfortable. Quieter operation and individualized zoning provide huge benefits whether a room is vacant or not. Adjusting room temperatures before a guest arrives or after checkout is easy and can result in great cost savings utilizing centralized control systems.

3. In healthcare facilities, zone control and heat recovery do more than warm or cool a patient's room. While VRF system provides patient comfort, it's saving energy by allowing for temperature adjustments within different areas of the same facility.

4. VRF systems bring a multitude of benefits to multi-family properties. The precise zoning lets each tenant maintain his or her own comfort level, while making it possible for the building owner to reduce flow to unoccupied apartments or condos.

5. For a successful office building, you have to maximize leasable space and then adapt that space to your tenants' needs. VRF system makes it possible. Smaller unit of VRF and longer pipe lengths mean you can add more floors, eliminate equipment rooms and open up useable square footage.

11. Conclusions

This review study gives a detailed overview of the configurations, operations, applications, advantages and limitations of variable refrigerant flow (VRF) systems. Besides, experimental studies associated with the effects of subcooler on cooling performance of inverter variable refrigerant flow (IVRF) type air conditioning system.

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.

It is observed that the compressor frequency and the EXV opening should be controlled simultaneously for the control strategies. 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.

The detail studies associated with the effects of subcooler on cooling performance of inverter variable refrigerant flow (IVRF) type air conditioning system reveals the following conclusions:

1. With increase in subcooling up to certain Degree (⁰C), COP of the air conditioning (AC) system increases.

2. Increase in COP of the system with subcooling is inversely proportional to ambient temperature.

3. Subcooling increases the reliability and stability of the system.

4. Subcooling provides the better flow distribution to multi indoor units (IDUs) of VRF AC system.

5. Subcooling allows the use of full evaporator surface for cooling.

6. Refrigerants with large latent heat of vaporization tend to benefit less from condenser subcooling.

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