

Variable Refrigerant Flow: An Emerging Air Conditioner and Heat Pump Technology

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ABSTRACT

This paper reviews the attributes of an emerging space conditioning technology; variable refrigerant flow (VRF) systems. Material presented in this paper was synthesized from the open literature, private interviews with industry experts and data (sometimes proprietary data) obtained from manufacturers. VRF systems are enhanced versions of ductless multi-split systems, permitting more indoor units to be connected to each outdoor unit and providing additional features such as simultaneous heating and cooling and heat recovery. VRF technology uses smart integrated controls, variable speed drives, refrigerant piping, and heat recovery to provide products with attributes that include high energy efficiency, flexible operation, ease of installation, low noise, zone control, and comfort using all-electric technology. VRF systems are very popular in Asia and Europe and, with an increasing support available from major U.S. and Asian manufacturers are worth considering for multi-zone commercial building applications in the U.S.

This paper provides an overview of variable refrigerant flow system technology, including the market situation, advantages and disadvantages for the customer, possible impact on the electric utility, applications recommendations, and technology attributes. Also addressed are what is holding back the technology, including lack of verified third party field data; codes and standards issues; technology improvements needed; and market actions needed to increase penetration of these systems.

Evolution of the Technology

Ductless space conditioning products, the forerunner of multi-split and VRF systems, were first introduced in Japan and elsewhere in the 1950s as split systems with single indoor units and outdoor units. These ductless products were designed as quieter, more efficient alternatives to window units (Smith, 2007).

Products have evolved from a few indoor units operating off each outdoor unit, to multi-split products with 4 units to 8 units in the late 1980s, to 16 units in the early 1990s, to 32 units by 1999. Today's advanced systems permit as many as 60 or more indoor units to operate off one outdoor unit, enabling application in large commercial buildings. Electronically commutated motors, inverter-driven/capacity modulated scroll compressors, multiple compressors, versatile configurations and complex refrigerant and oil circuitry, returns, and controls have enabled this addition of up to 60 indoor units. Refrigerants have also changed. The early "mini-split" systems used R-22 refrigerant, then R-407C, and today's systems rely on R-410A. Figure 1 shows the piping and refrigerant flow for conventional split systems (one indoor and one outdoor unit) multi-split systems, and variable refrigerant flow systems (Dyer, 2006).

Multi-splits offer some of the major advantages of VRF systems, such as zoning, capacity control, ease of retrofit, low installation costs, and minimizing ducting and use of secondary

fluids and associated costs and losses. On the other hand, their simpler piping results in longer total length of piping compared to VRF systems. Similarly, multi-split heat pumps do not have the opportunity for heat recovery between units that are cooling and units that are heating. As such, multi-split systems should be considered for smaller, simpler buildings where heat recovery is not a possibility and fewer numbers of zones need to be conditioned.

How Does VRF Work?

Multi-splits include multiple indoor units connected to a single outdoor unit. Ductless products are fundamentally different from ducted systems in that heat is transferred to or from the space directly by circulating refrigerant to indoor units (evaporators or condensers) located near or within the conditioned space. (When the indoor units are in the cooling mode they act as evaporators and when they are in the heating mode they act as condensers.) In contrast, conventional ducted systems transfer heat from the space to the refrigerant by circulating air (in ducted systems) or water (in chillers) throughout the building.

VRF systems are enhanced versions of ductless multi-split systems, permitting more indoor units to be connected to each outdoor unit and providing additional features such as simultaneous heating and cooling and heat recovery. VRF heat pump systems permit heating in all of the indoor units, or cooling of all the units, not simultaneous heating and cooling. Heat recovery systems provide simultaneous heating and cooling as well as heat recovery to reduce energy use during the heating season.

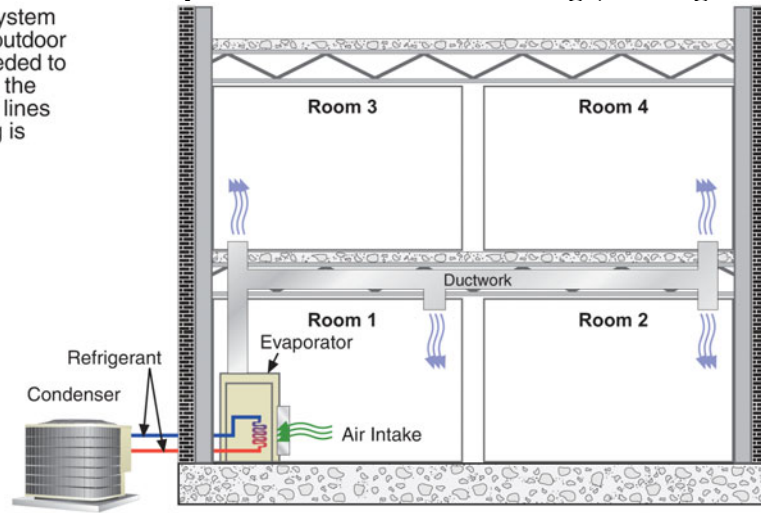
Over the past 15 years the technology has advanced in a number of areas:

- Standard compressors to variable speed and capacity modulated scroll compressors
- Direct driven outdoor fans to variable frequency drive, inverter-driven fans
- Direct driven indoor coil motors to direct current or ECM-type motors
- Variable capacity indoor units
- Better heat exchanger surfaces with multi-segmented coils
- Improved controls and diagnostics
- R-22 to R-410A
- Better refrigerant charge and oil management

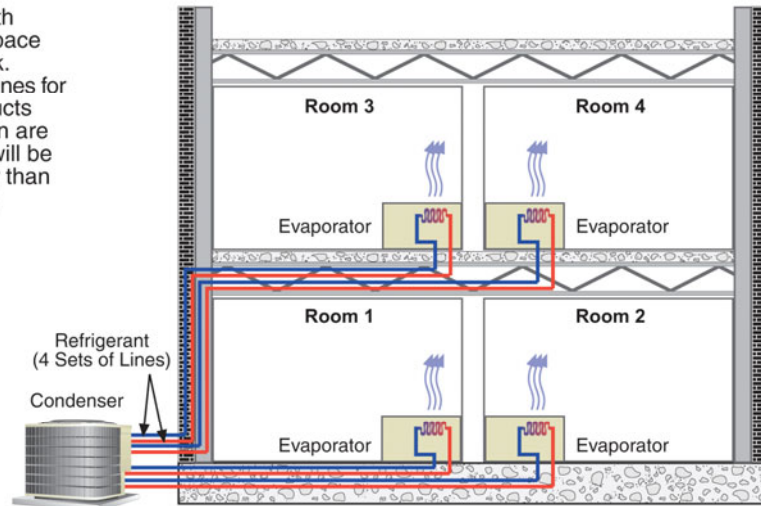
Other features include the addition of concealed ducted units and ceiling cassette configurations to the traditional wall-mounted units. Refrigerant piping runs of more than 200 feet are possible and outdoor units are available in sizes up to 240,000 Btu/ hr.

Figure 1. Split, Multi-Split and VRF Operation in a 4 Zone Building (Cooling Mode)

Conventional Split system showing indoor and outdoor units and ducting needed to serve the 4 zones in the building. Refrigerant lines are short but ducting is substantial.



Multi-split system with evaporators in the space minimizing duct work. Separate refrigerant lines for each indoor unit. (Ducts needed for ventilation are not shown but they will be considerably smaller than for the Split system.)



VRF system with evaporators in or near the space minimizing duct work. Parallel refrigerant lines for the indoor units minimize refrigerant line length and pressure drop and facilitate heat recovery between units that are cooling and those that are heating. (Ducts needed for ventilation are not shown but they will be considerably smaller than for the Split system.)

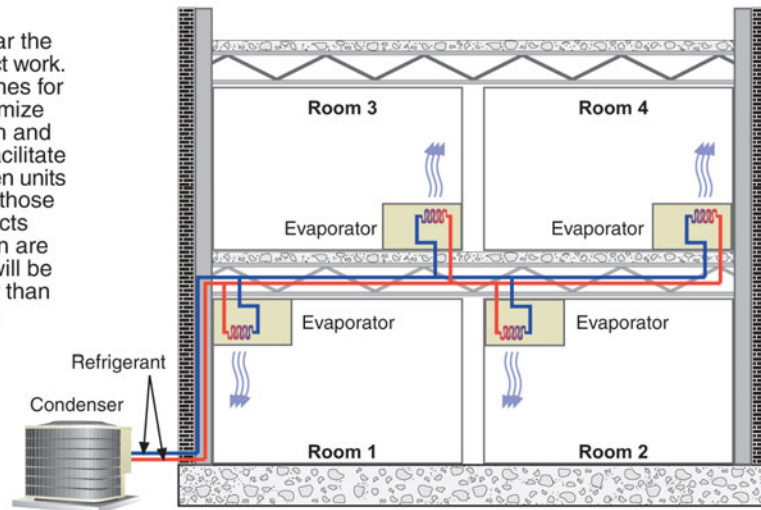
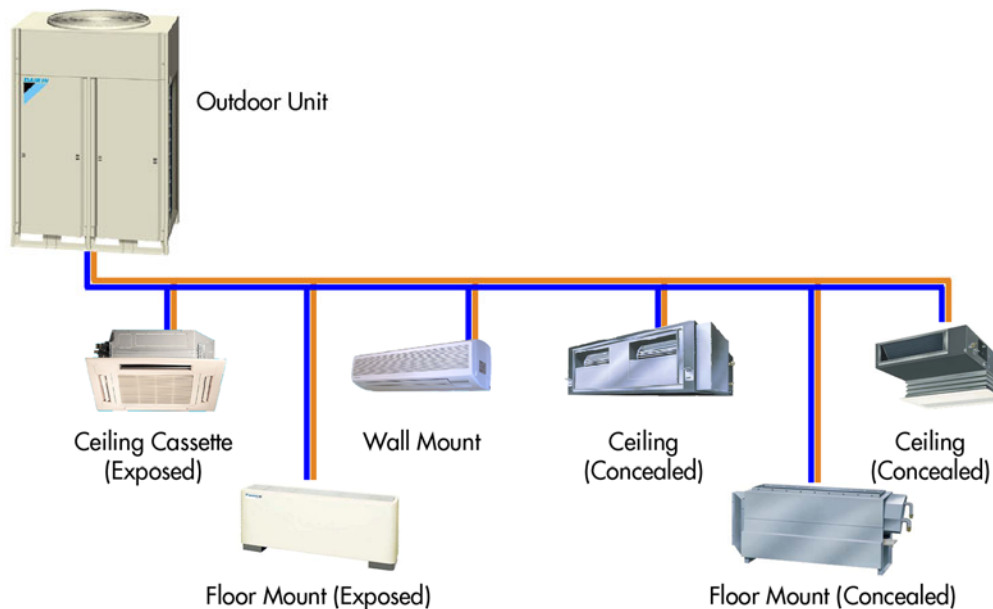


Figure 2 shows a single outdoor unit and a general schematic of multiple indoor units in a VRF heat pump system. The indoor units include wall mounted, floor mounted, ceiling cassette and concealed ducted configurations.

The term “variable refrigerant flow” 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. Most VRF condensers use variable frequency drives to control the flow of refrigerant to the evaporators. Refrigerant flow control lies at the heart of VRF systems and is the major technical challenge as well as the source of many of the system’s advantages (Goetzler, 2007).

In most cases, two-pipe systems can be used effectively (in VRF heat pump systems) when all the zones in the facility require cooling or all require heating during the same operating period. Three-pipe (a heating pipe, a cooling pipe and a return pipe) 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 medium-sized to large-sized buildings with a substantial core.) One manufacturer has a two-pipe system than can be used to provide simultaneous heating and cooling as well as heat recovery operations.

Figure 2. Major Components Of A VRF System Including The Range Of Possible Indoor Unit Configurations And A Typical Outdoor Unit. (Courtesy of Daikin)



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

Ventilation can be integrated with the VRF system in several ways. A dedicated VRF indoor unit could be used in a ducted configuration to condition the ventilation air. A separate ventilation system and conditioning unit could be installed using conventional technology and the VRF system function would be restricted to the recirculation air. Some VRF units have the ability to handle some outside air and could be used accordingly. Bringing the outside air into the room and then conditioning it with the VRF is not recommended (because of humidity issues) except in dry climates where condensation will not create moisture problems. Heat recovery ventilators can be used to reduce cooling loads on the VRF units.

Both water-cooled and air cooled systems are available as well as systems integrated with ice storage units.

Market Adoption of VRF Systems

Ductless and multi-split products are often considered factory-built systems, competing with traditional unitary products, whereas some manufacturers position their VRF systems as engineered systems that are alternatives to traditional field-applied systems such as chillers. U.S. sales of all ductless, multi-split and VRF products will be around 250,000 units in 2007. Less than 10,000 of these are VRF units (Goetzler, 2007).

Sales in Japan, where the VRF concept was developed, and other parts of Asia, have been strong. In Japan VRF systems are used in approximately 50% of medium sized commercial buildings (up to 70,000 ft²) and close to 33% of large commercial buildings (greater than 70,000 ft²). In Europe, where many existing buildings did not have air-conditioning, retrofit opportunities have also created strong demand (Goetzler, 2007).

Ductless products entered the United States market in the early 1980's but market penetration was minimal. Lack of Japanese manufacturer support infrastructure, and market unfamiliarity with the technology held back sales. Moreover, ozone depletion issues became a concern at that time, and the issue of a high refrigerant charge of multi-split systems was likely a strong negative for the system. Since that time, refrigerant developments, advances in charge management, controls and inverter technology have transformed the technology. Asian manufacturers have recently re-entered the U.S. market individually or in partnership with U.S.-based manufacturers to help promote the technology.

Evidence of the applicability of this technology in the U.S. is the inclusion of a multi-split variable refrigerant flow system with zoned inverter-driven heat pump and heat recovery in the renovation of the headquarters building of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in Atlanta, Georgia (Johnson, 2007).

Customer Issues

Customers desire products that enhance comfort and productivity at a reasonable capital cost and energy cost. The low noise, individual controllability and effective temperature control of multi-split system air conditioners and heat pumps have the potential to enhance workplace productivity. The energy saving features of the product, such as capacity modulation, zone control, heat recovery and low duct losses contribute to ownership cost savings. However, the cost effectiveness of the technology is highly application dependent. Cost and energy use data should be obtained from detailed analysis and corresponding rigorous laboratory and field testing

of multi-split systems. The need for this information currently exists for applications in the United States.

Manufacturer and case study information from outside the U.S. indicate that VRF systems are cost effective, but results, again, depend on specific application features. Typically, energy savings are achieved, ranging from 10% to 60%, depending on climate and the type of system displaced, among other factors. Initial costs are also typically higher, with payback periods dependent on energy savings. Examples of application and operation costs outside the U.S. include the following:

- Anecdotal information exists that shows savings of 38% in a side-by-side comparison with a rooftop variable air volume (VAV) installation, but this study compared a new VRF system to the existing rooftop VAV system (Roth 2002). Simulation results for a Brazilian climate showed savings of over 30% in summer and over 60% in winter. Savings of 5% to 15% were suggested to be more likely in the United States.
- A modeling study conducted with a version of EnergyPlus that was modified to simulate VRF systems showed that, in a ten story office building in Shanghai, a VRF system saved more than 20% of the energy compared to a VAV system and more than 10% compared to a fan coil plus fresh air system (Zhou 2006).
- Information obtained in discussions with one manufacturer suggests that the company's VRF systems could save up to 30% to 40% of the energy used by a chiller-based system for a 200-ton cooling system for a generic commercial building. The same data set indicates that the installed cost of a VRF system will be about 8% more than a water-cooled chiller and 16% more than an air-cooled chiller. Combining these energy use and installed cost projections provides an estimated payback period of about 1.5 years for the VRF compare to an air-cooled chiller and 2/3rds of a year compared to a water-cooled chiller.
- Data from another VRF manufacturer compared installation and operating costs for a set of 14 branch buildings in Central/Northern Italy, where a chiller/boiler system was installed in 7 of the buildings and a VRF system was installed in the other 7 buildings (designed to handle heating down to -20°C [-4°F]) in 1998. The VRF systems used 35% less energy and had 40% lower maintenance costs for the period studied. As suggested by other manufacturers, the equipment costs for the VRF systems were higher than the equipment costs for the chiller-based systems but this was offset by lower installation costs for the VRF systems.

Advantages of VRF and Multi-Split Systems

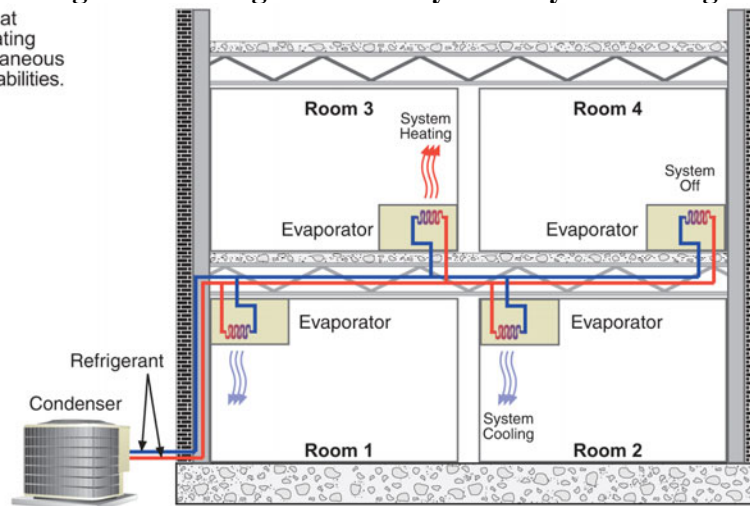
Some of the features of multi-split systems should provide energy savings. These include:

- Good part load performance due to multiple compressor and variable speed compressor systems permitting capacity modulation to serve 7% to 100% of the cooling or heating load. Many hours of HVAC system operation are spent between 30% and 70% of maximum capacity where the VRF system efficiency is high (Roth 2002).
- Good zone control, saving by not conditioning unoccupied zones and by providing capability to condition single zones off hours at a reasonable cost. Figure 3 shows how VRF systems can provide zone control, including simultaneous heating and cooling.

- Heat recovery is readily accomplished with the refrigerant when some of the indoor units are heating and some of the units are cooling. According to one manufacturer's published data, if a 50% demand for full cooling and a 50% demand for full heating exist, in the heat recovery mode the compressor would only be 48% loaded (Inman, 2007).
- Duct losses are confined to the ventilation air which is normally about 1/5th of the air flow of a ducted system circulating and conditioning both the ventilation air and the recirculated air. (Since ducts are often in unconditioned spaces, duct losses may not contribute to building space conditioning).
- Refrigerant is used directly as both the working fluid and the heat transfer fluid tending to make the VRF system more efficient than systems that use air or water as a secondary heat transfer fluid for delivering heating or cooling.
- The use of R-410A and other features such as variable speed compressors, multiple speed fans and blowers, refrigerant circuitry, electronic expansion valves and advanced controls contributes to enhanced low temperature performance that can avoid or minimize the need for supplementary heat in many U.S. climates.

Figure 3. Cooling and Heating Provided By VRF System Using One Outdoor Unit

Schematic of a VRF heat recovery system illustrating zone control and simultaneous heating and cooling capabilities.



Other non-energy advantages include:

- Better comfort. Since the system can be modulated to follow the load, units can remain running to maintain temperature within narrow limits, assuring a comfortable temperature envelope.
- Low noise levels. Levels are 24 dBA for the indoor unit and 56 dBA for the outdoor unit (Siddens, 2007).
- Flexible and quick installation. Only a small (3" or so) opening is needed for the refrigerant piping.
- Low-profile, low space requirements and light weight make units easier to fit into tight spaces and to avoid obtrusive terminal units that could spoil the esthetics of a space.
- Claimed low maintenance and high reliability. Although the large amount of refrigerant piping and numbers of connections is a concern to U.S. specifiers and installers,

manufacturers claim low maintenance costs and a record of reliability. Maintenance consists of changing filters and cleaning coils.

- Modularity allows easy apportioning of energy costs among tenants or operations. Increased useful building space is enabled by reducing floor to floor height (12” ceiling void vs. 20”) and eliminating the need for a machine room.
- Avoids the need for an on-site, trained operator as might be desirable with a large chiller-based system.

Disadvantages of VRF and Multi-Split Systems

Some of the features of the VRF and multi-split systems may result in increased energy costs relative to some competitive systems, and thus offset savings:

- Less economizer cycle benefit may occur with the smaller ventilation system since the ducting is sized just for ventilation.
- Use of supplementary heat may be required for quick recovery from night setback. This can be avoided to a great extent by providing sufficient time to allow the heat pump cycle to be used with the compressors running at maximum capacity to provide morning warm up.
- Use of backup strip heat for space heating in cold weather would be a detriment to the efficiency of the system. However, as indicated above in the list of advantages, speed variation and other features help increase the heat pump capacity to offset some of the vapor compression cycle degradation with lower temperatures. This can avoid or minimize the need for backup heat. Integrated gas heating systems are not available as yet as a dual fuel option.
- It may be less economical to provide high efficiency components (such as fans, or filter systems) for many decentralized indoor units compared to the efficiency of these systems when installed in a single larger centralized system.

Other disadvantages include:

- The need for a separate ventilation system to satisfy code requirements for delivery of outside air offsets some of the retrofit advantages of the VRF system.
- Each VRF indoor unit should be supplied with a condensate drain that needs to have access to a water collection system.
- Long refrigerant runs and large numbers of connections could result in refrigerant leakage that could be significant, causing safety issues and repair difficulties. One VRF manufacturer cautions not to install an air conditioner in a room where the limit density will be exceeded if refrigerant leaks. They assert that the refrigerant (R410A) used by this system is itself a safe refrigerant; however, if for some reason the refrigerant leaks and the limit density is exceeded, there is a risk of injury to persons due to a lack of oxygen.
- Oil return (and refrigerant positioning) could be an issue but many systems employ special oil retrieving modes that are periodically, automatically activated to flush oil (or refrigerant liquid) out of any locations where it has accumulated

Costs

Installed 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 VRF costs. Total costs for VRF systems are likely to be about 5% to 20% higher than chilled water systems of similar capacity (Roth 2002).

One manufacturer provided verbal information that VRF systems cost about 30% to 50% more than equivalent capacity single package ducted systems with a SEER of 13 to 14. And that VRF systems cost more than twice as much as packaged terminal units. This information is interesting but not as important as the comparisons of VRF and chiller systems if VRF manufacturers position their product as a chiller alternative.

In some retrofit situations where the distribution system needs to be replaced—or lack of access to the chiller makes chiller replacement untenable—the VRF system could have a lower cost.

Utility Issues

From a utility standpoint, one of the positive features of the VRF system heat pump is the ability of the customer to use an all-electric system. Since no integrated gas heating options currently exist for this technology, this provides the electric utility an opportunity to serve the heating load on buildings that install multi-split system heat pumps.

Summer peaking utilities can benefit from installations of VRF heat pumps, since the systems' additional heating loads will provide off-peak winter load that could improve capital utilization and return on investment.

For most of the cooling season, VRF systems will use less energy than many other cooling means that do not have comparable zoning or capacity modulation. (Much of the energy savings in the cooling mode will occur off peak due to capacity modulation and zone control that turns off units when the space is unoccupied.) On peak, when cooling systems are operating at or near 100% capacity, the VRF system could have lower demand than a rooftop direct expansion variable air volume system but will likely have higher demand than a high efficiency chiller-based fan coil system. Whether a summer peaking utility wants to encourage VRF systems or some other electric or gas system will depend on the local rates, reserve margins, regulatory environment and other factors. For a winter-peaking utility the use of electric heat may make the VRF system less attractive than it might be for a summer peaking utility.

Demand Response Issues

To use VRF systems as a demand response tool, it is possible to turn off the indoor units in one or more spaces, letting the space temperature and humidity drift (with some spillover of conditioned air from the adjacent conditioned spaces). The on-off sequencing between zones could be alternated to minimize temperature changes to minimize occupant discomfort. Alternately, units could be operated at a fraction of normal capacity to maintain minimally effective environmental conditions in the occupied space. Sequentially starting of the outdoor units serving a building is possible to spread out demand spikes caused by starting power transients.

With regard to interoperability, VRF system air conditioners and heat pumps have sophisticated controls and components that will enable the units to adjust their performance in response to internal or external signals.

Best Applications for VRF Systems

Initial applications of VRF in commercial buildings in the U.S. have included building add-ons such as a new data center and situations where spot cooling is needed. Historical buildings have benefited from the minimum alterations needed for the addition of a VRF system. Retrofit situations where air conditioning may be an addition/upgrade to the space can be good applications of ductless systems since additional duct work and conditioning needed for ventilation can be minimized with VRF systems compared to ducted systems.

Other applications well suited to VRF systems include any case in which there is an advantage to delivering personalized, compartmentalized comfort conditioning, such as: office buildings, strip malls, hotels and motels, hospitals and nursing homes, banks and schools.

Offices and strip malls have occupants with different space conditioning requirements, making the zoning opportunities of VRF attractive for these applications. Hospitals and nursing homes can be good candidates since the VRF system makes it easy to 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. Even in schools, which because of high occupancy often have a 100% outside air requirement, VRF units can be used (often with heat recovery ventilators) to meet the load.

What's Holding Back VRF in the United States

The traditional barriers to new technology have hampered market acceptance of VRF systems. These barriers include the natural resistance to change and unwillingness of specifiers and users to be subjected to the uncertainty of using a new, unproven technology. Other barriers common to this and most new technologies include: performance uncertainties; lack of knowledge of design, operation, servicing and maintenance; and ownership costs. Concerns also exist about manufacturer support and spare parts availability, especially since most of the manufacturers are not based in the U.S. These barriers tend to translate into higher first costs. Those specifiers and installers who are willing to take the risk of recommending the technology will expect to get paid extra for taking on the added risk. As specifiers become more familiar with VRF these markups will diminish. Barriers specific to VRF systems include:

- Concerns about potential for leaks. Having a system with long refrigerant piping runs and many connections exposes the systems to leakage. Brazed joints are used instead of flared or flanged connections in the refrigerant circuit to minimize/avoid leakage (Dyer June 2006). Leaks may be difficult to detect and repair in the field and a perception exists among engineers and building owners that these could cause safety issues since large quantities of refrigerant could be released. Safety problems caused by refrigerant leakage must be addressed in accordance with ASHRAE Standard 15-2007 that specifies the safe design, construction, installation and operation of refrigeration systems. The refrigerant charge, circuiting and occupied space served by the VRF circuits must be designed so as

not to exceed limits for the maximum permissible quantity of refrigerant that can enter the occupied space as specified in the standard (ANSI/ASHRAE 2007).

- Manufacturer presence and support in the United States has been limited but Japanese manufacturers have aggressively entered the market, with Daikin acquiring McQuay, and Carrier and Toshiba forming an alliance (and currently selling products in Europe and Latin America. Some Japanese and Korean manufacturers are using manufacturer's representatives to represent them in the U.S.
- Lack of availability of an integrated gas heating option may affect the cost effectiveness of the heat pump systems.
- The need for a separate ventilation system to provide fresh air to the occupied space to comply with ASHRAE Standard 62 requirements offsets a part of the advantage of using a refrigerant distribution system rather than an air distribution system for the bulk of the space conditioning.
- The lack of suitable test rating procedures and code compliance procedures certified by the Air-Conditioning and Refrigeration Institute (ARI) and approved by the U.S. Department of Energy (DOE) are also impediments to selection of VRF systems. European and Japanese testing procedures are well established.
- Work is needed to better simulate the performance of VRF systems to provide certified tools that predict energy use for compliance calculations to satisfy energy code requirements - or to capture energy credits for programs such as LEED (Leadership in Energy and Environmental Design Green Building Rating System™) - or to qualify for rebates for programs such as Savings by Design. Available programs include: Trace700, a program developed by the Trane Company (TRACE 2007) but widely used in the industry that has had the ability to model VRF systems since 2001. EnergyPlus subroutines have been developed to model VRF systems. Privately sponsored work is underway to develop a version of eQuest, and work is being done by EnergySoft to develop a version of EnergyPro that incorporate VRF technology. Both eQuest and EnergyPro programs have been accepted by the California Energy Commission and when completed as anticipated by mid-year 2008 should greatly facilitate the use of VRF systems in California. Both programs are well connected with California utility rebate programs and will make needed calculations and fill out corresponding utility rebate forms.

What Else is Needed?

Based on what we know about VRF applications outside the U.S., and applications that are occurring in the U.S., this space conditioning technology has the potential to reduce energy use, and could be well positioned for retrofitting multiple types of large commercial buildings, ranging from office buildings to retail establishments to nursing homes. To help end users and specifiers understand and take advantage of improved low temperature heat pump performance and the flexibility of the VRF systems requires testing, documentation, and market development for existing products as well as development of advanced features for future products.

To take advantage of the energy savings potential of VRF systems, considerable market barriers must be overcome, including lack of performance and cost data from unbiased third party organizations. Risk-averse specifiers and purchasers of space conditioning systems must

have reliable data on the efficacy of the VRF approach for U.S. applications. Ventilation system design refinements could also hasten applications acceptance.

To overcome reluctance by those who design, specify, and purchase systems, the following tools, resources, and technology are needed:

- Energy analysis tools should be enhanced to incorporate algorithms that can accurately model VRF systems.
- The development of rating and testing methods needs to be encouraged to provide a reasonable means of comparing the VRF systems to ducted and hydronic systems.
- Well designed field tests and design and construction evaluations by independent third parties to derive reliable energy use data and true installed costs of VRF systems.
- A U.S.-focused design guide based on field studies and including information that provides the type of trusted data that specifiers, users and other important market participants need to for selecting systems. Such a guide and other training materials could help overcome specifier resistance to change and lack of information.
- Technical references and articles in journal and industry trade publications are needed in addition to the design guide to enhance knowledge of the applicability of VRF systems.
- Better, more economical means are needed to integrate fresh air delivery with VRF systems to provide ventilation while maintaining ease of retrofit.
- Develop advanced VRF systems with improved low temperature heat pump performance using cycle and configuration improvements such as multi-stage, supercharged cycles and flash-injection circuits.
- Guidance on use of ice storage systems in conjunction with VRF systems. If ice storage systems are charged by VRF systems then the ice storage system could, in turn, be integrated into the ventilation system and VRF systems to provide cold water for dehumidification.

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