2021 WHITE PAPER

Achieving Optimal Indoor Environmental Quality (IEQ) in Commercial Buildings with VRF Systems

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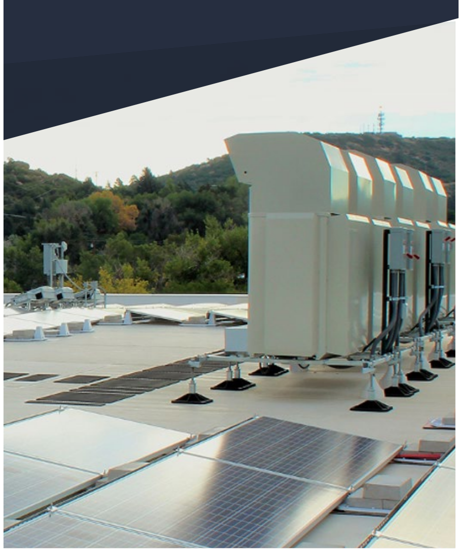
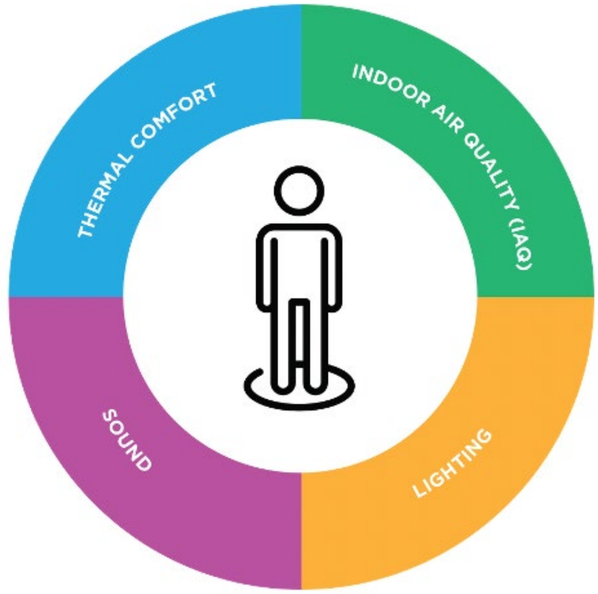
Introduction

The COVID-19 pandemic heightened both industry and mainstream awareness of how building systems operate and impact occupant wellness. The average person is reading articles, watching videos, engaging in social media exchanges and asking pointed questions. They want to know what building owners and facility managers are doing to provide healthy spaces to live, learn, work and visit. Buildings designed for occupant health and wellness are highly marketable and also offer improved comfort, efficiency, resilience and sustainability.

This White Paper presents wellness and sustainability as complementary aspects of smart, marketable buildings and describes the operational, financial and productivity benefits of designing for indoor environmental quality (IEQ). Particular attention is given to how Variable Refrigerant Flow (VRF) zoning systems improve sustainability and IEQ components including thermal comfort, acoustic comfort and indoor air quality (IAQ).



IEQ COMPONENTS



Understanding IEQ

IEQ describes how an indoor environment affects occupant health and wellness. Most people spend about 90 percent of their time indoors[1], so what they breathe, feel and hear within the built environment has significant implications for their quality of life. IAQ is the most well-known IEQ component with clean, fresh air universally recognized as a prerequisite for health. By necessity, IEQ is more comprehensive than IAQ alone. Project teams committed to maximizing IEQ must account for how the building's design, materials, systems and occupant lifestyles relate to factors like thermal comfort, acoustic comfort, water quality, lighting and opportunities for rest and recreation.

Relationship between IEQ and sustainability

Optimal IEQ and sustainability are interrelated. Sustainability is the judicious use of thoughtfully selected resources to meet human needs while minimizing environmental impacts and waste. Designs for improving sustainability and IEQ both require purposeful control over how air, thermal energy (heat) and moisture enter, exit and flow through the building.

Sustainable buildings feature air-tight envelopes, insulation and glazing to control the movement of thermal energy. Fresh air enters the building through controlled ventilation instead of haphazard air filtration and leakage. These measures give sustainable buildings reduced heating and cooling loads compared to a similarly sized conventional building in the same region. Low sensible loads and energy-efficient mechanical equipment like VRF zoning systems limit the building's demand on the electric grid. Sustainable buildings also use all-electric systems and appliances where possible to limit or eliminate greenhouse gas (GHG) emissions from on-site fossil-fuel combustion.

Superior control over how the building operates makes sustainability possible and creates opportunities to improve IEQ for occupants. For example, a VRF system for smart heating and cooling keeps energy consumption to a minimum and uses the same level of precision to maintain occupant thermal comfort. Order and predictability enable developers, building owners and project teams to truly design the indoor environment, rather than leaving it to chance.

Healthier environments and strategic electrification

Sustainability also intersects with IEQ by reducing the presence of pollutants both indoors and outdoors. Researchers have started to quantify the health and financial impacts of breathing the byproducts of fossil-fuel combustion, including nitrous oxide, sulfur dioxide, carbon dioxide (CO_2) and Particulate Matter (PM) 2.5. A study by the Harvard T. Chan School of Public Health suggests air pollution from commercial and residential buildings causes between **48,000 and 64,000 early deaths per year. The study also attributes $615 billion in health impacts to these stationary air pollution sources for 2017 alone.**[2] As recognized by state-level decarbonization plans[3] and Regional Energy Efficiency Organizations, the healthy, sustainable built environment of the future absolutely requires wider adoption of all-electric building equipment like VRF heat-pump systems.[4]

The rising demand for pollution mitigation and decarbonization make strategic electrification vital to the current push for sustainability. **Strategic electrification** is the movement to responsibly reduce our society's dependence on fossil fuels (e.g., coal, oil, natural gas) by switching to energy-efficient technologies powered by electricity. As renewable energy becomes the primary source of U.S. electricity production, strategic electrification will result in a cleaner environment and energy independence. Strategic electrification includes the following steps:

- Increase energy efficiency
- Adopt all-electric technologies including heat pumps
- Move fossil-fuel consumption from end users to energy production
- Power end uses with renewable energy sources (e.g., solar, wind)
- Decarbonize electrical grids

Read our **Strategic Electrification White Paper** for additional details.

EARLY ADOPTERS AND HEALTHY BUILDING CERTIFICATIONS

Recognizing IEQ and sustainability as complementary enables industry professionals and the public to assess the value and performance of buildings based on impacts to human beings. **LEED®** and newer building certification programs including **WELL®**, **Fitwel®**, **PHIUS+** and **Living Building Challenge™** provide pathways for environmentally responsible, human-centered design. There is also an evolving business case indicated by the willingness of major corporations to pay for healthy building certifications. **About 20 percent of Fortune 500 companies** participate in the International WELL Building Institute's healthy building certification program.[5] While pursuing a WELL certification adds 1 to 2 percent to a project's budget,[6] executives openly discuss how buildings with high IEQ lower absentee rates and foster first-class performance and productivity.

Sustainability and resilience

Resilience describes a building's capacity to meet occupant needs during disruptions (e.g., utility service outages, severe weather) and recover after the event. Sustainability and resilience are closely aligned since minimal waste and efficient resource use mean sustainable buildings are better prepared to do more with less in a crisis than conventional facilities.

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CASE STUDY:
1703 BROADWAY

1703 Broadway is among the most efficient high-rise commercial buildings in the U.S. 150 geothermal wells and a water-source VRF system provide heating and cooling. Exterior insulation and high-performance windows support radiant temperature control. On-site solar panels can generate 1 megawatt of electricity. Conservation and collection methods will reduce the demand for local utility drinking water by 97 percent. Natural light indoors and pedestrian-friendly green space outdoors support recreation and biophilic comfort. The most significant contributor to the project's success was the collaboration and shared vision of environmental stewardship between the owners and project team.

San Antonio, Texas | 200,000 square feet, 12 floors | Water-source VRF | 2,912 solar panels

WATCH THE VIDEO

Courtesy of Credit Human

Better Buildings for All

Fortune 500 adoption demonstrates recognition of the financial and operational benefits of IEQ and sustainable design at high-income and corporate levels. At the same time, high-performance construction methods and growing builder expertise are making it more cost-effective to improve the built environment for all. Net-zero and passive house multifamily buildings can be constructed at costs comparable to conventional buildings. Per Passive House Institute US (PHIUS), the cost premium for passive building methods runs about 0 to 3 percent over the standard ENERGY STAR® construction baseline for multifamily buildings.[7]

Low- and medium-income (LMI) housing constructed with these methods provide healthier spaces to live and cost less to heat and cool. Tenants can benefit from inexpensive utility costs, renewable energy from photovoltaic panels and exceptional comfort control with VRF zoning systems.

Improving IEQ with VRF technology

VRF zoning systems use the natural movement of thermal energy to customize heating and cooling for designated comfort zones. The systems are all-electric, require no fossil fuels, and include an outdoor unit and up to 50 indoor units connected by refrigerant lines. Linear expansion valves (LEV) and an INVERTER-driven compressor enable energy-efficient refrigerant cycling to transfer heat between the outdoor unit and the indoor unit(s) serving each zone. In heating mode, the outdoor unit expands the refrigerant gas until the gas is colder than the outdoor ambient air or a nearby water source. The outdoor unit then extracts thermal energy from the air or water and transfers the heat to the interior zones. Using this method, a VRF system can provide more thermal energy as heat than it consumes in electricity. In air-conditioning mode, the system operates in reverse with the indoor units acting as evaporators and transferring heat to the outdoor units for rejection.

The indoor units connected to a VRF heat-pump system operate in one mode at a time: heating or cooling. VRF heat-recovery systems can provide simultaneous heating and cooling, making them suitable for multi-zone buildings with diverse thermal profiles (e.g., dorms, multifamily applications, office buildings, hotels, mixed-use facilities). Heat-recovery systems use a branch circuit (BC) controller to separate subcooled liquid and superheated gas refrigerant, so the refrigerant can be metered and redirected to zones calling for heating or cooling.

VRF controls help facility managers optimize heating and cooling with centralized equipment control and performance data. The insights, reports and capabilities available through VRF controls support predictive maintenance and help coordinate complementary IEQ equipment for ventilation, filtration and humidity control. VRF systems can also integrate with building automation systems (BAS) through standard communication protocols like **BACnet®**.

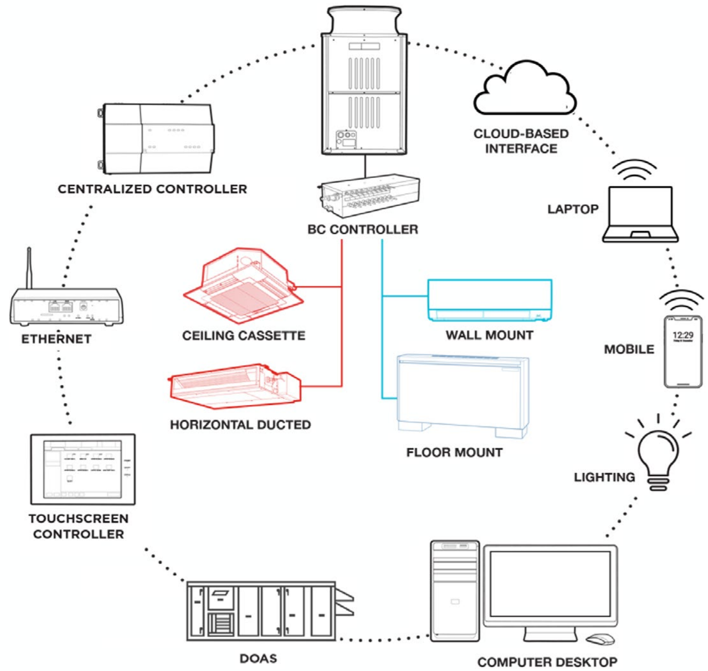
Acoustic comfort, thermal comfort and IAQ are the areas where a VRF system can have the most meaningful impact on IEQ strategy.

VRF Systems and acoustic comfort

Achieving acoustic comfort requires designs and product choices to limit mechanical noise. Excess sounds are disruptive for occupants and can negatively impact concentration, cognition and productivity. Also, as decibels increase, so does the risk of hearing damage. VRF indoor units and outdoor units operate at sufficiently low decibels to limit the risk of hearing damage and help to foster tranquil environments.

VRF outdoor units are lighter and more compact than conventional systems. Developers and building owners can take advantage of the system's small footprint and quiet operation to expand livable space and offer rooftop amenities. Some amenities like rooftop lounges and cafes might offer additional streams of revenue while giving occupants space to rest and enjoy themselves.

CONNECTED FOR COMFORT AND WELLNESS



SOUND LEVELS AND HEARING DAMAGE

2 minutes at 110 dB(A) can potentially damage hearing
Fireworks: 140-160 dB(A)
Sirens: 110-129 dB(A)

14 minutes at 100 dB(A) can potentially damage hearing
Headphones at Max: 94-110 dB(A)

8 hours at 85 dB(A) can damage hearing
Lawnmower: 80-100 dB(A)

Sounds are generally safe at 70 dB(A) and below
Normal conversation: 60-70 dB(A)
VRF Outdoor unit: as low as 56.5 dB(A)
Whisper: 30 dB(A)
VRF Indoor unit: 22 dB(A)

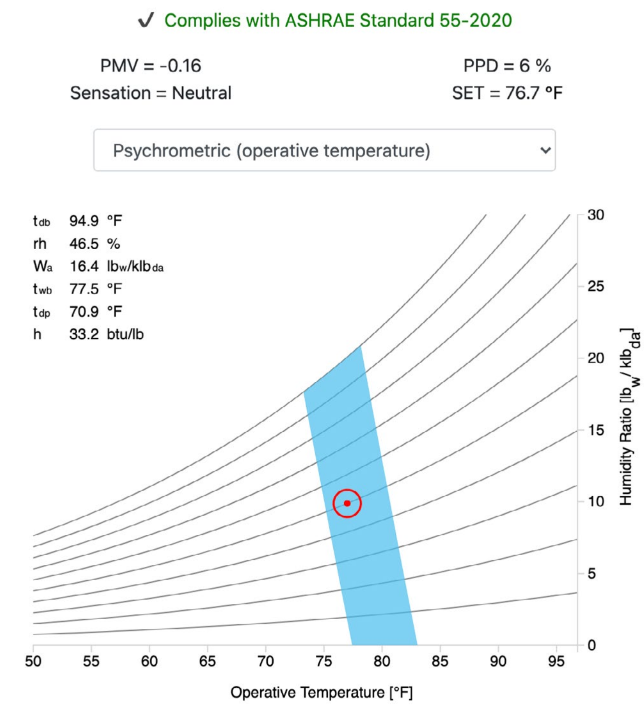
Source: National Institute on Deafness and Other Communication Disorders.

VRF Systems and thermal comfort

ASHRAE Standard 55 and the Predictive Mean Vote (PMV) concept use five factors to help engineers and architects design comfortable environments specific to occupants: operative temperature, air speed, relative humidity, metabolic rate and occupant clothing. Software like the Thermal Comfort Tool developed by the **Center for the Built Environment (CBE)** can help clarify the most comfortable settings for the majority of people. While thermal comfort is subjective, the coworker who always has a blanket is telling us something important about human performance and wellness.

Studies show the impact of thermal comfort on cognition and the implications for schools, offices and any facility where humans learn or work. Researchers from the Harvard T. Chan School of Public Health administered a stroop, or selective attention test, to students in their early 20s during a heat wave. **The test showed a 1 percent reduction in cognitive capacity for every 2° F variation from the preferred set point.**[8] Office workers in another study demonstrated a 4 percent drop in performance when they felt cold and a 6 percent drop when they felt hot.[9]

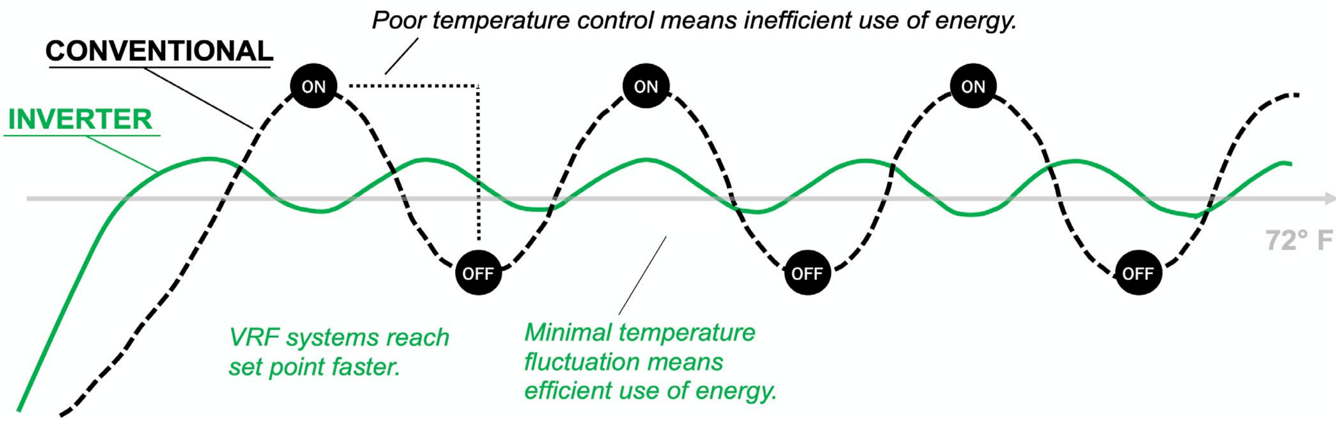
THERMAL COMFORT TOOL



Source: Center for the Built Environment

VRF systems mitigate the challenge of thermal comfort subjectivity with customizable comfort zones and the INVERTER-driven compressor. Each zone can have its own set point based on occupant activities, solar orientation and comfort preferences. Classroom A on the western side of a school can have one set point while Classroom B on the eastern side can have another. The INVERTER-driven compressor varies the VRF system's fan speeds and capacity to match the real-time loads and demand detected by the zone's indoor unit(s) and sensors. As loads change with occupancy, activities and outdoor temperatures, the VRF system keeps pace and maintains the set point using the minimal energy required. This method provides greater energy efficiency and comfort control than the noisy and energy-intensive start/stop cycles of conventional systems. The continuous operation of VRF fans helps maintain a tight deadband of temperature control and eliminate hot and cold spots.

THE INVERTER ADVANTAGE



Air distribution, speed and stratification affect how occupants experience a zone's temperature. If the zone's air is stratified, with cold air at the bottom and hot air at the top, occupants may be uncomfortable. By running continuously, VRF fans distribute air and reduce stratification. Also, continuous movement eliminates the need to blow air at high velocities. Sensors monitor temperatures as the air passes through VRF indoor unit coils, so the system can move the fan at the best rate for optimizing comfort.

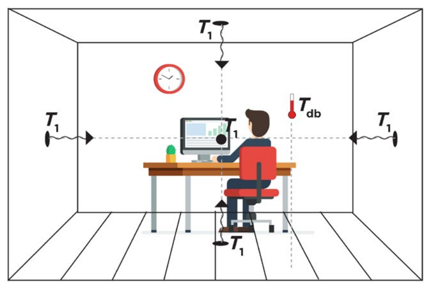
Thermal comfort in any climate

VRF zoning systems operate in temperatures as low as -27.4° F and as high as 115° F. Watch our on-demand webinar **Applying VRF Systems in Cold-Climate Applications** to learn more.

Additional design considerations for thermal comfort

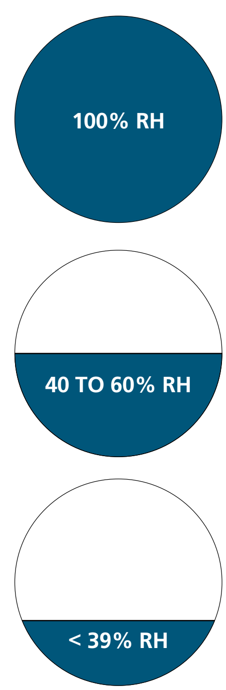
VRF systems effectively maintain dry-bulb air temperatures but designs and settings must also account for factors like mean radiant temperature and humidity when optimizing IEQ.

CONTINUOUS HEAT TRANSFER

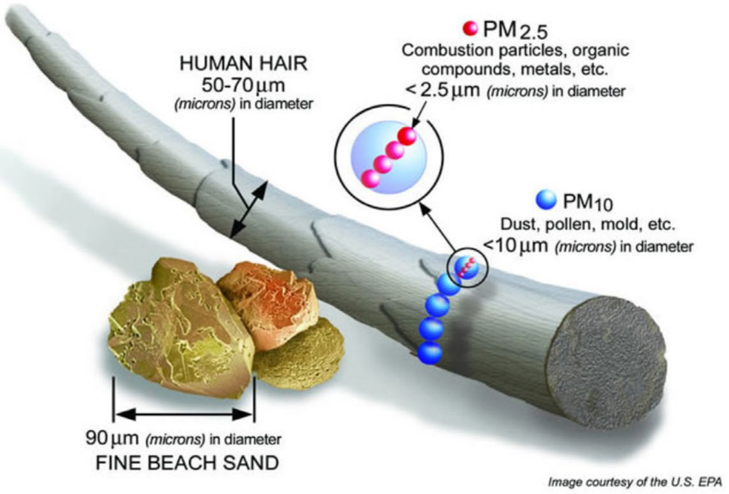


Radiation is the continuous electromagnetic transfer of energy between objects based on differences in temperature. Occupants, objects, surfaces, air and moisture typically have different temperatures, so they continually exchange heat. This heat transfer explains why there can be a difference between the dry-bulb temperature indicated by the thermostat and what an occupant feels. MRT measures the average temperature of surfaces around an object. Engineers and facility managers can use MRT to refine thermal comfort strategies and operation schedules. For example, if a facility (e.g., a school) closes during weekends, facility managers might keep the night-time setback less than 5° F to account for the time needed for heat exchanges. If the facility is too aggressive with the night-time setback (e.g., 8-10° F), the VRF system can bring the air temperature up to the dry-bulb set point (e.g., 72° F) on a weekday morning, but the occupants might still feel cold because the mass in the room (e.g., cinderblock walls, floors, desks, etc.) is still cold. Relative humidity (RH) is the ratio between moisture in a volume of air versus the amount of moisture it could hold at a given temperature and pressure. An RH between 40 and 60 percent, at dry bulb temperatures ranging from 68-75° F, will allow most people to regulate their interior temperatures with minimal sweating to expel heat or shivering to generate heat. ASHRAE 62.1 recommends keeping RH below 60 percent. An RH less than 40 percent can result in dry mucosa, which increases the occupant's susceptibility to respiratory issues.

RELATIVE HUMIDITY



PARTICLE SIZES RELATIVE TO HUMAN HAIR



Human performance and IAQ

Studies have shown how fresh air and high IAQ have positive effects on health, wellness, academic outcomes and overall human performance. ASHRAE Journal published a study in 2006 showing how increasing a school's ventilation rate from 7.5 CFM to 15 CFM per student led to an 8 percent increase in academic performance.[10] Indoor Air Journal published a similar study of fifth grade classrooms in 2011 finding a 3 percent increase in the proportion of students passing standardized math and reading tests for each 2 CFM increase in the ventilation rate across the range of 2 to 15 CFM.[11] Researchers at the Harvard T.H. Chan School of Public Health tracked cognitive scores for workers in an office space with conventional levels of VOC and pollutant exposure versus an office environment with low concentrations and low exposure to VOCs and pollutants. Their 2016 study reported cognitive scores were 61 percent higher when office workers experienced low concentrations of pollutants. When the researchers increased the ventilation rate in the healthier space, cognitive scores scores increased 101 percent compared to the conventional baseline.[12] Studies have also shown the health consequences of poor IAQ. A 2012 study published by Environmental Health Perspectives showed how the presence of PM 2.5, acrolein and formaldehyde caused negative health impacts equal to or greater than estimates for harm caused by secondhand smoke and radon.[13] A 2007 study published in the International Journal of Ventilation found students experienced a 5 percent decrease in ability to pay attention in poorly ventilated classrooms.[14]

IAQ strategies and VRF systems

To achieve high IAQ, contamination control strategies must mitigate contaminants like viruses, bacteria, allergens, dust, PM 2.5 and volatile organic compounds (VOCs). Strategies include source control, elimination, filtration and dilution.

Source control means avoiding building materials and products likely to introduce contaminants (e.g., formaldehyde, other VOCs). In multifamily applications, this may include using all-electric appliances to reduce onsite combustion and indoor emissions.

Elimination can be accomplished with exhaust fans in areas like bathrooms or commercial kitchens.

Filtration removes airborne contaminants and particulates. The Minimum Efficiency Reporting Value (MERV) under ASHRAE 52.2 uses a scale of 1-20 to describe how effectively a filter can capture particles of a given size. For example, a filter with a rating between MERV 13 and 16 can capture particles larger than 0.3 micron. A High Efficiency Particulate Air Filter (HEPA) has capabilities in the range of MERV 17 to 20 and can be expected to remove 99.97 percent of airborne particles as small as 0.3 microns. As pleated filters increase in depth and efficacy, engineers must account for potential pressure drops and slower air movement. Every increase in efficacy comes with performance tradeoffs like a need for greater fan energy. Since April 2020, ASHRAE has recommended using MERV-13 filters or the highest level achievable for non-healthcare buildings.[15]

Fresh outside air dilutes indoor contaminants including occupant CO_2. In an airtight building designed to optimize IEQ, dilution is handled by the ventilation system. VRF systems are purpose-built for heating and cooling but can coordinate the operation of complementary ventilation equipment through controls. Depending on the region and application, the mechanical engineer may recommend an energy recovery ventilator (ERV), dedicated outdoor air system (DOAS) or outside air unit (OAU) to introduce and condition fresh, outdoor air. In addition to diluting contaminants, ventilation systems increase oxygen levels and can help control humidity. All three options are regulated by state and local codes developed from ASHRAE 62.1 and the International Mechanical Code.

ERV

ERV

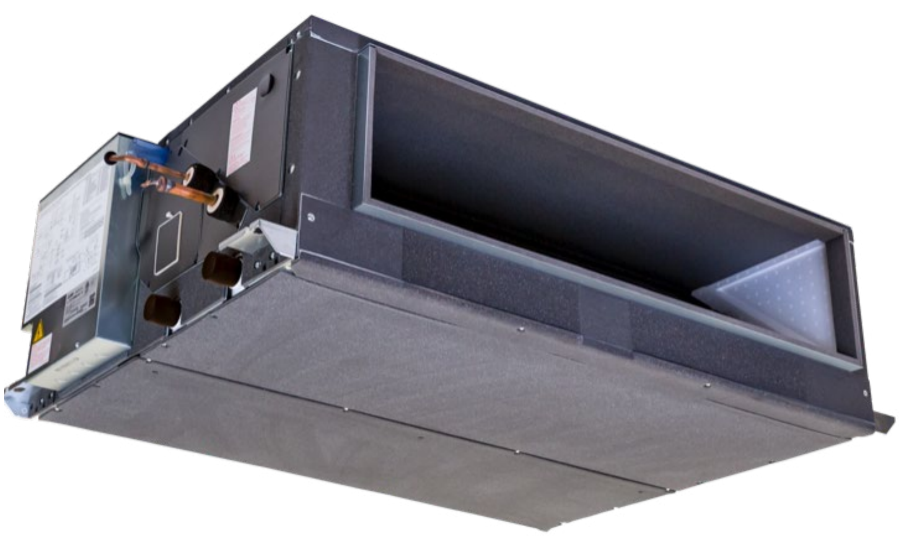
ERVs recover sensible and latent heat from building exhaust air while introducing outdoor air. Heat from the exhaust air tempers a stream of outside ventilation air moving across the ERV's fixed-plate heat exchanger from another direction. By indirectly crossing streams at the heat exchanger, the ERV recovers about 70 percent of the sensible energy and 60 percent of the latent energy. ERVs can offset up to 50 percent of the ventilation air load and are more cost effective than DOAS in moderate and dry climates. Designers must exercise caution when considering ERVs in very cold or humid climates.

DOAS

DOAS

DOAS can condition up to 100 percent of the ventilation air load. Outdoor air enters through one side of a rotating heat exchanger while exhaust air passes through the other side. A DOAS can offset humidity from the outdoor air and also deliver dry air to offset moisture already in the space. Most conventional DOAS have single-speed scroll compressors, but a DOAS with an INVERTER-driven compressor can be up to 25 percent more efficient.

OAU



OAU

OAUs are zoned-ventilation units connected directly to VRF systems like indoor units. Typically, OAUs are used for introducing ventilation air to a zone when ducting the localized exhaust to the ventilation device for heat exchange is a design challenge. The OAU handles incoming ventilation air only and tempers the air with heat recovered from refrigerant. Ideal for zoned ventilation and facilities with diverse outside air requirements, an OAU can deliver 350-1,200 CFM.

Conclusion

IEQ and sustainability are complementary design objectives. Both are functions of enhanced control of building operation and the methods for achieving one supports achieving the other. All-electric VRF systems improve sustainability and IEQ by enhancing control of both thermal comfort and energy use, coordinating IAQ equipment and operating quietly. The public's increased attention to how buildings operate, and impact human beings may give healthy, sustainable commercial buildings a market advantage. For further information on VRF systems and IEQ, consider watching our on-demand webinar.

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