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Optimizing Energy Efficiency and Improved Dehumidification Performance of Variable Capacity Air Conditioning Systems

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ABSTRACT

High-performance homes promote high efficiency, but some of these homes, with very low cooling loads, may have greater challenges in delivering acceptable comfort. This paper discusses challenges and options regarding energy-efficient comfort control in homes with ducted and ductless variable capacity air conditioners based on recent research in occupied homes and house lab tests.

Air conditioners cool and dehumidify. Well-designed homes can usually maintain acceptable temperature, but the likelihood of maintaining acceptable indoor humidity all the time is less certain. This is due to low sensible loads, variability in moisture removal effectiveness of air conditioning, and variability of moisture sources. As a result, some builders and high-performance home programs resort to using dehumidifiers. While dehumidifiers can improve relative humidity control, they present a different set of challenges and may cause significantly higher building energy use than owners expect.

Variable capacity cooling energy savings typically around 20%-30% have been measured compared to fixed capacity systems in controlled house lab study. Research also found that better dehumidification is possible that limits overcooling and energy use. Recent testing of a new variable capacity system measured indoor humidity reduction of up to 15% RH points during low cooling load periods. Optimized variable capacity air conditioners may adequately control humidity at moderate levels without need for supplemental dehumidifiers. Such systems would require less annual space conditioning energy than sub-optimal variable capacity systems that require supplemental dehumidifiers in low sensible load homes. This paper will present research that shows how performance can be optimized, and discuss the importance of considering how cooling performance metrics impact cooling and dehumidification energy use.

Introduction

Based upon SEER ratings, variable capacity (VC) systems offer the highest cooling efficiencies and have good potential for maintaining thermal distribution due to long runtimes. Cooling loads vary hour to hour in homes. VC systems are designed to deliver cooling over a range of capacity which makes them a better match to actual load variability. A VC system varies indoor fan airflow as well as the refrigerant flow designed to operate at more than two distinct cooling capacities. These systems are available as central ducted, minisplit ductless or ducted, and multisplit ducted or ductless.

VC systems have demonstrated good energy savings potential compared to central fixed capacity systems in lab and occupied home studies. An Oak Ridge National Lab study reported cooling savings of a ducted VC system of 41% in comfort mode and 44% in efficiency mode compared to a fixed capacity (FC) system (Munk et al. 2014). Another residential lab controlled study of 10 various test configurations measured cooling energy savings ranging from 19%-44% of ducted SEER 21/22 VC compared to a SEER 13 FC ducted system (Cummings, Withers, and Kono 2015). These ten tests were performed in a lab home without ASHRAE 62.2 ventilation with tight air ducts. The savings depended upon SEER, duct location, and system sizing. In another controlled lab study, with building leakage of 5 ACH50 and ASHRAE 62.2 mechanical ventilation, a ducted SEER 22 system had annual cooling savings of 22% and a supplemental SEER 21.5 ductless minisplit configuration had savings of 33% compared to a ducted central SEER 13 system (Withers 2016a). Testing with ASHRAE 62.2 ventilation was important due to the potentially high amount of moisture transported into homes during warm moist conditions that pose even greater challenges in controlling indoor humidity and increase energy use.

A field study of ten Florida homes measured cooling energy savings from adding high SEER supplemental minisplits to homes with existing central ducted air conditioners. The concept of supplemental minisplit conditioning is a practice that allows a very high SEER minisplit to be added to an existing home with existing older central ducted air conditioner. The minisplit is placed in a central living area and operated at 2-3°F cooler than the central system thereby shifting initial cooling loads to the higher efficiency system. The central system is used with a fan cycle control to circulate air and provide additional cooling as needed. Some new homes are even being built with ducted and ductless minisplits. The ten Florida retrofits had median cooling savings of 33% with a range from 2%-46% energy reduction (Sutherland, Parker, and Martin 2016). Other work evaluating field installed ductless minisplits claim reasons for a large range in measured savings can be due, in part, to occupant behavior over operation or operation under conditions much different than the American National Standards Institute (ANSI) / Air-Conditioning, Heating, and Refrigeration Institute (AHRI) rating procedure (Walczyk and Larson 2016). This work found that some occupants may treat the system more like an appliance turning it on and off as desired instead of leaving it on at a specific setpoint which can diminish savings potential.

While VC systems have shown good potential for energy savings, it is clear that they need better humidity control during warm moist weather in mechanically ventilated homes especially those with high internal moisture generation. There are various factors that could impact RH such as occupant variable loads, amount of mechanical ventilation, dehumidification performance of air conditioners, and occupant operation of equipment. Indoor RH can vary widely as the following studies illustrate. Periods of elevated indoor RH were observed in four new field study Habitat for Humanity homes solely cooled using mini and multisplit systems without supplemental dehumidification. The occupied homes exhibited indoor hourly average RH exceeding 60% an average of 61% of the time (range 11% to 86% frequency) (Martin et al. 2018). Another study of two homes in Austin, Texas found significant increases in humidity with 50% frequency or greater of hours with RH greater than 60% after central ducted systems were retrofitted with minisplit systems (Roth, Sehgal, and Akers 2013). Research in a house lab with ASHRAE 62.2 ventilation found a supplemental minisplit system test without supplemental dehumidifier resulted in average indoor RH exceeding 60% between 4%-15% of the test hours depending upon the room (Withers 2016b).

High-performance low cooling load homes can be challenged to maintain indoor RH below at least 60% many hours of the year. High performance homes can have improved thermal distribution, but may have decreased comfort and higher potential for moisture issues due to inadequate RH control. Air conditioning alone is challenged due to lower runtimes not just during cooler days, but also during overnight periods of hot weather. A supplemental dehumidifier is then needed where tighter control of indoor RH is required.

Supplemental dehumidification works generally well to ensure RH control, however it adds another appliance that must be maintained and can use a substantial amount of energy. On the higher end of use, dehumidifier energy in mechanically vented homes during hot-humid weather can be about 10 kWh/day representing about 49% of the cooling and dehumidifier energy use (Ruud, Lstiburek, and Ueno 2005). Accounting for the energy required for supplemental dehumidification is very important and may represent a significant amount of space conditioning energy. High performance homes being rated without accounting for dehumidifier energy in cases when it is needed may explain higher than expected energy use. One simulation indicated an energy increase of 2MBtu/year associated with a Building America Benchmark home with a dehumidifier set at 60% RH compared to one without supplemental dehumidification and higher RH (Kerrigan and Norton 2014).

Why Variable Capacity Systems May Have Poor RH Control

It helps to understand a little more about air conditioning performance to understand why some air conditioners have better RH control than others. The cooling load is made up of sensible (dry air-temperature controlled) and latent (heat content of moisture in air). The ratio of sensible load to the total cooling load is called the sensible heat ratio (SHR). Air conditioners have a rated SHR at very specific conditions, however the actual SHR varies depending largely upon the conditions entering the evaporator coil. A review of different manufacturer extended performance data tables show that air conditioners have high SHR when entering air is relatively cool and dry. Operating the system with a very cold coil will also lower SHR and improve moisture removal. This is primarily done by lowering the airflow through the evaporator coil at a specific amount of delivered cooling. Airflow is measured in cubic feet per minute (cfm) and the cooling capacity measured in tons which results in a metric known as cfm/ton. Conventional FC systems are rated at about 400 cfm/ton. VC systems can vary typically anywhere from about 180 up to about 650 cfm/ton.

The SHR performance of AC varies depending upon entering coil conditions, but many systems have SHR around 0.75 at rated condition of entering air at 80°F, 67°F wb, 95°F out. This means that 75% of the cooling goes towards lowering the air temperature and 25% removes water vapor from the air discarded as condensate. There can be more variability of SHR among VC systems. This will depend upon entering coil conditions and may also depend upon the cooling stage. Some VC systems have very high SHR at their highest EER, which means very little dehumidification occurs at that specific operational level. If a VC system only operates based on thermostat control, the sensible load is matched and system runs at the various stages for several hours and eventually cycles off before over-cooling. While long run-time is generally beneficial for improved dehumidification, some VC are doing so at low cooling stages with relatively warm coils (higher cfm/ton) resulting in supply air temperature (SAT) around 62°F and high SHR. This results in poor dehumidification and elevated indoor RH due to internal and external sources of moisture that can only be removed by dehumidification. Another challenge is that even if SHR is relatively low, around 0.65, the rate of moisture removal is low when operating at very low cooling stage. For example, during overnight periods a VC system operating with SHR=0.65 delivering a total cooling rate of 3,000 Btu/h has a latent cooling rate of 900 Btu/h. This is about 0.9 lbs/h (about 0.9 pints/h) water removal. This may not seem too bad until you consider that continuous mechanical ventilation delivered at 60 cfm with outdoor condition of 72°Fdp, is delivering water vapor that must be removed at a rate of about 2 lbs/h This rate does not include internal moisture generation which may be assumed to be around another 0.5 lb/hr on average (Rutkowski 2006), but can vary widely depending upon the number of occupants and behavior.

Figure 1 shows that warmer SAT during economy mode cooling result in higher indoor RH under certain circumstances (Withers 2016a). This data is from a minisplit VC unit that had about 250 cfm/ton during the coldest SAT and about 500 cfm/ton during the warmest SAT. An economy mode is designed to tolerate slow increases in room temperature within limits above cooling set-point and during low load periods run the compression cycle at minimum rates. This mode results in warmer coil temperatures at low load than fixed capacity systems. The data shown occurred during a warm moist period in September in a house lab with ASHRAE 62.2 mechanical ventilation.

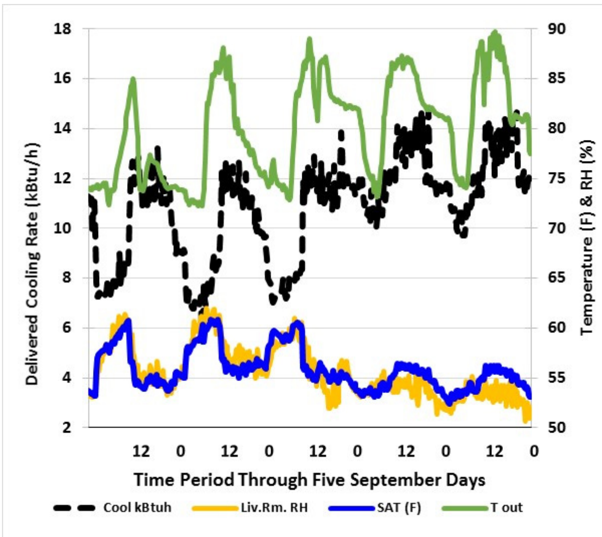

Figure 1. Economy mode cooling performance and indoor RH.

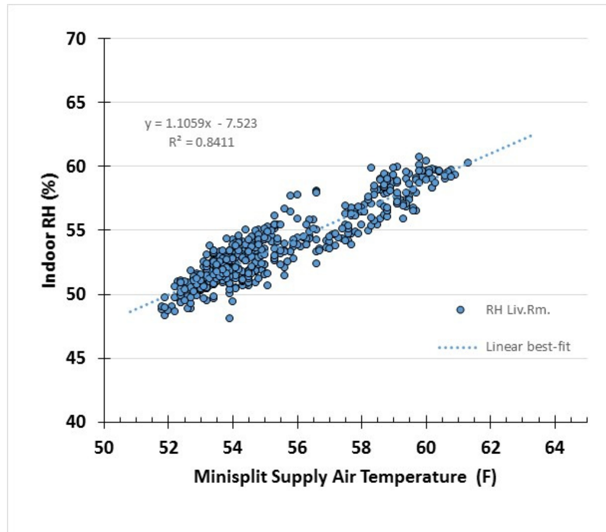

Figure 2. Indoor RH vs SAT of SEER 21.5 minisplit in research house.

There was a clear trend of indoor RH following the cold SAT (yellow and blue lines respectively). The warmest SAT can be seen occurring during the lowest delivered cooling capacity. These periods occur overnight and are also when the system SHR would tend to be higher than during the coldest SAT. Figure 2 shows the indoor RH vs supply air temperature during about the same period shown in Figure1. There is a good correlation of indoor RH to SAT in this controlled house lab experiment. Indoor temperature and RH were measured next to the thermostats on an interior wall in an open central living room. The data shown represent 15 minute average periods of samples taken every 10 seconds when only the minisplit was operating. Operating the minisplit in the standard or "dry" control mode limits the higher SAT and improves humidity control, but not enough to avoid indoor RH increasing above 60% during overnight summer periods. Figure 2 suggests that this minisplit should operate with SAT no higher than 57°F for good humidity control under the tested lab and weather conditions. Results from Figure 2 illustrate the important impact SAT has on indoor RH. A colder coil removes more moisture and helps lower indoor RH as long as the space is not overcooled. The results from Figure 2 pertain to a specific air conditioner with specific sensible and latent loads. This should not be used to predict RH in other homes under different circumstances.

Results from a SEER 14 SDHV Variable Capacity System

A new VC heat pump product called the iSeries by Unico was tested to evaluate cooling and dehumidification performance. It had AHRI ratings of 14 SEER and 8.35 HSPF. This system used a split DX design that can be used with indoor ducted and/or ductless units. The system was tested using the Unico indoor unit designed for small duct high velocity air distribution (SDHV) and outdoor inverter driven heat pump. SDHV systems use ducts that are much smaller than conventional ducted systems. The small ducts allow them to be more easily installed inside the conditioned space cavities reducing conductive gains/losses associated with installations in vented attics.

The SEER14 VC system tests were performed in a highly instrumented laboratory house also used in prior research to examine the relative performance of ducted FC (SEER 13), ducted VC (SEER 21), and supplemental minisplit (SEER 21.5) heat pumps (Cummings, Withers, and Kono 2015), (Withers 2016b). The research house is a 1600 ft^2 double-wide manufactured home built to Energy Star home standards in 2002 with a sealed crawl space, a vented attic, three bedrooms, and two bathrooms. It is located in Cocoa, Florida. The SEER14 VC test was performed with the ducts indoors.

Automated internal sensible and latent cooling loads were implemented and mechanical ventilation was provided in accordance with ASHRAE 62.2-2013, based on a measured airtightness of 5 ACH50. The mechanical ventilation was through a constant supply delivered into the utility room near the central return. The design cooling load of the house lab was 18,200 kBtu/h with indoor central ducts. Internal sensible loads had a daily average approximately 3,400 Btu/h with approximately 10 pounds of daily internal latent moisture generation.

The tested system had a rated cooling capacity of 29,200 Btu/h and heating capacity of 35,200 Btu/h. The variable cooling capacity could drop to as low as approximately 2,900 Btu/h, making it well-suited for very low-load periods. The system was designed for relatively lower cfm/ton of cooling which resulted in cold SAT. As pointed out earlier, operating a colder coil improves dehumidification which is why this system had very good dehumidification.

As in testing of previous systems, a data collection system recorded HVAC performance, internal load energy, and indoor and outdoor conditions. Greater testing details can be found in (Martin et al. 2018).

Energy Comparisons With Supplemental Dehumidifier at 60% RH

Daily total space-conditioning energy was plotted against the daily average temperature difference between the outside and inside, as shown in Figure 3. A least-squares regression analysis was completed with available data and best-fit lines. The most obvious result is how the SEER 14 VC dry mode daily energy was nearly the same as the SEER14 VC standard mode at daily average dT more than approximately -1°F. This was expected because dry mode was designed to move into standard mode performance during high cooling loads.

The significant increase in SEER 14 VC dry mode energy at low dT is also shown in Figure 3. Most of this used more energy than necessary to control RH during the coolest weather since RH was below 60%. This can be explained by the way the dry mode control algorithm was designed. The iSeries unit did not have an RH sensor, operating solely on interior temperature and the temperature set point. At very cool temperatures, the dry mode energy became constant because of a timer-based control at the dry cool level of the lowest cooling output. The dry mode allowed serious over-cooling. The cycle-off set point was reported to be 50°F. This excessively low shutoff point was pointed out to the manufacturer. Significant overcooling no doubt wasted energy not needed to dehumidify dry air and can increase potential building degradation from condensation on overcooled building surfaces under certain conditions. The manufacturer responded and quickly provided a firmware upgrade for the dry mode that increased the timer-based cooling cycle time compared to the previous version and also created a control based on a minimum room temperature limit associated with the set point temperature instead of an absolute indoor 50°F setpoint cut-off. When the room air temperature increased to more than the set point, the system began to operate in the normal cooling mode, thus the dry and standard energy converged at higher dT (warmer weather). Adding an RH sensor and incorporating a control sequence that transitions the system out of lower efficiency RH control mode into higher efficiency operation when RH is at desirable condition could help decrease energy use of this and other cooling systems.

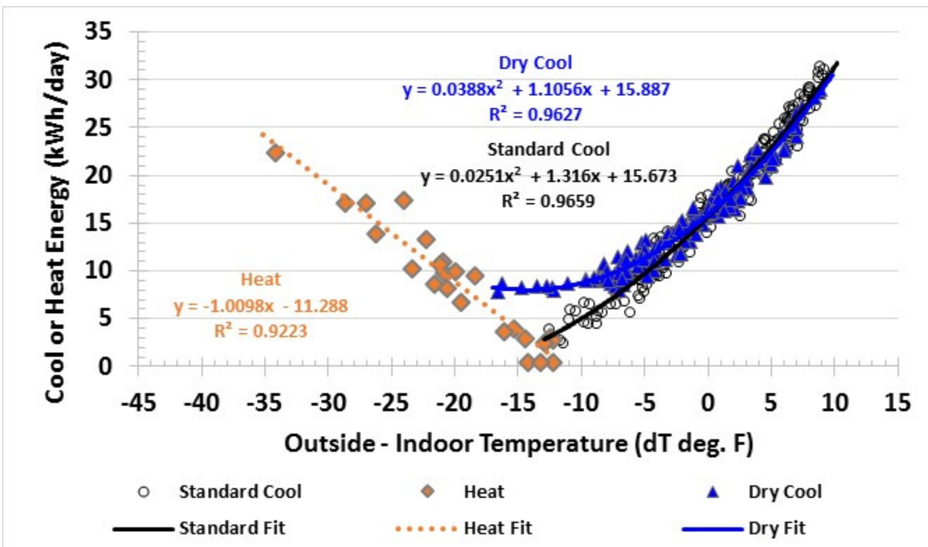

Figure 3. Heating and cooling energy use of SEER14 VC system before improved dry mode modifications.

Figure 4 compares four different system cooling tests completed in the same lab with the same internal load configurations across variable outdoor weather conditions. The minisplit & SEER 13 test was a supplemental SEER 21.5 1.25 ton capacity minisplit run as primary system with SEER 13 central ducted system used as backup cooling and fan cycled on 20 minute intervals to distribute airflow. The SEER 22 Dry Cool test was a ducted central 2 ton VC heat pump operated in the dry cool mode which is intended to improve RH control. This system had an RH sensor integrated thermostat control. The SEER 13 fixed capacity system was a central ducted system with only temperature-based control. The SEER 14 VC system was a SDHV system operated in the standard cooling test mode. This system was designed for improved dehumidification. Each test had supplemental dehumidifier set at 60% except for the supplemental minisplit test. This test was intentionally run without a dehumidifier to be able to see how high interior RH might rise.

The energy use shown in Figure 4 includes cooling and dehumidifier energy. With a humidity setpoint of 60% RH, there were many days with no dehumidifier operation and those days with dehumidifier operation typically represented less than 5% of the total energy shown so the energy shown is nearly all cooling. Figure 5 shows an example of relatively how little dehumidifier energy was used compared to cooling energy with the SEER14 VC iSeries system.

In the 188 standard cool test days, the dehumidifier operated only 12.7 hours out of 4,512 hours (0.28%). Dehumidifier operation occurred 27 days out of 188 days, or 14.4% of test days. Previous testing of other cooling systems under test conditions (Withers 2016b) similar to those of the iSeries testing indicate low dehumidifier runtime of 2% of the hours tested during summer conditions with an RH control setpoint of 60%. Although this represents low dehumidifier energy use, average indoor RH was still higher than with the SEER 14 VC system.

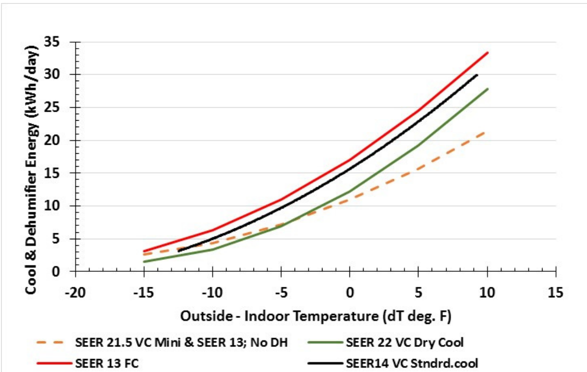

Figure 4. least-squares regression best-fit lines shown for 4 different cooling systems.

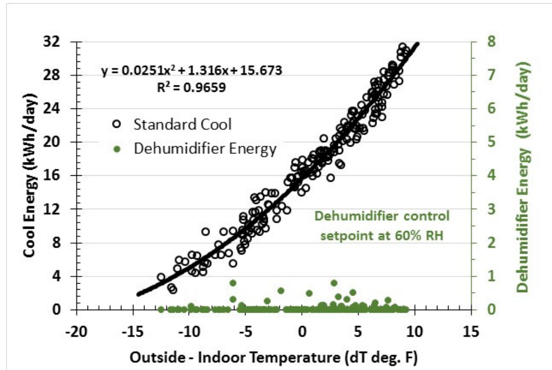

Figure 5. SEER14 VC standard cool energy shown separate from dehumidifier energy.

Least-squares regression analysis was used with TMY3 data for Daytona, FL to predict annual space conditioning energy use. Annual energy projections are summarized in Table 1 with indicated savings relative to a fixed capacity SEER 13 system. The ducted SEER 13 and SEER 22 tests were only available with attic duct configuration during ASHRAE 62.2 mechanical ventilation testing periods. While these tests were conducted with attic ducts, previous test data evaluated the impact of moving ducts to indoors (Cummings, Withers, and Kono 2015). New work using this past data found an annual reduced cooling energy by 10% for the SEER 13 FC and 13% for SEER 22 by moving these ducts indoors in this lab while meeting ASHRAE 62.2 ventilation standard. Table 1 values reflect annual energy adjustment to indoor ducts for tests in the residential test lab with 5 ACH50 air tightness mechanically ventilated to ASHRAE 62.2.

Table 1. Predicted annual cool and dehumidifier energy for 4 equipment tests with supplemental dehumidification set @60% RH, except minisplit, which had no supplemental dehumidifier

Test configuration	Annual kWh	Annual savings kWh/yr.	Annual savings %
Indoor ducted SEER 13 FC	4338	---	---
Indoor ducted SEER 14 VC	4109	229	5.3%
Indoor ducted SEER 22 VC	3256	1082	24.9%
Ductless SEER 21.5 supplemental minisplit; economy mode	3224	1114	25.7%

A select group of days having similar outdoor typical summer conditions were chosen to look at resulting indoor conditions. The indoor results are shown in Table 2 along with average daily cooling and dehumidifier or minisplit runtime, and the number of days used in the comparison. The table shows very similar outdoor conditions and similar indoor temperatures, but differing levels of indoor RH and absolute moisture shown as dewpoint temperature (Tdp) and also as grains of moisture. The data show the SEER 14 VC system had the lowest indoor RH that was about 7% RH lower on average than the two tests using SEER 21.5+ systems. Note that longer-term testing with lower sensible loads than represented in Table 2 will have higher indoor RH averages. As an example, hourly average data during low load periods showed that the SEER 14 VC had indoor RH around 47% RH and SEER 21.5 minisplit in economy mode (with no supplemental dehumidifier operation) had indoor RH at 62% (15% RH points higher).

The drier air resulting from better latent performance from the SEER 14 VC system is important to consider when comparing cooling energy based on sensible dry-bulb temperature control. Part of the extra energy used by the SEER14 VC system had been used to remove moisture, but the energy comparisons to higher SEER equipment in this paper so far have not accounted for this. The implications of space cooling plus supplemental dehumidifier energy become even more important at lower RH set points.

Table 2. Comparison of indoor and outdoor conditions, and conditioner runtime during similar outdoor hot humid weather

Test configuration	Tout (°F)	Tdp out (°F)	House avg. T (°F)	House avg. RH (%)	House avg. Tdp (°F); grains	Central AC runtime (% of day)	DH or MSHP runtime (% of day)	# Days
Ducted SEER 13 FC	80.1	70.2	76.8	48	55.5F; 65.8gr	57.2	0.0	6
Ducted SEER 14 VC	80.6	71.3	76.6	44	55.1F; 60.2 gr	72.1	0.2	5
Ducted SEER 22 VC	80.2	71.9	77.2	51	57.6F; 71.2 gr	78.6	0.9	8
Supplemental minisplit economy mode; no DH	80.0	71.1	77.5	52	58.7F; 73.9 gr.	9.2	95.0	10

Low SEER/Good RH Control vs High SEER/Fair RH control

While each of the VC systems discussed had different coil and air distribution designs, they all varied refrigerant flow and air flow through an evaporator coil. The cfm/ton most significantly impacted latent performance. The Unico SEER 14 VC testing demonstrated how lower cfm/ton in VC Systems can be used to maintain very good humidity control. The tested SEER14 VC system operated around an average 280 cfm/ton in standard cooling mode during low cooling load period, much lower compared to a tested SEER 21.5 VC minisplit system that operated around 466 cfm/ton. This same minisplit system had 4% RH lower indoor RH when it operated at 328 cfm/ton. The tested central ducted SEER 22 system operated at 650 cfm/ton at its lowest capacity, but tended to operate more around 549 cfm/ton on average. It was surprising that this particular system did not have higher indoor RH with such a high average, but it is believed the periodic swings much lower than this helped RH control.

Simply comparing cooling energy based solely upon indoor temperature can be inadequate. The previous tests presented were completed with conservative dehumidifier setpoints of 60% RH and one SEER 14 VC system maintained indoor RH about 8% RH lower than two other SEER 21+ systems (21+ refers to SEER 21 or higher). What if the tests were run again with about 50% RH setpoints to result in indoor conditions much closer to the long-term average indoor RH during SEER 14 VC iSeries test? It is expected that significant increase in dehumidifier energy and resulting waste heat into space increasing air conditioning could significantly diminish the total space conditioning energy savings between SEER 14 VC and

SEER 22 systems. No published controlled testing of such work has been able to be found at this time. A basic simulation was run to consider the merit of such testing.

Simulation Result

An annual simulation was completed to get a better idea of what the cooling, heating, and supplemental dehumidifier energy might be at different RH setpoints. The challenge is that, without details about actual air conditioner and dehumidifier dehumidification performance, the dehumidifier results can be very different from reality. The purpose of this simulation work was not to simulate using actual detailed performance curve data, but to see if a lower rated efficiency heat pump with good dehumidification performance might use less total annual space conditioning energy than a higher efficiency heat pump with perhaps typical dehumidification performance. SEER 14 VC system test results show it did not need a dehumidifier to maintain at least 60% RH if Dry mode could be used only as needed. This system also resulted in much lower humidity levels than previously tested SEER 22 system such that it may be able to maintain RH at 50% without supplemental dehumidification with some minor control modification.

The simulations used EnergyGauge USA v5.1.01 with the research house lab attributes. Seven simulations were run with a SEER 22 heat pump and supplemental dehumidifier rated at 70 pints/day and energy factor of 1.85 L/kWh. Each simulation was run by only changing the dehumidifier RH setpoint. Figure 6 shows an example of space conditioning energy use simulated for the house test lab. A separate simulation was run for a SEER 14 without supplemental dehumidification with the assumption that none would be needed for an optimized SEER 14 capable of maintaining indoor RH at no greater than 50% all hours of the year.

The simulations do not account for specific performance data such as variability in total cooling output and SHR under different conditions. An average SHR of 0.76 was used for each cooling system simulation. Dehumidifier energy would be greater than indicated if actual SHR is higher. This is possible since very high SEER equipment tends to have higher SHR under specific test conditions as indicated in manufacturer performance data. Likewise dehumidifier energy may be less than indicated in Figure 6 if SHR operates lower than the simulation assumption.

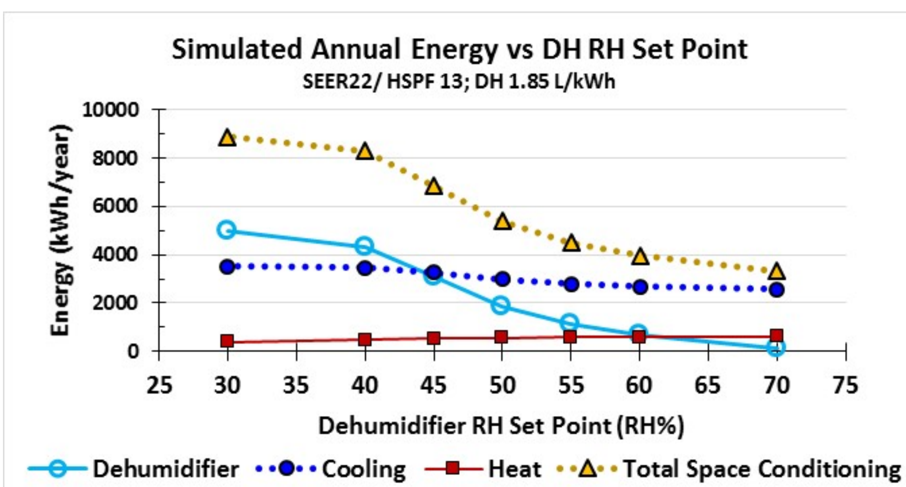

Figure 6. Simulated space conditioning energy with SEER 22 heat pump and dehumidifier.

It is important to note that simulation work shows that dehumidifier energy increases rapidly as the dehumidifier RH setpoint is lowered. In Figure 6, the dehumidifier energy increased noticeably from 60% RH down to 40% RH setpoint. The dehumidifier uses more energy than the cooling at a low RH setpoint of 40% and represents 44% of total annual space conditioning energy use. A lower RH setpoint of 50% shows the dehumidifier uses about 35% of the total annual space conditioning energy. Another key point is that heat from the dehumidifier increases air conditioning load and annual cooling energy increases as RH setpoint is dropped.

The most striking thing is that lower rated SEER air conditioning systems that provide much better dehumidification may actually result in lower total house space conditioning (heat + cool+ dehumidifier) than higher efficiency air conditioners. Simulation results with RH set at 50% are compared in Table 3.

Table 3. Simulated Annual Space Conditioning Energy in House Lab for SEER 22 Heat Pump With a Supplemental Dehumidifier and SEER 14 Heat Pump Presumed to Not Need Dehumidifier to Maintain 50% RH

Test configuration	Heating kWh	Cooling kWh	Dehumidifier kWh	Total kWh
SEER 22, DH @50%RH	549	2978	1875	5402
SEER 14 with excellent RH control; no DH	818	3556	0	4374

The tested SEER 14 VC iSeries system was able to maintain an average indoor RH of about 47% during all testing with some excursions between 50%-55% RH. If a Dry mode is activated only as needed and SHR could be dropped more in the lowest cooling stage, it is expected that no dehumidifier would be needed to maintain about 50% RH all hours of the year. When the simulation was performed for a SEER 14 system and no dehumidifier, the total annual space conditioning energy use was only 4,374 kWh. If this can maintain at least 50% RH all hours of the year without supplemental dehumidification, it indicates that the lab house with SEER 22 heat pump and a supplemental dehumidifier set at 50% RH may use about 5,402 kWh/yr. This is 1,027 kWh/yr (23%) more annual energy than the SEER 14 simulation that assumed no dehumidifier was needed.

Limited Test Comparison Between SEER 14 ducted VC vs SEER 21.5 Minisplit

An ideal experiment to run would be to compare the SEER 14 VC iSeries central indoor ducted system to a SEER 22 VC central indoor ducted system with each test having a supplemental dehumidifier controlled at 50% RH. The SEER 22 ducted system tested in a past project had been removed to make room to install the SEER 14 VC system, therefore this test was not able to be run. In order to at least explore if a SEER 21+ system would require substantial increases in supplemental dehumidifier energy at a lower RH setpoint, the existing ductless minisplit with rated SEER 21.5 was used in the research house lab with same internal loads and ventilation as previous tests with dehumidifier set at 60% RH.

The SEER 14 VC and SEER 21.5 minisplit systems were run in the standard cooling mode setting with a supplemental dehumidifier controlled at 50% RH. As in other tests the minisplit was set to provide primary cooling and a central SEER 13 ducted system was able to provide back-up cooling if needed. It was also used to distribute air around the home. To avoid complications of lower SEER central unit impacting comparisons, only days were used where the central SEER 13 unit did not provide cooling. Since the minisplit was not sized to meet the design cooling load, it is not the best test, but was able to demonstrate that higher SEER with fair RH control can require substantial amounts of dehumidification energy compared to lower SEER systems with better dehumidification.

A least-squares regression analysis was performed for both tests. Due to limited capacity the minisplit data does not go to dT as high as other tests. It includes warm moist days, but not the hottest summer type days. Since this data set is limited and system was undersized it should not be used to project annual energy predictions. Is useful for preliminary investigation and discussion particularly within the range of conditions for which data are shown. Figure 7 shows the results. A third data set taken from previous testing shows the supplemental minisplit results for when the minisplit was operated in economy mode with no supplemental dehumidification. This is only shown to demonstrate on this plot how much difference control modes and electing to not use a dehumidifier may have. What is not seen on this plot is that the supplemental minisplit with no dehumidifier had much higher resulting indoor humidity.

Figure 7 clearly shows that the SEER 21.5 minisplit test used more cooling and dehumidifier energy at lower dT than SEER 14 VC system test and would appear to use less at warmer outdoor conditions as dT becomes greater than -1.1°F. It was expected that a SEER 22 system would begin to use less cooling and dehumidifier energy at warmer temperatures as sensible load results in longer runtime or pushes VC into higher capacity resulting in increased moisture removal and less dehumidifier runtime. Dehumidifier energy becomes a smaller fraction of the total. So at design conditions a SEER 22 system with fair to poor dehumidification may appear to use less total energy, but could be missing what happens during the rest of the cooling season hours.

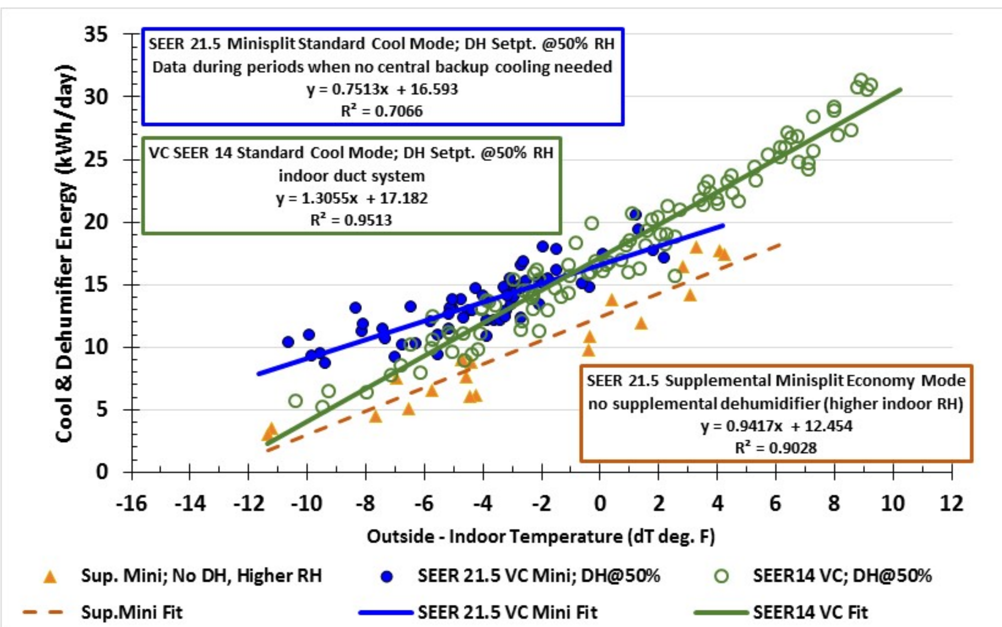

Figure 7. Cooling and dehumidifier daily total energy versus daily average temperature difference.

Table 4 shows a breakdown of daily cooling and dehumidifier energy for dT = -1.1 (about 75°F out; coincidently annual out avg. in S. Florida). This the point at which each system appears to use the same amount of daily total cooling and dehumidifier energy (15.8 kWh/day). However it is important to note, that while space cooling energy of the SEER 14 VC unit used about 4.5 kWh/day more (29.7%) than the higher SEER unit, the SEER 14 VC iSeries system required 86% less dehumidifier energy for dT at -1.1°F. The main point to be learned here is that one must consider cooling and dehumidifier energy in appropriately ventilated homes that occur during warm and humid weather. Since the SEER 21.5 unit was not sized to meet a design load, annual energy savings estimates are not calculated, however it is a successful demonstration in how homes with SEER 21+ systems can have severely diminished energy savings.

Table 4. Tested Results of Daily Energy at dT= -1°F With Dehumidifier Setpoint @ 50% RH

Test configuration	Total cooling + DH energy kWh	Cooling kWh	Dehumidifier kWh	Dehumidifier energy as % of total Cool+DH
Ducted VC SEER 14	15.80	15.07	0.73	4.6%
Ductless minisplit SEER 21.5	15.80	10.59	5.21	33.0%

Optimizing Energy Efficiency and Moisture Control in Variable Capacity Cooling Systems

At this time, there is no known residential air conditioning unit on the market that optimizes effective humidity control with SEER 21+ energy-efficiency during warm moist weather in low load homes. However, this author believes manufacturers can improve control algorithms of their respective products to operate at the highest efficiencies in standard cooling mode and very good RH control (RH below 60% all hours) in humidity control modes as needed.

The optimum VC air conditioner should prioritize energy-efficient sensible-based control in the standard or economy cooling modes. When RH control is desired, the system should have a humidity sensor integrated with a humidity control mode option that prioritizes indoor RH settings and limits overcooling to no more than 3°F of temperature setpoint. To improve efficiency, the RH control mode should allow the system to move into the standard cooling mode whenever humidity drops about 5% RH below the cooling system RH setpoint.

During humidity control, the system should be able to operate through all stages of cooling as load requires and be able to sustain long runtime during the lowest stage of cooling. The supply air temperature should be as cold as the design permits without frosting the coil and be no warmer than 55°F. It is important that the SHR be as low as possible, especially during the lowest stages of cooling in RH control modes. Low SHR is acquired by operating at low cfm/ton. Consider this example; A low stage of about 3,500 Btu/h total capacity with SHR of 0.55 would have a latent capacity of 1,925 Btu/h. This is close to the amount needed to remove the moisture load from continuous whole-house mechanical ventilation at about 60 cfm during summer conditions (Tout dp 72°F). This should be reasonably effective during overnight low-load periods. It may not keep up with all latent load overnight, but could be effective enough. As daytime heating and internal loads increase through the day, total and latent capacity increase, thereby removing internal and external latent loads faster than they are being generated. This can help make up for some overnight latent net gain.

Summary

Variable capacity air conditioner performance based on lab and field study in hot humid climate regions has been discussed with an emphasis on energy use and indoor RH in homes mechanically ventilated to ASHRAE Standard 62.2-2013. Mechanical ventilation is an important distinction since this may represent four times the moisture load than internal sources during hot humid weather. Variable capacity systems have demonstrated good cooling energy savings potential and fair moisture control most of the time, however supplemental dehumidification energy must also be considered, not just space cooling energy.

Preliminary hourly annual space conditioning (heat + cool + dehumidifier) energy simulation work and lab house testing showed that dehumidifier energy increased substantially as the RH setpoint was lowered from 60% RH to 50% RH. At dehumidifier settings 60% RH or higher, there is much less dehumidifier energy and annual space conditioning savings from SEER 21+ systems are more as expected. It was demonstrated that SEER 21+ systems may have severely diminished cooling and dehumidifier energy savings compared to SEER 14 VC systems that require little or no supplemental dehumidification at 50% RH or lower. Future research needs to run annual hourly simulations using known dehumidifier and air conditioning performance models. The SEER 21.5 VC vs SEER 14 VC with dehumidifier set at 50% RH test presented in this paper could not be run during the hottest weather conditions since the SEER 21.5 unit was undersized for a design day. It was appropriate to represent about 80% of the cooling season for homes in hot/humid climate zones. It clearly demonstrated significant periods of higher cooling + dehumidifier energy with a SEER 21.5 VC system than with a SEER 14 VC having better RH control. This was demonstrated for days with average outdoor temperature of 75F or cooler. Future lab test research is needed to compare an appropriate sized SEER 21+ VC system with supplemental dehumidifier that can be tested from low load up through design day weather conditions.

VC systems have more potential to improve energy-efficient comfort control. The most-efficient systems required supplemental dehumidification to maintain indoor RH below 60% as was seen in field studies and controlled lab tests. Lab controlled testing has demonstrated that SEER 21+ systems have been shown to save cooling energy when compared to lower SEER systems maintaining the same indoor temperature, but have higher indoor RH. Many SEER 21+VC systems have RH control modes that improve moisture removal, but these still need improvement and are not adequate to maintain indoor RH below 60% without supplemental dehumidification.

One SEER 14 VC system was tested and demonstrated the ability of VC systems to be able to deliver good humidity control by maintaining cold SAT when running at lower cfm/ton over a variety of weather conditions. Data was also presented from a SEER 21.5 VC minisplit that showed good correlation of indoor RH to SAT. A strategy for optimizing cooling, improved dehumidification, and energy efficiency has been presented. The results and discussion within this paper have been presented to demonstrate that RH control cooling modes of variable capacity air conditioners can be improved primarily by operating at the lowest cooling stage with the lowest SAT and cfm/ton possible during low load periods. RH control modifications to standard cooling modes are not recommended as this would lower efficiency when RH control is not necessary.

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