Making the Case for Oversizing Variable-Capacity Heat Pumps

James B. Cummings and Charles R. Withers, Florida Solar Energy Center

ABSTRACT

Oversizing of fixed-capacity (FC) heat pumps and air conditioning (A/C) systems is understood to reduce space conditioning energy efficiency, and is not permitted or at least severely restricted by various standards, state codes, and programs. Central ducted variable-capacity (VC) systems capable of delivering ~40%-120% of nominal capacity are available, promising high cooling and heating efficiency. Lab house experiments found that Nordyne iQ Drive 2 and 3-ton VC heat pumps are 43% more efficient at lowest capacity versus full nominal capacity (which is ~86% of maximum capacity) and 64% more efficient at lowest capacity versus maximum capacity. Analysis of two years of lab house data found that the 3-ton VC system consumed less cooling and heating energy, and had reduced peak demand, compared to the right-sized 2-ton system. By contrast, oversizing the FC heat pump generally yielded higher seasonal and peak energy consumption. Experimental data also suggest that concerns about the ability of oversized cooling systems to control indoor relative humidity (RH) are overblown.

This paper presents results that support right-sizing for FC but oversizing for VC systems. Oversizing VC heat pumps substantially decreases cooling and heating season energy consumption and peak demand. Oversizing heat pumps (both VC and FC) would also reduce operation of electric resistance back-up elements, yielding both seasonal and peak demand heating energy savings. Codes, standards, and programs that limit oversizing of heat pumps should be evaluated and likely modified to encourage or at least permit oversizing of VC systems.

Introduction

Fixed-capacity direct exchange (DX) space conditioning systems, whether heat pumps or A/C systems, cycle on and off to meet space cooling load. During system start up, there is a several-minute period during which the cooling coil becomes progressively colder. Sensible capacity recovers to 90% in about one minute while latent capacity takes longer to recover (Khattar, Ramanan, and Swami 1985). Therefore, during the first several minutes of each ON cycle, both capacity and efficiency are diminished (Shirey, Henderson, and Raustad 2006). Additionally, during the OFF period, sensible and latent cooling energy stored in the air handler unit (AHU) and ductwork is lost to ambient surroundings.

The number of ON/OFF cycles per day and the proportion of the time that the system is OFF then affects system efficiency. Right-sizing reduces the number of cycles. The thermostat Nmax property (Nmax = # cycles per hour when the system is at 50% load factor) and relative building mass (and mass surface area) also affect the number of cycles per day. Oversizing increases the number of cycles per day and shortens the length of each ON cycle. Therefore, the percentage of the time that the system is operating at full capacity and efficiency is decreased. While a FC system may cycle on and off 50-75 times per day, a VC system may cycle on and off only 10-15 times per day.

Besides cycle frequency, there are two other major factors that impact the efficiency of VC systems relative to FC systems. First, conductive losses are greater for systems with longer

runtime (Andrews 2002), therefore conductive duct losses are greater for VC systems which cause conditioned air to dwell in the ductwork for more hours per day. For the 2-ton and 3-ton systems operating in our lab house, the VC systems operated 60% to 90% longer compared to the respectively sized FC systems. Second, VC systems operate at much higher efficiency at their lowest capacity which suggests that oversized VC systems may yield significant energy savings compared to right-sized systems, because they spend more time at minimum capacity.

The ability of VC and over-sized FC A/C systems to control indoor relative humidity (RH) is a concern that is also addressed in this paper.

Laboratory Research

Experiments were performed in a highly instrumented laboratory house to examine the relative performance of "right-sized" (2-ton) and oversized (3-ton) FC (SEER 13) and VC (SEER 21 or 22) heat pumps. The research house is a 1600 ft^2 double-wide manufactured home built to Energy Star home standards in 2002 with a crawl space, a vented attic, three bedrooms, and two bathrooms. It is located in Cocoa, Florida. The lab has two R-6 duct systems – one in the attic and one indoors. When operating with the indoor duct system, the design cooling load is about 1.5 tons, including internal loads. With the attic duct system, the design cooling load increases to nearly 2 tons. Automated internal sensible and latent cooling loads were implemented following Hendron (2008), which provides guidance for implementing interior loads involved in residential building research. Mechanical ventilation was not provided however, the lab house has elevated natural infiltration based on an airtightness of 10.2 ACH50.

A data collection system recorded heat pump operation, HVAC and internal load energy consumption within the house, and indoor conditions. Temperature, RH, and cfm of AHU air flow were recorded when the heat pump was operating. Power meters recorded energy use for the house, the heat pumps, larger home appliances, and internal sensible and latent heat loads. A/C condensate was measured by tipping buckets. Outdoor air temperature, RH, rainfall, wind speed/direction, and solar radiation were measured.

Experiments examined the FC and VC heat pumps in cooling and heating modes, with indoor and attic duct systems, and with RH control active and deactivated for VC system in cooling mode. Four research questions were addressed:

1. Does oversizing a VC system yield higher or lower cooling and heating energy efficiency?
2. Does oversizing a FC system yield higher or lower cooling and heating energy efficiency?
3. Does oversizing a VC system yield cooling and heating peak demand savings?
4. Does oversizing a FC system yield cooling and heating peak demand savings?

Research Findings

Variable-Capacity System Performance Characteristics

Figures 1 and 2 present measured coefficient of performance (COP) versus operating capacity fraction for the right-sized and oversized Nordyne VC systems, respectively. Continuous 15-minute operation data points were segregated into five outdoor temperature bins

with return air typically at ~74°F/55% RH. Best-fit lines and equations characterize system efficiency for various outdoor conditions. For both the 2-ton and 3-ton units, nominal full capacity is ~86% of maximum capacity based on published manufacturer data (Table 1).

In Figures 1 and 2 it can be seen that the VC heat pumps are more efficient at low versus high capacity. Best-fit equations show that in temperature ranges from 78°-93°F both the 2- and 3-ton VC systems operate at 45% higher COP when at lowest capacity versus nominal capacity, and 69% higher COP versus maximum capacity. These performance data points do not reflect efficiency losses associated with cycling or conductive duct losses, because they represent 100% runtime periods and delivered capacity is measured from entry to exit of the AHU.
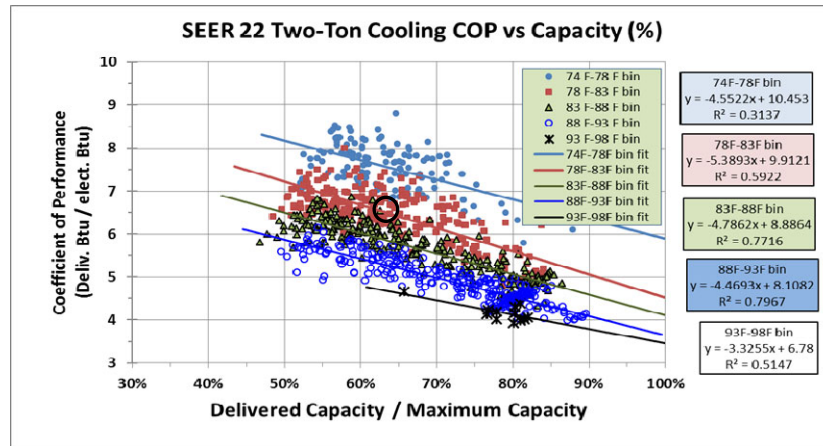

Figure 1. Measured COP versus capacity fraction for the 2-ton VC system; the best-fit line for the 78-83°F temperature bin is marked with black circle at 63% average capacity factor.
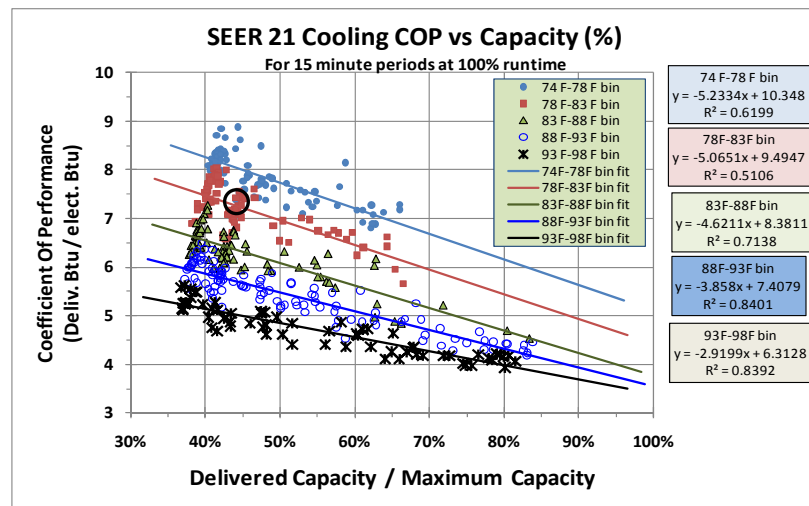

Figure 2. Measured COP versus capacity fraction for the 3-ton VC system. The best-fit line for the 78-83°F temperature bin is marked with a black circle at 42% average capacity factor.

Table 1. Nordyne VC (iQ Drive) heat pumps rated cooling performance (Nordyne 2009)

Outdoor Unit Model Number FT4BI	Indoor Unit	Range Cooling Capacity @ 95° OD Btu/h	EER @ Nominal Capacity	SEER	Nominal Capacity Btu/h	Range SCFM
024K	B4VM-E24K-B	11,300-26,900	14.6	22	23,000	500-950
036K	B4VM-E36K-B	14,200-40,700	13.0	21	35,000	680-1110
048K	B4VM-E48K-C	14,300-48,000	12.5	21	44,500	725-1800

For typical summer operation, the 2-ton system operates at about 63% of maximum capacity, on average, when operating in the lab house. By contrast, the 3-ton system operates at about 42% capacity fraction. Oversizing VC systems causes them to operate at smaller capacity fraction, on average, where system efficiency is higher. Calculations using the best-fit equations for the 78-83ºF temperature bin (average Florida summer weather) can be used to determine system efficiency at 63% capacity for the 2-ton system and 42% for the 3-ton system (see black circles in Figures 1 and 2). For the 2-ton system; COP is 6.52 (calculation: -5.3893 * 0.63 + 9.9121 = 6.52). For the 3-ton system, COP is 7.37 (calculation: -5.0651 * 0.42 + 9.4947 = 7.37). The oversized VC system has 13.0% higher COP compared to the right-sized system (calculation: ((7.37-6.52)/6.52 = 0.130).

The benefit of oversizing, however, is even greater than this 13.0% calculation. As it turns out, the 2-ton system has a SEER rating that is 4.8% higher than that of the 3-ton system (calculation: SEER 22/SEER 21 = 1.048). Our monitored data also confirms the higher innate efficiency of the 2-ton system. Using the best-fit equation for the 2-ton system for the 78-83ºF temperature bin, we find that at 42% of maximum capacity, for example, COP is 7.65 (calculation: -5.3893 * 0.42 + 9.9121 = 7.65) or 3.8% higher efficiency than the 7.37 for the 3-ton SEER 21 system (calculation: -5.0651 * 0.42 + 9.4947 = 7.37). Taking into account rounding errors associated with SEER rating being presented in whole numbers, 3.8% is in general agreement with 4.8%.The oversized 3-ton system then overcomes the approximate 3.8% efficiency advantage of the 2-ton system, and then adds 13.0% of additional efficiency. It can be concluded, therefore, that oversizing this VC system yields an efficiency improvement of 16.8% (calculation: 3.8% + 13.0% = 16.8%).

By itself, the preceding analysis might be sufficient to demonstrate that oversizing VC cooling systems enhances system operating efficiency. But there is additional evidence. Daily seasonal and hourly peak demand data are presented which also demonstrate that oversizing VC systems enhances system efficiency. However, before presenting that analysis, performance maps for 2- and 3-ton FC heat pumps is presented.

Fixed-Capacity Heat Pump Performance Characteristics

Measured system COP is not identical for the 2-ton and 3-ton FC (SEER 13) heat pumps. As can be seen in Figure 3, the 2-ton FC unit has a higher COP, especially at higher outdoor temperatures. Based on the best-fit equations and an outdoor temperature of 80ºF, the 2-ton unit has a COP that is 5.2% higher than that of the 3-ton (4.07 versus 3.87). While both units have identical SEER 13 ratings, the 2-ton unit has a higher EER rating (11.6 vs. 10.8) providing additional evidence that the 2-ton unit is in fact more efficient.
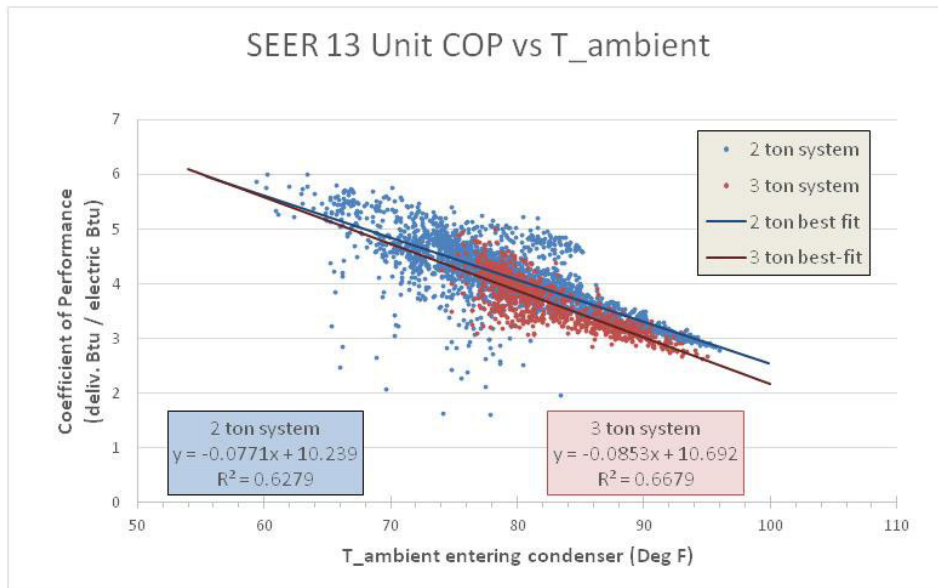
Figure 3. Measured system cooling COP for the 2- and 3-ton FC heat pumps vs. $T_{ambient}$.

Cooling Season Energy Savings

Cooling season energy consumption was measured over two summers. During the first summer, the oversized (3-ton) FC and VC systems were operated. During the second summer, the right-sized (2-ton) FC and VC systems were operated. Regression analysis found that oversizing the FC system increased energy consumption while oversizing the VC system reduced energy consumption (Figures 4 and 5 are representative; other plots for seasonal and peak demand for cooling and heating can be found in Cummings, Withers, and Kono (2013)).
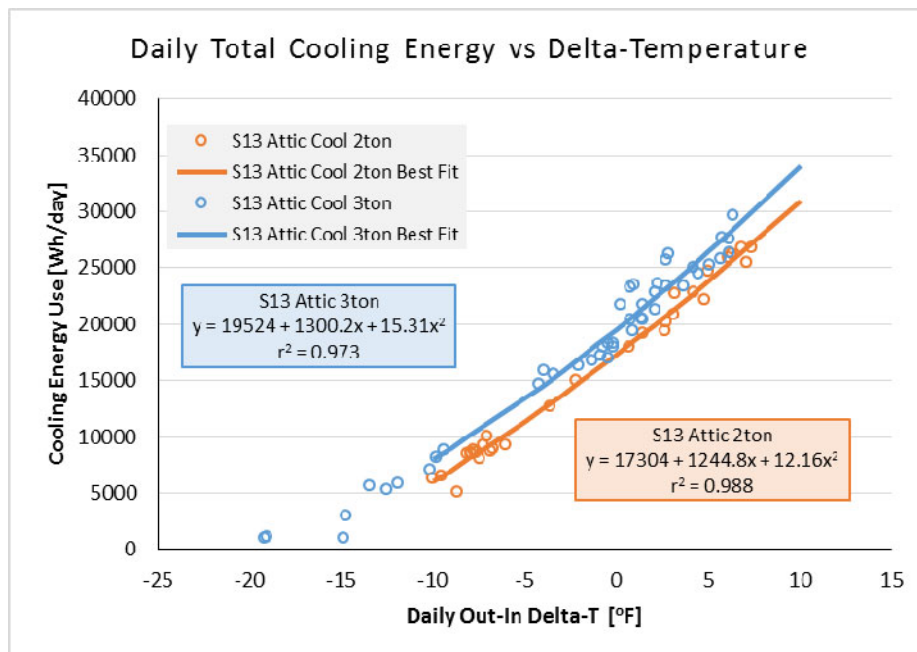

Figure 4. Cooling energy use versus delta-T for 2- and 3-ton FC heat pumps with attic ducts.
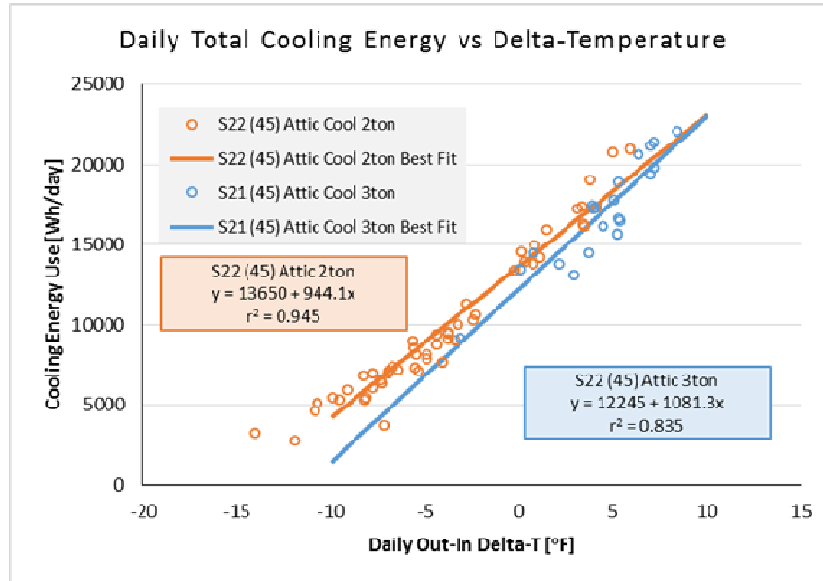
Figure 5. Cooling energy use versus delta-T for 2- and 3-ton VC heat pumps with attic ducts and RH control at 45%.

Cooling energy savings from right-sizing the FC and VC heat pumps are presented in Table 2, for typical summer day conditions of 77°F indoors and 82°F outdoors. Linear, Y=A + B (dT), or 2nd order polynomial, Y=A + B (dT) + C (dT^2), models were used in the regression analysis. The linear model was used if the C coefficient was not statistically significant at a 90% confidence level.

Table 2. Regression analysis found that right-sizing FC and oversizing VC heat pumps save energy on a typical summer day (77°F indoors and 82°F outdoors)

Heat Pump System	Size (tons)	Duct System	r^2	A	B	C	Energy Use at 5°F Delta-T (kWh/d)	Error[1] (+/-)	% Energy Savings from Right-Sizing
SEER 13	2	Attic	0.99	17304	1244.8	12.16	23.8	0.5	9.75%
SEER 13	3	Attic	0.97	19524	1300.2	15.31	26.4	0.7	
SEER 13	2	Indoor	0.97	15631	889.0	0.00	20.1	0.6	10.51%
SEER 13	3	Indoor	0.92	17042	1078.4	0.00	22.4	0.8	
SEER 22 (45)	2	Attic	0.95	13650	944.1	0.00	18.5	0.6	-4.07%
SEER 21 (45)	3	Attic	0.84	12245	1081.3	0.00	17.7	0.6	
SEER 22	2	Attic	0.97	11311	924.7	25.34	16.6	0.4	N/A[2]
SEER 21	3	Attic	0.90	11561	845.4	50.36	17.0	0.4	
SEER 22 (45)	2	Indoor	0.95	11389	868.2	17.54	16.2	0.8	-9.61%
SEER 21 (45)	3	Indoor	0.98	11038	702.4	8.02	14.8	0.4	

1. "Error" is the 95% confidence interval for this regression. For example, energy use for the 2-ton FC system with attic ducts at 5°F delta-T is 23.8 kWh/d ± 0.5 kWh/d at a 95% confidence level.
2. The data show no statistically significant difference for this configuration.

While right-sizing the FC systems appear to produce about 10% cooling savings and oversizing the VC systems about 7% cooling savings, this is not the full picture because for both the FC and VC cases, the smaller capacity units have higher innate efficiency. As indicated earlier, the 2-ton FC heat pump is 5.2% more efficient than the 3-ton FC heat pump at 80°F (Figure 3) and the 2-ton VC heat pump is 3.8% more efficient than the 3-ton VC heat pump at about 80°F (78°-83°F temperature bins of Figures 1 and 2). The savings values from Table 2 can then be normalized to account for these efficiency discrepancies. For the FC heat pump, right-sizing the system saves only about 5% (calculation: 10% gross savings - 5% higher efficiency of the 2-ton heat pump = 5% net savings from right-sizing) after normalizing for innate efficiency. For the VC heat pump, oversizing the VC heat pump saves about 11% (calculation: 7% gross savings + 4% higher efficiency of the 2-ton heat pump = 11% net savings from oversizing) after normalizing for innate efficiency. Stated another way; oversizing the VC system overcomes the innate 3.8% efficiency advantage of the smaller heat pump and then saves an additional 7% on top of that.

Cooling Peak Demand Savings

Peak cooling demand savings were examined for the FC heat pumps. Hourly cooling energy from 2 PM to 7 PM on hot afternoons was plotted versus hourly delta-T to develop a best-fit linear equation Y=A + B (dT). Based on regression analysis, right-sizing the FC system causes 9.2% and 17.1% energy use reduction when using attic and indoor ducts, respectively, when at 17°F delta-T (94°Fout – 77°Fin = 17°F; Table 3).

Table 3. Peak demand best-fit variables for the FC (SEER 13) with peak energy at dT=17 °F

	SEER 13 2-ton attic	SEER 13 3-ton attic	SEER 13 2-ton indoor	SEER 13 3-ton indoor
(A) Wh/hour	807.9	1121.7	948.8	1059.1
(B) Wh/hour-°F	76.9	71.1	41.9	55.5
(Y) Wh/hour @ 94°F (delta-T = 17°F)	2115	2330	1661	2003
Savings S13 2-ton vs S13 3-ton w/attic ducts	9.2%			
Savings S13 2-ton vs S13 3-ton w/indoor ducts			17.1%	

These savings from right-sizing almost disappear, however, when innate efficiency differences are considered. Based on the equations presented in Figure 3, the 2-ton FC unit is 12.2% more efficient than the 3-ton FC unit at 17°F delta-T. If we take the combined unadjusted peak demand savings from right-sizing for attic and indoor ducts together to be 13% (calculation: [9.2% + 17.1%]/2 = 13.1%), and if we then adjust for the 12.2% innate efficiency advantage of the smaller unit, it appears that right-sizing of the FC systems yields only about 1% peak demand savings (calculation: 13.1% - 12.2% = 0.9%).

Peak demand cooling energy savings were also examined for the VC heat pumps. On average, peak demand reduction from oversizing was 12.4% for the three experimental configurations (Table 4; calculation: (12.0% +2.5% + 22.7%)/3 = 12.4). These savings from oversizing are even greater when innate efficiency differences are considered. Based on manufacturer's energy efficiency ratio (EER) ratings of 14.6 and 13.0 for the 2-ton (SEER 22) and 3-ton (SEER 21) units, respectively, the smaller system has an efficiency advantage of 12.3% at 95°F (calculation: (14.6-13.0)/13.0) = 0.123). The normalized impact of oversizing is a nearly 25% increase in operating efficiency (calculation: 12.4% + 12.3% = 24.7%).

Table 4. Peak demand best-fit variables for the VC (SEER 21/22) with peak energy at dT=17 °F

	SEER 22 2-ton attic	SEER 21 3-ton attic	SEER 22 (45) 2-ton attic	SEER 21 (45) 3-ton attic	SEER 22 (45) 2-ton indoor	SEER 21 (45) 3-ton indoor
(A) Wh/hour	530.8	298.4	585.4	454.5	315.4	395.6
(B) Wh/hour-°F	89.1	88.3	78.7	83.5	82.7	55.0
(Y) Wh/hour @ 94°F (delta-T = 17°F)	2045	1800	1923	1874	1721	1331
Savings S21 3ton vs. S22 2ton w/attic ducts		12.0%				
Savings S21(45) 3ton vs. S22 (45) 2ton attic ducts				2.5%		
Savings S21(45) 3ton vs. S22(45) 2ton indoor ducts						22.7%

"What causes the oversized VC system to greatly outperform its EER rating relative to the right-sized VC system when tested in a real (lab) house?" The answer relates to heat pump capacity relative to peak cooling load, for the 2-ton and 3-ton systems, and to the fact that the systems are more efficient at lower capacity fractions. The design cooling load of the research house, when using the indoor and attic duct systems, are about 18,000 and 23,000 Btu/h, respectively. Therefore, even on hot summer afternoons the 3-ton VC system is only operating at about 50-65% of full nominal capacity, where its efficiency is higher. By contrast, the 2-ton VC heat pump is operating at about 78-100% of full nominal capacity, where its efficiency is lower.

Relative Humidity Control from Variable Capacity Systems

Some readers may be concerned that VC systems do not provide acceptable indoor RH control. Experimental data from this work indicates that the VC systems studied do effectively control RH. The 3-ton VC system produced 53.1% average indoor RH on all days with $T_{ambient,dp}$ > 70°F. On average Nordyne's VC systems operate at over 500 cfm/ton, which for a fixed capacity system would be expected to produce higher RH. However, it becomes clearer why there is good RH control in looking at 1 minute data intervals of the supply air temperature and cfm/ton shown in Figure 6.
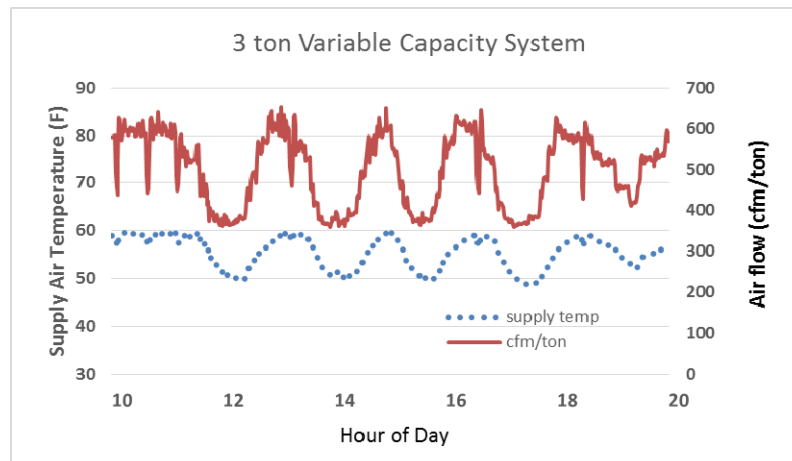

Figure 6. Typical pattern of supply temperature and flow rate (cfm/ton) during daytime August 18.

Here one can see recurring periods of cold supply air at 50° F and about 365 cfm/ton. At these points the SHR is 0.74 and latent removal rate is about 8.1 pounds of water/hour. At

periods when the supply peak temperatures are 60F, the flow rate increases to as much as 650 cfm/ton, SHR increases to 0.8 and water removal rate decreases to 2.9 lbs. water/hr, however, there is no on/off cycling of the cooling, so the coil stays cold for 10-12 hours straight during daytime enabling continuous moisture removal. The 3-ton VC system, which is oversized by about 55% when using the attic ducts, had only 11 cycles per typical summer day, compared to 60+ cycles for the FC system. Because the VC system cycles 5 to 6 times less than the FC system, much of the latent cooling penalty that could occur because of elevated cfm/ton is offset by the latent performance enhancement of nearly continuous operation (Cummings 2001).

Additionally, the system has an RH control option which lowers cfm/ton (slightly, on average), yielding 50.7% RH for days with $T_{ambient,dp} > 70^oF$. During the longer cooling season, which includes many days with $T_{ambient,dp} < 70^oF$, indoor RH averaged 52.9% in standard control and 50.9% with enhanced RH control.

Relative Humidity Control from Fixed Capacity Systems

Our research found that FC cooling systems can provide excellent indoor RH control, even when substantially oversized. The 3-ton FC system, with air flow of 423 cfm/ton, was oversized by about 55% (when using the attic ducts and including internal loads), and yet it produced average RH of 48.6% for all days with $T_{ambient,dp} > 70^oF$. Interestingly, installation of the smaller "right-sized" 2-ton system yielded slightly higher RH, averaging 50.2%. Note also that when the 3-ton FC system was operated with indoor ducts (in which case the 3-ton unit was oversized by 95%), it produced average indoor RH of 48.9%.

Heating Season Energy Savings

Experiments examined heating energy consumption for the 2- and 3-ton FC and VC heat pumps. Table 5 presents regression analysis results and predicted daily heating energy use at -22°F delta-T (indoors 72°F and outdoors 50°F). Based on this analysis, right-sizing the FC system yields 3.4% heating energy savings while oversizing the VC system yields 3.0% heating energy savings.

Table 5. Regression analysis found that right-sizing FC and oversizing VC heat pumps save energy on a typical winter day (72°F indoors and 50°F outdoors) using Y = A + B (dT)

Heat Pump	Size (tons)	Duct System	r^2	A	B	Energy Use at -22°F Delta-T (kWh/d)	Error[1]	% Energy Savings from Right-Sizing
SEER 13	2	Attic	0.88	-15877	-1439.1	15.8	1.4	3.4%[2]
SEER 13	3	Attic	0.98	-12873	-1327.8	16.3	0.8	
SEER 22	2	Attic	0.86	-9030	-963.6	12.2	0.9	-3.0%[2]
SEER 21	3	Attic	0.96	-8866	-939.8	11.8	0.7	

[1] "Error" is the extent of the 95% confidence interval for this regression. For example, energy use at -22oF delta-T is 15.8 kWh/d ± 1.4 kWh/d at a 95% confidence level.
[2] For both the SEER 13 and the SEER 21/22 configuration, the data showed no statistically significant difference in energy performance between 2-ton and 3-ton systems.

In neither case are the results statistically significant at a 95% confidence level. The 3.0% increase in efficiency for the oversized (3-ton) VC unit occurs in spite of a lower Heating

Seasonal Performance Factor (HSPF) rating. The 2-ton VC heat pump has a 10.0 HSPF while the 3-ton VC heat pump has a 9.6 HSPF. Based on the HSPF ratings alone, one would expect the right-sized system to be 4.2% more efficient. Because the oversized unit operates at 3.0% higher efficiency after having overcome the 4.2% higher rated efficiency of the right-sized system, it can be said that oversizing actually produces a 7.2% increase in operating efficiency (calculation: 3.0% + 4.2% = 7.2%).

Heating Peak Demand Energy Savings

Peak heating electrical demand for the coldest hours of the coldest days at the MH Lab was characterized for the 2- and 3-ton FC and VC systems using regression analysis which normalizes peak heating energy use to delta-T. Analysis was performed in the following manner. Heating hours from 2 AM to 8 AM were selected from a group of five or more colder-than-average winter days for each experimental configuration. Heating energy consumption for each hour was plotted versus the outdoor-indoor temperature differential. These heat pumps had no electric resistance heating, so all heating originated from compressor operation.

For a typical peak central Florida cold winter morning (72°F indoors and 30°F outdoors), the 2-ton FC system provides 10.6% demand reduction compared to the 3-ton system.

Analysis has been done for the VC systems, in this case using 2-hour data, which yielded significant improvement in r^2 versus 1-hour data. For a 30°F winter morning (-42°F delta-T), the 3-ton VC system provides 10.1% demand reduction compared to the 2-ton system.

Table 6. Heating peak demand savings calculations at -42°F delta-T using Y = A + B (dT)

	SEER 13 2-ton attic	SEER 13 3-ton attic	SEER 22 2-ton attic	SEER 21 3-ton attic
(A) Wh/hour	-401.5	-717.9	-946.8	-555.0
(B) Wh/hour-°F	-55.67	-68.66	-64.02	-50.48
(Y) Wh/hour @ 30°F (delta-T = -42°F)	1937	2166	1742	1565
Savings of SEER 13 2-ton vs. SEER 13 3-ton (Wh/h)	229			
Savings of SEER 13 2-ton vs. SEER 13 3-ton (%)	10.6%			
Savings of SEER 21 3-ton vs. SEER 22 2-ton (Wh/h)				177
Savings of SEER 21 3-ton vs. SEER 22 2-ton (%)				10.1%

Summary and Conclusions

Research performed in a lab house found that right-sizing FC heat pumps produces seasonal and peak energy savings while oversizing VC heat pumps produces seasonal and peak energy savings, for both cooling and heating periods. These results support current state codes and primary standards such as Air Conditioning Contractors of America (ACCA) Manual S to right-size fixed capacity systems, but challenges them to allow oversizing variable capacity systems. ACCA currently allows up to 15% oversizing for fixed and variable capacity units. They have recently begun a review process to allow variable capacity systems to be oversized by no more than 30%, however there is evidence presented here that supports considering a much higher limit of perhaps 100%.

Seasonal Cooling Energy Savings

Right-sizing the FC shows about 10% savings as a result of right-sizing before normalizing for system efficiency. Even though the two systems are both rated with SEER 13 efficiency, the smaller unit had 5.2% higher innate efficiency at 80ºF. After normalizing for the fact that the 2-ton system is more efficient, right-sizing the FC system yields about 5% seasonal cooling energy savings.

The results are reversed for the VC systems. Performance mapping of the 2-ton and 3-ton VC systems (Figures 1 and 2) found that both the 2-ton and 3-ton VC systems operate at 45% higher efficiency when at lowest capacity versus full nominal capacity, and 69% more efficient at minimum capacity versus maximum capacity. These findings do not take into account inefficiencies related to cycling or conductive duct losses. Based on this performance data alone, it is logical to conclude that oversizing causes the VC system to operate at lower capacity fraction a greater proportion of the time and therefore to yield greater energy efficiency.

Monitored data over two cooling seasons confirm that oversizing of VC heat pump system yields significant annual cooling energy savings. The 3-ton VC system yields about 7% savings compared to the 2-ton system. However, when accounting for the 2-ton system's 3.8% higher efficiency, oversizing the VC heat pump saves about 11% in seasonal cooling energy.

Peak Demand Cooling Savings

Analysis found that right-sizing the FC system causes approximately 13% energy use reduction when evaluated at 17ºF delta-T (94ºF – 77ºF = 17ºF). However, since the 2-ton FC system is 12.2% more efficient than the 3-ton FC unit at 17ºF delta-T (Figure 3), the normalized peak demand savings from right-sizing is only 0.9% (calculation: 13.1% - 12.2% = 0.9%). Conclusion: right-sizing the FC heat pump yielded negligible cooling peak demand reduction.

Analysis found that oversizing the VC system causes 12.4% energy use reduction (average from three experimental configurations) when evaluated at 17ºF delta-T. However, since the 2-ton VC system has an EER rating 11.0% higher than for the 3-ton VC unit (EERs of 14.6 and 13.0, respectively), normalized peak demand savings from oversizing increases to 23.4% (calculation: 12.4% + 11.0% = 23.4%). Conclusion: oversizing the VC heat pump yields substantial cooling peak demand reduction.

Heating Season Energy Savings

Analysis of data from two heating seasons found that right-sizing the FC system causes 3.4% energy savings when evaluated at -22ºF delta-T (50ºF – 72ºF = -22ºF). Analysis found that oversizing the VC system causes 3.0% energy use reduction when evaluated at -22ºF delta-T. While these values are notable, they were not considered statistically significant given the error indicated in Table 5. However, since the 2-ton VC system is rated by the manufacturer to be 4.2% more efficient than the 3-ton FC unit (HSPF of 10.0 and 9.6, respectively), the normalized energy savings from oversizing increases to 7.2% (calculation: 3.0% + 4.2% = 7.2%). Conclusion: rightsizing the FC heat pump and oversizing the VC heat pump both yield heating season energy savings, but more heating data is needed to gain more confidence.

Peak Demand Heating Savings

Right-sizing the FC heat pump reduced peak heating demand by 10.6% while oversizing the VC heat pump reduced heating peak demand by 10.1%. Conclusion: right-sizing the FC heat pump and oversizing the VC heat pump yielded significant heating peak demand reduction.

Conclusions Related to Indoor Humidity Control

It is believed by some that VC cooling systems cannot properly control indoor RH. However, the 2-ton and 3-ton VC systems produced average RH of 55% and 52%, respectively, during hot and humid weather, and RH was even lower when VC system humidistat control algorithms were activated. Good RH control was even measured during very cloudy and high outdoor dew point periods. Furthermore, alterations to the control algorithms could be readily implemented by manufacturers to produce lower supply air temperatures and considerably lower indoor RH without significant energy penalties (Cummings, Withers, and Kono 2013). It is also notable that the oversized 3-ton FC system also produced an average indoor RH of 49% during hot and humid weather.

Acknowledgements

References

Andrews, J. W. (2002). *Duct Retrofit Strategy To Complement A Modulating Furnace*. Upton, NY: Brookhaven National Laboratory. Accessed April 2014: http://www.bnl.gov/isd/documents/24650.pdf

Cummings, James B. Autumn 2001. "Humidity Problem? Trade in Your Thermostat", IAQ Applications, ASHRAE, Atlanta, GA.

Cummings, J, C. Withers, and J. Kono. 2013. *Cooling and Heating Season Impacts of "Right-Sizing" of Fixed Capacity (SEER 13) and Variable Capacity (SEER 22 and 21) Heat Pumps with Attic and Indoor Ductwork*. EERE, Building Technologies Program. Washington, DC: US DOE.

Hendron, R. 2008. *Building America Research Benchmark Definition (BARBD)*. NREL/TP-550-44816. Golden, CO: National Renewable Energy Laboratory. Accessed 2012: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/44816.pdf

Khattar, M., N. Ramanan, and M. Swami. 1985. "Fan cycling effects on air conditioner moisture removal performance in warm, humid climates." Presented at the International Symposium on Moisture and Humidity. Washington, D.C.

Nordyne Elite Training. 2009. *IQ Drive Heat Pump Training Manual*. Document #303D-0409, Technical Training Division, Nordyne Corporation, St. Louis, MO.

Shirey, D.B., Hugh I. Henderson, and Richard A. Raustad. 2006. *Understanding the Dehumidification Performance of Air-Conditioning Equipment at Part-Load Conditions*. Final Report. FSEC-CR-1537-05. Florida Solar Energy Center, Cocoa, FL. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1537-05.pdf