Energy Simulation of Integrated Multiple-Zone Variable Refrigerant Flow System

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ABSTRACT

We developed a detailed steady-state system model, to simulate the performance of an integrated five-zone Variable Refrigerant Flow (VRF)heat pump system. The system is multi-functional, capable of space cooling, space heating, combined space cooling and water heating, and dedicated water heating. Methods were developed to map the VRF performance in each mode, based on the data produced by the equipment system model. The performance maps were used in TRNSYS annual energy simulations. Using TRNSYS, we have successfully setup and run cases for a multiple-split, VRF heat pump and dehumidifier combination in 5-zone houses in 5 climates that control indoor dry-bulb temperature and relative humidity. We compared the calculated energy consumptions for the VRF heat pump against that of a baseline central air source heat pump, coupled with electric water heating and standalone dehumidifiers. In addition, we investigated multiple control scenarios for the VRF heat pump, i.e. on/off control, variable indoor air flow rate, and using different zone temperature setting schedules, etc. The energy savings for the multiple scenarios were assessed.

INTRODUCTION

Variable refrigerant flow (VRF) space cooling and space heating units are used widely in Asia for commercial and residential applications. A variable refrigerant flow system typically uses a variable-speed compressor or multiple compressors in the outdoor unit for capacity modulation. It has multiple indoor terminal units and requires no ducting for circulating air, so they are often referred to as ductless or multi-split systems. The VRF system design is modular and flexible; adding multiple outdoor units can support indoor units for an entire commercial building.

Steady-state vapor compression system modeling is an established area with well validated and robust system models. These advanced vapor compression system modeling tools can be linked with complex component models, e.g. phase-by-phase heat exchanger models or segment-by-segment heat exchanger models. In this study, we have enhanced our existing modeling capability to handle VRF multi-split systems, using advanced heat exchanger models, so as to simulate VRF space cooling, space heating, dedicated water heating and simultaneous space cooling and water heating modes.

Vapor compression system simulation models can be used to generate full- and part-load performance curves or tables for energy simulation software like EnergyPlus (2011) and TRNSYS (Klein 2010). A recent EnergyPlus release (version 6.0) includes functionalities of space cooling and space heating of VRF systems, based on combinations of two-variable performance curves.

For modeling zone cooling capacity, EnergyPlus uses off-design performance curves to consider terminal unit capacity as a function of ambient and indoor conditions as shown in Equations 1 and 2,

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$$CAPFT_{coil,cooling} = a + b\left(T_{wb,i}\right) + c\left(T_{wb,i}\right)^2 + d\left(T_c\right) + e\left(T_c\right)^2 + f\left(T_{wb,i}\right)\left(T_c\right) \quad (1)$$

$$\dot{Q}_{coil(i),cooling,total} = \dot{Q}_{coil(i),cooling,rated}\left(CAPFT_{coil,cooling}\right) \quad (2)$$

Where $CAPFT_{coil,cooling}$ = Zone Coil Cooling Capacity Correction Factor (function of temperature); $\dot{Q}_{coil(i),cooling,total}$ = Zone terminal unit total (sensible + latent) cooling capacity [W]; $\dot{Q}_{coil(i),cooling,rated}$ = rated total (sensible + latent) cooling capacity in zone i (W); $T_{wb,i}$ = wet-bulb temperature of the air entering the cooling coil in zone i (°C); T_c = temperature of the air entering an air-cooled condenser (°C); and $a - f$ = bi-quadratic equation coefficients for Cooling Capacity Correction Factor.

For equations (1) and (2), the basic assumption is that individual terminal cooling capacity only depends on the terminal wet bulb temperature and outdoor temperature, and has no interactions with other terminals. The related control strategy could use electronic expansion valves to control a fixed superheat degree for each terminal unit. Variable speed compressor operation is used to maintain a relatively constant evaporating pressure, and so the indoor air flow would see a relatively constant coil temperature.

In the EnergyPlus modeling approach, the heat pump unit energy input ratio (EIRFT) would depend on two inputs – weighted average wet-bulb temperature of the air entering all operating cooling coils and ambient temperature.

$$EIRFT_{cooling} = a + b(T_{wb,avg}) + c(T_{wb,avg})^2 + d(T_c) + e(T_c)^2 + f(T_{wb,avg})(T_c) \quad (3)$$

Where $T_{wb,avg} = \sum_{1}^{i}\left(T_{wb,i}\right)\left(\dot{Q}_{zone(i)} \big/ \dot{Q}_{zone,total}\right)$, the weighted average wet-bulb temperature of the air entering all operating cooling coils (°C), and $EIRFT_{cooling}$ = the cooling energy input ratio correction factor (function of temperature). The format of the energy performance curves in heating mode is similar to cooling mode, simply replacing the zone wet bulb temperature and the weighted average indoor wet-bulb temperature with the zone dry bulb temperature and the weighted average indoor dry-bulb temperature. A VRF heat pump unit can heat domestic water using the condensing heat. The energy performance curves for water heating is to replace the temperature of the air entering an condenser with the entering water temperature.

We want to extend the current curve-fitting methodology of EnergyPlus to a performance look-up table approach as described in this paper, using the same combination of independent variables.

VRF EQUIPMENT MODELING

Manufacturers provide data for building energy design and equipment selection, however, the available data is limited, compared to what can be generated with a system simulation model. Thus, we tuned our detailed vapor compression, VRF system simulation model to match a real product's performance at rated conditions, and conducted performance simulations to all the required operating condition ranges to generate maps as input to the TRNSYS analyses described later. The system configuration simulated is a five-zone, VRF heat pump, with water heating capability. The indoor units and outdoor unit use fin-&-tube coil heat exchangers, and the water heater uses a tube-in-tube heat exchanger. The fin-&-tube coil heat exchangers are modeled using a segment-by-segment approach and the tube-in-tube water heater is modeled using a phase-by-phase approach. The compressor used is a variable-speed rotary design, which is modeled using a ten-coefficient compressor map based on ANSI/AHRI Standard 540-2004, and we used linear interpolation between the speed levels.

Baseline VRF System

We identified manufacturer's performance data for a VRF product having five indoor units and one outdoor unit, using a variable speed, rotary compressor; it is the closest match to our targeted configuration. Our approach was to calibrate our system model using the product data at rating conditions so as to represent real product performance, and add a tube-in-tube heat exchanger to the system for water heating performance simulations. Some basic information for the chosen baseline product can be seen in Table 1. All five indoor units have the same rated capacity.

Table 1. Specification of Baseline Unit

Specification	Indoor Unit	Outdoor Unit
Cooling Capacity [Btu/h]/[W]	7000.0/2051	30000/8790
Heating Capacity [Btu/h]/[W]	8000.0/2344	34500/10109
Rated Air Flow Rate [CFM]/[m^3/s]	177* /0.0835	2119*/1.0
Sensible Heat Transfer Ratio (SHR)	70%	N/A
Fan Power [W]	30.0	130.0

*The indoor and outdoor air flow rates are assumed to be fixed at all compressor speeds.

The cooling capacities are rated at indoor DB/WB conditions of 80.6/66.2 °F (27/19 °C) and outdoor conditions of 95/75.2 °F (35/24 °C) DB/WB; the heating capacities are rated at indoor DB/WB conditions of 68/59 °F (20/15 °C), and outdoor conditions of 44.6/42.8 °F (7/6 °C) DB/WB.

We used a 2.5-ton (8.8 kW) variable-speed rotary compressor map, which has four sets of mass flow rate and power curves, at speeds of 1800 RPM, 3600 RPM, 5400 RPM and 7200 RPM, respectively. However, this compressor map needed calibration, since it is not the same brand used in the baseline system. The manufacturer's data in cooling mode was used for adjusting the system model to match the product performance. And, the same calibrated component models were used for heating mode predictions. The validity of the calibration could be determined by comparison to the heating mode performance.

Figures 1 and 2 present the comparisons between measured (product literature) and the predicted (model) efficiencies, based on the calibrated system model. Figure 1 shows good matches in cooling EERs, which is good because these points were used for calibration. There is a noticeable deviation at one indoor unit, likely because the required compressor speed is below 1800 RPM (the lowest available compressor speed from the map) necessitating extrapolation of the map data to the lower speed. The heating EER comparisons in Figure 2 demonstrate good validity of the calibration method. However, at the highest or lowest unit number, the agreement between the predicted and the measured EER values is poorer. At the lowest unit numbers, the lower bound of the compressor speed for map coefficients is exceeded. While at the combination of five indoor units in heating mode, it seems probable that there still may be some unaccounted operational factors.

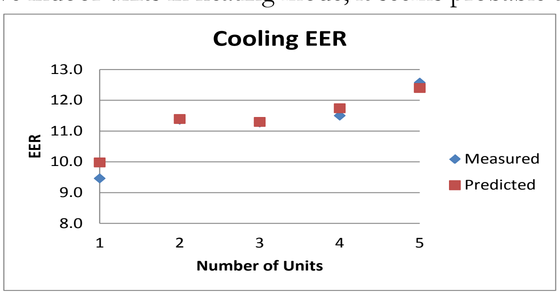

Figure 1. Comparisons between Measured and Predicted EERs in Cooling Mode

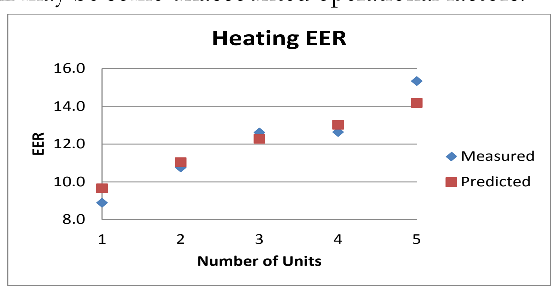

Figure 2. Comparisons between Measured and Predicted EERs in Heating Mode

The calibrated system model was extended to include water heating capability by adding a water-to-refrigerant tube-in-tube heat exchanger. The tube-in-tube heat exchanger uses fluted tubes, with refrigerant flowing outside and water flow inside, in counter flow arrangement. The fluted tubes are 11.42 feet (3.4 m) long, and have double flutes. The pump power is 40 W and water flow rate is controlled at 3 GPM (0.000189 m^3/s).

TRNSYS EQUIPMENT PERFORMANCE MAPPING METHODS

Space Cooling Mode:

For space cooling mode, there are two performance tables: one for terminal unit capacity and the other for the whole unit power consumption. The capacity table has five inputs: unit combination ratio (number of active indoor units/number of active indoor units at rating conditions), outdoor air dry bulb temperature, indoor terminal unit air flow rate, terminal unit inlet dry bulb temperature and relative humidity and three outputs: terminal unit total capacity, sensible capacity and fan power consumption. The unit power table has four inputs (unit combination ratio, outdoor dry bulb temperature, capacity weighted average indoor wet bulb temperature, and average indoor air flow rate (sum of indoor air flow rates/number of active indoor units) and two outputs (unit EER and outdoor fan power). The TRNSYS simulations have independent controls for each indoor terminal unit for turning the units on and off and altering the indoor air flow rate to control the zone temperatures. The sum of the number of active units, cooling capacities and air flow rates are used to determine the combination ratio, capacity weighted average wet bulb temperature, and the average terminal air flow rate.

Space Heating Mode:

Being similar to the space cooling mode, there are two performance tables for space heating mode. The capacity table has five inputs (unit combination ratio, indoor terminal air dry bulb temperature, terminal air flow rate, outdoor air dry bulb temperature and relative humidity). The power consumption table has five inputs (unit combination ratio, outdoor dry bulb temperature, outdoor air relative humidity, capacity weighted average indoor dry bulb temperature, and average indoor air flow rate). The outputs are the same as the space cooling mode.

Combined Space Cooling and Water Heating Mode:

The combined space cooling and water heating mode has very similar tables to the space cooling mode, replacing the outdoor air dry bulb temperature with the entering water temperature. There is one additional output from the power consumption table: the compressor shell heat loss ratio relative to the compressor power. To determine the water heating capacity, all the terminal total cooling capacities to the unit compressor power consumption are summed and the compressor shell heat loss is subtracted. The pump power and flow rate were fixed at 40 W and 3 GPM (0.000189 m^3/s). The EERs defined for the combined mode refer to the space cooling performance only.

Dedicated Water Heating Mode:

The dedicated water heating table structure has three inputs (outdoor air dry bulb temperature, relative humidity, and entering water temperature to the heat pump) and three outputs (water heating capacity, power consumption, and EER). The dedicated water heating mode has two separate operational modes ("FullSpeed" and "ControlledSpeed") for different control needs. In the case where there are simultaneous requests for space heating and water heating, the water heating request has a higher priority, and the "FullSpeed" mode is used running the compressor at the full speed for a maximum water heating capacity. In the case where there is only a request for water heating, the "ControlledSpeed" mode will be used maintaining higher efficiency levels. In "ControlledSpeed" mode, the compressor speed changes linearly with the ambient temperature, running minimum compressor speed at temperatures above 65 °F, and running maximum speed at temperatures below 45 °F. In the case where there are simultaneous requests for space cooling and water heating, the combined space cooling and water heating mode will be used. In the case that there is a request for water heating and the outdoor air temperature is higher than 75 °F, the combined space cooling and water heating mode will be used (allowing the indoor to be overcooled).

BUILDING ENERGY SIMULATIONS

We setup and ran cases for an integrated VRF heat pump and dehumidifier combination in a 5-zone house in 5 climates that controls both indoor dry-bulb temperature and relative humidity. The 5-ton (17.6 kW) house is 2600 ft^2 (241.5 m^2) and has two floors. It has dry-bulb thermostats located in each individual zone and standalone dehumidifiers in the family room of the first floor, and upper back room of the second floor.

The VRF heat pump has identical terminal units located in each zone, as well as a tube-in-tube water-to-refrigerant heat exchanger and a water tank for water heating. It is a multi-functional unit, capable of space cooling, space heating, combined space cooling and water heating, and dedicated water heating. Controls were set up in TRNSYS to automatically switch the modes.

The calculated house energy consumption for the VRF heat pump was compared to the calculated energy consumption for a baseline central air source heat pump, coupled with electric water heating and standalone dehumidifiers. The central air source heat pump has a rated SEER of 13.0 (cooling SPF of 3.8) and HSPF of 7.7 (heating SPF of 2.3). In this 5-zone setup, the baseline dehumidifier output is assumed to only be distributed into the room in which it is located, with further mixing with the air in the rest of the house only through return air to the central heat pump system.

Five different operating modes were calculated for comparison:

VRF On/Off:

For this case, the heat exchanger dimensions and compressor performance is the same as the baseline VRF product having five indoor terminals. The indoor terminals have on/off control and fixed air flow rates. The outdoor air flow rate and fan power vary in response to the active number of indoor terminals. The compressor speed is altered to control a fixed suction pressure or discharge pressure, upon varied combinations of indoor units. The terminals have fixed indoor air temperature control, with heat pump space cooling: on at 77 °F (24.4 °C), off at 76 °F (25 °C); heat pump space heating: on at 70 °F (21.1 °C), off at 71 °F(21.7 °C); auxiliary electric resistance heating: on at 68 °F (20 °C) off at 71 °F.

VRF Modulated:

For this investigation, the compressor is a more efficient variable-speed unit than the baseline VRF unit. In addition, the controlled suction saturation temperature (cooling mode) or discharge saturation temperature (heating mode), and the indoor and outdoor air flow rates are allowed to vary as a function of the ambient temperature. The relationships approximate the control strategies of the air source integrated heat pump study by Murphy et al. (2005), targeting optimum efficiency at varied conditions. The control function upon the ambient temperature is to facilitate the expected efficiency levels operating along an average house load line. The terminal and outdoor air flow rates were treated as a function of the ambient air temperature.

VRF Setback Schedule:

The above two cases have constant setpoint temperatures that are the same for both floors for either the cooling or heating season. For investigating the effect of a setback schedule, shown in Table 2, was used (from Baxter (2005); keeping the capacity modulation strategy the same as the VRF modulated case, regardless of the setback schedule.

Table 2. Zone Temperature Control Set Points (°F/°C) Used for Zoned System Analyses

Zone/time of day	11 pm – 7 am	7 am – 11 pm
	Heating Season	
Upstairs	68/20	65/18.3
Downstairs	65[a]/18.3	71/21.1
	Cooling Season	
Upstairs	76/24.4	80/26.7
Downstairs	80/26.7	76/24.4

*downstairs zone ramps up from 65 °F to 71 °F over 2-hour period (6-8 am) for electric system options to minimize use of electric resistance backup heat during warm-up period.

VRF Modulated with Variable Terminal Air Flow Control:

This scenario allows controlling individual terminal air flow rates to better match zone conditions, in addition to the VRF modulated control. The terminal air flows were varied at three steps: lowest, medium and highest. For space heating mode, with the zone temperature within 0.2 °F (0.12 °C) lower than the setting, the terminal runs at the lowest air flow rate (92 CFM); with the temperature 0.2 to 0.6 °F (0.12 to 0.36 °C) lower than the setting, the terminal runs at the medium air flow rate (154 CFM); with the temperature more than 0.6 °F (0.36 °C) lower, the terminals runs at the highest speed (217 CFM). For space cooling mode, the indoor air flow rate is also varied at the three steps, based on temperature differences higher than the room setting.

VRF Setback Schedule with Variable Terminal Air Flow Control:

This scenario adds the indoor air flow control to the case of VRF with setback schedule.

The TRNSYS simulation results of the load met and energy use for the 5-zone houses are given in Table 3, in percentages relative to those of the baseline central heat pump system, except that the energy uses of the resistance heat and ventilation fan are given in Watts. To provide a quantitative measure of the provided comfort levels, the hours were tabulated in Table 4 where one or more zones exceeded either temperature or RH conditions.

DISCUSSIONS AND CONCLUSIONS

The cooling and heating demand distribution in the two-story, five-zone house is imbalanced due to the effect of the sun on the roof. The upper floor has more cooling required in the summer but less heating required in the winter than the lower floor. The central air source heat pump distributes the capacities uniformly per area. It tends to over-heat or under-cool the upper floor, which results in extra heating in the winter and unmatched cooling in the summer. The multi-split VRF unit has individual capacity control to match the zone demands. In Table 4, we can see that the VRF unit led to significant enhancement in the comfort level for both the cooling season and heating season. The VRF unit reduced the over-heating in winter and provided better zone temperature control with better distribution of cooling energy. Looking at Table 3, we can tell that the multi-split VRF unit can lead to noticeable overall heating energy reduction for the climate zones with major heating needs like Chicago and San Francisco.

By comparing the energy uses in Table 3, according to the VRF On/Off case, the major energy savings are from the over-heating reduction and the switch from electric water heating to heat pump water heating, while the energy consumptions for space cooling are approximately the same as the baseline. It shall be noted that the VRF unit can significantly reduce the resistance heating needs for space heating in Chicago. In the VRF modulated case, the compressor, indoor blowers and outdoor fan ran at lower speeds at part load conditions, and so, the unit operated at optimum efficiency in a large range of ambient conditions. Consequently, it resulted in about 10% energy saving in comparison to the VRF On/Off case. Moreover, using the temperature setback schedule brought further energy saving.

For the VRF modulated and the VRF setback cases, the unit behaving as a function of the ambient temperature is based on the assumption of operating along an average house load line. This is not necessarily true for the warm-up periods in the setback schedule. Consequently, the resistance heat in heating mode was turned on more. Adding terminal variable air flow control results in much less electric resistance heating needs with and without using the setback schedule. Adding terminal variable air flow control to the modulated space cooling case leads to a similar level of energy consumptions, because varying the indoor air flow rate responding to the departure from setpoint is approximately equal to modulating the indoor air flow rate as a function of the ambient temperature. On the other hand, the VRF unit using the variable air flow control has less dehumidification capability than the modulated case, because the indoor air flow rate was varied in response to the dry bulb temperature, rather than the wet bulb temperature. At the maximum terminal air flow rate, the dehumidification capacity was decreased.

Table 3. TRNSYS Load Met Energy Use Results for 5-Zone Houses with a Baseline Central HP and Room Dehumidifiers, and Multi-Split VRF HP

	VRF On/Off		VRF Modulated		VRF Setback Schedules		VRF Modulated with Variable Air Flow		VRF Setback Schedule with Variable Air Flow	
mode	Load met	Energy use	Load met	Energy use	Load met	Energy use	Load met	Energy use	Load met	Energy use
Atlanta										
space heating	83%	73%	81%	58%	66%	50%	81%	57%	65%	46%
resistance heat [W]-SH		(23)		(26)		(92)		(10)		(25)
space cooling	108%	88%	108%	61%	102%	59%	114%	69%	100%	60%
water heating	96%	27%	96%	26%	96%	26%	98%	27%	98%	27%
resistance heat[W]-WH		(0)		(3)		(1)		(0)		(0)
dedicated dehumidifier	143%	138%	134%	132%	115%	110%	199%	200%	144%	142%
ventilation fan [W]		189		189		189		189		189

totals	96%	60%	95%	50%	87%	46%	99%	54%	86%	46%
mode	Load met	Energy use	Load met	Energy use	Load met	Energy use	Load met	Energy use	Load met	Energy use
Houston										
space heating	88%	80%	85%	62%	66%	50%	87%	62%	65%	46%
resistance heat [W]-SH		(6)		(9)		(25)		(4)		(10)
space cooling	108%	89%	106%	61%	98%	57%	114%	72%	97%	60%
water heating	96%	24%	96%	23%	95%	23%	97%	23%	97%	23%
resistance heat[W]-WH		(0)		(0)		(0)		(0)		(0)
dedicated dehumidifier	130%	125%	127%	124%	108%	101%	168%	166%	120%	115%
ventilation fan [W]		189		189		189		189		189
totals	104%	71%	103%	58%	93%	52%	110%	68%	94%	55%
Phoenix										
space heating	82%	78%	81%	62%	67%	53%	82%	62%	60%	46%
resistance heat [W]-SH		(2)		(4)		(18)		(3)		(10)
space cooling	99%	89%	101%	66%	97%	64%	102%	70%	93%	65%
water heating	95%	22%	95%	22%	95%	22%	97%	23%	97%	23%
resistance heat[W]-WH		(0)		(0)		(0)		(0)		(0)
dedicated dehumidifier	118%	97%	117%	91%	154%	127%	352%	291%	152%	137%
ventilation fan [W]		189		189		189		189		189
totals	96%	64%	97%	51%	92%	49%	98%	53%	89%	49%
San Francisco										
space heating	81%	77%	82%	65%	65%	53%	82%	64%	60%	47%
resistance heat [W]-SH		(1)		(2)		(32)		(3)		(11)
space cooling	182%	164%	212%	133%	157%	97%	235%	146%	133%	83%
water heating	96%	28%	96%	27%	96%	27%	98%	28%	98%	27%
resistance heat[W]-WH		(0)		(0)		(0)		(0)		(0)
dedicated dehumidifier	106%	93%	100%	89%	171%	155%	79%	69%	192%	178%
ventilation fan [W]		189		189		189		189		189
totals	88%	44%	90%	40%	80%	38%	91%	40%	78%	37%
Chicago										
space heating	86%	67%	83%	54%	71%	49%	83%	52%	70%	45%
resistance heat [W]-SH		(154)		(170)		(335)		(88)		(108)
space cooling	115%	96%	115%	68%	108%	63%	120%	74%	103%	61%
water heating	97%	30%	97%	30%	97%	30%	98%	31%	98%	31%
resistance heat[W]-WH		(62)		(100)		(100)		(127)		(126)
dedicated dehumidifier	157%	153%	132%	130%	118%	114%	181%	182%	137%	135%
ventilation fan [W]		189		189		189		189		189
totals	92%	57%	90%	48%	81%	45%	92%	49%	80%	43%

Table 4. TRNSYS Hourly Indoor Temperature and RH Excursions for 5-Zone 2600 Ft^2 Houses, Comparing Baseline to Multi-Split VRF Heat Pump

	Baseline Central HP	VRF On/Off	VRF Modulated	VRF Modulated with Variable Air Flow
Atlanta				
Total hours lower RH >60%	0	0	0	1
Total hours lower temp <68F	2	18	40	22
Total hours upper temp <68F	0	15	21	0
Total hours lower temp >79F	0	0	2	0
Total hours upper temp >79F	148	0	0	0
Total hours T or RH limits not met	150	33	63	23
Houston				
Total hours lower RH >60%	4	10	3	6
Total hours lower temp <68F	0	2	5	5
Total hours upper temp <68F	0	0	6	0
Total hours lower temp >79F	10	7	9	8
Total hours upper temp >79F	108	101	95	101
Total hours T or RH limits not met	122	120	118	120
Phoenix				
Total hours lower temp >79F	0	0	1	0
Total hours upper temp >79F	91	0	0	0
Total hours T or RH limits not met	91	0	1	0
San Francisco				
Total hours upper RH >60%	0	0	0	1
Total hours upper temp <68F	0	0	2	0
Total hours lower temp >79F	0	0	2	0
Total hours upper temp >79F	45	0	0	0
Total hours T or RH limits not met	45	0	4	1
Chicago				
Total hours lower RH >60%	0	3	2	1
Total hours lower temp <68F	47	45	75	15
Total hours upper temp <68F	43	41	19	3
Total hours upper temp >79F	243	0	0	0
Total hours T or RH limits not met	333	89	96	19

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