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ABSTRACT

The paper provides detailed results that show the impact of charge level on cooling capacity, heating capacity, and efficiency for units tested in the laboratory and for some data obtained from a manufacturer. The impacts of improper refrigerant charge amount on capacity vary for different units and operating conditions. Low refrigerant charge levels can cause significant reductions in both cooling and heating capacity. Also, running equipment at low or high refrigerant charge levels may shorten its lifespan. To evaluate the economic value, Seasonal Energy Efficiency Ratio (SEER) and annual cost of electricity were determined for some case studies based on the tested units. The results imply that charging inaccuracies could cause significant decreases in SEER, leading to increases in the operating costs. When the refrigerant was charged to 75 percent of normal, the SEER value decreased by 16 percent and annual operating cost was increased by US$ 100 per tons, on average for all systems considered.

1. INTRODUCTION

Continuous or frequent monitoring of charge level should lead to early detection of refrigerant leakage and avoidance of under or overcharging. These faults lead to loss of efficiency and increase in costs. Based on tests of more than 4,000 residential cooling systems in California, only 38 percent have correct charge (Proctor, 2002) and the data from Blasnik et al. (1996) and Proctor (1997, 1998) have indicated that an undercharge of 15 percent is common. Both undercharge and overcharge can reduce cooling equipment longevity, capacity, and efficiency. It has been reported that approximately 50 to 67 percent of all air conditioners suffer from improper charge or air flow problems causing them to operate 20 percent less efficiently than if they were properly installed or maintained (eg., Proctor, 1996). Another study indicated that improper refrigerant charge amount can reduce the efficiency of systems by 10 to 20 percent in the field (Downey and Proctor, 2002).

This paper provides detailed results that show the impact of charge level on cooling capacity, heating capacity, and efficiency for units tested in the laboratory at various test conditions and for existing data obtained from a manufacturer. The impacts of improper refrigerant charge amount on capacity vary for different units and operating conditions. Low refrigerant charge levels can cause significant reductions in both cooling and heating capacity. Also, running equipment at low or high refrigerant charge levels may shorten its lifespan. To evaluate the economic value, Seasonal Energy Efficiency Ratio (SEER) and annual cost of electricity were determined for some case studies based on the tested units.

2. Impact of refrigerant charge for existing data

An equipment manufacturer was contacted in order to acquire data for the effects of refrigerant charge inventory on performance. All tests were performed at nominal evaporator and condenser airflow rates and outdoor temperatures for cooling conditions. The data were obtained through laboratory testing by the manufacturer. Although there was not sufficient data available to confirm the accuracy of the measurements, the data were regarded as accurate considering the ARI standard based procedures that the commercial company had followed. System descriptions are given in Table 1 and testing conditions are listed in Table 2.

Table 1 System descriptions for manufacturers' data.

System	Capacity[KW]	Compressor	Refrigerant	Expansion device	Accumulator	Assembly type
I	14.5	Tandem	R-22	EEV	1500 [cc]	Split
II	15.2	Rotary	R-22	FXO	No	Split
					1000 [cc]	
III	14.5	Reciprocating	R-22	FXO	No	Split
					1000 [cc]	
IV	14.5	Tandem	R-22	FXO	1000 [cc]	Split

Table 2 Testing conditions for manufacturers' data.

System	Indoor temperature		Outdoor temperature		Indoor air flow rate	Refrigerant charge level
	Dry (C)	Wet (C)	Dry (C)	Wet (C)	[-]	Nominal Charge (%)
I	27	19	35	24	Nominal Air Flow Rate	80 ~ 100
II						60 ~ 110
						75 ~ 100
III						60 ~ 100
						80 ~ 100
IV						80 ~ 100

Figure 1 shows capacity ratio as a function of refrigerant charge for the manufacturers' data. The capacity ratio is the capacity at the indicated charge relative to the capacity at the rated condition and nominal charge. The capacity decreases with decreasing refrigerant charge primarily due to a drop of refrigerant mass flow rate. The flow rate decreases because of a decrease in evaporator pressure and an increase in compressor superheat. The capacity trends with refrigerant charge in Figure 1 are similar for the different systems. However, the impact of low charge on capacity seems to be less for system I. This system employed an electronic expansion valve (EEV) which adjusts the mass flow rate in response to reduced refrigerant charge. Systems II and III included data obtained both with and without a suction line accumulator. The accumulator seems to have little impact on the effect of refrigerant charge on cooling capacity. In general, a 30% reduction in charge resulted in about a 30% reduction in capacity for the systems considered.

Figure 2 shows the impact of refrigerant charge on COP ratio, which is the ratio of the COP at the indicated charge to the COP at the same conditions and nominal charge. The COP decreases with decreasing charge because lower evaporating pressure and higher compressor superheat lead to higher specific work. The impacts are less for the EEV system over the charge levels considered because the EEV controls compressor superheat. The impact of charge on COP seems to be greater for systems with accumulators.

3. Impact of refrigerant charge for laboratory tests

3-1 Description of laboratory tests

The previously tested units included residential split systems with either an EEV or FXO as the expansion device. Most of these tests did not cover a wide range of refrigerant charge levels and there was no data at low outdoor temperature conditions for cooling. In addition, there were no tests for heat pump operation in heating mode. New tests were performed to consider heat pump units that incorporate a low side accumulator and that considered a wide range refrigerant charges and indoor and outdoor conditions in both cooling and heating mode. Specifications of the units are given in Table 3 and the testing conditions in cooling and heating mode are given in Table 4.

Table 5 lists uncertainties of the dependent variables for the steady-state tests. The average differences between air and refrigerant-side capacities were approximately 3.6 percent. The uncertainty in the superheat and subcooling was estimated to be ±0.6 C on average. Due to the fact that the refrigerant mass flow meter fluctuated at ambient temperatures lower than 10 C, the refrigerant-side capacities were not measured at these conditions and only air-side capacities were used for these tests.

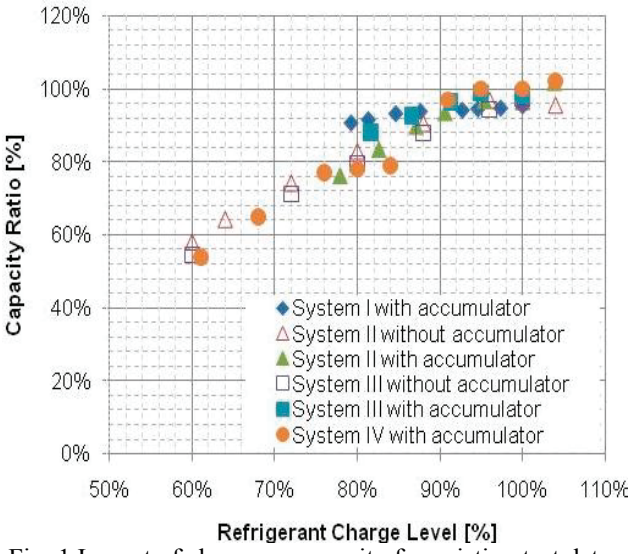

Fig. 1 Impact of charge on capacity for existing test data

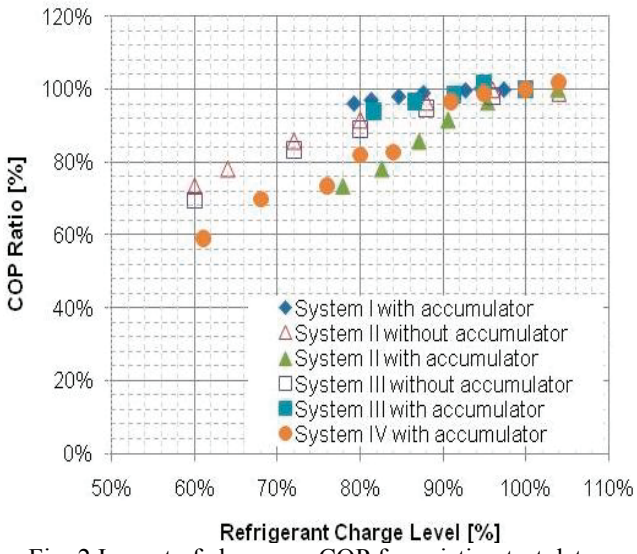

Fig. 2 Impact of charge on COP for existing test data

Table 3 System description for laboratory tests

System	Size (ton)	Refrigerant Type	Expansion Device	Accumulator	Assembly Type
V	3.0	R-22	TXV (Cooling / Heating)	yes	Split
VI	3.0	R-410a	TXV (Cooling) / FXO (Heating)	yes	Split

Table 4 Testing conditions of new laboratory test

System	Mode	Indoor / Outdoor Temperature						Indoor Unit Air Flow Rate	Refrigerant Charge Level
		A	B	C	D	E	F		
		(C)						(CFM)	(%)
V	Cooling	20/ 10	20/ 35	20/ 45	20/ 10	20/ 35	20/ 45	800(a,b,c), 1600(d,e,f)	70 ~ 130
	Heating	21/ -8	21/ 1	21/ 8	21/ -8	21/ 1	21/ 8	900(a,b,c), 1500(d,e,f)	
VI	Cooling	21/ 4	21/ 35	21/ 51	27/ 4	27/ 4		1000	40 ~ 130
	Heating	15/ -8	15/ 8	15/16	21/-8	28/-8		1000	

Table 5 Average uncertainties of the independent and dependent variables for laboratory test

Independent Variables	Uncertainty (absolute or relative)	Dependent Variables	Uncertainty (absolute or relative)
Refrigerant side temperature	± 0.5 ˚C	Indoor air flow rate	± 10 g/s
Air Side temperature	± 1.0 ˚C	Subcooling degree	± 0.6 ˚C
Refrigerant temperature	± 0.8 kPa	Superheat degree	± 0.6 ˚C
Barometric pressure	± 0.03 kPa	Airside capacity	± 2.5%
Dew point	± 0.2 ˚C	Refrigerant capacity	± 1%
Refrigerant mass flow rate	± 0.27 g/s	COP	± 3.5%
Power	± 10 W	-	-

3-2 Impact of refrigerant charge on performance

Figures 3 to 6 show the effect of charge on cooling capacity and COP ratio for system V at the different ambient temperatures and indoor air flow rates. The results referenced to the rated operating point with normal refrigerant charge. Overall, there was much lower degradation in capacity and COP with changes in the refrigerant charge as compared with the FXO systems. On average, a charge decrease of 30 percent reduced the cooling capacity by 7

percent and the COP by 9 percent for this system test. The TXV adjusts the mass flow rate of the system in response to changes in refrigerant charge. In cooling mode, the trends were similar for the different ambient temperatures and indoor air flow rates. However, in heating mode, the sensitivity of capacity and COP to charge was less at low ambient temperatures.

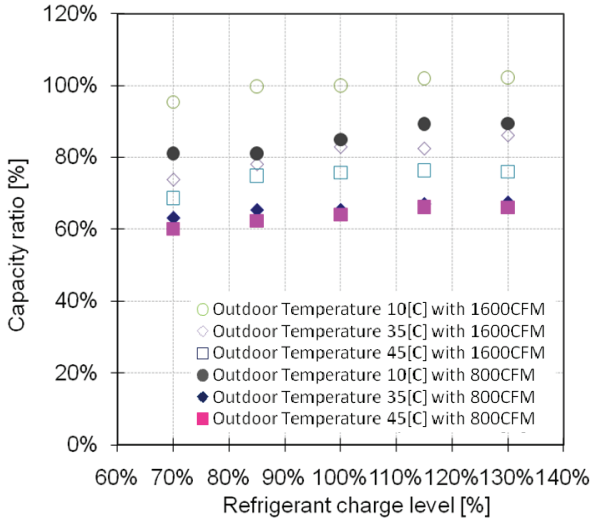

Fig. 3 Cooling capacity for system V with accumulator and TXV at different ambient temperature conditions

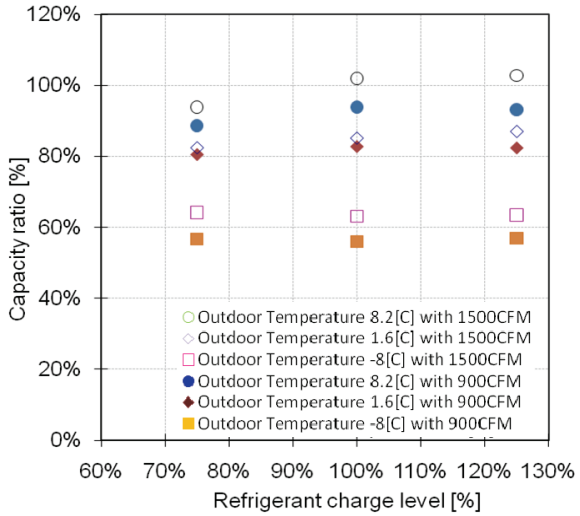

Fig.4 Heating capacity for system V with accumulator and TXV at different ambient temperature conditions

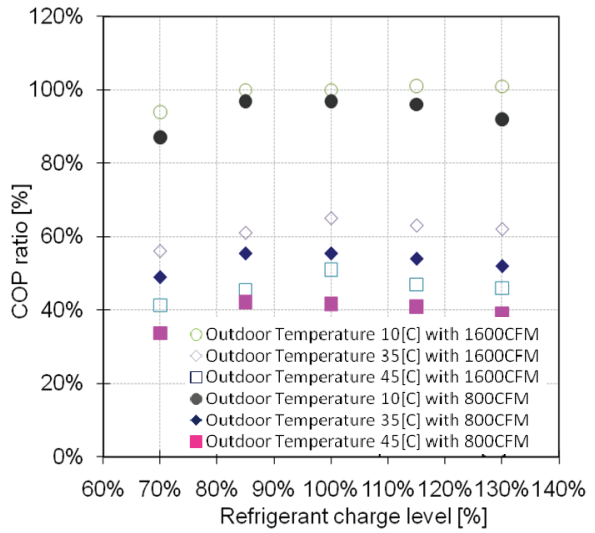

Fig. 5 Cooling COP for system V with accumulator and TXV at different ambient temperature conditions

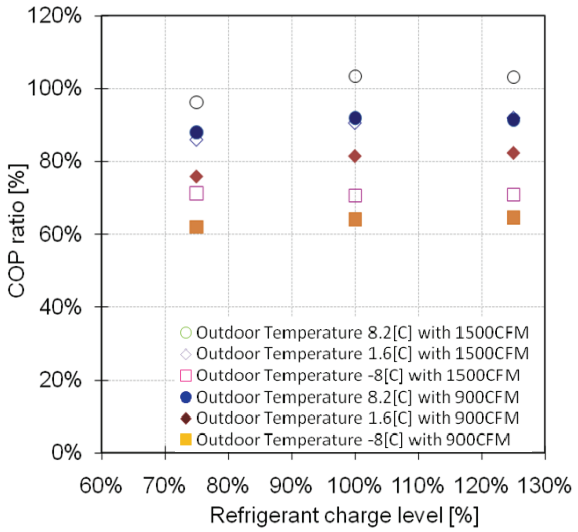

Fig. 6 Heating COP for system V with accumulator and TXV at different ambient temperature conditions

Figures 7 to 10 give capacity and COP ratio as a function of charge for system VI at different ambient and indoor conditions in both cooling and heating mode. This system incorporates a TXO for cooling mode and a FXO in heating mode. In both modes, the impact of charge on both capacity and COP is very significant below 70 percent of nominal charge. Below 70 percent, the TXV in cooling mode is probably wide open and the operation is similar to that for a FXO system. On average, the test data in cooling mode indicated that an undercharge of refrigerant by 60 percent reduced the cooling capacity by 70 percent and energy efficiency by 65 percent. Overcharging tends to increase capacity, particularly at higher indoor air temperatures. On average, overcharging by 30 percent increased cooling capacity by 20 percent, whereas the energy efficiency was decreased by 10 percent. The trends and magnitudes of the degradations are similar for both cooling and heating modes.

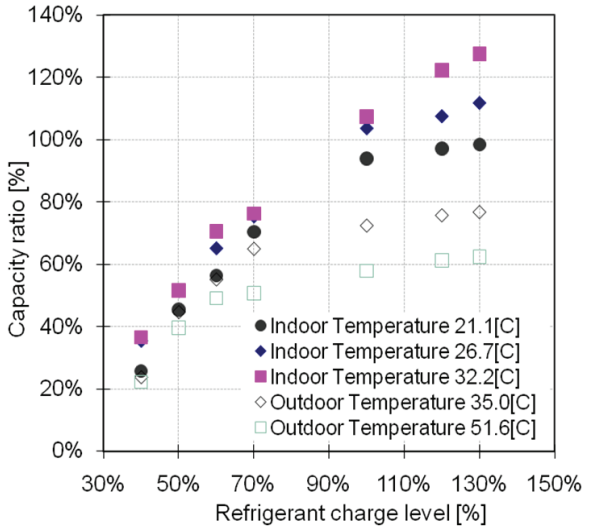

Fig. 8 Cooling Capacity for system VI with accumulator and TXV at different ambient temperature conditions

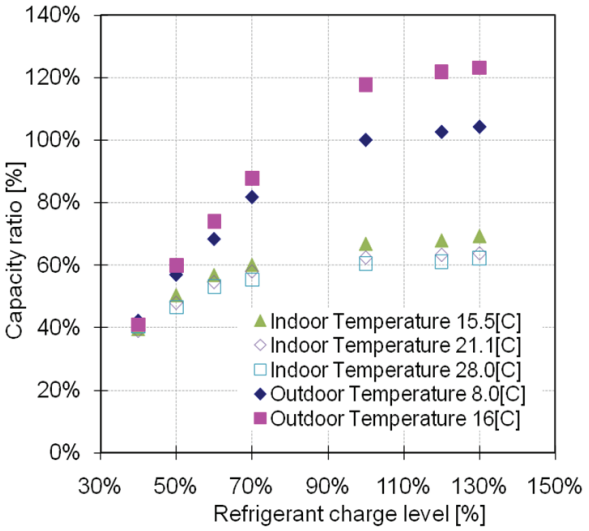

Fig.10Heating Capacity for system VI with accumulator and TXV at different ambient temperature conditions

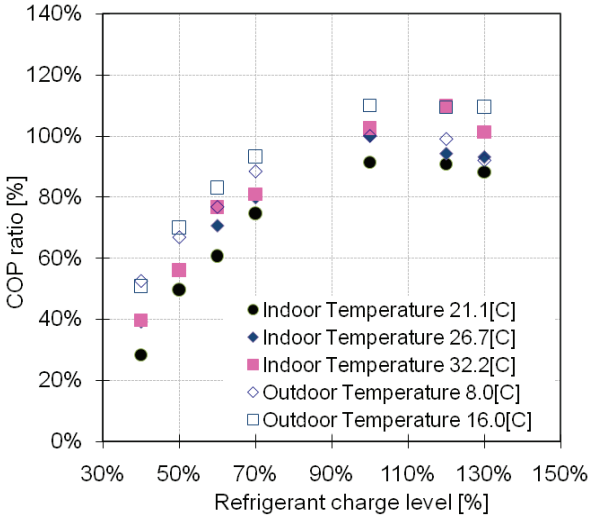

Fig. 9 Cooling COP for system VI with accumulator and TXV at different ambient temperature conditions

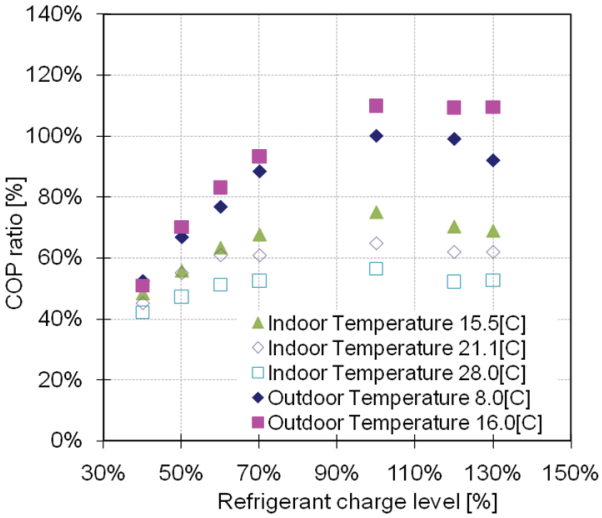

Fig. 11 Heating COP for system VI with accumulator and TXV at different ambient temperature conditions

4. Impact of Refrigerant Charge on Costs

To provide information on the impact of refrigerant charge on operating costs for cooling, SEER and annual cost of electricity were used. The efficiency of air conditioners is rated using SEER which is defined by the Air Conditioning, Heating, and Refrigeration Institute in its standard ARI 210. The SEER rating is the Btu of cooling output during a typical cooling-season divided by the total electric energy input in watt-hours during the same period. The higher the SEER rating of a unit, the more energy efficient it is.

The average electricity cost for the cost calculation was assumed to be 0.12$/kWh, based on the U.S. Energy Information Administration's Electric Power Monthly (released on February 13, 2009). Table 6 shows the bin weather data used in calculating SEER. The SEER equation was obtained from the ARI 210 Standard.

Table 6 Bin Weather data for SEER

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
OD Temp.	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Occurring Hrs.	196	225	225	240	181	122	93	92	35	11	6	4	0	0	0

The annual cost of electric power consumed for an air conditioner having a specified rated capacity (Btu/h), number of operating hours per year (h), SEER rating, and cost per kW·h of electrical usage ($/kW·h) is estimated as follows.

$$Annual.Cost.of.Power(\$) = \frac{UnitSize(Btu/h) \cdot hour.per.year(h) \cdot electric.rates(\$/kwh)}{SEER \cdot 1000} \quad (7)$$

Figures 12 and 13 show SEER and annual cost ratio of electricity that were determined using the existing and new laboratory test data as a function of charge level. The SEER ratio is the ratio of the SEER at the indicated charge to the rated SEER. Costs were estimated using the SEER, nominal capacity, estimated runtime, and average cost of electricity. The cost ratio is the ratio of the annual costs at the indicated charge to the cost at the same conditions and nominal charge. Low refrigerant charge can cause decreases in SEER with significantly higher operating costs.

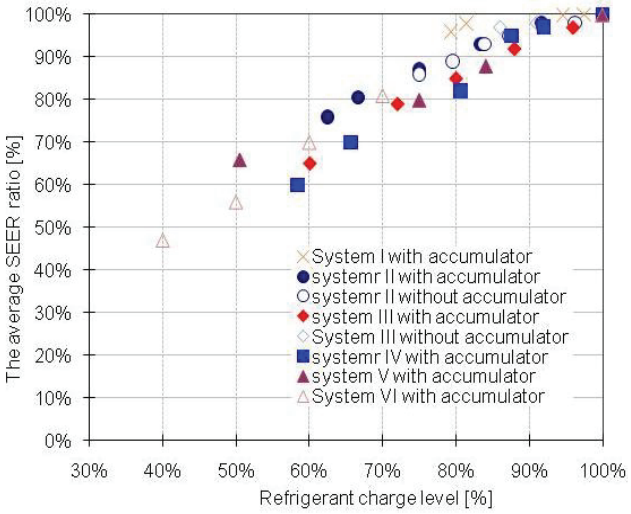

Fig. 12 The average SEER ratio for all testing data based on the refrigerant charge

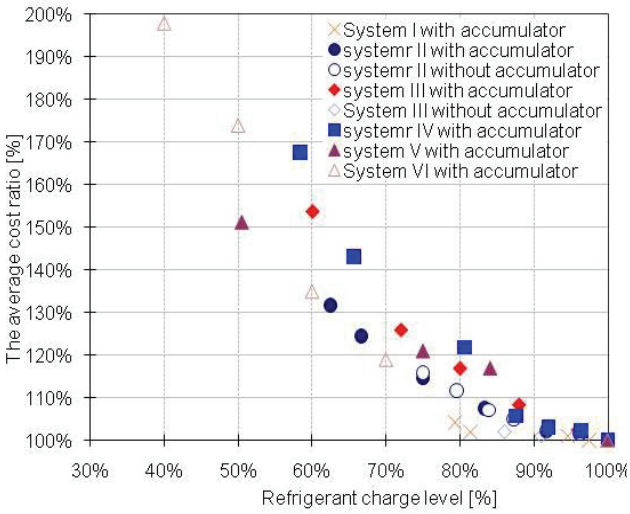

Fig. 13 The average annual cost ratio for all testing data based on the refrigerant charge

For the systems considered, the performance and cost penalties for insufficient refrigerant charge were more significant when an accumulator was employed. Overall, the penalties are greater than about 10% when the refrigerant is less than 85% of normal charge. Table 8 shows example results for impacts of reduced charge levels on the SEER and annual cost of electricity for the laboratory test units and data obtained from the manufacturers. In the case of system V without an accumulator, a 75 percent of refrigerant charge reduced the energy efficiency by 15 percent. This led to a decrease in the SEER value by 20 percent. For typical utility rates, the annual operating cost would increase by about US$ 100 per ton for this system. For system VI, A reduction of charge level by 60 percent decreased the SEER ratio by 46 percent, resulting in an estimated annual cost penalty of US$ 500 per ton.

Table 8 SEER and the annual cost of power for cooling testing data

System	Accumulator	Charge Level	SEER	Annual cost of power per unit rated capacity
		[%]	[-]	[US$/Ton]
II	yes	62.5	7.8	865
		100	10.3	656
	no	75	8.8	723
		100	10.2	667
III	no	60	6.2	1055
		100	9.5	687
IV	yes	58.4	6.5	1042
		100	10.9	621
V	yes	75	10.96	581
		100	13.7	481
VI	yes	40	6.93	951
		100	14.64	450

5. CONCLUSIONS

Important performance indices for an air conditioner are cooling capacity and COP. Undercharge or overcharge can reduce air conditioner life, capacity, and efficiency. For systems with a FXO, there is a rapid reduction in both cooling capacity and energy efficiency with decreasing refrigerant charge level. For systems with TXV, both capacity and COP do not decrease significantly until the refrigerant charge level reaches around 70 percent. When the charge level is under 70 percent, the TXV becomes fully open and then the system acts like a system having a FXO.

According to previous research on residential air conditioners, about 55 percent of systems are undercharged by 10 to 30 percent due to incorrect measurement of charging amount during installations or service. Based on the situations that are commonly encountered in the field, refrigerant undercharging in the range of 12 to 19 percent can lead to an average reduction of 12.87 percent in cooling capacity and 7.6 percent in energy efficiency. Furthermore, an undercharge of about 25 percent would cause an average penalty in SEER of about 16 percent and a cost penalty of US$ 100 per year per ton of rated capacity for typical electricity rates. These penalties could be considered as cost savings associated with improving refrigerant charge levels.

ACKNOWLEGEMENTS

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NOMENCLATURE

A_i	Dependent variable			**Subscripts**
COP	Coefficient of performance			
EEV	Electronic expansion valve		*air*	Air
FXO	Fixed orifice		*cond*	Condensing
h	Enthalpy [J/kg]		*cooling*	Cooling mode
Q	Heat transfer rate	[W]	*evap*	Evaporating
$\dot{m}$	Mass flow rate	[kg/s]	*fan*	Fan
SEER	Seasonal Energy Efficiency Ratio		*heating*	Heating mode
TXV	Thermostatic expansion valve		*in*	Inlet

Power	Power consumption	[W]	*indoor*	Indoor unit
w_A	Total uncertainty		*outdoor*	Outdoor unit
Z_i	independent variables		*rated*	Nominal total
			ref	Refrigerant
			total	Total

REFERENCES

ASHRAE, 1988, Standard 37, "Methods of testing for rating unitary air-conditioning and heat pump equipment", American Society of Heating, Refrigerating, and Air-Conditioning engineers, Atlanta, GA.

ASHRAE, 1995, Standard 116, "Methods of testing for rating seasonal efficiency of unitary air-conditioners and heat pumps", American Society of Heating, Refrigerating, and Air-Conditioning engineers, Atlanta, GA.

Cowan, A., 2004, Review of recent commercial rooftop unit field studies in the Pacific Northwest and California. Northwest Power and Conservation Council and Regional Technical Forum, Portland, Oregon, October 8

Downey, T. and Proctor, J., 2002, "What Can 13,000 Air Conditioners Tell Us?" In Proceedings of the ACEEE 2002 Summer Study on Energy Efficiency in Buildings, 1:53-68. Washington D.C.: American Council for an Energy-Efficient Economy.

Klein, S. A., and Alvarado, F.L., 2001, Engineering Equation Solver (EES), F-Chart Software, Madison. WI.

Kline, S. J., and McClintock, F.A., 1953, "Describing uncertainties in single-sample experiments," Mechanical \ Engineering, Vol.75, pp3-8

Proctor, J. and Downey, T., 1996, "Heat Pump and Air Conditioner Performance", Handout from oral presentation. Affordable Comfort Conference, Pittsburgh, PA, March 26-31.

Proctor, J., 1997, "Field Measurements of New Residential Air Conditioners in Phoenix, Arizona", ASHRAE Transactions ,103(1): 406-415. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Proctor, J. 1998, "Monitored in-situ Performance of Residential Air-Conditioning Systems", ASHRAE Transactions, 104(1): 1833-1840. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.