Design of a High-Efficiency Rooftop Air Conditioner

William L. Kopko, U.S. Environmental Protection Agent y
Douglas Hibberd, Conservation Through Innovation Ltd.

The California Institute for Energy Efficiency (CIEE) and Environmental Protection Agency (EPA) have funded the design and evaluation of a 10-ton high-efficiency air-cooled packaged air conditioner. The target energy efficiency ratio (EER) for the unit is 13 Btu/hour/watt at ARI (Air-Conditioning and Refrigeration Institute) rating conditions. This efficiency represents an improvement of 40 percent compared to conventional designs. The basic approach is to use readily available components to create a cost-effective package. Efficient fans and compressors and generously sized heat exchangers combine to give the improvement in design efficiency. Multiple compressors, improved controls, and variable speed drives on the fans further improve part-load efficiency. These improvements give an estimated integrated part load value (IPLV) of over 17 Btu/hour/watt, which is roughly twice that of a conventional unit. A laboratory testing program will verify performance. Estimated incremental consumer cost of the high-efficiency unit is between $2500 and $4000. Projections show that these efficiency improvements should be cost effective from both utility and customer perspectives.

Introduction

Packaged rooftop air conditioners represent a major opportunity in improving efficiency of commercial buildings. Surveys show that packaged units account for over half of the installed cooling capacity in commercial buildings. Their short life (typically about 15 years) results in a large turnover of equipment. First-cost considerations appear to dominate the current market with the design efficiency of virtually all the models bunched near 9.0 EER. The large retrofit market and combined with large potential for efficiency improvements create major opportunity for reducing energy use, The purpose of the work outlined in this paper is to demonstrate that large efficiency improvements are possible in the design of packaged air conditioners.

Design Objectives and Philosophy

This work is meant to provide a starting point for manufacturers to develop their own designs for efficient packaged air conditioners. The idea is to demonstrate design approaches that manufacturers could introduce quickly with a minimum of engineering. The specific design philosophies that support this objective include:

1. use low-cost, off-the-shelf technology wherever possible,
2. maximize use of common parts with existing products, and
3. minimize maintenance and reliability issues.

Description of the Design

Table 1 compares the new design to a conventional air conditioner.

Specific features of the design include the following:

1. Bigger cabinet: The design uses a standard 15-ton box for a 10-ton unit. The cabinet is the same as a Trane 15-ton unit with minor modifications. This feature allows more space for fans and heat exchangers.
2. Larger and better heat exchangers: The larger face area that is available with the larger box allows for more condenser and evaporator surface while lowering the coil air-side pressure drop. The coils use louvered fins and rifled tubes to maximize heat transfer. Coil circuiting maximizes face area for each circuit to improve heat transfer at part-load conditions.

Table 1. New High-Efficiency Design Compared to a Conventional Packaged Air Conditioner

	Base Unit	New Unit
Overall Unit:		
Model	Trane YC120B3B4BWL	
Net Cooling Capacity (Btu/hr)	119,000	122,000
Input Power (kW)	12.96	9.5
EER	9.2	12.9
IPLV	8.9	17.7
Dimensions (LxWxH in inches)	94x63x49	107x71x50
Number of circuits	2	3
Compressors:		
Type	reciprocating	reciprocating
Number and Size	two 5-ton	two 4-ton, one 2-ton
Condenser Coils:		
Face area (square feet)	14.58	23.96
Row deep	2	2
Fins per inch	16	22
Fin surface	corrugated	louvered
Tubing	plain	rifled
Condensing temperature	n/a	114 F
Condenser Fans:		
Quantity/diameter	one 26-inch	two 26-inch
Description	sheet-metal prop	air-foil prop
Motor hp	one 1 hp	two 0.75 hp
Input power	n/a	1.34 kw
CFM	7200 CFM	10500 CFM
External Δp (inches H20)	0.3	0.3
Total Static Δp (inches H20)		0.65
Evaporator Coils:		
Face area	11.18	17.5
Rows deep	2	3
Fins per inch	15	14
Fin surface	corrugated	louvered
Tubing	plain	rifled
Evaporating Temperature	n/a	51 F
Evaporator Fan:		
Fan type	centrifugal	centrifugal
Impeller Description	Forward Curved	Backward-Curved Airfoil
Input Power	~1.8 kw	0.49 kw
Air flow	4000 CFM	3200 CFM

Note: Performance values are at standard ARI rating conditions (80°F dry-bulb, 67°F wet-bulb temperature of air entering the evaporator with 95°F outdoor temperature).

3. Three compressors for capacity control: The new design uses one two-ton compressor and two four-ton compressors. This configuration gives five steps of capacity control (approximately 20, 40, 60, 80, 100 %). Each compressor has its own refrigerant circuit, which improves reliability. Using three compressors also means that the unit would have at least 60% capacity in case of compressor failure. This approach also takes advantage of high-efficiency compressors developed for the residential market.

4. Improved fan and motor efficiency: The new fans are larger and run slower that the base design, which improves efficiency. A backward-inclined airfoil centrifugal fan replaces the conventional forward-curve evaporator fan. The condenser fans use impellers with airfoil cross-sections to improve efficiency. Motor efficiencies are increased to 85%.

5. Variable-speed fans: The unit includes variable-speed fans for both the evaporator and condenser. This feature provides a major improvement in part-load efficiency.

6. Reduced evaporator air flow: It was found that reducing evaporator air flow by 20% below the maximum value gave better unit efficiency and improved humidity control.

7. Proper expansion valve selection: The thermal expansion valve was selected to give good control over the full range of operating conditions.

8. Evaporative economizer option: This feature can extend economizer operation under warm dry conditions and may be attractive in the western U.S.

There are additional opportunities for energy savings that are beyond scope of this short-term project. Design approaches that could save additional energy include:

1. Evaporative condenser: Using an evaporative condenser can lower the condensing temperature by 20°F or more. An early decision in the project was to stay with an air-cooled condenser. Current evaporative condensers found on larger equipment (usually over 50 tons) require regular water treatment to prevent fouling and other problems. Maintenance costs are typically several hundred dollars per year and would more than offset energy cost savings from an evaporative condenser 10-ton unit. Manufacturers of unitary air-conditioning equipment are generally unfamiliar with design of evaporative condensers, which creates another barrier to quick acceptance. In the long term, development of a low-maintenance evaporative condenser could improve efficiency of the unit by 30 percent or more. More work is necessary to develop such a condenser.

2. Variable-speed compressor(s): We considered using one variable-speed compressor instead of multiple compressors. An important concern with a single compressor is that it would not have any backup capability in case of compressor failure. Cost is also a consideration; variable-speed compressors are specialty items in this size range and are now very expensive. Large-scale production of low-cost variable-capacity compressors should eventually change this situation.

3. Multiple compressors on a single circuit: We seriously considered using four compressors on two circuits as way of achieving efficient capacity control. Letting compressors share the same circuit has the advantage that the heat exchanger surface for the entire circuit is available when any of the compressors are operating. The problem with this setup is that it requires special oil management arrangements to ensure that each compressor receives adequate lubrication under all conditions. Using three compressors on separate circuits allows for greater flexibility in compressor selection and eliminates any concern about how compressors share oil. Using multiple compressors on a single circuit could save additional energy at part-load conditions with proper arrangements for oil return.

4. Three-Row Condenser: Using a three-row-deep condenser coil with fewer fins per inch would improve performance over the current two-row deep design. The main advantage of the two-row coil is that it uses the same supporting structure as the standard 15-ton unit. A better long-term approach would be to modify the sheet metal to allow a three-row coil.

5. Scroll Compressors: Scroll compressors would give approximately the same performance as the reciprocating compressors used in the new design.

Economic Analysis

Table 2 summarizes a comparison of manufacturing costs for the new design compared to a typical 10-ton unit. One uncertainty is the cost add for a conventional 15-ton unit compared to a conventional 10-ton unit.

The difference in selling price between a 10-ton and 15-ton unit gives an upper bound to the cost difference. Data from distributors shows that a 15-ton packaged unit sells for $1400 more than a 10-ton unit. This price difference corresponds to roughly a $500 to $1000 increment in manufacturing cost. A typical distributor selling price for a 10-ton unit is on the order of $5000.

Table 2. Approximate Manufactured Cost Analysis

Standard 10 Ton Unit to Standard 15-Ton Unit	\$400-\$1000
Replace Two 7.5-Ton Compressors with Two 4-Ton and One 2-Ton Compressor	-\$100
Piping and Wiring for Three Small Compressors Instead of Two Larger Compressors	\$100
High-Efficiency Evaporator Fan and Motor	\$300
Variable-Speed Drive for Evaporator Fan	\$125
High-Efficiency Condenser Fans and Motors	\$90
Variable-Speed Drive for Condenser Fan	\$125
Evaporator Coil	\$130
Condenser Coil	-\$60
Controls	\$250
Total Cost Add	\$360 to \$1960

Looking at material and labor cost gives a much lower cost difference. The weight difference between a 10-ton and 15-ton unit is 225 pounds. Material cost for sheet metal, copper, and aluminum is all less than \$1.00 per pound. The assembly labor of the two units should be similar since they contain a similar number of components. Except for a small additional cost for the coils for brazing the additional u-bend joints, the assembly cost should not increase significantly for larger components. This crude analysis shows that the extra material and labor cost is roughly \$300 and \$500. This estimate is a reasonable value for the incremental cost difference to the manufacturer.

The difference between manufactured cost and selling price is a result of profit margins, distributor markup, and other factors. For a given model line, price from a manufacturer is frequently more or less constant in terms of dollars per ton. On the other hand, cost includes a large fixed component that is independent of unit size. This situation means that profit margin is greater on a big unit than on a smaller unit in the same model line. Mark-ups by distributors are usually some percentage of the wholesale price and magnify this effect. The net result is a large increase in selling price compared to the change in manufactured cost. One way to reduce this effect is for any utility incentives to go directly to the manufacturers and reduce the propagation of mark-ups through the distribution system.

The actual change in installed cost to the customer would also include overhead and profit to the manufacturer plus a mark-up from the distributor and the local dealer. Assuming a two to one ratio between final selling price and manufactured cost gives an increment to the building owner of \$2500 to \$4000.

Tables 3 and 4 show that the new design is cost-effective from both utility and customer perspectives. The building owner sees an 18 to 30 percent rate of return with no utility incentives. This rate of return is above the prime plus 6 percent criterion (now ~12%) used in EPA's Green Lights program. A utility avoided cost of \$300/kW and \$0.03/kWh is roughly equal to the high estimate for the incremental cost for the high-efficiency unit. Mass purchases or paying incentives directly to the manufacturer would reduce the cost of the high-efficiency unit and improve the economics.

Table 5 shows how combining energy-efficient packaged units with proper equipment sizing and lighting upgrades could give massive reductions in peak demand. The first step would be to install efficient lighting and reduce cooling load with improvements to the ducts and building envelop. Monitoring the on time of the existing rooftop unit combined with weather data would show how oversized the air-conditioning system is. A new high-efficiency unit would then be installed that closely match the reduced cooling load. This downsizing would, of course, save equipment cost. It would also reduce installation costs by allowing the smaller-capacity, high-efficiency unit to fit in space of the old unit. Reductions in peak demand and energy use of 50% or more are possible with this approach.

Table 3. Economic Analysis of a High-Efficiency 10-Ton Packaged Unit from the Perspective of a Building Owner

	Base Unit	New Design	Savings
EER	9.2	13	
Design kW	13.04	9.23	3.81
IPLV	8.9	17	
Annual Operating Hours	1500	1500	
Electric Rate ($/kWh)	0.08	0.08	
Annual energy use (kwh/yr)	20225	10588	9636
Annual electric bill	$1,618	$847	$771
Present value of savings (12% discount, 15 year life)			$7,487
	high cost estimate	low cost estimate	
First cost increment	$4,000	$2,500	
Payback period in years	5.19	3.24	
Return on investment	18%	30%	

Table 4. Value of Energy and Demand Savings to a Utility

	Avoided Cost for Peak Demand ($/kW)			
Avoided Cost for Energy ($/kwh)	0	200	300	500
0	$0	$763	$1,144	$1,906
0.02	$1,872	$2,634	$3,016	$3,778
0.03	$2,808	$3,570	$3,952	$4,714
0.05	$4,680	$5,442	$5,823	$6,586

Assumptions:
discount rate = 0.06
equipment life in years = 15
annual energy savings = 9636 kWh
peak kw savings = 3.81 kW

Conclusions and Future Work

A packaged air conditioner with an EER near 13 and an IPLV over 17 is feasible using existing technology. Estimated incremental manufacturing cost is roughly $1500 which corresponds to a cost to the building owner of approximately $3000. These estimates show that the design would be cost-effective from both utility and customer perspectives.

Future work will involve building and testing a prototype unit based on this new design. The unit will be first tested with HCFC-22 to compare actual performance to predictions. Additional tests with an HFC (hydrofluorocarbon) blend will show how the unit performs with a chlorine-free refrigerant.

Table 5. Combining Upgrades to Lighting and Rooftop Unit

	Old System	Upgrade	Savings
Building Floor Area in Square Feet	4500	4500	
Rooftop Unit:			
Nominal Capacity in Tons	15	10	
Actual Design Load in Tons	12	9.96	
EER	9	13	
Unit peak kw	20	9.23	10.77
Lighting:			
Lighting W/ft^2	2.5	0.9	
Lighting kw	11.25	4.05	7.20
Total kw	31.25	13.28	17.97
Percent Savings in Peak Demand			58%