Small Commercial Rooftops: Field Problems, Solutions and the Role of Manufacturers

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Synopsis

Small commercial HVAC systems are notorious for consuming more energy than is necessary to properly heat, cool, and dehumidify buildings. The electrical and natural gas energy wasted as a result of poorly integrated and operating small commercial HVAC systems in California is assumed to be quite significant. One element of a Public Interest Energy Research (PIER) project is investigating inefficient design and installation practices in small HVAC systems, and recommending strategies for solving these problems. Fieldwork conducted by the project includes short term monitoring of HVAC systems and on-site surveys of the buildings served by these systems. A total of 75 buildings and 215 roof top units were studied. Problems with equipment and controls (economizers, fan controls, thermostat programming), in-situ air flow and fan power, refrigerant charge, and operation/maintenance practices that lead to poor system performance were identified.

Solutions to these problems rest in the hands of market actors up and down the building design, construction and maintenance chain. This paper focuses on specific actions manufacturers can take to improve the overall installability and reliability of their product. Issues like fault-tolerant design, self-tuning diagnostic controllers, and enhanced reliability specifications are presented. A national initiative to develop a specification for improved packaged HVAC system controls addressing these issues is also discussed.

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Introduction

The New Buildings Institute (NBI) is conducting a Public Interest Energy Research (PIER) project for the California Energy Commission (CEC). NBI's project is called Integrated Energy Systems - Productivity and Buildings Science Program. As the name suggests, it is not individual building components, equipment or materials that optimize energy efficiency. Instead, energy efficiency is improved through the integrated design, construction and operation of building systems. The overall project has several elements, covering HVAC, thermal distribution, daylighting/skylighting, ceiling systems, and exterior lighting systems. The focus of the project described here is on small HVAC systems for commercial buildings. This element of the project was conducted for NBI by Architectural Energy Corporation, with field engineering support by RLW Analytics.

Why Small HVAC?

The distribution of HVAC system types present in new commercial buildings in California, by floor area served, is shown in Figure 1 below:

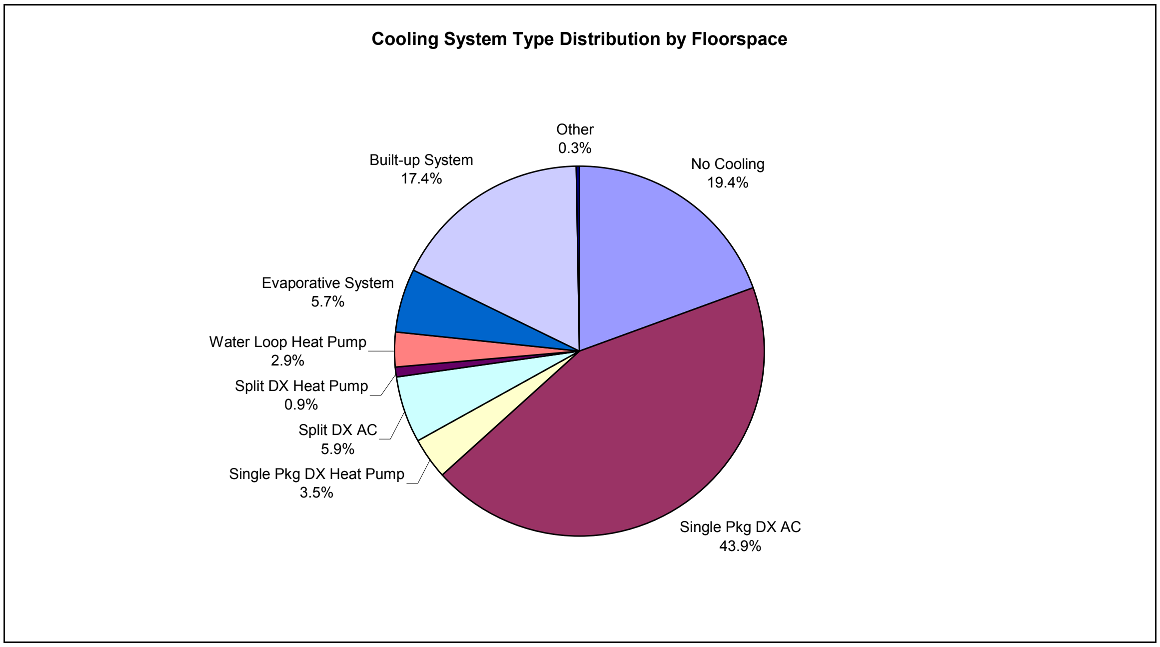

Figure 1: Floorspace Distribution of HVAC Systems in Commercial Buildings

Note that single package DX air conditioners are the most popular HVAC system type in new construction in the State, cooling about 44% of the total floorspace. The combined total of single package and split DX air conditioners and heat pumps represents slightly more than half of the total floorspace in the state. Note that a significant portion (about 19%) of the total NRNC floorspace is not cooled. The size distribution of packaged DX systems, in terms of number of systems installed, is shown in Figure 2.

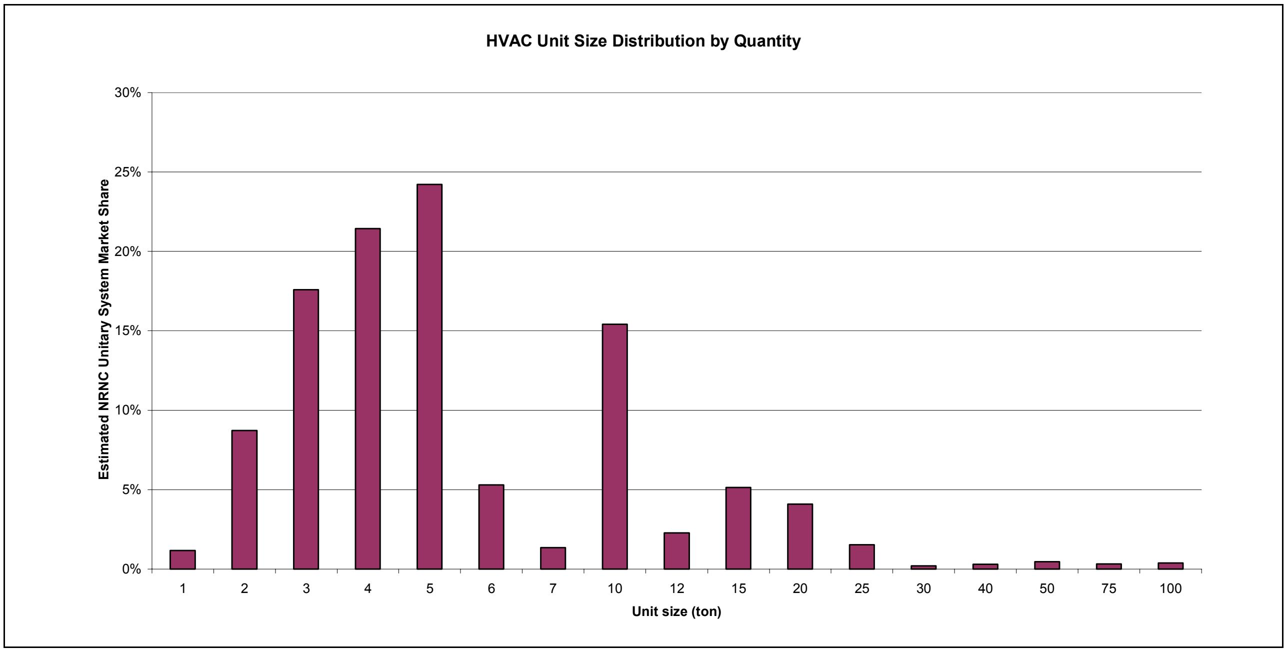

Figure 2: Distribution of Packaged DX System Size by Number of Systems

From the figure above, the most popular packaged DX system size is five tons. Units between one and 10 tons represent close to 90% of the total unit sales in new buildings in California. These small rooftop units are the "workhorses" of the commercial building industry, yet many systems fail to reach their full potential due to problems with design, installation, and operation.

Field Testing

To conduct this research, teams of engineers visited 75 newly constructed commercial buildings throughout California. A total of 215 rooftop units were surveyed. Units were subjected to a physical inspection, a series of one-time tests, and short-term monitoring of unit performance. Up to four units per building were selected for study.

Onsite survey

The on-site survey gathered information on building shell, lighting, internal loads, operating schedules, and so on, sufficient to develop a DOE-2 model of each space served by the treated units. Development of the DOE-2 model was facilitated by the SurveyIT/ModelIT software package developed by AEC. Building characteristics data was entered into a Microsoft Access database by the surveyor. The building characteristics data was read by the software, and a DOE-2 model was automatically developed from this data. This process greatly reduced the time required to develop a simulation model, allowing the AEC/RLW team to create models for each space served by each unit studied within the time and budget constraints of the project. The models are created from a series of rules embedded in the software, providing a consistent modeling approach across all sites and surveyors.

Besides basic building characteristics data, thermostat make and model data were collected to see if the thermostats were appropriate for commercial building applications. The thermostat control settings were observed and the calibration of the thermostat sensor was checked. Thermostat location was noted and compared to the spaces served by the system.

One-time tests

The second level of data collection involved a series of one-time tests conducted on the units selected for study. These tests are described below.

Fan flow and Power

The unit was cycled through each mode of operation (standby, fan-only, cooling stage one, and cooling stage two, if applicable) and the true electric power and current of the unit were measured during each mode using a portable wattmeter. Airflow rate was measured using a flow grid, which is an averaging flow meter designed to be installed in place of the filters. A digital micromanometer measures the pressure drop across the plate, and reads out directly in cfm. The manometer was also used to measure supply static pressure, return static pressure, and total unit external static pressure.

Economizer

If the unit had an airside economizer, the minimum outdoor air position potentiometer was adjusted to test the operation of damper motors and linkages. The economizer outdoor air temperature sensor was cooled down using a “cool” spray, simulating cool outdoor air conditions and the response of the economizer was observed.

Refrigerant charge

Service gauges and temperature sensors were used to verify the state of charge of the rooftop unit using the CheckMe![1] Procedure. The high side and low side pressures were measured, along with the suction line temperature, the condensed liquid temperature, outdoor drybulb temperature entering the condenser, and drybulb and wet bulb temperature entering the evaporator coil. Refrigerant was added or removed from the system until the suction line superheat on units with fixed metering devices, or the condenser line subcooling on units with thermostatic expansion valves (TXV), was within the target specified by the CheckMe! software.

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[1] CheckMe! is a product of the Proctor Engineering Group, San Rafael, CA.

Short Term Monitoring

Finally, selected units were monitored over a two to three week period using portable, battery-powered data loggers to observe unit operation over a variety of operating conditions. An AEC MicroDataLogger (MDL) was installed in each unit selected for the study. The MDL measured unit current, supply air temperature, return air temperature, and mixed air temperature. The data was stored on a five minute basis. The MDL uses thermistor sensors with a 0.5°F accuracy over the full range. The current sensors were equipped with signal conditioning equipment to provide true RMS current readings. True RMS current measurements were coupled with the spot kW and current measurements to estimate time series kW data for the unit. In addition to the MDL installed at each unit, the local rooftop temperature and humidity was monitored at each site.

AEC Enforma diagnostic software was used to analyze the short-term monitored data. Problems were identified based on the results of each test. An example of an economizer diagnostic plot resulting from the short-term monitored data is shown in Figure 3 below:

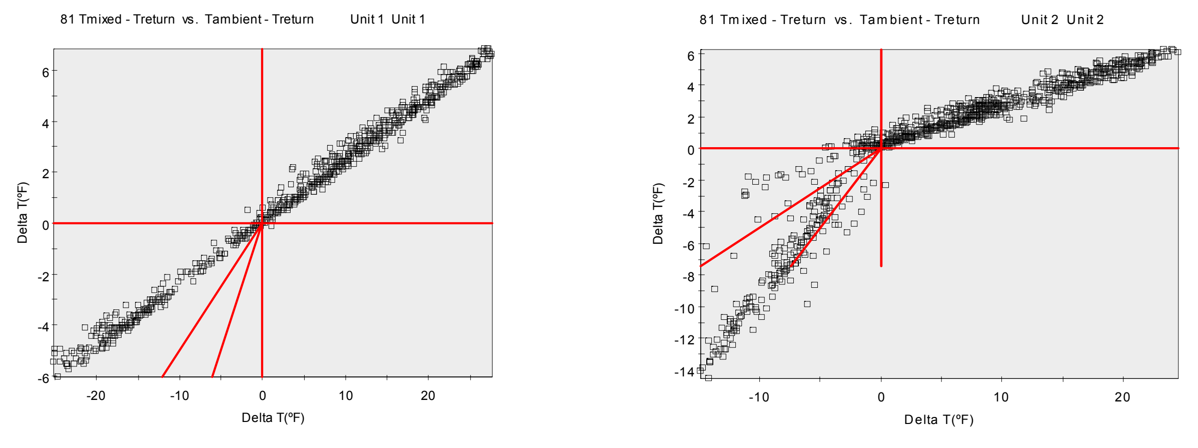

Figure 3: Economizer diagnostic plots.

The diagnostic software plots short-term monitored data in various formats to help diagnose system problems. To observe economizer operation, the difference between the cooling coil entering (i.e. mixed) air temperature and the return air temperature (Tmix – Treturn) on the vertical (Y) axis is plotted against the difference between the outdoor (ambient) temperature and the return air temperature on the horizontal (X) axis. The slope of the line is equal to the outdoor air fraction. Units with fixed outdoor air (no economizer) have a straight line relationship between these data, as shown in the chart on the left. Units with functioning economizers show a characteristic change in the slope of the line to the left of the vertical (Y) axis, as shown in the chart on the right. The slope in this region is equal to one, indicating a functioning dry bulb economizer allowing 100% outdoor air.

Findings

The NBI Pier project identified a number of problems with HVAC systems as they are installed and operated in the field. Problems identified include broken economizers, improper refrigerant charge, fans running during unoccupied periods, fans that cycle on and off with a call for heating and cooling rather than providing continuous ventilation air, low air flow, inadequate ventilation air, and simultaneous heating and cooling. A summary of the finding from the study is shown in Figure 4.

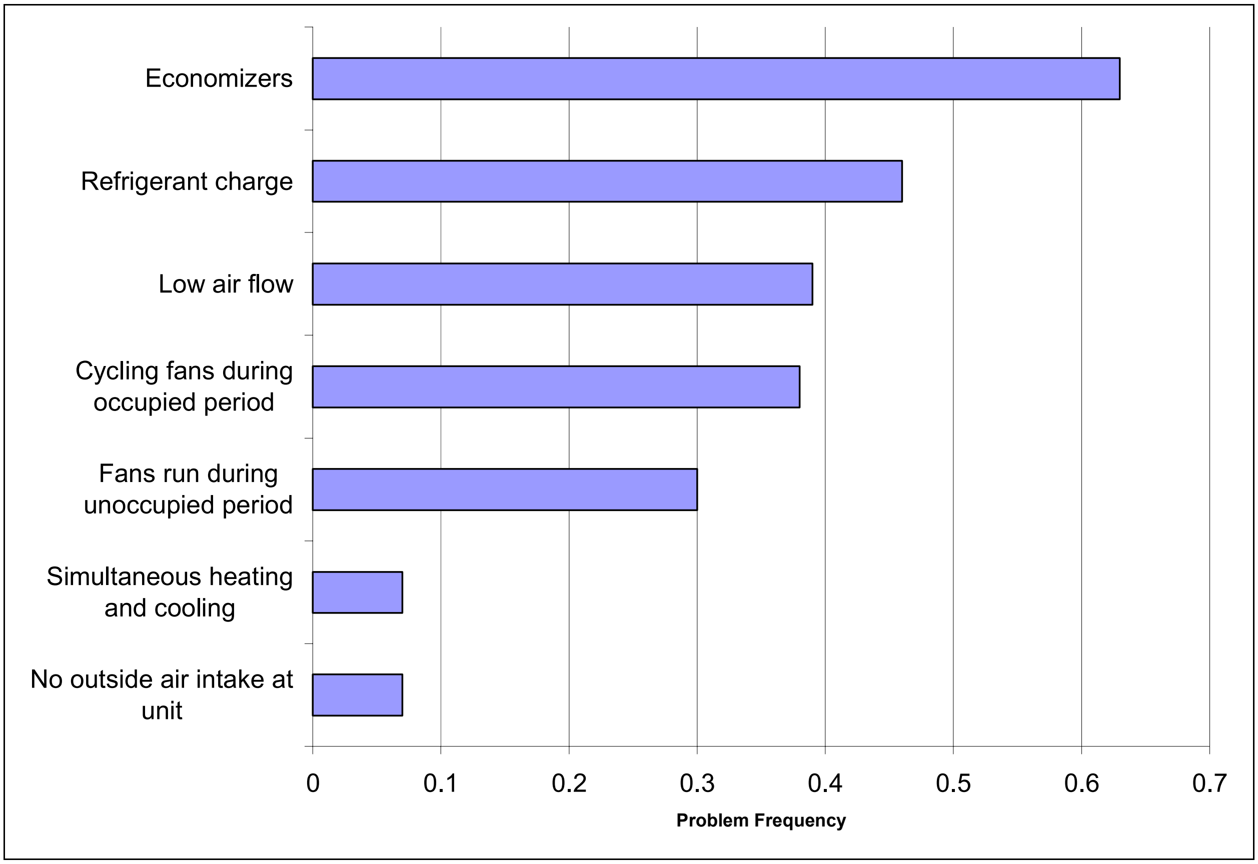

Figure 4: Frequency of problems encountered in the NBI study on small commercial HVAC systems.

Economizer Findings

Economizers show a high rate of failure in the study. Of the 215 units tested, 123 units were equipped with economizers. Of these, 30 units (24%) would not move at all, 36 units (29%) did not respond to the cold spray test, and an additional 13 (10%) displayed poor operation during the short-term monitoring period. Differential enthalpy economizers were the most popular style. According to the Title 24 Energy Standards, single point enthalpy economizers should use the "A" changeover setpoint, but this was rarely the case.

Refrigerant Charge

Target superheat or subcooling values were tested using the CheckMe! procedure. Any test not meeting the target temperature within five degrees failed the screening test. Of the 74 refrigerant tests, 33 (46%) did not pass the screening test. Refrigerant was added or removed from the system until the target value was reached. The charge variation was calculated based on the weight of refrigerant adjustment compared to the total refrigerant charge. A frequency distribution of the charge levels observed in the study is shown in Figure 5. The energy impact of the charge variation was calculated according to Farazad and O'Neal[2]. The average energy impact (not including units that were fully discharged and obviously leaking) was about 5% of the annual cooling energy.

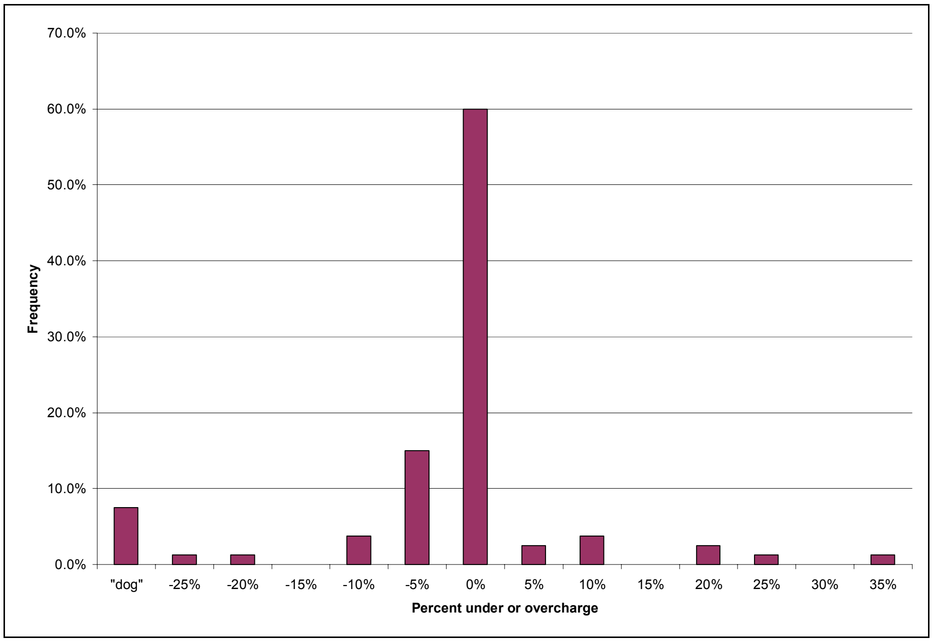

Figure 5: Frequency distribution of refrigerant charge.

Air Flow and Fan Power

Units were tested for in-situ airflow using flow grids. The distribution of the measured airflow is shown in Figure 6. Overall, of the 79 units tested for airflow, 28 (39%) had airflow less than 300 cfm/ton. The average airflow rate was 325 cfm/ton. ARI standards are based on airflow rates of 400 cfm/ton. The annual energy impact of low airflow is about 9% of the annual cooling energy. The measured fan power at the in-situ flow rate was 0.18 kW/ton, which is about 20% higher than the nominal fan power assumed in the Title 24 energy standards (365 W/cfm or about .15

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[2] Farazad and O'Neall, "Performance Characteristics Under a Range of Charging Conditions" ASHRAE Transactions, Vol. 99, 1993.

kW/ton). If the fan flow is increased to 400 cfm/ton, the fan power will increase to 0.34 kW/ton. This increase effectively drops the efficiency of a 10.3 EER unit to 9.1.

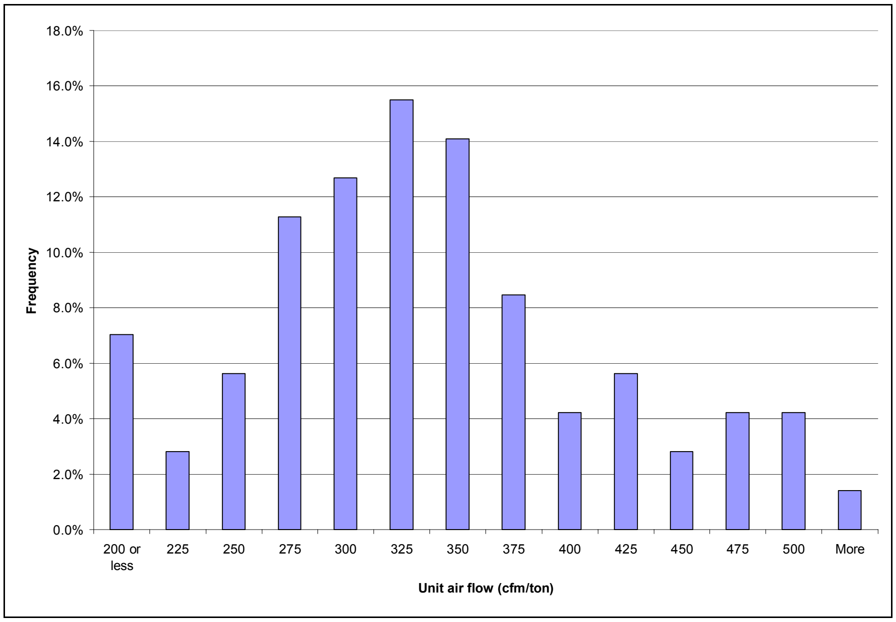

Figure 6: Frequency distribution of unit air flow rate.

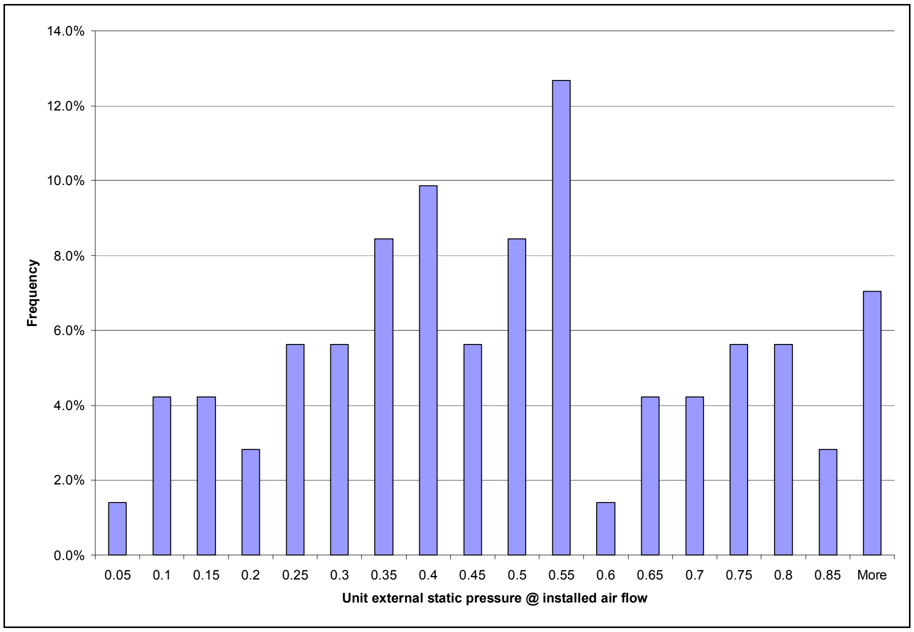

Figure 7: Frequency distribution of unit external static pressure.

The combination of high fan power and low flow rate is due largely to excessive pressure drop in the duct systems. The frequency distribution of unit external static pressure at the measured flow rate is shown in Figure 7. The average duct system pressure drop was 0.48 in WC. ARI efficiency ratings assume a duct system pressure drop of 0.1 to 0.25 in WC, depending on the system size. The average duct system pressure drop corrected to 400 cfm/ton would equal 0.625 in W.C., which is outside the capability of most fans used in small packaged systems.

Thermostats

System fans were found to be cycling on and off with a call for heating or cooling in 38% of the units tested. The Title 24 Energy Standards require that all buildings not naturally ventilated with operable windows or other openings be mechanically ventilated. Mechanical ventilation is required to occur at least 55 minutes out of every hour that the building is occupied. Building outdoor ventilation air is typically supplied during fan operation, with the minimum quantity of outdoor air determined by the outdoor air damper minimum position. The supply of continuous fresh air during occupied hours relies on continuous operation of the HVAC unit supply fan. The Standards further require operation of the ventilation system at least one hour before normal building occupancy in order to purge potential build-up of pollutants and out gassing from furniture, carpets, paint, etc.

Most of the thermostats surveyed were observed to be "commercial" type thermostats capable of controlling the systems according to the Title 24 and ASHRAE standards. These units can be set up to program fan schedule and mode independent of thermostat schedule. Failure to operate the building with a continuously operating fan can reduce the effective ventilation rate significantly, as shown in Figure 8.

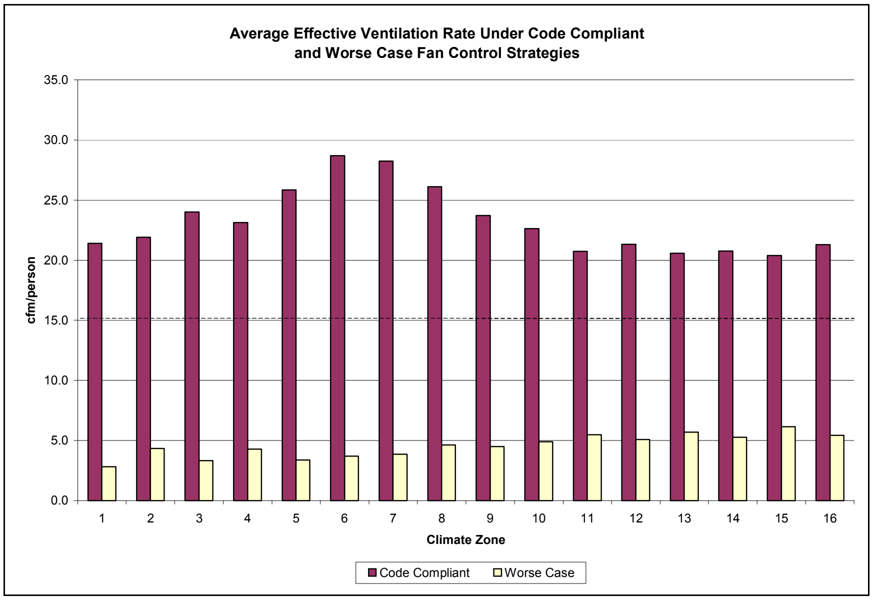

Figure 8: Effective ventilation rate for HVAC units with continuous and cycling fans.

In both cases shown above, the minimum outdoor air damper is set to provide 15 cfm/person of outside air. The code compliant case used continuous ventilation and an air-side economizer.

Economizer operation increased the effective ventilation rate above the nominal 15 cfm/person rate. A unit not equipped with an economizer and operated with cycling fans provided an effective ventilation rare of less than 5 cfm/person in most climate zones.

Potential Solutions and the Role of Manufacturers

Solutions to these problems rest in the hands of market actors up and down the building design, construction and maintenance chain. Equipment manufacturers are in a unique position to address many of these problems through product design changes and reliability improvements. Although many installation problems can be corrected during commissioning, and reliability problems can be corrected during normal operations and maintenance or recommissioning activities, it may be more effective to also address these problems at the product design level. The following is a list of suggestions for how manufacturers can improve the design of their product to avoid some of the problems encountered in the study:

- Improved economizer design. New designs feature direct drive actuators and damper blades driven by gears instead of linkages. These designs improve the mechanical reliability of the product by reducing the number of moving parts. Special connectors on the economizer controller terminal block can be used to prevent reversed polarity on sensors and actuators.
- Standard test for economizer reliability. A performance-based test of economizer reliability can be developed to evaluate economizer designs. Similar tests exist for smoke dampers. This test could be incorporated into the ARI performance test standard.
- Factory installed economizers. The majority of the economizers are installed in the field or at the distributor, even though most manufacturers offer factory-installed economizers. The failure rate of factory-installed economizers in this study was quite low. This may be due to the run test conducted at the factory prior to unit shipment. Promoting factory-installed economizers can improve reliability by avoiding field installation and wiring errors.
- Fault tolerant design. Encourage design features that minimize the impact of system problems on the energy performance of the system. An example is the use of thermostatic expansion valves, which allow the unit to perform at reasonable efficiency over a wide range of refrigerant charge.
- Unit self-diagnostics. There is a limit to what one can expect an HVAC service technician to accomplish during a service call. Built-in diagnostics can help the technician quickly and accurately diagnose and repair problems. Many problems go unnoticed by the occupants until they become so bad that the unit fails catastrophically. Diagnostic systems with occupant or service company alarm capability can help identify and fix problems before they get worse. It also prevents unneeded service procedures from degrading an otherwise well operating system. Recent research conducted by Purdue University under a concurrent PIER Program[3] has developed algorithms to detect

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[3] See http://aes1.archenergy.com/cec-eeb/

five common faults. Strategically located temperature probes are the only additional sensors required. Ongoing research shows promise of detecting more faults simultaneously using a power measurement and a "compressor map."

- Develop a labeling program to identify and certify thermostats for commercial building applications. Require that labeled thermostats have the capability to meet the commercial ventilation control strategy requirements, including continuous ventilation during occupied hours, one hour building purge prior to occupancy, and night space temperature setback with fans off during unoccupied periods.
- Develop rooftop units with a ventilation-only operating mode. Providing continuous ventilation through the rooftop unit supply fan may not be the most cost-effective method for introducing outside air in small commercial buildings. One option to provide ventilation during periods with no heating or cooling load is to use a multi-speed or electronically commutated motor on small roof top unit supply air fans. The multi-speed motor allows the fan speed to be set back to where it is just meeting minimum ventilation requirements when the unit compressor(s) is not running. This strategy would require that the unit have an economizer that would open to supply 100% outdoor air when the unit is operating at low fan speed.

In order to encourage these design changes, an incentive must also be provided to the manufacturers to give them a reason to invest in the engineering and tooling for new designs. Since these improvements will likely increase the cost of the units, incentive programs offered by utilities, and branding programs such as Energy Star, can be used to define, identify, and recognize products that meet performance and reliability goals.

Currently, the New Buildings Institute (NBI) and AEC are working with the Consortium for Energy Efficiency (CEE) to draft an initiative to develop a national specification for a high performance small package HVAC unit. CEE is a non-profit, public benefit corporation that actively promotes the use of energy-efficient products and services through its members, including electric and gas utilities, public benefit administrators (such as state energy offices, non-profit organizations, and regional energy groups), and research and development laboratories. CEE members voluntarily adopt common performance specifications and program strategies with the goal of permanently increasing the supply and demand of energy-efficient products and practices. Although currently under discussion, this initiative will likely develop a set of specifications for a high performance rooftop unit that address unit efficiency, controls, reliability, and other performance attributes that have broad applicability across the nation. The national performance specification will be developed for consideration by CEE's Hi Efficiency Commercial Air Conditioning (HECAC) Committee. If the Committee approves the concept and content of the specification, a proposal will be presented to the CEE Board for approval of a national initiative to advance market development of an advanced packaged rooftop unit. The goal of this work is to develop a national market for an advanced rooftop unit through the promotion of the product in efficiency programs conducted by CEE member organizations.