Measuring Advances in HVAC Distribution System Design

Ellen Franconi
Lawrence Berkeley National Laboratory, Berkeley, CA

Abstract

Substantial commercial building energy savings have been achieved by improving the performance of the HVAC distribution system. The energy savings result from distribution system design improvements, advanced control capabilities, and use of variable-speed motors. Yet, much of the commercial building stock remains equipped with inefficient systems. Contributing to this is the absence of a definition for distribution system efficiency as well as the analysis methods for quantifying performance.

This research investigates the application of performance indices to assess design advancements in commercial building thermal distribution systems. The index definitions are based on a first and second law of thermodynamics analysis of the system. The second law or availability analysis enables the determination of the true efficiency of the system. Availability analysis is a convenient way to make system efficiency comparisons since performance is evaluated relative to an ideal process.

A TRNSYS simulation model is developed to analyze the performance of two distribution system types, a constant air volume system and a variable air volume system, that serve one floor of a large office building. Performance indices are calculated using the simulation results to compare the performance of the two systems types in several locations. Changes in index values are compared to changes in plant energy, costs, and carbon emissions to explore the ability of the indices to estimate these quantities.

Introduction

The design and operation of the HVAC thermal distribution system can have significant effect on a commercial building energy consumption. Monitored performance data show that replacing a dual-duct constant air volume (CAV) system with a variable air volume (VAV) system in a university engineering center dropped fan motor electricity use by 50% in the swing season.(Claridge, et al. 1991). The Texas LoanSTAR program has implemented operation and maintenance measures on several buildings with dual duct systems to tune control strategies and optimize HVAC system operation. Calibrated HVAC systems models reveal that these measures can reduce the building energy cost from 10% to 60% (Liu, et al. 1994). Tuning the state of the art controls in a building's VAV system as part of an ASHRAE research project saved over 25% of the HVAC energy consumption (Bradford 1998).

National trends for new construction show that VAV systems have been the dominate system type installed in new commercial building since 1985 (Pietsch 1991). But other stock characterizations reveal that a large percentage of existing systems are CAV. Data from California utility surveys show that the most common distribution system type found in large offices (the predominant building type with central systems) is CAV systems (40%). VAV systems in large offices in California account for only 20% of installed systems (Modera, et al. 1996).

Based on performance and stock characterization data, there are significant opportunities for reducing building energy consumption by improving distribution system performance through design and control modifications. To encourage these improvements, analysis methods for assessing the effective use of energy in thermal distribution systems are needed. Determining system efficiency is important for evaluating new system designs, identifying effective operating strategies, developing commissioning benchmarks, tracking performance, and establishing standards.

This paper evaluates how performance indices can be used to make meaningful performance comparisons between systems. Typically, index definitions are based on a specific energy type, i.e. thermal or mechanical energy. This research investigates the use of indices using a different accounting system – available work rather than energy. "Availability" is determined using second law of thermodynamic analysis techniques. "Energy" is determined from a first law analysis. Second law analysis is a powerful and convenient way to make system efficiency comparisons since performance is evaluated relative to an ideal process. Second law analysis provides more accuracy than a first law energy analysis when the input energy/fuel streams are a different "quality" than the output streams (i.e. mechanical verses thermal).

The objective of this paper is to apply the concepts of availability to develop a second law based performance index for distribution systems. First and second-law based indices are evaluated to determine their ability to estimate reductions in plant energy use, energy costs, and carbon emissions. Two types of air systems serving a large office building are analyzed.

Background

The thermal distribution system includes the components that carry the heating and cooling needed to provide building space conditioning. In an all-air system, the components may include: ducts, cooling coil, heating coil, supply fan, exhaust fan, zone box reheat coils, and zone box fans. In an all-water system, the components may include: piping, pumps, induction units, and fan-coil units.

Performance indices or energy performance ratios provide benchmarks to evaluate and make design comparisons. In this paper, the term performance index includes performance efficiencies as well as other ratios that provide a useful measure of energy utilization in thermal distribution systems in commercial buildings. Typically, performance indices are defined separately for different types of energy. For thermal distribution systems, two types of energy are supplied - thermal (coils) and mechanical (fans).

This analysis uses two indices, one thermal and one mechanical, to make performance comparisons. It also investigates using "overall" indices. One of the overall system performance indices is the second law system efficiency. A second law analysis uses a thermodynamic basis to equate heat to work. Thus mechanical and thermal energy sources can be combined in a meaningful way to make performance comparisons. The energy-type and overall-system performance indices are discussed below.

Energy-Type Indices

Several performance indices have been proposed to assess thermal energy use in commercial building distribution systems (Jagemar 1994, Kreider and Rabl 1992, Reddy, et al. 1994). Terms have also been developed for residential systems (Jump, et al. 1996, Palmiter and Francisco 1996). Recently, design standards and analysis methods have been established for residential distribution systems by ASHRAE. Due to the design and operation differences, commercial distribution systems require different analysis techniques than residential systems. Performance issues most relevant to large building systems include diverse loads, coincident cooling and heating, duct/piping design, and sophisticated controls. In reheat systems, diverse loads result in cooled supply air being reheated at the zone. Because of this "thermal mixing", the heating and cooling loads imposed on the plant by the system can be much greater than the amount of heating and cooling delivered to the zones

One index evaluating commercial building distribution system thermal performance is called the energy delivery efficiency (EDE) (Reddy, et al. 1994). The index indicates the amount of thermal mixing or terminal reheating in single duct systems. It is equal to the ratio of the energy required to condition the space and the sum of the measured coiling coil and heating/reheat coil loads of the system serving the space. In this analysis, an annual EDE is determined for a system serving five zones comprising one floor of a large office building. The EDE is calculated from the following equation.

$$EDE_{5-Zone} = \frac{\sum_{hr=1}^{8760}\left[\sum_{z=1}^{5}\left|zone\_load_z\right|\right]}{\sum_{hr=1}^{8760}\left[\left|cool\_coil\_load\right| + \sum_{z=1}^{5}\left|reheat\_load_z\right|\right]} \tag{1}$$

The numerator is the total energy supplied to the five zones over the year. The denominator is the system central cooling coil and zone reheat coil loads. The loads are defined only for hours when the system is "on".

Jagemar has given examples of performance indices for analyzing the efficiency of HVAC systems and subsystems (Jagemar 1994). Two indices he describes for air distribution system performance are the specific fan power (SFP) and the utilization factor (UF). Both focus on the mechanical efficiency of the distribution system. The SFP is the design power divided by the design air flow rate. The UF indicates the fraction of energy consumed by the fan of a VAV system compared to that of a CAV system. In this analysis, the annual UF is used to measure fan performance and is determined by equation (2). For the CAV system, the UF is set equal to one.

$$UF = \frac{fan\_energy_{VAVsystem}}{fan\_energy_{CAVsystem}} \tag{2}$$

Overall Indices

Two overall system efficiencies are calculated in this study. One is based on a first law of thermodynamic analysis, the other on a second law analysis.

First Law Efficiency. The first law efficiency is the ratio of the energy output by the system to the energy input to the system. The energy output is equal to the building zone loads. The energy input is the cooling coil load, reheat coil loads, and fan energy. Equation (3) is used to calculate the annual average first law efficiency.

$$\eta_I = \frac{\sum_{hr=1}^{8760}\left[\sum_{z=1}^{5}\left|zone\_load_z\right|\right]}{\sum_{hr=1}^{8760}\left[\left|cool\_coil\_load\right| + \sum_{z=1}^{5}\left|zone\_load_z\right| + fan\_energy\right]} \tag{3}$$

Second Law Efficiency. According to the first law of thermodynamics, energy is conserved and cannot be destroyed. The second law states that something useful can be destroyed - the quality of the energy in the system. This commodity is know as availability. It has also been termed available-energy, exergy, utilizable energy, essergy, and potential energy (McGovern 1990). It has the same units as energy and work. Availability is that part of energy that can be transformed to produce useful work. Useful work is defined as work that can cause a mass to be lifted, a spring compressed, or a flywheel accelerated. While the first law of thermodynamics tracks the energy flows associated with a system, the second law enhances the energy balance by quantifying lost work potential.

Available energy is a property that measures a substance's maximum capacity to cause change. The capacity exists because the substance is not in equilibrium with the environment. In evaluating a substance's availability, it is necessary to define the environment reference state or dead state. In this analysis, the reference state is always taken to be the ambient conditions. Availability is a co-property of a substance. It is associated with a mass quantity or flow across a system boundary. It is also associated with energy transfers from thermal, mechanical, and chemical sources.

An availability balance is conducted like an energy balance. One difference though is that availability is not conserved. The availability balance includes a consumption term to account for availability lost from non-reversible processes. Availability is not destroyed in ideal processes that are reversible. In real processes, availability is expended so that equipment may be of finite size and processes may occur over a finite time period. Determining where the lost and destroyed availability occurs in the system indicates where the greatest opportunities for performance improvements are.

The availability "in" to an HVAC distribution system component is the availability associated with the inlet flow stream and energy transfers. The availability "out" is the exit flow stream availability. If no losses occur, the difference is the destroyed availability.

In general, second law efficiency is defined as

$$\eta_{II} = \frac{\dot{A}_{out}}{\dot{A}_{in}} = \frac{\dot{A}_{in} - \dot{A}_{lost} - \dot{A}_{destroyed}}{\dot{A}_{in}} \tag{4}$$

and the upper limit of its value is one. The value can only be one for ideal processes that are thermodynamically reversible.

An important consideration in calculating a second law efficiency is defining what the useful product is and identifying those streams considered losses. A meaningful way to compare the performance of different systems performing the same function is to calculate their "task efficiency". A second law task efficiency is the ratio of the minimum availability required to accomplish some task compared to the actual availability supplied. The task efficiency for the CAV and VAV distribution systems is defined in equation (5). It as the ratio of minimum availability required to meet zone loads to the availability supplied to the system by the cooling coil, reheat coils, and fans. The task availability or numerator value is independent of system type but is dependent on the building and location.

$$\eta_{II} = \frac{\sum_{hr=1}^{8760}\left[\sum_{z=1}^{5} zone\_avail_z\right]}{\sum_{hr=1}^{8760}\left[cool\_coil\_avail + \sum_{z=1}^{5} reheat\_avail_z + fan\_avail\right]} \tag{5}$$

Availability analysis provides a common accounting system for evaluating processes that use fuels of different qualities and/or produce products of different qualities than the supply fuels. Energy sources that have the same energy content may not have the same capacity to cause change. For example, a thermal source transferring 100 W of energy can not produce 100 W of useful work while a mechanical shaft transferring 100 W of energy can. A first law of thermodynamic analysis or energy balance reveals acceptable designs for a system or component. It is used only as an approximation of the actual efficiency of the process. A comparison of first and second law efficiencies for several processes is presented in Table 1 (Reistad 1980).

A first law efficiency for evaluating electric and fossil fuel heating applications is a particularly poor indication of actual performance. Since thermal distribution system performance is dependent on both thermal and mechanical potentials and the products are of a different quality than the fuels supplied, it is necessary to complete a second law analysis to accurately evaluate efficiency.

Availability Calculations. The determination of the quantity of availability transferred to the system depends on the form of energy transfer. The calculation of the availability transfer associated with mechanical energy is straight forward. It is equal to the useful work or shaft work that crosses the system boundary. For a fan powered by electricity, the rate of availability transfer to the air stream is equal to product of the electrical power drawn, the motor efficiency, and the fan efficiency. The availability supplied to the fan though, is equal to the electrical power drawn. Thus for fans, the input availability is equal to the input energy.

The availability associated with a thermal transfer is the quantity of work that could be produced from the heat flow by a perfect thermodynamic device, i.e. a ideal heat engine or a Carnot Cycle. For example, the availability or the ideal mechanical power that would be required to supply a building with a stream of heated air can be determined by calculating the work that must be supplied to a series of ideal heat pumps to accomplish the task (Kelvin 1852). The availability of the process is determined from equation (6) (Moran 1989). In the equation, the availability of the flow stream is determined in reference to the dead-state temperature T_o.

$$\dot{A} = \dot{m}C_p \int_{T_o}^{T} \left(\frac{T - T_o}{T}\right) dT = \dot{m}C_p \left\{ (T - T_o) - T_o \ln\left(T/T_o \right) \right\} = Q\left\{ 1 - \frac{T_o}{T - T_o} \ln\left(T/T_o \right) \right\} \qquad (6)$$

Equation (6) is used to determine the task availability associated with the building zone loads. In the calculation, the zone load is Q, the zone temperature is T, and the ambient temperature is T_o.

In evaluating distribution system performance, a form of (6) can be used to evaluate the availability provided by a heat exchanger flow stream. Equation (7) describes the availability associated with the heat transfer at the cooling and reheat coils in the distribution analysis. Temperatures T_2 and T_1 are the water outlet and inlet temperatures in the coil, ***m*** is water flow rate, and C_p is water heat capacity .

$$\dot{A} = \dot{m}C_p \int_{T_1}^{T_2} \left(\frac{T - T_o}{T}\right) dT = \dot{m}C_p \left\{ (T_2 - T_1) - T_o \ln\left(T_2/T_1 \right) \right\} \qquad (7)$$

Methodology

Performance comparisons are made for two types of all-air systems; CAV and VAV. Both systems have economizers and reheat. The system serves five zones – four perimeter and one core. The zones comprise one floor of a ten story, 150,000 square feet office building. The system performance for the prototypical large office is evaluated for three locations; Chicago, IL, Washington DC, and Charleston, SC. These three climates were selected because they represent the population-weighted average climate in the north U.S., in the U.S., and in the south U.S., respectively. The system performance is evaluated using a TRNSYS simulation model developed for this study. Specifically, the model is used to calculate the hourly energy and availability flows of the system.

In the TRNSYS model, system equipment and control components were adapted from FORTRAN subroutines developed in ASHRAE's HVAC Secondary Toolkit (Brandemuehl, et al. 1993). Also new components were written to model an open plenum return, and the CAV and VAV zone boxes. New components were also developed to perform the availability calculations. The distribution system simulation uses a one-hour time step.

In the simulation, the outdoor air ventilation rate is a constant percent of supply air flow rate, set at 12%. The system economizer is based on fixed-temperature control. The economizer is operational at ambient temperatures below 15.6°C (60°F). The cooling coil control is simple; a constant supply air set point temperature of 12.8°C (55°F) is maintained. The supply and return fans in the VAV system have variable speed drive control. For the VAV system, the minimum turndown of the boxes is 50%.

The office building loads were not calculated within TRNSYS but provided as input to the system simulation. The hourly loads were determined for a prototypical office building using the DOE-2 simulation program. The characterization of the office building and the DOE-2 input file are based on work completed in a previous study (Huang and Franconi 1995).

The cost analysis is also based on the DOE-2 simulations. The relationship between system heating and cooling loads and boiler and chiller plant fuel consumption data were developed using DOE-2 results. Regression analyses relating system cooling and heating part load ratio to chiller/cooling tower electric and boiler fuel, normalized by peak system load, were completed for the CAV system serving the 150,000 square foot office building in each location. The regressions equations were used to relate the TRNSYS simulation coil loads to boiler and chiller plant energy use. The chiller plant includes the chiller, cooling tower, and circulation pumps. Since a retrofit is assumed, the CAV and VAV systems have the same size plant equipment. Energy costs are determined from plant energy use and average commercial sector fuel prices for the nation. The energy costs are $22.24/Mbtu for electricity and $5.28/Mbtu for natural gas (EIA 1997b). No demand charges were accounted for. Carbon emissions are determined from plant energy use and weighted national average carbon coefficients for natural gas and electricity generation. The carbon coefficients are 14.5 for natural gas and 22.1 for electricity in million of metric tons per million BTUs (EIA 1997a)

Results

The TRNSYS simulations provide detailed system energy-use data that are not normally available in DOE-2 reports. To emphasize the large effect distribution system design can have on plant energy consumption, the data for Figure 1 were compiled. Figure 1 relates the building zone loads to system loads to plant energy consumption. It also shows fan energy use. The data are based on a CAV and VAV system meeting the same zone loads of the office building floor for each location.

Distribution System Energy Use

Figure 1 divides energy flows into those affecting the boiler plant and those affecting the chiller plant. The fan energy column separates these two sets of plant columns. The building loads are presented as light gray columns. The plants are dark gray columns. The system loads are black and white patterned columns. The building heat load is the sum of all heating zone loads over the year. The building cool load is the sum of all cooling zone loads over the year. The top stack on the cool load column is the heat added to the system by outdoor air introduced for ventilation. This quantity is the outdoor air flowrate multiplied by the enthalpy difference between the outdoor air and return air. It is summed for those hours when the economizer is not running and the outdoor air enthalpy is greater than the return air enthalpy. Under these conditions, the outdoor air increases the load on the coil.

The system load on the boiler is divided into two categories; 1) reheat coil loads that occur during hours when zones require heating and 2) reheat loads that occur during hours when zones require cooling. The "reheat to heat" column is much larger than the heat load column. The difference between them signifies the energy expended to heat the 12.8°C (55°F) supply air to the zone temperature (the actual energy delivered to the space is based on flow rate, delivery temperature, and zone temperature and is equal to the zone heating load). This portion of the "reheat to heat" column plus all of the "reheat to cool" column represent extra heating requirements due to over cooling the supply air. The overcooling may occur when the economizer operates and doesn't necessarily translate to a chiller load.

The "system cool" column separates the cooling coil load into latent and sensible components. The column also presents the cooling accomplished by the economizer. This quantity is the outdoor air flow rate multiplied by the enthalpy difference between the outdoor air and return air when the economizer is operating. Its large column segment shows the significant contributions to cooling a properly working economizer can have.

Some important observations about system performance can be made from the figure. For all locations, the annual fan energy use of the VAV system is about 40 % of the CAV system. The fan savings determined by the simulation is consistent with measured values reported for VAV retrofits of CAV systems (Jagemar 1994). Reheating cool air makes up most of the system load on the boiler for all the CAV systems. The "reheat to heat" system load is much greater than the heat load due to thermal mixing. As expected, the "reheat to cool" energy is much reduced in the VAV systems. The significantly higher CAV system loads show the disadvantage of system designs based on non-coincident loads and constant airflow rate. The VAV system can respond more dynamically to loads.

The CAV to VAV retrofit not only reduces fan energy consumption but significantly reduces cooling and heating energy use. This results from the interdependence of system cooling loads and heating loads on each other and on airflow rate. Additionally, the VAV retrofit substantially reduces system and plant equipment size requirements. For the locations analyzed, the peak reheat load for the VAV system is about 75% of the CAV system load. The peak cooling coil load for the VAV system is about 65% of the CAV system load.

Performance Indices

Table 2 presents companion data to Figure 1 - the energy and availability totals determined from the simulation analysis. The data are divided into task, system, performance efficiency, and plant categories. The task data are annual sums determined from the hourly building zone loads. The task energy is a first-law based minimum energy requirement to meet the energy needs of the five zones. It assumes that no mechanisms exist to move heat from interior zones to perimeter zones. Adding the absolute value of the task heating and cooling equals the total task energy load.

The task availability is the ideal work required to meet the zone loads based on a Carnot thermal cycle operating between the zone temperature and the ambient. The cycle heat transfer is equal to the zone load for the hour. A positive availability means that the cycle performs as a refrigerator or heat pump and work is required to meet the zone loads. A negative availability means the cycle performs as a heat engine and work is produced. The total task availability is the sum of the ideal work terms.

Based on the task availability analysis, an ideal process that provides space conditioning to the building floor produces more work than it consumes for all locations analyzed. Net useful work is produced by the ideal device because the office building is internal-gain dominant. During many hours of the year, energy gains from lights and equipment must be offset by zone cooling when the ambient temperature is cooler than the zone set point temperature. For skin-dominant buildings or internal-gain dominant buildings in very warm climates, this will not be the case.

Task availability quantifies to what extent a building is shell or internal-gain dominant relative to the climate. It indicates building space conditioning requirements. In establishing design standards or setting minimum system efficiency requirements, it may provide a measure for grouping buildings with similar end-use intensities.

In Table 2, four performance efficiencies are presented; 1) 1st law task efficiency, 2) 2nd law task efficiency, 3) EDE, and 4) UF. The first and second law task efficiencies have very different values. This results from energy being a poor indicator of useful work for this process. The second law efficiency is negative because useful work is not produced by the system but supplied to the system. The lower the absolute value of the task efficiency, the more opportunities exist for improving the system operation. On average, the CAV system is only about 1% efficient and the VAV system about 2%. The first law efficiency values range from 0.26 to 0.56. The EDE indices range from 0.29 to 0.35 for the CAV systems and from 0.55 to 0.63 for the VAV systems. The increase in EDE indicates a substantial reduction in thermal mixing for the VAV systems. The UF factors range in value from 0.36 to 0.38. The typical operating costs incurred to space condition the building floor with the CAV system is about $18000/year. For the VAV system it is about $9000. The retrofit reduces carbon emissions by more than half for all locations.

Table 3 compares the change in value of the performance indices for the CAV to VAV retrofit. The index ratios are compared to changes in plant energy and carbon emissions. In the table, overall indices, energy-type indices, and end-use indices are presented.

The ratio of 2nd law efficiencies provides a closer indication of change in plant energy and carbon emissions than the 1st law efficiency. The 2nd law efficiency tends to slightly over estimates savings while the 1st law efficiency tends to underestimate savings. The UF index, by definition, agrees with the change in plant (fan) energy use. The energy (EDE) and availability-based thermal indices show a weaker relationship to plant energy and carbon emissions. Therefore, they can not be used to directly measure plant energy use and costs. The end-use indices also show a weak relationship to plant energy and carbon emissions for both energy and availability. Based on these results, correction factors or plant factors need to be developed for each system end-use to correlate system energy to plant energy and costs.

While the total change in availability follows changes in plant energy and carbon emissions, the fractional contribution of the components are different at the system and plant levels. The doughnut chart in Figure 2 illustrates this point. The second law analysis tends to overemphasize the importance of mechanical energy. Therefore, availability can not be substituted for an end-use analysis when evaluating component performance trade-offs at the system level.

Conclusions

A second law analysis provides useful information for making performance comparisons of HVAC thermal distribution systems. The task availability provides a measure of the internal-gain or shell-loss dominance of a building. The second law efficiency reveals the extent of improvements that are possible relative to an ideal thermodynamic process.

This paper proposes using second law efficiency to measure performance advancements in thermal distribution system designs. The very low values determined for two system types, CAV and VAV, indicate that there is much room for improvement of distribution system designs for large commercial buildings. While VAV systems are more than twice as efficient as CAV systems, their 2nd law distribution system efficiency is only about 2%.

Evaluating system availability is a convenient way to include both thermal and mechanical energy types in a single efficiency term using a common accounting system with a rational thermodynamic basis. The change in 2nd law efficiency follows changes in plant energy use and carbon emissions closely, more so than a 1st law efficiency. However, availability calculations performed at the system level do not indicate plant end-use energy. This is also true for the thermal based index EDE and thermal energy end-use indices. Therefore, plant factors relating system energy or system availability to plant end-use energy and costs need to be used evaluate system design trade-offs and cost savings .

Acknowledgments

This project was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology and Community Systems, of the U.S. Department of Energy, under contract DE-AC03-76SF00098.

References

DOE 2.1E User's Manual: Lawrence Berkeley National Laboratory.

Bradford, "Optimized Supervisory Control of a Chiller Plant without Thermal Storage," in *Civil Engineering Department*. Boulder: University of Colorado, 1998.

Brandemuehl, Gabel and Andresen, *HVAC Secondary Toolkit*. Atlanta: ASHRAE, 1993.

Claridge, J.Haberl, Turner, O'Neal, Heffington, Tombari, Roberts and Jaeger, "Improving Energy Conservation Retrofits with Measured Energy Savings," *ASHRAE Journal*, pp. 14-22, 1991.

EIA, "Emissions of Greenhouse Gases in the United States 1987-1994," , Washington, DC DOE/EIA-0573(96), October 1997.

EIA, "Annual Energy Outlook 1998 with Projections through 2000," Department of Energy DOE/EIA-0383(98), December 1997.

Huang and Franconi, "Commercial Heating and Cooling Load Component Analysis," Lawrence Berkeley National Laboratory LBNL-38970, December 1995.

Jagemar, "Energy Efficient HVAC Systems in Office Buildings - with Emphasis on Air Distribution Systems," presented at ACEEE Summer Study, Pacific Grove, CA, 1994.

Jump, Walker and Modera, "Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Systems," presented at 1996 ACEEE Summer Study, 1996.

Kelvin, "On the Economy of Heating or Cooling of Buildings by Means of Currents of Air," presented at Glasgow Philisophical Society Proceedings, 1852.

Kreider and Rabl, *Heating and Cooling in Buildings: Design for Efficiency*: McGraw Hill, 1992.

Liu, Houcek, Athar, Reddy, Claridge and Haberl, "Identifying and Implementing Improved Operation and Maintenance Measures in Texas LoanSTAR Buildings," presented at 1994 ACEEE Summer Study, Pacific Grove, CA, 1994

McGovern, "Exergy Analysis - a different perspective on energy, Part 1: the concept of exergy," *Journal of Power and Energy*, vol. 204, pp. 253-262, 1990.

Modera, Feustal, Matson, Huzienga, Bauman, Arens and Borgers, "Efficient Thermal Energy Distribution in Commercial Buildings," CIEE, Draft Final Report April 1996 1996.

Moran, *Availability Analysis: a guide to efficient energy use*. New York: ASME Press, 1989.

Palmiter and Francisco, "A Practical Method for Estimating the Thermal Efficiency of Residential Forced-Air Distribution Systems," presented at 1996 ACEEE Summer Study, 1996.

Pietsch, "Water-Loop Heat Pump Systems: Assessment Study Update," Electric Power Research Institute 1991.

Reddy, Kissock, Katipamula and Claridge, "An Energy Delivery Efficiency Index to Evaluate Simultaneous Heating and Cooling Effects in Large Commercial Buildings," *Journal of Solar Engineering*, vol. 116, pp. 79-87, 1994.

Reistad, "Available-Energy Utilization in the United States," presented at Symposium on Theoretical and Applied Thermodynamics, Miami, FL, 1980.

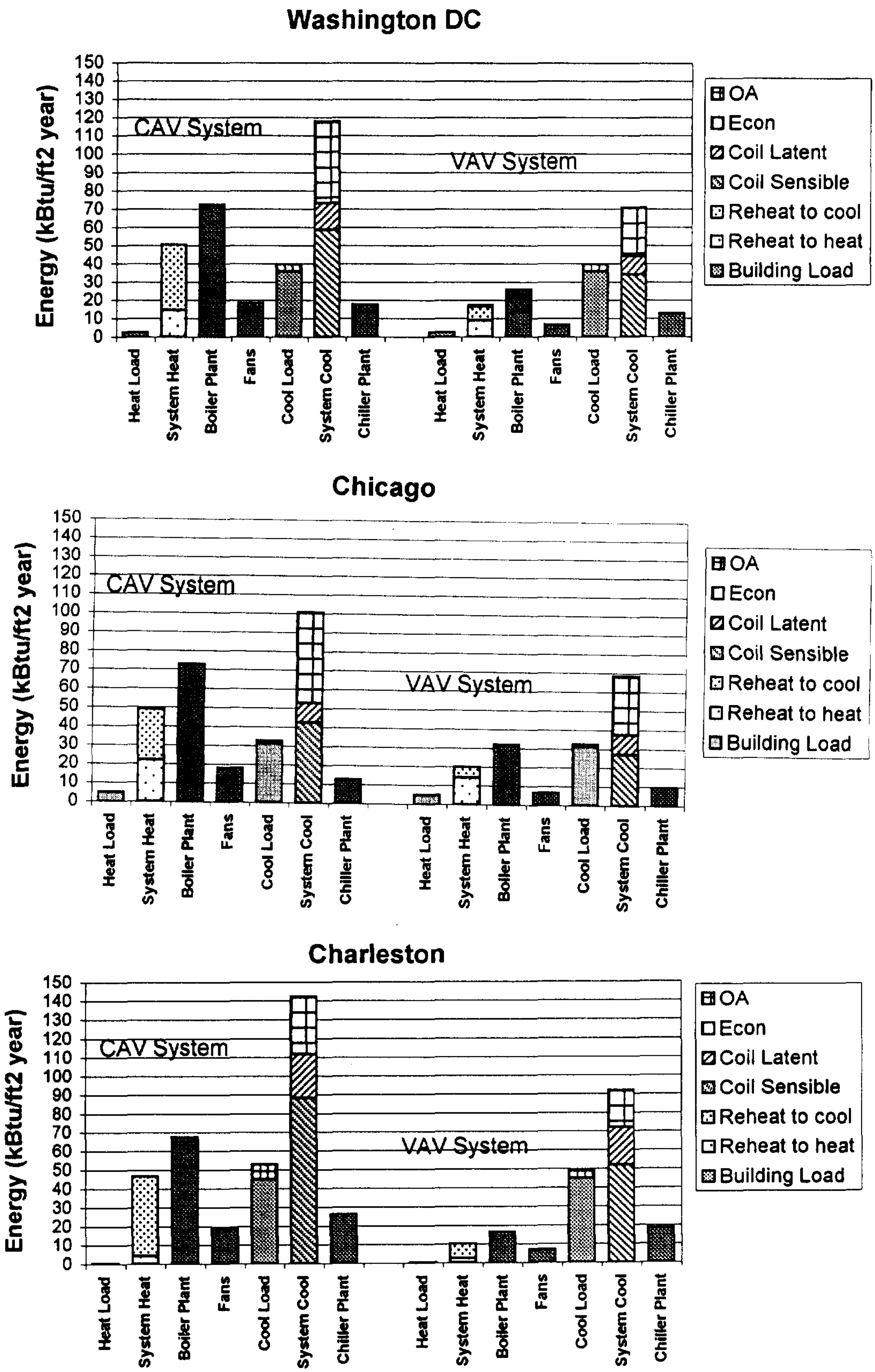

Figure 1. CAV and VAV System Performance Comparison System Serving 15000 ft^2 Office Building Floor

Table 1. First and Second Law Efficiencies of Select Processes

Energy Conversion System	1st Law (%)	2nd Law (%)
Steam Electric Generating Plant (coal-fired)	38	36
Large Electric Motor	90	90
Steam Boiler	91	49
Home Electric Hot Water Heater	93	16
Home Gas Furnace	80	13

Table 2. Distribution System Simulation Results
System Serving 15000 ft^2 Office Building Floor

	Washington DC		Chicago		Charleston	
	CAV	VAV	CAV	VAV	CAV	VAV
TASK DATA (kWh)						
Task heat	-11290	-11290	-21568	-21568	-2430	-2430
Task cool	157740	157740	136758	136758	197896	197896
Task energy	169030	169030	158326	158326	200326	200326
Task availability in	583	583	595	595	15	15
Task availability out	-1433	-1433	-1631	-1631	-1808	-1808
Task availability	-850	-850	-1036	-1036	-1793	-1793
SYSTEM DATA (kWh)						
Fans	81406	29319	80030	30182	83748	31305
CC load	322688	209930	231938	163992	491158	317291
RH load	221383	73407	215665	88522	205295	45103
CC avail	14153	9306	9314	7186	21894	14949
RH avail	23488	9286	25696	12005	17775	4722
Thermal Energy	544071	283337	447603	252514	696453	362394
Thermal Avail	37641	18592	35010	19191	39669	19671
Input energy	625477	312656	527633	282696	780201	393699
Input avail	119047	47910	115040	49374	123417	50976
PERFORMANCE EFFICIENCY						
1st law task-5 Zone	0.27	0.54	0.30	0.56	0.26	0.51
2nd law task-5 Zone	-0.0071	-0.0177	-0.0090	-0.0210	-0.0145	-0.0352
EDE task 5-Zone	0.31	0.60	0.35	0.63	0.29	0.55
Fan utilization factor	1.00	0.36	1.00	0.38	1.00	0.37
PLANT ENERGY CONSUMPTION (Mbtu/year)						
Cooling Plant	265	192	193	147	396	280
Heating Plant	1090	392	1094	477	1014	249
Fans	278	100	273	103	286	107
Total Thermal	1355	584	1287	624	1410	529
Total Thermal + Mechanic	1633	685	1560	727	1696	636
ANNUAL ENERGY COSTS ($/year)						
Cooling Plant	5904	4291	4297	3286	8835	6243
Heating Plant	5907	2194	5937	2646	5513	1447
Fans	6198	2232	6093	2298	6376	2383
Total	18008	8717	16327	8230	20723	10073
CARBON EMISSIONS (Metric Tons/year)						
Cooling Plant	5.9	4.3	4.3	3.3	8.8	6.2
Heating Plant	15.9	5.7	15.9	7.0	14.8	3.7
Fans	6.1	2.2	6.0	2.3	6.3	2.4
Total	27.9	12.2	26.2	12.5	29.9	12.2

Table 3. CAV to VAV System Retrofit Performance Evaluation System Serving 15000 ft^2 office building floor

	VAV/CAV Performance Ratios								
	Washington DC			Chicago			Charleston		
	DIST SYSTEM	PLANT ENERGY	CARBON EMISSIONS	DIST SYSTEM	PLANT ENERGY	CARBON EMISSIONS	DIST SYSTEM	PLANT ENERGY	CARBON EMISSIONS
Overall Indices									
Total Energy	0.50	0.42	0.44	0.50	0.38	0.41	0.54	0.47	0.48
Total Availability	0.40	NA	NA	0.41	NA	NA	0.43	NA	NA
Energy Type Indices									
Thermal Energy (EDE)	0.52	0.43	0.46	0.56	0.38	0.42	0.52	0.49	0.51
Mech Energy/Availability (UF)	NA	0.36	0.36	NA	0.38	0.37	NA	0.37	0.38
Thermal Availability	0.49	NA	NA	0.55	NA	NA	0.50	NA	NA
End-Use Indices									
Cooling Energy	0.65	0.73	0.73	0.71	0.71	0.71	0.65	0.76	0.76
Heating Energy	0.33	0.36	0.36	0.41	0.25	0.25	0.22	0.44	0.44
Fan Energy/Availability	NA	0.36	0.36	NA	0.38	0.37	NA	0.37	0.38
Cooling Availbility	0.66	NA	NA	0.77	NA	NA	0.68	NA	NA
Heating Availability	0.40	NA	NA	0.47	NA	NA	0.27	NA	NA

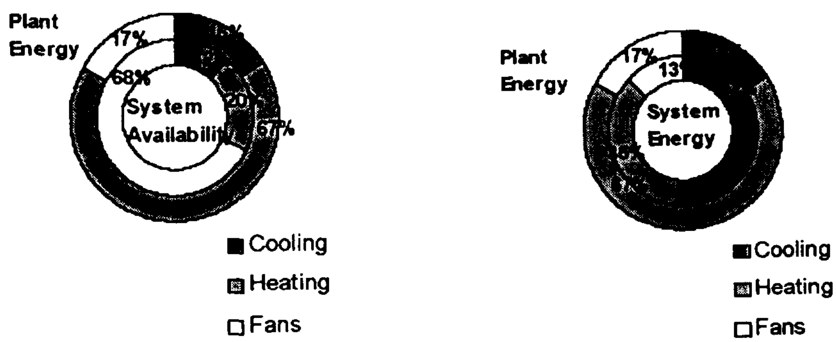

Figure 2. Plant and System End-Use Break Down CAV System in Washington DC