Impacts of Increased Outdoor Air Flow Rates on Annual HVAC Energy Costs

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Many existing buildings were designed for low ventilation rates (5 cfm outdoor air/person.) However, building owners and operators now face requests to raise ventilation rates to 20 cfm per occupant (ASHRAE Standard 62-1989 recommended value for office space) to improve indoor air quality. This represents a four fold increase in outdoor air ventilation. It is widely believed that this would result in substantially increased energy costs. Recent research suggests that the actual annual impacts may be less than expected (Eto & Meyer 1988; Eto 1990). However, more detailed analysis of the behavior of HVAC energy cost components is needed to fully understand why this is so, and whether it applies for different building types and HVAC characteristics. The purpose of this paper is to provide explanations of HVAC system dynamics that determine energy implications of increasing ventilation requirements, and to better understand how building and HVAC system parameters affect these impacts. Energy and ventilation impacts of increasing outdoor air flow from 5 to 20 cfm per person were analyzed based on data generated with DOE-2.1E office building simulations. Each of 14 building configurations were simulated in 3 climates, with Constant Volume (CV) and Variable Air Volume (VAV) HVAC systems, with and without air-side economizers. Seasonal and annual energy consumption were tracked for each case. The analyses explain why energy impacts are generally not as substantial as generally thought, and identifies conditions where annual energy cost increases can be trivial as well as conditions where energy costs can rise by substantial amounts.

INTRODUCTION

In order to achieve acceptable indoor air quality in office environments, ASHRAE's latest ventilation standard (Standard 62-1989) raises the recommended outdoor air ventilation rates from 5 cfm/occupant to 20 cfm/occupant for office spaces. Large increases in outdoor air ventilation rates is contrary to common energy conservation practices and has raised a number of questions concerning the feasibility and cost of implementing this standard. However, in contrast to the conventional wisdom that energy conservation goals are best served by minimizing outdoor air ventilation rates, it is common practice to employ an economizer strategy which provides ''free cooling'' by ***increasing*** outdoor air flow when the outdoor air is cooler than the return air. This strategy saves energy by reducing the need for mechanical cooling. Thus, raising outdoor air flow may either increase or decrease energy use depending on the outdoor air climate and the thermal demands of the indoor space.

Since outdoor air is important to the maintenance of indoor air quality, it is worthwhile to examine the relationship between outdoor air flow and energy use in more detail. This report examines the energy and energy cost impact of raising outdoor air ventilation rates in office buildings using both CV and VAV ventilation configurations. A sensitivity analysis is performed to determine how this impact is affected by various building parameters, economizers, and climate. Comparisons are made between ventilation systems that provide a minimum of 5 and 20 cfm of outdoor air per occupant during all occupied hours. The results of this analysis are valid for existing buildings with sufficient equipment capacity to accommodate both outdoor air ventilation rates, and for new building construction.

Background

This report is part of a larger modeling project to assess the compatibilities and trade-offs between energy, indoor air, and thermal comfort objectives in the design and operation of HVAC systems in commercial buildings. The methodology used in this project has been to refine and adapt the DOE-2 building energy analysis computer program for the specific needs of this study, and to generate a detailed database on the energy use, indoor climate, and outdoor air flow rates of various ventilation systems and control strategies.

Description of the Buildings and Ventilation Systems Modeled

A 12 story 339,000 square foot office building (Building A), along with 13 additional parametric variations (Buildings B-N) were modeled in three different climates representing cold (Minneapolis), temperate (Washington, D.C.), and hot/humid (Miami) climate zones. The office buildings are fully occupied during normal business hours, weekdays from 9 AM to 5 PM. Building lighting usage is 2.5 Watts per square foot and office equipment is modeled at 1.0 Watt per square foot, during occupied hours. Occupancy, lighting, and equipment are scaled back at night and on weekends. All buildings are modeled with an air handler on each floor servicing four perimeter zones corresponding to the four compass orientations, and a core zone. The core zone of the base building is twice the size of the perimeter zones so that the building HVAC system is cooling dominated. A dual duct constant volume (CV) system, and a single duct variable volume (VAV) system with reheat were modeled using alternative outdoor air control strategies. The fourteen building and HVAC configurations used in this analysis are summarized in Table 1.

The CV and VAV systems were each modeled using 5 cfm and 20 cfm of outdoor air per occupant. The system for both runs was sized to accommodate the heating and cooling load of 20 cfm per occupant rather than being separately sized for each case. This was done because existing systems sized

Table 1. *Building and HVAC Characteristics*

Building Configuration	Window R-Value (hr ft^2 °F/Btu)	Window Shading Coeffic.	Roof Insulation (hr ft^2 °F/ Btu)	Infiltration Rate (ACH)	Chiller COP (Btu/ Btu)	Boiler Effic. (%)	Occup. Density (Occup/ 1000 SF)	P/C Ratio * (ft^2/ft^2)	Exhaust Flow Rate (cfm)	Daily Operating Hours (hrs/day)
A. Base Case	2.0	0.8	10	0.5	3.5	70	7	0.5	750	12
B. High Effic. Shell	3.0	0.6	20	0.75	3.5	70	7	0.5	750	12
C. Low Effic. Shell	1.0	1.0	5	0.25	3.5	70	7	0.5	750	12
D. High Effic. HVAC System	2.0	0.8	10	0.5	4.5	80	7	0.5	750	12
E. Low Effic. HVAC System	2.0	0.8	10	0.5	2.5	60	7	0.5	750	12
F. High P/C Ratio*	2.0	0.8	10	0.5	3.5	70	7	0.8	750	12
G. Low P/C Ratio*	2.0	0.8	10	0.5	3.5	70	7	0.3	750	12
H. High Exhaust Rate	2.0	0.8	10	0.5	3.5	70	7	0.5	1500	12
I. High Occup. Density	2.0	0.8	10	0.5	3.5	70	15	0.5	750	12
J. Medium Occup. Density	2.0	0.8	10	0.5	3.5	70	10	0.5	750	12
K. Low Occup. Density	2.0	0.8	10	0.5	3.5	70	5	0.5	750	12
L. Very Low Occup. Density	2.0	0.8	10	0.5	3.5	70	3	0.5	750	12
M. Extended Oper. Hours	2.0	0.8	10	0.5	3.5	70	7	0.5	750	18
N. 24 Hour Operation	2.0	0.8	10	0.5	3.5	70	7	0.5	750	24

*__P/C Ratio__ is the ratio of Perimeter space floor area to Core space floor area, where Perimeter space is up to 15 ft. from exterior walls.

for 5 cfm per occupant may not have sufficient capacity to operate at 20 cfm per occupant. Providing sufficient capacity avoids this problem for existing buildings. An analysis of the HVAC capacity implications of raising outdoor air flow rates in existing buildings is presented elsewhere (Hall & Mudarri 1996a). This sizing strategy also makes the analysis applicable to new construction.

The basic outdoor air control strategy modeled is one that provides a constant outdoor air flow during all operating conditions. For CV systems, this is accomplished by maintaining a fixed outdoor air fraction (CV/FOAF). However, for VAV systems, a constant outdoor air (VAV/COA) flow strategy requires that the outdoor air fraction change in inverse proportion to changes in the supply air flow. While a fixed outdoor air fraction control strategy is common on VAV systems (VAV/FOAF), it does not maintain a constant outdoor air flow into the building, can result in significant reductions in outdoor air during part load conditions, and is not recommended (Hall & Mudarri 1996b). Comparisons between 5 cfm per occupant and 20 cfm per occupant would not be valid for VAV/FOAF systems since the designated flow rates are not maintained.

The effects of a temperature air-side economizer strategy is also assessed. The economizer uses additional quantities of outdoor air to provide ‘‘free cooling’’ when the outdoor air temperature is lower than the return air temperature. The outdoor air flow rate reverts to its base level (5 or 20 cfm per occupant) when the economizer is in the ‘‘off’’ mode. Because the core zone is large relative to the perimeter zones, both the CV and VAV system for the buildings are cooling load dominated during all seasons. The economizer modulates the amount of outdoor air as the outdoor air temperature changes so as to minimize the burden on the cooling coil. To avoid humidity problems, the economizer is set to shut off above 65°F. However, it continues to operate during the winter season, albeit at reduced outdoor air levels, to reduce the burden on the cooling coil. Coil freezing is avoided by sufficient preheat coil capacity, though it is seldom used.

APPROACH

The impact of increased outdoor air flow on annual energy use is often counterintuitive because it represents the end result of some increases and some decreases in both heating and cooling energy use with seasonal changes in outdoor climate conditions. DOE-2 generated hourly air flow and energy use data were therefore sorted into four bins defined by significant outdoor air temperature conditions. The binned energy analysis allows one to observe the pattern of changes in heating and cooling loads, and to understand why annual impacts may be higher or lower than expected. Since the energy associated with auxiliaries such as fans and pumps was only marginally affected by raising outdoor air flow rates, no specific analysis of these items is included in this paper, although the total HVAC energy reported includes energy used for such auxiliaries. The annual impact of raising outdoor air flow on energy use is most influenced by changes in heating and cooling loads under each climate condition, and the proportion of the year each climate condition is experienced. The way in which building parameters affect changes in energy use is assessed through parametric analysis using separate modeling runs for different buildings.

Energy consumption is converted to energy costs using the same energy price structure for all climates. The price structure chosen for this paper is the average price taken from utilities in 17 major cities around the country in 1994. The price of electricity was modeled at $0.05 per kilowatt-hour, and $8 per kilowatt. Gas for space heating and DHW service was modeled at $0.50 per therm.

RESULTS

Binned energy analysis is presented for the base building using selected HVAC configurations and climate conditions. Annual energy costs are then systematically assessed for all buildings, ventilation systems, and climates using energy cost summary tables.

Seasonal impact of increasing outdoor air flow

By way of example, Figures 1 through 3 summarize binned energy use results for Building A with a CV/FOAF system in Washington, D.C., and for Building A with a VAV/COA system in Minneapolis. Both systems are summarized with and without a temperature economizer.

Figure 1. *Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with CV (FOAF) Without Economizer in Washington, DC*

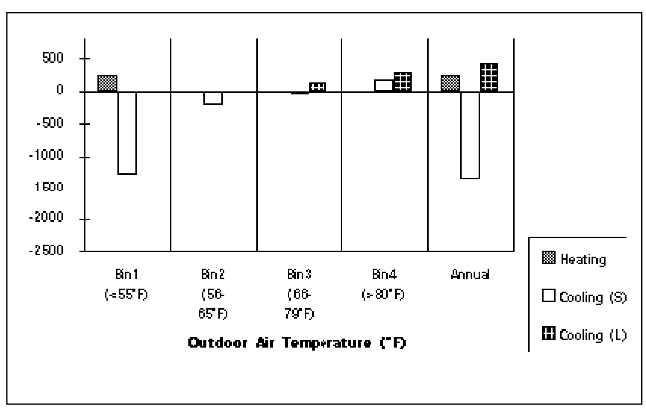


Figure 2. *Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with CV (FOAF) with Economizer in Minneapolis, MN*

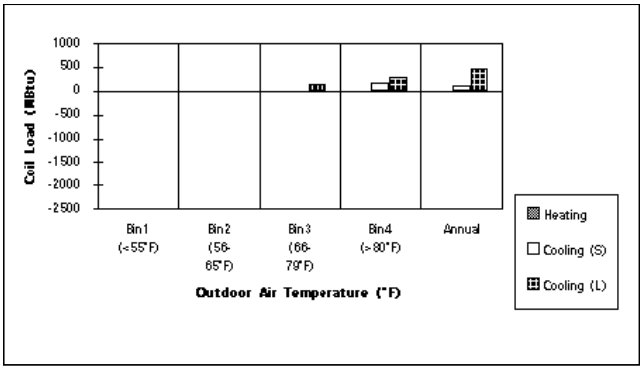
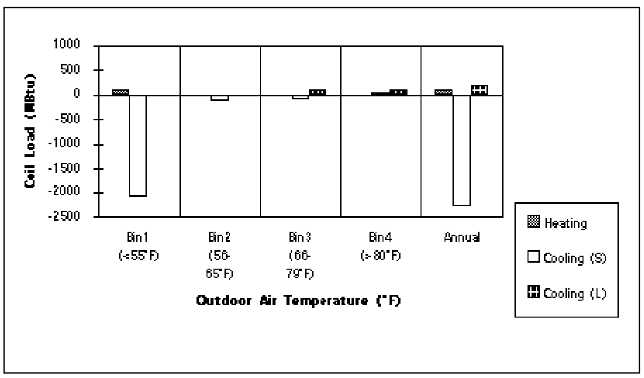


Figure 3. *Change in Coil Loads with Increased Outdoor Air Flow Rate for Building A with VAV (COA)Without Economizer in Minneapolis, MN*



CV system without economizer. Figure 1 presents the seasonal energy impacts of raising outdoor air flow from 5 to 20 cfm per occupant for the CV system without economizer in the Washington, D.C. climate. As expected, heating energy use is increased in the winter (Bin 1) with the higher outdoor air flow rate, while sensible cooling drops. In the intermediate spring and fall seasons, sensible cooling drops in Bin 2 with no change in latent load, while latent cooling rises in Bin 3 with no change in sensible load. In the summer (Bin 4), sensible and latent cooling energy use rises. Annually, the building experiences a net increase in heating energy, a net decrease in sensible cooling, and a net increase in latent cooling when the outdoor air flow rate is increased from 5 to 20 cfm per occupant.

CV system with economizer. The energy results for the same building with economizer is shown in Figure 2. This building demonstrates how the economizer minimizes any increases or decreases in energy during the cooler periods (Bins 1 and 2) leaving only the cooling penalty during the warmer periods (Bins 3 and 4). Raising outdoor air flow has little impact on heating energy use in winter (Bin 1) and in the colder intermediate season (Bin 2) because the economizer is already bringing in close to or more than 20 cfm of outdoor air per person during this period. When the economizer is off (Bins 3 and 4) both the sensible and latent cooling penalty is the same as the CV system without economizer. Annually, this building experiences little change in heating energy, and only modest increases in both sensible and latent cooling energy when the outdoor air flow rate is increased from 5 to 20 cfm per occupant.

VAV system without economizer. Figure 3 presents the seasonal energy impacts of raising outdoor air flow from 5 to 20 cfm per occupant for the VAV system without economizer in the Minneapolis climate. This building demonstrates that the heating penalty in winter is minimal for VAV systems, while the added cooling benefit in the cooler months can have a substantial effect on annual energy use. In the winter (Bin 1), the heating energy load increases only marginally, while the cooling energy load drops significantly because of the higher outdoor air. During the spring and fall weather conditions (Bin 2), sensible cooling falls while the latent cooling load shows no change. As the temperature warms (Bin 3) the sensible cooling load falls but the latent cooling load rises, until in the summer conditions (Bin 4), where both sensible and latent cooling loads rise. Since Minneapolis experiences cool weather during a large portion of the year the large reduction in winter cooling loads tends to dominate the change in energy use when outdoor air flow is raised from 5 to 20 cfm per occupant.

VAV system with economizer. The effect of the economizer on the VAV system is essentially the same as for the CV system; the economizer minimizes any increases or decreases in energy during the cooler periods (Bins 1 and 2) leaving only the cooling penalty during the warmer periods (Bins 3 and 4).

Annual Energy Cost Impacts of Increasing Outdoor Air Flow

The impacts of increased outdoor air flow on annual energy costs vary with HVAC system type, the presence or absence of an economizer, and building and climate factors. The effect of these parameters on annual energy cost impacts are summarized below.

CV versus VAV systems. Tables 2 and 3 summarize the energy cost impacts of increasing outdoor air flow rates for buildings A—N with CV and VAV systems without economizers. The VAV system experiences less of a cost increase than the CV system. In the cold and temperate climates of Minneapolis and Washington, D.C., HVAC costs typically rise 5%-8% for the CV system, while costs for the VAV system typically rise 2%-5%. Similar, (though

***Table 2.** Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: CV/FOAF Systems without Economizers*

	Minneapolis, MN			Washington, DC			Miami, FL		
Building Configuration	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)
A. Base Case @5	0.49	0.02	0.83	0.51	0.00	0.81	0.63	0.00	0.94
Increase	0.03	0.02	0.05	0.05	0.01	0.06	0.08		0.08
Percent Increase	6%	83%	6%	9%	156%	7%	13%	None	9%
B. High Eff. Shell @5	0.46	0.01	0.73	0.48	0.00	0.73	0.59	0.00	0.87
Increase	0.02	0.01	0.04	0.04		0.05	0.08		0.08
Percent Increase	5%	141%	5%	9%	None	6%	14%	None	9%
C. Low Eff. Shell @5	0.52	0.07	0.96	0.55	0.02	0.93	0.69	0.00	1.02
Increase	0.04	0.03	0.06	0.06	0.01	0.07	0.08		0.08
Percent Increase	7%	38%	7%	11%	72%	8%	12%	None	8%
D. High Eff. HVAC @5	0.37	0.02	0.71	0.39	0.00	0.68	0.48	0.00	0.78
Increase	0.02	0.02	0.04	0.04	0.01	0.04	0.06		0.06
Percent Increase	6%	83%	6%	10%	156%	6%	13%	None	8%
E. Low Eff. HVAC @5	0.70	0.03	1.05	0.73	0.01	1.03	0.91	0.00	1.21
Increase	0.05	0.02	0.07	0.07	0.01	0.08	0.12		0.12
Percent Increase	7%	83%	7%	10%	156%	8%	13%	None	10%
F. High P/C Ratio* @5	0.53	0.04	0.93	0.56	0.01	0.89	0.69	0.00	1.03
Increase	0.04	0.02	0.06	0.05	0.01	0.05	0.08		0.08
Percent Increase	4%	45%	4%	7%	69%	5%	9%	None	6%
G. Low P/C Ratio* @5	0.44	0.01	0.72	0.47	0.00	0.72	0.56	0.00	0.82
Increase	0.03	0.02	0.04	0.04	0.01	0.05	0.09		0.09
Percent Increase	6%	140%	6%	9%	250%	6%	16%	None	11%
H. High Exhaust @5	0.50	0.03	0.86	0.52	0.01	0.83	0.66	0.00	0.97
Increase	0.02	0.01	0.04	0.04	0.01	0.04	0.06		0.06
Percent Increase	4%	50%	4%	7%	102%	5%	9%	None	6%
I. High Occ. Dens. @5	0.54	0.03	0.91	0.60	0.00	0.99	0.72	0.00	1.05
Increase	0.07	0.05	0.13	0.10	0.02	0.11	0.19		0.19
Percent Increase	14%	199%	14%	17%	408%	11%	27%	None	18%
J. Medium Occ. Dens. @5	0.51	0.02	0.86	0.54	0.01	0.84	0.66	0.00	0.98
Increase	0.05	0.03	0.08	0.07	0.01	0.08	0.13		0.13
Percent Increase	10%	129%	10%	13%	226%	10%	19%	None	13%
K. Low Occ. Dens. @5	0.48	0.03	0.81	0.50	0.01	0.79	0.62	0.00	0.92
Increase	0.02	0.01	0.04	0.03		0.03	0.05		0.05
Percent Increase	4%	51%	4%	6%	None	4%	8%	None	6%
L. Very Low Occ. Dens. @5	0.46	0.03	0.79	0.49	0.01	0.78	0.60	0.00	0.90
Increase	0.01	0.01	0.01	0.01		0.01	0.02		0.02
Percent Increase	2%	19%	2%	2%	None	2%	3%	None	2%
M. Extended Op. Hours @5	0.50	0.04	0.88	0.53	0.01	0.86	0.65	0.00	0.97
Increase	0.02	0.03	0.06	0.04	0.02	0.05	0.09		0.09
Percent Increase	5%	81%	7%	7%	117%	6%	15%	None	10%
N. 24 Hour Operation @5	0.52	0.06	0.96	0.55	0.02	0.94	0.69	0.00	1.07
Increase	0.01	0.06	0.07	0.03	0.03	0.06	0.10		0.10
Percent Increase	2%	91%	7%	5%	128%	6%	15%	None	10%

****P/C Ratio** is the ratio of Perimeter space floor area to Core space floor area, where Perimeter space is up to 15 ft. from exterior walls.

Table 3. *Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: VAV/COA Systems without Economizers*

	Minneapolis, MN			Washington, DC			Miami, FL		
Building Configuration	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)
A. Base Case @5	0.48	0.10	0.77	0.49	0.05	0.71	0.57	0.00	0.76
Increase	0.01		0.02	0.03		0.03	0.07		0.07
Percent Increase	3%	None	2%	6%	None	4%	13%	None	10%
B. High Eff. Shell @5	0.44	0.05	0.64	0.45	0.02	0.62	0.54	0.00	0.71
Increase	0.01		0.01	0.03		0.03	0.08		0.08
Percent Increase	2%	None	2%	7%	None	5%	14%	None	11%
C. Low Eff. Shell @5	0.51	0.20	0.92	0.54	0.11	0.85	0.62	0.01	0.82
Increase	0.01		0.02	0.03		0.04	0.07		0.07
Percent Increase	3%	None	2%	6%	None	4%	11%	None	8%
D. High Eff. HVAC @5	0.36	0.09	0.64	0.37	0.04	0.59	0.43	0.00	0.62
Increase	0.01		0.01	0.02		0.02	0.06		0.06
Percent Increase	3%	None	2%	6%	None	4%	13%	None	9%
E. Low Eff. HVAC @5	0.68	0.12	0.99	0.70	0.06	0.93	0.82	0.00	1.01
Increase	0.02		0.02	0.05		0.05	0.11		0.11
Percent Increase	3%	None	2%	7%	None	5%	13%	None	11%
F. High P/C Ratio* @5	0.52	0.14	0.86	0.53	0.07	0.79	0.62	0.00	0.82
Increase	0.01		0.02	0.03		0.03	0.07		0.07
Percent Increase	2%	None	2%	4%	None	3%	9%	None	7%
G. Low P/C Ratio* @5	0.42	0.06	0.65	0.44	0.03	0.62	0.52	0.00	0.68
Increase	0.01		0.02	0.03		0.03	0.08		0.08
Percent Increase	3%	None	2%	7%	None	5%	15%	None	12%
H. High Exhaust @5	0.48	0.10	0.78	0.50	0.05	0.73	0.60	0.00	0.79
Increase	0.01		0.01	0.02		0.02	0.05		0.05
Percent Increase	2%	None	2%	5%	None	3%	9%	None	7%
I. High Occ. Dens. @5	0.52	0.10	0.82	0.56	0.06	0.83	0.65	0.00	0.84
Increase	0.04	0.03	0.07	0.08	0.01	0.11	0.17		0.17
Percent Increase	8%	31%	9%	14%	23%	14%	26%	None	20%
J. Medium Occ. Dens. @5	0.49	0.10	0.79	0.51	0.05	0.74	0.60	0.00	0.79
Increase	0.02	0.01	0.03	0.04		0.04	0.11		0.11
Percent Increase	5%	8%	4%	8%	None	6%	19%	None	15%
K. Low Occ. Dens. @5	0.46	0.10	0.74	0.48	0.05	0.70	0.56	0.00	0.74
Increase	0.01		0.01	0.02		0.02	0.05		0.05
Percent Increase	2%	None	1%	4%	None	3%	8%	None	6%
L. Very Low Occ. Dens. @5	0.45	0.10	0.72	0.47	0.05	0.69	0.55	0.00	0.72
Increase				0.01		0.01	0.02		0.02
Percent Increase	None	None	None	2%	None	1%	3%	None	3%
M. Extended Op. Hours @5	0.49	0.15	0.84	0.51	0.09	0.79	0.60	0.02	0.81
Increase		0.01	0.01	0.02		0.02	0.07		0.07
Percent Increase	None	5%	1%	4%	None	3%	12%	None	9%
N. 24 Hour Operation @5	0.51	0.20	0.94	0.54	0.14	0.90	0.64	0.05	0.91
Increase	-0.02	0.01		0.01		0.01	0.08		0.08
Percent Increase	-4%	7%	None	2%	None	2%	13%	None	9%

*__P/C Ratio__ is the ratio of Perimeter space floor area to Core space floor area, where Perimeter space is up to 15 ft. from exterior walls.

generally smaller) differences are found in Miami. This difference is partly accounted for by the smaller (insignificant) increase in heating cost experienced by the VAV system, compared to the CV system. The VAV system has a higher basic heating requirement than the CV system because it reheats the supply air after it is cooled. However, since the supply air temperature experiences little or no change with the addition of higher outdoor air quantities, there is little effect on heating costs. The main exception to this is the higher occupant density buildings where the higher outdoor air flows are substantial enough to trigger additional preheat coil loads in cold weather. The other reason that the energy cost increase for the VAV system is less than its CV counterpart is that the VAV system tends to experience a greater cooling energy cost reduction during the winter, spring and fall seasons. This is because the VAV system provides less supply air and a greater outdoor air fraction than the CV system under part load conditions, and this increases the cooling benefit of increased outdoor air.

Economizers. Tables 4 and 5 display the energy cost impact for the CV and VAV systems with economizers. Other studies have intuitively attributed the small rise in energy costs associated with increased outdoor air flows to the operation of economizers (Eto & Meyer 1988; Eto 1990). However, the closer analysis of this study demonstrate that economizers actually increase the energy impact over non-economizer systems. Overall, systems with economizers have lower initial costs, but they experience a greater energy cost increase, in both absolute and percentage terms, when compared to economizer systems. Economizers tend to add an additional $0.01 per square foot to the energy cost impact for CV systems, and $0.02-$0.04 per square foot for VAV systems. Energy cost increases for both CV and VAV systems with economizers rose 6%-10% when outdoor air flows were increased. This increase was due mostly to increased cooling costs. Since economizers already capture the free cooling benefit from increased outdoor air, raising the minimum outdoor air flow from 5 to 20 cfm per occupant produced a more substantial net cooling energy cost penalty than for systems without economizers. However, raising outdoor air flow produced little heating energy cost penalty (except in high occupant density buildings). This is because the economizer already brings in close to or more than 20 cfm per occupant of outdoor air to provide free cooling to the building core even during much of the winter.

Climate and building type. Cost increases are typically about twice as high in the hot humid climate of Miami when compared to Minneapolis and Washington because of the extended time period of hot humid weather where the outdoor air creates a substantial cooling burden. For systems without economizers, the hot humid climate also provides less time during the winter, fall and spring seasons where additional outdoor air can provide free cooling.

Certain building parameters also increased the cost impact over the base building (Building A): low efficency HVAC (Building E) increased the cost impact by approximately $0.02-$0.03 per square foot; and 24 hour operation (Building N) by $0.0-$0.02 per square foot. The low efficiency shell (Building C) and higher perimeter to core ratio (Building F) had surprisingly little effect on the cost impact. However, buildings with higher occupant densities (Buildings I and J) experience cost increases which are 2 to 3 times higher than the base building. This is because the added outdoor air is proportional to occupancy of the building. The combination of high occupant density and hot humid climate can increase costs by 15%-21%, and this is substantial.

The sensitivity of energy cost impacts to high occupant density situations has important implications. In this report, high occupant density is defined as 15 occupants per 1000 square feet. These densities are modest when compared to education buildings, auditoriums, theaters, and similar facilities where occupant densities can be 5 to 10 times that level. It raises special issues about the feasibility of maintaining adequate indoor air quality in these buildings by using the outdoor air ventilation rates recommended in ASHRAE Standard 62-1989. Because of this implication, this issue is addressed separately in detail elsewhere (Mudarri & Hall 1996).

CONCLUSIONS

Key findings of this study are summarized below.

- Economizers reduce cooling energy by using outdoor air to reduce the cooling load on the chiller when the outdoor air is cooler than the return air. For the CV system, the economizer provides free cooling for the core zone, but also results in a modest heating penalty when perimeter zones require heating in cold weather.

- The VAV system with reheat has a higher initial heating load than the CV system because it reheats supply air after it is conditioned to 55°F. The economizer on the VAV system with reheat does not increase heating costs as with the CV system because the economizer does not change the air temperature facing the reheat coil.

- For the CV systems without economizers, increasing outdoor air ventilation rates saves cooling energy during periods that an economizer would normally be operating, and this mitigates against the potentially large cooling energy increases during hot weather. However, these systems also experience a heating penalty when outdoor air flow rates are increased.

- VAV systems without economizers also experience a cooling energy savings when the economizer would

Table 4. *Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: CV/FOAF Systems with Economizers*

	Minneapolis, MN			Washington, DC			Miami, FL		
Building Configuration	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)
A. Base Case @5	0.40	0.10	0.82	0.43	0.06	0.79	0.62	0.00	0.93
Increase	0.05		0.05	0.07		0.06	0.09		0.08
Percent Increase	13%	None	7%	15%	None	8%	14%	None	9%
B. High Eff. Shell @5	0.36	0.07	0.69	0.40	0.04	0.69	0.58	0.00	0.85
Increase	0.05	0.01	0.05	0.06		0.06	0.09		0.08
Percent Increase	13%	7%	8%	16%	None	9%	15%	None	10%
C. Low Eff. Shell @5	0.44	0.15	0.97	0.48	0.09	0.93	0.68	0.01	1.02
Increase	0.05		0.06	0.07		0.07	0.08		0.08
Percent Increase	12%	None	6%	15%	None	8%	12%	None	8%
D. High Eff. HVAC @5	0.30	0.09	0.71	0.33	0.06	0.67	0.47	0.00	0.78
Increase	0.04		0.04	0.05		0.05	0.06		0.06
Percent Increase	13%	None	6%	15%	None	7%	14%	None	8%
E. Low Eff. HVAC @5	0.58	0.12	1.01	0.62	0.07	0.98	0.89	0.01	1.20
Increase	0.07		0.08	0.10		0.09	0.12		0.12
Percent Increase	13%	None	8%	16%	None	10%	14%	None	10%
F. High P/C Ratio* @5	0.44	0.13	0.93	0.48	0.08	0.89	0.68	0.01	1.02
Increase	0.05		0.05	0.06		0.06	0.08		0.08
Percent Increase	9%	None	4%	11%	None	6%	9%	None	6%
G. Low P/C Ratio* @5	0.35	0.06	0.68	0.39	0.04	0.68	0.55	0.00	0.82
Increase	0.05		0.06	0.06		0.06	0.09		0.09
Percent Increase	15%	None	8%	15%	None	9%	16%	None	11%
H. High Exhaust @5	0.42	0.10	0.84	0.45	0.06	0.81	0.65	0.00	0.96
Increase	0.04		0.04	0.05		0.05	0.06		0.06
Percent Increase	8%	None	4%	11%	None	6%	10%	None	6%
I. High Occ. Dens. @5	0.45	0.10	0.89	0.51	0.05	0.94	0.70	0.00	1.04
Increase	0.11	0.02	0.13	0.13		0.13	0.19		0.19
Percent Increase	25%	19%	15%	26%	None	14%	28%	None	18%
J. Medium Occ. Dens. @5	0.42	0.10	0.84	0.46	0.06	0.82	0.65	0.00	0.97
Increase	0.08	0.01	0.08	0.09		0.09	0.13		0.13
Percent Increase	19%	6%	10%	20%	None	11%	20%	None	13%
K. Low Occ. Dens. @5	0.39	0.10	0.79	0.43	0.06	0.78	0.61	0.00	0.91
Increase	0.03		0.04	0.04		0.04	0.05		0.05
Percent Increase	9%	None	5%	9%	None	5%	9%	None	6%
L. Very Low Occ. Dens. @5	0.38	0.09	0.77	0.42	0.06	0.76	0.59	0.00	0.90
Increase	0.01		0.02	0.02		0.02	0.02		0.02
Percent Increase	4%	None	2%	4%	None	2%	3%	None	2%
M. Extended Op. Hours @5	0.38	0.14	0.85	0.42	0.09	0.83	0.63	0.01	0.96
Increase	0.05	0.01	0.06	0.06		0.06	0.10		0.10
Percent Increase	14%	7%	7%	14%	None	8%	15%	None	10%
N. 24 Hour Operation @5	0.36	0.19	0.93	0.41	0.11	0.89	0.66	0.01	1.05
Increase	0.05	0.02	0.07	0.06	0.01	0.07	0.10		0.10
Percent Increase	13%	12%	8%	14%	12%	8%	16%	None	10%

*__P/C Ratio__ is the ratio of Perimeter space floor area to Core space floor area, where Perimeter space is up to 15 ft. from exterior walls.

Table 5. *Comparison of Annual HVAC Energy Costs for Outdoor Air Flow Rates of 5 and 20 cfm per Occupant: VAV/COA Systems with Economizers*

	Minneapolis, MN			Washington, DC			Miami, FL		
Building Configuration	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)	Cooling ($/sf)	Heating ($/sf)	Total ($/sf)
A. Base Case @5	0.39	0.10	0.69	0.42	0.05	0.65	0.57	0.00	0.75
Increase	0.04		0.04	0.05		0.05	0.07		0.08
Percent Increase	10%	None	6%	12%	None	8%	13%	None	10%
B. High Eff. Shell @5	0.36	0.05	0.57	0.39	0.02	0.56	0.53	0.00	0.70
Increase	0.04		0.04	0.05		0.06	0.08		0.08
Percent Increase	11%	None	7%	14%	None	10%	15%	None	11%
C. Low Eff. Shell @5	0.43	0.20	0.84	0.47	0.12	0.79	0.61	0.01	0.81
Increase	0.04		0.04	0.05		0.05	0.07		0.07
Percent Increase	9%	None	5%	11%	None	7%	11%	None	9%
D. High Eff. HVAC @5	0.30	0.09	0.58	0.32	0.04	0.54	0.43	0.00	0.61
Increase	0.03		0.03	0.04		0.04	0.06		0.06
Percent Increase	10%	None	5%	12%	None	7%	13%	None	9%
E. Low Eff. HVAC @5	0.57	0.12	0.88	0.61	0.06	0.84	0.82	0.00	1.00
Increase	0.06		0.06	0.07		0.08	0.11		0.11
Percent Increase	10%	None	7%	12%	None	9%	13%	None	11%
F. High P/C Ratio* @5	0.43	0.14	0.79	0.47	0.07	0.73	0.62	0.00	0.82
Increase	0.04		0.04	0.05		0.05	0.07		0.07
Percent Increase	7%	None	4%	8%	None	5%	9%	None	7%
G. Low P/C Ratio* @5	0.35	0.07	0.57	0.38	0.03	0.56	0.51	0.00	0.67
Increase	0.04		0.04	0.05		0.05	0.08		0.08
Percent Increase	11%	None	7%	13%	None	9%	15%	None	12%
H. High Exhaust @5	0.41	0.10	0.71	0.44	0.05	0.67	0.59	0.00	0.78
Increase	0.03		0.03	0.04		0.04	0.05		0.05
Percent Increase	7%	None	4%	9%	None	6%	9%	None	7%
I. High Occ. Dens. @5	0.44	0.10	0.75	0.50	0.06	0.76	0.64	0.00	0.84
Increase	0.09	0.03	0.12	0.11	0.01	0.14	0.17		0.17
Percent Increase	20%	26%	16%	22%	21%	19%	27%	None	21%
J. Medium Occ. Dens. @5	0.41	0.10	0.71	0.45	0.05	0.68	0.59	0.00	0.78
Increase	0.06	0.01	0.07	0.07		0.07	0.12		0.12
Percent Increase	15%	6%	9%	15%	None	10%	19%	None	15%
K. Low Occ. Dens. @5	0.38	0.10	0.66	0.42	0.05	0.64	0.55	0.00	0.73
Increase	0.03		0.03	0.03		0.03	0.05		0.05
Percent Increase	7%	None	4%	7%	None	5%	8%	None	6%
L. Very Low Occ. Dens. @5	0.37	0.10	0.65	0.41	0.05	0.63	0.54	0.00	0.72
Increase	0.01		0.01	0.01		0.01	0.02		0.02
Percent Increase	3%	None	2%	3%	None	2%	3%	None	3%
M. Extended Op. Hours @5	0.38	0.15	0.73	0.42	0.09	0.70	0.59	0.02	0.80
Increase	0.04		0.04	0.05		0.05	0.07		0.08
Percent Increase	10%	None	6%	11%	None	7%	13%	None	9%
N. 24 Hour Operation @5	0.36	0.22	0.80	0.41	0.15	0.78	0.62	0.05	0.89
Increase	0.04	0.01	0.05	0.05		0.05	0.09		0.09
Percent Increase	11%	4%	6%	12%	None	6%	14%	None	10%

***P/C Ratio** is the ratio of Perimeter space floor area to Core space floor area, where Perimeter space is up to 15 ft. from exterior walls.

normally be operating, and this too mitigates against the rise in summer cooling energy. However, for VAV systems without economizers, no increased heating penalty is experienced by raising outdoor air flow rates during cold weather.

- For both the CV and VAV system with economizers, cooling energy costs rise during hot weather, but there is minimal change during other climate conditions. There is no increase in heating energy for the CV system with economizers since the economizer brings in close to or more than 20 cfm per occupant even in the winter.

- An increase from 5 to 20 cfm per person in office buildings typically results in a small increase in annual HVAC energy costs—2%-8% without economizers and 6%-10% with economizers. HVAC systems in hot and humid climates experience increases which are higher than other due to the excess cooling load.

- A low efficiency HVAC system and extended operating hours marginally increased the impact of raising outdoor air flow rates. However, high occupant density increased the impact of raising outdoor air flow rates dramatically. The effect of occupant density on energy costs raises serious questions about the viability of following ASHRAE 62-1989 recommendations for buildings such as education and auditorium facilities, where occupant densities are higher than those included in this paper. This issue is more fully analyzed elsewhere (Mudarri &Hall 1996).

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