Building Simulation 2005

Ninth International IBPSA Conference
Montréal, Canada
August 15-18, 2005

SIMULATION OF THE EFFECT OF AN ENERGY RECOVERY VENTILATOR ON INDOOR THERMAL CONDITIONS AND SYSTEM PERFORMANCE

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ABSTRACT

In recent years, indoor humidity levels are gaining greater attention in building design and operation, due to the increasing concern over moisture-related problems, such as mold growth, indoor air quality and discomfort of the occupants. At the same time, building energy consumption, especially at peak electric demand, is also becoming a significant operating cost conern. It has been suggested that besides energy recovery, the inclusion of an energy recovery ventilator (ERV) with a right-sized cooling coil can improve temperature and humidity control in buildings. ERV also has the potential to reduce peak electric demand.

This paper presents the methodology and the findings from modeling the effect of an enhanced latent effectiveness ERV on indoor thermal conditions, system sizing and behavior, and system energy consumption under different system scenarios (with ERV and/or economizer and bypass mode), based on a generic building configuration. The applicability and effectiveness of the ERV for different climatic conditions as well as different outside air flow rates are also discussed.

INTRODUCTION

Human health and comfort in relation to temperature and humidity control performance of the HVAC systems are of increasing concern. Furthermore, energy efficiency as well as the ability to lower the peak electric demand is an important factor in reducing operating costs. Energy recovery fits in well with green building programs and is required by current standards in some configurations.

Poor humidity control in buildings can be attributed to two major factors: (1) the mismatch between the sensible heat ratio (SHR) of the air handling unit (AHU) and the occupied space; (2) the cycling of the cooling coil due to the part-load operating conditions.

Two trends have affected the SHR of commercial buildings in the last 30 years: (1) the improvement of building energy efficiency, reflected in ASHRAE Standard 90.1; (2) the requirement for the minimum amount of outside air for reasonable indoor air quality (IAQ), reflected in ASHRAE Standard 62 (TIAX, 2003). The historical change of minimum ventilation rate for office buildings prescribed in ASHRAE Standard 62 is shown in Figue 1 (Liao, 2004). Since moisture in the outside air is the major source for the humidity load in most commercial and institutional buildings (Harriman, 2002), the decreasing sensible load and unchanging, or even increasing, latent load have resulted in the decrease in building SHR over the past several decades.

Most of the HVAC systems in commercial buildings are designed and operated to maintain temperature setpoints. Indoor humidity could become a problem during off-peak cooling hours (Harriman and Judge, 2002; Sand and Fischer, 2003). Part-load of the coil, resulting from improper sizing of the coil or off-peak operating conditions, can lead to short cycling of the equipment. At the beginning of each cycle humidity is not removed until the coil is below the dewpoint of the inlet air. At the end of the cycle water condensed on the coil can be re-evaporated into the air stream, if the fan remains on for ventilation. Both could result in excess humidity in the space.

It has been suggested that the deployment of the energy recovery ventilator (ERV) can provide better humidity control for the space. The utilization of ERV also has the potential to improve the energy efficiency of the building system and reduce the peak electric demand (Wellford, 2004).

ERV can be based on many different technologies (ASHRAE, 2000). Flat plate devices and enthalpy wheels are particularly prominent commercially. While in general they all have high sensible effectiveness factors, there is more variability in latent effectiveness. One objective of this simulation study is to understand the performance characteristics needed for wide geographic applicability in buildings of different types and the benefit from certain design options such as the availability of bypass.

This paper presents the methodology developed for simulating the effect of the enhanced latent effectiveness ERV on system sizing and behavior, indoor thermal conditions, and system energy consumption under different system scenarios (with ERV and/or economizer and bypass mode), based on a generic building configuration. While some illustrative results are given, detailed findings from the use of the simulation system devised are beyond the scope of this paper.

MODELING APPROACH

The approach used for this study includes several aspects: (1) selection of the energy simulation software to support the modeling requirements of the study; (2) development of a generic building model that could be deployed for simulation studies as a function of geographic location; (3) development of various HVAC system configurations to test the applicability and effectivess of the ERV especially for packaged equipment.

The simulation software

DOE-2 and EnergyPlus are considered as two candidates for the building energy simulation software used in this study, although some other modeling programs such as ESP-r and TRNSYS might also be applicable. The modeling capabilities of both programs are investigated. EnergyPlus is selected over DOE-2 because (Crawley et al, 2004): (1) it provides a user-definable timestep for building and system simulation; (2) it can model the latent-load degradation performance of the DX cooling coil under part-load conditions; (3) the HVAC system is configurable; (4) the reporting of results is more flexible.

The building model

A single corner thermal zone in an intermediate floor, as shown in Figure 2, is used as the building model in this study. The zone has two exterior wall surfaces (south and east) and two adiabatic wall surfaces (north and west) as well as adiabatic floor and ceiling. The detailed parameters of the building model are indicated in Table 1.

The HVAC system

The thermostat setpoint is 20 – 23 ^{o}C and 10 – 50 ^{o}C for occupied and unoccupied hours, respectively. There is one hour pre-heating or pre-cooling period before the building is occupied. The setpoint for pre-heating is 17 ^{o}C and pre-cooling 26 ^{o}C. The HVAC system is available 24 hours/day, 7 days/week.

The following five system configurations are compared:

- Constant Air Volume (CAV),
- CAV with economizer,
- ERV,
- ERV with economizer,
- ERV with bypass,

based on common industry applications.

Configuration CAV includes an outdoor air mixer, a supply fan, a DX cooling coil and a gas-driven heating coil. A fixed amount of outside air and space return air is mixed in the outside air mixer and pushed through the DX cooling coil and heating coil where the mixed air is cooled, dehumidified, or heated as needed. There is no terminal reheat in the system. Neither is it able to operate in econmizer mode.

Configuration CAV with economizer is created based on the previous system configuration. All system components are kept the same as in Configuration CAV. But this configuration is able to work in economizer mode when the outdoor conditions are satisfactory. The DX cooling coil is deactivated when the system is in this operating mode.

Configuration ERV is also developed based on Configuration CAV. The outside air is pulled through the ERV to exchange heat and moisture with the space exhaust air, before it enters the outside air mixer. The delta pressure of the supply fan is elevated in order to overcome the supply side pressure drop of the ERV. An exhaust fan is added in order to overcome the exhuast side pressure drop of the ERV. Similar to Configuration CAV, a fixed amount of outside air is pulled through this system. The capability of operating in economizer mode is not provided.

Configuration ERV with economizer is developed based on Configuration ERV. As with CAV with economizer, this system is able to operate in economizer mode when the oudoor conditions are satisfactory. The energy recovery is suspended and the DX cooling coil is deactivated when the system is in this operating mode.

Configuration ERV with bypass is also created based on Configuration ERV. Depending on the enthalpy of the outside air and the space exhaust air as well as the requirement for space cooling or heating, the ERV might make “negative” contribution to the energy consumption of the system. For example, in cooling season, when the enthalpy of the outside air is less than that of the space exhaust air, the operation of ERV actually increases the cooling load on the DX coil. In addition, due to the supply and exhaust air side pressure drop of the ERV, extra fan power is consumed when ERV is deployed. Therefore it is necessary to compare the benefit and the penalty on system energy consumption resulting from the operation of the ERV in order to decide whether the ERV should be operated or bypassed. That is the idea implemented in Configuration ERV with bypass. The capability of operating in economizer mode is not provided in this configuration.

The diagrams of the various configurations are shown in Figure 3 and 4. When applied to Configuration CAV, the outside air and space exhaust air dampers in Figure 3 are normally open (NO) with fixed positions, allowing for the minimum required outside air flow in the system. When applied to Configuration CAV with economizer, the two dampers are also open, but with adjustable positions depending on the outdoor air conditions.

As for Figure 4, when applied to Configuration ERV, the outside air damper and the space exhaust air dampers to the ERV are NO with fixed positions. The exhaust air damper to the outside is normally closed (NC). The bypass damper is also NC. When applied to Configurations ERV with economizer and ERV with bypass, all dampers are adjustable depending on the outdoor air conditions. While the system is running in economizer mode, the outside air damper and the space exhaust air damper to the ERV are closed. The bypass damper and the exhaust air damper to the outside are fully open. There are two major differences between Configuration ERV with ecomozier and ERV with bypass. First, the control logic that decides the adjustment of the dampers is different, as mentioned above. Second, the dampers in ERV with bypass can only switch between close and NO. The capability of fully open is not provided.

Table 2 presents a matrix of the operational modes of various system components that are implemented in the various configurations. In the table, “Yes” means that the equipment is in operation and “No” means the equipment is not functioning.

In all system configurations, the rated SHR and coefficient of performance (COP) of the DX cooling coil is kept as 0.7 and 3, respectively. The supply air fan operates continuously and the latent-load degradation performance of the coil is simulated. In addition, the rated efficiency of the gas-driven heating coil is 0.8.

The delta pressure of the supply air fan in the Configurations CAV and CAV with economizer is assumed as 250 Pa based on certain engineering practice.

The performance indices of the ERV are taken as follows:

- sensible effectiveness at 100% airflow heating condition: 0.806
- latent effectiveness at 100% airflow heating condition: 0.678
- sensible effectiveness at 75% airflow heating condition: 0.843
- latent effectiveness at 75% airflow heating condition: 0.717
- sensible effectiveness at 100% airflow cooling condition: 0.806
- latent effectiveness at 100% airflow cooling condition: 0.678
- sensible effectiveness at 75% airflow cooling condition: 0.843
- latent effectiveness at 75% airflow cooling condition: 0.717
- ERV supply side pressure drop 52 Pa, exhaust side pressure drop 72 Pa

As shown from these data, the latent effectiveness of the ERV is significantly high and the pressure drop is considerably low, compared to the products currently available in the market.

In system configurations integrated with ERV, the delta pressure of the supply and exhaust fans is 302 and 72 Pa, respectively, considering the pressure drop of the ERV.

The satisfactory outdoor conditions for the economizer mode operation for Configurations CAV with economizer and ERV with economizer are: outside air temperature between 10 and 20 ^{o}C, and outside air enthalpy less than 38 kJ/kg (20 ^{o}C dry bulb temperature and 50% relative humidity (RH)).

The generic air-to-air heat recovery model availabe in EnergyPlus, with the aforementioned performance data, is used in the study. However, due to the lack of the desired control logic in EnergyPlus, the output results from EnergyPlus are post-processed using spreadsheets in order to predict the indoor thermal conditions and system energy performance of Configuration ERV with bypass.

RESULTS AND DISCUSSION

Initially, it was assumed that there were 10 occupants in the space based on certain design practice. The required outside air was 0.0944 m^3/s, which accounted for about 10% of the total supply air flow rate. The simulation was run for Configurations CAV and ERV. The savings on system energy consumption obtained from the ERV were compared to the existing literature (Wellford, 2004), for the city of Miami, Fl. A small percentage of energy savings was shown, mainly because of the small fraction of outside air in the total supply air flow. Then the outside air was increased to 0.283 m^3/s, which is about 30% of the total supply air flow. The results showed a larger percentage of savings in energy consumption. This indicates that the ERV is more effective when the heat loss and gain resulting from the outside air supply is a major contributor to the building heating and cooling load. In the rest of the study, 0.283 m^3/s outside air flow remains unchanged.

Simulations are performed for each of the five system configurations, with three different DX coil capacities: an initial size 18 kW, upsizing 20% to 21.6 kW and downsizing 20% to 14.4 kW. The effect of the DX coil capacity on the indoor temperature and RH conditions, as well as the annual energy consumption is shown in Figures 5 and 6.

Figure 5 plots the effect of coil sizing on annual energy consumption and indoor temperature condition. The graph illustrates that as the DX coil size is increased, the annual energy consumption increases and the number of hours when the temperature setpoint is not met decreases. The graph also indicates that for a fixed DX coil size (18 kW), the energy consumption of Configuration CAV compared to that of Configuration ERV with bypass is reduced from 14,634 to 13,576 kWh, a 7.2% reduction. The number of hours when the indoor temperature setpoint is not met is reduced from 327 to 43 hours, an 87% improvement.

Figure 6 plots the effect of DX coil sizing on indoor RH condition and annual energy consumption. In the analysis, the acceptable range of the indoor RH is set as 30 – 60%, based on ASHRAE Standarad 62-1999. The graph illustrates that as the DX coil size is increased, the number of hours when the indoor RH is not acceptable increases. This can be explained by the latend-load degradation of the coil under part-load conditions, as previsouly stated. The graph also indicates that for a fixed DX coil size (18 kW), the inclusion of the ERV with the bypass configuration reduces the number of hours when the acceptable indoor RH range is not met from 1518 to 1242 hours, an 18% improvement.

Figures 5 and 6 bring about an interesting phenomena that commonly occurs in the HVAC system design. When the problem of excess humidity happens in a space conditioned by a thermostatically controlled HVAC system, very often, the designers will try to address the humdity issue by increasing the cooling capacity of the AHU. From these two plots, it is clear that additional cooling capacity can help improve the temperature control, but it makes the humidity problem even worse.

Figure 7 plots the impact of the ERV on coil sizing and indoor RH conditions, given the same level of indoor temperature control. In this plot, the number of hours when the indoor temperature setpoint is not met is set to be the same (130 hours, or 5% of the occupied hours). The results indicate that the size of the DX coil can be reduced from 19.3 to 16.6 kW, with the deployment of ERV. The number of hours when the acceptable indoor RH range is not met is decreased from 1749 to 802 hours, a 55% improvement. The plot also shows a decreased level of indoor RH control with the economizer mode, which can be explained from the satisfactory outdoor conditions set for economizer operation.

Figure 8 plots the impact of the ERV on system energy consumption, given the same level of indoor temperature control. As seen from this graph, the deployment of the ERV reduces the system annual energy consumption from 15,022 to 13,770 kWh. The inclusion of the bypass operation further decreases the energy consumption to 13,251 kWh, a 12% reduction compared to Configuration CAV.

GEOGRAPHIC EXTENSION

The modeling approach described above creates fifteen EnergyPlus input files, one for each HVAC configuration and cooling coil capacity for the model office in a single location. Since the HVAC equipment is not available in arbitrary sizes, a fixed upsizing or downsizing percentage, ±20% of the typical size implied by the cooing design day of a specific city, is chosen independent of geographic location. In addition, the sensible and latent effectiveness factors and the pressure drop of the ERV, and the rated SHR and COP of the DX coil are kept constant.

The approach is then applied to 62 U.S. cities in order to study the geographic applicability of the ERV and the configuration of economizer and bypass. The 62 locations represent a wide range of climate, include most major cities of economic importance, and have at least one city in every state.

Analysis of the results for energy savings and other aspects of interest are conducted through statistical studies and graphical plots using MATLAB and MapViewer by Golden Software.

As a typical example, Figure 9 shows the national benefit of energy recovery as a function of geographic location. It is noted that in northerly climates the savings on heating dominates the savings on cooling due in part to the short cooling season and the bigger difference between indoor and outdoor temperature.

CONCLUSION

In this paper, five HVAC system configurations, CAV, CAV with economizer, ERV, ERV with economizer and ERV with bypass, are developed. The simulations are run on a generic building model for 62 U.S. cities in order to investigate the geographic applicablity and effectiveness of the ERV and associated economizer or bypass operations.

The results indicate that the indoor temperature control level increases with the increase in DX coil capacity. However, the increasing DX coil size tends to deteriate the indoor RH control and increase the annual system energy consumption, which is true for all of the five system configurations.

Depending on the climatic contexts, the depolyment of the ERV might improve the indoor RH conditions and the system energy efficiency, given the same level of temperaure control. The DX coil might also be downsized with the inclusion of the ERV.

In addition, the ERV is more effective when the heat loss and gain resulting from the outside air supply is a major contributor to the building heating and cooling load.

The simulation results also indicate that the capability of bypass operation helps achieve better energy efficiency of the system. Depending on the space exhuast air and outside air conditions, and the extra fan power required to pull the air through the ERV, the operation of the ERV might not make sense in all climatic contexts at all time.

ACKNOWLEDGMENT

This paper was prepared with the support of the U.S. Department of Energy (DOE), under Award No. DE-FC26-01NT41254. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE.

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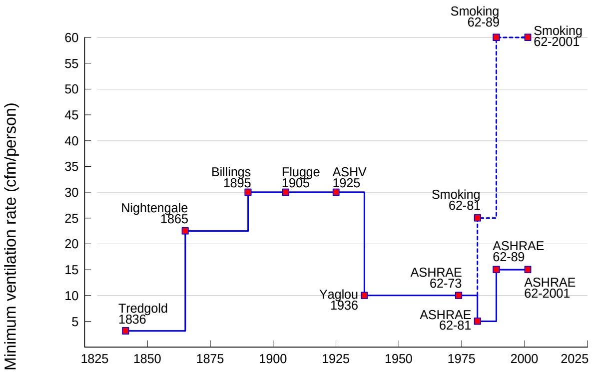

Figure 1 ASHRAE minimum ventilation rate history (1cfm = 0.47 l/s)

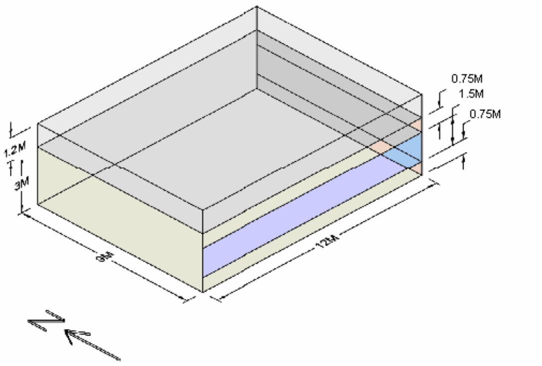

Figure 2 The building model

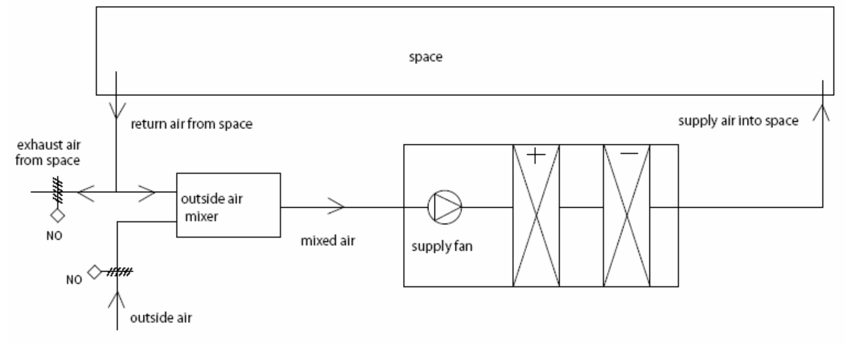

Figure 3 Diagram for Configurations CAV and CAV with economizer

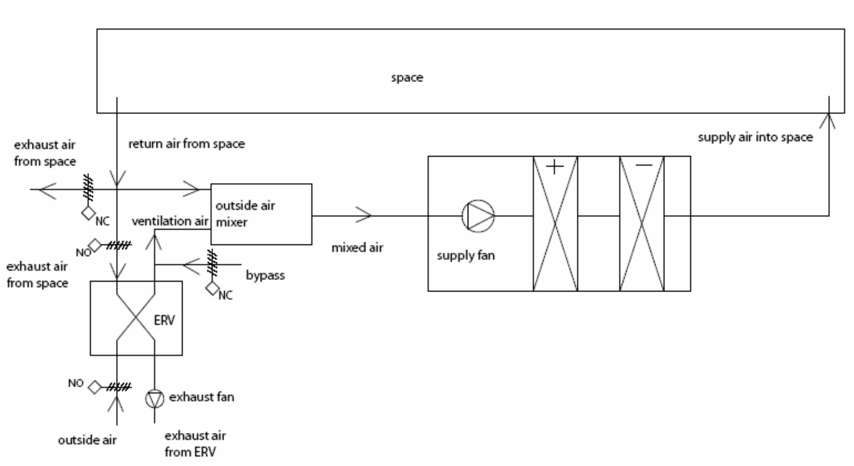

Figure 4 Diagram for Configurations ERV, ERV with economizer and ERV with bypass

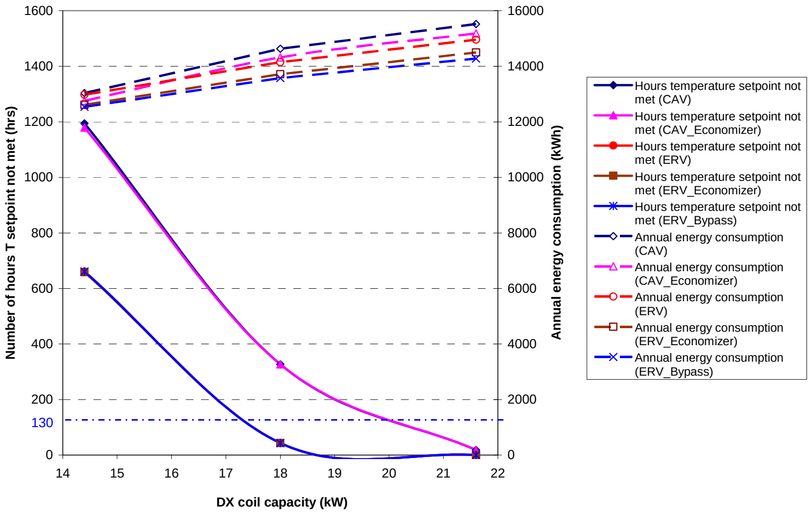

Figure 5 The effect of DX coil capacity on indoor temperature and energy consumption

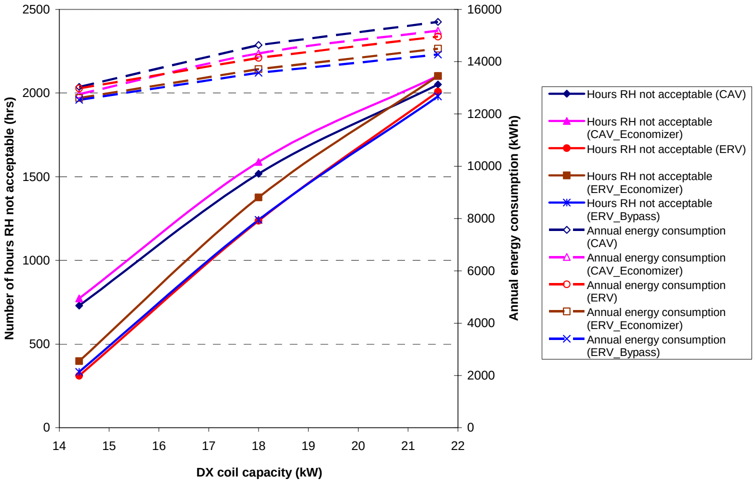

Figure 6 The effect of DX coil capacity on indoor RH and energy consumption

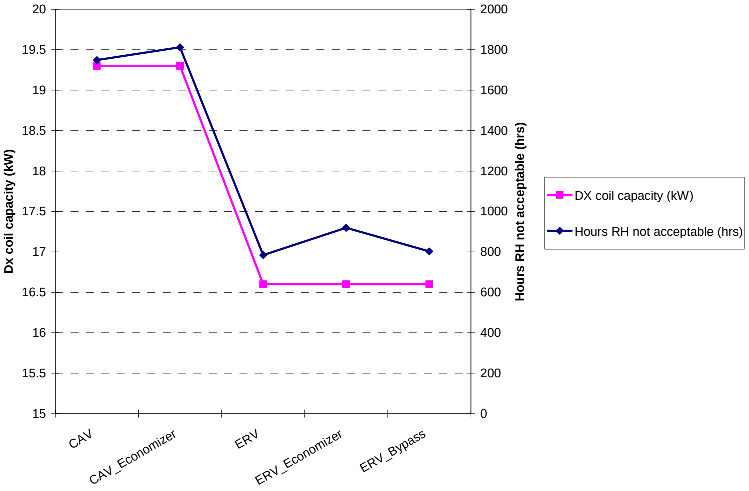

Figure 7 The effect of ERV on system sizing and indoor RH level

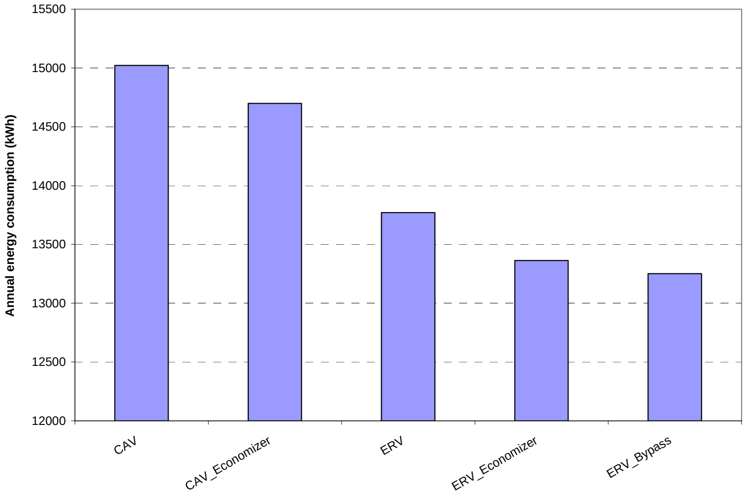

Figure 8 The effect of ERV on system energy consumption

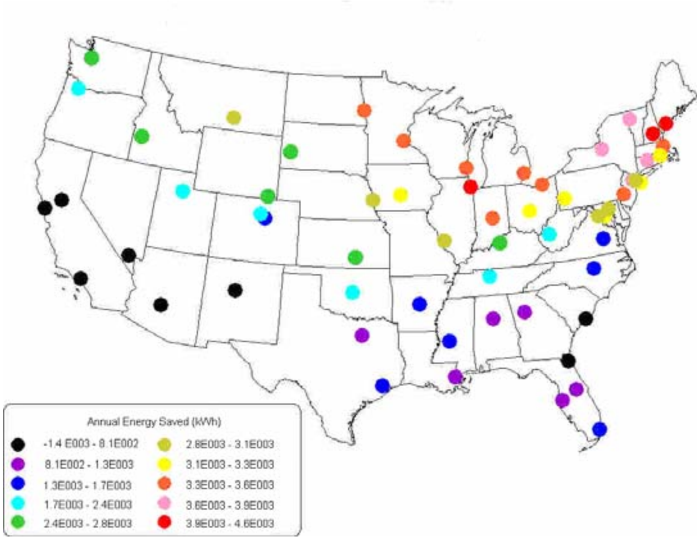

Figure 9 Annual energy saving resulting from the deployment of ERV (without bypass) by location

Table 1 Parameters for the building model

Geometry	x = 12.0 m (39.4 ft)	y = 9.0 m (29.5 ft)
	area = 108 m^2 (1163 ft^2)	z = 4.2 m (13.8 ft)
	plenum = 1.2 m (3.9 ft)	occupied zone = 3m (9.8 ft)
	window-to-wall ratio (WWR) = 50%	
Opaque construction	floor, roof, north and west walls: adiabatic	east and south walls: U-value = 0.349 W/m^2-°K (0.06 Btu/h-ft^2-°F)
Glazing	U-value = 1.45 W/m2-°K (0.25 Btu/h-ft2-°F) T_v = 0.41, SHGC = 0.35	
Infiltration	0.20 ACH, 24 hours/day, 7 days/week	
Lighting and plug load	36 W/m^2, 8am – 6pm, Monday-Friday	
Occupancy	10/30 occupants, 8am – 6pm, Monday-Friday	
Outside air requirement	0.00944 m^3/s-person (20 cfm/person) when occupied	

Table 2 Operational modes for the five system configurations

	System		ERV		Bypass mode	Economizer mode
	Supply fan	Coil	ERV unit	Exhaust fan		
CAV	Yes	Depends on building load	No	No	No	No
CAV_Economizer	Yes	No	No	No	No	Yes
		Depends on building load				No
ERV	Yes	Depends on building load	Yes	Yes	No	No
ERV_Economizer	Yes	No	No	No	No	Yes
		Depends on building load	Yes	Yes		No
ERV_Bypass	Yes	Depends on building load	No	No	Yes	No
		Depends on building load	Yes	Yes	No	