

Evaluation of Energy Efficiency Measures in Hot and Humid Climates

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ABSTRACT

Hot and humid climates present some of the most complex challenges for sustainable building designs. High temperatures coupled with high humidity create extreme comfort problems and exacerbate the potential for condensation, mold and mildew. These are usually remedied with conventional mechanical air conditioning systems, but the move toward sustainability urges designers to find less energy intensive solutions. An integrated design process coupled with energy modeling and lifecycle analysis can unite design teams around desired outcomes to provide an optimized design solution for projects in these climates. Such an approach involves first minimizing building loads and then reducing residual energy consumed by the HVAC systems.

This paper presents an integrated design approach to evaluating the most efficient energy measures in hot and humid climates and summarizes the findings of a series of cases using this approach, including international examples of office, education, and small retail buildings in ASHRAE Climate Zones 1A and 2A.

INTRODUCTION

Hot and humid climates present some of the most complex challenges for sustainable building designs. High temperatures coupled with high humidity create extreme comfort problems and exacerbate the potential for condensation, mold and mildew. This paper presents the results of information gleaned from a series of cases studies of commercial buildings designed for hot/humid climates. The case study buildings used an integrated design approach to evaluate the most efficient energy measures. The buildings span a variety of use types, including international examples of office, education, and small retail buildings in ASHRAE Climate Zones 1A and 2A.

The case study examples are summarized in Table 1. Because they represent examples from a sustainable design consulting practice, the buildings reflect a variety of building uses, sizes, and design characteristics. In some instances, they represent building prototypes that were modeled in a variety of climate zones.

INTEGRATED DESIGN APPROACH

High aspiration sustainable building designs require an integrated design approach to identify the desired outcomes and provide an optimized project

design solution. The complexities of designing for a hot/humid climate make this especially important. An integrated design approach involves early participation of the owner, design team, and construction team members to evaluate alternative design scenarios and investigate potential synergies between design options. The integrated approach frequently involves an eco-charrette, climate analysis, energy model and lifecycle analysis.

The integrated approach explores the potential of passive strategies and life cycle costing and may include first cost transfers from conventional HVAC systems to the building envelope. This approach usually moves through the following sequence to optimize building energy performance:

1. Minimize building loads through passive strategies
2. Design energy efficient building systems
3. Optimize controls of energy efficient building systems

The following sections present the findings from implementing this approach—in particular, the first two strategies—on building projects in climate zones 1A and 2A (see Table 1).

Table 1. Summary of Case Examples

| BUILDING # | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---------------------------------------|-------------------------------------|--------------------------------------|--------------------------------------|--|---|---|-----------------------------|
| Type | College Classroom Building | Office | Office | Prototype Office Building | Prototype, Storefront Retail Building | Prototype Stand-alone Retail Building | Small Retail |
| Location | Hawaii | West Africa | Thailand | various | various | various | various |
| Climate Zone(s) | 1A | 1A | 1A | 1A, 2A, 3B, 4A, 5A & 6A | 1A, 2A, 3B, 4A, 5A & 6A | 1A, 2A, 3B, 4A, 5A & 6A | 2A, 2B, 3C, 3B, 4A, 5A & 5B |
| Floor Plate Size | 258' x 33' | 217' x 180' | 150' x 90' | 270' x 110' | 178' x 40' | 77' x 53' | ~ 3,000 sq. ft. |
| # of Floors | 3 | 5 | 2 | 6 | 1 | 1 | 1 |
| Load Type | External | Internal | External | Internal | External | External | External |
| Window-to-wall area ratio | >40% | 23% | 31% | 40%, window evenly distributed on exterior walls | 35%, most windows on south and west walls | 35% | Various |
| Proposed HVAC System | VRV and DOAS | VAV with reheat, air-cooled chillers | VAV with reheat, air-cooled chillers | Same as ASHRAE baseline | Same as ASHRAE baseline | Same as ASHRAE baseline | Packaged rooftop units |
| ASHRAE 90.1-2004 Baseline HVAC system | #4 - Packaged single-zone heat pump | n/a | #4 - Packaged single zone heat pump | #7 - VAV with reheat, water-cooled chillers, gas fired boilers | #3 - Packaged single zone air-conditioner | #3 - Packaged single zone air-conditioner | n/a |

The simulation software used for the energy simulation analysis in this paper is eQuest. eQuest is a widely used program with a simulation engine derived from the latest version of DOE-2. It is also a qualified program for whole building energy performance simulation to meet ASHRAE 90.1 compliance.

MINIMIZE BUILDING LOADS

In order to optimize building energy performance, the first step is to minimize loads. Cooling energy use is often the largest end use for buildings in hot and humid climates. Cooling loads typically come from heat gain through building envelope, interior lighting, receptacle loads, occupants, ventilation and infiltration. This paper investigates the opportunities to minimize cooling loads from building envelope and daylighting design.

Envelope Load Reduction

Although the investigation of building siting and massing is the first step toward reducing external envelope loads, the case studies in this report assume a given building siting/massing and focus on the findings of appropriate envelope insulation values,

glazing specifications, shading design and the integration of these design parameters.

The examples illustrate the complexity of design decisions for a hot/humid climate, some of which may be counter intuitive. For example, design teams may not appreciate how the use of wall insulation may actually increase the cooling energy required and the need for coordination between the glass specifications for solar heat gain and external shading devices. This section also summarizes rules for the selection of glazing products in hot and humid climates based on the energy simulation results.

1. Appropriate opaque envelope insulation

In hot/humid climates, average exterior air temperatures may be consistently higher than interior temperatures, resulting in potential conductive heat gains through the envelope (see Figure 4); or in milder climates, temperatures may vary above and below the interior exhaust air temperature (see Figure 7), providing both heat gain and heat shedding possibilities. Thus, unlike colder climates, the use of building envelope insulation in hot/humid climates may trap heat inside buildings in these cooling dominated climates and actually increase building energy use.

These potential impacts are exacerbated by solar gain contributions to surface temperatures. High sun angles in tropical climates contribute significantly larger solar gains to building roof areas than to wall areas, so roofs are significantly more vulnerable to this solar loading than walls.

Because of these complex dynamics, the use of insulation in building envelope components may either beneficially or adversely impact energy performance, depending on how hot the climate is, how high the building's internal loads are and the orientation of the surface relative to solar gains. The case studies for Buildings #1, #2 and #3 below demonstrate this complexity.

The envelope component specifications in these case study buildings are compared either with the level recommended in ASHRAE Standard 90.1-2004 (the standard in place at the time of their construction) or, in the case of Buildings #2 and #3, the client's standard design for this building type. ASHRAE's exterior opaque envelope insulation requirement for climate zones 1A and 2A is lower than that for colder climate zones. Note that although ASHRAE Standard 90.1 version 2007 is more stringent than version 2004, the requirement for envelope insulation level for climate zone 1A did not increase from version 2004 to version 2007. For climate zone 2A, the 2007 version of the standard requires greater insulation only for roof, mass walls and floors. This suggests that the use of greater envelope insulation may not always be beneficial for building energy performance in these climate zones.

The energy impact of varying the amount of exterior envelope insulation was evaluated for Buildings #1, #2 and #3. Building #1 and Building #3 are external load dominated buildings. Building #2 is an internal load dominated building. Although all are in climate zone 1A, Building #1 and Building #2 are located in relatively milder climates than Building #3. As shown in Tables 2 and 3, energy savings are achieved when wall insulation levels are reduced in Buildings #1 and #2 relative to the initial designs. The predicted annual energy use of Building #1 decreases slightly by 0.1% when exterior wall insulation is removed (increasing the assembly U-factor from 0.08 to 0.124); and energy savings of 2.7% are predicted for Building #2 if the insulation in the exterior walls is removed entirely. However, Building #3 shows the opposite effect: its energy savings decrease as exterior wall insulation is reduced (Table 4).

The roof insulation parametric analyses for all three buildings show an increase of energy use when the roof insulation values are reduced.



Figure 1. Building #1 Initial Exterior Shading Design

Table 2. Building #1 Results

| | Assembly U-factor | Building Annual Energy Use (kWh) | Predicted % of Savings |
|------------------|-------------------------------------|----------------------------------|------------------------|
| ASHRAE 90.1-2004 | Exterior Wall: 0.124 Roof: 0.063 | 408,825 | n/a |
| Design wall | 0.08 | 409,219 | -0.1% |
| Design roof | 0.045 | 404,064 | 1% |

Table 3. Building #2 Results

| | Assembly U-factor | Building Annual Energy Use (kWh) | Predicted % of Savings |
|---------------------------|----------------------------|----------------------------------|------------------------|
| Initial design | Wall: 0.083 Roof: 0.048 | 1,946,088 | n/a |
| Wall with no insulation | 0.33 | 1,892,971 | 2.7% |
| Roof with less insulation | 0.091 | 1,949,200 | -1.5% |

Table 4. Building # 3 Results (Standard Design insulation values are shaded in light grey.)

| Roof Assembly U-factor | Wall Assembly U-factor | Annual Energy Savings from Standard Design (kWh) | % Savings from Standard Design |
|------------------------|------------------------|--|--------------------------------|
| 0.044 | 0.073 | -7,032 | -1.2% |
| | 0.045 | -1,758 | -0.3% |
| | 0.030 | 2,051 | 0.2% |
| 0.030 | 0.073 | -5,274 | -0.9% |
| | 0.045 | 0 | 0.0% |
| | 0.030 | 3,809 | 0.5% |
| 0.025 | 0.073 | -4,688 | -0.8% |
| | 0.045 | 586 | 0.1% |
| | 0.030 | 4,395 | 0.6% |

These case study results demonstrate that energy modeling is essential to evaluate the appropriate wall insulation values for buildings in hot/humid climates. For some combinations of climate and building configuration, both energy and cost savings can be achieved by reducing or eliminating wall insulation.

2. Appropriate glass products and window shades

Different glazing options were also evaluated for Building #1 in the schematic design phase. The initial design included exterior overhangs and fins that fully or partially shade most windows during daytime, but the glass specification was not set. To isolate the energy impact of glazing options, the consulting team started the analysis by modeling the building with envelope and HVAC systems required by ASHRAE 90.1-2004, using the schematic design window geometry and exterior shades.

In addition to size, orientation, and exterior shading conditions, window energy performance is a function of the glazing U-factor, solar heat gain (SHGC) and visible transmission (VLT) if daylighting controls are being implemented. Window assemblies with different glass options were evaluated for Building #1 through parametric simulation runs. Because the architectural design required the building to have a transparent appearance, these options did not include highly reflective and darkly tinted glass products (see Table 5). The estimated building annual energy use values (not including daylighting controls) for all options are illustrated in Figure 2.

Table 5. Glazing Options for Building #1

| | U-factor ¹ | SHGC | VLT |
|---|-----------------------|------|------|
| ASHRAE 90.1-2004 | 1.22 | 0.25 | n/a |
| Double-glazed high performance low-e | 0.25 | 0.28 | 0.62 |
| Laminated high performance low-e with clear glass | 1.07 | 0.41 | 0.72 |
| Single-glazed blue/green tint | 0.93 | 0.59 | 0.68 |
| Single-glazed clear | 0.93 | 0.94 | 0.89 |

Figure 2 shows that the ASHRAE window assembly has lower annual energy than all other options. Although both U-factor and SHGC vary by a factor of four to five among these examples, it appears that the variation in SHGC has a significantly higher impact on energy use than U-factor does. The following conclusions can be made with these results:

1. Glazing with greater insulation may result in greater energy use because of heat being retained inside the building.
2. For windows that are not fully shaded,

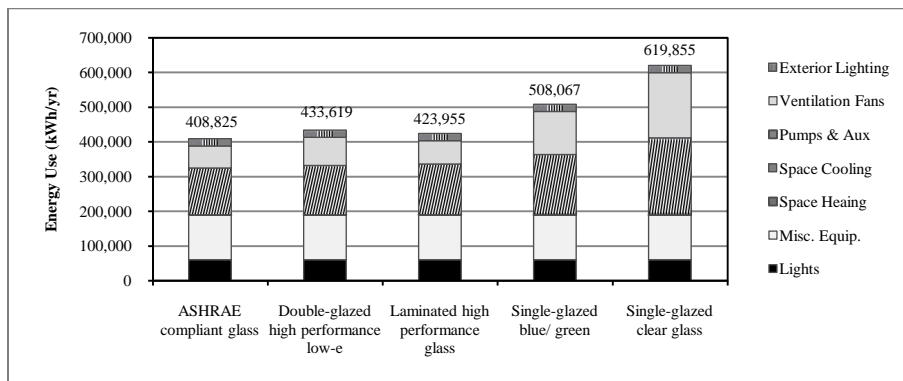


Figure 2. Building #1 Annual Energy Use Breakdown with Various Glazing Options

¹ The U-factors for the four selected glass products are all the center-of-glass U-factors.

glazing products with low SHGC are desired to reduce solar gains and their attendant cooling and fan energy use.

If very low SHGC glazing is not used, this design should have additional exterior shading for maximum energy savings.

Because very low SHGC glass tends to be either reflective or darkly tinted (counteracting the project’s goal of “transparency”), the next step in the analysis evaluated the use of additional exterior shading to reduce solar gains.

The design was modified to provide all south, west and east windows with shading devices that would provide full shade from 8am to 4pm. This reduced the building energy consumption so that the laminated glass and double-pane low-e glass products now perform slightly better than the ASHRAE glass (see Figure 3).

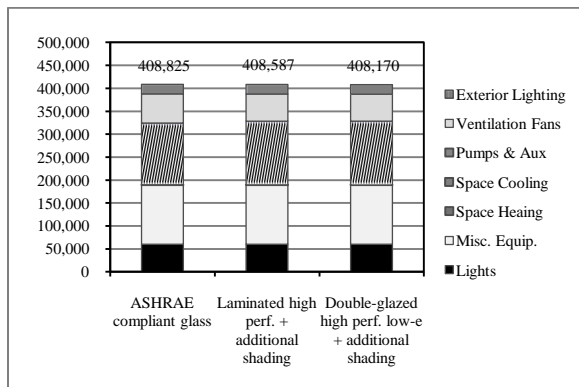


Figure 3. Building #1 Energy Use with All South, West and East Windows Fully Shaded

Another project tested the sensitivity of double glazing and exterior shading for prototype buildings in climate zones 1A and 2A. These prototype office and retail buildings (#4, #5 and #6) are ASHRAE 90.1-2004 compliant and were modeled with ASHRAE 90.1-2004 Appendix G requirements. The performance of double-pane glass and external shades were analyzed through parametric runs. The external shades were assumed to partially shade the south, west and east windows, and have a depth of one-half the window height. The double-pane window glass product was modeled with a center-of-glass U-factor of 0.27 and SHGC of 0.24. The energy savings over the ASHRAE baseline building are listed in Table 6.

Table 6. Energy Savings Relative to ASHRAE Baseline with Exterior Shades and Double-Glass in Climate Zones 1A and 2A

| Building | Honolulu, HI Zone 1A | | | Houston, TX Zone 2A | | |
|------------------------------|-------------------------|--------------|-----------------------|------------------------|--------------|-----------------------|
| | #4 Office | #6 Retail | #5 Store- front | #4 Office | #6 Retail | #5 Store- front |
| Double Glazing | -0.7% | 1.0% | 2.3% | 2.8% | 9.7% | 14.1% |
| Shades, SWE | 3.3% | 5.7% | 6.3% | 1.8% | 3.2% | 3.0% |
| Double Glazing + Shades, SWE | 2.1% | 7.3% | 8.5% | 4.5% | 13.1% | 16.3% |

These simulations show that the double-pane glass performs better than the ASHRAE glass for all situations except the internal load dominated office Building #4 in climate zone 1A. It also shows that the U-factor of the double glazing has a greater impact for climate zone 2A than for zone 1A. These simulations again demonstrate that the benefits of increased insulation for windows varies with the specifics of climate, building use and design, and thus requires a full building energy simulation to determine the magnitude of energy savings and whether they are positive or negative.

The results also show that external shades can significantly contribute to building energy savings in hot climates. Note that the external shades alone produce higher energy savings for Honolulu (latitude 21°) as compared to Houston (latitude 30°). This is probably because the fixed size shading devices are better able to reduce solar gains from the high sun angles in Honolulu.

Daylighting Controls

Daylighting controls can maximize the use of natural light and reduce electric lighting and cooling energy use. Prototype Buildings #4, #5 and #6 were analyzed to determine the potential energy savings with daylighting controls in six US climate zones. This analysis assumed that 67% of lights within daylight zones dimmed to 10% lighting level and these lights would automatically turn off if the daylight alone met the illumination set point of 50 footcandles. The total estimated building energy savings are reported in Table 7 relative to an ASHRAE baseline with no daylight controls. The results show that daylight control in hot climates has significantly greater energy saving potential than that in buildings in cold climates. This is probably due to the double benefit of electric lighting and cooling load reduction when electric lights are dimmed or turned off in hot climates.

Table 7. Energy Saving Potentials of Daylighting Controls

| Zone 1 | | Zone 2 | | Zone 3 | |
|--------------|--------|----------------|--------|-----------------|--------|
| Honolulu, HI | | Houston, TX | | Los Angeles, CA | |
| Office | Retail | Office | Retail | Office | Retail |
| 9.5% | 13.2% | 7.9% | 11.4% | 10.5% | 14.3% |
| Zone 4 | | Zone 5 | | Zone 6 | |
| New York, NY | | Pittsburgh, PA | | Minneapolis, MN | |
| Office | Retail | Office | Retail | Office | Retail |
| 6.8% | 5.6% | 6.3% | 4.3% | 5.7% | 4.8% |

Envelope and Daylighting Design Recommendations for Load Reduction

In summary, the envelope and lighting design recommendations for projects in hot and humid climates (climate zones 1A and 2A) are:

- Wall & Window Insulation:** In hot/humid climates increased window and wall insulation does not necessarily provide increased energy savings and in some cases may reduce savings (especially in Climate Zone 1A). Perform a whole building energy model analysis to determine optimum insulation levels and perform a life-cycle cost analysis to evaluate long term cost impacts.
- Roof Insulation:** Consider higher insulation levels than the ASHRAE minimum requirement for roofs and evaluate the benefit of additional roof insulation based on life-cycle cost analysis.
- Window Shading:** Use exterior shading on all windows that are exposed to solar gains during cooling dominated times or choose glass products with low SHGC.
- Daylighting:** Select glazing products with relatively high visible light transmittance (assuming that shading recommendations in #3 are met) and use automatic daylight controls to dim or switch electric lights when not needed.

ENERGY EFFICIENT BUILDING SYSTEMS

After the load reduction goal is achieved, the second step of the integrated design approach is to reduce residual energy use consumed by HVAC systems. This section summarizes two energy efficiency measures that were demonstrated effective based on the energy modeling analyses done for the example buildings in hot and humid climates. The performance of different types of exhaust air heat recovery to pre-cool and/or dehumidify the ventilation air is compared for different temperature and humidity conditions. Also, the energy saving

potential of dedicated outdoor air systems is evaluated.

Air-to-Air Heat Recovery

An air-to-air heat recovery system can be used to recover energy from conditioned air that is normally exhausted out of the building. Heat recovery is economical when there are large temperature differences between the air streams, the source of supply is close to the exhaust, and they are both relatively constant throughout the year.

The data in Figure 4 demonstrate that hot/humid climate temperatures frequently meet these conditions. For the location of Building #3, the difference between the exhaust air temperature and average outside air stream temperature ranges from 5 to 13 deg. F, and can exceed 25 deg. F at the times of maximum outside temperatures (see Figure 4). Also, Figure 5 shows the large difference in humidity between outside air as compared to the return air. Both of these indicate the potential for energy savings through an air side heat recovery system.

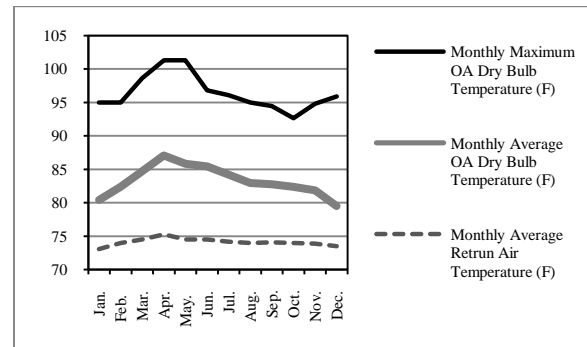


Figure 4. Monthly Outdoor Air Temperatures and Return Air Temperatures for Building #3 in Thailand

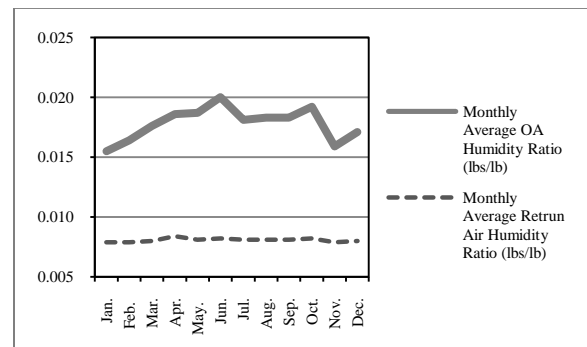


Figure 5. Average Monthly Outdoor Air Humidity Ratio and Return Air Humidity Ratio for Building #3 in Thailand

1. Types of air-to-air heat recovery for hot and humid climates

The following types of air-to-air heat recovery devices are often used: enthalpy wheels, run-around systems and heat pipes.

Enthalpy wheels recover both sensible and latent heat. An enthalpy wheel has a revolving cylinder filled with an air-permeable medium with a large internal surface area and desiccant coating. Adjacent air streams pass through opposite sides of the exchanger in a counter-flow pattern. Usually these systems are quite compact and can achieve high transfer effectiveness. Typically enthalpy wheel based heat recovery ventilators (energy recovery ventilators) are more efficient than other air-to-air heat recovery strategies that transfer sensible heat only. In fact, in cases where latent loads are higher than sensible loads, the enthalpy wheel offers the advantage of reducing a larger component of the load as it is more efficient at latent, due mainly to a reduction in the number of heat transfer processes that occur. The system requires little maintenance and is very simple to operate.

However, cross-leakage may occur if enthalpy wheels are used. The cross leakage rate is about 0.5-10%. This risk of leakage may raise security concerns in buildings that need to be protected from air-borne contaminants (disaster response centers, government buildings, etc).

If a run-around system is used, cross-contamination will not be a concern. A run-around system is typically a coil energy recovery loop that includes extended surface and finned tube coils placed in the supply and exhaust airstreams. The coils are connected in a closed loop via counter-flow piping through which an intermediate heat transfer fluid is pumped. However, the coil energy recovery loop cannot transfer moisture from one airstream to another, so latent savings are not achieved. In addition, the system requires a pump, which offsets some of the energy savings.

A heat pipe is a passive energy recovery heat exchanger that is divided into two sections by a sealed partition. Hot air passes through one side (evaporator) and is cooled while cooler air passes through the other side (condenser). While heat pipes are sensible heat transfer exchangers, if the air conditions are such that condensation forms on the fins, there can be some latent heat transfer and improved efficiency.

2. Energy savings from different types of air-to-air heat recovery

The design process for Building #3 involved a study of energy saving potential of different types of air-to-air heat recovery systems. The energy model results indicate that about 40% of the cooling load in the building is latent load. This suggests that a system recovering both sensible and latent heat would save more energy than a system that recovers sensible heat only.

The enthalpy wheel heat exchanger and the run-around heat exchanger were modeled to compare the energy savings. The results indicate that enthalpy wheel heat recovery reduces energy consumption for cooling with a slight increase in the fan energy caused by the pressure drop across the equipment. Figure 6 shows energy model results for both a baseline and the proposed design cases with the two heat recovery configurations.

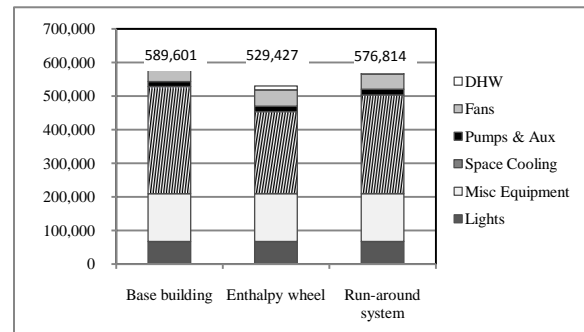


Figure 6. Annual Energy Consumption (kWh) for the Baseline and Heat Recovery Measures

The estimated reduction of cooling energy consumption is 23% with enthalpy wheels and only 8% with the run-around systems. The building's total annual energy use is reduced by 10% with enthalpy wheels and 2% with run-around systems. The energy saving potential of enthalpy wheels for this building is very significant.

3. Energy savings vs. climate conditions

Air-to-air heat recovery may not be effective if the return air temperature is close to the outdoor air temperature, even for buildings in climate Zone 1A. For example, the effectiveness of air-to-air heat recovery was evaluated for Building #1. As shown in Figure 7, the monthly average outdoor dry bulb temperatures in Honolulu, HI, are fairly close to the return air temperatures and fluctuate seasonally above and below them. The outdoor air humidity ratio for this building in Hawaii is also much lower than that for Building #3 in Thailand. Due to these milder temperature and humidity conditions, the energy models for Building #1 showed that all types

of air-to-air heat recovery systems noted above resulted in insignificant energy savings. The cooling energy use reduction was significantly offset by the fan energy use increase. This is true even if heat recovery is bypassed when it is inefficient because the enthalpy or the temperature of the outdoor air is not greater than that of the return air.

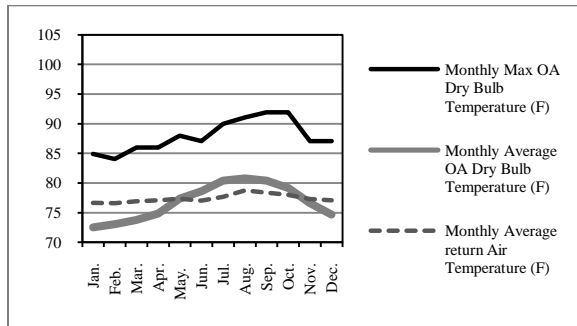


Figure 3. Monthly Outdoor Air Temperature and Return Air Temperature for Building #1 in Hawaii

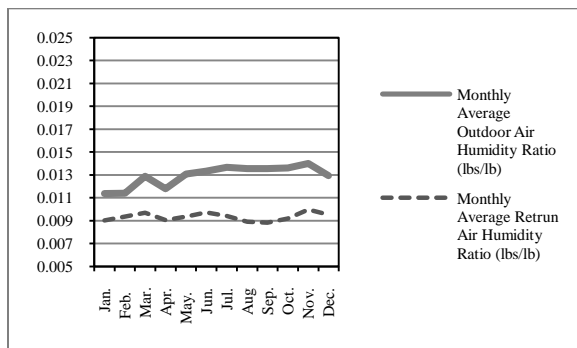


Figure 4. Monthly Outdoor Air Humidity Ratio and Return Air Humidity Ratio for Building #3 in Thailand

4. Design Recommendations.

These case study findings suggest the following heat recovery design recommendations:

1. The energy reduction effectiveness of air-to-air heat recovery should be evaluated based on climate analysis and energy model analysis.
2. The use of enthalpy heat recovery may help achieve greater energy savings than the use of other type of heat recovery devices, especially when there are high latent loads.

Dedicated Outdoor Air System (DOAS)

In most buildings, HVAC systems combine fresh outdoor air with re-circulated air, then condition and distribute the air into the interior space. With DOAS systems, outdoor air is conditioned separately from the return air, which can improve humidity control and deliver precise amounts of ventilation air,

therefore saving energy for buildings in hot and humid climates.

1. Energy savings for Building #1 and Prototype Building #4.

The energy benefit of DOAS was evaluated for Building #1. In the proposed design, variable refrigerant volume (VRV) units precondition outdoor air to 75°F dry bulb and 55°F dew point temperatures and supply it to the classrooms. Additional VRV fan coil units draw in the room air, further condition it to 64°F dry bulb temperature, and resupply it to the classrooms. In the eQuest energy model, these additional systems were modeled as their outdoor air is supplied through the DOAS systems.

The energy use of this design was compared with a baseline design that uses VRV fan coil units with conventional cooling and ventilation design. The air delivered to rooms is cooled to 55°F. The ventilation rates were identical in both energy models. Table 10 shows that the decoupled cooling and ventilation design can achieve a cooling energy reduction of 17%, resulting in a total building energy savings of 5%. Simulation hourly results show that the indoor air humidity levels of both runs do not exceed 65% RH year round.

A similar analysis was done for prototype office Building #4 for climate zones 1A and 2A. Building #4 has a standard VAV system with hot water reheat. In the feasibility study, a VAV DOAS system was added to pre-cool the outdoor air to 75°F dry bulb and 55°F dew point temperatures and to supply the pre-conditioned air to the units serving each floor. These units further cooled the air to 55°F dry bulb and 55°F dew point temperatures and supplied it to the spaces. The indoor air humidity level is controlled to a maximum of 60% RH.

This prototype office building was evaluated in two different climates: Honolulu, HI, and Houston, TX. The eQuest simulation results, listed in Table 11 and Table 12, show that the DOAS system can save cooling energy use by 23% and total energy use by 7% for the building in Honolulu (zone 1A). Similar results of 23% cooling savings and 6% total building savings were achieved for the building in Houston (zone 2A).

2. DOAS Conclusions and Recommendations

The use of a DOAS system that decouples ventilation and cooling can significantly reduce building energy use in hot and humid climates.

Specify such system for buildings in hot and humid climates if the incremented cost is acceptable.

In addition, because air-to-air heat recovery units may reduce building energy use, they can be attached to the DOAS units to help precondition the outdoor air. This combined measure may further reduce building total energy use. Note that for buildings in climate zones 1 and 2, if the DOAS system size is large (specifically, if the supply air capacity of the DOAS system is greater than 5,000 cfm), ASHRAE 90.1- 2004 and 2007 require that the system should have exhaust air recovery for cooling.

RECOMMENDATIONS FOR FUTURE WORK

This paper demonstrates a variety of both passive and active approaches to achieving energy savings in hot and humid climates. However, it cautions that the performance of many of these approaches depends on numerous factors and is sometimes counterintuitive. Thus the energy impact cannot be easily anticipated without a full building energy analysis.

Further research studies are needed to more completely understand the combinations of climate and building characteristics that move a measure from an energy saving asset to a liability in hot and humid climates. These studies should include:

1. What combination of climate parameters and building characteristics make additional

wall and window insulation desirable or undesirable.

2. The interaction between exterior shading and glass SHGC for both internal load dominated and external load dominated buildings.
3. How increased outdoor air ventilation, which is typically used to improve indoor air quality, impacts the annual energy use of buildings in hot and humid climates.

With a better understanding of these issues, rules of thumb can be developed to aid projects in the early phases of design, although energy simulations will still be required in later design phases.

Although for simplicity, the measures in this paper have been presented independently in the above analyses, they all interact. A true integrated design process iteratively evaluates these interactions throughout the design process. In any hot and humid climate, selecting the most effective energy strategies will require an integrated evaluation of packages of related efficiency measures. For example, the interplay between shading, glazing and interior lighting components can together be tuned to reduce cooling loads from solar gains while reducing electric lighting use by dimming or switching in response to daylight levels. When measures like this are evaluated as a package, cost tradeoffs among components can be used to achieve the best energy performance at the lowest possible cost.

Table 8. Building #1 Energy Reductions with DOAS in Honolulu, HI (Climate Zone 1A)

| Annual Energy Use (kWh/ yr) | Lights | Misc. Equip. | Space Heating | Space Cooling | Ventilation Fans | Ext. Lighting | Total |
|-----------------------------|--------|--------------|---------------|---------------|------------------|---------------|-----------|
| Building #1 | 60,379 | 128,917 | 15 | 127,153 | 22,065 | 20,806 | 359,336 |
| Building #1 +DOAS | 60,379 | 128,917 | 22 | 105,583 | 26,719 | 20,806 | 342,427 |
| % of Savings | - | - | - | 17% | -21% | - | 5% |

Table 9. Prototype Building #4 Annual Energy Use Reductions with DOAS in Honolulu, HI (Climate Zone 1A)

| Annual Energy Use (MBtu / yr) | Lights | Misc. Equip. | Space Heating | Space Cooling | Heat Rejection | Pumps & Aux | Ventilation Fans | DHW | Total |
|-------------------------------|---------|--------------|---------------|---------------|----------------|-------------|------------------|-------|-----------|
| Building #4 | 1,837.5 | 1,499.8 | - | 1,653.0 | 64.8 | 431.9 | 1,076.0 | 479.6 | 7,042.6 |
| Building #4 +DOAS | 1,837.5 | 1,499.8 | 24.5 | 1,280.0 | 31.2 | 308.0 | 1,076.3 | 479.7 | 6,536.7 |
| % of Savings | - | - | - | 23% | 52% | 29% | 0% | - | 7% |

Table 10. Prototype Building #4 Annual Energy Use Reductions with DOAS in Houston, TX (Climate Zone 2A)

| Annual Energy Use (MBtu / yr) | Lights | Misc. Equip. | Space Heating | Space Cooling | Heat Rejection | Pumps & Aux | Ventilation Fans | DHW | Total |
|--------------------------------------|---------------|---------------------|----------------------|----------------------|-----------------------|------------------------|-------------------------|------------|--------------|
| Building #4 | 1,837.5 | 1,499.8 | 319.4 | 1,219.4 | 60.3 | 373.6 | 801.6 | 530.2 | 6,641.7 |
| Building #4 +DOAS | 1,837.5 | 1,499.8 | 313.2 | 941.9 | 27.1 | 309.5 | 792.4 | 530.2 | 6,251.7 |
| % of Savings | - | - | 2% | 23% | 55% | 17% | 1% | - | 6% |

REFERENCES

1. *ANSI/ASHRAE/IESNA Standard 90.1, 2004, Energy Standard for Buildings Except Low-Rise Residential*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc, 1791 Tullie Circle NE, Atlanta, GA, 30329.
2. *ANSI/ASHRAE/IESNA Standard 90.1, 2007, Energy Standard for Buildings Except Low-Rise Residential*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc, 1791 Tullie Circle NE, Atlanta, GA, 30329.
3. *ASHRAE GreenGuide: The Design, Construction, and Operation of Sustainable Buildings*, 2nd Edition. American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc, 1791 Tullie Circle NE, Atlanta, GA, 30329.
4. *The ASHRAE Guide for Buildings in Hot & Humid Climates*, 2nd Edition. American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc, 1791 Tullie Circle NE, Atlanta, GA, 30329.