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ENERGY BENEFITS OF DIFFERENT DEDICATED OUTDOOR AIR SYSTEMS CONFIGURATIONS IN VARIOUS CLIMATES

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ENERGY BENEFITS OF DIFFERENT DEDICATED OUTDOOR AIR SYSTEMS CONFIGURATIONS IN VARIOUS CLIMATES

by

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ENERGY BENEFITS OF DIFFERENT DEDICATED OUTDOOR AIR SYSTEMS CONFIGURATIONS IN VARIOUS CLIMATES

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Dedicated Outdoor Air Systems (DOAS) are proven to be beneficial in many practices. However, not all DOAS configurations under different climates provide the same benefits. This study presents a simulation on evaluating various energy saving benefits of different DOAS configurations among diverse climate zones of commercial buildings in the United States.

Three DOAS configurations in a medium office building are simulated in this study: (1) fan-coil units (FCUs) as terminal units with a DOAS unit supplying conditioned outdoor air (OA) to each FCU intake; (2) FCUs with a DOAS unit supplying conditioned OA directly to each occupied space; and (3) a DOAS with active chilled beams. A baseline system consisting of a conventional Variable Air Volume (VAV) system was also simulated for comparison to the three selected DOAS configurations. All simulation inputs are recommended by Department of Energy (DOE) benchmark reference models. Validations of the baseline system and three selected DOAS configurations are based on and compared to previous studies in literature. Building energy simulation results were

collected for each system listed above. Additionally, two energy comparisons were performed: each DOAS configuration was compared with the baseline system, and a comparison of each DOAS configuration to the other DOAS configurations was made. Comparison of the simulation results indicates that DOAS energy savings ranged from 7.1% to 26% between the seven simulated locations when compared to simulated baseline with some DOAS configurations performing better in particular climate. The major energy savings are accomplished due to DOAS requiring the exact amount of ventilation for each space and employing high efficiency local Heating, Ventilation, and Air Conditioning (HVAC) units. Suggestions given as a result of this study include: (1) consider supplying the conditioned OA directly to each occupied space with a DOAS in all simulated locations, and (2) consider employing active chilled beams as the local terminal HVAC units in locations which experience extreme hot summers, such as Miami and Phoenix.

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Chapter 1 Introduction

1.1 Introduction

Dedicated Outdoor Air Systems (DOAS) were introduced into Heating, Ventilation, and Air Conditioning (HVAC) industry over the past few decades and widely adopted. Benefits of employing DOAS, such as more efficient ventilation, better Indoor Air Quality (IAQ), and potential system energy savings, were tested in previous HVAC practices. (Dieckmann & Roth 2007; Mumma 2001a)

However, these benefits were not studied for all DOAS configurations in various climates. Thus, it is very important to identify benefits of specific DOAS configurations in particular climates in order to help engineers employ DOAS in their daily practice. Furthermore, the rapidly increased demands for more efficient HVAC systems emphasize the urgency of more energy performance analyses of DOAS.

To examine energy performances of DOAS in various climates, three DOAS configurations were selected for this study based on the current literature and previous studies. (McDowell & Emmerich 2005; Murphy 2006; Mumma 2008) Seven locations from different climate zones as defined by ASHRAE Standard 90.1-2004 were selected.

In order to examine the potential energy saving of the selected DOAS configurations, a conventional Variable Air Volume (VAV) system was selected as a baseline system.

All simulation inputs pertaining to building simulations in this study were adopted from Department of Energy (DOE) benchmark reference building models. Specifically; building forms, envelop constructions, operating and loads schedules were adopted. Employing these benchmarks models provides a consistent building simulation. (Deru et al. 2011)

The simulation tool named IES-VE was selected to provide integrated building simulation function. Previous building energy simulation results were also collected from current literature. (McDowell & Emmerich 2005) The simulations were conducted by EnergyPlus, a free, powerful, and widely used building energy simulation tool. Comparisons were made between simulation results in this study and previous studies. Validations of simulations in this study were achieved through this action.

Building energy simulation results of the DOAS and baseline systems were collected. Comparisons and analyses of simulations provided the foundations for suggestions.

1.2 Research Objectives

- Investigate the system configuration details of three selected DOAS configurations.
- Compare building modeling with previous literature.
- Validate the DOAS and baseline systems modeling based on previous

literature.

- Investigate energy savings of the DOAS configurations by comparing the energy usage between each DOAS configuration and baseline system.
- Investigate energy performance diversity of the DOAS configurations by comparing the energy usage among selected DOAS configurations.

1.3 Research Scopes

The scope of this study was to fulfill the previously described objectives:

- Focus the building energy simulations of DOAS to the three selected DOAS configurations.
- Focus the building energy simulations of DOAS to the seven selected representative climate locations of the United States.
- Cost and budget analysis of the DOAS and baseline systems are excluded in this study.
- Suggestions of DOAS in various climates are solely based on the building energy simulations in this study.

1.4 Overview of Chapters

Chapter 2 lists the current literature that details the benefits of DOAS, DOAS configurations, and energy simulation tools. Relevant background information of DOAS and the configuration selection along with the definition of DOAS used in this study are presented. Chapter 3 explains the DOE benchmark models and all the detailed inputs to conduct a building energy simulation based on benchmark models. Chapter 4 consists of DOAS configurations, baseline system configuration, and simulated system validations based on current literature and previous studies. Chapter 5 collects all building energy simulation results for DOAS and baseline. Chapter 6 draws conclusions from simulation results and provides suggestions concerning the energy benefits of DOAS diverse configurations in various climates. Possible future works are also stated in the last chapter.

Baseline system unit sizing are shown on Appendix A. Appendix B and C cover system sizing for DOAS-1 and DOAS-2. DOAS-3 system sizing is found in Appendix D and E. The simulated system energy performances for the DOAS and baseline systems is found in Appendix F.

Chapter 2 Literature Review

Benefits and system configurations of Dedicated Outdoor Air Systems (DOAS) are discussed in this Chapter. The definition of this kind of system for this study is based on the current literature.

Details from previous studies of DOAS energy performance in various climates are reviewed and an energy simulation tools review is used to support the simulation tool selection.

2.1 History of DOAS and Definition of DOAS in this Study

The concept of DOAS was introduced in our industry over the past several decades. DOAS is capable of delivering the 100% required outdoor air (OA) to each occupied space independently or in conjunction with local terminal HVAC units. The system is the first recognized system that takes credit for decoupling humidity control and temperature control, which introduced the industry to the potential solution that fulfills ASHRAE Standard 62.1 ventilation requirements.

Decoupling the humidity control and temperature control (or decoupling sensible and latent load handling) becomes the major benefits of utilizing DOAS in the early 90s. Operating this kind of primary and secondary system combination with other advanced technologies of that time offered a cost saving advantage and better humidity control when compared to traditional HVAC systems. (Meckler 1986) The primary system delivers primary air at a low temperature (for example at 42° F). Thus, a small quantity of primary air capable of offsetting the building humidity load and fulfilling the ventilation requirement. Under particular building type or climates, the partial sensible cooling load can rely on the primary system in summer or under part-load conditions. The remaining sensible cooling is provided by terminal unit(s) using local recirculation air to maintain the space temperature level.

From decoupling the humidity control and temperature control, the most obvious benefit is the ability to downsize the system. Since the primary system is responsible for humidity control and delivering required ventilation air, the low supply air temperature causes a lower total requirement quantity than the system configuration can with a single system handling the required sensible and latent loads. Downsizing the primary system duct and fan size offer a cost savings advantage because the secondary system is only responsible of sensible cooling eliminating the need for humidity control from the secondary system.

Another major benefit is that the decoupling system configuration may provide good indoor air quality (IAQ) control. A VAV system with an air-side economizer may create problems causing the ventilation rate to fall below the required minimum rate during reduced building cooling loads. (Scoifield & Des Champs 1993) By supplying 100% outdoor air, the system provides better IAQ performance and potential energy efficiency in particular climates.

After ASHRAE published Standard 62-1989, DOAS received significant notice by American engineers. The new ASHRAE standard requires a complex routine for multi-zone ventilation and, when coupled with the tendency of increasing required minimum ventilation per person for better IAQ performance, engineers start looking at alternative system configurations to fulfill these requirements.

ASHRAE Standard 62-1989 increased the outdoor air requirement for some building types by two to four times when compared to the 1981 vision and provides the major boost to DOAS development in U.S. (Kosar et al. 1998) Additionally, the new routine of multi-zones system ventilation calculation along with the increased ventilation outdoor air requirement results in much higher ventilation flow rates compared to buildings designed under the older Standard 62.1 version. Furthermore, using outdoor air in non-arid climates can result in periods of increased indoor humidity levels. (Kosar et al. 1998)

Thus engineers begin to realize that the single system which uses a mixing chamber for mixing the outdoor air with return air should be replaced by two systems with one providing thermal comfort and the other providing IAQ. (Coad 1999)

ASHRAE introduced “100% OA systems” in Addendum 62n of Standard 62-2001. The distinguishing characteristic of this system is that it supplies 100% outdoor air (OA) (i.e., no central recirculated air) for ventilation to one or more zones.

The open literature (Stanke 2004; Mumma 2001a; Mumma 2001c; Jeong et al. 2003;

Scoifield & Des Champs 1993; Mumma n.d.) published in early 2000s, provides a clear definition and positive outcomes of DOAS indicated by some leading professionals in the HVAC industry. However, system configurations and understanding of DOAS have varied with time, and today considerable diversity of DOAS exists in the HVAC engineering community.

Personal communications were conducted between the student and 21 experienced engineers from 10 major U.S. HVAC designing and consulting firms to determine the version of DOAS used by the firm. Wide ranges of opinions were collected. The definition in this study attempts to be as inclusive as possible to reflect the various system configurations already applied under the name of DOAS. However, engineers who want to design a DOAS should be reminded that there are various pros and cons in each DOAS configuration. The benefits of DOAS are not be the same if different system configurations are applied.

DOAS, as presented in this study, is defined as: a system which uses separate equipment to condition all OA brought into a building for ventilation, delivered to each occupied space, either directly or in conjunction with local space or central (zoned) HVAC units serving those same spaces. The local or central HVAC units are used to maintain space temperature setpoint requirements.

2.2 Features/Benefits of DOAS

Based on current literature review, the benefits of DOAS compared to a conventional VAV system are:

1) Easier to provide proper ventilation. (Cummings. James B 2001; Jeong et al. 2003; Dieckmann & Roth 2007; Mumma 2009a; Mumma 2001a)
2) Decoupling sensible and latent cooling functions of air handling systems. (Dieckmann & Roth 2007; Kosar et al. 1998; Coad 1999; Mumma 2001a)
3) Increased degree of freedom in the selection of local unit(s). (Cummings. James B 2001; Dieckmann & Roth 2007; Mumma 2001a)
4) Potentially provide energy use and demand reduction for both the DOAS unit and local unit(s). (Jeong et al. 2003; Dieckmann & Roth 2007; Mumma 2001a)
5) Provide enhanced indoor environmental quality (IEQ). (Khattar & Brandemuehl 2002; Coad 1999)

2.2.1 Ventilation

In order to realize the ventilation benefit of DOAS, the OA must be supplied to each occupied space either directly or in conjunction with local HVAC units.

One of the difficulties of achieving good ventilation performance with central HVAC systems (e.g. VAV systems) serving multiple zones is that the individual zone sensible loads do not necessary vary with their ventilation requirement. This causes increased system total ventilation intake airflows - which are often required to ensure the proper ventilation for each zone at all operation conditions - in compliance with ASHRAE Standard 62.1. (Dieckmann & Roth 2007)

Another difficulty is over-ventilation of non-critical zones. In a multiple-zoned recirculating ventilation system, a single air handler supplies the mixture of OA and recirculated return air to more than one ventilation zone. Since the system delivers the same air mixture to each zone; proper ventilation to the critical zone (the zone requiring the highest OA fraction) will generally result in over-ventilation for other zones. (Stanke 2004)

When DOAS supplies required ventilation air to each zone, either directly or in conjunction with local unit(s), such system configurations overcome the above-listed problems. Allowing the DOAS to be sized separately ensures proper ventilation in each zone at design zone population. (Dieckmann & Roth 2007)

2.2.2 Humidity control

A DOAS approach provides humidity control benefits, albeit this is a secondary goal. The various humidity control benefits are potentially achieved only if the described system configuration associated with each benefit is applied.

Since the 1989 edition of ASHRAE Standard 62 increased earlier mandated OA requirements, proper indoor humidity control is even harder to achieve with some types of HVAC systems. Bringing more OA into the building may result in raising indoor humidity levels in non-arid climates. (Kosar et al. 1998) Also, this requirement brings more moisture into the system since OA accounts for a large portion of the overall latent load in most commercial buildings. (Dieckmann & Roth 2007) Rather than using one system to control both indoor humidity and temperature, DOAS uses two systems to control them separately. (Coad 1999) The DOAS unit (the unit conditioning the ventilation air separately) can be sized to supply the exact amount of required ventilation air at a low enough dew point to offset the indoor latent load, thus controlling the indoor relative humidity level without relying on local HVAC units. When humidity control becomes a goal of DOAS, a total-energy recovery device is generally required by ASHRAE Standard 90.1.

Humidity control requires engineers to pay more attention to part-load operations. Popular VAV systems usually reduce the amount of total air delivered to the space during part-load conditions to achieve energy efficiency. However, when the space loads changes, this can result in loss of indoor humidity control, even though indoor space temperatures remain at acceptable levels. DOAS overcomes this problem. During part-load conditions, with local unit(s) running under a reduced capacity mode to fulfill the reduced sensible loads, the DOAS unit continues to supply air at a low enough dew point to maintain acceptable indoor humidity levels. This humidity control benefit is potentially available for almost all DOAS system configurations.

2.2.3 Selection freedom of local unit(s)

DOAS may allow broader local unit selection options when the DOAS unit solely controls the indoor humidity and supplies OA to the occupied spaces, either directly or in conjunction with local HVAC unit(s). Also, if the DOAS unit controls all of the latent loads, the high efficiency sensible-only HVAC unit may be effectively used as the local HVAC unit. Using high efficiency local HVAC equipment can potentially increase the overall system energy efficiency. (Mumma 2001a)

2.2.4 Containment control

Because a DOAS approach generally results in conditioning less OA than a VAV system approach, there is an increased potential to reduce energy usage associated with the ventilation air components, air conditioning, and fan operation. Under part-load conditions, local unit(s) may be able to switch off to save energy, when the DOAS delivers ventilation air directly to each zone or to the supply-side of local HVAC units.

2.2.5 Enhanced indoor environmental quality (IEQ)

There is a view among certain professionals that a key fundamental change has to be made to achieve better IEQ, which is to “decouple the traditional (VAV or Constant Air Volume (CAV)) system dual functions of maintaining thermal environment and providing needed ventilation”. (Khattar & Brandemuehl 2002) From an indoor air pollutants transport perspective, the DOAS ventilation approach leads to predictable pressure differentials between adjoining spaces or zones, which minimizes transport of the potential airborne contaminants between zones. Furthermore, with DOAS applications, airborne contaminants that may be present in one zone are not immediately distributed throughout a facility by the HVAC systems. (Mumma 2009b)

2.3 DOAS Configurations

As mentioned above, different DOAS system configurations in current practices will lead to different benefits. In general, DOAS can be categorized into one of five system configurations:

1) Conditioned OA delivered directly to the occupied spaces.
2) Conditioned OA delivered to the supply-side of local HVAC units.
3) Conditioned OA delivered to the intakes of local HVAC units.
4) Conditioned OA delivered to return air plenums, near local HVAC units.
5) Conditioned OA delivered to the intakes of centralized, multiple-zone HVAC units.

The following sections address the fundamental differences between these configurations and associated special considerations.

2.3.1 Conditioned air dry-bulb temperature

There is more than one way to condition the air from a DOAS:

- The dry-bulb temperature (DBT) of the conditioned air (CA) is “neutral”, which approximates room air dry-bulb temperature.
- DBT of CA is “cold”, i.e. significantly cooler than the room air dry-bulb temperature—generally about the same as the required CA dew point temperature (DPT). (Murphy 2010; Murphy 2006)

The DOAS approach method of delivering “cold air” actually requires less overall cooling capacity than a “neutral-air” DOAS system approach. (Shank & Mumma 2001) Although the installed cooling capacity of the DOAS OA unit is the same in either case (because it is sized for the dehumidification load), the latter “cold air” approach reduces the required cooling capacity of each local unit and eliminates the central heating required to reheat the CA to the neutral temperature. Consequently, the cold-air system consumes less overall building system-wide (aggregate) cooling energy for much of the year compared to a “neutral-air” DOAS system approach and it consumes less system-wide heating energy by virtue of its reduced need to reheat the conditioned OA.

However, while the dehumidified OA should be delivered cold whenever possible, as the space sensible cooling load decreases, this cold air may provide more sensible cooling than the space requires, thus resulting in overcooling. When the potential for overcooling exists, design engineers should consider implementing CA temperature reset to reduce the cooling capacity. Alternatively, activating the corresponding local HVAC unit heating coil to prevent overcooling could be a possible choice. If the overcooling problem occurs occasionally or in only a few spaces, the sensible cooling benefit of delivering the OA cold to all other spaces served by the DOAS may outweigh the heating energy needed to prevent these few spaces from overcooling.

At some load conditions, however, it might be more economical to reheat the cold OA centrally, using recovered energy. In this case, design the DOAS to deliver the air cold, and only reheat when needed in order to avoid individual space/zone overcooling.

2.3.2 DOAS supplies OA directly to occupied space

In this system configuration, the conditioned OA is delivered by the DOAS directly to each occupied space. Meanwhile, the local unit(s) (such as fan coils, water-source heat pumps, packaged terminal air conditioners (PTACs), small packaged or split direct exchange (DX) units, radiant chilled ceilings, passive chilled beams, and variable refrigerant flow (VRF) equipment) located in or near each space provides cooling and/or heating to maintain space temperature (see Part A of Figure 2-1).

This approach easily ensures the required OA flow reaches each zone, and affords the opportunity to cycle off the local fan, or reduce its speed, when cooling or heating from local unit(s) is no longer needed in a given zone. Since the OA is not distributed to the zone through the local unit, the local fans do not need to operate in order to deliver OA to the conditioned zone. Thus, activating the DOAS during part-load periods does not require operating the local units.

When the conditioned OA is delivered at a cold temperature, rather than reheated to neutral, this configuration offers the opportunity to reduce the local equipment size (both airflow and cooling capacity) and hence also its capital and possibly operational energy costs. However, to prevent uncomfortable drafts when the conditioned OA is delivered at a cold temperature, one may need to utilize high performance diffusers that induce room air to mix with (and warm) the cold conditioned air before it reaches the occupied zone at the desired terminal velocity.

This configuration does require some additional ductwork and a separate diffuser for OA delivery to each occupied zone.

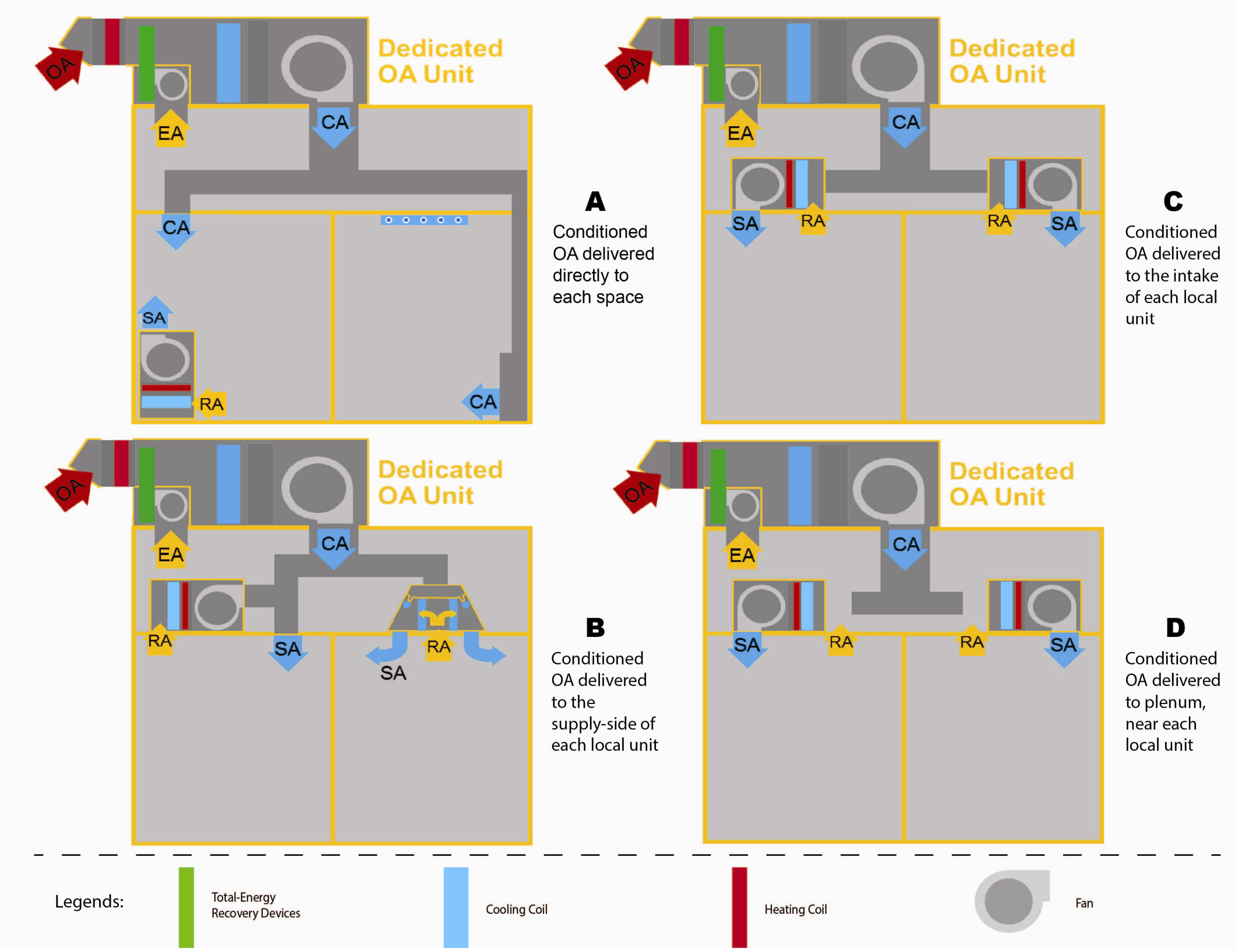


Figure 2-1: DOAS with total-energy recovery delivering OA (ASHRAE 2012).

2.3.3 DOAS supplies OA to the supply-side of local HVAC units

In this configuration, conditioned OA is ducted to the supply-side of each local unit(s) (See Part B of Fig.2-1), and is mixed with the local unit's supply air (SA) before being delivered to the zone/space. The local unit conditions only recirculated air.

Since OA flow is ducted to each unit, this configuration may ensure the required ventilation reaches each space, and the ventilation air is adequately distributed in the space through a common set of SA diffusers.

However, measurement and balancing of the ventilation system is more difficult with this approach than if the OA is delivered to the space. If the local fan cycles off, or varies its speed, the pressure in the supply duct decreases, potentially resulting in loss of proper-OA distribution.

This is prevented by installing a pressure-independent terminal-box to directly control the OA flow into the space under different static pressure in the SA duct. Use this terminal approach to incorporate some method of demand-controlled ventilation (DCV).

When the OA is delivered at a cold temperature, rather than reheated to neutral, this configuration may permit the downsizing of the local units (both airflow and cooling capacity).

2.3.4 DOAS supplies OA to the intake of local HVAC units

In this configuration, the DOAS delivers the conditioned OA to the intakes of local single-zone HVAC equipment (such as fan coils, water-source heat pumps, small packaged or split DX units, variable refrigerant flow (VRF), small packaged rooftop units, or single-zone air handlers), where it mixes with recirculated air from the zone (See Part c of Fig.2-1). The local unit conditions this mixture and delivers it to the zone through a single duct system and diffusers. This configuration ensures the required OA flow reaches each zone; since it is ducted directly to each unit, and often avoids some of the cost and space required to otherwise install additional space delivery ductwork and separate diffusers.

The OA is distributed by the local fan through a common set of diffusers (or via active chilled beam method) ensuring that it is adequately dispersed throughout the zone. However, local HVAC equipment employing fans must operate continuously whenever ventilation is needed during occupied modes; otherwise, if the local HVAC equipment fan cycles on and off or varies its speed, the ventilation is compromised since the local equipment fans are responsible for delivering ventilation air to the occupied zone/space.

In addition, when the conditioned OA is delivered to the intake of the local unit at a cold temperature, it results in cooler air entering the cooling coil of the local unit which derates its capacity. This requires less cooling capacity from the terminal device and permits downsizing (cooling capacity, but not airflow). However, this may cause an equipment selection challenge for some types of local units.

2.3.5 DOAS supplies OA to plenum, near local HVAC units

This configuration delivers conditioned OA to an open ceiling plenum, near the intake of each local unit (See Part D of Fig.2-1). The OA mixes with recirculated air in the plenum before being drawn into the intake of the local unit. Use this approach when local units are installed in the ceiling plenum, such as water-source heat pumps, fan-coils, or variable refrigerant flow (VRF) terminals.

This configuration saved the cost and space needed to install additional ductwork, separate diffusers, or mixing plenums on the local units. However, it is difficult to ensure the required amount of OA reaches each zone, since the ventilation airflow is not ducted directly. The ASHRAE Standard 62.1 User's Manual clarifies that the OA duct needs to deliver air near the intake of each local unit and include some means of balancing to ensure the right amount of ventilation air reaches each unit.

When cold conditioned OA is delivered to a plenum, it cannot be at a temperature below the prevailing DPT encountered. In most cases, the ventilation air should be reheated some amount to avoid condensation on surfaces within the plenum.

2.3.6 DOAS supplies OA to centralized, multiple-zone HVAC units

This approach uses DOAS to dehumidify all of the OA to a dew point condition that is drier than the zones. This dehumidified OA is then ducted to the intake of one or more air-handling units. In Figure 2-2, the DOAS delivers the conditioned OA (via ductwork) to floor-by-floor VAV air-handling units. Since OA is not directly delivered to each room and is mixed with the recirculating air, the multiple zone equations contained in ASHRAE Standard 62.1 should be used to determine the OA required at each air handler and to properly determine the total OA flow at the DOAS unit. However, this DOAS configuration may cause over-ventilation to satisfy the needs for the critical spaces.

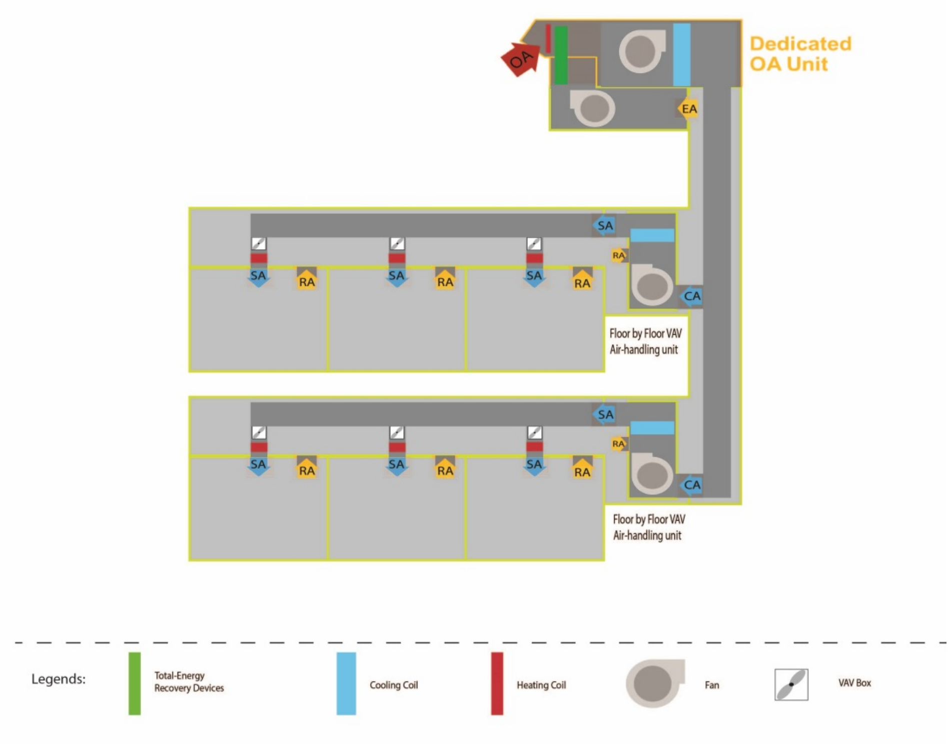


Figure 2-2: DOAS used with floor-by-floor VAV air-handling units (Modified from Murphy, 2010).

2.4 DOAS in Various Climates

Not only the different DOAS configurations have the distinguished advantages and disadvantages, but also the previous described DOAS configurations perform differently in various climates. There are some literature discussions and recommendations specific DOAS configuration in different particular climates.

“Simple” and “full” DOAS were pre-defined in one open literature for conducting the building energy performance comparison between DOAS and the conventional VAV system. (McDowell & Emmerich 2005) “Simple” DOAS was defined as system consisting of only a pre-heat coil and enthalpy wheel. “Full” DOAS was defined as system consisting of a pre-heat coil, enthalpy wheel, cooling coil, and sensible wheel. Both pre-defined DOAS configurations were equipped with water-source heat pump (WSHP) supported cooling coil as the local terminal unit. Building energy performances for five selected U.S. locations were simulated in that study, and the energy performances data was collected.

The conclusion in the literature indicated that: First, both “simple” and “full” DOAS show energy saving benefits compared to the conventional VAV system; second, “full” DOAS shows significant advantage only in extreme hot and humid climates, such as Miami.

However, there is no discussion in the literature about detailed DOAS configurations, which include supply location of conditioned OA, different type of local terminal units, and different DOAS units and this comparison hard to use for specific DOAS practices. In order to fill the knowledge gap and to identify the benefit of DOAS in various climates, the need for a more detailed study is emphasized.

2.5 Economizer in DOAS

The issue concerning the loss of the air-side economizer in a DOAS design frequently arises particularly when the local terminal unit is not an air system. (Mumma 2005) To comply ASHRAE Standard 90.1, an economizer is required, either air-side or water-side.

An air-side economizer is a collection of dampers, sensors, and control systems to determine the amount OA brought to the occupied space. The purpose of an air-side economizer is to eliminate part of mechanical cooling when outdoor air conditions are capable of removing the space cooling requirement. An air-side economizer is capable of modulating outdoor air and return air damper to provide up to 100% of the design supply air quantity by using outdoor air for cooling. (Mumma 2005)

However, since DOAS are already providing 100% of the design supply air quantity as outdoor air for cooling, another kind of economizer is called to serve a similar purpose as the air-side economizer. The water-side economizer is defined as a system by which the cooling supply air is indirectly cooled by water that is itself cooled by outdoor air. Usually this action is fulfilled by cooling tower. Employing a water-side economizer can further decrease mechanical cooling energy usage. Particularly for locations that are dry or experience cold winters. (Mumma 2005)

Furthermore, employing an air-side economizer to DOAS brings some drawbacks, like operating mechanical cooling during winter, or has a bigger operating cost compared to other DOAS configurations. (Mumma 2005) Replacing the air-side economizer with a water-side economizer saves more energy usage and complies with the Standard 90.1 requirement for economizers.

2.6 Energy Simulation Tools

There are many energy simulation tools in the market capable of providing detailed simulation results. Powerful results with careful simulation procedures can result in useful conclusions and suggestions.

Integrated environmental solutions (IES) is an integrated building simulation tool. User friendly interface and system configuration, Computational Fluid Dynamics (CFD), lighting, and other function integration are the major benefits for IES user. IES is capable of providing detailed system configurations with visualized control and system components.

EnergyPlus is a complex building energy simulation tool. Powerful functions and wide usage are the major benefits of EnergyPlus. However, the user interface is not friendly enough to provide visualization of simulated system.

Since the active chilled beams (ACB) were employed in this study, the selected energy simulation tool should be capable of modeling this kind of system configuration. Comparison was made in a previous study about energy simulation tools function of modeling ACB. (Betz et al. 2012)

This complex study provided fundamentals for simulation tools selection of ACB. The results of the study are found in Figure 2-3.

Chilled Beam Modeling Results					
Criteria/Software	eQuest (3.64b)	Trane TRACE	EnergyPlus (v7)	IES-VE	TRNSYS
System Induction Ratio	YES	YES	NO	NO	NO

Zone Induction Ratio	NO	NO	YES	YES	YES
Variable Induction Ratio	NO	NO	NO	NO	YES
CAV	YES	YES	YES	YES	YES
VAV	NO	NO	NO	YES	YES
Multiple CHW Loops	NO	NO	MIXED	YES	YES
Humidity Control	MIXED	MIXED	NO	YES	YES
Flexible HVAC Configuration	NO	NO	MIXED	YES	YES
Intuitiveness	MIXED	MIXED	NO	NO	NO
Compliance Model	YES	YES	YES	YES	MIXED
Design Assistance	NO	NO	MIXED	MIXED	YES
Modeling Time	LOW	LOW	MID	MID	HIGH
Software Cost	FREE	LOW	FREE	HIGH	MID
Simulation Time	FAST	FAST	MID	SLOW	SLOW

Table 2-1: Energy simulation tools comparison of modeling active chilled beams.

(Betz et al. 2012)

The very basic function of modeling ACB is modeling the ACB induction air ratio. Five selected energy simulation tools in the previous study show the capability of modeling the ACB induction air ratio. System level induction air ratio and zone level induction air ratio target different configurations of ACB. System level induction air ratio is applied to single zone systems or constant air volume systems. System modeling is simplified by using system level induction air ratio for ACB. However, real projects may require zone level induction air ratio since each zone may have different ventilation, cooling, and heating loads requirements. Thus, zone level induction air ratio works better on ACB simulation. Variable air volume induction air ratio, either system level and zone level, is a powerful function but might not be practical since constant air volume primary air is usually applied to zone level ACB induction air ratio.

The flexibility of modeling ACB is another important function of the ACB simulation tool. The flexibility includes using one Air Handler Unit (AHU) to serve multiple ACBs, adding another terminal HVAC unit working with the ACB, and even applying multiple water loops to an ACB can provide a good way of simulating an ACB close enough to the real project. Only three of five examined simulation tools provide the flexibility of modeling ACB.

Modeling time and simulation time are some general considerations for using energy simulation tools. Extreme high modeling time with very slow simulation time are common problems when modeling and tuning the ACB simulation.

Based on the basic requirements for ACB simulation, EnergyPlus, IES-VE, and TRNSYS are three preferred simulation tools which are capable of providing adequate functions of simulating ACB. However, EnergyPlus cannot provide user friendly interface and system visualization. And even though the TRNSYS can provide the most powerful ACB simulation within the comparison explained above, extreme high modeling time with very slow simulation time may bring difficult for simulation research.

IES-VE not only can provide adequate simulation functions for ACB simulations, the integrated functions also can accurately simulate any DOAS. Combined with other benefits such as user friendly interface, system visualization, acceptable modeling and simulation time, IES-VE is preferred for particular DOAS simulation study.

Chapter 3 DOE Benchmark Reference Building and Simulated Building

The U.S. Department of Energy (DOE) developed the commercial reference buildings, known as DOE Benchmark reference buildings models. Information of this reference models and simulation inputs are provided in this chapter.

The models represent approximately 70% of commercial building in United States. According to DOE's national renewable energy laboratory report, these reference models provide a consistent baseline for comparison and improve the value of energy simulation software use. (Deru et al. 2011)

Comparison between simulated buildings in this study and previous studies from literature is performed in this chapter and serves as validation of building simulation. International System (S.I.) units are the major units used in benchmarks models; however, the Inch-Pound (I.P.) unit system is primarily used in this study.

3.1 Determining Building Type

There are three visions of building type in benchmark models: new construction, post-1980 construction, and pre-1980 construction. Building forms, areas, and operation schedules in this three visions are the same, the differences are reflected in the insulation levels, lighting levels, and HVAC equipment types and efficiencies. For this study, new construction is selected. The construction type complies with the ANSI/ASHRAE Standard 90.1-2004. (Deru et al. 2011)

Medium office building type is selected for this study. The medium office model provides reasonable building size without being too small to collect useful information and conclusions. There are three floors with five rooms for each floor.

Table 3-1 shows the medium office reference building type forms and room sizing.

Building summary			
Total Room Area	(m²)	4982	
Floor-to-Ceiling Height	(m)	2.74	
Floor-to-Floor Height	(m)	4.4	
Room Sizing	(m²)		(m²)
Bottom interior room	984	Mid interior room	984
Bottom North (Zone 3)	207	Mid North (Zone 3)	207
Bottom East (Zone 4)	131	Mid East (Zone 4)	131
Bottom South (Zone 1)	207	Mid South (Zone 1)	207
Bottom West (zone 2)	131	Mid West (zone 2)	131
First to second plenum	1661	Second to third plenum	1661
Top North (Zone 3)	207	Top West (zone 2)	131
Top East (Zone 4)	131	Top interior room	984
Top South (Zone 1)	207	Third floor plenum	1661

Table 3-1: Benchmark reference building models selected building type forms and room sizing.

3.2 Benchmark Reference Building Models Climate Zones and Fabric

The recommended building envelop fabric of new construction building type is primarily based on the requirements of ASHRAE Standard 90.1-2004. Different envelop fabrics are made for various climates. The climate zone classification system is based on

DOE and ASHRAE Standard 90.1-2004.

3.2.1 Climate zone classification system

Locations were selected in benchmark models that represent the majority of climates in U.S. The climate zone classification system is mainly based on DOE and ASHRAE Standard 90.1-2004. Sixteen (16) numbers of climate zones were classified with the most populous cities in these climate zones selected to represent the climate zones. Two locations were selected for climate zone 3B because they represent different climate zones within one zone. However, the study will focus on only seven selected locations with variable characteristics. The selected seven climate zones are found in table 3-2.

Number	**Climate Zone**	**Representative City**	**Description**	**TMY2 Weather file location**
1	1A	Miami, Florida	Hot, humid	Miami, Florida
2	2B	Phoenix, Arizona	Hot, dry	Phoenix, Arizona
3	4A	Baltimore, Maryland	Mild, humid	Baltimore, Maryland
4	4B	Albuquerque, New Mexico	Mild, dry	Albuquerque, New Mexico
5	5A	Chicago, Illinois	Cold, humid	Chicago-O’Hare, Illinois
6	5B	Denver, Colorado	Cold, dry	Boulder, Colorado
7	8	Fairbanks, Alaska	Extreme cold	Fairbanks, Alaska

Table 3-2: Benchmark reference building models climate zone classification.

3.2.2 Roof, Wall, Ground Floor, and Window

ASHRAE Standard 90.1-2004 defines three major roof types based on the location of insulation relative to the roof. The three roof types with their assumptions are:

- Insulation entirely above deck: the continuous insulation above the structural roof deck.
- Metal building: the insulation compressed between structural members.
- Attic and other: the insulation is laid between roof joists.

The benchmark models recommends insulation entirely above deck for medium office building. The construction type of roof among selected locations is the same; the only difference is R-value for various locations.

For wall construction type, ASHRAE Standard 90.1-2004 defines four wall types based on functional performance of the wall.

- Mass Wall: continuous insulation.
- Metal Building Wall: insulation compressed between metal members, possibly augmented by continuous insulation to decrease the overall U-factor.
- Steel Framed Wall: a simple frame wall with different structural members.
- Wood Framed and Other Wall: a simple frame wall with different structural members.

The Benchmark models recommends steel framed wall for medium office building. The construction type of wall among selected locations is the same; the only difference is

R-value for various locations.

Benchmark models recommends ground floor construction type, mass floor is selected. Construction type and R-value for ground floor are the same for locations.

Simple window is recommended in benchmark models. Only overall U-factor, solar heat gain coefficient (SHGC) value, and visible transmittance value are required instead of specific window type. Various combinations of the required values are applied to different climates.

All the recommended values for roof, wall, window, and ground floor are found in Table 3-3 to Table 3-5.

Building Characteristic	**Miami**	**Phoenix**	**Baltimore**	**Albuquerque**	**Denver**	**Chicago**	**Fairbanks**
Climate Zone	1A	2B	4A	4B	5B	5A	8
Exterior walls							
Construction Type	Steel Frame	Steel Frame	Steel Frame	Steel Frame	Steel Frame	Steel Frame	Steel Frame
R-value ($m^2 \cdot K / W$)	1.42	1.42	1.42	1.42	2.10	2.10	2.75

Materials (From outside layer to inside layer)						
Wood Siding	Thickness (mm)	10.00	Thickness (mm)	10.00	Thickness (mm)	15.00
	Conductivity (W/m.K)	0.11	Conductivity (W/m.K)	0.11	Conductivity (W/m.K)	0.11
	Density (kg/m²)	544.60	Density (kg/m²)	544.60	Density (kg/m²)	544.60
	Specific Heat (J/kg.K)	1,210.00	Specific Heat (J/kg.K)	1,210.00	Specific Heat (J/kg.K)	1,210.00
Steel Frame	Thickness (mm)	53.90	Thickness (mm)	87.06	Thickness (mm)	124.00
	Conductivity (W/m.K)	0.05	Conductivity (W/m.K)	0.05	Conductivity (W/m.K)	0.05
	Density (kg/m²)	265.00	Density (kg/m²)	265.00	Density (kg/m²)	265.00
	Specific Heat (J/kg.K)	836.80	Specific Heat (J/kg.K)	836.80	Specific Heat (J/kg.K)	836.80
1/2 in Gypsum	Thickness (mm)	12.70	Thickness (mm)	12.70	Thickness (mm)	14.00
	Conductivity (W/m.K)	0.16	Conductivity (W/m.K)	0.16	Conductivity (W/m.K)	0.16
	Density (kg/m²)	784.90	Density (kg/m²)	784.90	Density (kg/m²)	784.90
	Specific Heat (J/kg.K)	830.00	Specific Heat	830.00	Specific Heat (J/kg.K)	830.00

Table 3-3: Exterior wall construction type.

Building Characteristic	**Miami**	**Phoenix**	**Baltimore**	**Albuquerque**	**Denver**	**Chicago**	**Fairbanks**
Roof							
Construction Type	Insulation Entirely Above Deck						
R-value ($m^2 \cdot K$ / W)	2.79	2.79	2.79	2.79	2.85	2.85	3.72

Materials (From outside layer to inside layer)						
Roof Membrane	Thickness (mm)	9.50	Thickness (mm)	9.50	Thickness (mm)	12.00
	Conductivity (W/m.K)	0.16	Conductivity (W/m.K)	0.16	Conductivity (W/m.K)	0.16
	Density (kg/m²)	1,121.30	Density (kg/m²)	1,121.30	Density (kg/m²)	1,121.30
	Specific Heat (J/kg.K)	1,460.00	Specific Heat (J/kg.K)	1,460.00	Specific Heat (J/kg.K)	1,460.00
Roof Insulation	Thickness (mm)	124.66	Thickness (mm)	127.34	Thickness (mm)	180.00
	Conductivity (W/m.K)	0.05	Conductivity (W/m.K)	0.05	Conductivity (W/m.K)	0.05
	Density (kg/m²)	265.00	Density (kg/m²)	265.00	Density (kg/m²)	265.00
	Specific Heat (J/kg.K)	836.80	Specific Heat (J/kg.K)	836.80	Specific Heat (J/kg.K)	836.80
Mental Decking	Thickness (mm)	1.50	Thickness (mm)	1.50	Thickness (mm)	2.20
	Conductivity (W/m.K)	45.01	Conductivity (W/m.K)	45.01	Conductivity (W/m.K)	45.01
	Density (kg/m²)	7,690.00	Density (kg/m²)	7,690.00	Density (kg/m²)	7,690.00
	Specific Heat (J/kg.K)	418.40	Specific Heat (J/kg.K)	418.40	Specific Heat (J/kg.K)	418.40

Table 3-4: Roof construction type.

Building Characteristic	**Miami**	**Phoenix**	**Baltimore**	**Albuquerque**	**Denver**	**Chicago**	**Fairbanks**
Program							
ASHRAE 90.1-2004 Climate Zone	1A	2B	4A	4B	5B	5A	8
Ground Floor							
Foundation Type	Mass Floor						
Construction Type	4 in Slab with Carpet						
R-value ($m^2 \cdot K$ / W)	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Materials (From outside layer to inside layer)							
Concrete	Thickness (mm)					101.60	
	Conductivity (W/m.K)					1.31	
	Density (kg/m^2)					2,400.00	
	Specific Heat (J/kg.K)					836.80	
Carpet	Thickness (mm)					5.00	
	Conductivity (W/m.K)					0.22	
	Density (kg/m^2)					160.00	
	Specific Heat (J/kg.K)					2,500.00	
Window							
U-Factor (W / $m^2 \cdot K$)	5.84	5.84	3.24	3.24	3.24	3.24	2.62
SHGC*	0.25	0.25	0.39	0.39	0.39	0.39	0.90
Visible transmittance	0.11	0.11	0.31	0.31	0.31	0.31	0.63

Table 3-5: Ground floor and window construction type and fabric.

3.2.3 Ceiling, internal wall, and internal floor

There is no recommendation or requirements in the Benchmark models on ceiling, internal wall, and internal floor constructions. However, from the reference simulations provided by DOE for medium office buildings, all three settings can be acquired. The construction type and characteristics values of ceiling, internal wall, and internal floor were the same for all climates. Detailed information on ceiling, internal wall, and internal floor is found in Table 3-6.

Building Characteristic					
Ceiling			**Internal Floor**		
Construction Type	Drop Ceiling		Construction Type	Concrete floor	
U-value (W/m^2·K)	2.18		U-value (W/m^2·K)	2.80	
Materials (From outside layer to inside layer)			**Materials (From outside layer to inside layer)**		
Drop Ceiling	Thickness (mm)	12.70	Concrete	Thickness (mm)	101.60
	Conductivity (W/m.K)	0.06		Conductivity (W/m.K)	1.31
	Density (kg/m^3)	288.00		Density (kg/m^3)	2,400.00
	Specific Heat (J/kg.K)	1,339.00		Specific Heat (J/kg.K)	836.90
Partition			Carpet	Thickness (mm)	10.00
Construction Type	1/2 in gypsum			Conductivity (W/m.K)	0.22
U-value (W/m^2·K)	2.54			Density (kg/m^3)	160.00
Materials (From outside layer to inside layer)				Specific Heat (J/kg.K)	2,500.00
1/2 in gypsum	Thickness (mm)	12.70			
	Conductivity (W/m.K)	0.16			
	Density (kg/m^3)	784.90			
	Specific Heat (J/kg.K)	830.00			
1/2 in gypsum	Thickness (mm)	12.70			
	Conductivity (W/m.K)	0.16			
	Density (kg/m^3)	784.90			
	Specific Heat (J/kg.K)	830.00			

Table 3-6: Ceiling, internal wall, and internal floor construction type.

3.3 Infiltration

Infiltration is different in various buildings and changes with building environment and operations. The benchmark models recommended a simplified method to estimate the building infiltration for the simulation. A fixed air change per hour (ACH) value was assigned to each room and plenum. The recommended infiltration information is found in Table 3-7.

Building Infiltration			
Air Changes per Hour	ACH		ACH
Bottom interior room	0	Mid interior room	0
Bottom North (Zone 3)	0.26	Mid North (Zone 3)	0.26
Bottom East (Zone 4)	0.28	Mid East (Zone 4)	0.28
Bottom South (Zone 1)	0.26	Mid South (Zone 1)	0.26
Bottom West (zone 2)	0.28	Mid West (zone 2)	0.28
First to second plenum	0.11	Second to third plenum	0.11
Top North (Zone 3)	0.66	Top West (zone 2)	0.67
Top East (Zone 4)	0.67	Top interior room	0
Top South (Zone 1)	0.66	Third floor plenum	1

Table 3-7: Building infiltration profile.

3.4 Schedule

This study does not examine the best operating schedule for buildings and systems. All the recommended schedules come from benchmark models. The operating schedule is divided into three sub-categories: Weekdays, Saturday, and Sunday or holiday schedule.

3.4.1 Occupancy Schedule

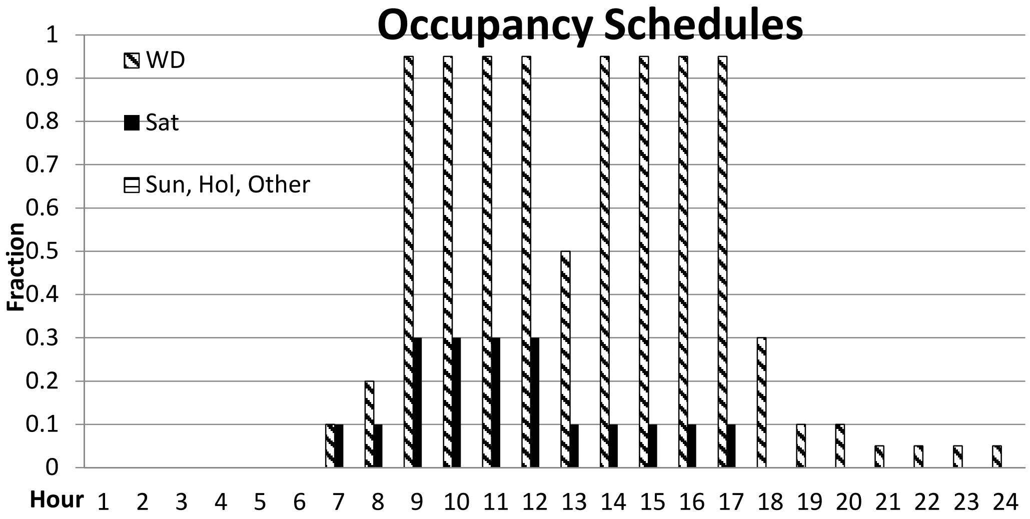


Figure 3-1: Occupancy Schedule.

3.4.2 Lighting schedule

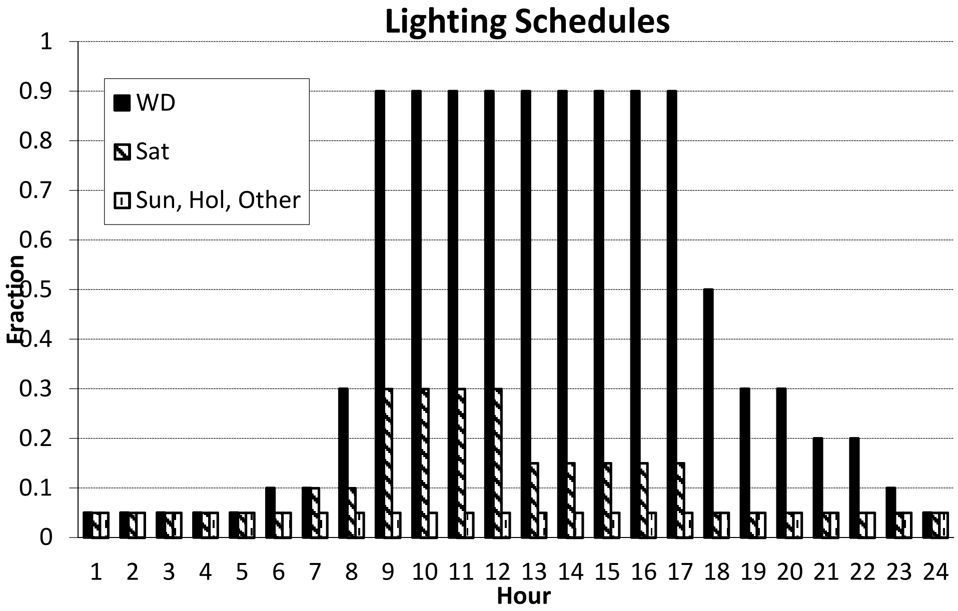


Figure 3-2: Lighting Schedule.

3.4.3 Office equipment schedule

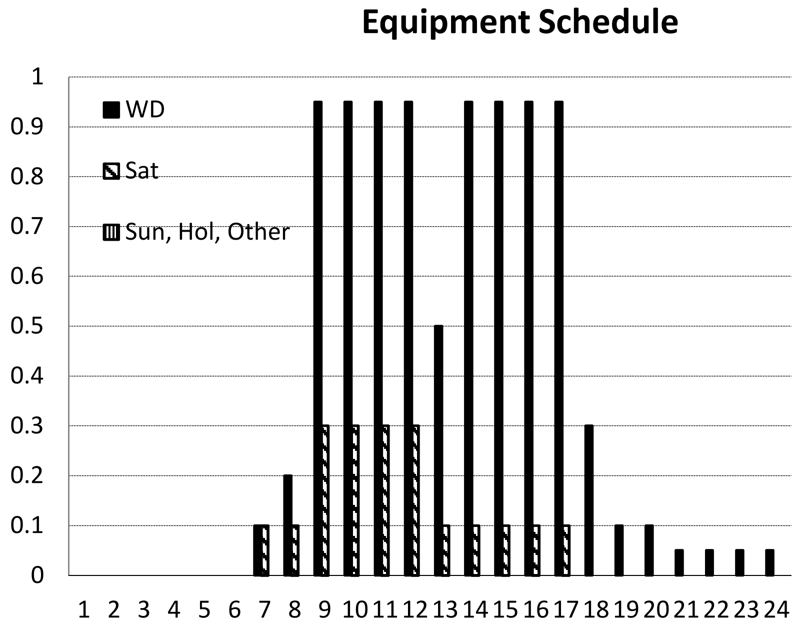


Figure 3-3: Equipment Schedule.

3.4.4 Elevator schedule

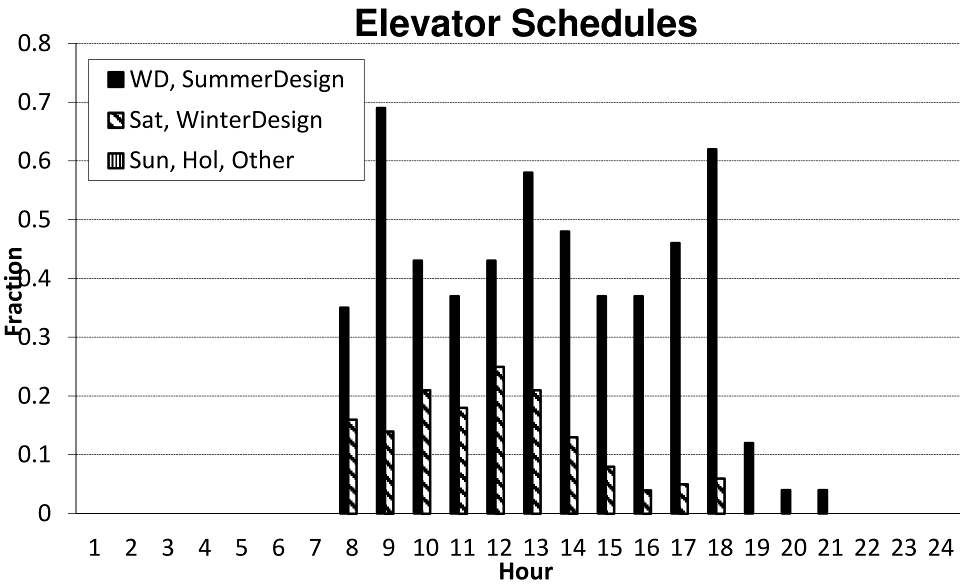


Figure 3-4: Elevator Schedule.

3.4.5 Infiltration schedule

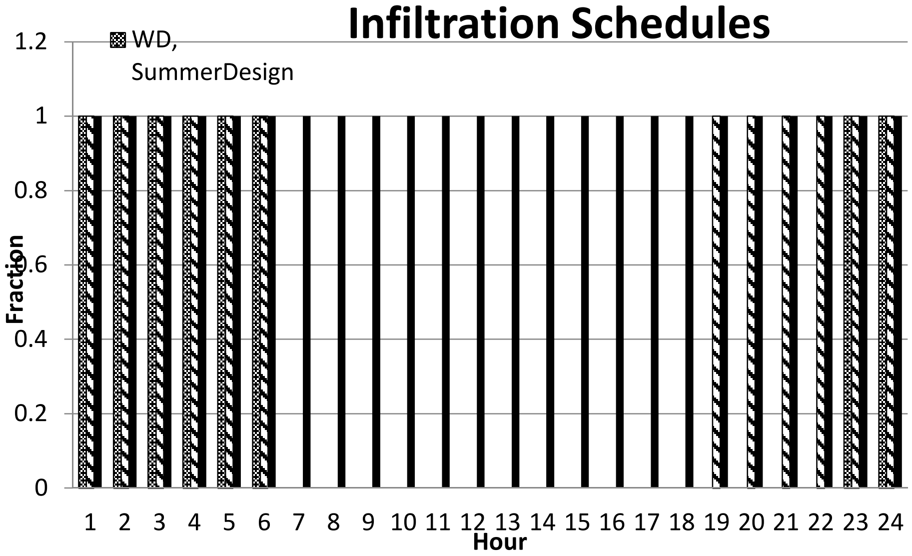


Figure 3-5: Infiltration Schedule.

3.5 Occupancy

The building occupancy profile used in this study follows the recommendations by benchmark models adopted from ASHRAE Standard 90.1-2004 occupancy for medium office. ASHRAE Standard 90.1-2004 refers to ASHRAE Standard 62-1999 as normative reference, thus, the ventilation requirement when based on occupancy is also from ASHRAE Standard 62-1999. However, compared to the current of Standard 62.1-2010, the medium office occupancy density of the previous version is the same as the current version. Note that ASHRAE Standard 62-1999 become Standard 62.1-2004 when the 1999 version was updated, and current Standard 62.1-2010 is the updated version of Standard 62.1-2004.

This study uses 18.6 m^2/person (200 ft^2/person).

3.6 Ventilation

The ventilation or OA flow rate requirement for benchmark models concerning medium office buildings is adopted from ASHRAE Standard 62-1999. The newest ASHRAE Standard 62 (also known as 62.1 when the 2004 version was published), differs from the older vision by requiring a larger amount of OA for occupancy instead of OA requirements per occupancy and floor area.

This study uses 9.44 L/s/person (20 cfm/person).

There was concern that the using ASHRAE Standard 62-1999 instead of ASHRAE

Standard 62.1-2010 (the newly vision) caused significant difference on simulation. Thus, a comparison was made between occupancy and ventilation requirements of the two visions and is found in Table 3-8.

Unlike the Standard 62-1999, the newly vision requires two separate ventilation airflow: part one is ventilation requirement per occupancy and part two is ventilation requirement per building floor area. The combined value of ventilation requirement was adopted from Standard 62.1-2010, which intent to compare with ventilation requirement in Standard 62-1999.

		ASHRAE Standard 62-1999	ASHRAE Standard 62.1-2010	Difference
Occupancy	Unit	#/100 m^2	#/100 m^2	%
	Value	**18.6**	**18.6**	0
Ventilation	Unit	L/s.person	L/s.person	%
	Value	**9.44**	**8.5**	9.96

Table 3-8: Ventilation and occupancy comparison between of ASHRAE Standard 62-1999 and 62.1-2010.

There was difference as shown in the comparison. However, since the difference remained within 10%, and since the ventilation requirement in all simulations of this research were consistently applied, the difference was acceptable and will not make the simulation results invalid.

3.7 Plug and Process Loads

Determining the plug and process loads in buildings is a hard task. Some assumptions and references were collected to determine the recommended plug and process loads. Furthermore, assumption was made that the power consumption of plus and process loads is the same as the internal heat gain. The detailed information is found in Table 3-9.

3.8 Building Loads Calculation

The selected simulation tool in this study is IES-VE. All load calculations are built on recommendations from benchmark models.

3.8.1 Building forms

The simulated building forms are exactly the same as the reference buildings simulated by DOE. The detailed building forms and room sizing are the same as in Table 3-1. Figure 3-6 shows the building layout and sketch.

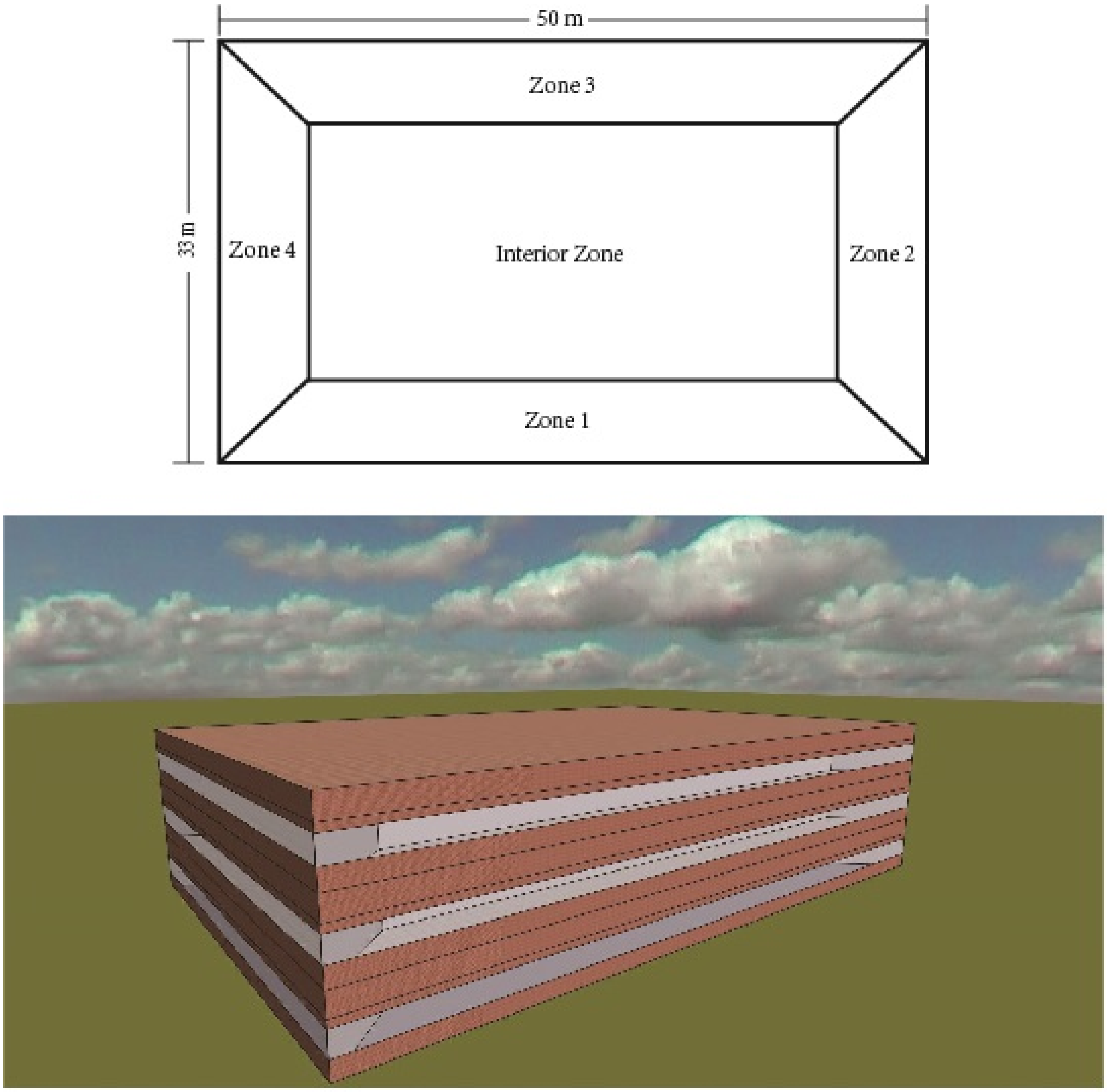


Figure 3-6: Layout and sketch of simulated building.

3.8.2 Internal Gains

Lighting, occupancy, office equipment, and elevator power consumption heat gain are four sources of internal gain. The four internal gains were recommended by benchmark models and found in Table 3-9.

Building Heat Gain			
Occupancy heat gain	W/person	**Lighting heat gain**	W/m^2
Sensible heat gain	105	Sensible heat gain	10.76
Latent heat gain	31.5	**Elevator heat gain (assign to bottom interior room**	Watts
Office equipment heat gain	W/m^2		
Sensible heat gain	10.76	Sensible heat gain	32109.89

Table 3-9: Building internal heat gains.

3.9 Building heat gain and building loads comparison

Simulated building heat gains and building loads were calculated in IES based on the previously described recommendations for benchmark models. Building heat gains and building loads in this study were then compared to the reference building provided by DOE. All building simulation recommendations applied to both simulated buildings were the same. The comparison between these two building simulations serves as the validation for simulated building in this study. A comparison was made to the studies on DOAS configurations built on this simulated building to establish study trustworthiness. The comparison was built using the Chicago location and is found in Table 3-10.

Location: Chicago	Benchmark models	Simulated building	Difference
Summary people heat gain	(MWh)	(MWh)	(%)
Floor 1	25.64	25.62	
Floor 2	25.64	25.62	
Floor 3	25.64	25.62	
Total	76.91	76.85	0.07
Summary lighting heat gain	(MWh)	(MWh)	
Floor 1	51.16	51.31	
Floor 2	51.16	51.31	
Floor 3	51.16	51.31	
Total	153.49	153.92	0.28
Summary lighting heat gain	(MWh)	(MWh)	
Floor 1	105.14	108.15	
Floor 2	59.38	59.34	
Floor 3	59.38	59.34	
Total	223.90	226.83	1.29
Summary Infiltration heat gain	(MWh)	(MWh)	
Floor 1	-10.62	-11.27	
Floor 2	-10.90	-11.60	
Floor 3	-10.51	-10.82	
Total	-32.03	-33.69	4.92
Summary Envelop heat gain	(MWh)	(MWh)	
Floor 1	-111.18	-138.31	
Floor 2	-67.04	-48.74	
Floor 3	-77.37	-82.77	
Total	-255.59	-269.82	5.27

Table 3-10: Building and envelop heat gains comparison.

Slight difference remained in this comparison. Differences of lighting, occupancy, and office equipment heat gain in both simulated buildings were too small to invalidate the simulated building. Difference of infiltration heat gain and building envelop heat gains were higher but remained reasonable. Different equations and thermal methods, the major cause for the differences, were applied to the two simulations since different simulation tools were used. EnergyPlus was applied to the benchmark models and IES was used to simulate the building in this study. However, differences between the two buildings remained reasonable and make building modeling comparable.

Chapter 4 DOAS System Modeling and Validation with Previous Studies

There are three DOAS configurations and one simulated baseline defined in this study. System modeling details of selected systems are found in this chapter.

Prior to analyzing the simulation results, validations were made toward all simulated systems. The baseline system energy simulation was compared to two similar systems found in literature. Energy performances of DOAS were also compared with similar system found in literature.

4.1 Heating and Cooling Setpoint of the Rooms

The heating and cooling setpoints of each room are defined in benchmark models. The heating and cooling setpoints were the same in all simulated DOAS configurations and baseline. Heating and cooling setpoints were cataloged into three columns and same as all other schedules in chapter 3. Work days (WD), Saturdays (Sat), and Sundays, holidays (Sun, Hol, Other) are the three catalog and setpoints found in Table 4-1 as cooling setpoint and Table 4-2 as heating setpoint.

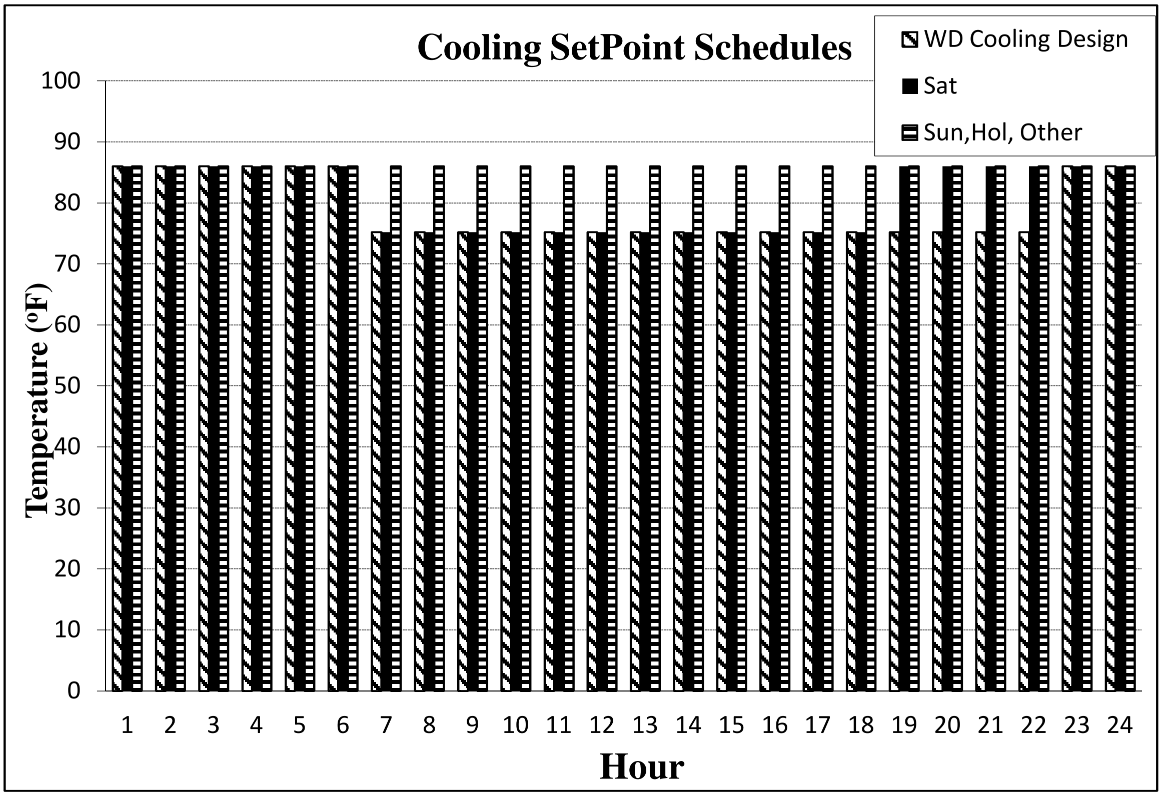


Table 4-1: System simulation cooling setpoint.

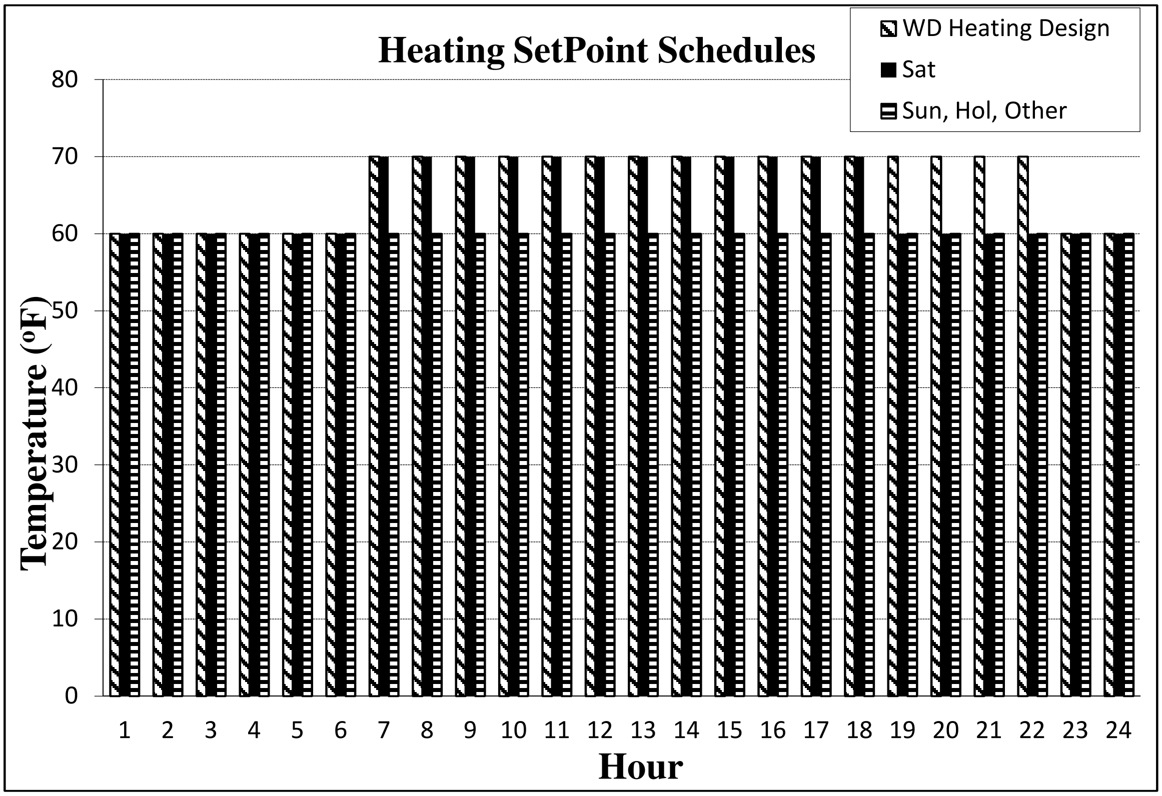


Table 4-2: System simulation heating setpoint.

4.2 System Modeling Summary

There were seven system modeling described in following sections. Summary of all simulated systems were listed in Table 4-3.

VAV-1-DX, DOAS-1-DX, and DOAS-2-DX were specifically modeled for comparisons and validations between system modeling in this research and system modeling in literature. The four system modeling were defined to identify energy benefits of DOAS in various climates.

Purpose	Comparisons and validations between system modeling in this research and system modeling in literature	Comparisons to identify energy benefits of DOAS in various climates

System	**VAV-1-DX**	**DOAS-1-DX**	**DOAS-2-DX**	**VAV-1**	**DOAS-1**	**DOAS-2**	**DOAS-3**
Description	Single duct VAV with reheat	DOAS supplies OA to intake of local unit	DOAS supplies OA to each occupied space	Single duct VAV with reheat	DOAS supplies OA to intake of local unit	DOAS supplies OA to each occupied space	DOAS supplies OA to space equipped with ACB
Primary System	DX cooling, gas furnace for preheat	DX cooling, boiler supported preheat		Chilled water cooling, boiler for preheat	Chilled water cooling, boiler for preheat		
Secondary System	Terminal reheat	FCUs with DX cooling coil and boiler supported heating		Terminal reheat	FCUs with chilled water cooling coil and boiler supported heating		
TER	No	Yes	Yes	Yes	Yes	Yes	Yes
Economizer	Air-side	Water-side		Air-side	Water-side		

Table 4-3: System modeling summary

4.3 Simulated Baseline System

In order to identify the energy usage reduction achieved by DOAS, a baseline system was also simulated that compared to all three simulated DOAS configurations. The baseline system consists of a conventional VAV system with the same ventilation, heating, and cooling requirements as the three simulated DOAS configurations. Furthermore, a quick validation of the simulated baseline was made to ensure the reasonability of simulated baseline.

4.3.1 Simulated baseline system configuration

The baseline system configuration was built using a benchmark models reference system. A single duct VAV with reheat per floor equipped with direct-expansion (DX) cooling coil and preheat and terminal reheat supported by gas furnace was defined in benchmark models. This system configuration named as VAV-1-DX. There were two fans: supply air fan and return air fan. A pump was used only to support the services heat water system (SHW). An energy recovery device was not employed in the benchmark models.

Thus, a similar system was modeled as baseline system, named as VAV-1. A single duct VAV with reheat per room. Chilled water chiller supported cooling coil was equipped in a VAV system. The gas furnace was replaced with a boiler to support both the heating coil and reheat coil. The SHW system was the same as in VAV-1-DX. An total energy recovery device was equipped in VAV-1.

Figure 4-1 and Figure 4-2 show the simulated baseline system.

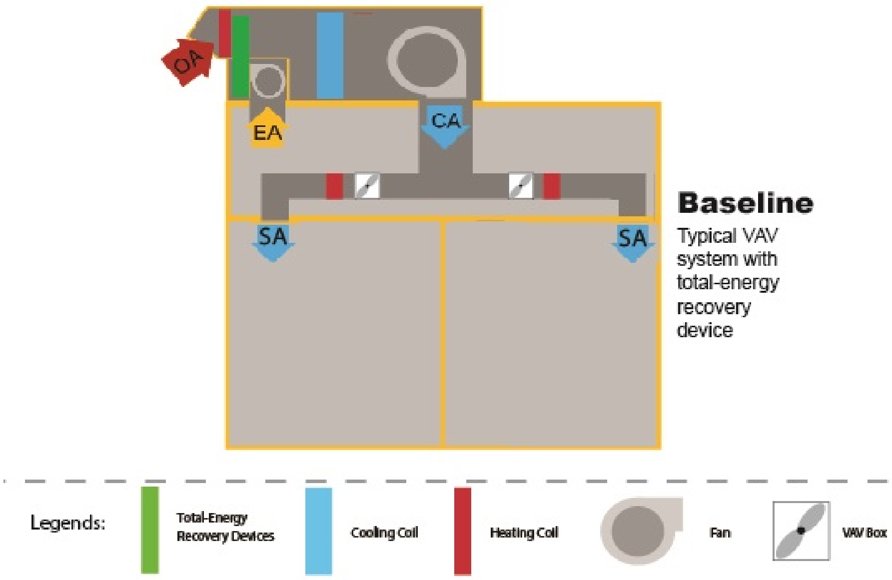


Figure 4-1: Simulated baseline system.

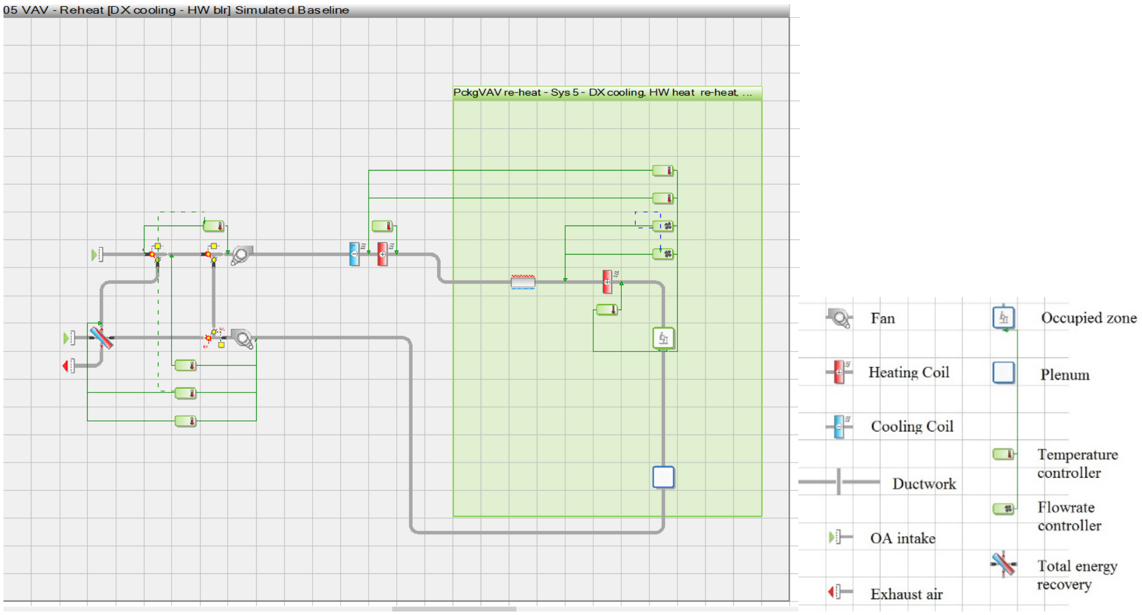


Figure 4-2: Simulated baseline system sketch.

4.3.2 Air-side economizer and air-side economizer controls

An air-side economizer was equipped in both VAV-1 and VAV-1-DX. The return air damper, mixing air damper, outdoor air damper, and one controller were combined together as the air-side economizer. Purpose of air-side economizer was to introduce more outdoor air for “free cooling”.

On-off control mode was applied to air-side economizer. When the outdoor air condition was below the on-limit, the air-side economizer cycled on to bring more outdoor air. When the outdoor air condition was exceeded the off-limit, the air-side economizer cycled off. The off-limit in air-side economizer control also known as high-limit. 1 °F or 0.5 Btu/lb deadband was defined to either fixed dry bulb control or fix enthalpy control.

The high-limit shutoff control strategy of the air-side economizer varied in different climates. Either a fixed dry bulb control type or a fixed enthalpy control type was used. However, in some climates where a fixed dry bulb control type for air-side economizer was allowed, the fixed enthalpy control type was prohibited. Thus, the air-side economizer control type varied in the baseline between climates. For climate zones 1a and 4a (defined by ASHRAE Standard 90.1-2010), where Miami and Baltimore were simulated, the fixed enthalpy control type was used. The fixed dry bulb was applied to all other simulated climates.

The high-limit of the fixed dry bulb control type was 70°F while the high-limit of the fixed enthalpy was 28 Btu/lb. All details and description of air-side economizer are found in Table 4-3.

Air-side economizer high-limit control type					
Number	**Climate Zone**	**Representative City**	**Control Type**	**Control Equation**	**Description**
1	1A	Miami, Florida	Fixed enthalpy	28 Btu/lb	Outdoor air enthaply exceeds 28 Btu/lb
2	2B	Phoenix, Arizona	Fixed dry bulb	70°F	Outdoor air temperature exceeds 70°F
3	4A	Baltimore, Maryland	Fixed enthalpy	28 Btu/lb	Outdoor air enthaply exceeds 28 Btu/lb
4	4B	Albuquerque, New Mexico	Fixed dry bulb	70°F	Outdoor air temperature exceeds 70°F
5	5A	Chicago, Illinois	Fixed dry bulb	70°F	Outdoor air temperature exceeds 70°F
6	5B	Denver, Colorado	Fixed dry bulb	70°F	Outdoor air temperature exceeds 70°F
7	8	Fairbanks, Alaska	Fixed dry bulb	70°F	Outdoor air temperature exceeds 70°F

Table 4-4: Air-side economizer high-limit control type.

4.3.3 Multi-zone VAV system ventilation calculation

A single duct VAV system was simulated in the baseline to serve all rooms. Thus, multiple-zone recirculating systems equations (section 6.2.5) were used to calculate the minimum required zone ventilation per ASHRAE Standard 62.1-2010 (ASHRAE 2010).

First, the uncorrected outdoor air intake (V_{ou}) was determined in equation 6-6 of Standard 62.1-2010.

$$V_{ou} = D * \sum_{all\ zones}(Rp * Pz) + (Ra * Az) \qquad (4\text{-}1)$$

Where: R_p: Floor area of zone, ft^2

P_z: Zone population, largest number of people expected to occupy zone, #

R_a: People outdoor air rate from Table 6.1, which office is 2.5 L/s-person

A_z: Area outdoor air rate from Table 6.1, which office is 0.3 L/s-m ^{2}

D: Occupant diversity ratio, #

Second, primary outdoor air fraction (Z_{pz}) was calculated by equation 6-5 of Standard 62.1-2010.

$$Z_{pz} = V_{oz}/V_{pz} \qquad (4\text{-}2)$$

Where: V_{oz}: Outdoor airflow to the zone corrected for zone air distribution effectiveness, L/s

V_{pz}: Primary airflow to zone from air handler. In VAV systems, use the design value**,** L/s

Third, Voz can be determined by the equation

$$V_{oz}= (Pz*Rp + Az*Ra)/Ez \qquad (4\text{-}3)$$

Where: E_z: Zone air distribution effectiveness, from Table 6-2 of Standard 62.1-2010, is equal to 1 in the baseline.

Then, acquired system ventilation efficiency (E_v) from the max value of Z_{pz} of Table 6-3.

At last, the outdoor air intake (V_{ot}) is calculated using in equation 6-8 of Standard 62.1-2010.

$$V_{ot} = V_{ou}/E_v \qquad (4\text{-}4)$$

Excel tables were made and used to calculate the outdoor air intake. All the calculations show the outdoor air intake (V_{ot}) was 4263 L/s for VAV-1 and VAV-1-DX in all simulated locations.

The occupant diversity ratio for the selected building type is 1. Zone air distribution effectiveness was selected based solely cooling. Appendix A shows all the outdoor air intake calculations and results for all climates.

4.3.4 VAV cooling coil and cooling controls

The cooling coil, either a DX cooling coil or chilled water chiller supported cooling coil, was controlled using the zone air cooling temperature setpoint, which shown in section 4.1.

On zone level, one controller with a sensor equipped to each occupied space which monitored the zone return air temperature. When the return air temperature exceeded the cooling setpoint, the controller gave on signal to damper to adjust the supply airflow. Supply air damper was then adjusted to increase the damper opening (below the max cooling or heating airflow rate calculated in Appendix A) to introduce more cold air to space.

Meanwhile, on system level, one controller will maintain the discharge air temperature of cooling coil at 55°F as supply air temperature whenever there is pressure drop between intake and discharge of cooling coil. This was achieved by controller control the cold water value to adjust the cold water flow rate.

Figure 4-3 shown the both zone and system level cooling control sketch.

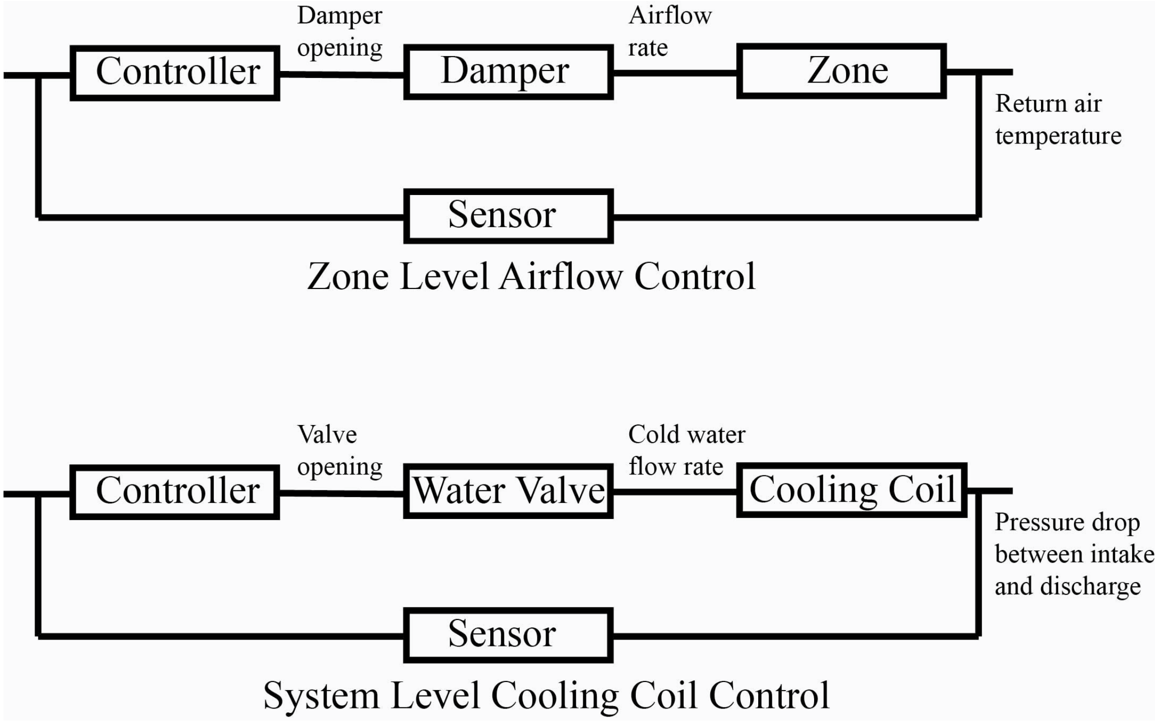


Figure 4-3: VAV cooling zone and system level control

4.3.5 VAV preheat and reheat coil and heating control

Both preheat and reheat coil were supported by a gas furnace in VAV-1-DX or a boiler in VAV-1. The purpose of the preheat was to maintain the entering temperature of TER over 32°F to prevent air entering TER from becoming too cold and damaging the device. The reheat coil served each occupied space for terminal reheat.

The preheat controlled by a controller with a sensor. When the sensed intake temperature of preheat below 32 °F, the controller gave heat water valve an “on” signal. However, the preheat coil will only control the heat water valve to maintain the discharge air temperature at 28 °F. The control method was adopted from literature.

The reheat coil controlled by controller which combined with sensor. Sensor placed on the return air duct for each occupied space. When the sensed return air temperature was below the heating setpoint, which shown in section 4.1, the controller give an “on” signal to heat water valve. Then the controller controlled the heat water valve to increase valve opening. The fixed entering heat water temperature was set to make sure the discharge temperature of reheat coil remained at 95°F.

Meanwhile, airflow rate for each space was controlled by one controller with sensor. The temperature sensor was also placed at each space’s return air duct. When the return air temperature below the heating setpoint, the controller will gave “on” signal to damper to bring more air.

Figure 4-4 shown the preheat, reheat, and zone level airflow control.

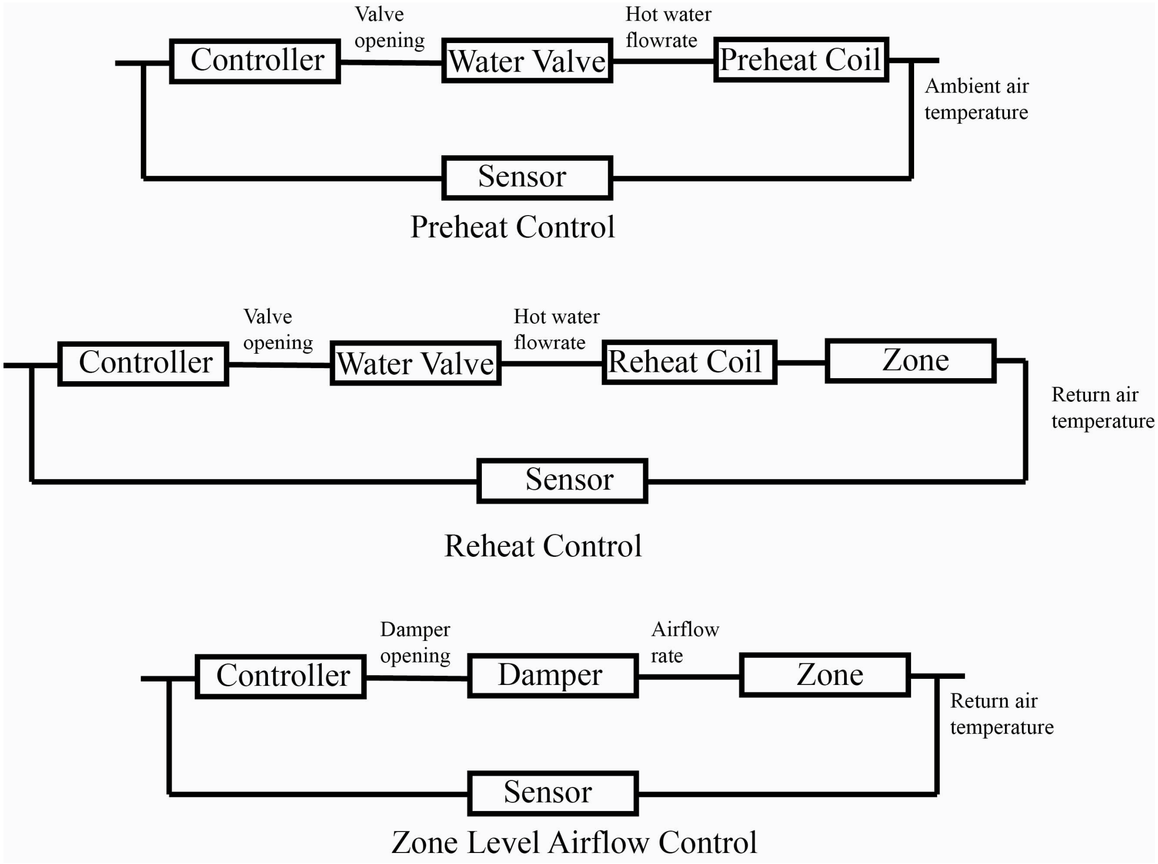


Figure 4-4: VAV heating control

4.3.6 Total energy recovery and total energy recovery controls

Total energy recovery (TER) was optional for baseline modeling. In VAV-1-DX, When the VAV system compared to benchmark models reference buildings or compared to other sources of reference, TER was not employed. However, in VAV-1, when the VAV system is compared to other simulated DOAS configurations, TER was applied to baseline to make a better comparison since TER was generally applied to DOAS.

TER is a combination of dampers, energy exchanger, and controllers. For the energy exchanger applied to TER, sensible heat effectiveness was 68% and latent heat effectiveness was 61%. This relatively high energy exchange effectiveness was assumed based on the value which used in benchmark models. Motor power consumption for TER was 0.2 KW.

TER transferred the “cold” (“heat” during winter) within the return air to introduced outdoor air. The control strategy of TER is to set a relatively unachievable target for energy exchanger. During summer, the purpose of TER is to reduce the introduced outdoor air temperature close to 50°F, thus the “cold” within the return air can reduce the introduced outdoor air temperature when the ambient temperature over return air temperature. The same method is used during the heating, TER designed to make the introduced outdoor air temperature close to 70°F. Figure 4-5 shown the control method and controller sketch,

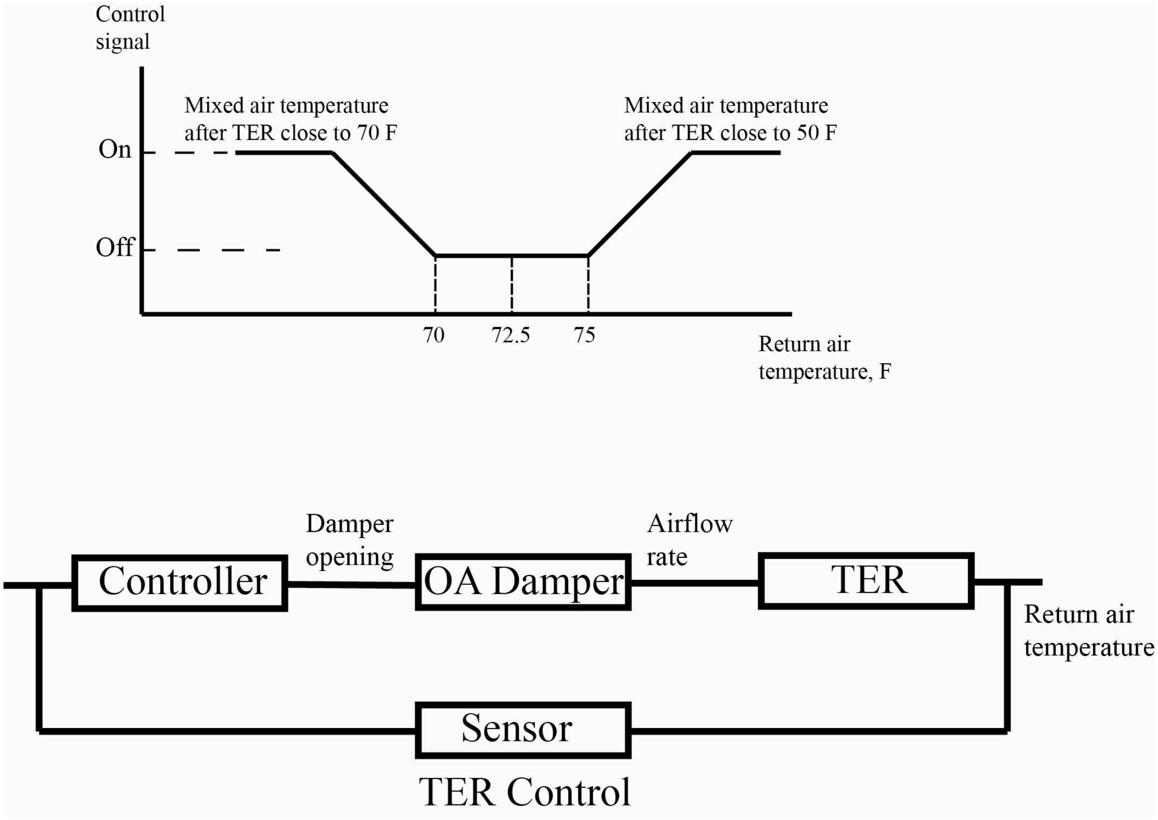


Figure 4-5: TER control method and sketch

4.4 VAV Reference from another Source

In order to validate the simulated baseline, another reference building simulation beside benchmark models reference was utilized.

A report from Pacific Northwest National Laboratory (PNNL) simulated building energy performances of DOE benchmark models. (Thornton et al. 2009) The VAV system modeling in this report consists of a single duct VAV system, equipped with DX cooling coil and gas furnace supported heating coil. The gas water heater was employed for SHW and an electric heating coil for reheat. The system modeling was very similar compared to benchmark reference buildings and simulated baseline. Thus, the building energy performance between the three VAV systems can validate the simulated baseline.

4.5 Baseline Modeling Validation (VAV System Comparison)

The system energy usage of three VAV systems; DOE benchmark reference buildings, simulated buildings of PNNL report, and VAV-1-DX, are presented in Table 4-4. The system energy usage is broken down into energy usage of cooling, fan, pump, energy recovery, heating, and SHW. Chicago is the selected comparison location.

Comparison results show the simulated VAV system, with all the models utilizing DOE benchmark models, displaying differences. The differences are caused by slight variation of the system models and simulation tools. A gas furnace was selected to support the heating coil in DOE benchmark models where a boiler was used in simulated baseline. A gas water heater was employed for reheat in DOE benchmark models when an electric heating coil was selected for reheating. A boiler was applied to reheat in the simulated baseline.

The simulation tools used by EnergyPlus, DOE benchmark models simulation, and simulation in PNNL report were different visions of simulation tools and caused some differences. IES-VE was selected in the simulated baseline.

From the VAV energy usage comparison among three systems, the simulated baseline shows reasonable difference between the other two published references. Thus, the simulated baseline can be used in further comparison.

Location: Chicago	**DOE Benchmark references**	**PNNL-19004-report**	**VAV-1-DX**
Building Area ft^2)	53626.248	53992.224	53626.248
System Description	Single duct, VAV with reheat, DX cooling, gas furnace heating, gas water heater for reheat and SHW	Single duct, packaged VAV, DX cooling, gas furnace heating, gas water heater for SHW, electric reheat	Single duct, packaged VAV, DX cooling, boiler for preheat, reheat and SHW
Convert and summary total energy	MMBtu	MMBtu	MMBtu
System energy: Cooling	201.548	296	204.757
System energy: Fan	63.378	287	86.912
System energy: Pump	1.205	0	16.693
System energy: Heating	933.349	930	1009.38
System energy: Water Heater	38.903	66	0
Total HVAC Energy (kBtu)	1.24E+06	1.58E+06	1.32E+06
Total HVAC EUI (kBtu/ft^2)	**23.093**	**29.245**	**24.573**

Table 4-5: VAV system comparison as baseline validation.

4.6 DOAS-1 system configuration

DOAS-1 referred to a DOAS where a dedicated OA unit supplies conditioned OA to the intake of each local HVAC unit. DOAS-1 consists of dedicated OA unit equipped preheat coil, cooling coil and TER, a fan-coil unit (FCU) equipped a heating coil and cooling coil to serve as the local terminal HVAC unit. DOAS-1 system configuration and system sketch is found in Figure 4-3 and Figure 4-4.

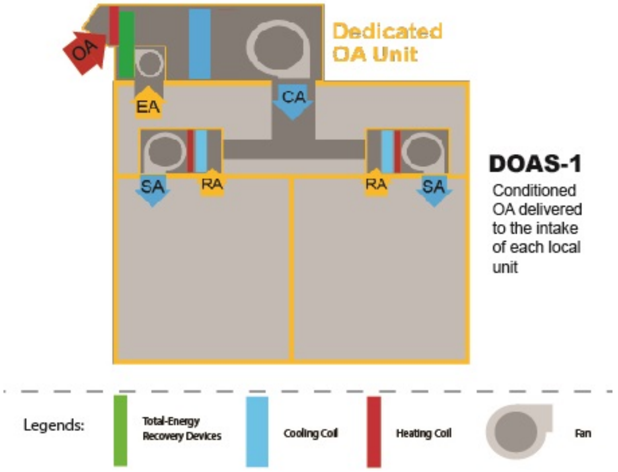


Figure 4-6: DOAS-1 system configuration.

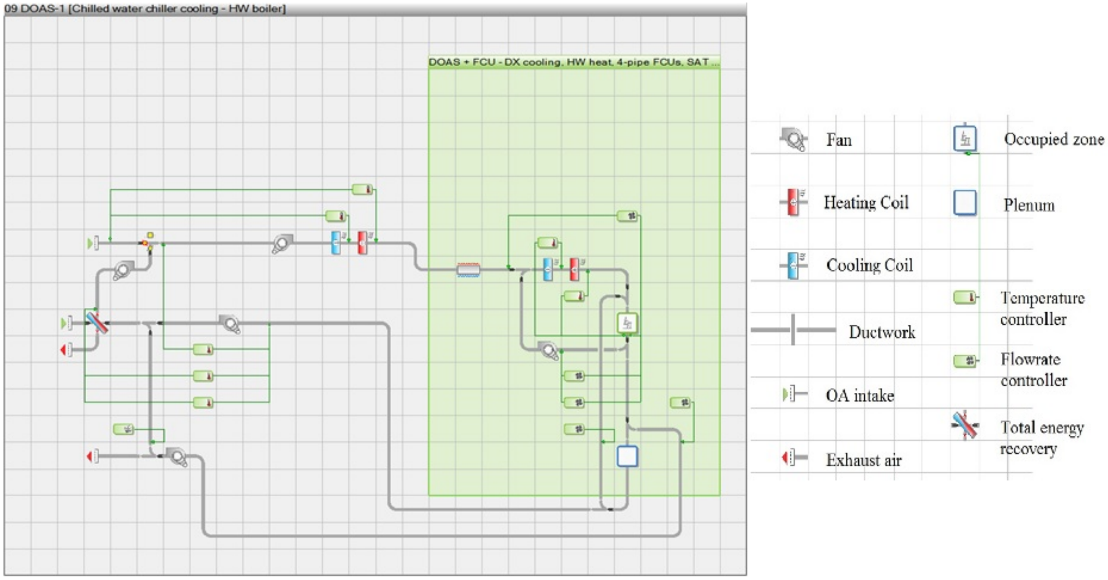


Figure 4-7: DOAS-1 system sketch.

4.6.1 Dedicated OA unit and ventilation control of DOAS-1

A dedicated OA unit consists of a heating coil supported by a boiler, a cooling coil supported by a chilled water chiller, and a supply and return air fan. TER was employed in the dedicated OA unit to recover energy from exhaust air.

The cooling coil control method in a dedicated OA unit maintains the cooling coil discharge temperature at 55°F when the ambient air dry bulb temperature exceeds 65°F. The cooling coil controller utilizes an on and off control with a 2°F temperature deadband. The cooling coil control method for a dedicated OA unit was adopted from the PNNL report.

The preheat coil control method in dedicated OA unit maintains the TER intake temperature over 25°F when the ambient temperature is below 32°F. The heating coil controller also utilizes an on and off with a 2°F temperature deadband. The preheat coil control method for a dedicated OA unit was adopted from a previous study. (Mumma 2001b)

The same sensible heat effectiveness and latent heat effectiveness of TER applied in the simulated baseline were applied in DOAS-1. The control method of DOAS-1 TER also remained as the same in the simulated baseline.

Ventilation airflow for each room was controlled remained at fixed value. The ventilation airflow was the minimum required ventilation air from Standard 62-1999 whenever the DOAS was operated. The ventilation requirement can be seen in section 3.6.

4.6.2 Local HVAC unit and components control of DOAS-1

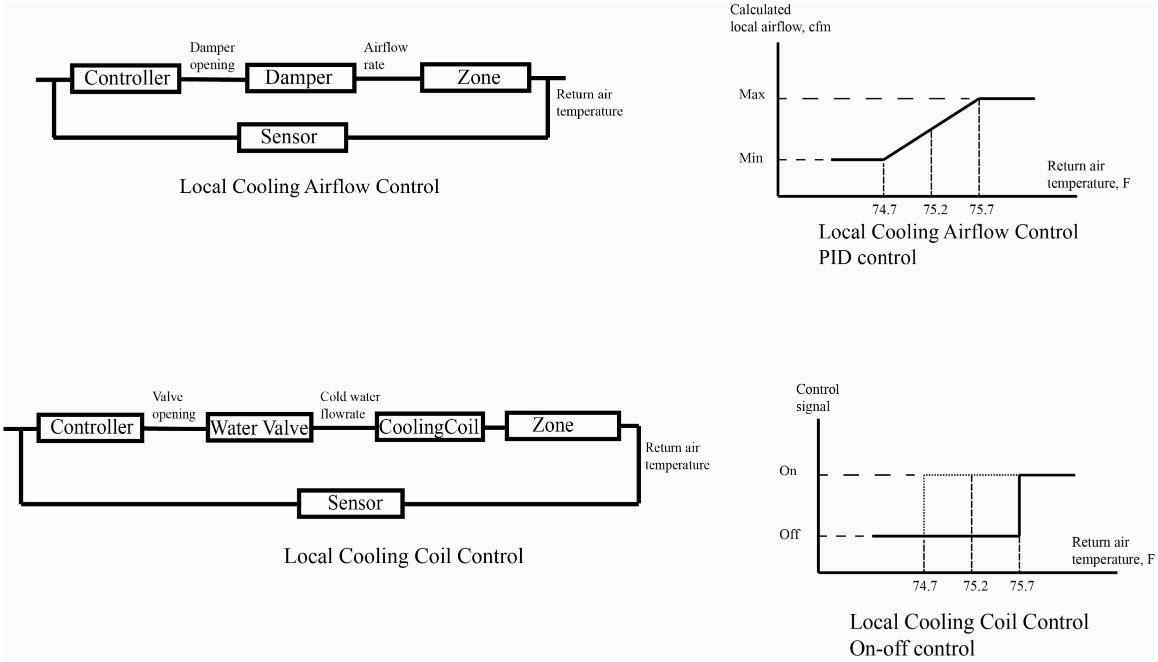
A fan-coil unit (FCU) serves as the local HVAC unit in DOAS-1. A heating coil, cooling coil, and supply air fan were equipped in the FCU. Similar heating and cooling sources as that of the heating and cooling coil for a dedicated OA unit were applied. The dedicated OA unit supplies conditioned air to the intake of each room's local HVAC unit in DOAS-1where the conditioned air is mixed with local recirculation air in the FCU before entering the FCU cooling coil and heating coil. After the FCU further conditions the air, the FCU supplies the supply air to each occupied room.

Four controller with sensor regulated the cooling and heating coil in the FCU, two controllers for airflow control and the rest two for coils control. All sensors were placed controllers in each room's return air duct.

For cooling coil and cooling airflow control, when the measured return air temperature exceeded the space cooling setpoint, in section 4.1, an "on" signal was given by controller to local recirculation damper and cooling coil cold water valve. The local recirculation damper increase the damper opening to increase the locally recirculation airflow from 0 to max calculated value (the max value were calculated in below section and shown in Appendix B). The cold water valve of cooling coil also increased the valve opening to introduce more cold water. The cold water introduced to cooling coil was to maintain the discharge air temperature of the cooling coil at 55°F.

For heating coil and heating airflow control, when the measured return air temperature belowed the space heating setpoint, in section 4.1, an “on” signal was given by controller to local recirculation damper and heating coil cold water valve. The local recirculation damper increase the damper opening to increase the locally recirculation airflow from 0 to max calculated value (the max value were calculated in below section and shown in Appendix B). The hot water valve of heating coil also increased the valve opening to introduce more hot water. The hot water introduced to heating coil was to maintain the discharge air temperature of the heating coil at 95°F.

In order to prevent the simultaneously heating and cooling the air, a 5°F temperature difference was applied to heating and cooling setpoint. The heating and cooling coil controller utilizes an on and off control method with a 0.5°F deadband. On-off control mode was applied to coil control and PID control mode was applied to airflow control. Figure 4-8 and 4-9 shown the control method of four controller.



Local Cooling Airflow Control

Local Cooling Airflow Control
PID control

Local Cooling Coil Control

Local Cooling Coil Control
On-off control

Figure 4-8: Local cooling coil and airflow control

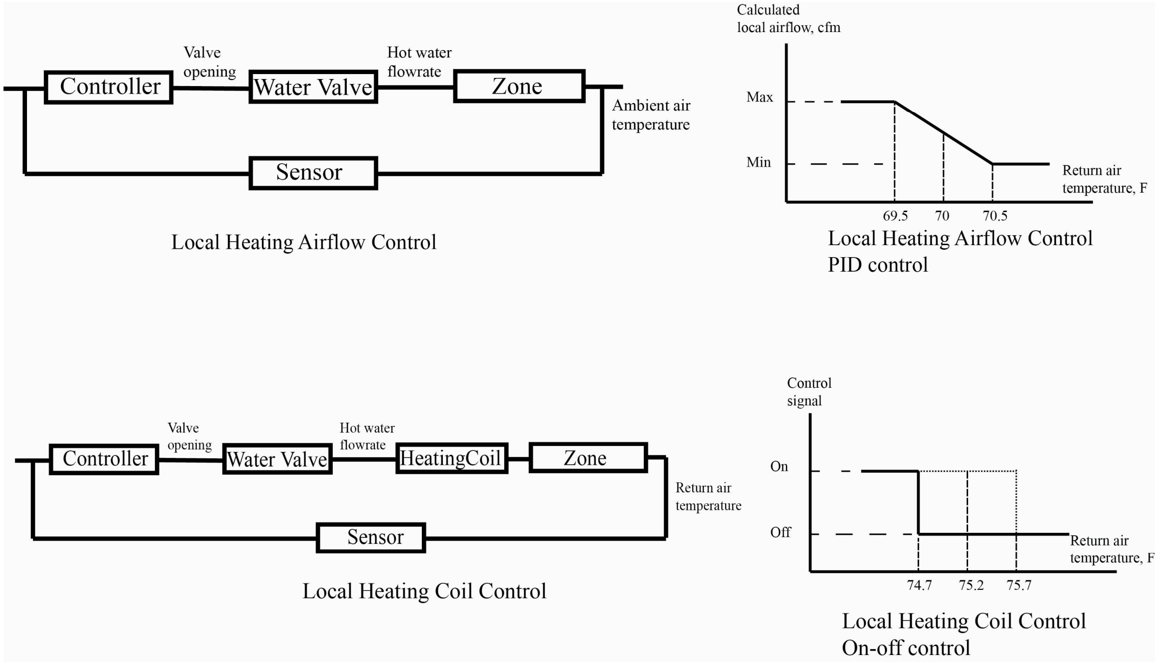


Figure 4-9: Local heating coil and airflow control

4.6.3 Other components and control of DOAS-1

The system level return air fan for the DOAS-1 balances the supply and exhaust air.

A water-side economizer applied to the chilled water loop serves as a replacement for the air-side economizer requirement. When this simplified design procedure for water-side economizer was utilized, the heat exchanger effectiveness for the water-side economizer was 0.84 and the cooling tower design load was 83.6 KW with 0.878 KW fan power and 1.071 KW pump power.

4.6.4 Ventilation air flow rate and recirculation air flow rate of DOAS-1

DOAS is capable of supplying the exact amount of required ventilation air to each occupied room. Thus, the OA from a dedicated OA unit can be sized separately to provide the exact amount of required air to each occupied room. The recommended ventilation air flow rate is found in the benchmark models.

The purpose of introducing recirculation air is to compensate the zone supply air. The ventilation air flow rate and supply air temperature are fixed values for each occupied room, thus, when the amount of ventilation air is not capable of offsetting the space cooling or heating load, more air at the cooling or heating supply air temperature is supplied to the room. Instead of using more OA, utilizing local recirculation air is more energy efficiency and realistic.

The local unit sizing calculation for the purpose of offsetting the rest loads after ventilation air delivered to each space used the following equations:

$$Q_{loads} = Q_{ventilation} + Q_{recirculation} \qquad (4\text{-}5)$$

Where: Q_loads: space sensible load of summer or winter, kBtu/hr

Q_ventilation: the amount of load that ventilation air can offset, kBtu/hr

Q_recirculation: the amount of load that locally recirculation air can offset, kBtu/hr

$$Q_{ventilation} = C * V_{ventilation} * (T_{return} - T_{supply}) \qquad (4\text{-}6)$$

Where:

V_ventilation: ventilation air flow rate for each space, cfm

C: specific heat capacity, 1.1

T_return: return air temperature, °F

T_supply: supply air temperature, °F

$$Q_{circulation} = C * V_{circulation} * (T_{return} - T_{supply}) \quad (4\text{-}7)$$

Where:

V_recirculation: local induced air flow rate, cfm

The calculated recirculation airflow serving as the Max local airflow in Figure 4-8 and 4-9. The Min value is 0 in these figures.

4.6.5 Checking space latent loads of DOAS-1

Since the system design is based on space sensible summer and winter loads, checking whether the latent loads applied air to each occupied space for various locations were already removed by ventilation air. This action make sure the space latent loads were effectively removed by ventilation air even the system sizing is designed of using sensible loads.

Thus, if the current calculated system supply air flow rate is insufficient to offset the space latent loads, an altered system supply air flow rate is applied. The altered system supply air flow is capable of covering all space latent loads. The latent loads check follows the procedure:

1. Read the space design latent load, Q_{read}.
2. Calculate the latent load the ventilation air of each zone can handle. Using equation 4-8.

$$Q_{latent\_ventilation} = C * V_{ventilation} * (w_{supply} - w_{return}) \tag{4-8}$$

Where: $Q_{latent\_ventilation}$: The latent loads the current designed ventilation air flow, kBtu/hr

$V_{ventilation}$: The current designed ventilation air flow rate, cfm

w_{supply}: The supply air humidity ratio, lb/lb

w_{return}: The return air humidity ratio, lb/lb

C: Specific heat capacity converted based on humidity, 4840

3. Compare calculated ventilation air latent loads with the read latent loads.
4. If the ventilation air latent load is less than read latent load, a new ventilation airflow was calculated based on equiation 4-9.

$$Q_{read} = C * V_{new} * (w_{supply} - w_{return}) \tag{4-9}$$

Where: Q_{read}: The read latent loads for each space, kBtu/hr

V_{new}: The new ventilation air flow rate, cfm

The altered ventilation airflow rate is not applied to system if the value of calculated Q_{latent_design} is larger than space design latent loads.

The calculation results of checking latent loads of all simulated DOAS-1 are found in Appendix C.

On the other hand, since the space humidity control is based on the space latent checking described above and system control method, the simulation results should show the space humidity levels were controlled within recommended levels, which is between

Rh 40% to 60%. Figure 4-10 to Figure 4-12 using Miami as reference to show that during typical cooling operation, humidity control of all DOAS configurations functional. Relative humidity is sensed near return air duct, treated as similar to zone relative humidity. System operating schedule is from 6:00 to 22:00.

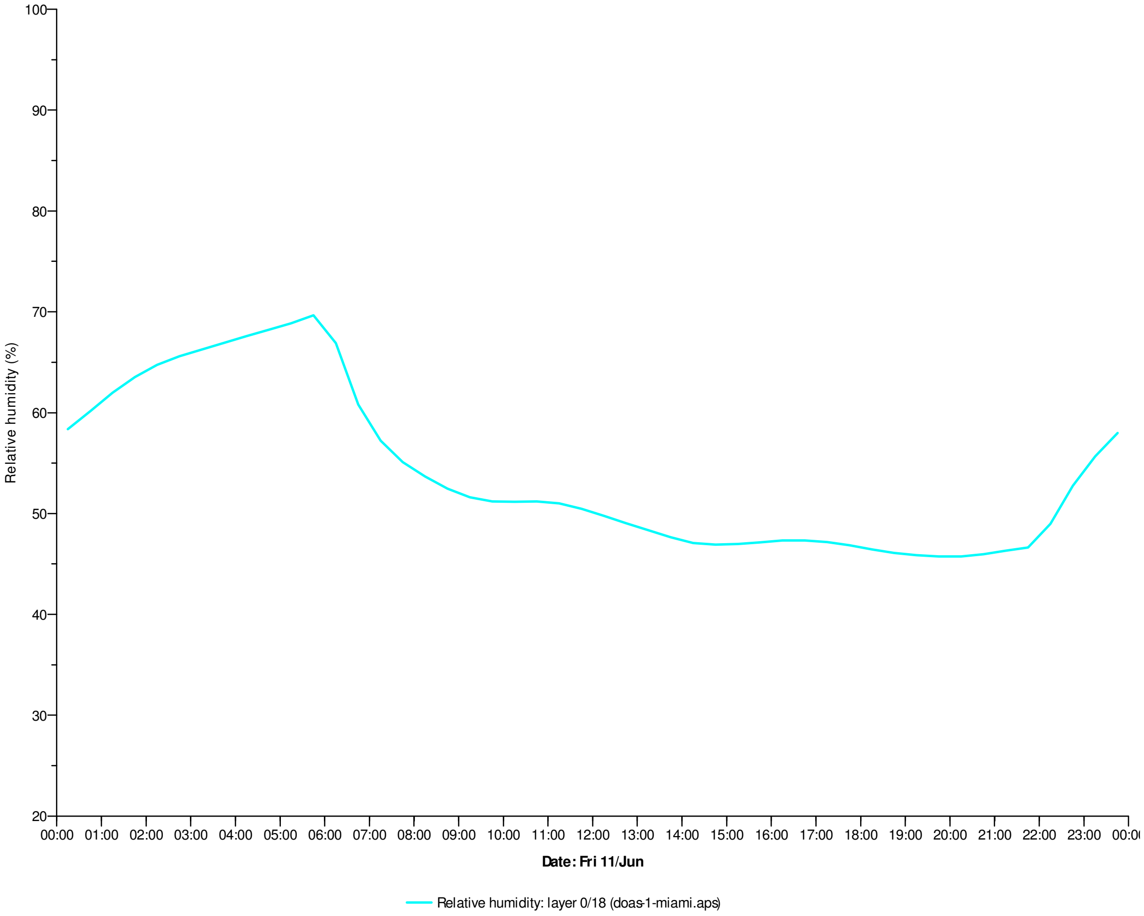


Figure 4-10: DOAS-1 return air humidity level

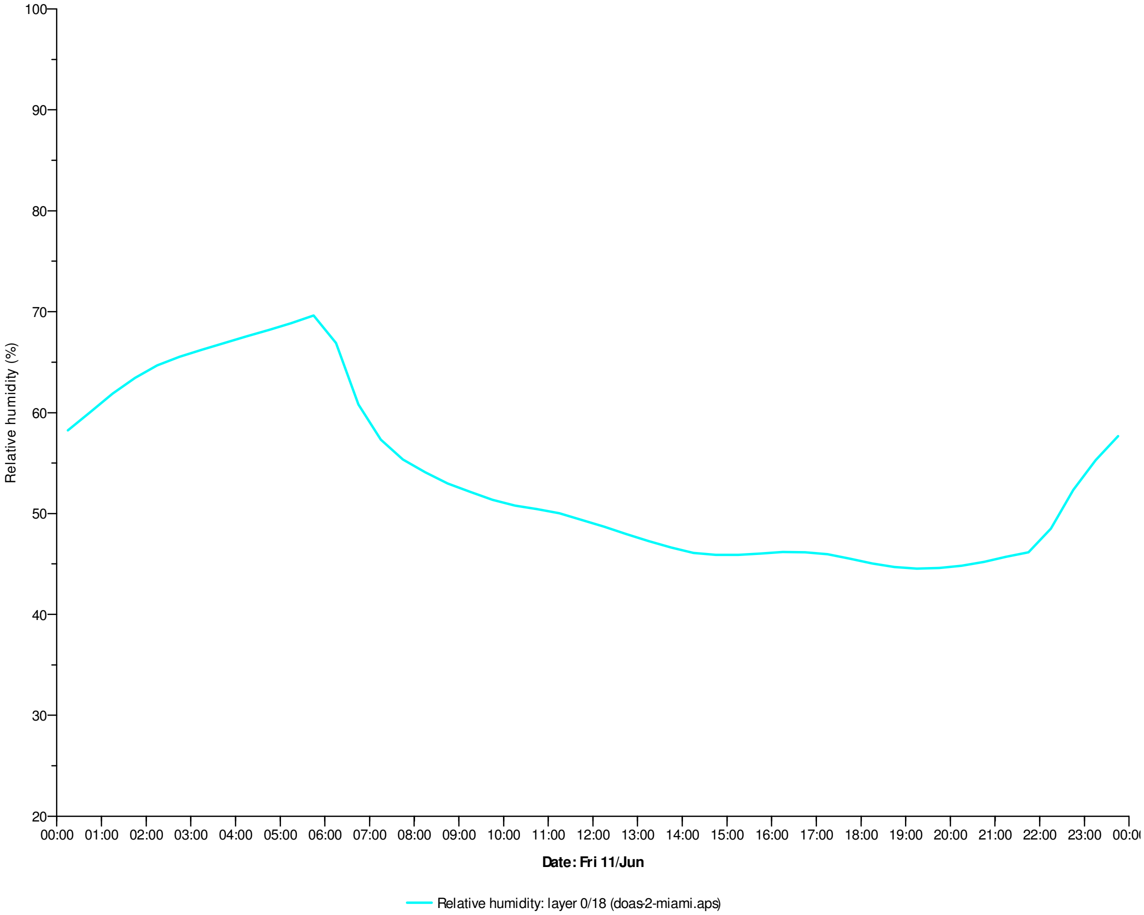


Figure 4-11: DOAS-2 return air humidity level

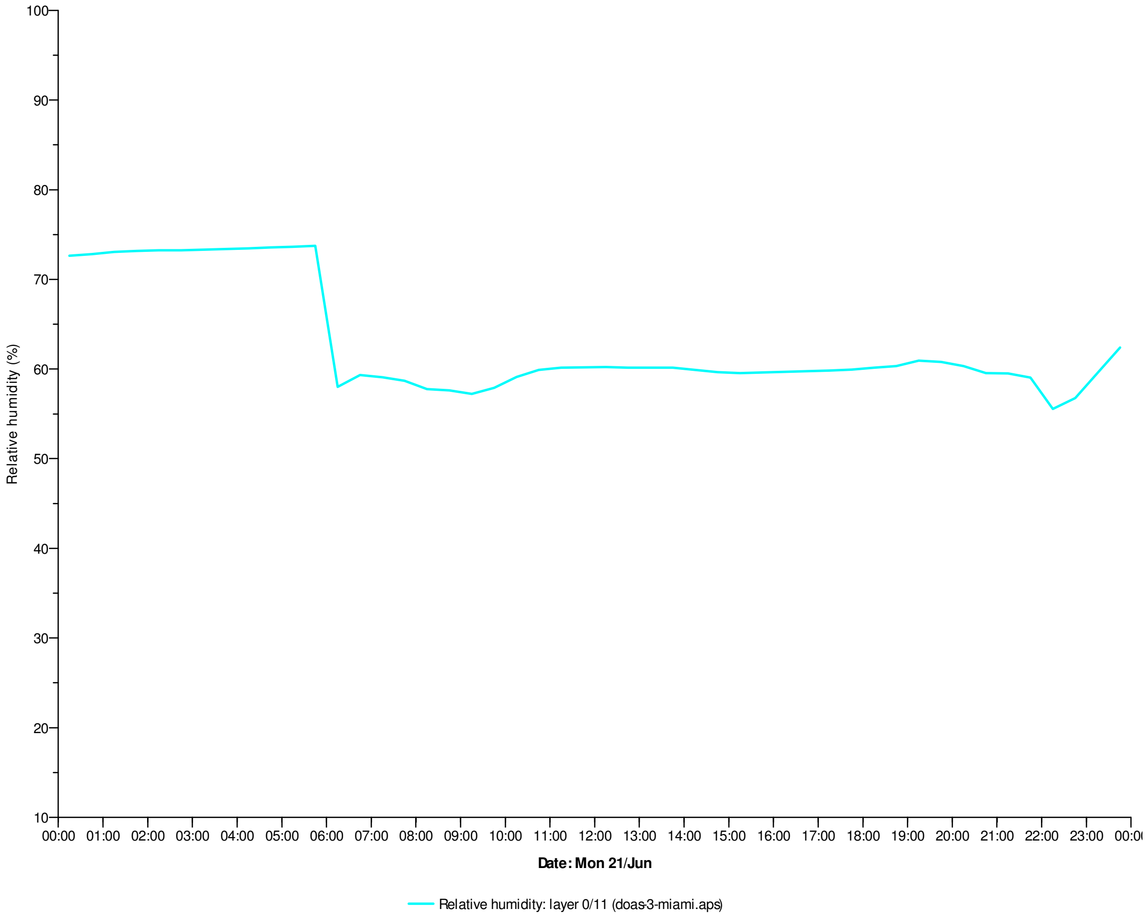


Figure 4-12: DOAS-3 return air humidity level

4.7 DOAS-2 system configuration

DOAS-2 refers to a DOAS where a dedicated OA unit supplies conditioned OA directly to each occupied space while the local HVAC unit maintains the space temperature requirement. DOAS-2 consists of a dedicated OA unit equipped with preheat coil, cooling coil and TER, Fan-coil unit (FCUs) equipped with heating coil and cooling coil serving as the local terminal HVAC unit. DOAS-2 system configuration and system sketch is found in Figure 4-13 and Figure 4-14.

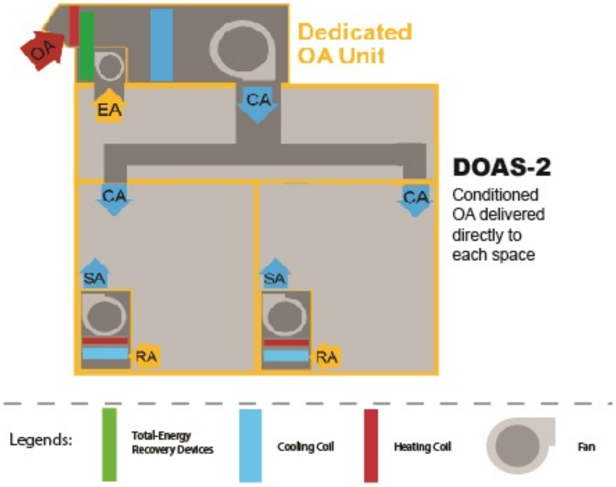


Figure 4-13: DOAS-2 system configuration.

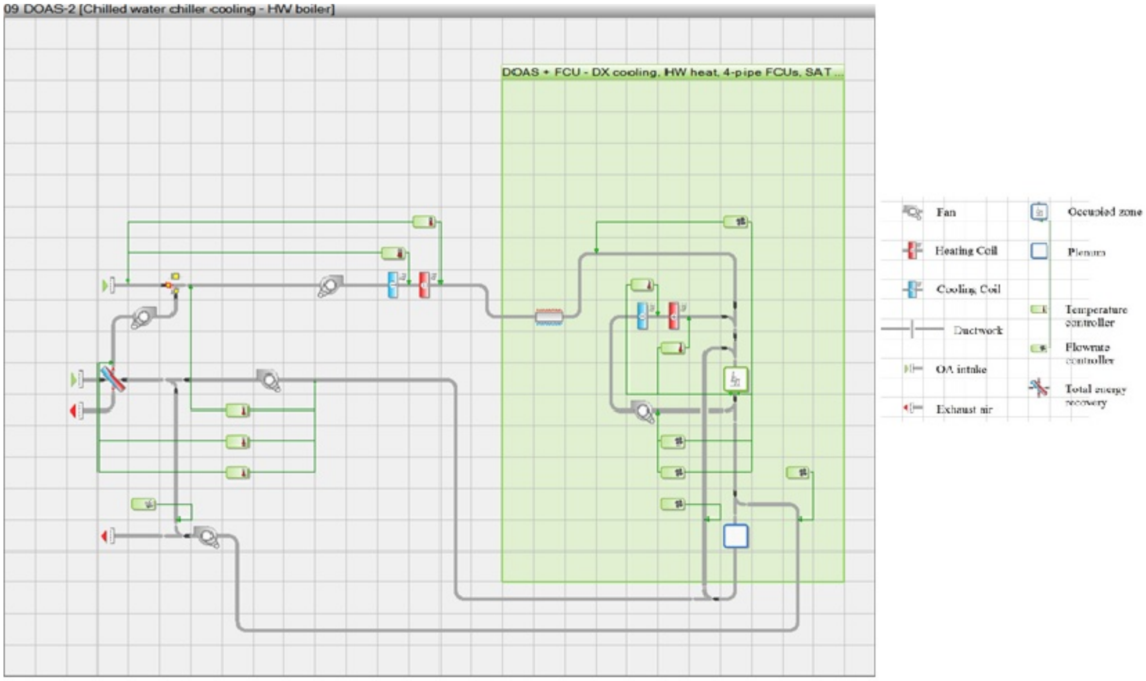


Figure 4-14: DOAS-2 system sketch.

4.7.1 Dedicated OA unit and ventilation airflow control of DOAS-2

A same dedicated OA unit and ventilation airflow control of DOAS-1 were applied to DOAS-2. See section 4.6.1 for details.

4.7.2 Local HVAC unit and components control of DOAS-2

The fan-coil unit (FCU) serves as a local HVAC unit in DOAS-2. A heating coil, cooling coil, and supply air fan are equipped in the FCU. The same heating and cooling sources as heating and cooling coil in a dedicated OA unit are applied. The dedicated OA unit supplied conditioned air directly to each occupied space. The FCU serves as a local HVAC unit to maintain the space temperature setpoint. The local recirculation air was mixed in the FCU with conditioned OA downstream of the FCU.

Even the DOAS-2 supplies the conditioned OA directly to occupied space, control method and local unit components in DOAS-2 were the same as in DOAS-1. See section 4.6.2 for details.

4.7.3 Other components and control of DOAS-2

The system level return air fan in DOAS-2 balances the supply and exhaust air.

A water-side economizer used in the DOAS-2 was the same as in DOAS-1, see section 4.6.3 for details.

4.7.4 Ventilation airflow rate and recirculation airflow rate of DOAS-2

DOAS-2 ventilation airflow and local recirculation airflow calculations were the same as DOAS-1, see section 4.6.4 for details.

4.7.5 Checking space latent loads of DOAS-2

DOAS-2 applied the same procedure of checking latent loads as in DOAS-1 and is found in Appendix C. See section 4.7.5 for details.

4.8 DOAS-3 System Configuration

DOAS-3 refers to a DOAS where a dedicated OA unit supplies conditioned OA directly to each occupied space while active chilled beams serve as a local HVAC unit and maintain the space temperature requirement. DOAS-3 consists of a dedicated OA unit equipped heating coil, cooling coil and TER. The active chilled beams (ACB) are employed to the system as a local terminal HVAC unit. DOAS-3 system configuration and system sketch are found in Figure 4-15 and Figure 4-16.

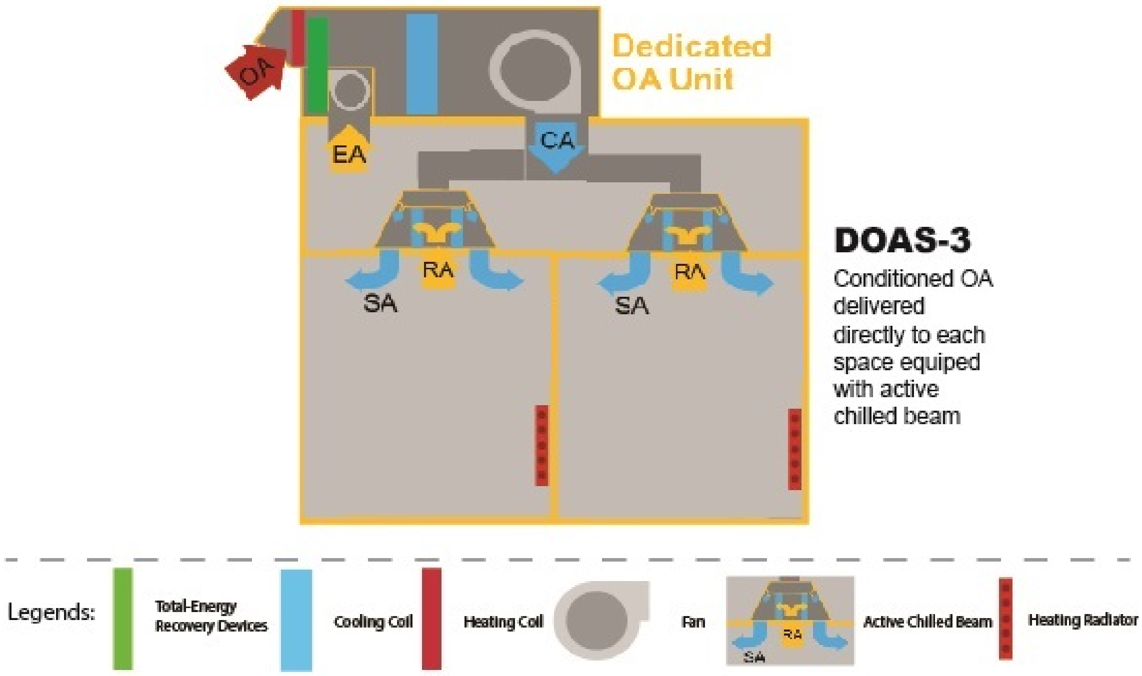


Figure 4-15: DOAS-3 system configuration.

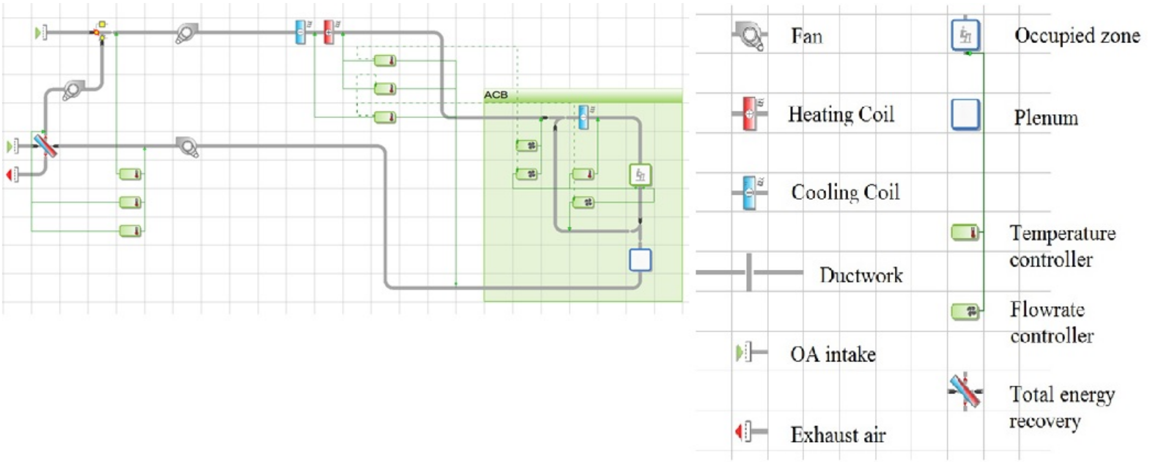


Figure 4-16: DOAS-3 system sketch.

4.8.1 Dedicated OA unit and ventilation controls of DOAS-3

The dedicated OA unit for DOAS-3 consists of a cooling coil supported by a chilled water chiller, a preheat coil and heating coil supported by a boiler, TER, and a supply air fan.

The ventilation, TER, preheat coil, and cooling coil controls of DOAS-3 were the same as in DOAS-1. See section 4.6.1 for details.

The heating coil in DOAS-3 was optional for find-tube heating radiator of each space.

4.8.2 Local HVAC unit and components control of DOAS-3

An active chilled beam is equipped in DOAS-3. Cooling is the only function provided in this kind of ACB.

The ACB controller combined with sensor maintains the occupied space temperature at the setpoint. A sensor is placed at each space return air duct. When the sensed air temperature exceeded the cooling setpoint, the controller sent an on signal to the ACB. The ACB maintained the discharge temperature of induced air at 62°F. The reference for the ACB control method is from the PNNL report. (Thornton et al. 2009) The basic control mode of ACB was the same as local cooling coil control of DOAS-1, see section 4.6.2 for details.

4.8.3 Other components and control of DOAS-3

DOAS-3 used a system level return air fan to balance the supply and exhaust air.

The water-side economizer in DOAS-3 was the same as in DOAS-1, see section

4.6.3 for details.

Since the DOAS-3 ACG employs cooling only, a fine-tube heating radiator was equipped to each occupied space for local heating. The heating radiator is supported by the boiler and maintains the space temperature at the heating setpoint.

4.8.4 Ventilation air flow rate and induced air flow rate of DOAS-3

DOAS is capable of supplying the exact amount of required ventilation air to each occupied room. Thus, the OA from a dedicated OA unit can be sized separately to provide the exact amount of air of each occupied room requires. The recommended ventilation air flow rate is found in benchmark models.

ACB differs from the FCU because the ACB induces the amount of local air proportionally to the ventilation air (primary air as for ACB). DOAS-3 uses the same calculation method applied to as DOAS-1 and DOAS-2: the ACB takes care of the remaining sensible load after the ventilation offset part of the space total sensible load. DOAS-3 uses the same equations as DOAS-2 and DOAS-1. See section 4.6.4 for details. Appendix D shows the induced air calculation for the ACB of DOAS-3.

4.8.5 Checking space latent loads of DOAS-3

DOAS-3 uses the same latent loads check procedure as DOAS-1 and is found in Appendix E. See section 4.6.5 for details.

4.9 System Sizing Procedure

IES applied an automatic system sizing procedure to size the system components.

For the heating and cooling coils, the system sizing is automatic calculated when the entering air and leaving dry bulb air temperatures of coils are defined. The air flow rates (calculated in Appendix B and C) are applied to the auto sizing procedure. Other factors such as the coil contact factor or the over-sizing factor are defined manually. Thus, the heating and cooling coils auto sizing are conducted without any unknown value.

For fans, the system sizing is automatic calculated based on pre-defined air flow rates in Appendix B and C. The Fan characteristic curve (relationship of fan power, flow rate, and motor power) is defined by the prototype fan information collected by IES from major fan manufactures.

Chilled water chillers, boilers, gas furnaces, electric heater, water heater, and DX roof top unit are all sized based on heating coil and cooling coil capacities.

4.10 DOAS Modeling Validation (DOAS Comparison with Previous Study)

Most system control methods for the DOAS configurations simulated in this study come from the PNNL report. Since no DOAS reference building simulation exists for DOE benchmark buildings, the DOAS in the PNNL report is used to compare the simulated DOAS configurations in this study. The comparison result validates the simulated DOAS configurations and makes the all energy usage results from the simulated DOAS configuration comparable. Chicago is the selected location for this comparison.

System cooling, fan, pump, energy recovery, and heating energy usage values of DOAS from the PNNL report were reported as reference DOAS. The same energy usage from simulated DOAS-1 and DOAS-2 were compared to the reference DOAS. Differences from the original DOAS modeling concerned the use of DX cooling instead of the chilled water chiller for system cooling. The reason for this alternation was to reduce the possible differences between the reference and simulated DOAS since DX cooling was applied to the reference DOAS. A gas furnace was applied to heating in the reference DOAS and a boiler was applied to the simulated DOAS. Other than the cooling coil and heating coil, the same model settings were applied to both the reference DOAS and the simulated DOAS. The simulated DOAS-1 and DOAS-2 compare to the reference DOAS named after DOAS-1-DX and DOAS-2-DX.

Comparison shows a slight difference between systems cooling. However, all other comparison components show noticeable differences.

Since the fans applied to the reference DOAS were unknown, the fan energy usage difference cannot be analyzed. The pump and energy recovery in both DOAS are comparable. Since different heating equipment were equipped in the reference DOAS and the simulated DOAS, different heating energy usages are applied.

Overall, the comparison shows the simulated DOAS remains reasonable and can be trusted within this study. Future system modeling may further reduce the simulated DOAS energy usage. However, the results and conclusions may remain the same as in the following chapters.

Reference DOAS and simulated DOAS comparison is found in Table 4-6.

Location: Chicago	**PNNL-19004-DOAS**	**Simulated DOAS-1-DX**	**Simulated DOAS-2-DX**
Building Area (m^2)	5016	4982	4982
System Description	DOAS-FCU, DX cooling, gas furnace, water heater for SHW, Total energy recovery	DOAS-FCU, DX cooling, boiler for heating and SHW, Total energy recovery	DOAS-FCU, DX cooling, boiler for heating and SHW, Total energy recovery
Convert and summary total energy	MMBtu	MMBtu	MMBtu
System energy: Cooling	142	157.585	157.837
System energy: Fan	48	72.381	76.858
System energy: Pump	10	12.229	11.213
System energy: Energy recovery	2	2.185	5.484
System energy: Heating	246	462.756	385.496
System energy: Water Heater	56	0	0
Total HVAC Energy (kBtu)	5.04E+05	7.07E+05	6.37E+05
Total HVAC EUI (kBtu/ft^2)	**9.335**	**13.186**	**11.876**

Table 4-6: DOAS configuration comparison as DOAS validation.

Chapter 5 Simulation Results and Energy Performance Analysis

After the system modeling validations in previous chapters, the energy simulation results for three selected DOAS configurations and baseline system are explained in this chapter. The energy performance of each DOAS configuration is compared to simulated baseline to identify the energy saving potentials of DOAS configurations. Energy performance comparison among each DOAS configuration is also made to examine the DOAS energy performance for a particular climate.

5.1 Simulated Systems Energy Performance

The simulated system energy performance of the simulated baseline, DOAS-1, DOAS-2, and DOAS-3 annual energy usage are found in Table 5-1.

Location/ Unit	Simulated baseline EUI	Simulated DOAS-1 EUI	Simulated DOAS-2 EUI	Simulated DOAS-3 EUI
	kBTU/ft^2	kBTU/ft^2	kBTU/ft^2	kBTU/ft^2
Miami	12.550	10.387	10.237	9.820
Phoenix	10.462	8.671	8.365	8.267
Baltimore	10.893	9.920	9.001	9.530
Albuquerque	10.047	8.204	7.438	7.783
Denver	11.273	10.378	9.423	9.888
Chicago	14.362	13.341	11.998	12.720
Fairbanks	37.425	33.554	32.128	33.444

Table 5-1: Simulated system EUI for various locations.

The energy usage intensity (EUI) is used in this study to describe the system energy performance among different system configurations. The unit for the EUI is kBtu/ft^2.

The simulated system energy performance details for each location is found in Appendix F.

5.1.1 Electricity and Gas Usage

The operating cost for electricity and gas usage vary. Thus, building energy usages are combined into electricity and gas categories. Figure 5-1 shows the system EUI for electricity and gas usage for all the simulated locations.

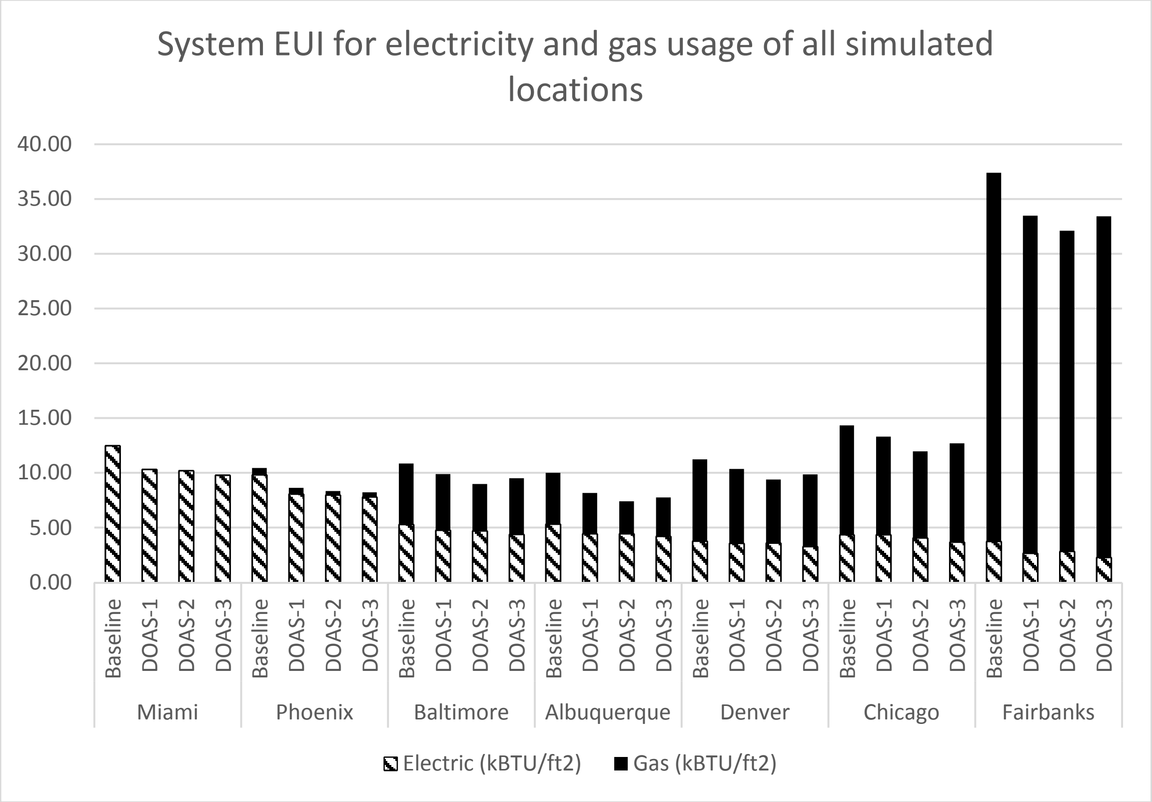


Figure 5-1: System EUI for electricity and gas usage of all simulated locations.

The electricity usage and gas usage are shown in Figure 5-2 and 5-3.

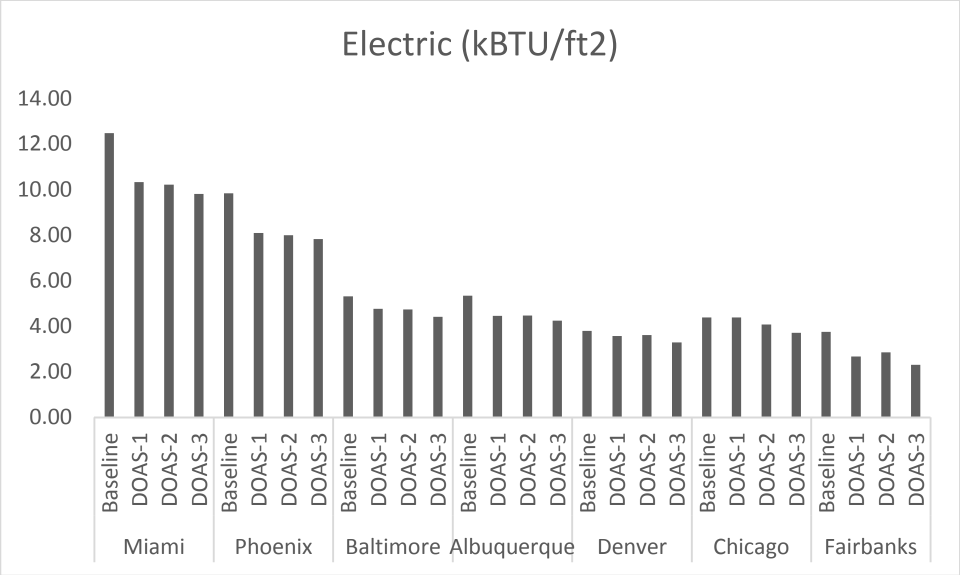


Figure 5-2: System EUI for electricity

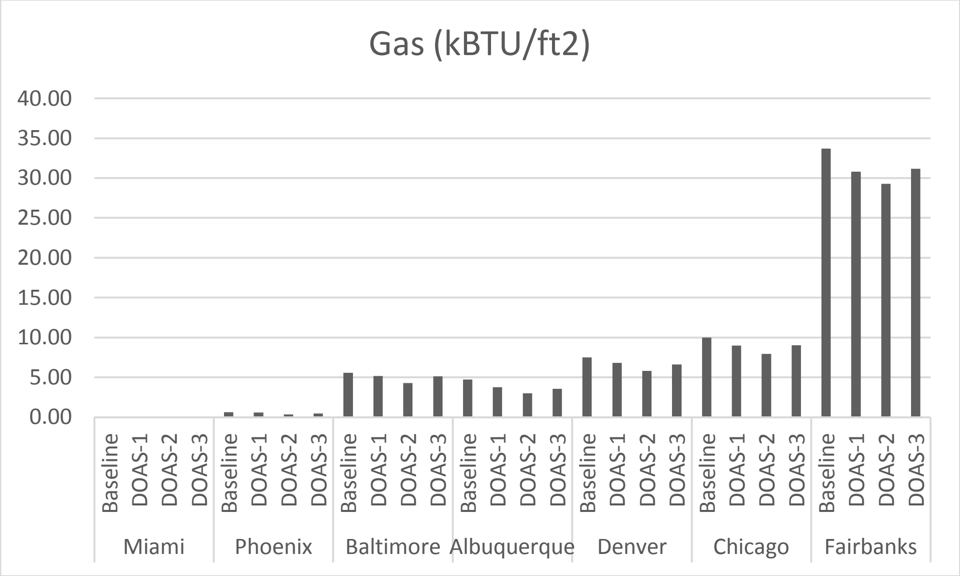


Figure 5-3: System EUI for gas

5.1.2 System EUI Savings compared to Baseline

Each system EUI of DOAS configuration is compared to EUI of simulated baseline. Energy saving of each DOAS configuration is collected. Since the energy saving values of DOAS configurations are low, the energy saving percentages are calculated to show the energy advantage of DOAS configurations. The energy saving percentage is found in Figure 5-4 and defined as:

$$Energy\ saving\ percentage = \frac{(EUI_{baseline} - EUI_{DOAS})}{EUI_{baseline}}\ \% \qquad (5\text{-}1)$$

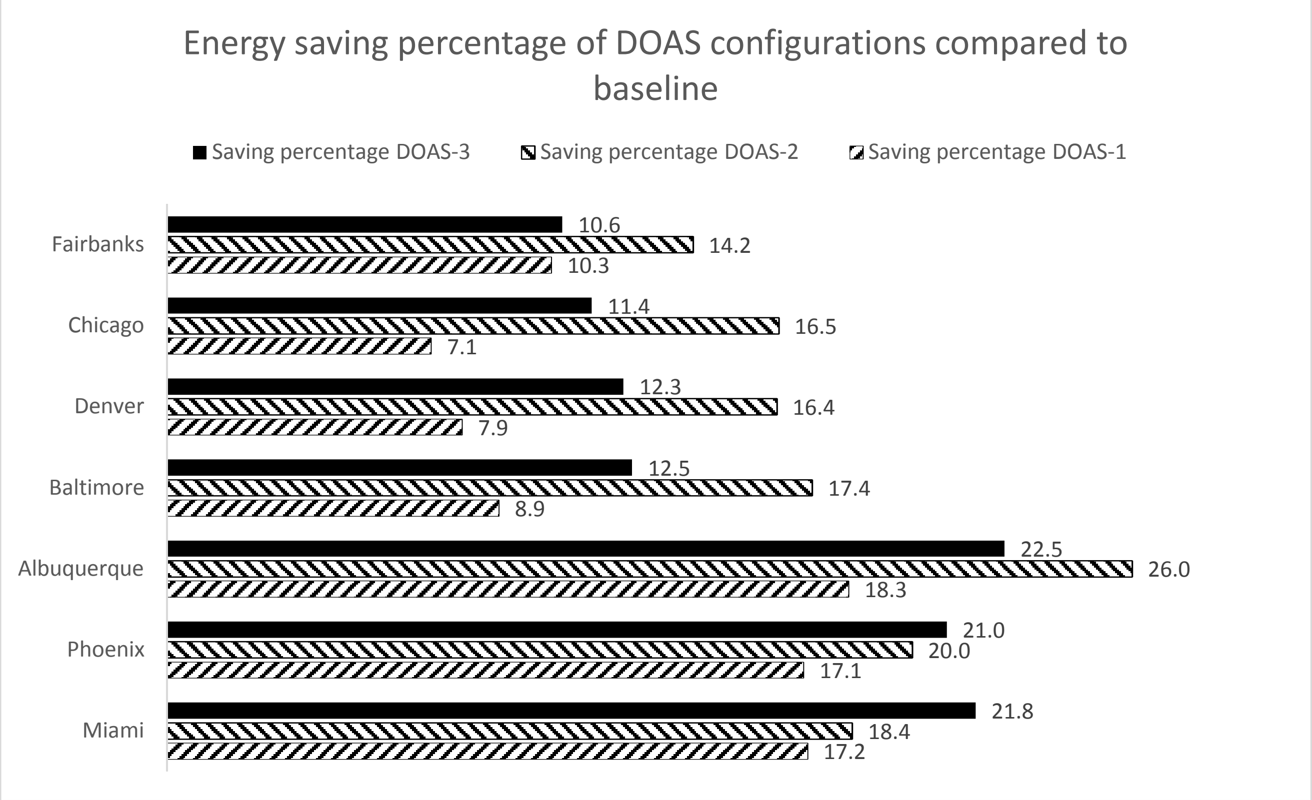


Figure 5-4: Energy saving percentage of DOAS configurations compared to baseline.

The system energy saving percentage comparison shows that all simulated DOAS configurations have energy saving potentials ranging from 7.1% to 26% when compared to the simulated baseline system. However, different energy saving percentage is applied to different DOAS configuration in various locations.

5.2 DOAS Saves Energy when Compared to Simulated Baseline System

The energy simulation results show all DOAS configurations in the various climates save more energy than the simulated baseline system. The energy saving potentials range from 7.1% to 26% and similar to previously documented studies.

The largest energy savings of DOAS uses less ventilation air flow than the baseline system. A VAV with a multi-zone is used as the baseline system. From the equations explained in chapter 4, more than the minimum ventilation air is needed in the baseline system. DOAS supplies the minimum required amount of ventilation to each occupied space. Thus, more cooling energy, heating energy, cooling tower energy, fan energy, and pump energy are required for the baseline system than DOAS. Table 5-2 shown the energy savings of all components of DOAS compared to baseline VAV.

	Unit	Chiller Mbtu	Boiler Mbtu	Fan Mbtu	Pump Mbtu	Cooling tower Mbtu	Energy recovery Mbtu
Fairbanks	VAV	35.4	2113.0	270.4	13.4	32.4	2.3
	DOAS-1	28.7	1652.7	83.0	10.4	19.1	2.4
	DOAS-2	28.4	1570.1	95.1	8.8	18.1	2.4
	DOAS-3	31.9	1670.3	54.1	12.1	22.8	2.3
Chicago	VAV	96.3	535.4	82.4	8.5	45.5	2.0
	DOAS-1	91.8	480.7	89.0	10.7	41.2	2.1
	DOAS-2	91.7	425.0	76.3	8.4	39.8	2.1
	DOAS-3	86.3	483.4	53.2	16.5	40.7	2.0
Denver	VAV	76.0	401.0	84.3	5.8	35.4	2.1
	DOAS-1	77.3	365.1	68.4	6.5	37.0	2.1
	DOAS-2	76.3	312.2	73.7	5.6	35.4	2.1
	DOAS-3	79.3	354.2	52.7	10.2	32.0	2.0

Albuquerque	VAV	118.0	252.6	116.2	9.1	40.9	2.0
	DOAS-1	111.3	201.1	71.6	6.9	47.0	2.0
	DOAS-2	110.5	159.7	75.0	6.0	45.7	2.0
	DOAS-3	115.1	190.2	52.5	15.9	41.8	1.9
Baltimore	VAV	133.0	299.1	87.4	9.4	53.3	2.0
	DOAS-1	121.8	276.5	70.3	11.5	49.9	2.0
	DOAS-2	121.0	229.2	73.7	8.8	48.0	2.0
	DOAS-3	114.5	274.3	52.6	18.8	48.8	1.9
Phoenix	VAV	262.4	33.3	163.6	13.7	86.0	2.0
	DOAS-1	243.2	30.9	91.6	16.1	81.0	2.0
	DOAS-2	242.7	19.4	90.5	13.5	80.4	2.0
	DOAS-3	250.0	23.8	53.5	28.6	85.4	2.0
Miami	VAV	372.3	3.4	155.8	18.3	121.6	1.7
	DOAS-1	338.4	3.0	87.2	22.1	104.7	1.5
	DOAS-2	338.8	1.1	85.2	17.4	104.9	1.5
	DOAS-3	313.4	0.7	53.4	46.2	111.0	1.9

Table 5-2: DOAS components energy usage

Since the DOAS uses a separate unit to condition ventilation air, using of local HVAC unit with high efficiency, such as ACB, is possible. When compared to baseline system, the increased overall system efficiency provides an energy saving potential for DOAS.

Besides the energy saving benefits shown in Table 5-1 and Figure 5-2, DOAS provides other benefits when compared to the baseline system. Such as exact the amount of required ventilation to deliver to each occupied space, system savings reduction, more accurate humidity controls, and selection freedom of the local unit. These benefits are not shown on the energy simulation results; however, these all achieved by employing DOAS configurations.

5.3 DOAS-3: Outstanding Energy Performance in Extreme Hot Climates

DOAS-3 configuration shows the best energy saving potential compared to the other simulated DOAS configurations in the simulated locations that experience an extreme hot summer.

Active chilled beams are applied to DOAS-3 as the local HVAC unit. When compared to the chilled water cooling coil, ACB generally have higher overall system cooling efficiency. The system cooling energy usage of ACB is lower than that of the chilled water cooling coil employed by DOAS-1 and DOA-2 when the same amount of cooling loads are applied to system. Figure 5-5 shown the slightly benefits of cooling energy of using ACB. Especially in extreme hot locations.

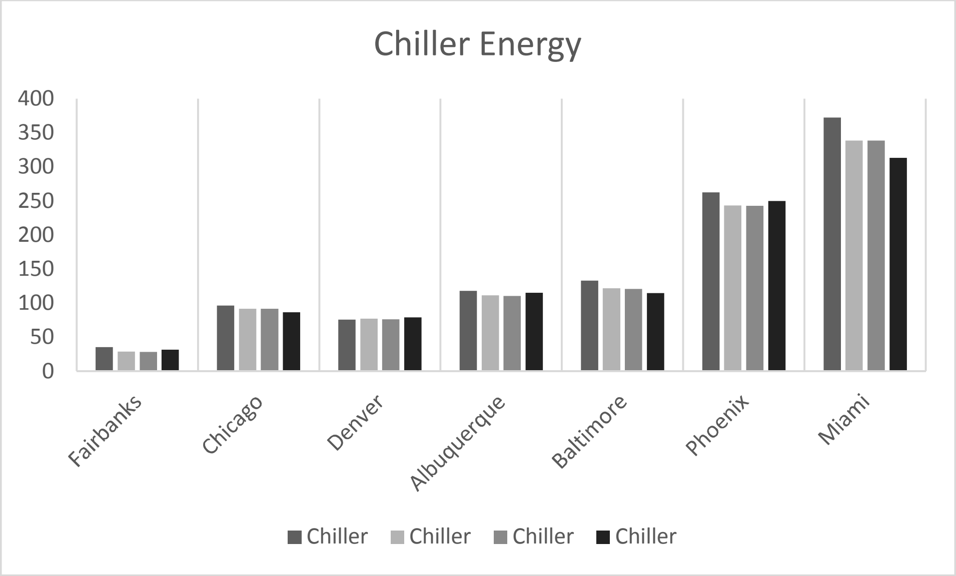


Figure 5-5: Chiller energy usage comparison

Furthermore, ACB usually consumes much less fan energy than an all air system, thus, reduced fan energy consumption is attached to overall system energy usage of DOAS-3. Figure 5-6 shown the fan energy reduction of employing ACB.

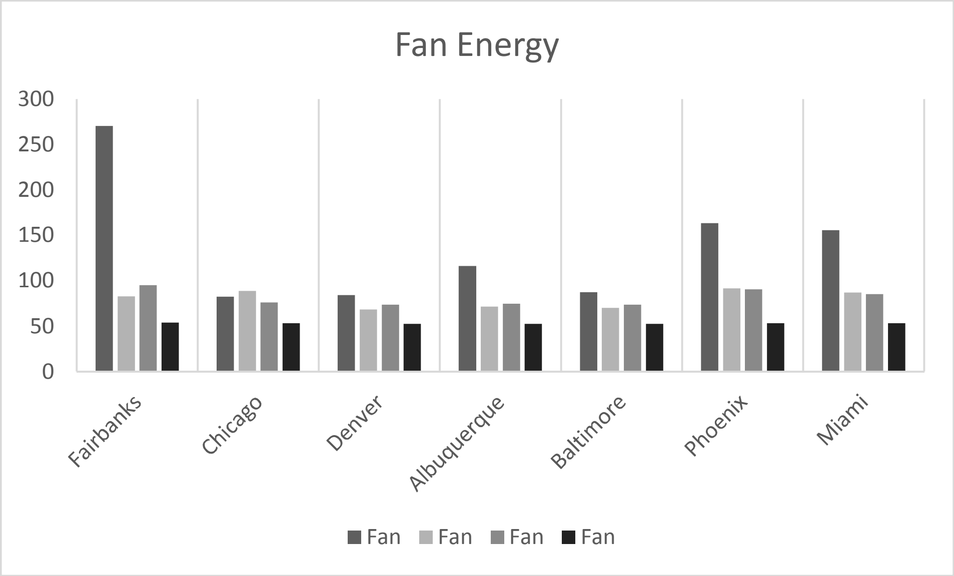


Figure 5-6: Fan energy usage comparison

However, pump energy usages of ACB are usually higher than in all air systems. This is because ACB using much more cold water than all air system. Figure 5-7 shown the pump energy usage of ACB.

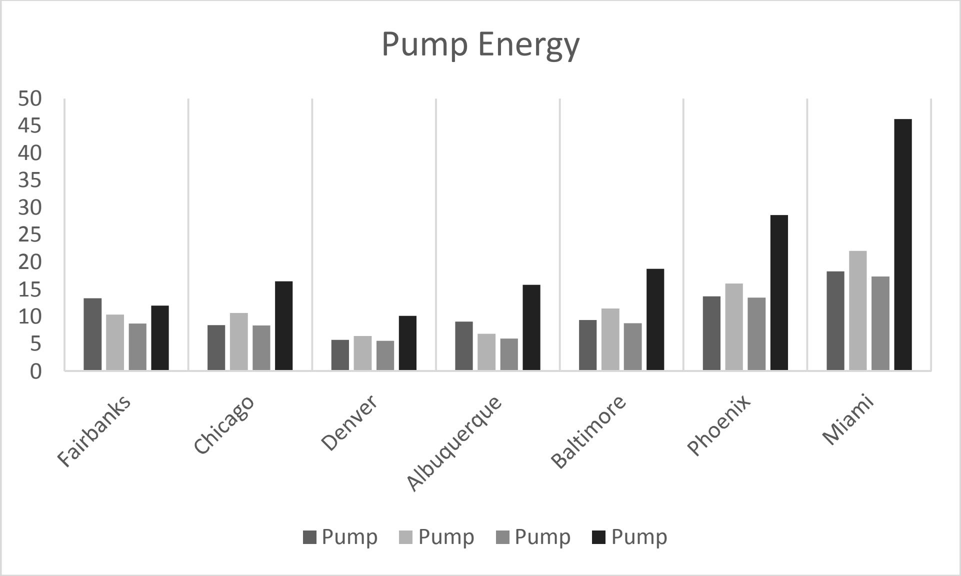


Figure 5-7: Pump energy usage comparison

When summary chiller, fan, and pump (even some of fan and pump energy are used for heating) energy usage of all simulated systems in various climates together, the results still shows that the DOAS-3 has the most energy savings compared to DOAS-1 and DOAS-2. Thus, when only comparing the cooling function, DOAS-3 has the most energy savings. Figure 5-8 shown the energy savings on cooling of DOAS-3.

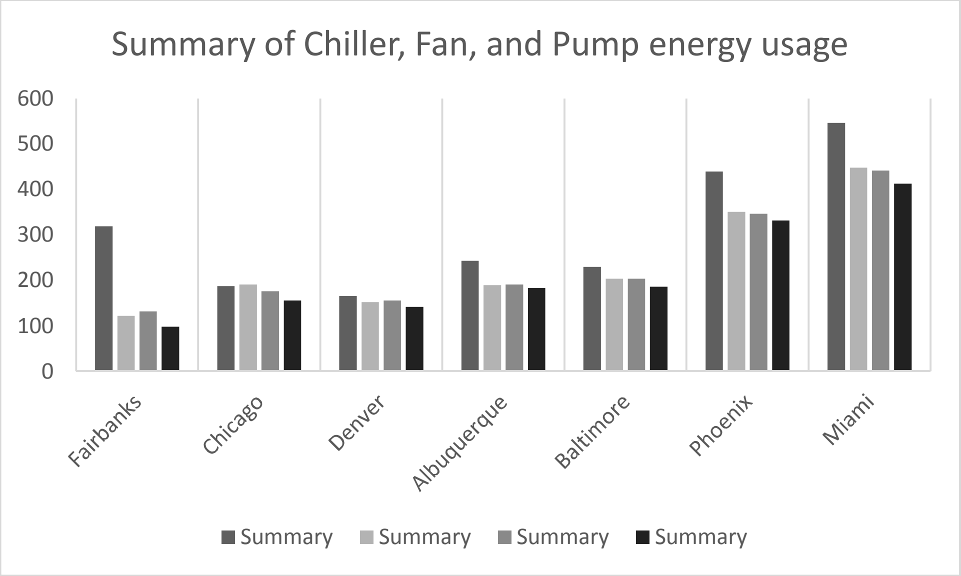


Figure 5-8: Cooling energy saving of DOAS-3

However, as shown in Figure 5-2, the DOAS-3 energy saving percentage decreases when decreased summer cooling loads are applied to one location. In extremely hot locations, such as Miami or Phoenix, DOAS-3 shows the best energy saving potential when compared to all other simulated systems. However, less energy saving percentages are shown when the location becomes colder and colder.

The reason for this trend is that only a very small amount of heating energy is required in extreme hot climate locations. Thus, the energy saving potential for ACB in DOAS-3 is amplified since the major energy saving potentials of systems in such locations is energy savings in cooling operation. On the other hand, as shown in Figure 5-1, the system required heating energy increased dramatically when locations change from Miami to colder locations. Thus, the major energy saving potentials of the system shifts from cooling to heating. The advantages of employing ACB no longer show major significance.

5.4 DOAS-2: Superior to DOAS-1 in All Simulated Locations

DOAS-2 uses the same DOAS unit and local HVAC unit as DOAS-1. The only difference between this two system configurations is DOAS-1 supplies the conditioned OA to a local HVAC unit while DOAS-2 supplies the conditioned OA directly to each occupied space. Thus, the EUI difference between DOAS-1 and DOAS-2 provides an indication about the locations where conditioned OA is supplied.

The results from simulations suggest that DOAS-2 always save more energy than DOAS-1 in all simulated locations. However, advantages of DOAS-2 are bigger when the system is not applied to an extreme hot location.

The noticeable system energy usage related advantages of DOAS-2 when compared to DOAS-1 in this study are the less airflow applied to DOAS-2 configuration. The DOAS-1 supplies the conditioned OA to intake of each local unit while DOAS-2 supplying the conditioned OA to each occupied space. Thus, OA in DOAS-1 will be mixed with local recirculation air, then go through the local unit. This brings more air for local unit in DOAS-1. Table 5-3 shown the DOAS-1 has bigger local unit airflow rate than DOAS-2.

	DOAS-1	DOAS-2	Difference
Unit/Location	10763 ft^3	10763 ft^3	%
Miami	145679.8	99801.69	31.49
Phoenix	151440.5	107007.3	29.34
Albuquerque	118888.6	81816.43	31.18

Baltimore	116633.7	79589.67	31.76
Denver	113193.3	79272.23	29.97
Chicago	126963	83538.27	34.20
Fairbanks	135938.3	113365.4	16.61

Table 5-3: DOAS-2 use less local recirculation air than DOAS-1

Since the less local recirculation air is used in DOAS-2, the local fan energy applied to DOAS-2 is less than local fan energy usage in DOAS-1. Furthermore, the pressure drop of local unit of DOAS-2 is less than DOAS-1 since less airflow is required.

Besides, this is possible that the chilled water temperature which entering the DOAS-2 local unit is higher (or lower during heating). (Mumma 2008) Combined with less local recirculation airflow and lower chilled water entering temperature, energy usage of DOAS-2 is lower than DOAS-1.

Chapter 6 Conclusion and Future Work

Suggestions and conclusions are made in this chapter based on the system energy performance results and analysis from the previous chapter. However, future works are still needed for more general conclusions.

6.1 Conclusion

The simulation results in this study suggest that simulated DOAS configurations have system energy saving potentials ranging from 7.1% to 26% when compared to the simulated baseline system in all simulated climates. However, the DOAS-3 configuration is recommended in locations that experience extremely hot summer. The DOAS-2 configuration is recommended for all simulated locations when compared to the DOAS-1 configuration.

Thus, engineers, who are interested in employing DOAS may consider using active chilled beams if the project location experiences extremely hot summers, such as Miami and Phoenix. DOAS with ACB in mild or colder climates may not save as much energy as locations with an extremely hot summer.

Consider supplying the conditioned outdoor air directly to each occupied space. All the simulated locations show advanced energy savings using this configuration when compared to supplying conditioned outdoor air to intakes of a local unit.

6.2 Future Work

This study only presented the conclusions based on the selected DOAS configurations in selected climates. A larger scope for future works is suggested.

First, only three selected DOAS configurations are simulated in this study. By identifying and employing other DOAS configurations, more conclusions can be made in the future.

Secondly, sizing the DOAS units in this research are based on the sensible loads of the buildings and the ventilation requirements from ASHRAE Standard-62.1. Even though latent loads checks are conducted in this study to make sure the space humidity levels remain within acceptable levels, there is a possibility for a very different energy performance when sizing DOAS units is based on total building latent load. (Murphy 2010)

Thirdly, only seven climate locations were simulated. More simulation results could be done for more general conclusions.

Finally, the first costs and operating costs (such as, utility costs, maintenance costs) of these HVAC systems are not analyzed in this study, which is important in any design process.

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Appendix – A: Simulated Baseline VAV Outdoor Air Calculations

		ZONE LEVEL-Miami														
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	**470**	**590**	**652**	**768**	**840**	**900**	**492**	**604**	**706**	**61**	**723**	**717**	**2482**	**2499**	**2573**
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	117.5	147.5	163	192	210	225	123	151	176.5	15.25	180.75	179.25	620.5	624.75	643.25
Zp	Primary outdoor air fraction, Voz/Vpzm	0.75	0.60	0.54	0.29	0.27	0.25	0.72	0.59	0.50	3.68	0.31	0.31	0.68	0.67	0.65
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az,	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.14	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	3.68														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**28%**	= Vot/Sum of Vpz											
	Cooling Max	**470**	**590**	**652**	**768**	**840**	**900**	**492**	**604**	**706**	**61**	**723**	**717**	**2482**	**2499**	**2573**
	Cooling Min	**117.5**	**147.5**	**163**	**192**	**210**	**225**	**123**	**151**	**176.5**	**15.25**	**180.75**	**179.25**	**620.5**	**624.75**	**643.25**
	Heating Max	**95**	**126**	**168**	**63**	**84**	**110**	**92**	**124**	**167**	**63**	**84**	**110**	**0**	**101**	**284**

Table A-0-1: Miami simulated baseline VAV outdoor air calculation

		ZONE LEVEL-Phoenix														
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	614	819	897	832	957	1042	498	693	833	655	803	810	2243	2632	2763
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	153.5	204.75	224.25	208	239.25	260.5	124.5	173.25	208.25	163.75	200.75	202.5	560.75	658	690.75
Zp	Primary outdoor air fraction, Voz/Vpzm	0.58	0.43	0.40	0.27	0.23	0.22	0.71	0.51	0.43	0.34	0.28	0.28	0.75	0.64	0.61
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az.	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.12	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	0.75														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**25%**	= Vot/Sum of Vpz											
	Cooling Max	**614**	**819**	**897**	**832**	**957**	**1042**	**498**	**693**	**833**	**655**	**803**	**810**	**2243**	**2632**	**2763**
	Cooling Min	**153.5**	**204.75**	**224.25**	**208**	**239.25**	**260.5**	**124.5**	**173.25**	**208.25**	**163.75**	**200.75**	**202.5**	**560.75**	**658**	**690.75**
	Heating Max	**170**	**177**	**235**	**114**	**118**	**155**	**169**	**176**	**234**	**113**	**117**	**154**	**141**	**156**	**411**

Table A-0-2: Phoenix simulated baseline VAV outdoor air calculation

		ZONE LEVEL-Baltimore														
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	489	645	713	797	898	963	420	551	648	644	765	756	2395	2536	2600
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	122.25	161.25	178.25	199.25	224.5	240.75	105	137.75	162	161	191.25	189	598.75	634	650
Zp	Primary outdoor air fraction, Voz/Vpzm	0.73	0.55	0.50	0.28	0.25	0.23	0.84	0.64	0.55	0.35	0.29	0.30	0.70	0.66	0.65
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az.	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.13	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	0.84														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**27%**	= Vot/Sum of Vpz											
	Cooling Max	**489**	**645**	**713**	**797**	**898**	**963**	**420**	**551**	**648**	**644**	**765**	**756**	**2395**	**2536**	**2600**
	Cooling Min	**122.25**	**161.25**	**178.25**	**199.25**	**224.5**	**240.75**	**105**	**137.75**	**162**	**161**	**191.25**	**189**	**598.75**	**634**	**650**
	Heating Max	**223**	**243**	**338**	**148**	**161**	**221**	**220**	**240**	**336**	**149**	**161**	**221**	**156**	**218**	**642**

Table A-0-3: Baltimore simulated baseline VAV outdoor air calculation

		ZONE LEVEL-Albuqueque														
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	468	654	710	878	1010	1071	403	587	664	653	805	759	2590	2835	2692
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	117	163.5	177.5	219.5	252.5	267.75	100.75	146.75	166	163.25	201.25	189.75	647.5	708.75	673
Zp	Primary outdoor air fraction, Voz/Vpzm	0.76	0.54	0.50	0.26	0.22	0.21	0.88	0.60	0.53	0.34	0.28	0.30	0.65	0.59	0.63
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az,	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.13	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	0.88														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**25%**	= Vot/Sum of Vpz											
	Cooling Max	**468**	**654**	**710**	**878**	**1010**	**1071**	**403**	**587**	**664**	**653**	**805**	**759**	**2590**	**2835**	**2692**
	Cooling Min	**117**	**163.5**	**177.5**	**219.5**	**252.5**	**267.75**	**100.75**	**146.75**	**166**	**163.25**	**201.25**	**189.75**	**647.5**	**708.75**	**673**
	Heating Max	**247**	**261**	**363**	**163**	**172**	**237**	**242**	**256**	**360**	**163**	**172**	**237**	**205**	**244**	**701**

Table A-0-4: Albuquerque simulated baseline VAV outdoor air calculation

	ZONE LEVEL-Chicago															
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	484	656	697	763	872	931	405	571	633	610	745	737	2393	2623	2644
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	121	164	174.25	190.75	218	232.75	101.25	142.75	158.25	152.5	186.25	184.25	598.25	655.75	661
Zp	Primary outdoor air fraction, Voz/Vpzm	0.73	0.54	0.51	0.29	0.26	0.24	0.88	0.62	0.56	0.37	0.30	0.30	0.70	0.64	0.64
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az,	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.14	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	0.88														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**27%**	= Vot/Sum of Vpz											
	Cooling Max	**484**	**656**	**697**	**763**	**872**	**931**	**405**	**571**	**633**	**610**	**745**	**737**	**2393**	**2623**	**2644**
	Cooling Min	**121**	**164**	**174.25**	**190.75**	**218**	**232.75**	**101.25**	**142.75**	**158.25**	**152.5**	**186.25**	**184.25**	**598.25**	**655.75**	**661**
	Heating Max	**280**	**303**	**429**	**185**	**201**	**281**	**276**	**300**	**427**	**186**	**201**	**280**	**180**	**249**	**806**

Table A-0-5: Chicago simulated baseline VAV outdoor air calculation

		ZONE LEVEL-Denver														
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	436	625	665	822	952	997	373	554	606	601	751	695	2570	2872	2579
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	109	156.25	166.25	205.5	238	249.25	93.25	138.5	151.5	150.25	187.75	173.75	642.5	718	644.75
Zp	Primary outdoor air fraction, Voz/Vpzm	0.81	0.57	0.53	0.27	0.24	0.23	0.95	0.64	0.59	0.37	0.30	0.32	0.65	0.59	0.65
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az.	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.13	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	0.95														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**26%**	= Vot/Sum of Vpz											
	Cooling Max	**436**	**625**	**665**	**822**	**952**	**997**	**373**	**554**	**606**	**601**	**751**	**695**	**2570**	**2872**	**2579**
	Cooling Min	**109**	**156.25**	**166.25**	**205.5**	**238**	**249.25**	**93.25**	**138.5**	**151.5**	**150.25**	**187.75**	**173.75**	**642.5**	**718**	**644.75**
	Heating Max	**300**	**319**	**455**	**200**	**212**	**299**	**297**	**317**	**454**	**199**	**211**	**298**	**219**	**275**	**881**

Table A-0-6: Denver simulated baseline VAV outdoor air calculation

ZONE LEVEL-Fairbanks																
	Zones served by system	**1-S**	**2-S**	**3-S**	**1-E**	**2-E**	**3-E**	**1-N**	**2-N**	**3-N**	**1-W**	**2-W**	**3-W**	**1-I**	**2-I**	**3-I**
	Space type	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac	Office spac
Az	Floor area of zone, m2	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	207.3375	207.3375	207.3375	131.2579	131.2579	131.2579	983.5366	983.5366	983.5366
Pz	Zone population, largest # of people expected to occupy zone	10.6	10.6	10.6	6.71	6.71	6.71	10.6	10.6	10.6	6.71	6.71	6.71	50.29	50.29	50.29
Rp	People outdoor air rate from Table 6.1, L/s-person	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Ra	Area outdoor air rate from Table 6.1, L/s-m2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Pz*Rp		26.5	26.5	26.5	16.775	16.775	16.775	26.5	26.5	26.5	16.775	16.775	16.775	125.725	125.725	125.725
Az*Ra		62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	62.20125	62.20125	62.20125	39.37737	39.37737	39.37737	295.061	295.061	295.061
Ez	Zone air distribution effectiveness, Table 6.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Voz	Outdoor airflow to the zone corrected for zone air distribution effectiveness, (Pz*Rp + Az*Ra)/Ez, L/s	89	89	89	56	56	56	89	89	89	56	56	56	421	421	421
Vpz	Primary airflow to zone from air handler. **In VAV systems, use the design value.** L/s	1404	1723	1701	1016	1207	1215	462	754	744	888	1109	1082	2041	3093	3072
Vpzm	The minimum value of the primary airflow to zone from air handler. **In CAV systems, Vpzm = Vpz.** L/s	351	430.75	425.25	254	301.75	303.75	115.5	188.5	186	222	277.25	270.5	510.25	773.25	768
Zp	Primary outdoor air fraction, Voz/Vpzm	0.25	0.21	0.21	0.22	0.19	0.18	0.77	0.47	0.48	0.25	0.20	0.21	0.82	0.54	0.55
SYSTEM LEVEL																
Ps	System population, maximum simultaneious # of occupants of space served by system	254.73														
D	Occupant diversity, ratio of system peak occupancy to sum of space peak occupancies, = Ps/ΣPz	1.00														
Vou	Uncorrected outdoor air intake, = D*ΣRp*Pz +ΣRa*Az,	2131														
Xs	Mixing ratio at primary air handler of uncorrected outdoor air intake to system primary flow, = Vou/Vps	0.10	Not used in calculation													
SYSTEM EFFICIENCY																
Max Zp	Max Zp	0.82														
Ev	System ventilation efficiency, Table 6.3 based on maxZp	0.50														
				Percent outdoor air intake												
Vot	**Minimum outdoor air intake, Vou/Ev, L/s**	**4263**		**20%**	= Vot/Sum of Vpz											
	Cooling Max	**1404**	**1723**	**1701**	**1016**	**1207**	**1215**	**462**	**754**	**744**	**888**	**1109**	**1082**	**2041**	**3093**	**3072**
	Cooling Min	**351**	**430.75**	**425.25**	**254**	**301.75**	**303.75**	**115.5**	**188.5**	**186**	**222**	**277.25**	**270.5**	**510.25**	**773.25**	**768**
	Heating Max	**383**	**400**	**585**	**253**	**264**	**381**	**378**	**395**	**582**	**253**	**264**	**381**	**265**	**321**	**1158**

Table A-0-7: Fairbanks simulated baseline VAV outdoor air calculation

Appendix – B: DOAS-1 and DOAS-2 Local HVAC Unit Sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*8606*	29365	*4481*	15290	75	55	62	95	106	1335	524	673	**212**	1.1
Second-S	*10790*	36817	*5986*	20425	75	55	62	95	106	1674	684	860	**300**	1.1
Third-S	*11936*	40727	*7960*	27161	75	55	62	95	106	1851	768	1104	**415**	1.1
First-W	*14062*	47982	*2973*	10144	75	55	62	95	67	2181	962	443	**142**	1.1
Second-W	*15374*	52458	*3955*	13495	75	55	62	95	67	2384	1058	565	**199**	1.1
Third-W	*16469*	56195	*5216*	17798	75	55	62	95	67	2554	1138	721	**273**	1.1
First-N	*8997*	30699	*4334*	14788	75	55	62	95	106	1395	553	655	**203**	1.1
Second-N	*11059*	37735	*5886*	20084	75	55	62	95	106	1715	703	847	**294**	1.1
Third-N	*12925*	44102	*7891*	26925	75	55	62	95	106	2005	840	1096	**411**	1.1
First-E	*11724*	40004	*2999*	10233	75	55	62	95	67	1818	791	446	**143**	1.1
Second-E	*13241*	45180	*3967*	13536	75	55	62	95	67	2054	902	566	**200**	1.1
Third-E	*13117*	44757	*5217*	17801	75	55	62	95	67	2034	893	721	**273**	1.1
First-I	*45426*	154998	*0*	0	75	55	62	95	503	7045	2822	554	**-241**	1.1
Second-I	*50643*	172803	*4778*	16303	75	55	62	95	503	7855	3204	1147	**38**	1.1
Third-I	*51991*	177399	*13441*	45863	75	55	62	95	503	8064	3303	2222	**546**	1.1

Table B-0-1: Miami DOAS-1 and DOAS-2 local unit sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*10802*	36858	*7755*	26461	75	55	62	95	106	1675	685	1079	**403**	1.1
Second-S	*14398*	49128	*8054*	27481	75	55	62	95	106	2233	948	1116	**421**	1.1
Third-S	*15771*	53813	*10669*	36404	75	55	62	95	106	2446	1048	1441	**574**	1.1
First-W	*14626*	49906	*5171*	17644	75	55	62	95	67	2268	1003	716	**271**	1.1
Second-W	*16834*	57440	*5377*	18347	75	55	62	95	67	2611	1165	741	**283**	1.1
Third-W	*18321*	62514	*7032*	23994	75	55	62	95	67	2842	1274	946	**380**	1.1
First-N	*8763*	29901	*7692*	26246	75	55	62	95	106	1359	535	1071	**400**	1.1
Second-N	*12179*	41556	*8017*	27355	75	55	62	95	106	1889	785	1112	**419**	1.1
Third-N	*14649*	49984	*10651*	36343	75	55	62	95	106	2272	966	1438	**573**	1.1
First-E	*11517*	39298	*5131*	17508	75	55	62	95	67	1786	776	711	**268**	1.1
Second-E	*14112*	48152	*5331*	18190	75	55	62	95	67	2189	966	735	**280**	1.1
Third-E	*14247*	48613	*6987*	23841	75	55	62	95	67	2210	976	941	**377**	1.1
First-I	*39429*	134537	*6411*	21875	75	55	62	95	503	6115	2383	1350	**134**	1.1
Second-I	*51007*	174043	*7093*	24202	75	55	62	95	503	7911	3231	1434	**174**	1.1
Third-I	*53282*	181806	*18695*	63790	75	55	62	95	503	8264	3397	2874	**853**	1.1

Table B-0-2: Phoenix DOAS-1 and DOAS-2 local unit sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*8893*	30344	*10517*	35885.494	75	55	62	95	106	1379	545	1422	**565**	1.1
Second-S	*11740*	40059	*11432*	39007.603	75	55	62	95	106	1821	753	1535	**619**	1.1
Third-S	*12979*	44286	*15940*	54389.538	75	55	62	95	106	2013	844	2095	**883**	1.1
First-W	*14501*	49479	*6967*	23772.391	75	55	62	95	67	2249	994	938	**376**	1.1
Second-W	*16348*	55782	*7563*	25806.027	75	55	62	95	67	2536	1130	1012	**411**	1.1
Third-W	*17535*	59832	*10419*	35551.104	75	55	62	95	67	2720	1216	1367	**578**	1.1
First-N	*7643*	26079	*10359*	35346.375	75	55	62	95	106	1185	453	1402	**556**	1.1
Second-N	*10821*	36923	*11299*	38553.788	75	55	62	95	106	1678	686	1519	**611**	1.1
Third-N	*11798*	40256	*15846*	54068.796	75	55	62	95	106	1830	758	2083	**877**	1.1
First-E	*11719*	39987	*7007*	23908.876	75	55	62	95	67	1818	791	943	**378**	1.1
Second-E	*13928*	47524	*7587*	25887.919	75	55	62	95	67	2160	952	1015	**412**	1.1
Third-E	*13765*	46968	*10431*	35592.049	75	55	62	95	67	2135	940	1368	**579**	1.1
First-I	*43606*	148790	*7338*	25038.295	75	55	62	95	503	6763	2689	1465	**188**	1.1
Second-I	*51042*	174163	*10253*	34984.688	75	55	62	95	503	7916	3233	1826	**359**	1.1
Third-I	*52255*	178301	*30235*	103166.102	75	55	62	95	503	8105	3322	4306	**1529**	1.1

Table B-0-3: Baltimore DOAS-1 and DOAS-2 local unit sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*7041*	24025	*9626*	32845	75	55	62	95	106	1092	409	1311	**513**	1.1
Second-S	*9851*	33613	*10160*	34667	75	55	62	95	106	1528	615	1377	**544**	1.1
Third-S	*10695*	36493	*14157*	48306	75	55	62	95	106	1659	677	1873	**778**	1.1
First-W	*13221*	45112	*6332*	21606	75	55	62	95	67	2051	901	860	**339**	1.1
Second-W	*15200*	51865	*6691*	22831	75	55	62	95	67	2357	1046	904	**360**	1.1
Third-W	*16118*	54997	*9231*	31497	75	55	62	95	67	2500	1113	1219	**508**	1.1
First-N	*6061*	20681	*9423*	32153	75	55	62	95	106	940	338	1286	**501**	1.1
Second-N	*8842*	30170	*9989*	34084	75	55	62	95	106	1371	541	1356	**534**	1.1
Third-N	*9989*	34084	*14033*	47883	75	55	62	95	106	1549	625	1858	**771**	1.1
First-E	*9828*	33535	*6332*	21606	75	55	62	95	67	1524	652	860	**339**	1.1
Second-E	*12115*	41338	*6691*	22831	75	55	62	95	67	1879	820	904	**360**	1.1
Third-E	*11426*	38987	*9232*	31501	75	55	62	95	67	1772	769	1219	**508**	1.1
First-I	*38986*	133026	*7981*	27232	75	55	62	95	503	6047	2351	1544	**226**	1.1
Second-I	*46822*	159763	*9510*	32449	75	55	62	95	503	7262	2924	1734	**315**	1.1
Third-I	*44479*	151769	*27292*	93124	75	55	62	95	503	6899	2753	3940	**1357**	1.1

Table B-0-4: Albuquerque DOAS-1 and DOAS-2 local unit sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*6556*	22370	*11670*	39820	75	55	62	95	106	1017	374	1565	**632**	1.1
Second-S	*9396*	32060	*12405*	42328	75	55	62	95	106	1457	582	1656	**676**	1.1
Third-S	*9990*	34087	*17708*	60422	75	55	62	95	106	1549	625	2314	**986**	1.1
First-W	*12353*	42150	*7778*	26540	75	55	62	95	67	1916	837	1039	**423**	1.1
Second-W	*14307*	48818	*8256*	28171	75	55	62	95	67	2219	980	1098	**451**	1.1
Third-W	*14986*	51134	*11608*	39608	75	55	62	95	67	2324	1030	1514	**648**	1.1
First-N	*5604*	19122	*11562*	39451	75	55	62	95	106	869	304	1551	**626**	1.1
Second-N	*8332*	28430	*12319*	42034	75	55	62	95	106	1292	504	1645	**670**	1.1
Third-N	*9102*	31057	*17657*	60248	75	55	62	95	106	1412	560	2308	**983**	1.1
First-E	*9025*	30795	*7729*	26372	75	55	62	95	67	1400	594	1033	**420**	1.1
Second-E	*11292*	38530	*8210*	28014	75	55	62	95	67	1751	759	1093	**449**	1.1
Third-E	*10441*	35626	*11571*	39482	75	55	62	95	67	1619	697	1510	**645**	1.1
First-I	*38617*	131767	*8511*	29041	75	55	62	95	503	5989	2324	1610	**257**	1.1
Second-I	*47190*	161019	*10681*	36445	75	55	62	95	503	7319	2951	1879	**384**	1.1
Third-I	*42453*	144856	*34272*	116941	75	55	62	95	503	6584	2605	4807	**1766**	1.1

Table B-0-5: Denver DOAS-1 and DOAS-2 local unit sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*8670*	29583	*12952*	44194	75	55	62	95	106	1345	529	1724	**708**	1.1
Second-S	*11735*	40041	*14036*	47893	75	55	62	95	106	1820	753	1858	**771**	1.1
Third-S	*12480*	42584	*19877*	67823	75	55	62	95	106	1936	808	2583	**1113**	1.1
First-W	*13664*	46624	*8585*	29293	75	55	62	95	67	2119	933	1139	**471**	1.1
Second-W	*15604*	53243	*9292*	31706	75	55	62	95	67	2420	1075	1227	**512**	1.1
Third-W	*16664*	56860	*12995*	44341	75	55	62	95	67	2585	1153	1686	**729**	1.1
First-N	*7242*	24711	*12762*	43546	75	55	62	95	106	1123	424	1700	**696**	1.1
Second-N	*11011*	37571	*13875*	47343	75	55	62	95	106	1708	700	1838	**762**	1.1
Third-N	*11329*	38656	*19766*	67444	75	55	62	95	106	1757	723	2569	**1107**	1.1
First-E	*10925*	37278	*8628*	29440	75	55	62	95	67	1694	733	1144	**473**	1.1
Second-E	*13326*	45470	*9302*	31740	75	55	62	95	67	2067	908	1228	**513**	1.1
Third-E	*13193*	45016	*12981*	44293	75	55	62	95	67	2046	899	1685	**728**	1.1
First-I	*42833*	146152	*8333*	28433	75	55	62	95	503	6643	2632	1588	**247**	1.1
Second-I	*51793*	176725	*11509*	39270	75	55	62	95	503	8033	3288	1982	**433**	1.1
Third-I	*52167*	178001	*37329*	127372	75	55	62	95	503	8091	3316	5186	**1945**	1.1

Table B-0-6: Chicago DOAS-1 and DOAS-2 local unit sizing

Design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	*Sensible load winter (W)*	Sensible load winter (Btu/hr)	T_return summer (F)	T_supply summer (F)	T_return winter (F)	T_supply winter (F)	Ventilation air flow (l/s)	Flow rate summer (cfm)	Flow rate summer (l/s)	Flow rate winter (cfm)	**Flow rate winter (l/s)**	C_1
First-S	*25288*	86286	*17850*	60907	75	55	62	95	106	3922.102	1745.026	2331.583	**994.38**	1.1
Second-S	*31038*	105906	*18624*	63548	75	55	62	95	106	4813.911	2165.913	2427.619	**1039.71**	1.1
Third-S	*30628*	104507	*27257*	93005	75	55	62	95	106	4750.322	2135.902	3498.783	**1545.24**	1.1
First-W	*18301*	62446	*11806*	40284	75	55	62	95	67.1	2838.437	1272.493	1538.795	**659.13**	1.1
Second-W	*21744*	74194	*12303*	41980	75	55	62	95	67.1	3372.437	1524.513	1600.462	**688.23**	1.1
Third-W	*21880*	74658	*17766*	60620	75	55	62	95	67.1	3393.530	1534.468	2278.300	**1008.14**	1.1
First-N	*8315*	28372	*17602*	60061	75	55	62	95	106	1289.634	502.640	2300.811	**979.86**	1.1
Second-N	*14625*	49903	*18398*	62777	75	55	62	95	106	2268.299	964.518	2399.577	**1026.47**	1.1
Third-N	*14431*	49241	*27106*	92490	75	55	62	95	106	2238.210	950.317	3480.048	**1536.40**	1.1
First-E	*15994*	54574	*11806*	40284	75	55	62	95	67.1	2480.627	1103.626	1538.795	**659.13**	1.1
Second-E	*19970*	68140	*12303*	41980	75	55	62	95	67.1	3097.294	1394.660	1600.462	**688.23**	1.1
Third-E	*19484*	66482	*17767*	60624	75	55	62	95	67.1	3021.917	1359.086	2278.424	**1008.20**	1.1
First-I	*36751*	125400	*12332*	42079	75	55	62	95	502.9	5699.983	2187.192	2084.232	**480.75**	1.1
Second-I	*60592*	206748	*14943*	50988	75	55	62	95	502.9	9397.658	3932.301	2408.200	**633.64**	1.1
Third-I	*60325*	205837	*53978*	184181	75	55	62	95	502.9	9356.247	3912.757	7251.580	**2919.46**	1.1

Table B-0-7: Fairbanks DOAS-1 and DOAS-2 local unit sizing ion

Appendix – C: DOAS-1 and DOAS-2 Latent load checks

Latent load check	*Latent load summer (W)*	Latent load summer (Btu/hr)	W_return summer (lb/lb)	W_supply summer (lb/lb)	Supply air rate summer (cfm)	Latent load design summer (Btu/hr)	Latent load rest summer (Btu/hr)	Latent load check	C_2	Altered flow rate summer (cfm)	Altered flow rate summer (l/s)
First-S	*626*	2136	0.00919	0.00873	1335	2972	-836	0	4840	1335	524
Second-S	*594*	2027	0.00919	0.00873	1674	3726	-1699	0	4840	1674	684
Third-S	*579*	1976	0.00919	0.00873	1851	4122	-2146	0	4840	1851	768
First-W	*338*	1153	0.00919	0.00873	2181	4856	-3702	0	4840	2181	962
Second-W	*338*	1153	0.00919	0.00873	2384	5309	-4155	0	4840	2384	1058
Third-W	*338*	1153	0.00919	0.00873	2554	5687	-4534	0	4840	2554	1138
First-N	*535*	1825	0.00919	0.00873	1395	3107	-1281	0	4840	1395	553
Second-N	*535*	1825	0.00919	0.00873	1715	3819	-1993	0	4840	1715	703
Third-N	*535*	1825	0.00919	0.00873	2005	4463	-2638	0	4840	2005	840
First-E	*338*	1153	0.00919	0.00873	1818	4048	-2895	0	4840	1818	791
Second-E	*338*	1153	0.00919	0.00873	2054	4572	-3419	0	4840	2054	902
Third-E	*338*	1153	0.00919	0.00873	2034	4529	-3376	0	4840	2034	893
First-I	*2538*	8660	0.00919	0.00873	7045	15686	-7026	0	4840	7045	2822
Second-I	*2538*	8660	0.00919	0.00873	7855	17488	-8828	0	4840	7855	3204
Third-I	*2538*	8660	0.00919	0.00873	8064	17953	-9293	0	4840	8064	3303

Table C-0-1: Miami DOAS-1 and DOAS-2 Latent loads check

Latent load check	Latent load summer (W)	Latent load summer (Btu/hr)	W_return summer (lb/lb)	W_supply summer (lb/lb)	Supply air rate summer (cfm)	Latent load design summer (Btu/hr)	Latent load rest summer (Btu/hr)	Latent load check	C_2	Altered flow rate summer (cfm)	Altered flow rate summer (l/s)
First-S	600	2047	0.00919	0.00873	1675	3730	-1683	0	4840	1675	685
Second-S	566	1931	0.00919	0.00873	2233	4972	-3040	0	4840	2233	948
Third-S	600	2047	0.00919	0.00873	2446	5446	-3399	0	4840	2446	1048
First-W	338	1153	0.00919	0.00873	2268	5050	-3897	0	4840	2268	1003
Second-W	338	1153	0.00919	0.00873	2611	5813	-4660	0	4840	2611	1165
Third-W	375	1280	0.00919	0.00873	2842	6326	-5047	0	4840	2842	1274
First-N	535	1825	0.00919	0.00873	1359	3026	-1200	0	4840	1359	535
Second-N	535	1825	0.00919	0.00873	1889	4206	-2380	0	4840	1889	785
Third-N	606	2068	0.00919	0.00873	2272	5058	-2991	0	4840	2272	966
First-E	338	1153	0.00919	0.00873	1786	3977	-2824	0	4840	1786	776
Second-E	338	1153	0.00919	0.00873	2189	4873	-3720	0	4840	2189	966
Third-E	346	1181	0.00919	0.00873	2210	4920	-3739	0	4840	2210	976
First-I	2538	8660	0.00919	0.00873	6115	13615	-4955	0	4840	6115	2383
Second-I	2538	8660	0.00919	0.00873	7911	17613	-8953	0	4840	7911	3231
Third-I	2557	8725	0.00919	0.00873	8264	18399	-9674	0	4840	8264	3397

Table C-0-2: Phoenix DOAS-1 and DOAS-2 Latent loads check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summer (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	570	1945	0.00919	0.00873	1379	3071	-1126	0	4840	1379	545
Second-S	538	1836	0.00919	0.00873	1821	4054	-2218	0	4840	1821	753
Third-S	535	1825	0.00919	0.00873	2013	4482	-2656	0	4840	2013	844
First-W	338	1153	0.00919	0.00873	2249	5007	-3854	0	4840	2249	994
Second-W	338	1153	0.00919	0.00873	2536	5645	-4492	0	4840	2536	1130
Third-W	338	1153	0.00919	0.00873	2720	6055	-4902	0	4840	2720	1216
First-N	535	1825	0.00919	0.00873	1185	2639	-814	0	4840	1185	453
Second-N	535	1825	0.00919	0.00873	1678	3737	-1911	0	4840	1678	686
Third-N	535	1825	0.00919	0.00873	1830	4074	-2248	0	4840	1830	758
First-E	338	1153	0.00919	0.00873	1818	4047	-2893	0	4840	1818	791
Second-E	338	1153	0.00919	0.00873	2160	4809	-3656	0	4840	2160	952
Third-E	338	1153	0.00919	0.00873	2135	4753	-3600	0	4840	2135	940
First-I	2538	8660	0.00919	0.00873	6763	15058	-6398	0	4840	6763	2689
Second-I	2538	8660	0.00919	0.00873	7916	17625	-8965	0	4840	7916	3233
Third-I	2538	8660	0.00919	0.00873	8105	18044	-9384	0	4840	8105	3322

Table C-0-3: Baltimore DOAS-1 and DOAS-2 Latent loads check

Latent load	Latent load	Latent load	W_return summer	W_supply summer	Supply air rate summer	Latent load design	Latent load rest summer	Latent load	C_2	Altered flow rate	Altered flow rate

check	summe r (W)	summer (Btu/hr)	(lb/lb)	(lb/lb)	(cfm)	summer (Btu/hr)	(Btu/hr)	check		summer (cfm)	summer (l/s)
First-S	624	2129	0.00919	0.00873	1092	2431	-302	0	4840	1092	409
Second-S	586	2000	0.00919	0.00873	1528	3402	-1402	0	4840	1528	615
Third-S	566	1931	0.00919	0.00873	1659	3693	-1762	0	4840	1659	677
First-W	338	1153	0.00919	0.00873	2051	4565	-3412	0	4840	2051	901
Second-W	338	1153	0.00919	0.00873	2357	5249	-4095	0	4840	2357	1046
Third-W	338	1153	0.00919	0.00873	2500	5566	-4412	0	4840	2500	1113
First-N	535	1825	0.00919	0.00873	940	2093	-267	0	4840	940	338
Second-N	585	1996	0.00919	0.00873	1371	3053	-1057	0	4840	1371	541
Third-N	535	1825	0.00919	0.00873	1549	3449	-1624	0	4840	1549	625
First-E	338	1153	0.00919	0.00873	1524	3394	-2240	0	4840	1524	652
Second-E	338	1153	0.00919	0.00873	1879	4183	-3030	0	4840	1879	820
Third-E	338	1153	0.00919	0.00873	1772	3945	-2792	0	4840	1772	769
First-I	2538	8660	0.00919	0.00873	6047	13462	-4802	0	4840	6047	2351
Second-I	2538	8660	0.00919	0.00873	7262	16168	-7508	0	4840	7262	2924
Third-I	2538	8660	0.00919	0.00873	6899	15359	-6699	0	4840	6899	2753

Table C-0-4: Albuquerque DOAS-1 and DOAS-2 Latent loads check

Latent load check	Latent load summe	Latent load summer	W_return summer (lb/lb)	W_supply summer (lb/lb)	Supply air rate summer (cfm)	Latent load design summer	Latent load rest summer (Btu/hr)	Laten t load check	C_2	Altered flow rate summer	Altered flow rate summer

	r (W)	(Btu/hr)				(Btu/hr)				(cfm)	(l/s)
First-S	653	2228	0.00919	0.00873	1017	2264	-36	0	4840	1017	374
Second-S	611	2085	0.00919	0.00873	1457	3245	-1160	0	4840	1457	582
Third-S	587	2003	0.00919	0.00873	1549	3450	-1447	0	4840	1549	625
First-W	338	1153	0.00919	0.00873	1916	4266	-3112	0	4840	1916	837
Second-W	338	1153	0.00919	0.00873	2219	4940	-3787	0	4840	2219	980
Third-W	338	1153	0.00919	0.00873	2324	5175	-4021	0	4840	2324	1030
First-N	635	2167	0.00919	0.00873	869	1935	232	1	4840	973	353
Second-N	535	1825	0.00919	0.00873	1292	2877	-1052	0	4840	1292	504
Third-N	585	1996	0.00919	0.00873	1412	3143	-1147	0	4840	1412	560
First-E	338	1153	0.00919	0.00873	1400	3116	-1963	0	4840	1400	594
Second-E	338	1153	0.00919	0.00873	1751	3899	-2746	0	4840	1751	759
Third-E	338	1153	0.00919	0.00873	1619	3605	-2452	0	4840	1619	697
First-I	2539	8663	0.00919	0.00873	5989	13335	-4671	0	4840	5989	2324
Second-I	2539	8663	0.00919	0.00873	7319	16295	-7632	0	4840	7319	2951
Third-I	2539	8663	0.00919	0.00873	6584	14659	-5996	0	4840	6584	2605

Table C-0-5: Denver DOAS-1 and DOAS-2 Latent loads check

Latent load check	Latent load summer (W)	Latent load summer (Btu/hr)	W_return summer (lb/lb)	W_supply summer (lb/lb)	Supply air rate summer (cfm)	Latent load design summer (Btu/hr)	Latent load rest summer (Btu/hr)	Latent load check	C_2	Altered flow rate summer (cfm)	Altered flow rate summer (l/s)

First-S	553	1887	0.00919	0.00873	1345	2994	-1107	0	4840	1345	529
Second-S	535	1825	0.00919	0.00873	1820	4052	-2227	0	4840	1820	753
Third-S	535	1825	0.00919	0.00873	1936	4309	-2484	0	4840	1936	808
First-W	338	1153	0.00919	0.00873	2119	4718	-3565	0	4840	2119	933
Second-W	338	1153	0.00919	0.00873	2420	5388	-4235	0	4840	2420	1075
Third-W	338	1153	0.00919	0.00873	2585	5754	-4601	0	4840	2585	1153
First-N	535	1825	0.00919	0.00873	1123	2501	-675	0	4840	1123	424
Second-N	535	1825	0.00919	0.00873	1708	3802	-1977	0	4840	1708	700
Third-N	535	1825	0.00919	0.00873	1757	3912	-2087	0	4840	1757	723
First-E	338	1153	0.00919	0.00873	1694	3772	-2619	0	4840	1694	733
Second-E	338	1153	0.00919	0.00873	2067	4602	-3448	0	4840	2067	908
Third-E	338	1153	0.00919	0.00873	2046	4556	-3402	0	4840	2046	899
First-I	2538	8660	0.00919	0.00873	6643	14791	-6131	0	4840	6643	2632
Second-I	2538	8660	0.00919	0.00873	8033	17885	-9225	0	4840	8033	3288
Third-I	2538	8660	0.00919	0.00873	8091	18014	-9354	0	4840	8091	3316

Table C-0-6: Chicago DOAS-1 and DOAS-2 Latent loads check

Latent load check	Latent load summer (W)	Latent load summer (Btu/hr)	W_return summer (lb/lb)	W_supply summer (lb/lb)	Supply air rate summer (cfm)	Latent load design summer (Btu/hr)	Latent load rest summer (Btu/hr)	Latent load check	C_2	Altered flow rate summer (cfm)	Altered flow rate summer (l/s)
First-S	553	1887	0.00919	0.00873	3922	8732	-6845	0	4840	3922	1745

Second-S	535	1825	0.00919	0.00873	4814	10718	-8892	0	4840	4814	2166
Third-S	535	1825	0.00919	0.00873	4750	10576	-8751	0	4840	4750	2136
First-W	338	1153	0.00919	0.00873	2838	6319	-5166	0	4840	2838	1272
Second-W	338	1153	0.00919	0.00873	3372	7508	-6355	0	4840	3372	1525
Third-W	338	1153	0.00919	0.00873	3394	7555	-6402	0	4840	3394	1534
First-N	535	1825	0.00919	0.00873	1290	2871	-1046	0	4840	1290	503
Second-N	535	1825	0.00919	0.00873	2268	5050	-3225	0	4840	2268	965
Third-N	535	1825	0.00919	0.00873	2238	4983	-3158	0	4840	2238	950
First-E	338	1153	0.00919	0.00873	2481	5523	-4370	0	4840	2481	1104
Second-E	338	1153	0.00919	0.00873	3097	6896	-5743	0	4840	3097	1395
Third-E	338	1153	0.00919	0.00873	3022	6728	-5575	0	4840	3022	1359
First-I	2538	8660	0.00919	0.00873	5700	12690	-4030	0	4840	5700	2187
Second-I	2538	8660	0.00919	0.00873	9398	20923	-12263	0	4840	9398	3932
Third-I	2538	8660	0.00919	0.00873	9356	20831	-12171	0	4840	9356	3913

Table C-0-7: Fairbanks DOAS-1 and DOAS-2 Latent loads check

Appendix – D: DOAS-3 Primary and Induced Air Calculations

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	*8606*	29365	**106**	225	75	55	24424	64	2018	**953**	1.1
Second-S	*10790*	36817	**106**	225	75	55	31876	64	2634	**1243**	1.1
Third-S	*11936*	40727	**106**	225	75	55	35786	64	2958	**1396**	1.1
First-W	*14062*	47982	**67**	142	75	55	44854	64	3707	**1749**	1.1
Second-W	*15374*	52458	**67**	142	75	55	49330	64	4077	**1924**	1.1
Third-W	*16469*	56195	**67**	142	75	55	53067	64	4386	**2070**	1.1
First-N	*8997*	30699	**106**	225	75	55	25758	64	2129	**1005**	1.1
Second-N	*11059*	37735	**106**	225	75	55	32794	64	2710	**1279**	1.1
Third-N	*12925*	44102	**106**	225	75	55	39161	64	3236	**1527**	1.1
First-E	*11724*	40004	**67**	142	75	55	36876	64	3048	**1438**	1.1
Second-E	*13241*	45180	**67**	142	75	55	42052	64	3475	**1640**	1.1
Third-E	*13117*	44757	**67**	142	75	55	41629	64	3440	**1624**	1.1
First-I	*45426*	154998	**503**	1066	75	55	131555	64	10872	**5131**	1.1
Second-I	*50643*	172803	**503**	1066	75	55	149360	64	12344	**5826**	1.1
Third-I	*51991*	177399	**503**	1066	75	55	153956	64	12724	**6005**	1.1

Table D-0-1: Miami DOAS-3 primary and induced air calculation

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	10802	36858	106	225	75	55	31917	64	2638	1245	1.1
Second-S	14398	49128	106	225	75	55	44187	64	3652	1723	1.1
Third-S	15771	53813	106	225	75	55	48872	64	4039	1906	1.1
First-W	14626	49906	67	142	75	55	46778	64	3866	1825	1.1
Second-W	16834	57440	67	142	75	55	54312	64	4489	2118	1.1
Third-W	18321	62514	67	142	75	55	59386	64	4908	2316	1.1
First-N	8763	29901	106	225	75	55	24959	64	2063	974	1.1
Second-N	12179	41556	106	225	75	55	36615	64	3026	1428	1.1
Third-N	14649	49984	106	225	75	55	45043	64	3723	1757	1.1
First-E	11517	39298	67	142	75	55	36170	64	2989	1411	1.1
Second-E	14112	48152	67	142	75	55	45024	64	3721	1756	1.1
Third-E	14247	48613	67	142	75	55	45485	64	3759	1774	1.1
First-I	39429	134537	503	1066	75	55	111094	64	9181	4333	1.1
Second-I	51007	174043	503	1066	75	55	150600	64	12446	5874	1.1
Third-I	53282	181806	503	1066	75	55	158363	64	13088	6177	1.1

Table D-0-2: Phoenix DOAS-3 primary and induced air calculation

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	8893	30344	106	225	75	55	25403	64	2099	991	1.1
Second-S	11740	40059	106	225	75	55	35117	64	2902	1370	1.1
Third-S	12979	44286	106	225	75	55	39345	64	3252	1535	1.1
First-W	14501	49479	67	142	75	55	46352	64	3831	1808	1.1
Second-W	16348	55782	67	142	75	55	52654	64	4352	2054	1.1
Third-W	17535	59832	67	142	75	55	56704	64	4686	2212	1.1
First-N	7643	26079	106	225	75	55	21138	64	1747	824	1.1
Second-N	10821	36923	106	225	75	55	31982	64	2643	1247	1.1
Third-N	11798	40256	106	225	75	55	35315	64	2919	1377	1.1
First-E	11719	39987	67	142	75	55	36859	64	3046	1438	1.1
Second-E	13928	47524	67	142	75	55	44396	64	3669	1732	1.1
Third-E	13765	46968	67	142	75	55	43840	64	3623	1710	1.1
First-I	43606	148790	503	1066	75	55	125347	64	10359	4889	1.1
Second-I	51042	174163	503	1066	75	55	150720	64	12456	5879	1.1
Third-I	52255	178301	503	1066	75	55	154859	64	12798	6040	1.1

Table C-0-3: Baltimore DOAS-3 primary and induced air calculation

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	7041	24025	106	225	75	55	19084	64	1577	744	1.1
Second-S	9851	33613	106	225	75	55	28672	64	2370	1118	1.1
Third-S	10695	36493	106	225	75	55	31552	64	2608	1231	1.1
First-W	13221	45112	67	142	75	55	41984	64	3470	1638	1.1
Second-W	15200	51865	67	142	75	55	48737	64	4028	1901	1.1
Third-W	16118	54997	67	142	75	55	51869	64	4287	2023	1.1
First-N	6061	20681	106	225	75	55	15740	64	1301	614	1.1
Second-N	8842	30170	106	225	75	55	25229	64	2085	984	1.1
Third-N	9989	34084	106	225	75	55	29143	64	2408	1137	1.1
First-E	9828	33535	67	142	75	55	30407	64	2513	1186	1.1
Second-E	12115	41338	67	142	75	55	38210	64	3158	1490	1.1
Third-E	11426	38987	67	142	75	55	35859	64	2964	1399	1.1
First-I	38986	133026	503	1066	75	55	109583	64	9056	4274	1.1
Second-I	46822	159763	503	1066	75	55	136320	64	11266	5317	1.1
Third-I	44479	151769	503	1066	75	55	128326	64	10605	5005	1.1

Table C-0-4: Albuquerque DOAS-3 primary and induced air calculation

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	6556	22370	106	225	75	55	17429	64	1440	680	1.1
Second-S	9396	32060	106	225	75	55	27119	64	2241	1058	1.1
Third-S	9990	34087	106	225	75	55	29146	64	2409	1137	1.1
First-W	12353	42150	67	142	75	55	39022	64	3225	1522	1.1
Second-W	14307	48818	67	142	75	55	45690	64	3776	1782	1.1
Third-W	14986	51134	67	142	75	55	48006	64	3967	1872	1.1
First-N	5604	19122	106	225	75	55	14180	64	1172	553	1.1
Second-N	8332	28430	106	225	75	55	23489	64	1941	916	1.1
Third-N	9102	31057	106	225	75	55	26116	64	2158	1019	1.1
First-E	9025	30795	67	142	75	55	27667	64	2287	1079	1.1
Second-E	11292	38530	67	142	75	55	35402	64	2926	1381	1.1
Third-E	10441	35626	67	142	75	55	32498	64	2686	1268	1.1
First-I	38617	131767	503	1066	75	55	108324	64	8952	4225	1.1
Second-I	47190	161019	503	1066	75	55	137576	64	11370	5366	1.1
Third-I	42453	144856	503	1066	75	55	121413	64	10034	4736	1.1

Table C-0-5: Denver DOAS-3 primary and induced air calculation

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	8670	29583	106	225	75	55	24642	64	2037	961	1.1
Second-S	11735	40041	106	225	75	55	35100	64	2901	1369	1.1
Third-S	12480	42584	106	225	75	55	37642	64	3111	1468	1.1
First-W	13664	46624	67	142	75	55	43496	64	3595	1696	1.1
Second-W	15604	53243	67	142	75	55	50115	64	4142	1955	1.1
Third-W	16664	56860	67	142	75	55	53732	64	4441	2096	1.1
First-N	7242	24711	106	225	75	55	19770	64	1634	771	1.1
Second-N	11011	37571	106	225	75	55	32630	64	2697	1273	1.1
Third-N	11329	38656	106	225	75	55	33715	64	2786	1315	1.1
First-E	10925	37278	67	142	75	55	34150	64	2822	1332	1.1
Second-E	13326	45470	67	142	75	55	42342	64	3499	1652	1.1
Third-E	13193	45016	67	142	75	55	41888	64	3462	1634	1.1
First-I	42833	146152	503	1066	75	55	122709	64	10141	4786	1.1
Second-I	51793	176725	503	1066	75	55	153282	64	12668	5979	1.1
Third-I	52167	178001	503	1066	75	55	154558	64	12773	6028	1.1

Table C-0-6: Chicago DOAS-3 primary and induced air calculation

Summer design condition	*Sensible load summer (W)*	Sensible load summer (Btu/hr)	**Primary air flow (l/s)**	Primary air flow (cfm)	T_return summer (F)	T_supply summer (F)	Sensible load summer rest (Btu/hr)	T_leaving ACB coil (F)	Flow rate induced (cfm)	**Flow rate induced (l/s)**	C_1
First-S	25288	86286	106	225	75	55	81345	64	6723	3173	1.1
Second-S	31038	105906	106	225	75	55	100965	64	8344	3938	1.1
Third-S	30628	104507	106	225	75	55	99566	64	8229	3883	1.1
First-W	18301	62446	67	142	75	55	59318	64	4902	2314	1.1
Second-W	21744	74194	67	142	75	55	71066	64	5873	2772	1.1
Third-W	21880	74658	67	142	75	55	71530	64	5912	2790	1.1
First-N	8315	28372	106	225	75	55	23431	64	1936	914	1.1
Second-N	14625	49903	106	225	75	55	44961	64	3716	1754	1.1
Third-N	14431	49241	106	225	75	55	44299	64	3661	1728	1.1
First-E	15994	54574	67	142	75	55	51446	64	4252	2007	1.1
Second-E	19970	68140	67	142	75	55	65013	64	5373	2536	1.1
Third-E	19484	66482	67	142	75	55	63354	64	5236	2471	1.1
First-I	36751	125400	503	1066	75	55	101957	64	8426	3977	1.1
Second-I	60592	206748	503	1066	75	55	183306	64	15149	7150	1.1
Third-I	60325	205837	503	1066	75	55	182395	64	15074	7114	1.1

Table C-0-7: Fairbanks DOAS-3 primary and induced air calculation

Appendix – E: DOAS-3 Latent Loads Check

Latent load check	Latent load summer (W)	Latent load summer (Btu/hr)	W_return summer (lb/lb)	W_supply summer (lb/lb)	Supply air rate summer (cfm)	Latent load design summer (Btu/hr)	Latent load rest summer (Btu/hr)	Latent load check	C_2	Altered flow rate summer (cfm)	Altered flow rate summer (l/s)
First-S	626	2136	0.00919	0.00873	2243	4994	-2858	0	4840	2018	953
Second-S	594	2027	0.00919	0.00873	2859	6365	-4338	0	4840	2634	1243
Third-S	579	1976	0.00919	0.00873	3182	7085	-5109	0	4840	2958	1396
First-W	338	1153	0.00919	0.00873	3849	8570	-7416	0	4840	3707	1749
Second-W	338	1153	0.00919	0.00873	4219	9393	-8240	0	4840	4077	1924
Third-W	338	1153	0.00919	0.00873	4528	10081	-8928	0	4840	4386	2070
First-N	535	1825	0.00919	0.00873	2353	5239	-3414	0	4840	2129	1005
Second-N	535	1825	0.00919	0.00873	2935	6534	-4709	0	4840	2710	1279
Third-N	535	1825	0.00919	0.00873	3461	7706	-5880	0	4840	3236	1527
First-E	338	1153	0.00919	0.00873	3190	7102	-5948	0	4840	3048	1438
Second-E	338	1153	0.00919	0.00873	3618	8054	-6901	0	4840	3475	1640
Third-E	338	1153	0.00919	0.00873	3583	7976	-6823	0	4840	3440	1624
First-I	2538	8660	0.00919	0.00873	11938	26579	-17919	0	4840	10872	5131
Second-I	2538	8660	0.00919	0.00873	13409	29855	-21195	0	4840	12344	5826
Third-I	2538	8660	0.00919	0.00873	13789	30700	-22040	0	4840	12724	6005

Table E-0-1: Miami DOAS-3 Latent Loads Check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summer (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	600	2047	0.00919	0.00873	2862	6373	-4325	0	4840	2638	1245
Second-S	566	1931	0.00919	0.00873	3876	8630	-6699	0	4840	3652	1723
Third-S	600	2047	0.00919	0.00873	4264	9492	-7445	0	4840	4039	1906
First-W	338	1153	0.00919	0.00873	4008	8924	-7770	0	4840	3866	1825
Second-W	338	1153	0.00919	0.00873	4631	10310	-9157	0	4840	4489	2118
Third-W	375	1280	0.00919	0.00873	5050	11244	-9964	0	4840	4908	2316
First-N	535	1825	0.00919	0.00873	2287	5093	-3267	0	4840	2063	974
Second-N	535	1825	0.00919	0.00873	3251	7237	-5412	0	4840	3026	1428
Third-N	606	2068	0.00919	0.00873	3947	8788	-6720	0	4840	3723	1757
First-E	338	1153	0.00919	0.00873	3131	6972	-5818	0	4840	2989	1411
Second-E	338	1153	0.00919	0.00873	3863	8601	-7448	0	4840	3721	1756
Third-E	346	1181	0.00919	0.00873	3901	8686	-7505	0	4840	3759	1774
First-I	2538	8660	0.00919	0.00873	10247	22814	-14154	0	4840	9181	4333
Second-I	2538	8660	0.00919	0.00873	13512	30083	-21423	0	4840	12446	5874
Third-I	2557	8725	0.00919	0.00873	14153	31511	-22786	0	4840	13088	6177

Table E-0-2: Phoenix DOAS-3 Latent Loads Check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summer (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	570	1945	0.00919	0.00873	2324	5174	-3229	0	4840	2099	991
Second-S	538	1836	0.00919	0.00873	3127	6962	-5126	0	4840	2902	1370
Third-S	535	1825	0.00919	0.00873	3476	7740	-5914	0	4840	3252	1535
First-W	338	1153	0.00919	0.00873	3973	8845	-7692	0	4840	3831	1808
Second-W	338	1153	0.00919	0.00873	4494	10005	-8852	0	4840	4352	2054
Third-W	338	1153	0.00919	0.00873	4828	10750	-9597	0	4840	4686	2212
First-N	535	1825	0.00919	0.00873	1972	4389	-2564	0	4840	1747	824
Second-N	535	1825	0.00919	0.00873	2868	6385	-4559	0	4840	2643	1247
Third-N	535	1825	0.00919	0.00873	3143	6998	-5173	0	4840	2919	1377
First-E	338	1153	0.00919	0.00873	3188	7099	-5945	0	4840	3046	1438
Second-E	338	1153	0.00919	0.00873	3811	8485	-7332	0	4840	3669	1732
Third-E	338	1153	0.00919	0.00873	3765	8383	-7230	0	4840	3623	1710
First-I	2538	8660	0.00919	0.00873	11425	25436	-16776	0	4840	10359	4889
Second-I	2538	8660	0.00919	0.00873	13522	30105	-21445	0	4840	12456	5879
Third-I	2538	8660	0.00919	0.00873	13864	30866	-22206	0	4840	12798	6040

Table E-0-3: Baltimore DOAS-3 Latent Loads Check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summer (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	624	2129	0.00919	0.00873	1802	4011	-1882	0	4840	1577	744
Second-S	586	2000	0.00919	0.00873	2594	5776	-3776	0	4840	2370	1118
Third-S	566	1931	0.00919	0.00873	2832	6306	-4374	0	4840	2608	1231
First-W	338	1153	0.00919	0.00873	3612	8042	-6888	0	4840	3470	1638
Second-W	338	1153	0.00919	0.00873	4170	9284	-8131	0	4840	4028	1901
Third-W	338	1153	0.00919	0.00873	4429	9860	-8707	0	4840	4287	2023
First-N	535	1825	0.00919	0.00873	1525	3396	-1571	0	4840	1301	614
Second-N	585	1996	0.00919	0.00873	2310	5142	-3146	0	4840	2085	984
Third-N	535	1825	0.00919	0.00873	2633	5862	-4037	0	4840	2408	1137
First-E	338	1153	0.00919	0.00873	2655	5911	-4758	0	4840	2513	1186
Second-E	338	1153	0.00919	0.00873	3300	7347	-6194	0	4840	3158	1490
Third-E	338	1153	0.00919	0.00873	3106	6915	-5761	0	4840	2964	1399
First-I	2538	8660	0.00919	0.00873	10122	22536	-13876	0	4840	9056	4274
Second-I	2538	8660	0.00919	0.00873	12332	27455	-18795	0	4840	11266	5317
Third-I	2538	8660	0.00919	0.00873	11671	25984	-17324	0	4840	10605	5005

Table E-0-4: Albuquerque DOAS-3 Latent Loads Check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summer (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	653	2228	0.00919	0.00873	1665	3707	-1479	0	4840	1440	680
Second-S	611	2085	0.00919	0.00873	2466	5490	-3405	0	4840	2241	1058
Third-S	587	2003	0.00919	0.00873	2633	5863	-3860	0	4840	2409	1137
First-W	338	1153	0.00919	0.00873	3367	7497	-6343	0	4840	3225	1522
Second-W	338	1153	0.00919	0.00873	3918	8723	-7570	0	4840	3776	1782
Third-W	338	1153	0.00919	0.00873	4110	9150	-7996	0	4840	3967	1872
First-N	635	2167	0.00919	0.00873	1397	3109	-943	0	4840	1172	553
Second-N	535	1825	0.00919	0.00873	2166	4822	-2996	0	4840	1941	916
Third-N	585	1996	0.00919	0.00873	2383	5305	-3309	0	4840	2158	1019
First-E	338	1153	0.00919	0.00873	2429	5407	-4254	0	4840	2287	1079
Second-E	338	1153	0.00919	0.00873	3068	6831	-5677	0	4840	2926	1381
Third-E	338	1153	0.00919	0.00873	2828	6296	-5143	0	4840	2686	1268
First-I	2539	8663	0.00919	0.00873	10018	22304	-13641	0	4840	8952	4225
Second-I	2539	8663	0.00919	0.00873	12436	27686	-19023	0	4840	11370	5366
Third-I	2539	8663	0.00919	0.00873	11100	24712	-16049	0	4840	10034	4736

Table E-0-5: Denver DOAS-3 Latent Loads Check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summer (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	553	1887	0.00919	0.00873	2261	5034	-3147	0	4840	2037	961
Second-S	535	1825	0.00919	0.00873	3125	6958	-5133	0	4840	2901	1369
Third-S	535	1825	0.00919	0.00873	3336	7426	-5601	0	4840	3111	1468
First-W	338	1153	0.00919	0.00873	3737	8320	-7166	0	4840	3595	1696
Second-W	338	1153	0.00919	0.00873	4284	9538	-8384	0	4840	4142	1955
Third-W	338	1153	0.00919	0.00873	4583	10203	-9050	0	4840	4441	2096
First-N	535	1825	0.00919	0.00873	1858	4138	-2312	0	4840	1634	771
Second-N	535	1825	0.00919	0.00873	2921	6504	-4678	0	4840	2697	1273
Third-N	535	1825	0.00919	0.00873	3011	6704	-4878	0	4840	2786	1315
First-E	338	1153	0.00919	0.00873	2964	6600	-5447	0	4840	2822	1332
Second-E	338	1153	0.00919	0.00873	3642	8108	-6954	0	4840	3499	1652
Third-E	338	1153	0.00919	0.00873	3604	8024	-6871	0	4840	3462	1634
First-I	2538	8660	0.00919	0.00873	11207	24951	-16291	0	4840	10141	4786
Second-I	2538	8660	0.00919	0.00873	13734	30576	-21916	0	4840	12668	5979
Third-I	2538	8660	0.00919	0.00873	13839	30811	-22151	0	4840	12773	6028

Table E-0-6: Chicago DOAS-3 Latent Loads Check

Latent	Latent	Latent	W_return	W_supply	Supply air	Latent load	Latent load	Laten	C_2	Altered	Altered

load check	load summe r (W)	load summer (Btu/hr)	summer (lb/lb)	summer (lb/lb)	rate summer (cfm)	design summer (Btu/hr)	rest summer (Btu/hr)	t load check		flow rate summer (cfm)	flow rate summer (l/s)
First-S	553	1887	0.00919	0.00873	6947	15468	-13581	0	4840	6723	3173
Second-S	535	1825	0.00919	0.00873	8569	19078	-17252	0	4840	8344	3938
Third-S	535	1825	0.00919	0.00873	8453	18820	-16995	0	4840	8229	3883
First-W	338	1153	0.00919	0.00873	5044	11231	-10078	0	4840	4902	2314
Second-W	338	1153	0.00919	0.00873	6015	13393	-12239	0	4840	5873	2772
Third-W	338	1153	0.00919	0.00873	6054	13478	-12325	0	4840	5912	2790
First-N	535	1825	0.00919	0.00873	2161	4811	-2986	0	4840	1936	914
Second-N	535	1825	0.00919	0.00873	3940	8773	-6947	0	4840	3716	1754
Third-N	535	1825	0.00919	0.00873	3886	8651	-6826	0	4840	3661	1728
First-E	338	1153	0.00919	0.00873	4394	9783	-8629	0	4840	4252	2007
Second-E	338	1153	0.00919	0.00873	5515	12279	-11126	0	4840	5373	2536
Third-E	338	1153	0.00919	0.00873	5378	11974	-10820	0	4840	5236	2471
First-I	2538	8660	0.00919	0.00873	9492	21132	-12472	0	4840	8426	3977
Second-I	2538	8660	0.00919	0.00873	16215	36101	-27441	0	4840	15149	7150
Third-I	2538	8660	0.00919	0.00873	16140	35933	-27273	0	4840	15074	7114

Table E-0-7: Fairbanks DOAS-3 Latent Loads Check

Appendix – F: Simulated System Energy Performance

Location: Miami	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	372.262	338.43	338.757	313.363
Cooling Tower	121.564	104.698	104.912	110.988
System energy: Fan	155.803	87.242	85.241	53.397
System energy: Pump	18.306	22.102	17.381	46.24
System energy: Energy recovery	1.71	1.527	1.528	1.907
System energy: Heating	3.363	3.024	1.129	0.705
Total HVAC Energy (kBtu)	6.73E+05	5.57E+05	5.49E+05	5.27E+05
Total EUI (kBtu/ft^2)	**12.550**	**10.387**	**10.237**	**9.820**

Table F-0-1: Miami System Energy Performance

Location: Phoenix	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	262.36	243.239	242.708	250.044
Cooling Tower	86.02	81.021	80.395	85.404
System energy: Fan	163.633	91.616	90.489	53.466
System energy: Pump	13.725	16.123	13.505	28.64
System energy: Energy recovery	2.016	2.043	2.043	2.023
System energy: Heating	33.298	30.932	19.428	23.767
Total HVAC Energy (kBtu)	5.61E+05	4.65E+05	4.49E+05	4.43E+05
Total EUI (kBtu/ft^2)	**10.462**	**8.671**	**8.365**	**8.267**

Table F-0-2: Phoenix System Energy Performance

Location: Baltimore	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	132.995	121.757	121.032	114.532
Cooling Tower	53.253	49.885	47.997	48.766
System energy: Fan	87.428	70.343	73.696	52.634
System energy: Pump	9.405	11.512	8.808	18.812
System energy: Energy recovery	1.957	2.009	2.016	1.948
System energy: Heating	299.094	276.455	229.165	274.348
Total HVAC Energy (kBtu)	5.84E+05	5.32E+05	4.83E+05	5.11E+05
Total EUI (kBtu/ft^2)	**10.893**	**9.920**	**9.001**	**9.530**

Table F-0-3: Baltimore System Energy Performance

Location: Albuquerque	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	117.999	111.328	110.483	115.079
Cooling Tower	40.895	47.039	45.742	41.767
System energy: Fan	116.155	71.598	74.953	52.531
System energy: Pump	9.126	6.863	5.993	15.892
System energy: Energy recovery	1.969	2.013	2.016	1.888
System energy: Heating	252.627	201.109	159.702	190.221
Total HVAC Energy (kBtu)	5.39E+05	4.40E+05	3.99E+05	4.17E+05
Total EUI (kBtu/ft^2)	**10.047**	**8.204**	**7.438**	**7.783**

Table F-0-4: Albuquerque System Energy Performance

Location: Denver	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	75.98	77.294	76.273	79.259
Cooling Tower	35.363	37.004	35.396	31.993
System energy: Fan	84.268	68.447	73.717	52.696
System energy: Pump	5.774	6.484	5.61	10.184
System energy: Energy recovery	2.089	2.146	2.148	1.988
System energy: Heating	401.044	365.146	312.191	354.16
Total HVAC Energy (kBtu)	6.05E+05	5.57E+05	5.05E+05	5.30E+05
Total EUI (kBtu/ft^2)	**11.273**	**10.378**	**9.423**	**9.888**

Table F-0-5: Denver System Energy Performance

Location: Chicago	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	96.282	91.762	91.718	86.338
Cooling Tower	45.52	41.227	39.805	40.708
System energy: Fan	82.433	88.951	76.338	53.189
System energy: Pump	8.503	10.717	8.416	16.493
System energy: Energy recovery	2.035	2.108	2.11	2.041
System energy: Heating	535.391	480.668	425.001	483.382
Total HVAC Energy (kBtu)	7.70E+05	7.15E+05	6.43E+05	6.82E+05
Total EUI (kBtu/ft^2)	**14.362**	**13.341**	**11.998**	**12.720**

Table F-0-6: Chicago System Energy Performance

Location: Fairbanks	**Simulated baseline**	**Simulated DOAS-1**	**Simulated DOAS-2**	**Simulated DOAS-3**
Building Area (m^2)	4982	4982	4982	4982
System Description	Singel duct, packaged VAV, Total ER, CW cooling, boiler for preheat and heating	DOAS-FCU, CW cooling, boiler for Preheat and heating, Total energy recovery	DOAS-FCU, CW cooling, boiler for preheat and heating, Total energy recovery	DOAS-Active chilled beam, CW cooling, boiler for preheat and heating, total energy recovery
Convert and summary total energy	Mbtu	MMBtu	MMBtu	MMBtu
System energy: Cooling	35.445	28.69	28.355	31.866
Cooling Tower	32.467	19.097	18.133	22.827
System energy: Fan	117.417	85.983	95.089	54.116
System energy: Pump	13.48	10.435	8.796	12.051
System energy: Energy recovery	2.281	2.416	2.418	2.302
System energy: Heating	1805.857	1652.729	1570.114	1670.33
Total HVAC Energy (kBtu)	2.01E+06	1.80E+06	1.72E+06	1.79E+06
Total EUI (kBtu/ft^2)	**37.425**	**33.554**	**32.128**	**33.444**

Table F-0-7: Fairbanks System Energy Performance