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A Model for Analyzing Heating and Cooling Demand for Atria Between Tall Buildings

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ABSTRACT

A Model for Analyzing Heating and Cooling Demand
for Atria Between Tall Buildings

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The heating and air-conditioning energy demand of skyscrapers with atria between buildings is explored. Radiation, conduction, convection, and ventilation were evaluated to determine annual heating and cooling energy demands for a 100-building city located in Provo, Utah. Spreadsheets models were developed and calibrated with a computational fluid dynamics model. Three spreadsheet model cases were examined: a baseline no-atrium case, a conditioned atrium case, and an unconditioned atrium case. The energy demands and atrium temperatures were compared between the different cases. The research concludes that atria can be used between buildings to reduce the heating and cooling energy demands. The exposed surface area of the city was reduced by 73.7%. This resulted in a 49.7% reduction in heating and cooling energy consumption for the unconditioned atrium case and a 16.0% reduction in energy consumption for the conditioned atrium case.

Keywords: Greenplex, atrium, energy, heating, air-conditioning

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

The research described in this thesis investigated the heating, ventilation, air conditioning (HVAC) energy demand of a new urban form called the "greenplex". The greenplex is defined as a car-free city composed of tall buildings interconnected with sky bridges and atria between the buildings. Such atria may be constructed by spanning between the roofs of the buildings with a network of cable-spring trusses supporting cushions made from the transparent material Ethylene TetraFluoroEthylene (ETFE) as shown in Figure 1-1. These atria protect people from severe weather conditions. The tall fins on the thermal heat sink in Figure 1-2 (a) are designed to maximize heat transfer. Tall buildings like those shown in Figure 1-2 (b) also transfer a lot of energy to and from the surrounding environment. An additional benefit of the ETFE atria is that the exposed surface area of the greenplex system is far less than that of buildings without atria, potentially leading to significant reductions in HVAC energy demand.

The contributions of this work were: 1) to determine how much the HVAC energy demand could be reduced by placing atria between tall buildings and 2) to develop spreadsheet models capable of determining annual heating and cooling demands in buildings with atria. To determine how much HVAC energy demand could be reduced by placing atria between tall buildings, three cases (a no-atrium case, conditioned atrium case, and unconditioned atrium case) were defined and analyzed. Three spreadsheet models were developed to evaluate these cases. The spreadsheet models needed to adequately model atria and account for internal heat gains, radiation, convection, conduction, and ventilation. These models were intended for use in the classroom as well as in preliminary design. The work required that the spreadsheet model be calibrated with a sophisticated computational fluid dynamics (CFD) analysis using the Star-CCM+ software (MacDonald 2014).

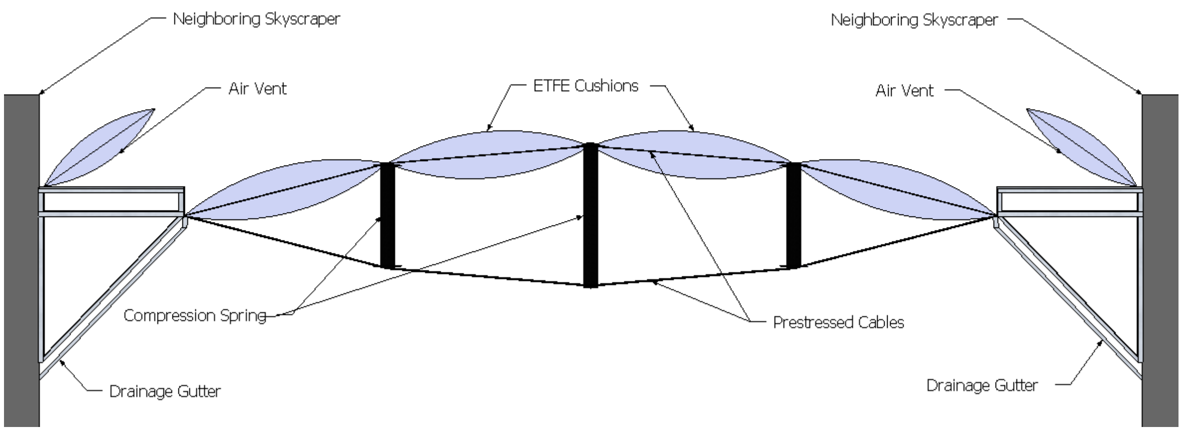

Figure 1-1 Cable-spring truss supporting ETFE cushions between buildings.

(a) (b)

Figure 1-2 (a) Finned heat sink and (b) Hong Kong skyline. (Johnson 2004; Louie and Spears 2008)

The literature review on atria and building energy analysis in Chapter 2 presents many advantages and disadvantages of atria, and explores the development of building energy software and models. This work presents the spreadsheet models for the conditioned atrium case in Chapter 3, the no atrium case in Chapter 4, and the unconditioned atrium case in Chapter 5. Calibration of the spreadsheet models using CFD analysis is presented in Chapter 6. The research results from the spreadsheet models are presented and discussed in Chapter 7 along with ideas for future research. Conclusions on the analyses and research are presented in Chapter 8.

2 LITERATURE REVIEW

Buildings in the United States collectively use a large portion of the nation's total energy consumption to maintain a comfortable indoor environment. There are two approaches to saving energy according to Tam (2011): increasing efficiency and decreasing demand. Many incentives including Leadership in Energy and Environmental Design (LEED) certification and tax breaks have been employed to get owners and developers to increase the energy efficiency of current and future buildings within reasonable fiscal and comfort limits (USGBC 2009). Reducing energy demands has been the driving force behind the establishment of the Department of Energy and HVAC engineering procedures and analysis models for the last century and especially since the 1973 oil embargo (Hunn et al. 2010). Good HVAC design and management result in a comfortable indoor environment for people at a minimized cost to maintain. This literature review explores atria history, characteristics, issues and solutions, and HVAC simulation.

2.1 Atria History

The atria's beginnings can be traced back to the courtyards and central halls of the Greek and Roman eras. They were employed to allow light and ventilation into inner rooms of buildings. Glazed atria did not exist until the mid 19th century when glass and iron technological advancements made spanning larger distances with a brittle glass more feasible. Glazing causes a reduction in natural light penetration in exchange for protection from the outside environment.

Early atria had very small glass panels supported by lots of supporting ironwork (see Figure 2-1 source (Storye 2009)). Improvements in glass and steel have allowed for larger spans and clearer glass. ETFE has added a new dimension to modern atria with its capability of very large spans, superlight support structure, and controllable transparency. Atria are often used as an architectural or aesthetic feature. (Boëthius 1934; Sharples and Shea 1999; Winser 2004)

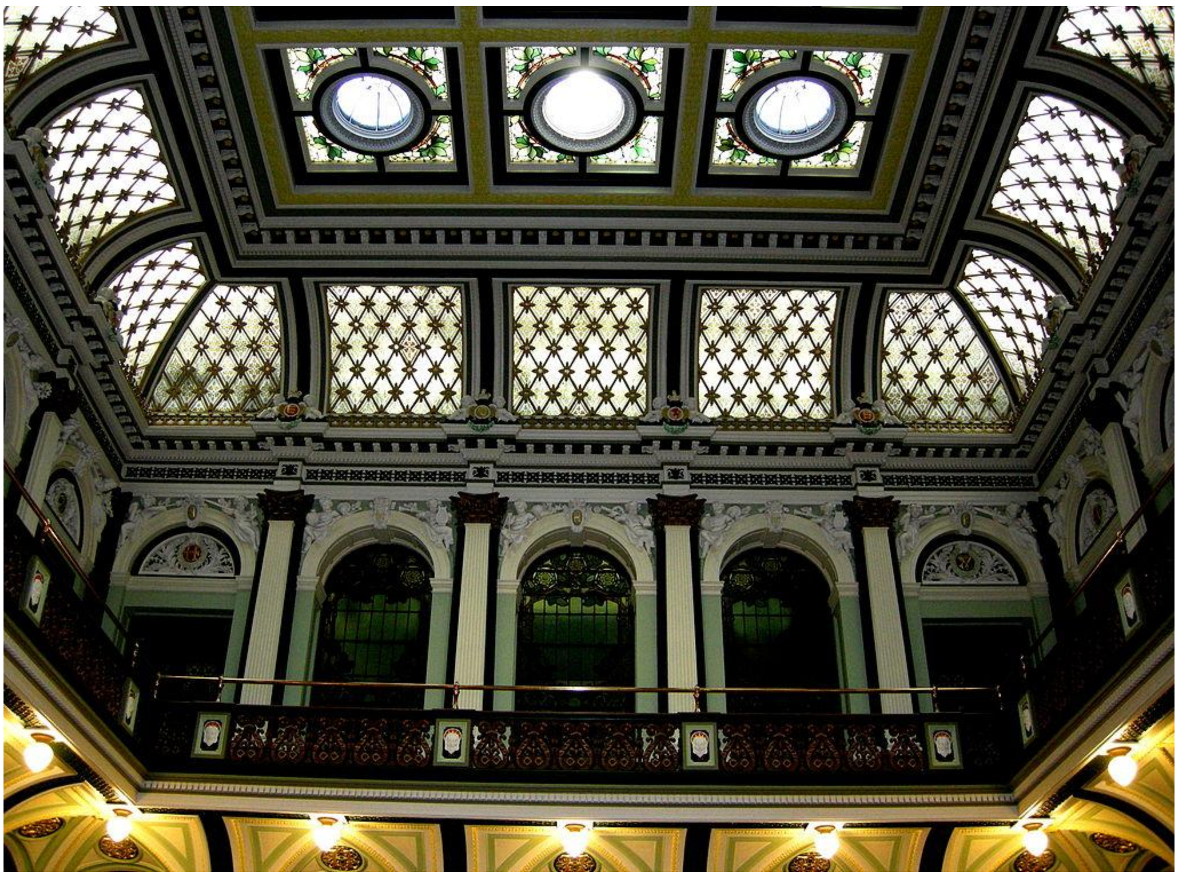

Figure 2-1 Atrium in Halifax Town Hall, UK built in 1863

2.2 Modern Atria Characteristics

Modern atria are typically composed of large open spaces usually several stories high enclosed by a transparent (or mostly transparent) envelope. Many modern atria utilize their large volumes and solar gains to help with the ventilation of the atria and adjacent spaces. Modern atria utilize more insulative and clear fenestration and are capable of spanning very large distances (see Figure 2-2). Even though the primary function of many atria is aesthetics, many atria are also used to help with the building's natural or mixed-mode ventilation strategy.

Figure 2-2 Parkview Green atrium with ETFE roof and glass walls

Atria are becoming more popular in architectural applications according to Hung and Chow (2001) because of their versatility and architectural beauty. In highly populated areas like Hong Kong, atria are being used more often as public spaces because they are large and light enough to feel like outside but often more comfortable (Xue et al. 2012). This increased popularity has exposed many issues with atrium design.

2.3 Atrium Issues and Solutions

Atria have several issues that typically govern how they are designed. One issue is light penetration into the adjacent rooms and areas. There are also conditioning issues with solar gains in large, highly glazed areas like atria as well as temperature stratification issues. Finally, atrium envelopes are somewhat limited in their insulation capability. Each of these issues poses a problem to the aesthetics and/or cost of the atrium, and some of them compete with each other.

Atria are often used to bring natural light into areas of a building that otherwise could only be artificially lit. This can help reduce the cost of artificial lighting. The first issue with using an atrium to provide natural light is that the envelope blocks some of the sunlight. Sharples and Shea (1999) conducted a study on atrium roof configurations under real sky conditions. They concluded that mathematical models used did not accurately account for the loss of light penetration due to the envelope. This implies that the envelope needs to be considered when analyzing natural lighting. Once the natural lighting in the atrium is accounted for, the next issue is with the amount that gets into the adjacent rooms. Du and Sharples (2011) explored how far natural light gets into areas directly adjacent to a rectangular atria. They used a ray-tracing program with a parametric model to adjust the atrium size, building height, room depths, balcony proportions, and wall reflectivity. They found that more light penetrates deeper in the upper story rooms and less light penetrates shallower in the lower story rooms. However, if adjacent room walls and windows are designed well, the differences in natural light penetration between the top floors and the bottom or middle floors can be minimized. This implies that there is a tradeoff between less expensive construction and uniform natural lighting for the areas near the bottom of the atrium.

Atrium envelopes require regular maintenance and cleaning. Even with self-cleaning glass or ETFE, dust and debris accumulate over time on the surfaces of the envelope. This debris affects the amount of natural light that gets into the atrium and the atrium's aesthetic appeal. Cleaning cost must be added to the atrium design. (Gritch and Eason 2010)

Natural lighting is great for aesthetics but can increase solar gains. During the winter months solar gains are a welcome source of free heating, but during the summer months solar gains become an extra load on the air-conditioning system and might result in very uncomfortable conditions in the atrium. (Chwieduk 2009) One technology that has been developed to help control solar gains is variable shading ETFE foil cushions (see Figure 2-3). These cushions consist of two layers with positive and negative printed patterns that transmit sunlight when the layers are apart and reflect sunlight when the layers are together. (Colmenar-Santos et al. 2013; Vector Foiltec 2012) Another solution for glass envelopes is shading through the use of blinds, panels, or even photovoltaic panels. (James et al. 2009)

Figure 2-3 Variable shading ETFE foils used in the Kingsdale School in London, UK and Festo headquarters in Esslingen, Germany. (Vector Foiltec 2012)

Another issue, especially relative to the use of sky bridges in the atrium, is temperature stratification. Stratification occurs when warm air rises and cool air sinks, due to air buoyancy, and settles into two separate temperature layers. This stratification can occur depending on the locations and rates of thermal sources, sinks, and vents. Kuesters and Woods (2012) adjusted the heat source and ventilation rates and observed how the stratified layers changed based on certain rates. Their CFD and analytical models were confirmed with a scale water and salt physical model. They also observed how thermal plumes, caused by a heat source in a cold layer or a heat sink in a warm layer, affected the two stratification layers. They concluded that maintaining a uniform temperature throughout a large volume could be difficult and expensive but it is possible to use hydronic cooling fins to maintain thermal comfort in specific occupied areas (see Figure 2-4).

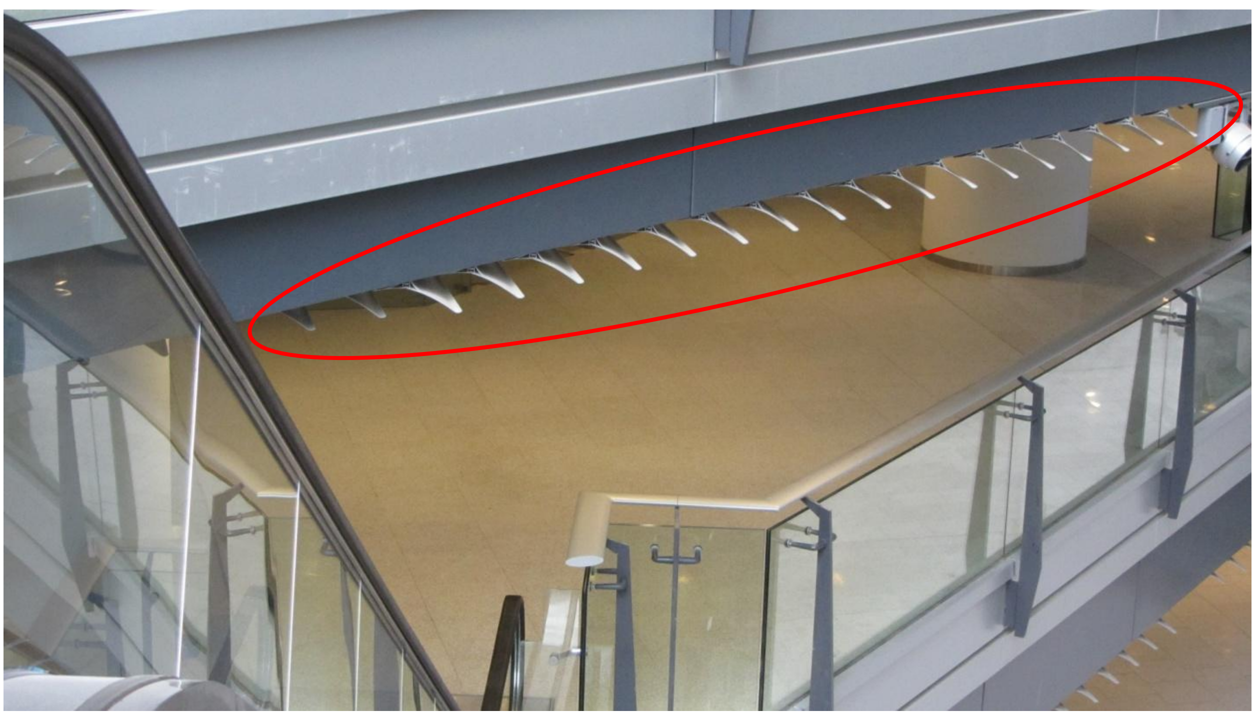

Figure 2-4 Hydronic cooling fins under balconies in the Parkview Green atrium

A possible benefit of certain atrium geometries is that they can reduce the total building surface area. Since heat transfer is usually directly proportional to the surface area, this reduction can provide an avenue of energy savings (Incropera et al. 2011). An issue with this concept, especially if the atrium is conditioned, is the envelope's resistance to heat transfer. Atrium envelope materials are often not as insulative as other wall, window, or roof materials. Increasing insulation of the atrium envelope usually means more layers (or thicker layers) of material which makes the envelope less transparent. Additionally, surface treatments to reduce radiative heat transfer from the envelope surface often make the surface more reflective as well.

Often these issues combine and can result in cases where maintaining a comfortable environment throughout can be very costly. To help the atrium conditioning systems, green studies are conducted to determine if the atria can be used for natural ventilation (Brager and De Dear 2001; Brager et al. 2000; Eisele and Kloft 2003; Etheridge and Ford 2008; Lee and Strand 2009; Pasquay 2004; Priyadarsini et al. 2004). Nightly cooling, thermal reservoirs (Santamouris et al. 1996), solar chimneys (Ding et al. 2005), or some other naturally occurring phenomenon could also be used to reduce the costs of heating and cooling buildings.

2.4 Atrium Simulation

Understanding the phenomena that may control an atrium is extremely important in ensuring that the atrium cost is, or can be, controlled and managed. To understand these phenomena, numerical analyses need to be conducted and evaluated. Several options exist in the realm of HVAC analysis, but very few methods can handle atria well. These methods range from the simplest rough empirical approximations, through standard linear heat transfer theory, up to extensive discretized CFD methods used to solve the differential equations that describe the transfer of energy, mass, and momentum.

The simplest methods proposed in the literature do not work well with atria. They include the Overall Thermal Transfer Value (OTTV) method, which only very roughly estimates normal building energy demands. There is also a quadratic method proposed by Jaffal et al. (2009). It is similar to the OTTV method, but uses a few more variables. The key characteristic of these models is that heat transfer theory is not included directly. It is only an indirect result based on curve fitting.

The OTTV method proposed by Chow and Chan (1995) uses several empirical graphs and correction coefficients to approximate cooling loads. While the method is very simple, it does not handle climates that get very cold during the winter and it requires the indoor temperature to be 25.5°C (78°F) throughout the year. The correction factors would have to be modified for different indoor temperatures and climatic conditions. It also cannot handle complicated building elements including atria.

A quadratic building energy method was proposed by Jaffal et al. (2009). They attempted to model a building's annual energy demand as a function of envelope material. They used linear and quadratic approximations to help the designer decide on an envelope material early on. Basic heat rates are calculated from different sources, multiplied by different coefficients, and summed together. Their annual energy demand values were low and some of the options resulted in infeasible, negative, annual energy consumption values. While these methods are simple, they lack the insight of theory and the proof of reality.

Methods with medium complexity are based on the linearized equations of heat transfer. Radiation is a very nonlinear phenomenon that is linearized to reduce complexity. The most popular method is the heat balance method published by the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE), which balances the heat transfer between the different facets of the model with a series of linear equations. A few other methods have been proposed with the same heat balance foundation and added capabilities including: solar ray tracing or natural ventilation prediction. ASHRAE's radiant time series method uses many of the heat balance equations and correlations with the difference of being designed for spreadsheet implementation (ASHRAE 2001). The basic framework for ASHRAE's heat balance method is the use of zones and surfaces. Zones are volumes of air that are controlled by some HVAC system. The surfaces are the interfaces between the interior zone and the outside environment. A series of empirical formulas are used to determine solar and weather parameters for the model. That information along with geometry, materials, space usage, and occupancy schedules provide the needed input information for the analysis. The method then balances the heat transfer between zones and through walls and windows with linear equations for conduction, convection, radiation, internal sources, and ventilation. The heat balance method can also account for basic transient effects of heating and cooling different materials. The heat balance method is usually implemented in software packages such as EnergyPlus (USDOE 2013).

Several analysis engines have been developed over the years to analyze HVAC designs. The most successful ones have been Building Loads Analysis and System Thermodynamics (BLAST) (Pedersen 1993) and Department of Energy version 2 (DOE-2) (LBL 1980). Several current building energy modeling software packages include many of the algorithms and modules from BLAST and DOE-2. The most popular packages are EnergyPlus (USDOE 2013) and the Quick Energy Simulation Tool (eQUEST) (Hirsch 2014). The eQUEST package is a continuation of DOE-2, and the EnergyPlus package is a combination of different parts of BLAST and DOE-2 (Crawley et al. 2000; Pedersen et al. 1997). Capability and accuracy are improved with each new release of the different programs. Crawley et al. (2008) compared 20 different proprietary building energy modeling software packages based on usability, library databases, and accuracy. They ultimately concluded that each of them started from very similar foundations and produced very similar results.

One of the issues with these larger software packages is understanding and acquiring the needed input information. Pan et al. (2010) proposed a few point value models that assume a temperature profile in the different zones, and use that information as the input for a heat balance method program. As many software systems have been improved by increasing options, capabilities, complexity, etc., many people have attempted to develop simpler implementations of the ASHRAE heat balance method. For example, Wang et al. (2009) worked on a block model that divides a large atrium into vertical zones. A heat balance was done on each of the zones to determine the thermal loads in the atrium, predict the atrium temperature profile, and predict reasonable values for natural ventilation using buoyancy. This concept could have been used in the spreadsheet models described in Chapters 3 - 5, but it would have added a significant level of complexity and nonlinearity.

Another simplified method that is included in the ASHRAE manual is the radiant time series (RTS) method (ASHRAE 2001). The RTS method uses many aspects of the ASHRAE heat balance method, except that it captures transient information by using thermal response time series information for different materials. It is also designed to be used in a spreadsheet. The RTS method does not have information on how to analyze atria or their affect on adjacent rooms and areas. Chen and Yu (2009) suggested that the ASHRAE method for selecting weather input information for an energy analysis may not be the most accurate because many extremes do not happen coincidently. They used the RTS method to determine overall heat transfer information of different weather sources for a building. Then they measured the building throughout the year and determined that for each of the months the RTS method overestimated the heat transfer by 4 to 20%. They recommend using historical statistical data (incident solar, temperatures, winds, etc.) to more accurately model the building. ASHRAE has adopted more of this approach to modeling in recent years, but it requires much more specific weather information that ASHRAE requires a subscription to access (ASHRAE 2013).

The most complex analysis methods are CFD analyses. CFD analyses use the general differential equations governing fluid flow and heat transfer, and apply them to a discretized model. Often the differential equations are highly nonlinear and therefore sensitive to issues in the discretization, definition, initial conditions, and boundary conditions. Several CFD programs and algorithms have been proposed through the years to deal with the complexities involved in building and atrium analysis. Voeltzel et al. (2001) designed a CFD-like modeling program (AIRGLAZE) to attempt to accurately model airflows and temperatures in highly glazed atria. They compared their program data to empirical data collected from IEA Annex 26 experimental atrium in Japan. The highly glazed spaces that they explored were not very deep, and much of the sunlight reflected out of the atrium. They did not test their program on any large or deep atria. Their modeling program accounts for solar patches and the effects of long and shortwave radiation effects on the thermal environment in an atrium. Their software is not currently available but many of the radiation algorithms they pioneered are included with other programs like Star-CCM+. (CD-Adapco 2014)

CFD analyses are typically used to identify air currents in a space, and their effect on the energy usage of the space. For example, Hussain and Oosthuizen (2012) looked at different configurations of atria and vents in a simple three story building. They evaluated temperatures, natural ventilation rates, and thermal comfort for their models.

An issue with CFD analyses is the amount of data they require. As a result, they are often simplified. The simplifications usually only allows the analysis to answer very specific questions. For example, Kim et al. (2001) explored how a semi-enclosed room next to an atrium exchanges heat with the adjacent atrium. The CFD analysis was used in conjunction with a radiative and HVAC system simulation, which increased the complexity of the analysis. In order to keep the analysis from getting too complicated, a very simple situation was analyzed. The model consisted of a large atrium with one ground-level adjacent room. The temperature control in the room was modeled with a radiative panel. While the analysis was very complicated, the case that was evaluated was too simple to account for all of the variables. Attempting to capture all of the information and variables in one analysis is often infeasible due to computing constraints (Wang and Zhai 2012).

2.5 Chapter Summary

Atria are typically defined as a large open areas that are enclosed by transparent envelopes. Modern atria are often used for their architectural aesthetics. Their large unobstructed volumes and clear envelopes provide many benefits to adjacent buildings such as increased natural sunlight, but they also have issues that require careful consideration. Atrium simulation is often much more complicated than standard building energy simulation. This complexity has resulted in several programs and algorithms to capture different aspects of energy simulation. As part of this research, a spreadsheet analysis model was developed capable of accounting for atria and determining annual HVAC energy demands.

3 CONDITIONED ATRIUM SPREADSHEET MODEL

Determining annual HVAC energy demands on a typical building is straightforward and a good method is presented in Fundamentals Handbook published by ASHRAE (2013). Including an atrium in the analysis increases the complexity of the analysis because of the possibility of coupling between the heat transfer between the atrium, inside, and outside environments. This chapter presents the equations and information used to develop the conditioned atrium spreadsheet model. The key feature of this model is that the average atrium temperature is set and directly controlled by an independent atrium HVAC system. This chapter describes the problem definition and the spreadsheet organization.

3.1 Problem Definition

A 100-building, pyramid-shaped greenplex as shown in Figure 3-1 was analyzed to determine its annual HVAC energy demands. The footprint of each tower was 50 meters square. The story height was 4 meters. The towers were spaced 25 meters apart in a square grid. The buildings were configured as follows: 36 thirty-story towers, 28 forty-story towers, 20 fifty-story towers, 12 sixty-story towers, and four seventy-story towers. There were 420,000 people living and working in this city. The atrium roof did not cover any of the tower roofs but did slope up from the shorter perimeter towers to the 70-story center towers (see Figure 3-1).

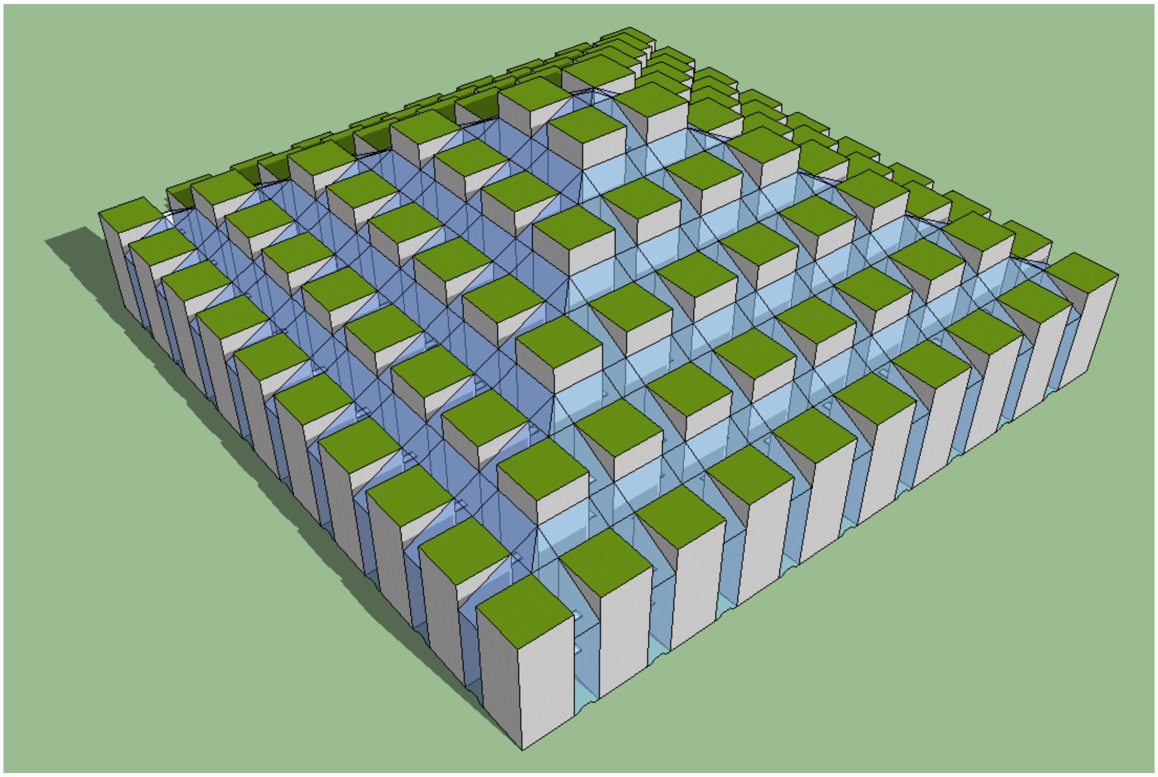

Figure 3-1 Pyramid greenplex

The facades of the towers were 20% stone/insulation and 80% glass fenestration. There were large atria between all of the buildings. The atrium envelope was three-layer ETFE cushions supported by a cable-spring trusses.

The outside temperatures ranged between a minimum of 0°F (-17.8°C) in the winter and a maximum of 100°F (37.8°C) in the summer. The indoor temperature was maintained between 65°F (18.3°C) and 75°F (23.9°) throughout the year. This pyramid greenplex was located in Provo, Utah. Climate and location data were used to assist in the solar calculations and climatic considerations. It should be noted that this particular greenplex configuration was somewhat arbitrary and could have been defined with different geometry, materials, populations, or climatic information.

3.2 Spreadsheet Description

The spreadsheet program developed for this research computed the annual HVAC energy demands for the greenplex with a conditioned atrium. The spreadsheet program consisted of 15 separate sheets. The first sheet was labeled the "Constants" sheet. The next 12 sheets were monthly sheets, one for each month. The "Annual" sheet compiled the information from each of the monthly sheets. The final sheet was the "Reference" sheet. Equations 3-1 to 3-12, Figure 3-3, and the data included in Tables 3-4 to 3-9 are from ASHRAE's Fundamentals handbooks (ASHRAE 2001; ASHRAE 2013). The rest of the equations listed in this chapter were developed from specific applications of Fourier's Law (conduction), Newton's Law of Cooling (convection), and specific heat mass flow rate equation (ventilation). Fourier's Law and Newton's Law of Cooling were implemented as resistor models (Incropera et al. 2011).

3.2.1 Constants Sheet

The values entered on the "Constants" sheet corresponded to values that were constant for the model. These values included building geometry, material thermal properties, and some location information. For example, the following values were used for the pyramid greenplex:

lat = location latitude = 40.2 degrees north

L = tower length = 50m

W = tower width = 50m

A_{floor} = floor area = 9,450,000m^2

V_{towers} = total volume of all 100 towers = 3.78x10^7 m^3

V_{atrium} = volume of the atrium = 3.34x10^7 m^3

$R_{conv.i}$ = R-value for convection inside the buildings = 0.2m^2-K/W

$R_{conv.a}$ = R-value for convection inside the atria = 0.75m^2-K/W

$R_{conv.o}$ = R-value for convection outside = 0.05m^2-K/W

R_{wall} = R-value for conduction through wall = 2.5m^2-K/W

R_{roof} = R-value for conduction through roof = 5.0m^2-K/W

R_{glass} = R-value for conduction through glass = 0.366m^2-K/W

R_{ETFE} = R-value for conduction through ETFE = 0.55m^2-K/W

α_{wall} = absorptivity of the wall = 0.7

τ_{glass} = transmissivity of glass = 0.93

τ_{ETFE} = transmissivity of ETFE = 0.45

Δ = percentage of air volume changed each hour = 0.35ch/hr

ρ_{air} = density of air = 1.015kg/m^3

c_p = specific heat of air = 1.007kJ/kg-K

p_{glass} = percentage of facade that is "glass" = 80%

p_{wall} = percentage of facade that is "wall" = 20%

$A_{wall.a.i}$ = opaque wall area inside the atrium in section i = 168,000m^2

$A_{win.a.i}$ = window area inside the atrium in section i = 672,000m^2

$A_{ETFE.t}$ = total tilted ETFE area = 312,340m^2

$A_{ETFE.v}$ = total vertical ETFE area = 82,200m^2

$A_{wall.i}$ = opaque wall area facing in direction i = 17,000m^2

$A_{win.i}$ = window area facing in direction i = 68,000m^2

A_{roof} = total roof area = 250,000m^2

$\Sigma_{ETFE.t}$ = tilted ETFE tilt angle = 28.1°

$\Sigma_{ETFE.v}$ = vertical ETFE tilt angle = 90°

Σ_{roof} = roof tilt angle = 0°

The latitude (lat) for Provo, Utah is 40.2 degrees north. This is entered as positive for northern latitudes and negative for southern latitudes.

Several geometric properties were calculated from the dimensions given in Section 3.1 including the: length (L), width (W), total floor area (A_{floor}), tower volume (V_{towers}), and atrium volume (V_{atrium}). Additionally, wall, window, roof, and atrium envelope surface areas, facing directions, and tilts were determined and listed in Tables 3-1, 3-2, and 3-3.

Table 3-1 Atrium Section Panel Geometric Information

	Roof				**Wall**			
	North	East	South	West	North	East	South	West
Tilt [°]	28.1	28.1	28.1	28.1	90	90	90	90
Direction [°]	0	90	180	270	0	90	180	270
Areas [m^2]	78085	78085	78085	78085	20550	20550	20550	20550

Table 3-2 Tower Wall and Window Areas in Each Atrium Section

	North	East	South	West
Wall Area [m^2]	168000	168000	168000	168000
Window Area [m^2]	672000	672000	672000	672000

Table 3-3 Exposed Tower Geometric Information

	Walls				**Roof**
	North	East	South	West	
Tilt [°]	90	90	90	90	0
Direction [°]	0	90	180	270	180
Wall Areas [m^2]	17000	17000	17000	17000	250000
Window Areas [m^2]	68000	68000	68000	68000	-

The indoor convection resistance values ($R_{conv.i}$) were set based off information from a paper by Awbi (1998). The outside convection resistance ($R_{conv.o}$) was calibrated using a CFD analysis with a wind speed of 2.0 m/s that will be discussed in Chapter 6. The CFD values for the outside resistance coefficient was compared to several empirical convection results (see Figure 3-2) from several sources. (ASHRAE 2001; ASHRAE 2013; Incropera et al. 2011). The atrium coefficients were assumed to be between inside and outside resistance values because the atrium is shielded from the outside winds however its larger volume and ventilation rates allow for larger convection currents than typically occur inside a normal space. (Gritch and Eason 2010)

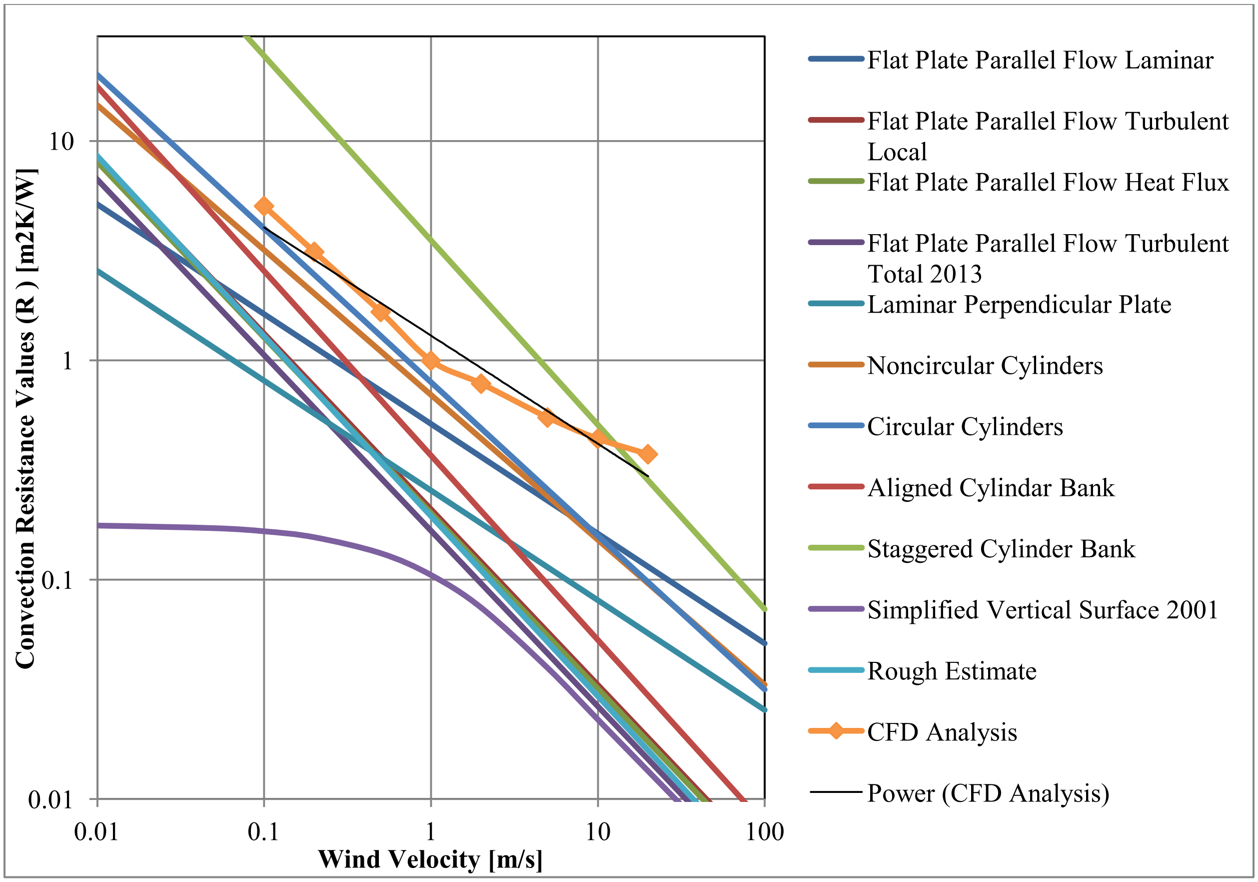

Figure 3-2 Comparison of several different convection correlations.

The wall resistance value (R_{wall}) refers to the portions of the tower facade that are opaque and they were assumed to have a layer of masonry (R = 0.15), an air gap (R = 0.18), a layer of wood (R = 0.14), a layer of foam insulation (R = 1.95), and a layer of gypsum sheetrock (R = 0.08). Each layer can be added together to get a total conduction resistance value (R_{wall} = 2.50m^2-K/W). The resistance value used to represent a 7/8 inch thick panel of insulated glass

(R_{glass}) was 0.366m^2-K/W. The roof resistance value (R_{roof}) was assumed to be a green roof and consist of 12 inches of soil (R = 1.59), at least 4 inches of concrete (R = 0.15), an air space (R = 0.18), 6 inches of insulation (R = 3.00), and a layer of sheetrock (R = 0.08) with a total resistance of 5.00m^2-K/W. The resistance value for ETFE (R_{ETFE}) represents a three-layer ETFE cushion from Vector Foiltec which equals 0.55m^2-K/W (Winser 2004).

The radiative absorptivity of the opaque tower facade (α_{wall}) was set at 0.70 to represent the absorptivity of a light-gray masonry surface. The transmissivity of the glass windows (τ_{glass}) were 0.93, which is standard for glass. The three-layer ETFE cushion used in the model had one layer of white ETFE used to diffuse the light in the atrium. This white ETFE cushion had a transmissivity (τ_{ETFE}) of 0.45.

The air changes per hour parameter (Δ) refers to the percentage of the tower or atrium air volume that is replaced with outside air each hour. There are a few lower bounds for this value based on occupancy and space use type. Enough air needs to be replaced to keep carbon dioxide and contaminant levels low enough to keep occupants from getting sick. This value was set at 0.35 air changes per hour which is a standard minimum for general occupancy spaces (ASHRAE 2013).

Table 3-4 Basic Minimum Ventilation Rates and Criteria (ASHRAE 2013)

Ventilation Criteria	Lower Limits
Minimum per person	27 m^3/hr
General Use Building Minimum	0.35 changes/hr
Infiltration	0 to 1 changes/hr
(New Construction, Conservative)	(0.5 changes/hr)

3.2.2 Monthly Sheets

The monthly sheets required month-specific information and performed calculations for one "design day" in each month. The design day was the 21st day of each month and it conservatively approximated the two weeks before and the two weeks after the design day. All of the thermal loads on the buildings were calculated at each hour of the design day for the different control volumes. The monthly sheets ultimately calculated the greenplex HVAC energy demand for the whole design day. Each month sheet was subdivided into an input block, an atria block, a tower block, and a summary block.

The input block contained month-specific input information as well as some general information transferred from the "Constants" sheet. As an example, the following values were used in the "July" monthly sheet in addition to the values used in Section 3.2.1:

A = apparent solar irradiation = 1085W/m^2

B = atmospheric extinction coefficient = 0.207

C = parameter depending on dust and moisture content of atmosphere = 0.136

ρ_g = ground reflectivity = 0.15

CN = clearness number = 1.0

δ = declination of the earth = 20.57deg

T_{atrium} = average temperature in the atrium = 23.89°C

T_{in} = average temperature inside the towers = 23.89°C

T_{high} = daily outside high temperature = 37.78°C

T_{low} = daily outside low temperature = 21.18°C

The first six values in this section (A, B, C, ρ_g, CN, δ) were used in the atria and tower blocks to calculate the amount of solar radiation incident upon different surfaces in the model.

Table 3-5 includes the values for A, B, C, and δ for the 21st day of each month. These values were used in conjunction with the temperature information above to solve for surface temperatures, and to ultimately determine the heat transfer rates between the greenplex and the surrounding environment.

Table 3-5 Solar Parameters for the 21st Day of Each Month (ASHRAE 2001)

Month	E_o W/m^2	δ deg	A W/m^2	B	C
Jan	1416	-20.00	1230	0.142	0.058
Feb	1401	-10.80	1215	0.144	0.060
Mar	1381	0.00	1186	0.156	0.071
Apr	1356	11.60	1136	0.180	0.097
May	1336	20.00	1104	0.196	0.121
Jun	1336	23.45	1088	0.205	0.134
Jul	1336	20.60	1085	0.207	0.136
Aug	1338	12.30	1107	0.201	0.122
Sep	1359	0.00	1151	0.177	0.092
Oct	1380	-10.50	1192	0.160	0.073
Nov	1405	-19.80	1221	0.149	0.063
Dec	1417	-23.45	1233	0.142	0.057

The atria block balanced the heat transfer between the buildings and the outside environments through the atrium for each hour of the design day. It specifically calculated the surface temperatures of the tower walls inside the atrium, and determined how much solar heat conducted into the towers and how much convected into the atrium. The outside temperature (T_{out}) for each hour of the day is determined from Equation 3-1:

$$T_{out} = T_{low} + PDT(T_{high} - T_{low}) \tag{3-1}$$

where T_{low} is the low temperature for the design day, T_{high} is the high temperature for the day, and PDT is the percentage of the daily temperature range determined from Table 3-6 for each hour of the day.

Table 3-6 Percentage of Daily Temperature Range (PDT) (ASHRAE 2013)

Time (h)	%	Time (h)	%	Time (h)	%
1	13	9	29	17	90
2	8	10	44	18	79
3	4	11	61	19	66
4	1	12	77	20	53
5	0	13	89	21	42
6	2	14	97	22	32
7	7	15	100	23	24
8	16	16	97	24	18

The solar geometry angles shown in Figure 3-3 (ASHRAE 2013) must be determined. The hour angle (H) in degrees is calculated with Equation (3-2:

$$H = (t - 12hours)\frac{360°}{24hours} \tag{3-2}$$

where t is the time of day in hours. The height of the sun in the sky or solar altitude (β) is calculated from Equation 3-3:

$$\sin(\beta) = \cos(lat)\cos(\delta)\ \cos(H) + \sin(lat)\sin(\delta) \tag{3-3}$$

where lat is the site latitude and δ is the declination.

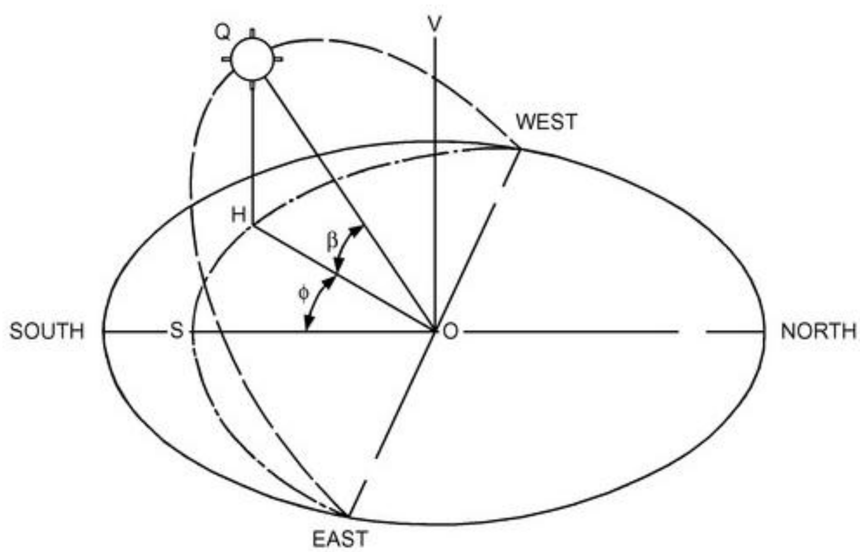

Figure 3-3 Solar geometry angles.

The solar azimuth (ϕ) can also be calculated from Equation 3-4:

$$\cos(\phi) = \frac{\sin(\beta)\cos(\text{lat}) - \sin(\delta)}{\cos(\beta)\cos(\text{lat})} \tag{3-4}$$

where δ is the Earth's declination in degrees. The surface solar azimuth (γ) can be determined from Equation 3-5:

$$\gamma = \phi - \psi \tag{3-5}$$

where ψ is the surface facing azimuth in degrees (south is 0°, east is -90°, and west is 90°). Finally, the surface-solar incident angle (θ) can be calculated from Equation 3-6:

$$\cos(\theta) = \cos(\beta)\cos(\gamma)\sin(\Sigma) + \sin(\beta)\cos(\Sigma) \tag{3-6}$$

where Σ is the surface's tilt from horizontal in degrees and β is calculated from Equation (3-3.

After the solar geometry angles have been determined, they are used to determine the amount of solar radiation that makes it through the atmosphere to the surface of the earth. The direct normal irradiance is calculated from Equation 3-7:

$$E_{DN} = \begin{bmatrix} \left(\dfrac{A}{e^{\left(B/\sin(\beta)\right)}}\right) CN \quad if\ \beta > 0 \\ 0 \quad otherwise \end{bmatrix} \tag{3-7}$$

where CN is the clearness number, A is the apparent solar radiation, B is the atmospheric extinction coefficient, and β is the solar altitude. The sun is only shining if it is above the horizon ($\beta > 0$). The clearness number (CN) represents how clear the sky is. For a perfectly clear day CN would be equal to one, and for a cloudy day CN would be about 0.5. Surface direct irradiance (E_D) is the amount of direct beam solar radiation incident upon a surface at a given time and location. It is calculated from Equation 3-8:

$$E_D = \begin{bmatrix} E_{DN}\cos(\theta) \quad if\ \cos(\theta) > 0 \\ 0 \quad otherwise \end{bmatrix} \tag{3-8}$$

which is only valid if the sun is in front of a surface (i.e. $\cos(\theta) > 0$). Y is the ratio of sky diffuse on vertical surface to sky diffuse on horizontal surface. Y is calculated from Equation 3-9:

$$Y = \begin{bmatrix} 0.55 + 0.437\cos(\theta) + 0.313\, cos^2(\theta) \quad if\ \theta > -0.2 \\ 0.45 \quad otherwise \end{bmatrix} \tag{3-9}$$

where θ is the surface-solar incident angle. The diffuse solar irradiation (E_d) refers the sunlight that is scattered as it enters the atmosphere and lights up the sky. The sky shines in all directions and is the major source of radiation gain on shaded surfaces. It is defined by Equation 3-10:

$$E_d = \frac{C\, Y\, E_{DN}(1+\cos(\Sigma))}{2} \tag{3-10}$$

where C is the atmospheric parameter and Σ is the surface tilt. Sometimes a significant amount of radiation is reflected from the ground onto a surface. This ground-reflected solar radiation is determined from Equation 3-11:

$$E_r = \frac{E_{DN}(C+\sin(\beta))\rho_g(1-\cos(\Sigma))}{2} \tag{3-11}$$

where ρ_g is the ground surface reflectivity (typically 0.2 for a standard mixture of ground surfaces). Finally, the total surface irradiance can be determined by summing the contributions from direct beam solar, diffuse solar, and ground reflected solar radiation in Equation 3-12:

$$E_t = E_D + E_d + E_r \tag{3-12}$$

This total incident solar heat rate E_t needs to be determined for each surface in the model (walls, windows, roofs, ETFE, etc.) for each hour of the design day.

Once the incident solar heat rate was calculated, the amount of radiation transmitted through the ETFE envelope was determined from Equation 3-13:

$$E_{atria} = \tau_{ETFE}\, E_{ETFE} \tag{3-13}$$

where E_{ETFE} is E_t for an ETFE envelope surface, and τ_{ETFE} is the transmissivity (or transparency) of the ETFE. Then the solar energy transmitted into the atrium needed to be divided between the tower walls inside the atrium. This was done by multiplying the energy into each atrium section by an ETFE envelope to interior wall area ratio in Equation3-14:

$$E_{wall} = E_{atria} \frac{A_{ETFE}}{A_{wall}} \tag{3-14}$$

The value of E_{wall} represents the average amount of energy from the sun that makes it into the atrium and is absorbed into or transmitted through a unit area of wall or window material.

The next section of the atrium block calculated the thermal forces including incident solar radiation and ventilation from Equations 3-15 to 3-17:

$$F_{wall} = \alpha_{wall}\, E_{wall}\, A_{wall.a} + \frac{T_{in}\, A_{wall.a}}{R_{conv.i}+R_{wall}} + A_{wall.a} \frac{T_{atrium}}{R_{conv.a}} \tag{3-15}$$

$$F_{window} = \frac{T_{in}\, A_{glass.a}}{R_{conv.i}+R_{glass}} + A_{wall.a} \frac{T_{atrium}}{R_{conv.a}} \tag{3-16}$$

$$F_{atrium} = \left(\frac{T_{out}\, A_{ETFE}}{R_{conv.a}+R_{conv.o}+R_{ETFE}}\right) + 0.277\, V_{at}\, \mathit{\Delta}_{at}\, \rho_{air}\, c_p \tag{3-17}$$

These values were used in Equations 3-18 and 3-19 to determine the surface temperatures of the tower walls and windows inside the atrium:

$$T_{s.wall} = \frac{F_{wall}}{\frac{A_{wall.a}}{R_{conv.i}+R_{wall}} + \frac{A_{wall.a}}{R_{conv.a}}} \tag{3-18}$$

$$T_{s.window} = \frac{F_{window}}{\frac{A_{glass.a}}{R_{conv.i}+R_{glass}} + \frac{A_{glass.a}}{R_{conv.a}}} \tag{3-19}$$

Finally, the wall and window surface temperatures were used to determine the amount of heat transferring through the components of the greenplex. The heat conducting into the towers is calculated from Equations 3-20 and 3-21:

$$q_{wall.a} = \frac{A_{wall.a}(T_{s.wall.a} - T_{in})}{R_{wall}+R_{conv.i}} \tag{3-20}$$

$$q_{window.a} = \frac{A_{windo.a}(T_{s.window.a} - T_{in})}{R_{glass}+R_{conv.i}} \tag{3-21}$$

The heat convecting into the atrium is calculate from Equation 3-22:

$$q_{atrium} = \frac{A_{ETFE}(T_{out}-T_{atrium})}{R_{conv.a}+R_{ETFE}+R_{out}} + 0.277\ V_{atrium}\ \Delta_{atrium}\ \rho_{air}\ c_p(T_{out} - T_{atrium}) +$$

$$0.277\ V_{towers}\ \Delta_{towers}\ \rho_{air}\ c_p(T_{in} - T_{atrium}) + \sum_{i=1}^{n}(T_{s.i} - T_{atrium})\frac{A_i}{R_{conv.a}} \tag{3-22}$$

where n is number of surfaces (windows and walls) inside the atrium.

The tower block balances the heat transfer between the towers and the outside environment through the exterior tower walls and windows. Equations 3-2 through 3-12 were used to determine the solar radiation incident on each of the exterior walls. The heat flux of incident solar radiation absorbed was calculated from Equation 3-23:

$$E_{wall} = \alpha_{wall}E_t \tag{3-23}$$

where E_t is the incident solar heat rate on the exterior wall surfaces of the towers. Then the outside wall surface temperature was calculated from Equation3-24, and the outside window surface temperature was calculated from Equation 3-25:

$$T_{s.wall} = \frac{E_{wall}+\frac{T_{out}}{R_{conv.o}}+\frac{T_{in}}{R_{conv.i}+R_{wall}}}{\frac{1}{R_{conv.i}+R_{wall}}+\frac{1}{R_{conv.o}}} \tag{3-24}$$

$$T_{s.window} = \frac{\frac{T_{out}}{R_{conv.o}}+\frac{T_{in}}{R_{conv.i}+R_{glass}}}{\frac{1}{R_{conv.i}+R_{glass}}+\frac{1}{R_{conv.o}}} \tag{3-25}$$

With the outside surface temperatures, the heat rate into the towers through the exterior walls was calculated from Equations 3-26 and 3-27:

$$q_{wall} = \frac{A_{wall}(T_{s.wall}-T_{in})}{R_{wall}+R_{conv.i}} \tag{3-26}$$

$$q_{window} = \frac{A_{window}(T_{s.window}-T_{in})}{R_{glass}+R_{conv.i}} \tag{3-27}$$

Note that heat fluxes could be computed by first leaving the areas out of Equations 3-26 and 3-27, and then the total heat rate could be determined by multiplying the heat flux by the total wall or window area according to Equation 3-28:

$$q_i = A_i \, q''_i \tag{3-28}$$

The summary block compiled the information generated from the atria and tower blocks, and accounted for internal heat gains from people, lights, and equipment. It added all of the hourly information from each of the other blocks into a final daily heating and air-conditioning energy demand. The average metabolic heat rates for a person present in the building for each hour were entered into one column. Then equipment and light heat rates per floor area were entered into the next two columns for each hour of the day. The total heat generated inside the towers by the people can be determined from Equation 3-29:

$$q_{people} = n_{people} \, q_{met} \tag{3-29}$$

where n_{people} is the number of people inside the pyramid greenplex and q_{met} is the average metabolic heat rate per person in a given hour. The total heat generated by the equipment and lights can be determined from Equations 3-30 and 3-31:

$$q_{equip} = A_{floor} \, q''_{eq} \tag{3-30}$$

$$q_{lights} = A_{floor} \, q''_{lights} \tag{3-31}$$

where q''_{eq} is the average heat rate for the equipment in the building per floor area and q''_{lights} is the average lighting heat rate per floor area for the whole building (see Table 3-7). These values could be determined alternatively by assigning space uses throughout the building and then choosing appropriate equipment and lighting heat rates for each space use. The total heat rate due to equipment and/or lights could be calculated for each space usage type from Equations 3-30 and 3-31. The total heat rate for lights and equipment in the whole pyramid greenplex could be determined by summing up all of the heat rates for all of the individual spaces.

The conduction heat rates into the towers were computed by summing the heat rates from each of the exterior walls and windows. The conduction rates through the windows and walls into the towers from the atrium (see Equations 3-20 and 3-21 from the atrium block) were also combined. The solar radiation heat rates into the towers were computed for the sunlight that was transmitted through the atrium and interior windows and exterior windows. Finally, the tower ventilation heat rates from adjusting the temperature of air from outside to match the tower air temperature were computed using equation 3-32:

$$q_{vent} = 0.277\, V_t\, \Delta_t\, \rho_{air}\, c_p (T_{out} - T_{in}) \quad (3\text{-}32)$$

where V_t is the volume of the towers, Δ_t is the percentage of the tower air volume that it exchanged every hour, ρ_{air} is the density of air, and c_p is the specific heat of air.

Each of these hourly totals can be summed up for a total heating energy demand for the hour. Positive values indicate the amount of thermal energy the air-conditioner needs to remove from the system and negative values indicate the amount of energy the heater must supply to the system to maintain the temperatures in the towers and atria. The total daily energy demand is the sum of the absolute value of the hourly total heat rates for the towers and the atrium.

3.2.3 Annual Sheet

The last calculation sheet was the annual sheet. It took the total daily energy demand heating and air-conditioning values from each of the month sheets and calculated a total annual heating/air-conditioning energy demand. This was done by integrating a linear interpolation between each of the design days for the whole year from Equation 3-33:

$$E = \sum_{i=1}^{12} \frac{E_i + E_{i+1}}{2}\, nD_i \quad (3\text{-}33)$$

where E_i is the total energy demand for design day i, E_{i+1} is the total energy demand for design day i+1, and nD_i is the number of days in month i. The annual HVAC energy demand was also divided by the total floor area. This energy per floor area parameter can be used to compare the energy performances of buildings of different sizes.

3.2.4 Reference Sheet

The reference sheet had several tables of condensed data from the ASHRAE manuals and material specification sheets (ASHRAE 2013; Vector Foiltec 2012; Winser 2004). These were to help a designer determine some basic input information. Examples of how to calculate conduction resistance values for layered walls similar to the calculation of R_{wall} and R_{roof} in Section 3.2.1 were also included. Table 3-4 is included on the references sheet as well as the tables included below. The majority of the information included in Tables 3-7 through 3-9 came from the ASHRAE manual Fundamentals 2013. Some more specific information, or at least information about more unique materials, was compiled from several online resources and technical papers. (ASHRAE 2013; Awbi 1998; Winser 2004)

Table 3-7 Heat Sources Based on Space Use

Space Use Type	Area per Person [m^2]	Light per area [W/m^2]	Appliances per Area [W/m^2]
Office	18	18	5 to 22
Residential [High]	28	21	5
Residential [Mid]	45	18	5
Residential [Low]	75	15	5
Hotel	5	10	5
Hospital [max]	15	16	5 to 140
Restaurant	2	10 to 20	5 to 15
Retail	2	10 to 20	5
School	2	15 to 25	5

Table 3-8 Human Metabolic Heat Generation Rates

Activity Level	Metabolic Heat [W/person]
Sleeping	40
Standing	70
Walking	115
Cleaning	115 to 200
Hard Work	120 to 280
Basketball	290 to 440

Table 3-9 Material Thermal Properties

Materials	R-Values [m^2K/W]	Absorption (α)	Transmission (τ)
Glass			
Single Pane	0.150	-	0.90
Insulated Glass 7/8 inch	0.366	-	0.90
Low-E Glass	0.431	-	0.90
Low-E with Argon	0.766	-	0.90
ETFE		-	
Single Layer	0.200	-	0.92
Three Layer Cushion	0.550	-	0.85
Three Layer White	0.550	-	0.45
Walls			
Brick (4inch)	0.145	0.60	-
Concrete Block (8 inch)	0.193	0.60	-
Wood	0.135	0.4 to 0.7	-
Insulation 3inch	1.930	-	-
Insulation 6inch	3.340	-	-
Sheet rock	0.080	-	-
Steel/Aluminum Siding	0.100	0.2 to 0.80	-
Air	0.176	-	1.00
Roofing			
Asphalt (shingles)	0.100	0.85	-
Soil (per inch)	0.140		-
Grass		0.50	-

3.3 Chapter Summary

A spreadsheet model was developed specifically to determine the annual HVAC energy demands of a 100-building greenplex with an atrium conditioned to the same temperature as the towers. The conditioned atrium spreadsheet model consisted of 15 sheets: a "Constants" sheet, 12 month sheets, an "Annual" sheet, and a "Reference" sheet. The "Constants" sheet contained all of the information in the model that was constant throughout the year including: geometric, location, and material data. Each month sheet determined the HVAC energy demands for the 21st day of that month. The "Annual" sheet used the daily HVAC energy demands from each of the month sheets to determine a total annual HVAC energy demand.

4 NO-ATRIUM SPREADSHEET MODEL

The no-atrium spreadsheet model is more simple application of ASHRAE's RTS method without the time series information included (ASHRAE 2013). This chapter presents the information used to develop the no-atrium spreadsheet model. The key feature of this model is that there is no atrium between the buildings. This chapter describes how the no-atrium spreadsheet model was setup differently from the conditioned atrium spreadsheet model.

4.1 Spreadsheet Description

Many aspects of the no-atrium spreadsheet were similar to the Conditioned Atria Spreadsheet Model in Chapter 3. This model consisted of 15 sheets, which included the "Constants" sheet, the 12 month sheets, the "Annual" sheet, and the "Reference" sheet. Since so much of the separate models were similar to each other, only differences will be discussed.

The "Constants" sheet had all of the same values as the conditioned atrium spreadsheet model except for the atrium parameters. The monthly sheets had the most significant differences. These sheets were set up with only two blocks: an input block and a tower block. The input block consisted of several values from "Constants" sheet and a few month-specific values. The tower block was where all of the calculations for each design day took place. The tower block was set up to represent several towers at once, but if the towers were significantly different it would be more advantageous to copy the tower block from the first tower and adjust it for successive towers. The tower block was divided into several sections with one section per surface (wall or roof). This allowed additional walls or roof sections to be inserted easily, as needed. In each section the incident solar radiation was calculated using Equations 3-2 through 3-12 in Chapter 3. The incident solar radiation was used with Equations 3-24 and 3-25 to determine the wall and window surface temperatures. A shadow parameter was introduced where the percentage of a wall that was in the shade was specified. Determining actual shading can be a very complicated process depending on diffuse solar radiation and surface reflectivity. These shading values were estimated by drawing the model in Google Sketchup (Trimble et al. 2013) and using the built-in shading rendering capability to visually estimate the percentage of each wall that was shaded. This was done for each hour of the twelve design days. Equations 3-26 and 3-27 were used to determine the conduction rates through the walls and windows. The solar radiation incident on the windows was used to determine the radiation transmitted through the windows. The window-transmitted solar was assumed to get absorbed within the buildings.

The last section of the tower block finished off the design day calculations. It included the calculations for the internal gains from people, lights, and equipment. It also accounted for the ventilation energy demand using Equation 3-32. Finally, it summed all of the heat rates from each of the sections to determine an hourly total heat rate. The absolute value of the total hourly heat rates were summed for the whole day to determine the total design day HVAC energy demand.

4.2 Chapter Summary

The no-atrium spreadsheet model was much simpler than the atrium models because no atrium calculations needed to be performed and the wall and window surface temperatures could be easily determined from Equations 3-24 and 3-25. The no-atrium spreadsheet model was also designed to handle very different building designs and configurations because the wall sections and the tower blocks were more modular. Additional walls, roofs, or window surfaces could be added to the model by copying more wall sections into the tower block and adjusting some of the formulas to include them. Several different towers could be analyzed at once be copying the tower block and adjusting parameters in the copied blocks to represent the other additional towers.

5 UNCONDITIONED ATRIUM SPREADSHEET MODEL

Determining annual HVAC energy demands on a typical building is usually straightforward (see Chapter 4). Including an atrium in the analysis increases the complexity of the analysis because of the possibility of thermal coupling between the atrium, inside, and outside environments. This chapter presents the equations and information used to develop the unconditioned atrium spreadsheet model. The key feature of this model is that the average atrium temperature is unknown and coupled with the atrium solar gains, conduction rates, and ventilation rates. This chapter describes the unique aspects of the unconditioned atrium spreadsheet setup.

5.1 Spreadsheet Description

Many aspects of the unconditioned atrium spreadsheet were similar to the conditioned atrium spreadsheet in Chapter 3. The unconditioned atrium spreadsheet model consisted of 15 sheets, which included the "Constants" sheet, the 12 month sheets, the "Annual" sheet, and the "Reference" sheet. The "Constants," "Annual," and "Reference" sheets were identical to the conditioned atrium model. Only the differences in the 12 month sheets will be discussed.

The month sheets were set up in a series of five blocks similar to the Conditioned Atrium Model. There was an input, atrium, tower, and summary block with an added resistance matrix block for the greenplex. The input block did not have a value for the atrium temperature. The tower block was identical between the unconditioned and conditioned atrium models. The only difference in the summary block was there was no atrium energy demand column because the atrium energy demand was zero.

This case maintained the tower temperature at a comfortable range throughout the year, but the atrium not directly conditioned and the atrium temperature could change throughout the design day. On the month sheets, the average atrium temperature and the tower wall and window surface temperatures had to be determined. To complicate things, these temperatures were coupled with conduction rates through walls, windows, and ETFE, the solar loads, and ventilation rates in the atrium. A system of linear equations (see Equation 5-1) was developed to solve for atrium wall and window surface temperatures as well as the average atrium air temperature.

$$R\,T = F \rightarrow\ T = R^{-1}F \tag{5-1}$$

The resistance matrix block was composed of resistances for the nine different temperature degrees of freedom (DOF) (four atrium-section wall surface temperatures, four atrium-section window surface temperatures, and an average atrium air temperature). The surfaces were assumed to be uncoupled from each other but coupled with the average atrium temperature. The formulas for each surface DOF are given by Equations 5-2 and 5-3:

$$R_{i,i} = A_i\left(\frac{1}{R_{conv.in}+R_i}+\frac{1}{R_{conv.a}}\right) \tag{5-2}$$

$$R_{i,at} = R_{at,i} = -A_i\left(\frac{1}{R_{conv.a}}\right) \tag{5-3}$$

where R_{ii} is the matrix resistance value for surface i, A_i is the area of surface i, and R_i is the resistance value for surface i. The ventilation DOF is defined by Equation 5-4:

$$R_{at,at} = \frac{\sum_i^n A_i}{R_{conv.a}} + \frac{A_{ETFE}}{R_{conv.a}+R_{conv.o}+R_{ETFE}} + 0.2778V_{at}\Delta_{at}\rho_{air}c_p + 0.2778V_t\Delta_t\rho_{air}c_p \tag{5-4}$$

where the V_{at} is the volume of the atrium, Δ_{at} is the percent of the atrium volume that is replaced every hour, ρ_{air} is density of air, and c_p is the specific heat of the air. These values (R_{ii}, $R_{i,at}$ and $R_{at,at}$) were put into the resistance matrix R given by Equation 5-5:

$$R = \begin{bmatrix} R_{11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{1at} \\ 0 & R_{22} & 0 & 0 & 0 & 0 & 0 & 0 & R_{2at} \\ 0 & 0 & R_{33} & 0 & 0 & 0 & 0 & 0 & R_{3at} \\ 0 & 0 & 0 & R_{44} & 0 & 0 & 0 & 0 & R_{4at} \\ 0 & 0 & 0 & 0 & R_{55} & 0 & 0 & 0 & R_{5at} \\ 0 & 0 & 0 & 0 & 0 & R_{66} & 0 & 0 & R_{6at} \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{77} & 0 & R_{7at} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R_{88} & R_{8at} \\ R_{at1} & R_{at2} & R_{at3} & R_{at4} & R_{at5} & R_{at6} & R_{at7} & R_{at8} & R_{at} \end{bmatrix} \tag{5-5}$$

The load vector (F) was generated for each hour of the day. The thermal load on the wall surfaces inside the atrium depends on the radiative thermal load from the sun and the conductive thermal load from the inside of the tower. The load vector values for the wall surfaces inside the atrium is given by Equation 5-6:

$$F_i = \alpha_i E_i A_i + \frac{T_{in} A_i}{R_{conv.in} + R_i} \tag{5-6}$$

where α is the absorptivity of the wall surface i, E_i is the incident solar on wall i (see Equation 3-14), and R_i is the conductivity of the wall surface i. The load vector values for the window surfaces inside the atrium is given by Equation 5-7:

$$F_i = \frac{T_{in} A_i}{R_{conv.in} + R_i} \tag{5-7}$$

where R_i is the conductivity of window i. Note that there is no solar load on the surface of the window only conductive loading from inside the towers. This is because any radiation loads get transferred through the window and very little energy is absorbed by the window. Finally, the load vector value for the atrium ventilation DOF is given by Equation 5-8:

$$F_{at} = T_{out}\left(\frac{A_{ETFE}}{R_{conv.a} + R_{ETFE} + R_{out}} + 0.2778 V_{at} \Delta_{at} \rho_{air} c_p\right) + T_{in} 0.2778 V_t \Delta_t \rho_{air} c_p \tag{5-8}$$

The resistance matrix was inverted and multiplied by the load vector to get the average surface temperatures of each of the walls and windows as well as the average air temperature in the atrium (see second part of Equation 5-1). These surface temperatures could then be used to determine the heat rates into the towers from Equations 3-26 and 3-27.

5.2 Development

The series of linear equations for the unconditioned atrium spreadsheet model that balanced the heat transfer rates through the atrium were developed using a resistor model. The resistor model specifically accounted for conduction, convection, radiation, and ventilation using Fourier's Law, Newton's Law of Cooling, ASHRAE's solar formulas, and the specific heat equation (ASHRAE 2013; Incropera et al. 2011). The resistor model consisted of several temperature nodes connected to each other by thermal resistors (see Figure 5-1). The heat rates at each node must balance. There were four main node types: indoor air temperature, wall or window surface temperature on the atrium side, average atrium air temperature, and outside air temperature. There are also six thermal resistor types: wall, window, ETFE, indoor convection, atrium convection, and outside convection. In addition, thermal forces were applied through solar radiation incident upon the atrium walls and ventilation into the atrium air.

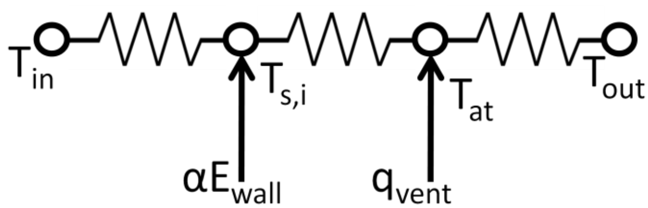

Figure 5-1 Basic resistor model

A linear equation was developed from each unknown node (see Equation 5-9 for node $T_{s,i}$). These equations were then rearranged in terms known and unknown nodal information (see

Equation 5-10). The coefficients of the unknown temperature nodes became the resistance values in the resistance matrix block (see Equations 5-2 to 5-5). All known information was put into the load vector (F) (see Equations 5-6 through 5-8). And the unknown atrium and surface temperatures could be determined with Equation 5-1.

$$q_{in} + q_{sun} - q_{conv.a} = \frac{A_i(T_{in} - T_{s,i})}{R_{conv.in} + R_i} + \alpha_i E_i A_i - \frac{A_i(T_{s,i} - T_{at})}{R_{conv.a}} = 0 \tag{5-9}$$

$$T_{s,i}\left[A_i\left(\frac{1}{R_{conv.in} + R_i} + \frac{1}{R_{conv.a}}\right)\right] + \mathrm{T_{at}}\left[-A_i\left(\frac{1}{R_{conv.a}}\right)\right] = \alpha_i E_i A_i + \frac{T_{in} A_i}{R_{conv.in} + R_i} \tag{5-10}$$

5.3 Chapter Summary

The unconditioned atrium spreadsheet model was nearly identical to the unconditioned atrium spreadsheet model presented in Chapter 3. The sheets were identical except for the 12 month sheets. The main differences on the monthly sheets were the addition of the resistance matrix block and the formulas used in the atrium block. It required the development of a series of linear equations based on Fourier's Law (conduction), Newton's Law of Cooling (convection), and the mass flow rate specific heat equation. These linear equations with the solar calculations from ASHRAE allowed the average atrium air temperature and the wall and window surface temperatures to be determined. The wall, window, and atrium temperatures were used to determine the heat transfer rates into the towers.

6 CALIBRATION OF SPREADSHEET MODELS WITH CFD

Computational fluid dynamics (CFD) models have the capability of evaluating how different fluid currents are caused by obstructions and how those currents affect the heat transfer or forces on the obstructions. This chapter focuses on the CFD modeling of the no-atrium case. The CFD model and assumptions are explored followed by the results and limitation of the CFD analysis. The CFD results are compared to the spreadsheet and hand calculated results.

6.1 CFD Model Definition and Assumptions

A more detailed CFD model was developed to help calibrate the exterior convection rates in the spreadsheet model. The greenplex without atria was modeled in a simulated wind tunnel scenario to determine what heat rates would result from different wind velocities and temperature differences between inside and outside. The CFD model consisted of 100 square prismatic boxes representing the towers inside a large wind tunnel box.

The model was created, meshed, and analyzed with the Star-CCM+ software (MacDonald 2014). Star-CCM+ includes a built-in CAD module that can be used to generate the geometric information for the model. Star-CCM+ uses three datasets to define and analyze a model (continua, regions, and interfaces). The continua dataset includes the meshing and physics subsets that define how the model is discretized and what physical/mathematical models should be used to develop a solution. The physics continua subset also includes information on the initial conditions for the solution. The regions dataset includes the geometry, mesh parameters, physics parameters, and some boundary condition values for each of the control volumes in the model. The interfaces dataset includes meshing and physics information about the boundaries between the wind tunnel and tower control volumes (the tower walls).

Post-processing was done using the reports, monitors, plots, and scenes datasets. The reports datasets calculated overall information, like total greenplex heat transfer, using the individual element values. The monitors datasets were set up to keep track of the report information at each iteration, and the plots datasets were generated from the monitored information. The scenes dataset presents visual representations of the data.

6.2 Procedure

The model geometry was created with the built-in CAD module and geometric boolean operations. This had to be done carefully to ensure that the resulting volumes were feasible and didn't have any orphaned surfaces or edges. The geometry was transferred to the regions dataset where the boundaries between the towers and wind tunnel were defined along with the mesh and physics continua subsets.

The meshing algorithms used to discretize the model were: the surface remesher, the polyhedral mesher, and the prism layer mesher. The surface remesher discretized all of the surfaces of the model into sets of nearly equilateral triangles. It then conducted several refinements and optimizations to make the triangular surface mesh as uniform as possible. The polyhedral mesher divided the volumes into multi-sided, nearly spherical, polyhedra with diameters as close to the base size as possible. The prism layer mesher created prismatic polyhedral elements starting from each of the wall and roof interfaces in the model. This prism layer was sized to accurately capture the boundary layer development along the walls of the model. The prism layer mesher and the polyhedral mesher were optimized together to adequately transition from a primarily two-dimensional flow regime next to a wall to a three-dimensional turbulent flow away from the boundaries (see Figure 6-1). A volumetric control was specified that refined the volume mesh in the area right around the towers. More specific meshing information was defined under the regions and interfaces properties.

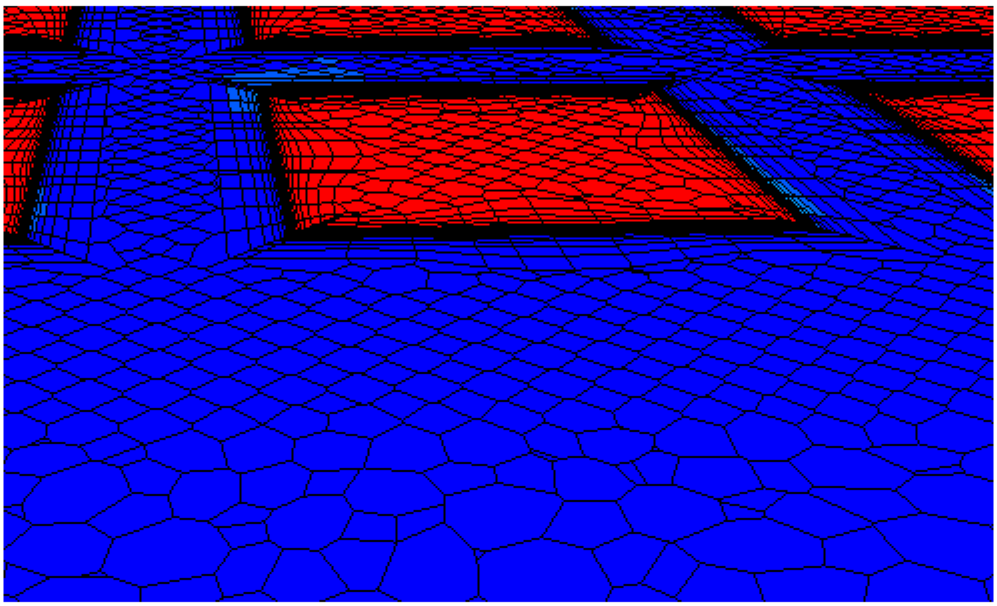

Figure 6-1 Volume mesh on a horizontal cross section through the city.

There were two separate physics continuum subsets created to be used for tower and wind tunnel control volumes, respectively. They differed only in the initial conditions. The physics continuum subset algorithms selected were: Three Dimensional, Gradients, Steady, Ideal Gas, Segregated Flow, Segregated Fluid Temperature, Turbulent, Reynolds-Averaged Navier-Stokes, K-Omega Turbulence, and SST K-Omega. The default values were used for the reference values and initial conditions with the exception of the temperature and velocity initial conditions in the wind tunnel. The velocity was set to a specified magnitude (initially 2.0m/s but later adjusted as shown in Table 6-1) and the wind tunnel temperature was set to 255.4K (0.0°F).

The physics properties were further defined for each of the regions and the interfaces between the regions. The tower/wind tunnel interface boundary conditions were specified as a baffle interface. The baffle interface was further modified to be a conductive interface with a conduction resistance of 0.471m^{2}K/W. This value was determined using parallel resistance given by Equation 6-1:

$$R_{eff} = \frac{A_{wall}+A_{window}+A_{roof}}{\frac{A_{wall}}{R_{wall}}+\frac{A_{window}}{R_{window}}+\frac{A_{roof}}{R_{roof}}} \tag{6-1}$$

where A_{wall} is the total surface area of all of the wall in the city, A_{window} is the total surface area of all of the glass, and A_{roof} is the area of all of the roof, and R_{window} is equal to R_{glass}.

The model was meshed at this point. The surface meshing routine was executed and the model was checked for errors. Then the volume meshing routine was executed. Next, the wind tunnel surfaces were separated, renamed, and assigned boundary conditions. The boundary conditions included: velocity inlet, pressure outlet, slip wall for the top, symmetry plane for the side surfaces, and no-slip wall for the ground surface. The physics boundary conditions for each of these wind tunnel surfaces were further defined. An air velocity and temperature that matched the wind tunnel velocity and temperature initial condition was specified for the velocity inlet. The surface temperatures of the other wind tunnel boundary surfaces were specified to match the wind tunnel initial air temperature.

Some user defined field functions were used in conjunction with the K-Omega Turbulence algorithm to set and hold the temperature inside the towers. The field functions were defined by Equations 6-2 and 6-3:

$$Q = C\ (T_{cell} - T_{set}) \tag{6-2}$$

$$\frac{dQ}{dT} = -C \tag{6-3}$$

where T_{cell} is the cell, or element, temperature, T_{set} is the indoor temperature setting, C is a large constant chosen to get the temperatures set quickly, Q is the volumetric heat rate, and dQ/dT is the volumetric heat rate temperature derivative. The volumetric heat source option was selected in the towers' physics conditions energy source options. The towers' volumetric heat source, under their physics conditions category, was defined as the field function Q and the towers' energy source temperature derivative was set as the field function dQ/dT. This method for maintaining an air temperature was given in the user's manual for Star-CCM+ (CD-Adapco 2014).

Finally, some post processing information was defined before running the analysis. These included scenes and reports datasets. Several scenes datasets were defined to view the geometry, surface and volume meshes, and different solution results (air velocity vectors, air temperatures, and surface pressures). The air temperature and air velocity scenes were set up with information shown on a cut plane through the model (see Figures 6-1 and 6-5). The pressure information was selected for the exterior surfaces of the towers. Heat transfer report datasets were created and defined to determine the heat transfer rate through the walls of the towers from the point of view of the towers and the point of view of the wind tunnel. This was done to ensure that the heat transfer balanced on both sides of the wall. Then monitors and plots were created to record and plot the heat transfer rates at each iteration.

6.3 CFD Model Results

Three different element base sizes were analyzed. The element base size in the wind tunnel away from the greenplex was maintained at 20 meters. The element base size in the greenplex and out to at least 100 meters surrounding the greenplex was set to 20, 10, and 5 meters for the 2.0 m/s velocity models as shown in Figure 6-2. Several velocities were analyzed with the 5 meter base size mesh.

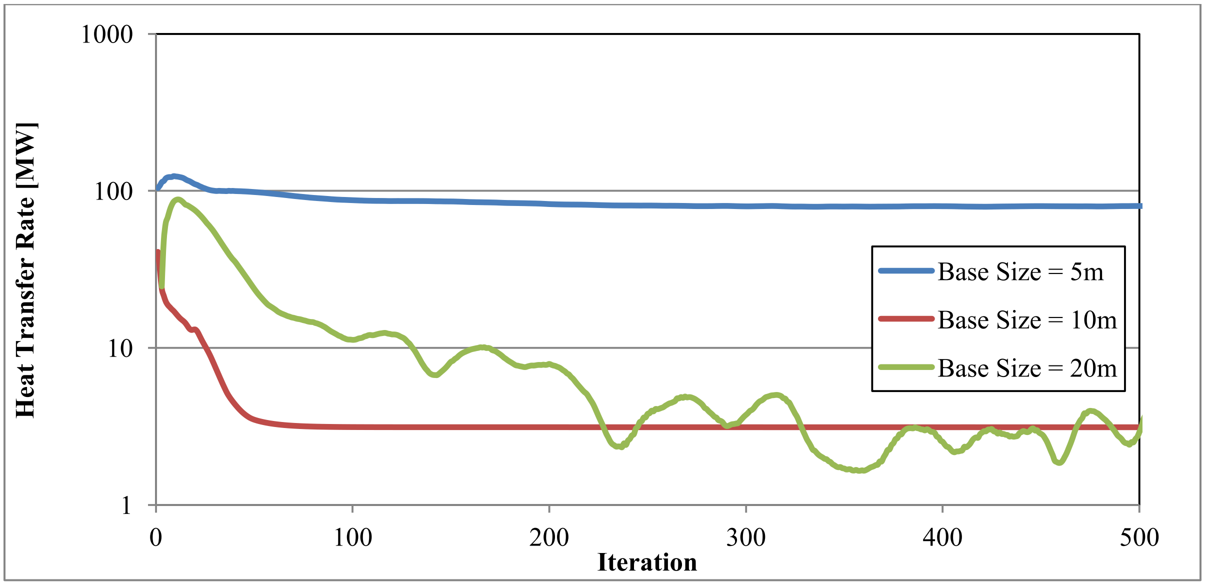

Figure 6-2 Plots of heat transfer rate for the city for different base size values.

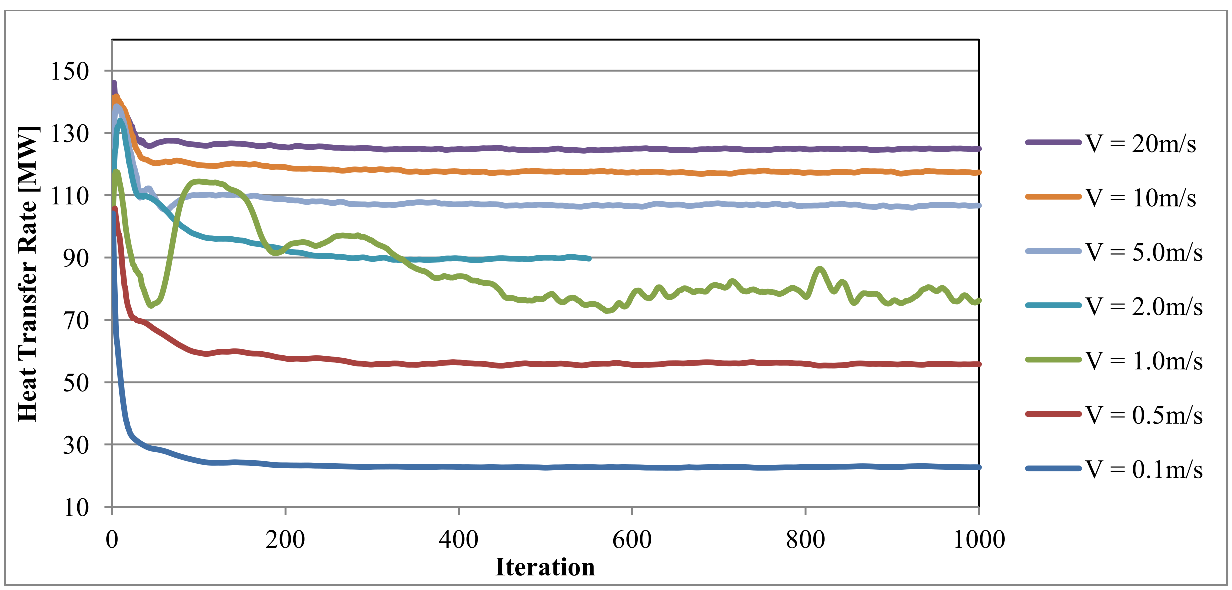

Figure 6-3 Heat transfer rates for the greenplex vs. wind speed at 5 meter base size.

The data for the positive heat transfer dataset was exported and plotted as shown in Figure 6-3. The flat sections of these plots were assumed to be converged, and the average conduction rates after convergence for the different air velocities are included in Table 6-1. These values were used to calculate effective external convection coefficients for the greenplex.

Table 6-1 Greenplex Heat Transfer Rates for Different Wind Speeds.

Velocity [m/s]	Conduction Rate [MW]
0.1	22.81
0.2	34.39
0.5	55.90
1	78.23
2	89.70
5	106.91
10	117.49
20	124.86

Additionally, heat transfer scalar scenes and flow vector scenes were produced. (see Figures 6-4 and 6-5). These were used to verify that the solution was reasonable. They were also used in early models to find errors in the input parameters and analysis results.

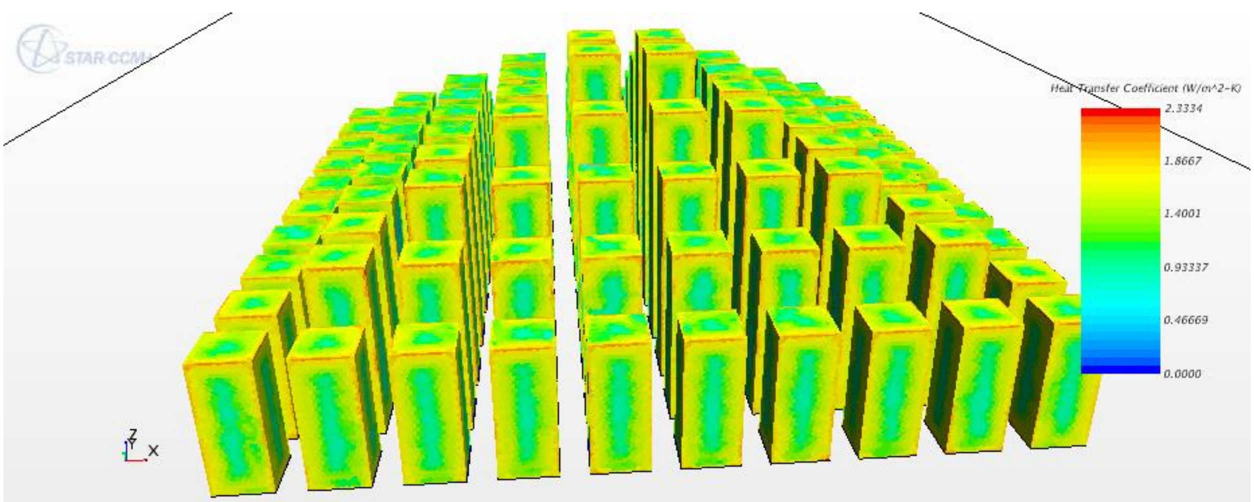

Figure 6-4 Heat transfer rates through the walls from a 2.0m/s wind.

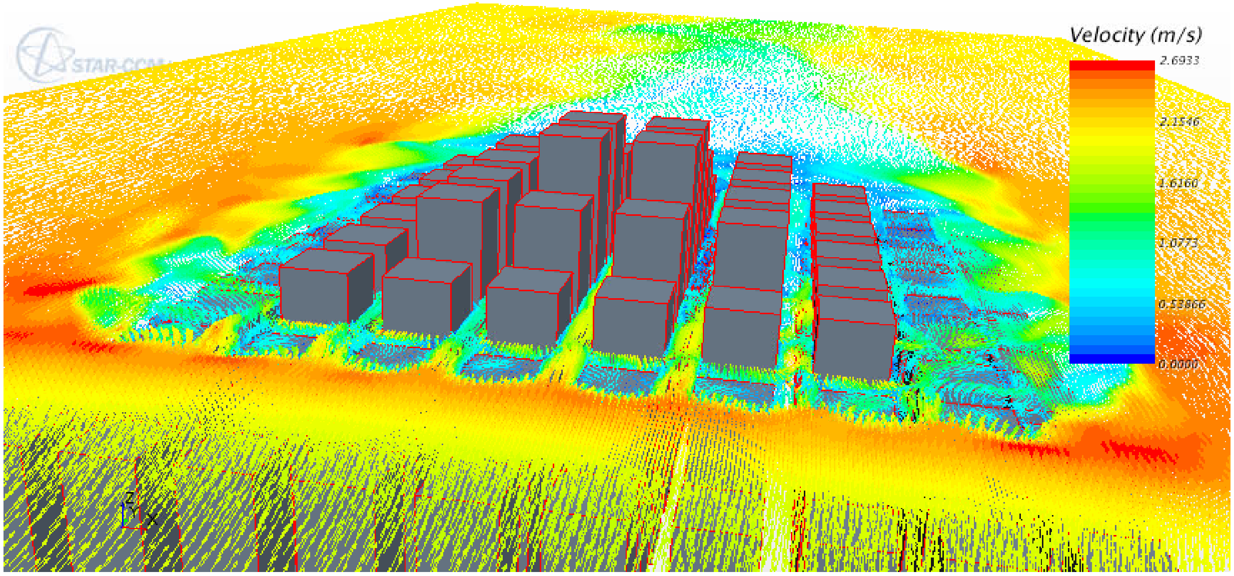

Figure 6-5 Horizontal flow vector plane showing flow around buildings.
(wind direction is from bottom to top)

6.4 Limitations

There was one main limitation to the CFD analysis (computer memory) which caused two major limitations to the model (element size and scope). The models were created, meshed, and modified on a computer with a maximum of eight gigabytes (8GB) of memory. This memory limit placed constraints on the element size and the model scope. The model file size could only be 5.5GB before file modification became an issue. As a result, the maximum number of elements was 13 million with 70 million faces. It should be noted that files this large required more than 20GB of computer memory and up to 52 hours to complete each simulation. These files had to be transferred to a supercomputer to run the simulation.

The model was very large (2000m wide by 4000m long by 800m high). The greenplex was 725 meters wide and 280 meters tall. Typically, it is recommended that the wind tunnel is at least six times as wide as the object, at least six times as long as the object, and at least five times as tall as the object so that the wind tunnel walls do not interfere with the flow around the greenplex (CD-Adapco 2014). These recommended values resulted in such a large model that it was necessary to reduce the wind tunnel size to only 2.75 times the greenplex width, 5.5 times the greenplex length, and 2.85 times the greenplex height. These reductions reduced the model volume by 75%.

Initially, a maximum element size was set to twenty meters. This resulted in a small file that could be run quickly but had major errors in the heat transfer values. Then a mesh volumetric control was implemented that refined the mesh within 100 meters of the greenplex (300 meters downwind). The elements within this volumetric control could have minimum base size of five meters before file size constraints were reached.

Due to the element size limitations, the detail and complexity of the model was also limited. For example, elements could not be sized small enough to capture data between floors or solid wall and window facade differences. So tower floors were not modeled and window and wall sections were modeled with effective values. (see Figure 6-1). The CFD analyses do not include radiation models or analyses. This is mainly because the solar models require opaque surfaces to absorb solar radiation and the mesh size did not permit useful or accurate modeling of the different transparent and opaque surfaces in the model.

The atrium models were attempted in Star-CCM+ however, a large component of the heat transfer was ventilation, especially in the unconditioned atrium. The mesh was not fine enough to model intake and exhaust vents in the atrium. Ventilation (natural or forced) was not included in the CFD analysis because it was very difficult to define correctly and more difficult to get the solution to converge. Additionally, vent locations, sizes, velocities, pressures, etc. were not known or defined.

6.5 Comparison with Spreadsheet and Hand Calculated Results

The CFD tower model was compared with a very basic hand calculated model and a non-solar spreadsheet model. The hand calculated model used several different convection coefficient correlations to determine a reasonable range of heat transfer rates for the CFD model and to help with troubleshooting. The total greenplex heat transfer rate was computed from Equation 6-4:

$$Q_{total} = \frac{(A_{wall}+A_{window}+A_{roof})(T_{out}-T_{in})}{R_{eff}+\mathrm{R}_{\mathrm{conv.o}}} \tag{6-4}$$

where Q_{total} is the total heat transfer rate for the whole greenplex, $R_{conv.o}$ is a convection correlation that is a function of wind velocity, and R_{eff} is the value from Equation 6-1. Plots of the greenplex heat rate using different convection correlations have been included in Figure 6-6. The different convection correlations apply to very specific flow geometries and Reynolds number ranges. For many of these empirical correlations, the greenplex's (or even a tower's) Reynolds number was well above the valid Reynolds number range. The simplified vertical surface convection correlation is from ASHRAE and is designed to conservatively approximate the exterior convection due to both wind and buoyancy. It should also be noted that the maximum value (2.767×10^8W) for the vertical axis of Figure 6-6 was the greenplex's heat transfer rate if the inside and outside convection resistance values ($R_{conv.i}$ and $R_{conv.o}$) were both equal to zero.

Equation 6-4 can be rearranged to solve for $R_{conv.o}$ as shown in Equation 6-5. The average greenplex outside convection resistance values can be directly compared to the empirical convection correlations as shown in Figure 6-7.

$$R_{conv.o} = \frac{(A_{wall}+A_{window}+A_{roof})(T_{out}-T_{in})}{Q_{city}} - \mathrm{R}_{\mathrm{eff}} \tag{6-5}$$

The non-solar spreadsheet was created from a no-atrium spreadsheet model. For this model the solar gains and internal gains were set to zero. Furthermore, the outside and inside temperatures were set at the same values that were used for the CFD and hand calculated models.

It was determined that the CFD model follows the trends of the different correlations but is probably unconservative. Refining the mesh pushed the CFD solutions closer to the hand calculations. It could converge towards a solution for the system if the mesh could be refined more. Unfortunately, there was not enough computer memory on the systems used to create and save the file to refine the mesh further.

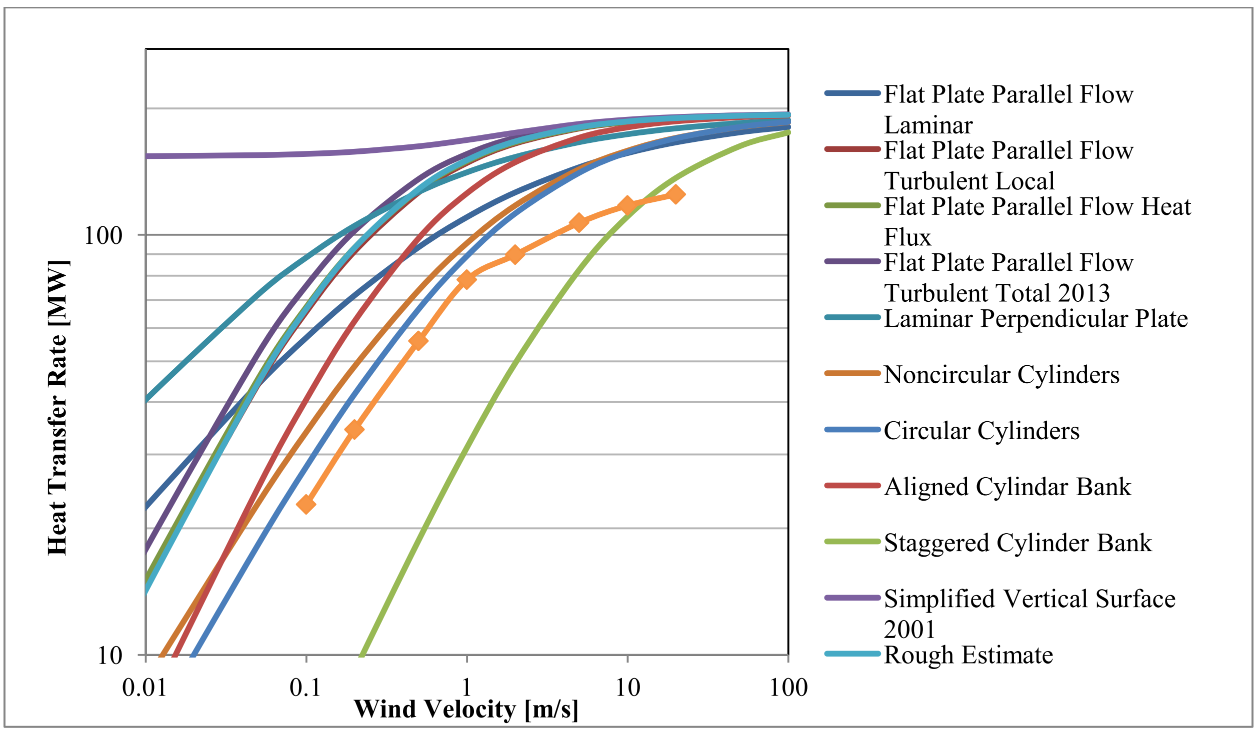

Figure 6-6 Total greenplex heat transfer rate for a temperature difference of 65°F and several outside convection correlations.

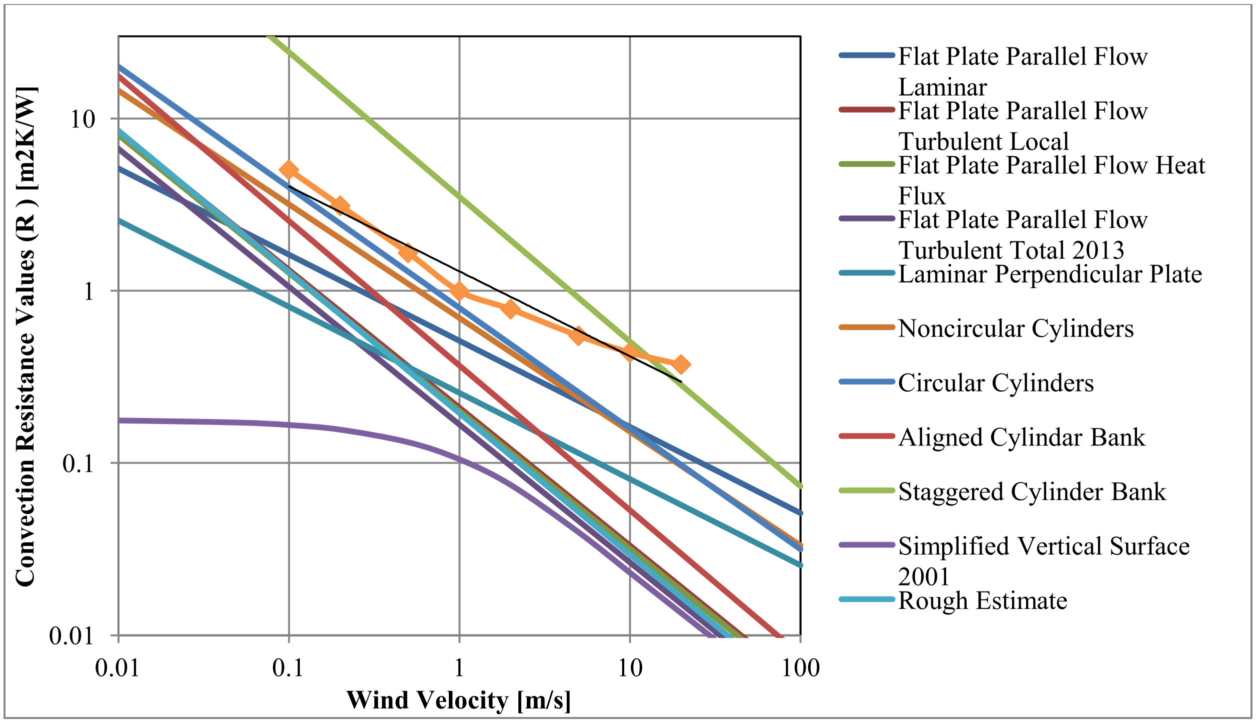

Figure 6-7 Convection resistance values (R-Values) for different convection wind speed correlations.

6.6 Chapter Summary

Several CFD analyses were conducted to determine reasonable outside convection resistance values for the spreadsheet models. The CFD analyses required sophisticated algorithms and a significant amount of computer memory. The CFD analyses were compared to simple hand calculations that used several different convection correlations and a non-solar spreadsheet model.

7 RESULTS AND DISCUSSION

The spreadsheet models presented in Chapters 3, 4, and 5 progressed through several stages of calculations to determine total annual heating and cooling energy demands for their specific atrium configurations. This chapter will present the energy demand and temperatures from the three spreadsheet models. The major factors that contributed most significantly to the energy demand and temperatures will be discussed further along with the limitations of these models and areas of future research.

7.1 Energy Demand

Three greenplex configuration cases were examined with the spreadsheet analysis programs. The design day results for the 12 design days for each of the three cases are presented in Table 7-1 and Figure 7-1. The annual energy demand for the no-atrium case was 2093 GW-hr/yr and the annual energy demand per floor area was 221.5 kW-hr/m^2. In the conditioned atrium analysis the annual energy demand was 1759 GW-hr/yr and the annual energy demand per floor area was 186.1 kW-hr/m^2. In the unconditioned atrium analysis the atrium temperatures were not actively controlled or known. The atrium behaved mainly as an extra layer of insulation from the towers and the annual energy demand was 1055 GW-hr/yr and the annual energy demand per floor area was 111.5 kW-hr/m^2. All of these values are within the range of energy consumption values compiled by Wood and Salib (2012).

Table 7-1 Design Day Heating and Cooling Energy Demands in MW-hr/day

Month	Day of the Year	No Atria	Unconditioned Atria	Conditioned Atria
Jan	21	7133	1952	4320
Feb	52	5443	1605	4239
Mar	80	3021	1031	4344
Apr	111	3045	1781	4816
May	141	5910	3640	5059
Jun	172	7974	4714	5379
Jul	202	8607	5089	5402
Aug	233	7858	4864	5254
Sep	264	5850	3886	4975
Oct	294	4116	2840	4579
Nov	325	4044	1359	4674
Dec	355	5666	1761	4756
Annual Energy	GW-hr	2093	1055	1759
per Floor Area	kW-hr/m^2	221.5	111.5	186.1
Percent Savings		-	49.7%	16.0%

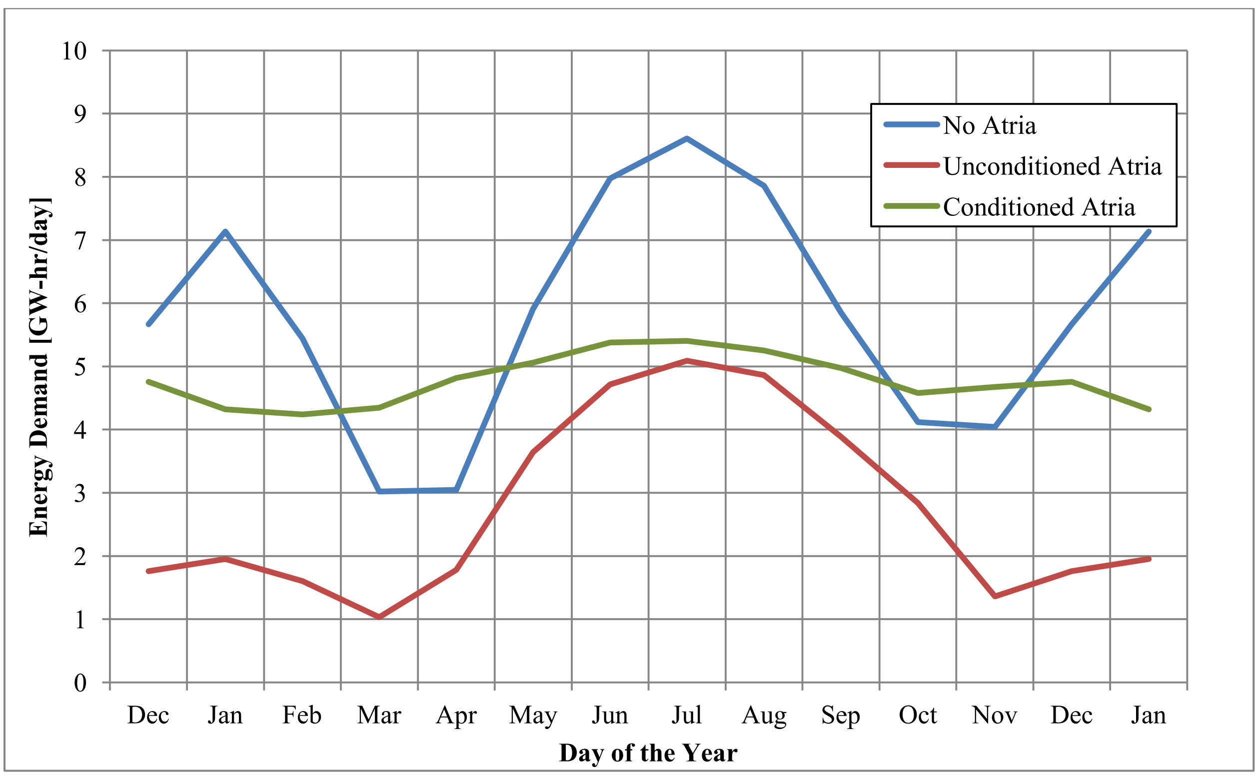

Figure 7-1 Plot of the Design Day energy demand for the different atria cases

7.2 Temperature Ranges

Figure 7-2 and Table 7-2 show the different temperatures during each of the 12 design days used in the analysis. The outside and inside temperatures were consistent between the different cases. The conditioned atrium temperature was maintained at the same temperature as the indoor temperature. The average atrium temperatures in the unconditioned atrium were determined. As can be seen in Figure 7-2, the atrium high and low temperatures stay between the outside and inside temperatures.

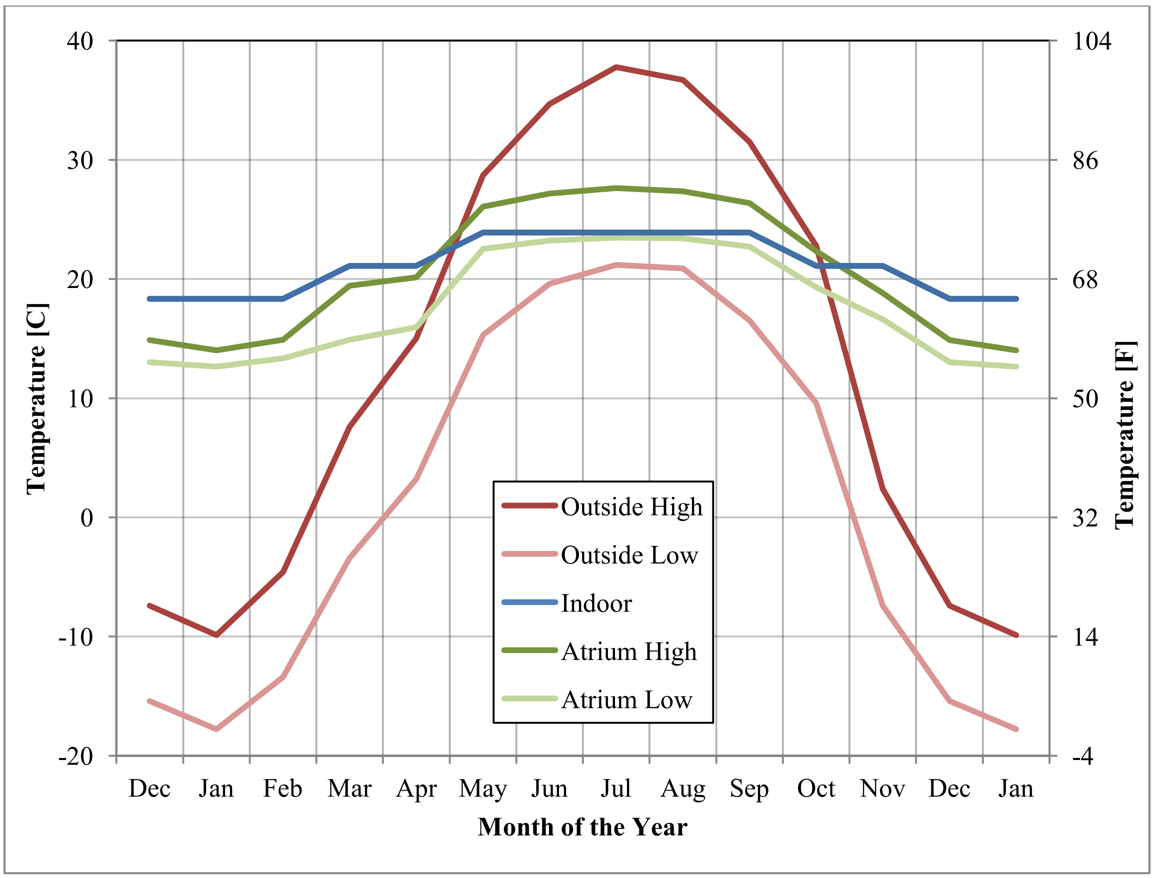

Figure 7-2 Plot of the high and low air temperatures.

Table 7-2 Table of Temperatures for Design Days

Month	Inside [°F/°C]	Atrium High [°F/°C]	Atrium Low [°F/°C]	Outside High [°F/°C]	Outside Low [°F/°C]
Jan	65.0 / 18.3	57.2 / 14.0	54.8 / 12.6	14.2 / -9.88	0.0 / -17.8
Feb	65.0 / 18.3	58.8 / 14.9	56.0 / 13.3	23.7 / -4.60	7.88 / -13.4
Mar	70.0 / 21.1	67.0 / 19.4	58.8 / 14.9	45.7 / 7.60	25.9 / -3.40
Apr	70.0 / 21.1	68.2 / 20.1	60.7 / 15.9	59.0 / 15.0	37.8 / 3.20
May	75.0 / 23.9	78.9 / 26.1	72.6 / 22.5	83.7 / 28.7	59.5 / 15.3
June	75.0 / 23.9	80.9 / 27.2	73.8 / 23.2	94.5 / 34.7	67.3 / 19.6
July	75.0 / 23.9	81.7 / 27.6	74.2 / 23.5	100.0 / 37.8	70.1 / 21.2
Aug	75.0 / 23.9	81.3 / 27.4	74.2 / 23.4	98.1 / 36.7	69.6 / 20.9
Sept	75.0 / 23.9	79.5 / 26.4	72.9 / 22.7	88.7 / 31.5	61.7 / 16.5
Oct	70.0 / 21.1	72.2 / 22.3	66.7 / 19.3	73.0 / 22.8	49.3 / 9.60
Nov	70.0 / 21.1	65.9 / 18.8	61.9 / 16.6	36.3 / 2.40	18.7 / -7.40
Dec	65.0 / 18.3	58.8 / 14.9	55.4 / 13.0	18.7 / -7.4	4.28 / -15.4

7.3 Discussion of Results

The results of this study show that placing atria between tall buildings can reduce energy consumption from heating and cooling the buildings. There were a few factors that affected the energy demands the most. They include: internal loads, reduced surface area, and ventilation.

For the conditions considered, the internal loads contributed a significant amount of heat to the internal spaces (around 10% to 17% each). These internal loads were held constant between the models, but there is a potential for savings by using more efficient equipment or control systems that shut down equipment and lights that are not actively being used. It should also be noted that if the internal loads are increased the conditioned atrium case can require more energy to heat and cool than the no-atrium case because the tower and atrium systems would compete even more.

Reducing the exposed surface area was the largest contributor to energy savings. Atria between skyscrapers reduce the exposed surface area of all of the buildings such that energy consumption is reduced even if the air-conditioner and heater compete between the towers and the atrium. If the atrium is actively held at the same temperature as indoors there are times when the tower and atrium systems may work against each other, but it still results in a 16.0% reduction in energy consumption over the course of the year when compared to the no-atrium case. In the unconditioned atrium case, the atrium functions more as a buffer zone between the inside and the outside. The temperatures inside the atrium are more reasonable than outside but not as comfortable as inside. This case does save 49.7% of the energy required for the no-atrium case.

Ventilation played a major role in the amount of energy the greenplex used in two main ways. First, it provided a way to help cool the inside if the outside air was cooler than the inside air. Second, it caused large heating and cooling demands on the system if the outside air temperature had to be adjusted by the HVAC system. Ventilation was around 65% for the conditioned atrium and no-atrium cases and close to 50% in the unconditioned atrium case during the winter months. During the summer months, ventilation was responsible for about 15% of the total daily energy demand in all three cases.

7.4 Assumptions and Limitations

There were several assumptions involved with this analysis. The first was that surface and air temperatures were assumed to be constant average temperatures for the whole hour (i.e., well mixed air). Next, only heating and cooling demands were determined. Also, a quasi steady-state assumption was used in creating the analysis spreadsheets and CFD models. Additionally, the full radiant time series method was not used so actual daily peaks were not determined. Finally, the sensitivity of these models to changes in the different input parameters has not been explored.

It is expected that the temperature in the atrium would likely vary with height. This means that the heat may be transferring one direction for the bottom stories and the reverse direction in the upper stories. The actual atrium temperature profile or stratification was not determined because it would have added significant complexity to the spreadsheet model and the CFD model. The spreadsheets only determined average atrium temperatures if they weren't already specified. While using average temperatures does not offer much insight into localized heat transfer, it does provide enough information for total heat transfer calculations.

These analyses were only an exploration of basic heating and air-conditioning loads. No HVAC systems have been designed. The inefficiencies inherent in all of the HVAC systems would cause the actual electrical energy demand to be higher than the values predicted in these models. The values presented in this chapter were conservative minimum demands on the HVAC system. Including HVAC systems would have increased the complexity of the problem and still shown similar energy savings between the three cases.

Additionally, the electrical demands of the HVAC system, lights, and electrical equipment have not been determined. The electrical demands of the lights and equipment would be a constant added to all three cases. The thermal demands caused by the lights and equipment offer some savings especially during the winter when their heat gains reduce the heater demands somewhat. Therefore the values given in this analysis are not electrical demands of the greenplex on the electrical grid. The lighting schemes were not altered for the cases with atria. It was assumed that people will leave the lights in their offices and homes on during the day even if there is plenty of natural sunlight entering through the windows.

These analyses used a steady-state assumption. The rise and fall of ambient temperature, solar gains, and ventilation rates are transient by nature. They change cyclically on a daily and annual basis. This assumption might not be as accurate as transient models used in the heat balance method or the differential equations solved in CFD analyses. However, the steady-steady state assumption is reasonable for situations where the building's thermal mass is not changing drastically (quasi steady-state or steady periodic conditions). The parameters defined for each of the design days is supposed to help reduce the error that might occur by not accounting for transient effects. Each design day used parameters for an average day in a week of very similar days right around the 21^{st} of each month of the year as recommended by ASHRAE (2013).

The spreadsheets do not use the full radiant time series method. They specifically do not use the thermal time series aspect. Normally, right after the incident solar radiation is determined for the different surfaces with the radiant time series method, the values for each hour are multiplied by a time series distribution that attempts to capture the transient nature of thermal responses. A key feature in all of these distributions is that they do not change the total energy inputs. They only change when the energy is applied to the HVAC system. It was determined early on that using the time series information did not alter the total daily energy demands. They only affected when daily peaks occurred and how substantial they were. Since the objective of these spreadsheets was to determine energy consumption totals, the added complexity of the time series information was ruled unnecessary. The full radiant time series method should be used for a few extreme days in the year to calculate hourly peaks that the HVAC system needs to be capable of handling when the HVAC system is designed.

7.5 Future Research

There are several more aspects of these models that were not explored but would be worth looking into in the future. These aspects include the affects of: different exposed surface area reductions, atrium stratification on adjacent building heat transfer, moisture on the analysis, HVAC systems, lights, and other control systems on total energy demand, insulation, as well as several naturally occurring phenomena that may assist or inhibit energy reduction. Sensitivity and uncertainty analyses should be conducted to determine the useful limits of these spreadsheet tools presented in this research. Design optimizations should also be performed to develop a range of designs that minimize the energy consumption of the greenplex while still maintaining a comfortable indoor environment.

For the models analyzed in this project, the distance between the towers was not very large. Placing an atrium between all of the towers reduced the exposed surface area of the greenplex from 3.61 million square meters to 948,540 square meters (73.7%). If the buildings were spaced further apart, the atrium may lose all of the energy reduction predicted in these models because of increased solar load on the atria. The sensitivity of energy savings due to reduced surface area should be investigated further.

Another aspect of environmental control that was not addressed in this analysis but would need to be considered in more complete analyses is moisture. Moisture is introduced to a space through the ventilation system and people. The HVAC system can alter the air temperature if there is water vapor present the majority of time without a noticeable difference in the heating or cooling load. However, if the HVAC system causes the water vapor to condense or if the there are active humidity controls, these latent heat demands can require additional energy from the heating and cooling systems. There is also a possibility that high humidity and localized low surface temperatures can cause water to condense inside the buildings or atria and cause corrosion or other damage. Either ventilation rates need to increase under certain circumstances or humidity control systems must be implemented in both the buildings and atria to mitigate possible moisture issues.

The HVAC system has not been designed as part of this research but further exploration would require an HVAC design in order to predict how well comfortable conditions could be maintained inside the towers and atrium. There is also a possibility that buoyancy pressure could over power a standard forced air system in buildings and atria of this size. There is a further question as to where ventilation air is taken in from and exhausted to. For the atrium spreadsheet models all ventilation air was pulled from outside and a portion was exhausted into the atrium. This is what keeps the unconditioned atrium so comfortable. Several other ventilation configurations could be implemented and each would affect the HVAC energy demand and atrium temperatures.

Along with the HVAC design, the atrium should be analyzed to see if there are some natural phenomena that occur in the atrium that could be used to further reduce the energy demands on the HVAC system or produce energy for the system. These phenomena should at least include: stack effect, natural ventilation, Venturi effect, nightly cooling, use of thermal masses, variable shading, passive heating, etc.

The spreadsheet tools developed in this research were based on several proven methods for HVAC analysis. The energy results obtained from each of these analyses were compared to published results of energy-efficient buildings in the literature. While the spreadsheet results and methods are reasonable, the sensitivity and uncertainty inherent in the spreadsheet tools are not completely known or proven. It is recommended that additional sensitivity and uncertainty studies be conducted with these spreadsheet tools to further validate the tools and results.

7.6 Chapter Summary

The results of the spreadsheet models were presented and discussed. The exposed surface area of the greenplex was reduced by 73.7% and resulted in a maximum of 49.7% HVAC energy demand reduction for the unconditioned atrium case. The atrium temperatures are reasonably comfortable throughout the year in both atrium cases. Several limitations to the scope of this research were presented along with recommendations for future sensitivity, detailed analysis, and optimization research.

8 CONCLUSIONS

The purpose of this research was to explore the effects on the HVAC energy demands of placing ETFE atria between tall buildings and to develop simplified HVAC analysis tools capable of handling atria. Three greenplex configurations were explored: a no- atrium case, a conditioned atrium case, and an unconditioned atrium case. A spreadsheet energy model was developed for each of these cases. The main contributions of this research included the evaluation of the effectiveness of reducing exposed surface area by using ETFE atria between tall buildings and the development of the spreadsheet models to determine the annual energy demands of each of the three cases.

Reducing the exposed surface area of a group of skyscrapers by constructing ETFE atria between buildings is a viable way to reduce the HVAC energy demands of the buildings. The exposed surface area of a 100-building greenplex was reduced from 3.61 million square meters to 948,540 square meters (73.7% reduction). For the conditions specified, an unconditioned atrium case uses 49.7% less energy than the no atria case and the atrium temperatures stay between 54°F and 82°F throughout the year even though outside temperatures range between 0°F and 100°F. This is likely a result of the atrium acting as an additional layer of insulation between the towers and outside. The atrium temperatures are also mild because some of the tower's room-temperature exhaust ventilation air is sent to the atrium.

The conditioned atrium case used 16% less energy than the no-atrium case. More energy is consumed than the unconditioned atrium case because during most of the year the heating system in the atrium and the air-conditioning system in the towers are both running. The heater is running to keep the atrium warm and the air-conditioning system is running in the towers to remove the heat gains from people, lights, and equipment. During the summer months both cooling systems are working together and result in energy demands only slightly above the unconditioned atrium case.

The spreadsheet models developed are a fast method for analyzing conceptual designs of buildings with atria. The objective of these spreadsheet analysis tools was to quickly approximate total annual energy demands for a preliminary design. The spreadsheet models accounted for internal gains from people, lighting, and equipment as well as heat transfer due to conduction, convection, radiation, and ventilation between the inside, atrium, and outside environments. The atrium spreadsheet models were designed to be capable of handling Furthermore, the models are designed with the ability to evaluate and quantify the affects of changes in geometry, materials, temperature settings, local weather, ventilation rates, and internal loads.

Based on the results, it is recommended that unconditioned atria should be used in a greenplex. This provides a comfortable environment in the buildings, a reasonably comfortable environment in the atria, and the lowest HVAC energy demand. Further research should be conducted with these spreadsheet tools to verify their accuracy, validity, and sensitivity with respect to different input parameters.

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