Dynamic Simulation of a Superinsulated Residential Structure with a Hybrid Desiccant Cooling System

THESIS

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By

Matthew Edward O’Kelly

Graduate Program in Mechanical Engineering

The Ohio State University

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Master's Examination Committee:

Dr. Mark Walter, Advisor

Dr. Gary Kinzel
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Matthew Edward O’Kelly

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Abstract
This thesis explores the efficiency and performance of residential HVAC systems applied to new high performance buildings which meet the standards of the Passivhaus movement. Chapter 1 recounts the need for energy efficiency as well as the requirements for a Passivhaus. Furthermore, it reviews available building simulation techniques as well as state of the art desiccant dehumidification systems. Chapter 2 details the dynamic simulation in the climate of Columbus, Ohio of The Ohio State University’s entry into the 2011 Solar Decathlon competition. This portion of the study explores the use of a conventional vapor compression conditioning system as well as the effects of occupant behavior on the parameters affecting comfort within the structure. It adds to the current literature on the subject by presenting a simulation in a mixed climate where cooling and dehumidification are traditionally required. Furthermore it adopts a simulation tool which acts on time scales less than one hour. It is concluded that the house, while energy efficient, has difficulty controlling moisture levels. In the summer season it is too humid and in the winter it is too dry. Chapter 3 seeks to address these issues through the use and modeling of a new desiccant assisted heat pump designed at Ohio State. Chapter 3 concludes that the new system called HAWC (Hybrid Air/Water Conditioner) is capable of completely eliminating high humidity events in the summer time while still saving energy as compared to a traditional HVAC system. Chapter 4 summarizes the document and lists future work.
Dedication

For Morton and Susan O’Kelly.
Acknowledgments

I am extremely grateful for all of the guidance that I have received during this process. My family, friends, and teachers have given many hours in order for me to get to this point. I’m especially thankful that Dr. Mark Walter has dedicated so much of his time to the cause of energy conservation. His participation in the Solar Decathlon projects helped me to find a true interest in research and to get hands on experience implementing what I had learned. The friends and contacts that I made through the Solar Decathlon competitions have made an enormous impact on my life.

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Matthew O’Kelly
Vita

2005……………………….. St. Charles Preparatory School

2010………………………. B.S. Mechanical Engineering, The Ohio State University

2010 to present ……………. Graduate Research Associate, Department of Mechanical Engineering, The Ohio State University

Publications


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Fields of Study

Major Field: Mechanical Engineering
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Chapter 1: Introduction

1.1 The Energy Problem

1.1.1 An Increasing Demand for a Depleted Resource

Currently the world is facing unprecedented growth in population, depletion of fossil fuels, and most importantly an increasing demand for energy. It is absolutely essential that steps be taken sooner rather than later to curtail wasteful energy use. Energy shortages significantly decrease quality of life, hamper development, cause economic uncertainty, and lead to political instability. Unfortunately, developed countries have long used systems and technologies that waste energy. Put quite simply, our current pace of energy usage is unsustainable. There are many means to reduce energy consumption. Transportation, industrial processes, commercial buildings, and residential buildings must all be considered as sectors that need optimization and energy efficiency measures. This study will focus on what may be done to reduce residential heating and cooling energy expenditures while still meeting indoor comfort expectations and requirements of occupants.

1.1.2 Residential Heating and Cooling Energy Expenditures

HVAC systems utilize energy to keep conditioned spaces within strict environmental conditions. They account for enormous amounts of energy use in the United States. In 2009 residential energy consumption accounted for 37% of total electricity use [1]. In
fact, out of the 3,884 billion kWh consumed in 2009, 22% was for air conditioning alone [1]. Furthermore, today there are nearly 100 million American homes which have air conditioning. This is nearly 87% of American homes, a statistic which has increased from 68% in 1993[1]. Adoption of air conditioning systems worldwide is growing at an alarming rate. In 1990 less than 1% of Chinese households had air conditioning by 2003 nearly 62% had air conditioning systems [2].

1.2 Improved Building Envelopes and the Passive House Movement

Building scientists around the world have recently championed the reduction in complexity of space conditioning systems in conjunction with building towards a standard known as Passive House or Passivhaus [3]. The concept of the Passivhaus standard is not particularly new or unusual. Its origins may be traced back to the 1970’s when an oil crisis forced a turn towards more energy efficient vehicles and buildings. The building methods employed in the 1970’s, however, proved ultimately to provide dangerous and unhealthy residences. These issues are primarily related to inadequate indoor air quality. Furthermore, after the oil crisis ended and energy prices returned to lower levels the economic impetus for such improvements was no longer there. Finally the success of these houses was further handicapped by the fact that the building methods and techniques deviated heavily from traditional construction methods that have been and still are passed along through generations.

The roots of today’s most sophisticated residential structures may be seen in to two nearly forgotten North American structures: the Leger House in Pepperell, Massachusetts
and the Saskatchewan Conservation House in Regina, Saskatchewan [4, 5]. The early claims surrounding these houses were fantastic; the houses did indeed have miniscule energy consumption, even in difficult climates. Figure 1 shows a photo of the Saskatchewan Conservation House.

![Saskatchewan Conservation House](image)

**Figure 1**: Saskatchewan Conservation House

These houses approached the problem of energy consumption using a variety of novel techniques which exploited clever use of new insulation materials to maximize the air tightness and thermal resistance of the building envelope. The Saskatchewan Conservation house boasted R-40 walls and R-60 ceilings; these are numbers that would seem familiar to the *Passivhaus* movement today. Furthermore, both buildings strove to maximize airtightness [5]. Massachusetts physicist William Shurcliff states in a press release regarding the Leger house the following [4]:

> “Consider the Saskatchewan Energy Conserving Demonstration House. Or consider the Leger House in Pepperell, Mass. The essence of the new category is:
1. Truly superb insulation. Not just thick, but clever and thorough. Excellent insulation is provided even at the most difficult places: sills, headers, foundation walls, windows, electric outlet boxes, etc.
2. Envelope of house is practically airtight. Even on the windiest days the rate of air change is very low.
3. No provision of extra-large thermal mass. (Down with Trombe walls! Down with water-filled drums and thick concrete floors!)
4. No provision of extra-large south windows. Use normal number and size of south windows — say 100 square feet.
5. No conventional furnace. Merely steal a little heat, when and if needed, from the domestic hot water system. Or use a minuscule amount of electrical heating.
6. No conventional distribution system for such auxiliary heat. Inject the heat at one spot and let it diffuse throughout the house.
7. No weird shape of house, no weird architecture.
8. No big added expense. The costs of the extra insulation and extra care in construction are largely offset by the savings realized from not having huge areas of expensive Thermopane [windows], not having huge well-sealed insulating shutters for huge south windows, and not having a furnace or a big heat distribution system.
9. The passive solar heating is very modest — almost incidental.
10. Room humidity remains near 50 percent all winter. No need for humidifiers.
11. In summer the house stays cool automatically. There is no tendency for the south side to become too hot — because the south window area is small and the windows are shaded by eaves.

What name should be given to this new system? Superinsulated passive? Super-save passive? Mini-need passive? Micro-load passive? I lean toward ‘micro-load passive.’ Whatever it is called, it has (I predict) a big future.”

It should be noted that for some time there has also been a movement centered around passive solar building design and there are many books and websites dedicated to the ideas of capturing and storing (or rejecting) the sun’s heat [6]. In this work, passive solar is distinguished from Passivhaus in that Passivhaus focusses only on standards for the building envelope and heating loads. In reality, many people designing and building Passivhaus homes are taking advantage of site orientation for passive solar heat gains. Given the stated advantages of Passivhaus buildings, one must question why there were not more Passivhaus homes built in North America between 1978 and the early 2000s. In Europe, which is dominated by the heating season (homes often do not have cooling or dehumidification systems), a modest number (more than 10,000) of such structures (with
small modifications which will be addressed shortly) have been built. Until recently, in
the United States the number could be counted on two hands. The primary reasons for the
lack of *Passivhaus* homes in North America seem to be:

- The reduced cost of mechanical systems is exaggerated (in Europe heating is
  primarily hydronic which is not the case in the US)[7].

- The performance of early structures was inherently flawed by the airtightness and
  the lack of mechanical ventilation. The problems associated with the lack of
  ventilation are especially acute in North America [3][7].

- Builders and designers were unfamiliar with the construction techniques and wary
  of such structures due to the first two drawbacks listed.

- The energy crisis subsided and builders went back to business as usual [4].

German physicist Dr. Wolfgang Feist who eventually founded the *Passivhaus* movement
(now PHIUS in the United States) was a student of both the Leger House and the
Saskatchewan Conservation House and recalls their flaws in an article which describes
the *Passivhaus* standard. Since the building envelope was so airtight, if occupants did not
open windows frequently enough the indoor air quality became unacceptably low. In
addition, without air infiltration, the relative humidity in the house was high enough to
result in mold growth in any areas that had reduced insulation or where there were
thermal bridges to the outside. Feist addresses these issues in a paper [3] proposing strict
ventilation requirements and championing the use of energy and heat recovery ventilators
as well as the reduction of thermal bridges to improve upon the performance of the early
structures. As a result the movement is well respected in Europe and relies on a set of performance based standards which engineers and architects must meet by any means that they deem to be necessary. While there is no specific recipe, superinsulation and airtightness remain features found in every residential Passivhaus which has successfully been certified. The standards are extremely simple, albeit quite quantitative [3]:

- Specific heating demand of $\leq 15\text{ kWh/(m}^2\text{yr)} [4756\text{ Btu/ft}^2\text{/yr}]
- Specific cooling demand of $\leq 15\text{ kWh/(m}^2\text{yr)} [4756\text{ Btu/ft}^2\text{/yr}]
- Specific primary energy demand of $\leq 120\text{ kWh/(m}^2\text{yr)} [38\text{ kBtu/ft}^2\text{/yr} \text{ or } 11.1\text{ kWh/ft}^2\text{/yr}]
- Airtightness of 0.6 ACH @50 Pascal

One stipulation is provided with the standards: each performance metric must be met while achieving a “high level of thermal comfort.” Whether or not North American Passive Homes achieve a high level of thermal comfort has not yet been widely explored. This study specifically seeks to investigate suitability of HVAC plants in humid and mixed climates (that would be uncommon in Germany) as they relate to Passivhaus construction and its unique challenges.

1.3 Current and Past HVAC Solutions Are Insufficient

The building techniques proposed by Feist and others have proved to be extremely good at cost effectively reducing energy consumption in Europe; however, they result in a new set of challenges which must be met through more precise and effective mechanical, electrical, and plumbing systems. Traditional means of ventilation such as operable
windows may no longer provide appropriate indoor air quality. Traditional space heating and cooling systems which focus primarily on sensible loads may fail to adequately manage the humidity of the space. The importance is paramount because HVAC system shortcomings may lead to long term damage to the building as moisture control is essential in air tight, super-insulated building envelopes. Furthermore, in order to better utilize energy resources and meet the energy consumption goals of Passivhaus-type standards in new climates it is essential to optimize the performance of the mechanical equipment utilized. This means that new appliances should improve on current SEER (Seasonal Energy Efficiency Rating) metrics, employ waste heat recovery, utilize modern controls, and be optimized for use within a super-insulated structure with very small heating and cooling loads.

1.4 Dehumidification Methods and Pyschrometrics

When considering occupant comfort inside a built environment engineers must focus on two parameters, temperature, and humidity. In order to properly manage moisture inside a building envelope it is important to understand the mechanisms which may be used to control it in the conditioned space. Interior moisture levels are strongly influenced by the behavior of the occupants; an average household evaporates up to 10 liters of water per day. In order to ensure a comfortable and healthy environment, moisture must be removed either by ventilation or by air conditioning [8].

In current residential construction thermostats only measure the dry bulb air temperature. The dry bulb temperature is simply a measure of the amount of sensible heat in the air. In the case of a dehumidification system it is also important to measure relative humidity.
Relative humidity is a function of temperature and pressure; it measures the amount of water vapor in the air relative to the total amount of water vapor the air is capable of holding at the current temperature and pressure. This parameter may be measured by a humidistat and controlled in variety of ways. However, almost all single family residential buildings in existence today do not monitor humidity and humidity reduction is usually achieved as a side effect of vapor compression air conditioning system.

1.4.1 Vapor Compression

Vapor compression systems are currently the most prevalent means of reducing humidity in residential structures. They cool air below the dew point and thus cause moisture to condensate from the air. The condensate may then be drained out of the coil and removed from the residence. Vapor compression systems boast high coefficients of performance, especially when they do not attempt to control humidity directly. The main problem with vapor compression systems is that they may have to cool air further than necessary to reach the dew point and condense water from the air. This results in several difficulties:

- Air may need to be reheated before being distributed to the zones of the structure.
- The coil may freeze making moisture removal impossible.
- A latent load may occur that is not in conjunction with a sensible load and the equipment will not operate.

Mini-split heat pumps are the most common mechanical means of cooling Passivhaus-style residences. Often, however, no cooling system is installed at all. There are many different vapor compression configurations available on the market today. Currently air
to air heat pump systems are the most prevalent; however, there also exist commercial air
to water, water to water, and geothermal systems. All of the systems may provide
significant energy savings in both residential and commercial applications. The choice
amongst the different system configurations depends largely on climactic and geological
conditions. Some systems may be more efficient than others; however, they all possess
the inherent difficulties with dehumidification noted previously.

1.4.2 Desiccants

In response to the shortcomings of vapor compression dehumidification one would
ideally develop technology capable of removing moisture content from the air
independent of temperature. Desiccant systems, both liquid and solid, are one such
technology. Desiccants are hygroscopic materials which may be used to remove latent
heat from an air stream. Desiccant systems allow one to implement a control system
which handles the latent and sensible heat loads independently; thus, allowing much
greater control over the properties of the conditioned zone. Desiccant systems may take a
variety of forms, but there are two primary configurations: liquid and solid.

1.4.2.1 Liquid

Liquid desiccants absorb moisture from the air stream. Absorption means that there is a
chemical reaction present and the desiccant itself is chemically changed. In a liquid based
system humid air is routed through media or a surface which has been immersed in the
desiccant liquid. The desiccant liquid absorbs moisture from the air and becomes diluted
[9]. The air is then supplied to the space and the diluted desiccant is exchanged with fresh
desiccant. The diluted desiccant may then be regenerated using heat to desorb moisture.

Common liquid desiccant materials are [9]:

- Lithium Chloride
- Calcium Chloride Brine
- Sodium Chloride Brine
- Ethylene Glycol

1.4.2.2 Solid

Solid desiccant systems differ significantly from liquid systems as they do not react chemically with the moisture in the air. They achieve air drying through a difference in vapor pressure between their surface and the moist air. The vapor pressure of the air is the driving mechanism for the adsorption of water by a solid desiccant system. Each water molecule present in the air will exert a force; the sum of the forces exerted by the each water molecule in the measured environment is known as the vapor pressure [10]. The existence of pressure differences between materials can cause water molecules to be adsorbed.

This study seeks to examine solid desiccants in a “wheel” configuration which continuously rotates to achieve regeneration. Other configurations such as packed beds are common, but less effective. Common solid desiccants are [9]:

- Silica Gel
- Alumina Gel
- Zeolites
1.5 Building Simulation Tools

There are a great number of building simulation tools available to engineers and architects. Each year they become more sophisticated and accurate. Building simulation tools are essential for the production of net zero energy homes and Passivhaus-style houses. Despite their popularity and recent improvements they are not all equal. Some of the major commercial packages are Trane Trace, eQuest, and Green Building Studio. Trane Trace focuses on equipment sizing (determining the peak load). eQuest determines the effectiveness of energy efficiency measures (using a quasi-steady state simulation). Green Building Studio is integrated with the software package Revit which allows users to create 3D building plans. All of these programs are used frequently when designing large commercial projects where equipment is costly and sizing is critical. Building simulation tools are also gaining some traction in high end residential design. None of these programs offers the ability to examine the house’s dynamic performance on time scales less than one hour.

Several programs which seek to quantify the dynamic performance of buildings have been developed and presented in the academic realm. One of these programs is HAMLab [11]. This study employs the HAMLab package implemented in MATLAB and Simulink to examine a new superinsulated air tight residence that is close to the standards set forth by the Passivhaus movement.
1.6 Goals of this Study

Columbus, Ohio has unique weather which makes it especially relevant to study the performance of Passivhaus homes. The Columbus climate is classified as both humid continental and humid subtropical on the Koeppen climate scale [12]. This means that the summer is often hot and humid and the winter tends to be cold and relatively dry. Essentially, a Passivhaus home located in Columbus, Ohio is exposed to a wide range of climatic conditions. Thus, the results of this study should be relevant to many different regions. The simulation itself will be useful in identifying potential temperature and humidity problems within the structure.

While several authors have identified the dynamic simulation of Passivhaus homes to be of importance, few have implemented satisfactory simulations. Some do not investigate humidity in the structure [13] [14] [15], others are located in climates with no cooling season [13], while still others use software with large time steps [16].

There are relatively few scientific investigations of Passivhaus home portray them in any negative light. This does not mean that the standard is well studied and mature in North America. Very recently, the founders of the movement have indicated that there is a need for the development of new strategies necessary for cooling and dehumidification in North America [7]. Despite these new concerns, it is clear that there have been successful implementations of Passivhaus standards around the world. Thus, the broad goals of this study are as follows:

- Examine a Passivhaus-style construction in a mixed climate that requires active cooling and features high humidity.
Perform dynamic building simulations at a time scale appropriate for determining the operation of HVAC equipment (seconds or minutes).

Include moisture, not just temperature in the simulation.

Identify factors, if any, which significantly influence house performance.

Identify novel HVAC equipment capable of efficiently correcting performance deficiencies.

Identify future work related to both the dynamic simulations and any subsequent HVAC systems.

1.6.1 Dynamic Building Energy Simulation of a Super-Insulated House

Chapter 2 details the dynamic simulation in the climate of Columbus, Ohio of The Ohio State University’s entry into the 2011 Solar Decathlon competition. This portion of the study explores the use of a conventional vapor compression conditioning system as well as the effects of occupant behavior on the parameters affecting comfort within the structure. It adds to the current literature on the subject by presenting a simulation in a mixed climate where cooling and dehumidification are traditionally required. Furthermore it adopts a simulation tool which acts on time scales less than one hour. It is concluded that the house, while energy efficient, has difficulty controlling moisture levels. In the summer season it is too humid and in the winter it is too dry.

1.6.2 Modeling Advanced HVAC Systems with Separate Sensible and Latent Control

Chapter 3 seeks to address the moisture related concerns uncovered in Chapter 2 through the use and modeling of a new desiccant assisted heat pump designed at Ohio State. In
this study solid desiccant cooling cycles are reviewed. Furthermore, a hybrid desiccant cooling cycle is explained and a prototype machine based on the cycle is described. The machine known as HAWC (Hybrid Air/Water Conditioner) accomplishes cooling, dehumidification, ventilation, and domestic hot water heating. Chapter 3 concludes that the new system is capable of completely eliminating high humidity events in the summer time while still saving energy as compared to a traditional HVAC system.

1.7 Thesis Organization

This thesis contains four chapters. This first chapter was a brief overview of energy consumption in buildings as well as recent developments in building envelope construction, HVAC technology, and building simulation. Chapter 2 describes the application of dynamic modeling software known as HAMlab to the Passivhaus-type house which was constructed for the 2011 Solar Decathlon Competition. Chapter 3 describes the application of an advanced HVAC system with separate sensible and latent heat control. The last chapter summarizes the results and suggests areas for future work.
References


Chapter 2: Simulated Hygrothermal Performance of a Super Insulated Residential Structure under Dynamic Load

Abstract

Chapter 2 details the dynamic simulation of The Ohio State University’s entry into the 2011 Solar Decathlon competition. This portion of the study explores the use of a conventional vapor compression conditioning system as well as the effects of occupant behavior on the parameters affecting comfort within the structure. It adds to the current literature on the subject by presenting a simulation in a mixed climate where cooling and dehumidification are traditionally required. Furthermore it adopts a simulation tool which acts on time scales less than one hour. It is concluded that the house, while energy efficient, has difficulty controlling moisture levels. In the summer season it is too humid and in the winter it is too dry.

2.1 Introduction

Starting in the 1960s new home construction began to feature less massive building materials and a greater percentage of fenestration. The resulting houses have high potential for overheating and other unforeseen climate control problems [1]. New, tighter construction that continues to feature light construction materials exacerbates the need for independent moisture control or latent cooling. Through the years new techniques have been developed to analyze the dynamic performance of buildings in order to determine
the likelihood of overheating. With the ever-increasing power of personal computers, the use of computer-based building energy models is now more common.

2.1.1 Dynamic Building Energy Modeling

Almost all current buildings are designed based on steady-state conditions. Engineers size heating and cooling systems only to meet peak loads. This technique usually results in buildings which are comfortable to the occupants but not necessarily efficient. The steady-state analysis often results in oversized systems. However, the advent of tighter construction techniques makes previous steady-state techniques less effective. Oversized building conditioning systems perform poorly largely due to excessive cycling.

Furthermore, in the cooling season they may fail to adequately address the latent heat load.

In an effort to establish standards in building energy simulation, the International Energy Agency (IEA) established `Annex 41.’ Annex 41 proposed that creating models and simulations for whole building heat and moisture (HAM) exchange processes and whole building interaction with HVAC systems is essential to producing more comfortable and more efficient buildings [2]. Annex 41 encouraged the development of multiple HAM simulation tools rather than one universal tool and provided standardized tests as a means for benchmarking the various simulation tools [2]. The program ran from 2003-2007. In conjunction to the IEA’s efforts, the National Renewable Energy Laboratory (NREL) maintains a list of whole building simulation tools on its website, some of which were developed through Annex 41 [3]. Due to unfamiliarity with dynamic simulation packages
and time constraints, except for the most sensitive and complex projects, many of these dynamic simulation tools have been largely ignored outside of academia. Energy modeling programs, typically based on DOE-2, may be used to perform cost analysis and to examine the performance of the building. These programs take hourly weather data as their input. Unfortunately, they also often resolve the simulation only on an hourly basis. The available DOE-2 based software packages have proven to be quite reliable and effective. In fact programs (which use DOE-2) such as e-Quest even feature graphical user interfaces (one of the main drawbacks of the standard DOE-2 engine). However, HVAC systems and modern thermal storage systems do not operate on time scales of hours and these programs are therefore not always effective in analyzing the control or dynamic performance of HVAC systems [4]. Furthermore, their ability to model complex HVAC installations is poor. It is very difficult to deviate from standard layouts and equipment sizes [5]. DOE-2 based programs also tend to be better for commercial structures; they have a wide variety of systems available in commercial sizes but fewer that would suit small residences with extremely low peak heating and cooling loads (on the order of 1 ton or less). Finally, DOE-2 is known to have some inaccuracies in its modeling of certain humidity conditions. Studies claim that this stems from the lack of moisture capacitance and quasi-steady state modeling which both exacerbate errors during conditions under which cooling loads are small [5]. Several alternate packages exist which address time scale issues, moisture capacitance, and allow greater flexibility in selecting and creating appropriate equipment sizes [6,2].
HAMLab was one of the many tools which resulted from the IEA Annex 41 program and has been widely used in the Netherlands. The thermal network used in HAMLab is based on the ELAN model by M.H. de Witt [7]. The ELAN model was later revamped by de Witt to function in the MATLAB® environment and named HAMBase. HAMbase_S was then developed from HAMBase and features the ability to use the Simulink® programming environment. For the current project, HAMLab (the overall collection of related tools including HAMbase_S) was chosen primarily because it is simple to implement a wide variety of components and controls in the Simulink environment. Furthermore, it is one of only a few validated software packages available for simulating buildings in Simulink [4]. Configuring the equipment layout is as simple as connecting the appropriate models with “wires” which mimic the schematic layout. Furthermore, with only small changes Simulink models may be exported to dSPACE™ and implemented as real time controls. The developer of HAMLab, A.W.M. van Schijndel, has used the simulation package to preserve a church organ facing humidity issues[8] and to investigate the hygrothermal properties of a museum[9]; other dynamic simulations have been undertaken to investigate passive homes[10] and hybrid desiccant units[5] using TRNSYS.

2.1.2 The Need for New Solutions

The increase in the prevalence of air conditioning systems and the rise in energy costs have necessitated new more innovative and more complicated HVAC systems. In addition, to enable appropriate control of sensible and latent loads in an energy-efficient manner, houses with very efficient building envelopes require novel heating and cooling
technologies. Kreith and Johnson state “heat pumps are one of the most underused means of conserving energy for heating and cooling buildings” [11]. There are many ways to improve the efficiency of heat pump systems. Current manufacturers are primarily focused on improving variable speed systems. Other research has been conducted using solar thermal energy to improve system performance. Working fluids (refrigerants) are also of great concern to manufacturers as CFCs and HFCs are being phased out. New systems seek to find more environmentally friendly working fluids such as carbon dioxide. Finally, desiccant technology is emerging as a new means of improving heat pump efficiency. All of these advances require more complex and precise control systems. Kreith et al state that without proper control even the most sophisticated and efficient HVAC systems will fail to deliver comfort and will waste energy [11]. The use of dynamic modeling will enable designers to validate control systems and optimize components in the development stage of new systems.

This paper presents the implementation and results of HAMLab dynamic building energy simulation to address the performance of an air to water heat pump system in a small super insulated residential structure. The house used is a model of The Ohio State University’s 2011 Solar Decathlon entry enCORE. enCORE was built to meet Passivhaus or Passive House Institute Standards [12], and, in particular, has a super insulated, airtight building envelope. In what follows the HAMLab model is described along with the TMY2 data that is used to provide hourly climate data for the model. The steps necessary to model the HVAC plant and its capacity to perform both sensible and latent heat reduction are described. Furthermore, a means of estimating energy use is
provided. These results are analyzed in an attempt to identify potential hygrothermal performance deficits which could be subsequently addressed through a variety of means.

2.2 Theory: A HAMLab Model of the OSU Solar Decathlon House

2.2.1 Thermal Network Model and Transformation
The model of the OSU Solar Decathlon House assumes that there is one room with only one air temperature node. That is, the air temperature and moisture content of the air in the room is constant throughout the entire volume. While this may not be physically accurate, it is directly analogous to the information which modern building control systems use as feedback. In other words, almost all residential single zone systems contain only one temperature sensor that measures air temperature at a single point in the space. If the sensor is placed intelligently and the HVAC system is properly balanced, this single measurement may be used to provide adequate comfort within the single zone for which it provides feedback [11]; furthermore, it has been well documented that Passivhaus-type houses do not need complex distribution systems (at least for heating) as there is little temperature variation within and even amongst zones [12].

In order to examine the dynamic response of buildings to outdoor climatic conditions, HAMLab uses a clever thermal network which was derived from simple hand calculation methods. The simplest 1st order thermal networks used to represent buildings include only one node (thermal storage) which is connected to the conditioned air. This one node approach simulates thermal storage but is said to be inaccurate [7]. More accurate, two
node representations connect the outdoor conditions as well as the internal air to the thermal mass (the wall).

Modern computers have the power to solve more complicated networks efficiently; new networks have multiple walls, geometries, and include windows. As such Figure 2, details the delta representation of another classical thermal network which is again more complicated [4]. The delta representation features two walls (each considered one node) as well as an internal air temperature node. Wall 1 at temperature, $T_1$ is connected to the room air temperature $T_a$ through a thermal conductance defined as the area of wall 1 multiplied by the convective heat transfer coefficient, $h_{cv}$. Wall 2 is connected to the room air temperature $T_a$ in exactly the same manner. There also exists radiant heat transfer between walls 1 and 2. This transfer occurs through a thermal conductance defined by the radiant heat transfer coefficient $h_r$ multiplied by the area of wall 1, $A_1$. Furthermore, at the room air temperature node, $T_a$, there exists a convective heat flow $\Phi_{cv}$ which represents the addition of conditioned and ventilation air to the room. There also exist two radiant heat flows at each wall node. Finally, there exists a net heat flow out of the structure at each wall node. In general all models must ensure the overall heat balance; that is heat lost plus heat stored is equal to heat gains (from the environment) plus any auxiliary heat. This paper examines the efficient addition of the auxiliary heat needed to maintain appropriate temperature and humidity conditions. In the representation depicted in Figure 2 the net heat flows out of the structure may be defined as follows in Equations 2.1 and 2.2 [8]:
\[ \Phi_{Ax1} = \frac{A_1}{A_1 + A_2} \Phi_r + A_1 h_{cv} (T_a - T_i) + A_1 h_r (T_2 - T_i) \]

\[ \Phi_{Ax2} = \frac{A_2}{A_1 + A_2} \Phi_r + A_2 h_{cv} (T_a - T_2) - A_1 h_r (T_2 - T_i) \]

Figure 2: Delta Representation of a Classical Thermal Network [4]

Since Equations 1 and 2 include radiation terms, the treatment applied in Figure 2.1 requires that view factors be computed for the interaction between each wall. In a two wall model this is certainly feasible; however, in a more complex 6 sided model which
may or may not have walls which are orthogonal to each other the task may become intractable for certain geometries. Thus, it is desirable to simplify the model such that all the walls (excluding fenestration) are at the same radiant temperature. The simplification is derived by applying a delta star transformation to the classical delta thermal network presented and is shown in Figure 3 [7]. The center node in the delta star configuration is known as the environmental temperature node. A delta star transformation is possible if the resistances (in this case thermal resistances) between terminals remain constant. For example the resistance between terminal B and C in the delta configuration must be equal to the resistance between B and C in the star configuration.

![Delta Star Transformation Example](attachment:image.png)

**Figure 3: Delta Star Transformation Example**

Figure 4, details the delta transformation of the classical thermal network presented in Figure 3. The model features the environmental temperature node within the delta star transformation [4, 7]. The transformation applies the integrating sphere approach [7] such that all radiant heat transfer occurs at a single radiant temperature. Thus the
environmental temperature node allows all radiant heat transfer to occur at a single temperature, which eases restrictions on geometry and reduces model run time. The environmental temperature node is then connected to the room air temperature node by a coupling coefficient. The coupling coefficient determines the heat transferred from the environmental temperature node to the air temperature node.

Figure 4: Star Representation of Classical Thermal Network [4]

Some authors have considered the physical validity of the environmental temperature formulation [13,14]; however, its use here is not as a physically measureable variable but rather as a means for estimating heat exchanges in the form of radiation between the interior surfaces. Because of the lack of information regarding the stratification of the room air temperature, authors [15] have deemed the simplification of the radiant heat
exchanges between walls to be appropriate. Furthermore, this formulation has been shown to be accurate using BESTEST, a common exercise which determines the accuracy of building energy simulations [16]. Thus, the thermal network which underlies the HAMLab model is appropriate for measuring the dynamic response of the building so as to simulate and optimize control systems and measure the dynamic behavior of mechanical system components. Now the treatment of the external environment may be examined through the use of the “admittance method.”

2.2.2 The Admittance Method

The HAMLab model is based on the admittance concept developed in 1974 by Milbank and Lynn [17]. When buildings are subjected to external conditions (daily changes in weather) they undergo a complex series of processes. One such process includes the storage of thermal energy within the wall construction. This thermal energy is eventually admitted to the interior of the building through conductive and radiant heat transfer. The calculation of cooling loads requires the solution of the Fourier equation for the distribution of temperature within the walls of the structure. The admittance method assumes that both the variations of temperature externally and internally are sinusoidal in nature. The input differs from the output in magnitude and phase. Three factors: the admittance factor, the decrement factor, and the surface factor are defined to describe the interaction of climate conditions with the wall. The admittance factor is “the ratio of sinusoidal heat flux to the sinusoidal temperature at a specific surface”. The decrement factor describes “the ratio of the sinusoidal transmittance to the steady state
transmittance”. Finally, the surface factor describes the “ratio of the sinusoidal heat flow readmitted to the space over the sinusoidal heat flow absorbed by the surface” [18].

2.2.3 HAMLab Climate, Building Data Entry, and Occupancy

In order to use HAMLab it is necessary to initialize the model with the appropriate climate conditions and building information. The climate data for this project is sourced from the TMY2 data set made available by NREL [19]. The building model is derived from a slightly simplified representation of The Ohio State University’s 2011 Solar Decathlon entry, a super insulated 1000 square foot energy efficient home. Since the house is located in Columbus, Ohio, the simulation is carried out using TMY2 data for Columbus.

2.2.3.1 Typical Meteorological Year Data Sets

A typical meteorological year (TMY) data set consists of historical weather data. The data contained in the TMY2 set is created from measured weather data representing average conditions from a collection period which lasted from 1961-1990. TMY2 data is often used to gauge the quality of buildings (specifically how they respond to the outdoor climate) in terms of energy use and yearly energy costs [20] and is suitable for the simulation of both building construction systems and solar energy conversion systems. The TMY2 set contains hourly values for numerous parameters, and the categories necessary for HAMLab are serially complete for the 30 year period studied. Other categories are not complete; however, they do not apply to this research.
The TMY2 data must be reformatted for use with HAMLab. A MATLAB m-file (script) was used to extract the relevant information from the TMY2 data set. The first line of each TMY2 data file contains a header which includes information regarding the station name, location, and elevation. The WBAN number for the Columbus, Ohio station is 14821. It is located at Latitude 40 degrees and Longitude 82 degrees and 53 minutes. It has an elevation of 254 feet above sea level. The station location information is removed from the dataset as HAMLab requires that this information be entered into a separate array during the initial input regarding the structure to be simulated. Figure 5 shows a typical TMY2 file format and some of the relevant measurements contained within it. A full explanation of the data contained in each column is presented in the TMY2 users guide available from NREL.

Figure 5: TMY2 Data File Format
In order to use HAMLab to simulate the climate in Columbus, Ohio it was necessary to extract the following data from the TMY2 set: Year, Diffuse Solar Radiation (W/m^2), exterior air temperature (Celsius) multiplied by 10, direct normal solar radiation (W/m^2), cloud cover (scale of 1:8), relative humidity (percentage), 10x wind velocity (m/s), and finally wind direction (degrees with north=0).

Fortunately the TMY2 data set uses metric units; thus, most conversions are relatively simple procedures. The main difference between the TMY2 set and required input array is the cloud cover measurement. NREL employs a 0-10 scale whereas HAMLab requires a scale of 1-8. In order to convert the data, each value in the cloud cover array is increased by 1, resulting in a 1-11 scale. The resulting array values are then multiplied by (8/11) and rounded to rescale to integer values between 1 and 8. Each parameter necessary for HAMLab is then saved into an 8 column, 8760 row array.

2.2.3.2 Building Information

The building to be modeled in this research is an approximation of The Ohio State University’s 2011 Solar Decathlon house called enCORE. This model is chosen because it would give the investigators an opportunity to validate the HAMLab results and building model. Furthermore, the house features a unique and flexible controls system as well as novel climate control technologies which would allow the investigators to explore the efficiency of these new systems.

The house itself is approximately 975 square feet. The geometry of the house and the controls system make it relatively easy to model with a few simplifications. It is a relatively simple shape (square) with an almost flat roof. It currently is controlled as one
zone. Figure 6 shows a three dimensional representation of the structure as it was input into HAMLab.

![3-D Representation of enCORE Model for HAMLab](image)

Several simplifications were made in order to facilitate the simulation. First the breezeway area on the West side of the house was removed and disregarded. Shading was added to the fenestration in order to account for the presence of manually operated screens on the outer façade of the house (including shading provided by the breezeway). The walls of the house are constructed to maximize the thermal resistance of the structure. A variety of measures ensure air tightness, high thermal resistance, and reasonable cost. Figure 7 shows a 3D cut away of a typical wall section. The wooden “2x6” advanced-framing construction allows for a much thicker layer of blown in fiberglass insulation and fewer thermal bridges, all at reduced cost. The taped-seam sheathing system employed an integrated moisture barrier which lessened install time and
improved wall performance. The 2” of rigid exterior insulation with taped seams is another air barrier that keeps the dew point outboard of the wall cavity and boosts overall insulation. The final R-value of the wall was calculated to be R-43. The roof and floor feature similar construction with thicker layers of rigid and fiberglass insulation respectively.

![Figure 7: Typical Wall Construction](image)

The windows included on the house are also very high performance, feature R-values as high as 10, and are tuned to have high solar heat gain coefficients on the south side. Furthermore, they feature movable shading devices to maximize solar gain in the winter time and minimize it during cooling seasons. The shading devices are modeled in the HAMLab simulation using the “sun blinds” feature.
Appendix A contains tables with details regarding the composition, surface, and orientation of each of the 6 surfaces of the building envelope. Furthermore, it contains detailed data outlining the material id and thickness for each building component as entered in HAMLab.

2.2.3.3 Usage Profiles

The occupancy of the structure and actions of the occupants greatly affects the internal conditions. By generating several likely scenarios based upon the day of the week it is possible to create a relatively accurate schedule of building use. enCORE was designed to be inhabited by a young, three-person family (two adults and one child). It is assumed that the two adults work on weekdays and that the child is old enough to attend school. For simplicity it is assumed that all three family members enter and leave the house at the same time. On the weekend no family member works and a greater percentage of time is spent in the house. The house was tested using weekday mode. Appendix A outlines the daily activities of the family.

Furthermore, HAMLab considers the possibility of sun blinds and free cooling. Each day is divided into periods, during these periods one may enter a threshold value for the use of shading devices (in terms of solar irradiance), free cooling (controlled by outdoor temperature), active heating and active cooling (controlled by indoor temperature). HAMLab is also programmed to include sensible heat recovery for ventilation air. This feature is utilized for all models.

Researchers at Lawrence Berkeley National Laboratory (LBNL) investigated the effects of new ventilation regulations on indoor humidity [21]. In this process they reviewed
published sources which gave estimates of internal moisture generation rates for residential structures. Table 1 outlines the published rates. The table clearly indicates that the published rates for moisture production vary widely. This is due to the personal preferences of each resident as well as the number of residents. Some examples of sources that contribute to the total production per day are bathing, cooking, perspiration, washing, and cleaning. Furthermore, new construction may include damp building materials which release moisture into the space as they dry. Finally, basements often are not completely dry and may contribute to the internal moisture load present in the structure.

Researchers at LBNL [21] elected to use a modified version of ASHRAE 160P which takes into account reduced occupancy and assumes that the use of task specific exhaust fans (rather than general mechanical ventilation) to reduce moisture generation. The end result was 6.5 kg/day (0.000394 kg/sec) generation rate which is quite low compared to the other estimates shown in Table 1. Just as in the LBNL study, moisture generation is input into the simulation continuously throughout the course of the day.
Table 1: Published Residential Moisture Generation Rates (Derived from [21])

<table>
<thead>
<tr>
<th>Source</th>
<th>Production Rate Kg/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Building Digest (1960)</td>
<td>7.7</td>
</tr>
<tr>
<td>NRCan (1983)</td>
<td>5-7.4</td>
</tr>
<tr>
<td>Canadian Building Digest (1984)</td>
<td>17.2</td>
</tr>
<tr>
<td>ASHRAE Humidity Control Design Guide</td>
<td>9.5</td>
</tr>
<tr>
<td>ASHRAE 160P (for a family of four)</td>
<td>13.8 (6.5 with exhaust)</td>
</tr>
</tbody>
</table>

2.3 Systems Modeling and Calculations

The simulation will evaluate a simple high efficiency HVAC solution which includes an air-to-water heat pump that interfaces with a forced air distribution system through a fan coil unit. The heat pump is sized at 1.5 tons of refrigeration (18,000 btu/hr). In order to quantify the hygrothermal performance of the structure using a typical vapor compression dehumidification method, the model incorporates both sensible and latent cooling. There are several necessary components that are programmed in MATLAB.

- Building model
- Calculation of humidity ratio
- Coil moisture removal
- Power draw of the heat pump

The building model was discussed in section 2.2. The humidity ratio is necessary for estimating the sensible heat ratio (SHR) which in turn provides a means for estimating
the moisture removal capacity of the heat pump. Finally, it was important to find a means to estimate the power draw of the heat pump in order to be able to compare the energy use of this simple system to much more complex HVAC installations.

2.3.1 Computation of Humidity Ratio

In order to calculate the moisture removal capacity of the heat pump system it is necessary to determine the humidity ratio of the supply air. The humidity ratio is defined as follows [22]:

\[
W = 0.62198 \frac{p_w}{p-p_w},
\]

where \( W \) is the humidity ratio, 0.62198 is the ratio of the molecular weight of water to the molecular weight of air, \( p_w \) is the partial pressure of water and \( p \) is the atmospheric pressure. Thus, it is clear that in order to calculate the humidity ratio it is first necessary to know the partial pressure of water over air. Although the HAMLab simulation and weather data does not specifically include this metric, it is possible to express the partial pressure of water over air as a function of temperature and relative humidity. The method chosen for this application is derived from the Arden Buck equation [23] which is written as follows:

\[
p_{ws} = (1.0007 + 3.46 \times 10^{-6}) \times 6.1121 \times \exp\left(\frac{17.502}{240.97 + T}\right)
\]
where \( p_{ws} \) is the saturation vapor pressure of moist air over water and \( T \) is the dry bulb temperature in degrees Celsius. Equation 2.4 is known to be accurate between -80 and +50 °C. From the saturation vapor pressure it is then possible to calculate the vapor pressure as a function of relative humidity in the following manner [22]:

\[
p_w = RH \times p_{ws}(T),
\]

where \( RH \) is the relative humidity and \( T \) is the local dry bulb temperature in degrees Celsius. Thus all the information needed to calculate the humidity ratio can be determined and \( W \) is known as a function of temperature and relative humidity.

### 2.3.2 Moisture Removal by the Evaporator

In order to accurately quantify the baseline performance of a heat pump system, it is necessary to determine the amount of moisture removed at the evaporator coil. The sensible heat ratio (\( SHR \)) may be defined for both the building and the coil. The building load may be divided into two categories: sensible and latent; there ratio can be expressed as an SHR. The coil is also capable of removing a certain amount of sensible heat per unit of latent heat and this can also be expressed as an SHR. If the two SHRs (building and coil) are unequal either the sensible or latent load will not be adequately served. The coils may be manipulated; however, for this case a generic coil was chosen to match previous studies.

In this case the SHR of the coil is calculated (each time step) using several empirically determined formulas following the procedure used by investigators at LBNL [21]. The
SHR is determined as a function of the humidity ratio \((W)\) of the air entering the evaporator coil.

\[
SHR = 1 - 50(W - 0.005)
\]

A property of moist air known as the latent heat of evaporation or condensation \((q_{\text{latent}})\) is defined as a function of dry bulb temperature in degrees Celsius [21]:

\[
q_{\text{latent}} = -.00061432 * T^3 + .00158927 * T^2 - 2.36418 * T + 2500.79
\]

Finally, the mass flux of moisture to the evaporator coil is defined as [21]:

\[
m_{\text{coil}} = \frac{(1 - SHR) * \text{System Capacity}}{q_{\text{latent}}}
\]

In this simulation it is assumed that all moisture which condenses on the coil is drained out of the system and removed from the conditioned air. In reality some of the moisture will make its way back into the house as the heat pump cycles on and off. Thus, this study presents a best case scenario for summertime moisture removal capacity of the system. Real systems will likely remove even less moisture. Adding greater detail is possible, and authors suggest that the addition of such a model could increase indoor humidity levels by 5-10% (during active cooling only) [24]. Future studies should include more accurate first principles based heat pump models, coil latent performance degradation, and the possibility for re-evaporation of moisture. This level of detail could
assist engineers pursuing vapor compression dehumidification of a Passivhaus in coil selection. The logic behind the implementation of the current heat pump model is explained in the following section.

2.3.3 Heat Pump Coefficient of Performance

The evaluation of the energy consumption of heat pumps and chillers requires determination of the coefficient of performance (COP) based on the outdoor conditions. Articles in the literature suggest that, at a simple level, there are two main approaches for determining the COP [25]. The first is to simply fit curves to real performance data. This is also known as a functional fit model. The other approach analyzes the performance of each heat pump component with first principles models. There are, of course, also models which fall somewhere between these two extremes.

The goal of the current research is not to investigate or optimize any specific individual component, but rather to evaluate the potential for moisture problems in a super insulated structure. Thus, a functional fit model was used with a generic 1.5 ton heat pump.

The equations used for deriving the power draw of the heat pump are based on data from tests conducted in accordance with the European Heat Pump Association standards. The equations are presented by Baster in [26] and are developed using the regression analysis tool in MATLAB. The following equation provides the COP as a function of the difference ($\Delta T$) between the return temperature of the working fluid (in this case water) and the outdoor temperature:
Once the COP is known, the power draw of the heat pump system is determined from the cooling (or heating) power output by the system in the following manner:

\[
\text{COP} = 6.70 \times \exp(-0.022 \times \Delta T)
\]

2.3.4 Auxiliary Power

Because enCORE features a forced air system it is also necessary to add other power draws associated with the air distribution. Table 2 details the measured auxiliary power consumption of the system.

Table 2: Auxiliary Power Consumption

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Consumption (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>43</td>
</tr>
<tr>
<td>Blower</td>
<td>570</td>
</tr>
<tr>
<td>Fan A</td>
<td>49</td>
</tr>
<tr>
<td>Fan B</td>
<td>6</td>
</tr>
</tbody>
</table>
2.4 Results and Discussion

2.4.1 One and a Half Ton Heat Pump with an HRV and 24.5°C Set Point

2.4.1.1 Indoor Air Temperature

Dynamic simulations in HAMLab provide many interesting results regarding the comfort levels within the structure. In all cases, the indoor air temperature was maintained at the desired set points with the 1.5 ton heat pump. This is important because it demonstrates that the cooling plant and (heating plant) are adequately sized to meet the peak loads faced by the structure and that moisture problems which may be indicated by the simulation are not the result of a system which is undersized for the peak load. Figure 8 details the indoor air temperature of the structure over the course of a one year period beginning January 1st. For this simulation the cooling set point was maintained between 24.5 and 24 degrees C. The heating set point was maintained between 20.5 and 21 degrees C. The simulation shows that the house consumes 5.85 kWh/(m^2*year) in this instance. This amount of energy consumption meets Passivhaus standards.
Figure 8: Indoor Air Temperature with 1.5 ton Heat Pump and 24.5°C Set Point

2.4.1.2 Sensible Heat Ratio (SHR)

Throughout this investigation the moisture removal capacity of the heat pump system was the only means for dehumidification in the structure. As such, the SHR (calculated from Equation 2.6 from with TMY2 temperature and relative humidity data) was used to estimate the moisture removed from the conditioned air. Figure 9 shows the SHR of the system over the course of the one year time period.
As expected, when it is cold outside there is very little moisture in the air, and therefore the heating season SHR value is maintained around 1. This aspect of the data, however, is largely irrelevant to this study as there is no cooling taking place during this time and thus moisture removal is not physically possible. During the cooling season the graph in Fig. 2.9 indicates that the SHR ranges between 0.8 and 0.47. This represents a significant amount of moisture removal at the cooling coil. For the SHR values shown in Figure 9 and used in this simulation, the 1.5 ton heat pump should ordinarily be an adequate means of removing moisture from the house if the traditional balance of sensible and latent loads is considered [22].

2.4.1.3 Indoor Relative Humidity

In a study conducted by Walker and Sherman [21] the authors concluded that:
- It is appropriate to use relative humidity to measure moisture within the house because the temperatures are controlled. The use of controlled temperatures ensures that false conclusions will not be drawn about high relative humidity ratios which may occur at low temperature.
- Leaky homes generally do not experience many high humidity events.
- The standard home (less leaky) experiences more high humidity events than the leaky home.

Figure 10 details the relative humidity of the enCORE house vs. time. Despite the indications that the sensible load is met the indoor conditions related to the amount of moisture present in the building remain high during the summer time. In particular, the relative humidity is often over 60% and there are also occasional values over 70%. ASHRAE Standard 55 for thermal comfort indicates that relative humidity above 60% (at these temperatures) within a structure is not within the comfort zone [27]. Furthermore, mold growth is a concern at relative humidity above 70%.
The results presented in Figure 10 indicate that, even in climates such as the Midwest which have not traditionally been problematic, super-insulated homes with high levels of air sealing are more susceptible to high humidity events. Table 3 details the percentage of time the structure was in different humidity ranges, keeping in mind that the ASHRAE standard is 40-60% relative humidity.
Table 3: Percentage of time structure exceeds acceptable relative humidity levels

<table>
<thead>
<tr>
<th>Relative Humidity</th>
<th>Hours</th>
<th>Percentage of Total Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>10-20%</td>
<td>807.24</td>
<td>9.22%</td>
</tr>
<tr>
<td>20-30%</td>
<td>1757.96</td>
<td>20.07%</td>
</tr>
<tr>
<td>30-40%</td>
<td>1592.97</td>
<td>18.18%</td>
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<td>40-50%</td>
<td>1603.00</td>
<td>18.30%</td>
</tr>
<tr>
<td>50-60%</td>
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<td>19.31%</td>
</tr>
<tr>
<td>60-70%</td>
<td>1195.38</td>
<td>13.65%</td>
</tr>
<tr>
<td>70-80%</td>
<td>112.04</td>
<td>1.28%</td>
</tr>
<tr>
<td>80-90%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>90-100%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total Hours&gt;60%</td>
<td>1307.42</td>
<td>14.92%</td>
</tr>
<tr>
<td>Total Hours&gt;70%</td>
<td>112.04</td>
<td>1.28%</td>
</tr>
<tr>
<td>Total Hours&lt;40%</td>
<td>4158.16</td>
<td>47.47%</td>
</tr>
</tbody>
</table>

The data in Table 3 indicates that the home is out of the comfort zone (over 60% relative humidity) approximately 15% of the year. The numbers are not alarming from a health or mold growth standpoint, but they do indicate a need for better control of the comfort zone. Furthermore, the home is below 40% humidity for 47.5% of the year. Columbus, Ohio is characterized as climate zone 5 by ASHRAE and is considered a cold climate. Walker and Sherman do not consider a home in climate zone 5, but they do consider Kansas City a mixed humid climate (4a), whose summer conditions are not extremely different from Columbus. The results presented in this study are not significantly different then the characterizations presented in Walker and Sherman in which a house with a continuous exhaust (and tight construction) had 1653 hours above 60% relative humidity and 240 hours above 70% relative humidity [21]. It is also clear from their data
for Kansas City that houses with an HRV/ERV (and tighter construction) spend more time above 60% relative humidity than more leaky homes (despite avoiding many hours above 70% relative humidity).

The most obvious reason for the number of hours above 60% relative humidity is that, unlike in structures that are not as well insulated; the sensible load in the house is not always bigger than the latent load. In other words passive house construction has damped out external temperature swings but has not removed internal moisture generation.

Although the structure is controlled to 24.5°C with a 0.5°C dead band, the indoor air temperature often dips below the cooling set point and the cooling system does not turn on. Walker and Sherman suggest that commercial systems, reheat-type systems could be employed; however, these systems are inefficient and would certainly be counter to the goals of a passive house.

Another clear issue is that of the winter time relative humidity. While it was not the original intention of this study to show out of range humidity in the winter time, it must be noted that they are extremely low. In fact the structure is below 40% relative humidity nearly half of the year. Again, Walker and Sherman note low winter time humidity in their investigation within the Kansas City climate [21]. Low winter time humidity is a problem more prevalent in houses with continuous ventilation. This phenomenon has also been noted by other authors investigating Passivhaus [28]. These investigators note that in climates such as Austria where there are cool and dry winters, the outside air contains very little moisture (less than 4 g of water per m^3 of air). When this air is brought into the structure by the mechanical ventilation system and heated the relative humidity...
becomes very low [28]. The low humidity is of concern to occupant health and should be addressed; however, this issue will require further research and study before a solution can be proposed.

2.4.2 One and a half Ton Heat Pump with an HRV: Set Point Reduction

One potential method to address the high moisture levels in the building is to reduce the set point of the cooling system, causing it to increase total time in operation. Lowering the set point, however, will reduce the moisture capacity of the indoor air and, despite removing more moisture, potentially increase relative humidity. Furthermore, it is worthwhile to note that the 24.5°C set point is relatively high for the average American homeowner and it is also worth studying alternate set points as each resident will choose their own.

The simulation was re-run with a cooling set point reduced to 23°C. Figure 11 shows the relative humidity vs. time for a one year period for the 23°C set point.

Table 4 shows the percentage of yearly time spent in different ranges of humidity for the 23°C set point. In this case 18.66% of hours are above 60% and 3.19% are above 70%. Unfortunately, this is not an improvement. In addition, this configuration used a total of 570.2 kWh (6 kWh/m^2*year) for the cooling season (slightly more than the baseline case).
The house is simulated again at an even lower set point of 22°C to see if even greater cooling system on-time will affect the summertime indoor relative humidity. Figure 12
shows the relative humidity vs. time for a one year period at the lowest set point, and Table 5 shows the percentage of yearly time spent in different ranges of humidity. Again, the results are worse with now nearly 22.32% of days above 60% relative humidity. Furthermore, the system now uses 7.4 kWh/(m^2*year) or 687.84 kWh/year for cooling which is a 26.5% increase in energy use for cooling.

Figure 12: 22°C Set Point Relative Humidity
Table 5: 22°C Set Point Relative Humidity

<table>
<thead>
<tr>
<th>Relative Humidity</th>
<th>Hours</th>
<th>Percentage of Total Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>10-20%</td>
<td>807.28</td>
<td>9.22%</td>
</tr>
<tr>
<td>20-30%</td>
<td>1757.55</td>
<td>20.06%</td>
</tr>
<tr>
<td>30-40%</td>
<td>1521.50</td>
<td>17.37%</td>
</tr>
<tr>
<td>40-50%</td>
<td>1428.81</td>
<td>16.31%</td>
</tr>
<tr>
<td>50-60%</td>
<td>1290.05</td>
<td>14.73%</td>
</tr>
<tr>
<td>60-70%</td>
<td>1464.69</td>
<td>16.72%</td>
</tr>
<tr>
<td>70-80%</td>
<td>487.60</td>
<td>5.57%</td>
</tr>
<tr>
<td>80-90%</td>
<td>2.51</td>
<td>0.03%</td>
</tr>
<tr>
<td>90-100%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total Hours&gt;60%</td>
<td>1954.81</td>
<td>22.32%</td>
</tr>
<tr>
<td>Total Hours&gt;70%</td>
<td>490.11</td>
<td>5.59%</td>
</tr>
<tr>
<td>Total Hours&lt;40%</td>
<td>4086.33</td>
<td>46.65%</td>
</tr>
</tbody>
</table>

2.4.3 One and a Half Ton Heat Pump with HRV and 24.5°C Set Point: Dead band Increase

Another parameter which can affect heat pump performance is the size of the dead band. Increasing the size of the dead band is common amongst users who wish to reduce energy consumption, as it can increase the duration of each cooling cycle. Previously the dead band for cooling was set at 0.5°C; this simulation changes the dead band to 1°C. The results are worse performance in terms of moisture control but less energy consumption. Over 17% of the hours are now over 60% relative humidity and 3% are over 70% relative humidity. As energy consumption for cooling is already exceptionally low, increasing the dead band is considered to be an unnecessary change.
2.4.4 Two Ton Heat Pump with HRV and 24.5°C Set Point

Increasing plant size could increase ability to remove moisture; however, it could also decrease on time, increasing cycling. Theoretically, both increased cycling and increased size should increase energy consumption. Changing the plant size to two tons results in 20% of the hours over 60% relative humidity and 5% of the hours above 70% relative humidity. Again, this modification does not appear to be advantageous to the performance either in terms of moisture control. For completeness, a 1 ton heat pump was also tested; however, this plant failed to maintain the winter indoor temperature at a set point of 21°C. This failure indicates that the plant was too small to meet the peak wintertime sensible loads and cannot be considered for further study.

2.4.5 One and a half Ton Heat Pump with HRV and 24.5°C Set point: Moisture Generation Rate

The simulations show that the main problem with enCORE is that it is too dry in the winter and too humid in the summer. As discussed in section 2.2.3.1, there are many possible moisture generation rates depending on each occupant’s preferences and activities. For this study, a relatively low rate has been chosen (6.5 kg/day). It is likely that actual generation rates will differ. Thus, testing various moisture generation rates may help to guide builders and designers to make more universal envelope and mechanical system choices. Since the current moisture generation rate is already as low as any others found in the literature (see section 2.2.3.1), the approach will be to raise the levels. Thus, the moisture generation parameter was varied to 9.75 kg/day and the building was simulated at the 25°C set point with the normal 0.5°C dead band and 1.5 ton
heat pump. In this case energy consumption increased to 7.27 kWh/(m^2*year).

Furthermore, the house was over 60% relative humidity for 21% of the year and over 70% relative humidity approximately 5% of the year. This shows that increasing the moisture generation is comparable to decreasing the set point by 2°C. Clearly, in the face of unpredictable user behavior one needs to plan for better moisture control. Logically, one may achieve this through better mechanical systems especially the use of dehumidification technologies coupled to a humidistat for control.

2.5 Summary

2.5.1 enCORE Energy Consumption

The best configuration of the HVAC plant in both performance and energy consumption was the 1.5 ton heat pump set at 25°C with an HRV (sensible heat recovery system entered in building model details 2.2.3). This system consumed 5.85 kWh/m^2*year, which easily meets the Passivhaus guidelines for energy consumption. These results show that Passivhaus requirements for the building envelope are effective even in mixed climates with relatively extreme weather. However, researchers are finding out every climate is going to have its own unique challenges. The ability to model houses such as enCORE will validate rules of thumb for different regions very quickly. It is much better to explore these issues using a simulation than to discover them after mechanical equipment has been installed and the house is complete.
2.5.2 General Moisture Concerns and Variability of Homeowner Behavior

While it is reasonable to expect many homeowners (especially those willing to build super insulated structures) to accept the high cooling set points used in the base case of this simulation, it is clear that even in the best case scenario (high set point) traditional air conditioning equipment may not be appropriate for maintaining a comfortable environment and acceptable indoor air quality. The extreme air tightness and high R-value of Passivhaus construction cause significant lag between outside temperature changes and internal temperature changes. The net result is a building that needs little sensible heating and cooling, regardless of the climate and the occupant actions.

On the other hand, latent loads are significantly influenced by occupant behavior and the building envelope does not mitigate issues associated with latent loads. Not only do occupants alter internal moisture generation through their daily activities, but changing the set point also influences the latent load. The Passivhaus building techniques can obviously do little to influence internal moisture loads. Mechanical ventilation may be used to remove internally generated moisture loads, but if nothing is done to specifically address the humidity in the outside air.

In conclusion because, traditional conditioning methods do not directly address latent loads, but rather deal with them as a side effect of vapor compression. Even the best-case of this study, a 1.5 ton heat pump with a set point of 25°C, the house is out of the comfort zone for nearly 64% of the year. In the case of a 23°C one sees an increase in time outside of the comfort zone to nearly 70% of the year. There is no question that this home would benefit from a mechanical system which could offer better control over moisture.
2.5.3 Does an ERV make Sense?
One way that Passivhaus owners attempt to alleviate moisture problems is through the addition of an energy recovery ventilator (ERV). ERV use is varied in this climate zone; many homeowners opt for an HRV. While ERVs can help to solve some problems related to the amount of moisture within the building envelope they can only function as well as the conditions inside and outside the building allow. For example if both the indoor air and outdoor air are too humid the ERV cannot bring either air stream back into spec. Future study may indicate that owners of passive homes should use an ERV. Furthermore, some models for enthalpy exchange wheels (the key component of an ERV) may be modified to perform desiccant dehumidification [29], thus, allowing for two alternate mechanical system options to be explored.

2.5.4 Separate Sensible and Latent Cooling
It is clear that this house needs a means for active dehumidification for optimal control over the comfort zone. There are several innovative new dehumidification techniques that are currently being explored by researchers. One such technique is hybrid heat pump and solid desiccant systems which are also known as separate sensible and latent cooling systems. These systems would be ideal because they improve the performance of the mechanical system in terms of its ability to control the latent load and they also reduce the energy consumption of the heat pump. Thus, it is recommended to undertake a companion study to investigate the idea of using a desiccant assisted heat pump to handle the sensible and latent load separately.
References


Chapter 3: Simulated Performance of Hybrid Air/Water Conditioning System Configurations under Dynamic Load

Abstract

Chapter 3 seeks to address the moisture related concerns uncovered in Chapter 2 through the use and modeling of a new desiccant assisted heat pump designed at Ohio State. In this study solid desiccant cooling cycles are reviewed. Furthermore, a hybrid desiccant cooling cycle is explained and a prototype machine based on the cycle is described. The machine known as HAWC (Hybrid Air/Water Conditioner) accomplishes cooling, dehumidification, ventilation, and domestic hot water heating. Chapter 3 concludes that an improved version of HAWC is capable of completely eliminating high humidity events in the summer time while still saving energy as compared to a traditional HVAC system.

3.1 Introduction

Engineers and architects have recently redoubled efforts to achieve cost effective means for constructing highly efficient, net zero buildings. Many engineers advocate Passivhaus construction: super-insulated, air tight structures with mechanical ventilation systems. These structures are common in Europe; however, they are only beginning to gain traction in North America. Each climate zone carries with it unique challenges, and much of North America faces summertime temperatures which require cooling and
dehumidification. This aspect of passive homes remains largely uninvestigated in the European climate where cooling is largely unnecessary. With the use of new, super-insulated residential structures in cooling climates, building scientists, engineers, and architects must seek new solutions to minimize energy consumption, maintain occupant comfort and health, and prevent damage to building materials.

3.1.1 New Challenges in Modern Construction

New high efficiency Passivhaus-type structures face new challenges related to the guiding construction principles set forth in literature [1]. The key elements of a European Passivhaus are as follows [2]:

- Superinsulation
- Mechanical Ventilation with Heat Recovery
- Passive Solar Gain
- Efficient Electrical Appliances
- Minimization of Remaining Energy Demand with Renewables

Due to the superinsulation and air tightness of passive structures they tend to significantly attenuate the magnitude of outdoor climate conditions. They do not respond quickly to swings in temperature and are even prone to overheating if they are designed improperly. The problems of a Passivhaus are much more similar to commercial construction then traditional residential construction. In particular, modern commercial structures may face troubles due to poor ventilation and mold growth [3]. They also face overheating due to a combination high internal heat gains and passive solar gains [4]. Clearly, airtight passive
homes must be ventilated; super insulated designs must have adequately controlled and planned passive gains; and steps must be taken to prevent mold growth within the thick wall assemblies.

Improperly constructed modern homes can face problems which are much more serious than related issues in traditional homes. As in commercial buildings, overheating, poor indoor air quality, mold growth, and humidity problems can render a Passivhaus uninhabitable. These symptoms are often lumped together and termed “sick building syndrome”[3]. In structures diagnosed as such the occupants complain of health problems, fatigue, odors, and even difficulty breathing. As such, special care must be taken when constructing passive homes in new climates.

3.1.2 Results of a Dynamic Simulation of a Super insulated Residential Structure in Columbus, Ohio

As documented in the previous chapter, in an initial simulation of a super insulated structure based on the 2011 OSU Solar Decathlon entry it was found that it was extremely difficult to use the traditional heating and cooling system to control the moisture within the structure. Initially, higher cooling Set Points were used as many energy conscious home owners attempt to minimize energy use by straying slightly from the AHSRAE recommended comfort zone. This decision was not made arbitrarily, but rather, followed the parameters set forth in a study by Walker and Sherman [5]. It was found that the house exceeded 60% relative humidity 15% of the time and was below 40% relative humidity 47.5% of the time. Various strategies were employed in order to improve these numbers and test alternate occupant behaviors. Modifications such as a
decreased cooling temperature set point, an increased dead band, and increased heat pump capacity all increased the percentage of time out of the appropriate humidity range as well as energy consumption. It was concluded that new strategies need to be employed, and it was suggested that a dedicated dehumidification system and/or an ERV (energy recovery ventilator) should be explored.

3.1.3 Separate Sensible and Latent Load Technology could Improve Occupant Comfort

Previous research has concluded that separate sensible and latent load conditioning (SSLC) technology has strong potential [6]. SSLC technology generally consists of a desiccant (solid or liquid) to remove latent heat and a heat pump or other means for removing sensible load only. SSLC systems improve the efficiency of the conditioning system are particularly attractive if they may be regenerated using low grade waste heat or solar thermal energy [7]. SSLC systems reduce energy consumption and improve system coefficient of performance (COP) by decreasing the amount of work done by the compressor. This is possible because the condenser no longer needs to remove moisture (latent load) from the conditioned air stream. Thus, it may operate at a higher temperature [8,6].

Past studies of solid desiccant systems indicate that the maximum theoretical thermal COP for a non-hybrid system is approximately 4.66 [9]. Researchers estimate that residential desiccant assisted heat pump systems may save 3.25 to 6.5*10^6 megawatt hours per year. Converted to primary energy use savings through an efficiency estimate of approximately 33%, this equates to between 33 and 67 million Btu/year [10].
Two SSLC systems have been designed and built at The Ohio State University. These include a solar thermally regenerated system employed in the 2011 Solar Decathlon house and a self-regenerating hybrid air-water conditioning system as part of the Department of Energy’s MaxTech and Beyond competition. The working physical prototypes have undergone preliminary testing and have shown promising results at steady state. While testing the systems it became apparent that multiple configurations were possible and that robust controls would be essential to satisfactory and efficient operation. Furthermore, it was desirable to investigate the seasonal performance of the devices to compare against more traditional systems. Reconfiguring the systems, developing the controls, and providing the conditions necessary to quantify seasonal performance is both time consuming and expensive. Thus, an appropriate dynamic simulation tool was needed.

### 3.1.4 Dynamic Building Energy Modeling

Previous work conducted consisted of a study of the 2011 Solar Decathlon house, enCORE using dynamic simulation with small time steps. A software toolbox known as HAMLab was chosen primarily because it is simple to implement a wide variety of controls in the Simulink environment. Simulink is exceptionally useful because it allows engineers to create blocks simulating various building components in a graphical user interface. There are no constraints on the type or size of equipment available because the end user may choose to create their own models and schematics. Configuring the equipment layout is as simple as connecting the appropriate models with “wires” which
mimic the schematic layout. Furthermore, with only small changes Simulink models may be exported to dSPACE™ and implemented as real time controls. Other authors have also undertaken the study of separate sensible and latent systems using dynamic simulation [11]. These studies have primarily used the software package TRNSYS and the DesiCalc [12] model in DOE-2. TRNSYS is a viable alternative to HAMLab but is not as transparent as MATLAB based codes. The DOE-2 DesiCalc simulations do not take into account the moisture storage capability of building materials or furnishings which leads to inaccuracies in the calculation of indoor humidity [11]. In some cases the DOE-2 model does not accurately predict moisture removal by the evaporator coil [11]. Finally, there is little or no ability to model alternate system configurations. The great advantage of MATLAB and Simulink is the transparent implementation of code and the simple configuration of systems. DOE-2 is so complicated that modeling such custom systems is extremely difficult.

This study investigates a SSLC cooling system developed at The Ohio State University as a successor to a SSLC system implemented on the 2011 Solar Decathlon entry enCORE. It details several possible SSLC and desiccant cooling systems configurations as well as the techniques used to model them. Most current commercial software does not provide the opportunity to easily customize HVAC equipment for a particular climate, let alone a specific structure. Thus, a simulation in HAMLab, a dynamic building modeling code, was implemented in MATLAB. The proposed system requires more complex controls than traditional plants. Thus, quality and efficiency of the system must be examined as a dynamic system rather than in steady state. The HAMLab implementation allows for the
investigation of the effectiveness of proposed controls for the system. Finally, the study seeks to validate the effectiveness SSLC systems in super insulated buildings facing increasing ratios of latent load to sensible load.

3.2 Traditional Dehumidification Methods and Psychrometrics

When considering occupant comfort inside a built environment, engineers must focus on three parameters: air quality, temperature, and humidity. Engineers must design and/or specify systems that adequately control these parameters while meeting deliverable deadlines and, more importantly, staying within a budget. Although mindsets are slowly changing, most clients do not value energy efficiency (and long term savings) above first costs. The current study focuses on desiccant systems that can provide superior control of humidity and simultaneously improve energy efficiency.

3.2.1 Vapor Compression Dehumidification

Commercial HVAC systems, which are generally more complex than residential installations, have controlled humidity for years in a relatively simple, albeit inefficient manner. These systems typically supply super cooled air to each zone and reheat the air to the appropriate temperature before it reaches the space [13] [14]. By cooling the air below the dew point, moisture is removed and appropriate relative humidity is supplied to each zone. To some degree this technique is employed in residential systems and is reasonably effective in reducing the humidity in the house as the cooling coil (assuming a forced air system) will first remove a large part of the latent load. As the system is
controlled based upon the sensible load alone, no reheating is ever required as the air is never overcooled to remove extra moisture.

There are, however, many scenarios where such a system fails to provide adequate humidity control. In order for the cooling coil to effectively reduce the humidity of the cooling supply air the supply air temperature must be below the dew point for moisture removal to occur. If either the supply air temperature is too high, or more likely, the sensible heat set point for the conditioned space has been satisfied, the air conditioning system turns off, and dehumidification is incomplete.

3.3 Desiccant Systems

Throughout the years building scientists experimenting with super insulated air tight structures have found that moisture problems are extremely detrimental to the longevity of the building and the health of its occupants [15, 16, 17]. In response to the shortcomings of vapor compression dehumidification, one would ideally develop technology capable of removing moisture content from the air independent of temperature. Desiccant systems, both liquid and solid, are one such technology. Desiccants are hygroscopic materials which may be used to remove latent heat from an air stream. The vapor pressure of the air is the driving mechanism for the adsorption of water by a solid desiccant system. Each water molecule present in the air will exert a force; the sum of the forces exerted by the each water molecule in the measured environment is known as the vapor pressure. The existence of pressure differences between materials can cause water molecules to be adsorbed [13]. Desiccant systems allow one to implement a control
system which handles the latent and sensible heat loads independently; thus, allowing much greater control over the properties of the conditioned zone.

3.3.1 Solid Desiccants

In this study a solid, silica gel desiccant wheel is to be investigated. The solid desiccant configuration was chosen because it is cost effective, commercially available in small sizes, compact, and less complex than a liquid desiccant system. Furthermore, the use of air as the working fluid for the regeneration function was deemed to be desirable. Solid desiccant systems are coated or impregnated in honeycomb structures and rolled into a wheel. The entire wheel is then mounted on a shaft and driven by a gear motor at very slow speeds. Enthalpy wheels or energy recovery ventilators are also capable of removing moisture from an air stream. An enthalpy wheel simply transfers the moisture from one air stream to another. The desiccant wheel completes 15-20 revolutions per hour while the enthalpy wheel completes 15 revolutions per minute on average. The net effect is that the desiccant wheel removes much more moisture from the air stream and allows it to be completely desorbed into the regeneration air stream. Figure 13, details the operation of a solid rotary desiccant wheel.
The wheel modeled in this study used silica as the desiccant; however, many other desiccants are available. Silica was chosen primarily because it exhibits better performance at low regeneration temperatures than some other commercially available materials; it features a relatively low minimum regeneration temperature (40°C) and a greater sorption capacity than alumina. Furthermore, silica is readily available and relatively cheap compared to other materials. An ideal material would be able to be regenerated efficiently (not minimally) at very low temperatures (45-50°C), have a large sorption capacity, and a low heat of sorption. Other researchers (Hwang and Hashimi) are actively pursuing new desiccant materials which meet these ideal characteristics with promising results [18].

3.4 Common Desiccant Based Thermodynamic Cycles

Desiccants, both solid and liquid, have been deployed in many different configurations. For solid desiccant wheels there are two primary cycles which may be used: the
Pennington Cycle (also known as the ventilation cycle) and the Recirculation Cycle. Almost all other cycles involving solid desiccants are modifications or derivatives of these two basic concepts.

### 3.4.1 Pennington Cycle

The Pennington Cycle uses a process in which ventilation air is preconditioned before entering the building. Figure 14 shows a schematic diagram of the Pennington Cycle. In this process two primary flows exist: the process air and the regeneration air. The process air is made up of ventilation air (outside air) which is initially drawn through the solid desiccant wheel. As the air passes through the desiccant its latent heat is reduced (moisture is removed) and its sensible heat is increased. The rise in sensible heat occurs because of the heat of sorption which is due directly to the removal of water molecules from the air. The magnitude of the heat of sorption is roughly equal to the amount of latent heat removed. The air then passes through a rotary heat exchanger which cools the air using evaporatively cooled return air from the residence as the heat sink. This process reduces the sensible heat of the air. The same evaporative cooling system is then also used to cool the process air. As the process airstream passes through the evaporative cooler it gains back some latent heat in order to further reduce the sensible heat (apparent temperature) of the air stream. The air is then distributed to the conditioned space. Finally, a solar heat source is used to increase the sensible heat of the regeneration air (and reduce the vapor pressure). The regeneration air then passes through the desiccant wheel and removes moisture from the wheel (regenerating the wheel for continuous use).
Figure 14: Pennington Cycle Schematic [7]

Figure 15 shows the approximate states of air at various numbered points in the Pennington cycle (Figure 14) relative to their absolute moisture content and dry bulb temperature.

3.4.2 Recirculation Cycle

The concept of the recirculation cycle is exactly the same as the Pennington cycle except that it uses return air from the room as the air to be conditioned and outside air as the
regeneration stream. It accomplishes no ventilation as outside air is exhausted immediately after it is used to regenerate the desiccant wheel. Figure 16 shows a schematic representation of the recirculation cycle.

Figure 16: Recirculation Cycle Schematic [7]

Figure 17 shows the approximate states of air at various numbered points in the Recirculation cycle (Figure 16) relative to their absolute moisture content and dry bulb temperature.
3.4.3 Integrating Desiccant Cooling and Vapor Compression Cycles

It is well known that vapor compression systems are a very efficient means for achieving sensible cooling and heating [15, 19]. However, vapor compression systems may struggle to control the latent load efficiently and consistently. An ideal system would seek to combine the two technologies. The psychrometric charts shown in Figures 18-A, 18-B, and 18-C detail the reduction of both sensible and latent heat using (a) a heat pump, (b) a regenerative desiccant wheel with evaporative cooling, and (c) a combination heat pump and regenerative desiccant wheel. When using the vapor compression system alone (Figure 18-A), the heat pump must first reduce the sensible load such that the air reaches its dew point; then moisture will condensate out of the air and the latent load is reduced. This entire process requires a large input of electrical energy, and often results in the need to reheat the cooled air before it is distributed.

When using a desiccant system the air is first dehumidified (the absolute moisture content of the air is reduced). This process increases the sensible heat of the air due to the heat of the adsorption process. Then a system of sensible heat exchangers and evaporative coolers is used to increase the latent heat (to an allowable amount) and decrease the sensible heat (to a set point). There are several drawbacks of a stand-alone desiccant a system with the cycle shown in Figure 18-B:

- The system still requires electrical energy to heat the regeneration air stream to the necessary temperature. Most often this energy comes from resistance heaters which are not as efficient as vapor compression systems.
- Evaporative cooling adds moisture back into the air. Inherently there is a limit in how much moisture one can add (both practically in terms of desirable relative humidity values and absolutely in terms of saturation of the air stream). These stipulations may result in inadequate cooling power and overheating of the building.

- Evaporative cooling systems are unfamiliar to installers, designers, and plant maintenance providers.

![Figure 18: Cooling Process Variations: (A) Vapor Compression, (B) Desiccant, (C) Hybrid](image)

The hybrid system’s cycle shown in Figure 18-C combines the vapor compression cycle with the desiccant cooling cycles and eliminates many of the drawbacks of the two stand-alone systems. It requires less electrical energy input and does not face limitations on sensible cooling due to humidity. Furthermore, it allows separate control of the sensible and latent loads, reduces the work done by the compressor, and reduces the complexity of the desiccant cooling cycle. Hybrid systems also present the opportunity for use of waste heat from other processes and thermodynamic cycles.
The reverse Carnot cycle used in vapor compression systems requires two thermal reservoirs to operate (just as any thermodynamic cycle). In the case of cooling, the cold refrigerant at the evaporator is heated by warm air from the building and it rejects this heat at the condenser. Almost all split-system vapor compression air conditioners reject the heat at the condenser coil to the external environment. Instead of sending the heat rejected at the condenser into the environment, it is possible to use the waste heat as a means to regenerate the desiccant system. In this way solid desiccant wheels and vapor compression systems may be integrated.

Beyond providing better, more efficient control of the latent load within buildings, desiccant systems allow a reduction in the size of the vapor compression equipment necessary to cool the residence. Reducing the size of the vapor compression equipment provides several benefits. One obvious plus is a reduction in the cost of the vapor compression system. Smaller equipment costs less money. This means upfront capital savings on the vapor compression unit for the building owner, freeing up more capital for investment in the desiccant system which provides better performance and efficiency. Hybrid systems were heavily investigated in the late 1980’s and the early 1990’s by many thermal engineers [5, 9]. They have been shown to give significant improvements to the COP of the cooling system [6]. Furthermore, they have been used for many specialty commercial applications such as super markets, hospitals, labs, and process drying [20,21,7].

There are many opportunities to use solar heat, recapture waste heat from the vapor compression system, and perform sensible heat exchanges. Furthermore, the
hybridization of the system does not prevent the application of technologies such as evaporative cooling as used in the typical desiccant cooling cycle or the variation of desiccant cycles to include return air such as in the recirculation cycle. The following is a list of different combinations of renewable technologies, air stream routing, and varying heating sources that could be applied to an integrated vapor compression and desiccant system:

- Waste heat desiccant regeneration
- Solar thermal desiccant regeneration
- Combined heat and power generation with active cooling
- Regeneration with energy storage
- Process air source: ventilation, return, or combination
- Evaporative cooling
- Sensible heat exchange between air streams

The myriad of options as well as the complexity of the controls necessary for such a system make this an ideal candidate for dynamic simulation. Finally, its applicability to moisture problems in tight buildings due to ventilation is obvious. This is a system that separates control of sensible and latent loads, increases latent cooling capacity, and reduces energy use. Figure 19 depicts the basic components of a hybrid desiccant system based on the ventilation cycle.
Figure 19: Simple Hybrid System Base Configuration [7]

3.5 System Configurations

OSU has developed two hybrid system configurations. One system was developed for the 2011 Solar Decathlon (SD2011). It was fully designed, installed, and commissioned. A description of the SD2011 system is included to highlight the development that led to the Hybrid Air/Water Conditioner (HAWC). The HAWC system was developed for the 2012 Max Tech and Beyond Competition. It has been designed, built, and tested as a bench prototype. It was built on an abbreviated schedule and has rudimentary controls and non-optimal, proof-of-concept components. Despite the shortcomings, the HAWC system exhibited a 20% improvement in COP against an identical, non-hybridized vapor compression system (due largely to hot water production). The goal of the simulation is to verify control strategies and identify improvements to individual system components.
3.5.1 Desiccant Assisted Heat Pump: OSU Solar Decathlon 2011

The OSU SD2011 entry, enCORE, featured a unique desiccant assisted heat pump system that incorporated solar thermal hot air as an economical and energy efficient means of regenerating a desiccant wheel. The system also employed a phase change material thermal storage system to extend the usefulness of the hot air collectors. The heat pump was 1.5 tons (18,000 btu/hr) and used R-410A as the working fluid. The small desiccant wheel was used in a recirculation cycle configuration. It used a small axial fan to draw return air from the kitchen and dining area, dehumidify it and route it back to the main return plenum at the house’s central air handling unit. Outside air was routed through the solar thermal collectors to the desiccant wheel and used to regenerate the system. The air was then immediately exhausted to the outside. Again a small axial fan and damper system was used. Figure 20, shows a schematic representation of the system. Though not shown in Figure 20, there is also a home-made sensible heat exchanger that attempts use exhaust air from the ERV to cool the air coming from the desiccant wheel.
The system developed for the 2011 Solar Decathlon house was a custom installation that was very specific to the floor plan of that particular house. It would be difficult to implement such a system without detailed and involved work for each new floor plan. Thus, a new iteration meant to function as a standalone appliance was developed.

3.5.2 Hybrid Air-Water Conditioner: OSU Max Tech and Beyond 2012

The HAWC system was designed to enhance the performance and efficiency improvements garnered by the SD2011 system while still increasing the functionality and decreasing installed complexity. The new system efficiently uses waste heat from the vapor compression cycle to accomplish both dehumidification and hot water heating.
The relatively compact device currently achieves four functions:

- Hot water heating.
- Ventilation
- Cooling
- Dehumidification

The appliance is called the HAWC or Hybrid Air-Water Conditioner. It features a silica desiccant wheel which is configured to process (dehumidify) either all outdoor air or a mixture of indoor and outdoor air. The scheme is similar to the Pennington Cycle with a unique means for regenerating the desiccant (waste heat from the vapor compression cycle). Using a combination of waste heat from the vapor compression cycle in conjunction with electrical resistance increases the functionality of the desiccant wheel, guaranteeing that regeneration heat will be available. The SD2011 system which used solar thermal heat for regeneration faced limitations to the on-time of the desiccant system in poor weather, robbing the configuration of robust control over humidity levels. Furthermore, the addition of hot water production in the HAWC greatly increases the COP and the functionality of the device (but it further complicates controls). Finally, the addition of ventilation capacity addresses an urgent need in passive homes by consolidating mechanical equipment towards a single, lower capacity multifunctional plant. Figure 21 shows a schematic representation of the HAWC device and Figure 22 shows a labeled solid model of the same.
Figure 21: HAWC (Hybrid Air/Water Conditioner) Prototype Schematic

Figure 22: Labeled HAWC Prototype Isometric
3.6 Component Models

3.6.1 Desiccant Wheel

There are many models available for desiccant wheels [22]. Many authors contend that although the mass and heat transfer occurring in the operation of a desiccant wheel is not fully understood, complete understanding is not necessary for the successful creation of a model. Furthermore, many desiccant wheel manufacturers publish data and create software programs which describe inlet and outlet conditions of the wheels [23]. From these simulations it is possible to validate the performance of the system without going into great detail investigating the physics of the wheel. The desiccant wheel model used in this simulation was implemented by Ralph van Ororschot [24]. The van Ororschot model draws from principles developed by Howe and Jurinak [25] [26]. Howe’s model is based on the development of a theory of simultaneous heat and mass transfer by Banks and I.L Maclaine-Cross [27]. Banks demonstrated that the phenomenon may be described utilizing two first order wave equations. Eventually Jurinak arrives at the following equations which describe the “potential lines” which connect inlet and outlet states of the desiccant wheel air streams [24]:

\[ F_{1PR} = -\frac{2865}{T^{1.490}} + 4.344 * W^{0.8624} \]

\[ F_{2PR} = \frac{T^{1.490}}{6360} - 1.127 * W^{-0.7969} \]
where $F_{1P/R}$ and $F_{2P/R}$ represent ideal outlet conditions from the wheel’s process stream and regeneration stream, respectively; $T$ is the temperature in degrees Celsius, and $W$ is the humidity ratio. These equations represent ideal conditions which are thermodynamically achievable in theory. Effectiveness values are used to modify the results. In order to improve accuracy and match the output to real desiccant wheels, the true outlet states may be calculated according to the following effectiveness value:

$$
\varepsilon_{Fi} = \frac{Fi_D - Fi_P}{Fi_R - Fi_P} \quad i = 1,2
$$

where $\varepsilon_{Fi}$ is the effectiveness and $Fi_D$ is the actual outlet state (which is the value to be calculated). In an ideal case $\varepsilon_{F1}$ is zero and $\varepsilon_{F2}$ is one. $F1_{P}$ is the state of the process air inlet and $F1_{R}$ is the state of the regeneration air inlet. $F2_{P}$ is the state of the process air outlet and $F2_{R}$ is the state of the regeneration air outlet. By modifying the effectiveness values one may change the mode of operation of the desiccant wheel. For example in the case that one would like to simulate an ERV, the effectiveness values may be changed and wheel will act as an enthalpy exchanger. The model has been validated by van Ororschot and shows good accuracy [24]. This simulation uses this model with only changes to the inputs such as the mass flow rates and regeneration temperatures that represent the actual device constructed at OSU.

3.6.2 Thermal Storage

In order to fully capture the performance of the HAWC system it is necessary to examine its ability to generate hot water for domestic use. The prototype system is connected to a
single 55 gallon tank. The water in the tank acts as a thermal storage system and is not distributed to fixtures. Instead, water from the mains is drawn through a heat exchanger in the tank in order to increase its temperature. Though several projects dating back to the 2009 OSU Solar Decathlon house suggest that it is neither essential nor efficient for the heat pump to fully heat the water to a temperature over 130°F. This is because at high tank temperatures (especially in un-stratified tanks) air to water heat pumps exhibit low COPs. Instead the tank is allowed to fluctuate up to 140 degrees depending on the availability of heat input from the HAWC system. Regardless of heat pump performance auxiliary heating would be necessary in the winter time. Preferably this would be achieved through point of use heaters rather than a submerged auxiliary element in the tank.

It is well documented that stratified tanks are generally preferable for thermal storage systems. The prototype, however, was assembled as a proof-of-concept, and the simple 55 gallon drum does not stratify. The tank is best represented as fully mixed at a single temperature. Bench tests determined that a single temperature was appropriate as there was no difference between tank temperature at the top and bottom of the tank. An existing stratified tank model that divides the tank into sections with water a one particular temperature [28] was modified to contain only one section. The governing equation for the fully mixed section or node is as follows:

$$M c_p \frac{dT_i}{dt} = \alpha_i \phi_{c} c_p (T_c - T_i) + \beta_i \phi_{d} c_p (T_{mains} - T_i) - h_{env}(T_i - T_{env})$$
\[ \frac{dM}{dt} = c_p \cdot M \left( T_i - T_e \right) + \dot{Q}_e \cdot \alpha \cdot M + \dot{Q}_d \cdot \beta \cdot M + \dot{Q}_w \cdot \delta \cdot M - h_{env} \cdot M \cdot \beta - h_{env} \cdot M \cdot \alpha \\
\]

where \( M \) is the mass of the tank, \( c_p \) is the specific heat of the tank, \( T_i \) is the temperature of the tank, \( t \) is time, \( \alpha \) is a binary variable which indicates whether or not the heating loop is on, \( \dot{Q}_e \) is the mass flow rate of the heated hydronic loop, \( T_c \) is the temperature of the hydronic loop, \( \beta \) is a binary variable which indicates whether or not hot water is being demanded, \( \dot{Q}_d \) is the mass flow rate to the fixtures, \( T_{mains} \) is the temperature of the water in the mains supply, \( h_{env} \) is the overall heat loss coefficient of the tank, and \( T_{env} \) is the temperature of the environment in which the tank is located.

### 3.6.3 Modes of Operations and Energy Consumption

One of the challenges faced in the development of the HAWC prototype was the development of effective controls that can insure effective and efficient operation. There are several scenarios which may be faced by the system.

I. Desiccant system and heat pump both on.

II. Desiccant system on and heat pump off.

III. Desiccant system off, heat pump on, and thermal storage tank less than the maximum temperature.

IV. Desiccant system off, heat pump on, and thermal storage tank greater than or equal to the maximum temperature.

Table 6 outlines the system components used in each mode of HAWC operation (HAWC I-IV). \( \dot{W}_{pump} \) is the power used by the pump that circulates the hydronic loop, \( \dot{W}_{compressor} \) is the power consumed by the compressor, \( \dot{W}_{blower} \) is the power consumption of the 400 cfm air distribution fan, \( \dot{W}_{regen\,fan} \) is the power consumption...
of the regeneration fan, $W_{process\ fan}$ is the power consumption of the process air fan, $W_{desiccant\ wheel}$ is the power consumed to rotate the desiccant wheel, $W_{electrical\ resistance}$ is the power consumed to regenerate the desiccant wheel using electrical resistance heat (only if necessary). The baseline operation represents a simple heat pump (vapor compression system).

Table 7 details the steady state power consumption of HAWC components as measured on the prototype test stand.

### Table 6: System Components by Operation Mode

<table>
<thead>
<tr>
<th>Power Consumed</th>
<th>Variable</th>
<th>Baseline</th>
<th>HAWC I</th>
<th>HAWC II</th>
<th>HAWC III</th>
<th>HAWC IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_{pump}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>$W_{compressor}$</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>$W_{blower}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>$W_{regen\ fan}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>$W_{process\ fan}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>$W_{desiccant\ wheel}$</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$W_{electrical\ resistance}$</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

### Table 7: System Component Steady State Power Consumption

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Consumption (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>43</td>
</tr>
<tr>
<td>Blower</td>
<td>570</td>
</tr>
<tr>
<td>Desiccant Wheel Motor</td>
<td>24</td>
</tr>
<tr>
<td>Regeneration Fan</td>
<td>49</td>
</tr>
<tr>
<td>Process Booster Fan</td>
<td>6</td>
</tr>
<tr>
<td>Heater</td>
<td>1152</td>
</tr>
</tbody>
</table>
3.7 Results and Discussion

3.7.1 Implementation of ERV for Enthalpy Exchange

Energy recovery ventilators (ERVs) are mechanical ventilation systems which may be employed in residences. ERVs exchange both heat and moisture between the ventilation air and exhaust air with only 9-10% of cross contamination. They employ an enthalpy wheel which is essentially the same as a desiccant wheel but with higher rotation speeds. They accomplish moisture transfer between the air streams rather than moisture removal. An ERV was chosen to be implemented on enCORE because previous results had shown that winter time humidity was extremely low. Thus it would be desirable to capture some of the moisture generated in the house but about to be exhausted by the ventilation system. A ventilation rate of 80 cfm was chosen based on Passive House Institute United States (PHIUS) guidelines.

Table 8 displays a comparison of the performance of the house with and ERV and the house with the same mechanical system but only an HRV. The numbers for the simulation using the HRV are derived from the results of Chapter 2 (using the best scenario).
Table 8: Comparison of Performance between HRV & ERV

<table>
<thead>
<tr>
<th></th>
<th>HRV</th>
<th>ERV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hours</td>
<td>% of Total Hours</td>
</tr>
<tr>
<td>Total Hours&gt;60%</td>
<td>1307</td>
<td>14.92%</td>
</tr>
<tr>
<td>Total Hours&gt;70%</td>
<td>112</td>
<td>1.28%</td>
</tr>
<tr>
<td>Total Hours&lt;40%</td>
<td>4158</td>
<td>47.47%</td>
</tr>
</tbody>
</table>

The addition of the ERV reduces both the time spent above the allowable humidity range and the time spent below the acceptable humidity range. The total hours above 60% relative humidity are reduced from 15% to 13.8%. Similarly the time below 40% relative humidity is reduced from 47.5% to 47.1%. The improvements are nominal. Furthermore, there is the issue of energy consumption. The addition of the ERV increases energy consumption from 5.85 kWh/(m^2*a) to 6.43 kW/(m^2*a). ERV’s are not appropriate in every climate, there is the possibility that the ERV could actually be increasing humidity levels in the summer and forcing the heat pump to work harder and longer increasing
the energy consumption. Figure 23 details the relative humidity of the house over the course of the year.

![Graph showing relative humidity vs. time with ERV](image)

Figure 23: Relative Humidity vs. Time with ERV

### 3.7.2 Ability of HAWC to Maintain Comfort Zone

Section 3.4.3 describes how one might integrate desiccant dehumidification with a heat pump system and Section 3.5.2 describes an implementation of such a system designed at The Ohio State University. The system described in Section 3.5.2, the HAWC, has been modeled with HAMLab using component models presented in Chapter 2 and in Section 3.6. Bench prototype tests of the HAWC system in steady state suggest that it will greatly improve the ability to control humidity in cooling situations. Furthermore, the HAWC will do so in an energy efficient manner while meeting other household needs such as ventilation and domestic hot water heating.
Just as in the previous study in Chapter 2, the size of the heat pump is 1.5 tons. The cooling system set point is 24.5°C with a dead band of 0.5°C. The heating system set point is 21°C also with a 0.5°C dead band. The HAWC system acts as an ERV in the winter. Sensible enthalpy exchange and removal is accomplished by the HAWC through the use of the silica desiccant wheel processing 80 cfm of fresh outside air. Figure 24 shows the indoor air temperature vs. time using the HAWC system. It is clear from the figure that the system is able to maintain set point conditions. The one deviation from the summer set point occur because no air heating has been allowed during that portion of the year and low overnight temperatures coupled with ventilation have cooled the structure towards the heating mode. The restriction to prevent air heating during the summer season was added so that the two systems would not work against each other. Generally, thermostats in residential buildings are set by the occupant to only be in either heating or cooling mode, thus the modeled system mimics reality.

Figure 24: Indoor Air Temperature with HAWC
Figure 25 contains a graph of indoor relative humidity vs. time using the HAWC system. In this simulation the relative humidity is controlled by a humidistat which interfaces with the HAWC system to determine the operating mode of the desiccant wheel. The humidistat is set to operate the dehumidification mode if the relative humidity in the structure exceeds 57%. The dehumidification mode operation continues until relative humidity is reduced to 40%. The HAWC is able to dehumidify even if no sensible cooling is necessary, but with a penalty to energy consumption due to the increased need for the application of electrical resistance heat for regenerating the desiccant wheel.

![Figure 25: Indoor Relative Humidity with HAWC](image)

The addition of the HAWC eliminates all high humidity events within the structure and greatly reduces the total amount of time out of the comfort zone. This, however, does not solve the low humidity issues faced by the structure. Table 9 presents the amount of time that the house spends in each relative humidity bin over the course of the year.
### Table 9: Relative Humidity Percentages with HAWC

<table>
<thead>
<tr>
<th>Relative Humidity</th>
<th>Hours</th>
<th>Percentage of Total Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>38.59</td>
<td>0.44%</td>
</tr>
<tr>
<td>10-20%</td>
<td>1280.31</td>
<td>14.62%</td>
</tr>
<tr>
<td>20-30%</td>
<td>1707.65</td>
<td>19.49%</td>
</tr>
<tr>
<td>30-40%</td>
<td>1363.86</td>
<td>15.57%</td>
</tr>
<tr>
<td>40-50%</td>
<td>1944.52</td>
<td>22.20%</td>
</tr>
<tr>
<td>50-60%</td>
<td>2425.07</td>
<td>27.68%</td>
</tr>
<tr>
<td>60-70%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>70-80%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>80-90%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>90-100%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total Hours&gt;60%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total Hours&gt;70%</td>
<td>0.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total Hours&lt;40%</td>
<td>4390.41</td>
<td>50.12%</td>
</tr>
</tbody>
</table>

The simulation of the HAWC system in conjunction with enCORE shows that the system is able to maintain the sensible heat load just as effectively as a traditional heat pump system. Furthermore, the HAWC is able to eliminate all high humidity events. With the HAWC the indoor relative humidity never exceeds 60% and in fact could be controlled to significantly lower conditions if the occupant desired.

#### 3.7.3 Hot Water Production by HAWC

Rough estimates show that the HAWC system is able to maintain a hot water tank at approximately 32.5°C once the summer heating season has begun. Tests of the
prototype show that temperatures approaching 40°C were possible after hour long system run times. These tests, however, did not incorporate hot water draws. Thus, the HAWC technology shows very promising results as a domestic hot water heating device and more work should be done to verify the consistency of the tank model. Figure 26 shows the HAWC hot water tank temperature vs. time.

![Figure 26: HAWC Hot Water Tank Temperature vs. Time](image)

### 3.7.4 HAWC Energy Consumption and Modification

Section 3.7.2 demonstrates that the HAWC system is capable of controlling the latent load independently of the sensible load within the house. This is a very important development for passive house structures; however, there is still more potential for the system.

The main advantage of separate sensible and latent heat conditioning systems is that they may allow a reduction in compressor power use because the heat pump is no longer
required to remove moisture from the air. Thus, the temperature of the refrigerant within
the evaporator may be increased above the dew point. This allows for an increase in the
COP, which is a strictly increasing function of the difference between outdoor
temperature and the temperature of the working fluid within the evaporator. At 24.5°C
and 50% relative humidity the dew point of the air in the house is 12.8°C. Thus, by
increasing the temperature of the refrigerant to 12.8°C the system will experience an
increase in the coefficient of performance.
Currently the HAWC system consumes approximately 9.5 kWh/(m²*year). This amount
is significantly more than is consumed by the basic heat pump system; however, a direct
comparison cannot be made because the HAWC system also produces hot water.
Literature suggests that increasing the temperature of the working fluid in the evaporator
may improve the COP of the HAWC system [8]. Another way which the HAWC’s power
consumption could be significantly reduced is the adoption of a sensible heat exchanger
between the process and regeneration air streams. The heat exchange would occur before
regeneration air passes through the wheel but after the process air has based through the
wheel. At this point the process air has passed through the dehumidifier and gained
sensible heat from the adsorption process. The exchange between the two streams would
act to preheat the regeneration air and cool the process air. To investigate this idea, a
HAMLab simulation with a perfectly efficient heat exchanger shows that the HAWC
system power consumption reduces to 5.66 kWh/(m²*year). This result shows less
energy consumed than the base heat pump system coupled, all the while maintaining
ASHRAE comfort standards.
3.8 Summary

Section 3.7 contains discussion of the data obtained from the simulation of an ERV and two versions of the HAWC system. The conclusions related to the ERV are as follows:

- The addition of an ERV reduces the number of high humidity events but does not eliminate them.
- The ERV also reduces the number of low humidity events.
- The ERV adds to energy consumption

The conclusions from modeling the HAWC are as follows:

- The addition of HAWC eliminates all high humidity events.
- HAWC is also effective at reducing low humidity events as an ERV
- HAWC uses 9.5 kWh/(m^2*year) as compared to 6.43 kWh/(m^2*year) for the ERV
- However, HAWC is also able to maintain a 50 gallon water tank at 32.5°C throughout the summer cooling season.

When assuming that the evaporator temperature can be increased and when adding a sensible heat exchanger to preheat the regeneration air and cool the process air for HAWC, the following conclusions can be drawn:

- The increase in evaporator temperature during cooling season improves the energy consumption of HAWC and maintains equivalent thermal conditions.
- The addition of a sensible heat exchanger to reduce the temperature of dehumidified process air greatly improves system performance.
- HAWC with a sensible heat exchanger and increased evaporator temperature uses 5.61 kWh/(m^2*year) as compared to 9.5 kWh/(m^2*year) for the base HAWC system and 6.43 kWh/(m^2*year) for the base heat pump system with ERV. It is the most efficient and effective configuration tested in any chapter.

3.8.1 Recommendations for Future Improvement

3.8.1.2 Heat Pump Performance Enhancement

There are several recommendations for continuing the development of the HAWC system and the dynamic model. The first is to include a much more detailed model of the heat pump used in the HAWC system. The initial goals of this investigation were simply to investigate the performance of a super insulated Passivhaus-style structure in a new climate (Columbus, Ohio). The heat pump model was adequate for this task as it accurately predicts moisture removal, sensible heat reduction, and power consumption. As such, the model predicts superior moisture control with the addition of the HAWC but likely does not fully capture the interaction of the HAWC system with the compressor. It would also be desirable to improve the detail concerning condenser temperatures so as to optimize the HAWC. In particular, understanding condenser temperatures better would allow optimization of the following:

- The flow rate of water through the refrigerant to water gas cooler (condenser)
- The flow rate to the hot water heating loop as compared to the desiccant regeneration loop
- Ideal evaporator temperature to minimize energy consumption and maximize regeneration temperatures
- The effect of varying refrigerant charges

Furthermore it would be advantageous to compare the HAWC to the performance of the original SD2011 desiccant assisted heat pump. Finally, the addition of model predicative optimal control in conjunction with a stratified thermal storage system would garner the remaining performance enhancements available using the HAWC system.

3.8.1.2 The Need for Humidification

Both studies (Chapter 2 and Chapter 3) show that a Passivhaus-style residence in the Midwest needs humidification in the winter months. The addition of HAWC eliminated all high humidity events but did little to reduce the number of low humidity events. The addition of an evaporative cooler to the HAWC would make cooling more efficient and allow for direct humidification of air. It is recommended that future studies explore this configuration.
References


Chapter 4: Conclusions

After briefly summarizing the conclusion of Chapters 2 and 3, this chapter details suggestions for future work with the dynamic model implemented for this Masters project. In conjunction with improvements to the model, plans are being made to implement a sensor array in enCORE to verify the results of Chapters 2 and 3. Furthermore, both the hybrid air water conditioner (HAWC) prototype as well as enCORE could undergo further development.

4.1 Dynamic Simulation of a “Passive House”

The best configuration of the HVAC plant in both performance and energy consumption was an HRV with a 1.5 ton heat pump set at 24.5°C. This system consumed 5.85 kWh/m^2*year, which meets the Passivhaus guidelines. These results show that Passivhaus measures are effective even in mixed climates with relatively extreme weather. However, researchers are finding that every climate has its own unique challenges. The ability to model houses such as enCORE will validate rules of thumb for different regions very quickly. It is much better to explore these issues using a simulation then to discover them after mechanical equipment has been installed and the house is complete.

While it is reasonable to expect many homeowners (especially those willing to build superinsulated structures) to use the high cooling setpoints used in the base case of this simulation. It is clear that even in the best case scenario (high setpoint), traditional air
conditioning equipment may not be appropriate for maintaining a comfortable environment and acceptable indoor air quality.

The extreme air tightness and high R-value of the wall causes a significant lag between outside temperature changes and internal temperature changes. Superinsulated structures strongly attenuate the magnitude of the heat flows to and from the exterior. The net result is a building that needs little sensible heating and cooling, regardless of the climate and the occupant actions.

On the other hand, latent loads are significantly influenced by occupant behavior. Not only do occupants alter internal moisture generation through their daily activities, but changing the set point also influences the latent load. The Passivhaus building techniques can obviously do little to influence internal moisture loads. Mechanical ventilation may be used to remove internally generated moisture loads, but if nothing is done to specifically address the humidity in the outside air taken in there is likely little benefit. Even an ERV will fail in the situation of high indoor and outdoor moisture levels.

Traditional conditioning methods do not directly address latent loads. If comfort zone is defined as 40-60% relative humidity, even the best-case, 1.5 ton heat pump with a set point of 24.5°C left the house out of the comfort zone for nearly 64% of the year.

Furthermore, it is not reasonable to expect the every homeowner to set air conditioning levels to 25°C. Many will set their thermostats much lower. In the case of a 23°C one sees an increase in percent time outside of the comfort zone to nearly 70% of the year.

There is no question that this home would benefit from a mechanical system which could offer better control over moisture.
4.2 Dynamic Simulation of HAWC

Section 3.7 contains discussion of the data obtained from the simulation of an ERV and two versions of the HAWC system. The conclusions related to the ERV are as follows:

- The addition of an ERV reduces the number of high humidity events but does not eliminate them.
- The ERV also reduces the number of low humidity events.
- The ERV adds to energy consumption

The conclusions from modeling the HAWC are as follows:

- The addition of HAWC eliminates all high humidity events.
- HAWC is also effective at reducing low humidity events as an ERV.
- HAWC uses 9.5 kWh/(m^2*year) as compared to 6.43 kWh/(m^2*year) for the ERV.
- However, HAWC is also able to maintain a 50 gallon water tank at 32.5°C throughout the summer cooling season.

When assuming that the evaporator temperature can be increased and when adding a sensible heat exchanger to preheat the regeneration air and cool the process air for HAWC, the following conclusions can be drawn:

- The increase in evaporator temperature during cooling season improves the energy consumption of HAWC and maintains equivalent thermal conditions.
- The addition of a sensible heat exchanger to reduce the temperature of dehumidified process air greatly improves system performance.
- HAWC with a sensible heat exchanger and increased evaporator temperature uses 5.61 kWh/(m^2*year) as compared to 9.5 kWh/(m^2*year) for the base HAWC system and 6.43 kWh/(m^2*year) for the base heat pump system with ERV. It is the most efficient and effective configuration tested in any chapter.

4.3 Future Work

The flexibility of the HAMLab implementation will be a tremendous asset in performing future work with Passivhaus-style structures in innovative mechanical systems. The possibilities for extensive studies in numerous fields are very promising.

4.3.1 First Principles Models of System Components

One of the most important areas to explore is the improvement of HAMLab component models. The current set of models serves the purpose of the current investigation but is very specific to the application. The development of a high quality library of system components which have been verified and tested with the simulation will be very valuable to the implementation of future work. One component which would benefit greatly from more detailed modeling would be the heat pump. Highly developed and detailed models of heat pumps are available from Oak Ridge National Laboratory. It would be extremely desirable to implement these in Simulink so that individual heat pump components may be optimized. Furthermore, it would be beneficial to improve the model of the thermal storage system to include stratification. While the current prototype does not have a tank that functions in this manner, future iterations of HAWC almost
certainly will. Finally a model of phase change material to be charged by the solar hot air system would be useful in helping to quantify the performance of the SD2011 heating and cooling system.

4.3.2 Verification of Performance using enCORE

One of the main reasons for modeling enCORE for this study was its long term availability for research work. enCORE will soon be installed on the OSU campus and features a powerful user programmable control system, a wide array of sensors, and the ability to perform remote monitoring. In the near future it would be advantageous to confirm the model-based conclusions of Chapter 2 by verifying enCORE’s performance in Columbus, Ohio’s mixed climate conditions.

4.3.4 Implementation of Model Predictive Control

One of the most important impacts that this research could have is the use of the building model in the implementation of a real-time predictive control system. The current building model would be simplified and verified against enCORE so that it may be solved in a reasonable amount of time (quickly enough) using weather forecast data. Furthermore a model of the phase change material thermal storage system would be implemented as model predictive control systems are particularly effective at controlling thermal storage systems. The performance of this control system could then be tested against a typical PID controller in simulation and on the house itself.
4.3.5 Development of HAWC II

The current HAWC prototype has shown great potential including a 20% increase in COP and cost competitiveness with current heat pump systems. Furthermore, the performance documented in Chapter 3 shows that it is extremely effective at controlling relative humidity within the space of a super insulated home like enCORE. The model also demonstrated the need for including a sensible heat exchanger and has the potential to help design the most efficient control algorithms. Furthermore, the team recently received a larger desiccant wheel and it would be advantageous to explore alternate configurations and airflow rates in HAMLab in order to further improve the system’s performance.


CEEE Conducts Joint International Project with Korea Institute of Science and Technology [WWW Document], 2012. . URL http://www.ceee.umd.edu/content/news-archive-2012


Downloads - Desiccant Wheels [WWW Document], 2012. . URL


http://www.greenbuildingadvisor.com/blogs/dept/musings/forgotten-pion

http://sel.me.wisc.edu/trnsys/trnlib/desiccants/1302.des


Schijndel, van AWM (Jos), Wit, de MH (Martin), Hens, H (Hugo), Technische Universiteit Eindhoven, 2007. Integrated heat air and moisture modeling and simulation.


User’s Manual for TMY2s [WWW Document], 2012. . URL


Appendix A: HAMLab Model Data
### Table 10: TMY2 Data Position

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MATLAB &quot;fscanf&quot; Column</th>
<th>TMY2 Field Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>1</td>
<td>002-003</td>
</tr>
<tr>
<td>Diffuse Solar Radiation</td>
<td>13</td>
<td>030-033</td>
</tr>
<tr>
<td>10x External Air Temperature</td>
<td>34</td>
<td>068-071</td>
</tr>
<tr>
<td>Direct Normal Solar Radiation</td>
<td>10</td>
<td>024-027</td>
</tr>
<tr>
<td>Cloud Cover</td>
<td>28</td>
<td>060-063</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>40</td>
<td>080-082</td>
</tr>
<tr>
<td>10x Wind Velocity</td>
<td>49</td>
<td>096-098</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>46</td>
<td>091-093</td>
</tr>
</tbody>
</table>

### Table 11: Exterior Building Surface Data

<table>
<thead>
<tr>
<th>Surface</th>
<th>Area (m^2)</th>
<th>Orientation (vertical, horizontal)</th>
<th>Special Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Wall</td>
<td>32.5</td>
<td>90,-90</td>
<td>External Wall</td>
</tr>
<tr>
<td>West Wall</td>
<td>32.5</td>
<td>90,90</td>
<td>External Wall</td>
</tr>
<tr>
<td>North Wall</td>
<td>29.75</td>
<td>90,180</td>
<td>External Wall</td>
</tr>
<tr>
<td>South Wall</td>
<td>29.75</td>
<td>90,0</td>
<td>External Wall</td>
</tr>
<tr>
<td>Roof</td>
<td>94.5</td>
<td>0,0</td>
<td>External Wall</td>
</tr>
<tr>
<td>Floor</td>
<td>94.5</td>
<td>0,0</td>
<td>Constant Temperature 12 C</td>
</tr>
</tbody>
</table>

### Table 12: Constant Envelope Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Surface Heat Gain Resistance</td>
<td>Ri</td>
<td>(K*m^2/W)</td>
<td>0.13</td>
</tr>
<tr>
<td>External Surface Heat Transfer Resistance</td>
<td>Re</td>
<td>(K*m^2/W)</td>
<td>0.04</td>
</tr>
<tr>
<td>External Solar Radiation Absorption Coefficient</td>
<td>ab</td>
<td>NA</td>
<td>.04-.06</td>
</tr>
<tr>
<td>External Longwave Emissivity</td>
<td>eb</td>
<td>NA</td>
<td>0.9</td>
</tr>
</tbody>
</table>
### Table 13: External Wall Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Material ID</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>381</td>
<td>.015875</td>
</tr>
<tr>
<td>Blown-in Fiberglass Insulation</td>
<td>422</td>
<td>.1524</td>
</tr>
<tr>
<td>Oriented Strand Board</td>
<td>505</td>
<td>.0127</td>
</tr>
<tr>
<td>Rigid Insulation</td>
<td>457</td>
<td>.0508</td>
</tr>
<tr>
<td>Lightly Ventilated Air Cavity</td>
<td>2</td>
<td>0.0127</td>
</tr>
</tbody>
</table>

### Table 14: Roof Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Material ID</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drywall</td>
<td>381</td>
<td>.015875</td>
</tr>
<tr>
<td>Blown-in Fiberglass Insulation</td>
<td>422</td>
<td>.254</td>
</tr>
<tr>
<td>Oriented Strand Board</td>
<td>505</td>
<td>.0127</td>
</tr>
<tr>
<td>Rigid Insulation</td>
<td>457</td>
<td>.1016</td>
</tr>
<tr>
<td>Roof Membrane</td>
<td>605</td>
<td>.0015875</td>
</tr>
</tbody>
</table>

### Table 15: Floor Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Material ID</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Floor</td>
<td>501</td>
<td>.01905</td>
</tr>
<tr>
<td>Subfloor</td>
<td>505</td>
<td>.01905</td>
</tr>
<tr>
<td>Fiberglass Batt</td>
<td>422</td>
<td>.254</td>
</tr>
<tr>
<td>Plywood</td>
<td>505</td>
<td>.003175</td>
</tr>
</tbody>
</table>
Table 16: Building Profile

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Period Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Time for each Period</td>
<td>1  8  17  22</td>
</tr>
<tr>
<td>Irradiance Level For Sunblinds</td>
<td>300 300 300 300</td>
</tr>
<tr>
<td>Ventilation ACR for each Period</td>
<td>0.5 0 0.5 0.5</td>
</tr>
<tr>
<td>Ventilation ACR for each Period (Free Cooling)</td>
<td>1  1  1  1</td>
</tr>
<tr>
<td>Threshold for Free Cooling</td>
<td>60  60  60  60</td>
</tr>
<tr>
<td>Setpoint for Heating Switch</td>
<td>67  60  67  67</td>
</tr>
<tr>
<td>Setpoint for Cooling Switch</td>
<td>75  80  75  75</td>
</tr>
<tr>
<td>Internal Heat Gains</td>
<td>1139 469 1139 670</td>
</tr>
<tr>
<td>Internal Moisture Gains</td>
<td>0.000394 0 0.000394 0</td>
</tr>
<tr>
<td>Setpoint for Humidification</td>
<td>NA  NA  NA  NA</td>
</tr>
<tr>
<td>Setpoint for Dehumidification</td>
<td>60% 60% 60% 60%</td>
</tr>
</tbody>
</table>