EXPLORING THE FEASIBILITY OF PASSIVE COOLING TECHNOLOGY

IN THE NON-RESIDENTIAL BUILDING SECTOR

OVER VARIOUS CLIMATIC REGIONS IN THE UNITED STATES

A THESIS

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1.0 INTRODUCTION

1.1 THE HYPOTHESIS

Buildings are objects ensuring comfort for their inhabitants. The thermal behavior of buildings is related to various factors, having climate as the top priority. During summers, buildings are exposed to high solar radiation and high temperatures, leading to overheated conditions, exceeding comfort levels in the interiors. At this time, cooling of buildings is important. Harmony with local climate is the best solution. In hot dry climates, buildings with massive construction should have few windows and small openings and light colored walls. Pools, water bodies and vegetation complete the cooling effect. In hot humid climates, where ventilation is needed, buildings should have large openings and overhangs. Modern buildings, however, do not follow these traditions. Adapting ideas, styles and technologies have lead us to the immense use of mechanical equipment, to most of the cooling needs, even if they can be fulfilled through traditional methods. Air quality needs are being met by mechanical ventilation strategies, leading to the usage of unnecessary amounts of energy. The thesis thus questions the context and significance of direct cooling techniques and their feasibility in the United States over different climatic regions, passive cooling being one of the more architecturally interesting ways by which architects could make buildings energy efficient.
Energy conservation and passive cooling are the most effective alternatives to conventional cooling systems. Passive cooling systems are receiving considerable attention recently. The decision to use these systems has a fundamental influence on the comfort of the occupants and also influences sustainability by adapting a more ‘green’ approach. Applying the insights of these cooling techniques presents an adaptive response to thermal conditions of the building. These systems, if adopted widely, will reduce fossil fuel consumption.

1.2 DEFINING PASSIVE COOLING

A passive cooling system uses elements of the building to store and distribute energy and when prevailing conditions are favorable to discharge heat to the cooler parts of the environment like the sky, atmosphere and ground. Since the collection, discharge, storage and distribution of energy is generally accomplished by the architectural elements and features of the building, the passive cooling system components are not easily distinguishable from the remainder of the structure. A space cooling system generally is composed of –

a. A space [or, more specifically, contents] to be cooled

b. An environmental sink [sky, atmosphere or ground] to which heat is discharged

c. Thermal storage [this may be nothing more than the normal thermal capacity of the building mass]

Passive cooling involves the discharge of energy by “selective coupling” of the system to the cooler parts of the environment. If the environmental conditions are acceptable, this energy flow will occur by natural means. (Holtz, 1979, p. 6)

The different cooling processes can be summarized as –
a. Direct cooling: occurs when the interior surfaces and contents of the space are exposed directly to the “environmental energy sink[s]”. (Holtz, 1979, p. 6)

b. Indirect cooling: occurs when the space is cooled by uncontrolled convection or radiation to storage that is in turn cooled by exposure to the “environmental energy sink[s]”. (Holtz, 1979, p. 6)

c. Isolated cooling: occurs when the space is cooled by controlled convection or radiative transfer to storage that is in turn cooled by exposure to the “environmental energy sink[s]”. (Holtz, 1979, p. 6)

A variety of climate classification systems has developed in this country, specifically designed to meet the needs of agriculturalists, mechanical engineers, and climatologists. Whenever energy conscious or climate adaptive architecture is desired, these climate classifications are adapted for use by the building design professions. In a building design it is necessary to define the range of temperature and humidity in which a majority of people engaged in normal activity would be thermally comfortable. This ‘comfort zone’ will in turn determine either the desirable or the potentially acceptable temperature and humidity conditions that the building must achieve for human occupancy.

“A great deal of effort has been spent to determine a more accurate description of the comfort zone. Since early 1920’s with the existence of the Effective Temperatures Scale [ET] for thermal comfort, the lower limits of acceptable living temperatures have risen from 62 F to a present day design standard of 75 F. in 1950’s ASHRAE reexamined the Effective Temperature Scale and replaced it with a new comfort design scale which would better reflect modern living patterns, lighter clothing habits, and diet changes. A much smaller comfort zone resulted, which allowed a design temperature range of 72 F – 78 F, and established the stable indoor comfort standards of today.” (Holtz, 1979, p. 3)
A matrix can be developed to incorporate the ordinates of both the temperature and humidity axes. A first count of temperature and humidity conditions falling in and around the base comfort zone reveals the basic thermal design conditions in this country, which vary from overheated to comfortable to under heated. The stress conditions, in which man cannot
actively survive without mechanical cooling, divides the overheated conditions above the comfort zone into warm [tolerable] and hot [intolerable] design climates.

1.3 PASSIVE COOLING STRATEGIES

Passive cooling can be classified as direct loss or cooling, indirect loss or cooling and isolated loss or cooling as described above. In this thesis I am focusing on the direct cooling strategies where interior surfaces and contents of the space are exposed directly to the “environmental energy sink[s]”. (Holtz, 1979, p. 6).

Direct cooling has four major types: keeping heat out, providing ventilation, underground construction and evaporative cooling. The direct cooling strategy can be sub-categorized as –

1.3.1 Cross [or wind driven] Ventilation: Cross ventilation establishes a flow of cooler outside air through a space. This flow carries heat out of a building. (Kwok A., Grondzik W., 2007, p. 139) Wind driven ventilation or cross ventilation design in buildings provides ventilation to occupants using the least amount of resources. Mechanical ventilation drawbacks include the use of equipment that is high in “embodied energy” and the consumption of energy during operation. (Natural Ventilation) By utilizing the basic design of the building, wind driven ventilation/cross ventilation takes advantage of the natural passage of air without the need for high energy consuming equipment. Wind-catchers are able to aid wind driven ventilation by directing air in and out of buildings. Wind driven ventilation depends on wind behavior, on the interactions of wind with the building envelope; and on openings or other air exchange devices such as inlets or chimneys. The effectiveness of this kind of cooling strategy is a function of size of inlets, outlets, wind speed and outdoor air temperature. This ventilation capacity is dependent on
the temperature differences of indoor and outdoor air. Lesser the temperature difference, only marginal cooling effect can be achieved.

![Figure 3: Cross Ventilation strategies for different room configurations. The diagrams are drawings in plan of different room combinations.](image)

1.3.2 **Stack Ventilation and Solar Chimneys:** Stack effect is temperature induced. When there is a temperature difference between two adjoining volumes of air the warmer air will have lower density and be more buoyant thus hot air will rise above the cold air creating an upward air stream. Forced stack effect in a building takes place in a traditional fire place.

In order for a building to be ventilated adequately via stack effect the inside and outside temperatures must be different so that warmer indoor air rises and escapes the building at
higher apertures, while colder, denser air from the exterior enters the building through lower level openings. Stack effect increases with greater temperature difference and increased height between the higher and lower apertures. Stack driven ventilation has several significant benefits:

- Does not rely on wind and can take place on still, hot summer days when it is most needed.
- Naturally occurring force [hot air rises]
- Stable air flow [compared to wind]
- Greater control in choosing areas for air intake
- Sustainable method

Limitations of stack driven ventilation:

- Lower magnitude flow or cooling compared to wind ventilation
- Relies on temperature differences [inside/outside]
- Design restrictions [height, location of apertures] and may incur extra costs [ventilator stacks, taller spaces]
- The air it introduces in buildings may be polluted; for example due to proximity to an urban or industrial area

Passive ventilation and passive cooling in buildings relies mostly in wind pressure differences but stack effect can augment this type of ventilation/cooling and partly restore air flow rates during hot, still days. Stack ventilation can be implemented in ways such that air inflow in the building does not rely solely on wind direction. In this respect it may provide improved air quality in some types of polluted environments such as cities. For example air can be drawn through the backside or courtyards of buildings avoiding the direct pollution and noise of the street façade. Wind can add to the stack effect but also reduce its effect depending on its speed, direction, and the design of air inlets and outlets.
Therefore prevailing winds must be taken into account when designing for stack effect ventilation.

![Diagram of stack ventilation strategy in different cross sectional room configurations](image)

**Figure 4: Stack Ventilation Strategy in different cross sectional room configurations**

A solar chimney — often referred to as a thermal chimney — is a way of improving the passive ventilation of buildings by using convection of air heated by passive solar energy. A simple description of a solar chimney is that of a vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building. Direct gain warms air inside the chimney causing it to rise out the top and drawing air in from the bottom. This drawing of air can be used to ventilate a home or office or to ventilate only a specific area. The chimney has to be higher than the roof level, and has to be constructed on the wall facing the direction of the sun. Absorption of heat from the sun can be increased by using a glazed surface on the side facing the sun. Heat absorbing material can be used on the opposing side. The size of the heat-absorbing surface is more important than the cross-
section of the chimney. A large surface area allows for more effective heat exchange with the air. Heating of the air within the chimney will enhance convection, and hence airflow through the chimney. Relief openings in the chimney should face away from the direction of the prevailing wind.

To further increase the cooling effect, the incoming air may be led through underground ducts before it is allowed to enter the building. A solar chimney can be improved by integrating it with a trombe wall. The added advantage of this design is that the system may be reversed during the cold season, providing solar heating instead.

A variation of the solar chimney concept is the solar attic. In a hot sunny climate the attic space is often blazingly hot in the summer. In a conventional building this presents a problem as it leads to the need for increased air conditioning. By integrating the attic space with a solar chimney, the hot air in the attic can be put to work. It can help the convection in a stack, improving ventilation. (Natural Ventilation)
1.3.3 **Night ventilation of building mass:** Night ventilation is the use of the cold night air to cool down the structure of a building so that it can absorb heat gains in the daytime reducing the daytime temperature rise. It is usually applied to buildings that are not occupied at night, although an occupied building would probably be ventilated anyway. Night ventilation can be driven by natural forces – i.e. stack or wind, but may use auxiliary fan power, either to provide sufficient airflow at times when the natural forces are weak, or to allow smaller duct to be used. The success of this strategy is however highly dependent on large diurnal temperature differences. High daytime temperatures producing cooling loads and low nighttime temperatures providing heat sinks is very essential for this ventilation strategy. (Kwok A., Grondzik W., 2007, p. 157) Night ventilation is an overheating prevention strategy which uses little or no fossil energy, and together with other passive strategies such as natural ventilation and shading, can avoid the use of air-conditioning. This saves energy, and once set-up would require lower maintenance than mechanical systems. It may not, however, be without initial costs, since the requirement for ducts and controls may represent an additional cost. The problem of security has not already been touched on. Where open windows are the ventilation inlets, this may cause problems when the building is unoccupied at night, especially on the ground floor. Two solutions are available – provide intruder proof grills or bars to the windows, although these may be considered unsightly. Or separate out the view, daylight and ventilation functions and have independent louvered air inlets. This is an example of how passive techniques can incur extra costs. (Sustainability Hub)

1.3.4 **Evaporative Cool towers:** Cool towers use the principles of direct evaporative cooling and downdraft to passively cool hot dry outdoor air and circulate through a building. The resulting cooler and more humid air can be circulated through a building using the inertia
inherent in the falling cool air. Cool towers are sometimes referred to as reverse chimneys. Hot dry air is exposed to water at the top of the tower. As water evaporated into the air inside the tower, the air temperature drops and the moisture content of the air increases; the resulting denser air drops down the tower and out of an opening at the base. The air movement down the tower creates a negative pressure at the top of the tower and a positive pressure at the base. Air exiting the base of the tower enters the space or spaces requiring cooling. (Kwok A., Grondzik W., 2007, p. 151)

An evaporative cooling tower can provide a very low-energy alternative to active cooling for a building in a hot and dry climate. Cooling towers may either use the evaporation of water to remove process heat and cool the working fluid to near the wet-bulb air temperature or rely solely on air to cool the working fluid to near the dry-bulb air temperature. (Cooling Tower) As the process proceeds, dry bulb and wet bulb temperatures converge. The air emerging from the evaporation process would have a dry bulb temperature equal to the wet bulb temperature. (Kwok A., Grondzik W., 2007) Cool towers can add architectural feature to the building. They do not rely on wind for air circulation and require a minimum energy input, hence can be used in areas with little or no wind resources or access.
1.4 IMPACTS OF COOLING

Universal Building Styles:

Adopting a building style may have a great impact on the cooling demand of a building. Modern architectural works that are not appropriately adapted to local climatic conditions are deficient in solar and thermal control and have limited potential for passive cooling. Surveys have been carried out in different types of office buildings that show comfort conditions in glazed buildings are worse than in bioclimatic buildings. Also the level of indoor air pollution is higher because of improper air circulation in the buildings.

Climate Change and Heat Island Effect:

The temperature in urban environments is high. The air temperature in cities is higher than in the countryside. This is termed the heat island effect and it affects the energy consumption of buildings for cooling. It has been the most important factor contributing to climate change. It has a great impact on air conditioning demand. (Akbari H., 1992)

The Impact of Heat Waves:

Recently, heat waves have accelerated the demand for air-conditioning equipment in buildings, also causing huge energy impacts and problems. Passive cooling techniques help reduce pay back the need for air conditioning during heat waves.

Environmental –

Because of the wide use of air conditioning, electrical energy consumption during the summer has reached a peak high. The resulting electricity produces exploitation of finite fossil fuel reserves, atmospheric pollution and climatic changes. The heat produced by the use of air
conditioners increases the urban heat island phenomenon. Ozone layer depletion is also an immediate effect of the usage of air conditioners.

Economic –

There is an economic and political dependency of countries with limited natural resources on other countries, expansive in these natural resources. This leads to economic dependency and affects the economy of a country.

Problems with air Conditioning:

There are innumerable problems that come with the use of air-conditioning; apart from the serious increase in energy consumption.

a. Increase in electricity load

b. Environmental problems associated with ozone depletion and global warming

c. Potential indoor air quality problems

It can often provide human comfort during the daytime. Its overall effect can be positive. Design strategies should be focused to – obtain a continuous air flow throughout the building, direct the air flow through the occupied zones, and achieve high air velocities at occupancy levels.

1.5 CHALLENGE

The operation and effectiveness of passive cooling techniques is more dependent on climate than passive heating techniques. Passive cooling is based on processes fundamentally linked to climate. An improper choice of cooling technique could create an unpleasant internal environment. Also the thermal comfort requirements during summer are different for each
climate type. The choice of cooling technique depends not only on the local climate conditions but also the “building typology and occupancy patterns”. (Santamouris M., 1996, p. 52). “However, the applicability of passive cooling strategies could be limited by – Climate and Microclimate, air pollution and noise levels, site topography and building regulations, lack of regulations, and insufficient information”. (Santamouris M., 1996, p. 53)

1.6 INTENT OF THESIS

The thesis is written to clarify numerous factors surrounding passive cooling systems, and to present a general framework for thinking about passive cooling systems and how they can be utilized in the daily life in the case of non-residential buildings in the United States. The challenge is not to merely study of the passive techniques that could be incorporated in our day-to-day life but to question the applicability of these systems in various climatic regions in the United States. I am from a place where these techniques are used more as a norm than an option and it interests me to study their feasibility in climates and regions in the United States where they are simply not used very much. This is unfortunate since these passive cooling techniques can have immense impacts on the environment: improving air circulation, and air quality, producing carbon emission reductions, and leading to better and more healthy ways of life.
A passive cooling system is one in which heating or cooling effect is obtained and distributed through a building by natural means, enabling the system to function with little or no external power. (The American Institute of Architects, 1982, p. 3) Conventional office buildings with airtight envelope systems are typically conditioned with mechanical heating, ventilating, and air-conditioning (HVAC) systems. HVAC systems maintain fairly constant thermal conditions and can be applied in any geographical location. Since mechanical cooling and fan energy use account for approximately 20% of commercial building electrical consumption in the United States, the concept of integrating passive natural ventilation in office buildings has received attention from both the international and U.S. building industry. In addition, users are increasingly interested in measures that can improve indoor air quality via free ventilation through windows, in part as a reaction to the problems that result from poorly maintained HVAC systems [e.g., sick building syndrome, Legionnaire's disease, etc.] (Double Skin Facades and Natural Ventilation)
2.1 PASSIVE COOLING

Climate and Passive Design in the United States:

The many variations of climate in the United States have been much more challenging for passive cooling than for passive heating. In summer, buildings in most American locations require some space cooling. Especially large commercial buildings that are not skin dominated, cooling may be required throughout most of the year. The wide variation of climatic conditions reinforces the use of mechanical environmental control and challenge passive systems. (Bankston C. and Clark G., 1989, p. 15) The use of air conditioning in the building sector is increasing rapidly. “The use of air conditioning in the service sector is estimated to be close to 100% in Japan, 63% in U.S. and 27% in Europe.” (Waide, 16 - 18 February, 2006)

Intensive use of air conditioning is the result of many factors, in particular:

a. Adoption of a universal style of buildings that does not consider climatic issues and results in increasing energy demands during the summer period
b. Increase of ambient temperature, particularly in the urban environment, owing to the heat island phenomenon, which exacerbates cooling demand in buildings
c. Changes in comfort culture, consumer behavior and expectations
d. Improvement of living standards and increased affluence of consumers
e. Increase in building internal loads particularly plug loads (Santamouris, Advances in Passive Cooling, 2007)

The energy demands of existing buildings in moderate climates are dominated today by heating energy due to low levels of insulation. In warm climates cooling dominates the total consumption. However as building standards continuously improve, there is a clear shift from the dominance of thermal energy demands to electrical energy consumption. (Eicker, 2009, p. 19)
Heating energy can be drastically reduced even in cold climates, while cooling energy demand is on the increase due to higher expectations for comfort, but also due to ever increasing internal loads. (Eicker, 2009, p. 20) Cooling of buildings can be achieved at very different energy consumption levels. The application of different systems depends on the cooling load, which basically has to be removed. Ambient air can be directly used to cool office buildings through night ventilation or daytime ventilation using various methods. (Eicker, 2009, p. 61)

2.2 ADVANTAGES OF PASSIVE COOLING

Passive cooling is part of building and operation in order to deliver a comfortable thermal environment and adequate indoor air quality. Passive cooling is increasingly used to provide internal thermal comfort in buildings. (Santamouris, Advances in Passive Cooling, 2007, pp. 140-141)

Benefits of Passive Cooling:

In hot climates, energy needs for cooling can amount to two or three times those for heating, on an annual basis. Utilization of the basic principles of heat transfer, coupled to the local climate, and exploitation of the physical properties of the construction materials, could make possible the passive control of comfort conditions in the buildings. Even in areas with average minimum ambient temperature, comfortable conditions inside buildings can be achieved by means of proper building design. Passive cooling strategies in the design of buildings should be considered, since the extensive use of air-conditioning units is associated with the environment. Passive ventilation, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy to deliver fresh air into buildings. Fresh air is required in buildings to alleviate odors, to provide oxygen for respiration, and to achieve thermal comfort. However, unlike true air-conditioning, natural
ventilation is ineffective at reducing the humidity of incoming air. This places a limit on the application of natural ventilation in humid climates. (Santamouris M.; Asimakopoulos D., 1996, pp. 35-36)

2.3 A SUSTAINABLE IMPACT

Almost all historic buildings were ventilated naturally, although many of these have been compromised by the addition of partition walls and mechanical systems. With an increased awareness of the cost and environmental impacts of energy use, natural ventilation has become a method for reducing energy use and cost and for providing acceptable indoor environmental quality and maintaining a healthy, comfortable, and productive indoor climate rather than the prevailing approach of using mechanical systems.“In favorable climates and building types, natural ventilation can be used as an alternative to air-conditioning, saving 10%-30% of total energy consumption.” (Natural Ventilation) Because of much higher cost of electricity than natural gas and the effects of demand charges, the pattern of cost savings due to implementation of a passive cooling strategy will often be quite different from the pattern of on-site energy savings. (Bankston C. and Clark G., 1989, p. 502)

2.4 PASSIVE COOLING STRATEGIES

Passive cooling can be introduced in a variety of ways:

a. with operable windows, ventilation can be driven by wind or stack effect to ventilate a single side of a building or to cross ventilate the width of a building;
b. stack-induced ventilation uses a variety of exterior openings [windows in addition to ventilation boxes connected to under floor ducts, structural fins, multi-storey chimneys, roof vents, etc.] to draw in fresh air at a low level and exhaust air at a high level and

c. atria enables one to realize a variant of stack ventilation, where the multi-storey volume created for circulation and social interaction can also be used to ventilate adjacent spaces.

With single-sided ventilation using operable windows, there are general rules used to estimate the effective depth of ventilation. For all-glass façades, solar chimneys are essentially the glazed manifestation of a stack-induced ventilation strategy. A glass, multi-story vertical chimney is located on the south façade of the building. Operable windows connect to this vertical chimney. Similar to the heat extraction concept described above for double-skin façades, solar heat gains absorbed within the chimney cause hot air to rise, inducing cross ventilation from the north side of the building. Mechanical ventilation can be used to supplement this ventilation if natural means are insufficient. Stack-induced ventilation through atria works using the same principle as a solar chimney but can serve more functions. Atria can be situated in the core of the building or form a single-, double-, or triple-sided, all-glass, multi-storey zone at the exterior of the building. The roof is typically glazed. Atria can be used to provide daylight to adjacent spaces and can act as a thermal buffer during the winter season. (Double Skin Facades and Natural Ventilation)

Passive cooling techniques can be used to reduce, and in some cases eliminate, mechanical air conditioning requirements in areas where cooling is a dominant problem. The cost and energy-effectiveness of these options are both worth considering. In many parts of the southwest, summer cooling is as important as winter heating. In the arid part of the country, cooling is the primary design consideration.
Thermal comfort in summer means more than keeping the indoor air temperature below 75° F. High temperatures, or high humidity [or both] leads to discomfort. Fortunately, the regions of high summer temperatures are quite arid [relative humidity is usually low]. The only regions of fairly high humidity, the coastal regions, are also among the coolest parts of the region in summer. Many of the principles and techniques of passive solar heating are adaptable to natural cooling. For optimum summer cooling, a building's surroundings should be designed to minimize summer sunlight striking external surfaces, and to prevent surrounding area heat re-radiation and reflection. The next step in natural cooling is to take advantage of convective cooling methods - those which use the prevailing winds and natural, gravity-induced convection to ventilate a building at the appropriate times of the day.

The oldest, straightforward convective method admits cool night air to drive out the warm air. If breezes are predominant, high vents or open windows on the leeward side [away from prevailing breeze] will let the hottest air, located near the ceiling, escape. The cooler night air sweeping in through low open vents or windows on the windward side will replace this hot air. To get the best cooling rates, leeward openings should have substantially larger total area (50% to 100% larger) than those on the windward side of the house. To a point, increasing the vent area will increase the airflow rate by natural convection. Turbine vents at the roof peak are one way to enhance airflow and improve the cooling rate. Even gentle breezes flowing up and over the roof peak create an upward suction that draws out warm interior air. An even better approach is to use solar radiation to induce a more rapid flow. One of the many possible approaches uses a Trombe wall vented to the outside. Sunlight striking the concrete wall will heat the air in the space between glass and wall to temperatures above 150°F. This very hot air rises quickly and escapes, drawing cool air into the house through low vents on the north wall. Additionally, specifically constructed "solar chimneys", composed of passive air heaters with seasonal dampers can be
incorporated where solar heated air can be dumped into the building in the winter, and used as a "ventilator driver" in the summer to draw outdoor air through a building and ventilate it. (Passive Solar Heating and Cooling Manual, Part 3 & 4)

If there are only light breezes at the site, natural convection can still be used to ventilate and cool a building as long as the outdoor air is cooler than the indoor air at the peak of the house. Since warm air rises, vents located at high points in the interior will allow warm air to escape while cooler outdoor air flows in through low vents to replace it. The coolest air around a house is usually found on the north side, especially if this area is well shaded by trees or shrubs and has water features. Cool air intake vents are best located as low as possible on the north side. The greater the height difference between the low and high vents, the faster the flow of natural convection and the more heat mitigation can occur. Some of the materials and methods used to provide natural ventilation systems in buildings are solar chimneys, wind towers, and summer ventilation control methods. A solar chimney may be an effective solution where prevailing breezes are not dependable enough to rely on wind-induced ventilation and where keeping indoor temperature sufficiently above outdoor temperature to drive buoyant flow would be unacceptable. The chimney is isolated from the occupied space and can be heated as much as possible by the sun or other means. Air is simply exhausted out the top of the chimney creating suction at the bottom which is used to extract warm air.

Wind towers, often topped with fabric sails that direct wind into the building, are a common feature in historic Arabic architecture, and are known as “malqafs.” The incoming air is often routed past a fountain to achieve evaporative cooling as well as ventilation. At night, the process is reversed and the wind tower acts as a chimney to vent room air. A modern variation called a “Cool Tower” puts evaporative cooling elements at the top of the tower to supply cool, dense air. In the summer, when the outside temperature is below the desired inside temperature,
windows should be opened to maximize cool air intake. Lots of airflow is needed to maintain the inside temperature at no more than 3-5 °F above the outside temperature. During hot, calm days, air exchange rates will be very low and the tendency will be for inside temperatures to rise above the outside temperature. The use of fan-forced ventilation or thermal mass for radiant cooling may be important in controlling these maximum temperatures. (Natural Ventilation)

2.5 PASSIVE COOLING VARIANTS

Passive cooling can broadly cover all the measures that contribute to the control and reduction of the cooling needs of buildings. It includes all the preventive measures to avoid overheating in the interior of buildings and strategies for rejection to the external environment of the internal heat, either generated in the interior or entering through the envelope of the building. Natural sources like the upper atmosphere, ambient air and earth can be utilized as cooling sinks to absorb the indoor built-up heat. (Santamouris M.; Asimakopoulos D., 1996, p. 37)

To avoid overheating and create thermal comfort conditions in the interior of buildings during summer, cooling strategies should be designed at three levels – prevention of heat gain in the building, modulation of heat gains, and the rejection of heat from the interior of the building to heat sinks. The first two measures aim to minimize the heat gains and the air temperature inside the building, while the third one attempts to lower the interior air temperature. (Santamouris M.; Asimakopoulos D., 1996, p. 38) However, if environmental conditions are right, it is possible to take advantage of natural cooling forces in the environment to reduce the large cooling requirements of most commercial buildings. (The American Institute of Architects, 1982, p. 40) Also, as a result of many differences between residential and commercial buildings, there are variations in thermal performance between the building types. Lighting and energy
dominate the energy usage in non-residential buildings. (Bankston C. and Clark G., 1989, p. 492)

The interactions between highly variable lighting and occupancy loads, building thermal mass, multizone heating and simultaneous cooling requirements, commercial building energy use must be viewed as an integrated system rather than as a series of components. (Bankston C. and Clark G., 1989, p. 493)

Direct cooling –

It involves both avoiding heat gains and cooling a space by exposing it directly to environmental heat sink[s]. (The American Institute of Architects, 1982, p. 40). Commercial applications of direct, indirect and multistage direct/indirect evaporative mechanical coolers have become common in arid climates. Evaporative cooling is found to provide sufficient building cooling without conventional cooling backup in the Pacific Northwest and Central Mountain regions of the United States. (Bankston C. and Clark G., 1989, p. 497)
Isolated cooling –

It involves cooling a space with air that is conditioned passively at a remote location. (The American Institute of Architects, 1982, p. 40). Controlled introduction of outside air into conventional ducted cooling systems is already common. “O’Connor and Utzinger have simulated the benefits of night ventilation of a small office building in Madison, Wisconsin and concluded that night ventilation can displace more than 30% of the annual sensible cooling load.” The benefits of ventilation increase for later occupancy schedules. (Bankston C. and Clark G., 1989, p. 500)

Indirect cooling –

It involves cooling a space by spontaneous radiation of thermal energy to storage [or some exchange surface] that is in turn cooled by exposure to environmental heat sink[s]. (The American Institute of Architects, 1982, p. 40). The relatively small ratio of roof area to floor area in large office buildings restricts the radiant heating dissipation potential of high rise office buildings. (Bankston C. and Clark G., 1989, p. 500)

Earth contact cooling –

The thermal behavior of large earth contact buildings has been extensively simulated providing information on heat transfer rates through earth contact walls and the sensitivity of this heat transfer to changes in soil type, moisture content, soil surface treatments, and amount and location of insulation. (Bankston C. and Clark G., 1989, p. 501)

Cooling from seasonal storage –

Seasonal cooling concepts have been applied in commercial buildings. One such concept is storage of winter cold in an unconfined aquifer. This concept has low first cost; low operating
cost, and is immediately compatible with conventional buildings. (Bankston C. and Clark G.,
1989, p. 501)
3.0 METHODOLOGY

3.1 INTRODUCTION

This thesis explores the feasibility of passive cooling strategies in the U.S., with a focus on non-residential building types. The thesis has been developed using multiple methods, including in particular case studies and interviews. The case studies defend the types of design strategies used and focus on the important aspects of these techniques. The ventilation strategies used in these case studies, drawn from different regions, have been explored. The research focuses on passive systems for cooling, but will also touch upon indoor air quality. It will also technical and social aspects related to passive ventilation. This study is not merely a study of the passive techniques that could be incorporated in our day-to-day life but will question the applicability of these systems. I am from a place where these techniques are used more as a norm than an option and it interests me to study their feasibility in climates and regions in the United States where they are simply not used very much. This is unfortunate since these passive techniques can have immense impacts on the environment: improving air circulation, and air quality, producing carbon emission reductions, and leading to better and more healthy ways of life.

3.2 DEVELOPMENT OF INTERVIEWS

3.2.1 QUESTIONNAIRE:
To enable this research work I interview people in different fields related to this topic, people who are professors, people who are active designers, people who are researchers, and also students. The questionnaire is as follows:

a. What do you think about the feasibility of passive cooling in non-residential buildings in the United States?

b. Do you think the clientele will accept this system?

c. If the client does not accept would you try to influence his/her decision and encourage them to use this system?

d. How do you feel the people would react to such a system? What would be your personal opinion?

3.2.2 PILOT TEST AND RESULTS:

I developed a questionnaire that relates to the question of passive cooling techniques. The questions were a bit broad encouraging descriptive answers. I took these questions for the personal face-to-face interview, but halfway I realized that I was not getting satisfactory answers and my questions had to be more precise. So along with the broad interview, I developed more precise set of questions. I undertook personal interviews as well as email interviews and people responded and put forward their answers. I observed in this case that everyone was more comfortable with email interviews, than personal interviews, where they get enough time to react and develop a response to the questions.

3.2.3 INTERVIEW GUIDE:

With this experience I then prepared an interview guide that introduced the interviewees to my research question and give them a brief description of the purpose of my thesis.
Then I ask them their opinion on the research question followed by the new set of questions. I have revised the questions as follows.

a. What do you think about the feasibility of passive cooling in non-residential buildings in the United States?
   ** Are passively cooled non-residential buildings technically feasible in the United States?
   ** If so, are there limits to passive cooling applicability?
   ** If not, why not? What are the barriers?

b. Do you think the clientele will accept this system?
   ** Are passively cooled non-residential buildings socially and culturally feasible in the United States? If so, are there limits to acceptance?
   ** If not, why not? What are the barriers?

c. If the client does not accept would you try to influence his/her decision and encourage them to use this system?

d. How do you feel the people would react to such a system? What would be your personal opinion?
   ** How do you feel occupants would react to a passive cooling system?
   ** How would you personally react to a building with a passive cooling system?
   ** Would you need more information about passive cooling systems before feeling comfortable about including them in your designs?

3.2.4 RESPONSES

Interviewee 1 – Architect: Practitioner

Interviewee 2 – Architect: Practitioner and Professor
1. **What do you think about the feasibility of passive cooling in non-residential buildings in the United States?**

Interviewee 1 – Perhaps the issue isn't "passive cooling" in terms of achieving total thermal control passively as much as how design can reduce the dependency on energy consumptive means.

Interviewee 2 – Yes . . . but only in mild, arid regions where evaporative, radiative, and mass-effect cooling are all most effective.

Interviewee 3 – It is not only possible, it is imminent.

Interviewee 4 – Very feasible in many parts of the US, but you has to recognize that this is a big place with lots of different climates.

Interviewee 5 – Yes, but difficult in hot, humid regions of the US.

Interviewee 6 – Cooling buildings and cooling people are separate tasks; their utility depends on the climate location. Night-flushing of a building mass is very different from day-flushing of people.

2. **Are passively cooled non-residential buildings technically feasible in the United States?**
Interviewee 1 – Based on the above clarification, absolutely - we can effectively reduce our dependency on energy consumptive cooling through effective design.

Interviewee 2 – Yes . . . but only in mild, arid regions where evaporative, radiative, and mass-effect cooling are all most effective.

Interviewee 3 – Yes! Even in humid climates.

Interviewee 4 – Of course

Interviewee 5 – Above a certain ambient temperature and humidity, passive cooling may not be possible.

Interviewee 6 – No response

3. If so, are there limits to passive cooling applicability?

Interviewee 1 – With non-residential buildings often including a major interior heat gain, it is unlikely that passive cooling will have as significant an effect.

Interviewee 2 – Hot humid climates are very resistant to passive strategies. Best in these locations is probably closed-loop, indirect evaporation with hybrid fan assist. I don't believe that purely passive desiccant systems are practical . . . certainly not cost-effective.

Interviewee 3 – Only barriers of cost and site.

Interviewee 4 – Hot humid climates are always the most difficult- the gulf coast. you must think in terms of mixed-mode buildings, with many more options for energy conserving operation than simply 'passive' vs. nothing.

Interviewee 5 – No response
4. **If not, why not? What are the barriers?**

Interviewee 1 – In addition, large non-residential structures are often dependent on mechanical controls that often enforce sealing of the enclosure, limiting the use of natural ventilation. On the other hand, there is the opportunity to include sophisticated solar control, although this is rare.

Interviewee 2 – Virtually all U.S. clients financially capable of hiring an architect have been accustomed to expect a high level of thermal comfort.

Interviewee 3 – No response

Interviewee 4 – No response

Interviewee 5 – Passing air over chilled water can reduce its temperature, but this doesn't work in high humidity.

Interviewee 6 – Most technical interventions are straightforward.

5. **Do you think the clientele will accept this system?**

Interviewee 1 – Yes, if not effectively

Interviewee 2 – As the sole comfort system, no. Possibly yes if supplemented by active (mechanical) system.

Interviewee 3 – Once prototypes demonstrate success they will cone.

Interviewee 4 – Depends on who the clientele is. Education and cultural change necessary for broad acceptance. Easier in some climates than others.
6. Are passively cooled non-residential buildings socially and culturally feasible in the United States? If so, are there limits to acceptance?

Interviewee 1 – They should be, but there is an assumption that occupants of on-residential structures do not engage in any way with environmental control, other than perhaps contacting the building manager to request some change. Of course, today most Americans unfortunately also do not expect to engage in making adjustments to the thermal control of their houses other than adjusting the thermostat. The time when we made seasonal adjustments to our buildings (summer vs. winter drapes, changing of furniture, etc.) seems past, although "passive" approaches generally mean personal engagement, and in that sense tend to be more "active."

Interviewee 2 – More now than ever before, thanks to LEED. Initial and life-cycle cost; convenience; operational reliability; serviceability.

Interviewee 3 – Yes.

Interviewee 4 – See above. Dress norms etc.. Are social factors. Also technical/social issues such as acoustical issues, indoor environmental quality control

Interviewee 5 – Certainly. Air conditioning is "invisible" to building occupants. They just want to be cool. If passive cooling means less cooling, occupants may resist. Unfortunately, US building occupants are now accustomed to extreme cooling in buildings.
Interviewee 6 – Yes. Depends on the degree of interaction needed and the informational feedback.

7. **If not, why not? What are the barriers?**

Interviewee 1 – In addition to the above, the focus on first costs rather than life-cycle costing seems to continue.

Interviewee 2 – initial and life-cycle cost; convenience; operational reliability; serviceability.

Interviewee 3 – Ideology, inertia, stupidity.

Interviewee 4 – No response

Interviewee 5 – No response

Interviewee 6 – Clarity of public understanding about technology.

8. **If the client does not accept would you try to influence his/her decision and encourage them to use this system?**

Interviewee 1 – If effective environmental control is inclusive to design, then there is a greater possibility that these techniques will be accepted. But if they are "add ons" it is less likely.

Interviewee 2 – No. The architect's responsibility should be to present any passive cooling design alternatives in a neutral and objective manner.

Interviewee 3 – Absolutely.

Interviewee 4 – Of course
Interviewee 5 – I think they would have to experience a passively cooled building themselves to be convinced.

Interviewee 6 – To save energy.

9. **If a client does not readily accept passive cooling would you try to influence his/her decision and encourage them to use a passive cooling system?**

   Interviewee 1 – The way to influence the decision is to make them essential to the design, which should be fundamental to it - orientation, basic planning, material selection, and construction details.

   Interviewee 2 – No. Either accept the client's decision or resign and wait for a more sympathetic client. A reluctant client will blame you for the slightest glitch or discomfort. Can you spell "law suit"? On the other hand, it is likely that the architect was selected originally for his/her expertise in designing passive buildings. The hiring process itself makes it very likely that the client will be receptive to passive cooling strategies.

   Interviewee 3 – Yes.

   Interviewee 4 – No response

   Interviewee 5 – No response

   Interviewee 6 – No response

10. **How do you feel the people would react to such a system? What would be your personal opinion?**

   Interviewee 1 – No response

   Interviewee 2 – Positive provided its operation was intuitively obvious.
Interviewee 3 – Cooling is cooling.

Interviewee 4 – Personally I would love it if my office had operable windows.

Interviewee 5 – They would welcome it as long as it made them comfortable.

Interviewee 6 – Positively; if well informed.

11. How do you feel occupants would react to a passive cooling system?

Interviewee 1 – Rather than "telling them" about how effective they might be, let them experience the benefits and come to realize the benefits in this way rather than as another "gimmick" applied to make the design special.

Interviewee 2 – It would depend on whether the building was comfortable and its operation did not inconvenience the occupants.

Interviewee 3 – Comfortably.

Interviewee 4 – No response

Interviewee 5 – No response

Interviewee 6 – Positively; if well informed.

12. How would you personally react to a building with a passive cooling system?

Interviewee 1 – No response

Interviewee 2 – It would depend on whether the building was comfortable and its operation did not inconvenience the occupants.

Interviewee 3 – Confidence and pleasure.
Interviewee 4 – No response

Interviewee 5 – I haven't used air conditioning in my home in Muncie for 2 years, so I am very content to sacrifice a little comfort to save energy, environment and money. with passive cooling.

Interviewee 6 – No response

13. **Would you need more information about passive cooling systems before feeling comfortable about including them in your designs?**

Interviewee 1 – Today, any competent building designer should be comfortable with effective environmental adaptation. Architecture is more than just large scale 3D sculpture.

Interviewee 2 – No; I feel I personally have a grasp of the basic passive cooling alternatives. Other thoughts: The best approach to passive cooling is to use basic passive strategies (shading, insulation, ventilative, evap, radiative, and esp) to reduce cooling energy and supplement with conventional mechanical cooling. As with passive solar heating, in most climates it is impractical to achieve 100% passive cooling and eliminate conventional cooling systems entirely.

Interviewee 3 – No Answer

Interviewee 4 – Better design guides always needed. Again i would return to the point about mixed-mode. In the Wisconsin climate, there are times when the building could be cooled passively and there are times when some more sophisticated strategies are necessary. We don't have much understanding of the best ways to design these hybrid systems. Or from another perspective, we don't have the professional fee structure or
building finance models necessary to build carefully engineered solutions designed for long term sustainability. That is a cultural shift that is separate from but related to the question of accepting slightly greater temperature or rh fluctuations etc...

Interviewee 5 – Not me personally, but most architects need more info and examples.

Interviewee 6 – Yes, of course, information would be useful; comfortable is not the operative word for inclusion in design considerations.

3.3 DEVELOPMENT OF CASE-STUDIES

Case studies have always been viewed as a stepping stone in making better the existing element. The case studies presented here include a range of buildings selected to provide a diversity of geographic locations, climates, building types, and strategies. The studies established here will cover the precedent studies with the different passive cooling strategies of cross-ventilation, stack ventilation and solar chimneys, night ventilation of building; and evaporative cooling towers. These studies also are projected in varied climates in the United States helping us to understand the applicable systems that can be used in different climatic regions. Each case study provides a general description of the project, an introduction to the area/region, and design team information. The case studies are concentrated and touch upon only the aspects of ventilation strategies. The motive of case studies is to comprehend the approach towards passive cooling.
3.3.1 Case Study # 1 – Princeton Professional Park, New Jersey

Architects: Harrison Fraker, Architects Princeton Energy Group

Gross square footage: 64,000 square feet

Program: Office Building

The Princeton Professional Park is a trio of speculative office buildings. The design embeds offices in a garden environment, with three buildings linked by wandering paths. An atrium in each building serves as a thermally isolated space where heat is collected during the day in the heating season. It is a buffer zone that lessens the number of office walls exposed to the outside air, improving the skin-to-volume ratio. For heat storage, an inexpensive horizontal rock bed is used. A draw-down air-handling system supplies the rock bed with the heat from the atrium. Heat stored during the day radiates through the slab at night. About half the heating energy for each building is provided by internal gains, with another 40% from solar. The rock bed and the atrium, together with natural ventilation and wet-roof evaporative system also reduce the annual cooling load of each building by 80% - 90%.

Figure 1: The rock bed atrium, natural ventilation and wet-roof evaporative system at The Princeton Professional Park
Climate analysis shows that natural ventilation cools the building from April through June, and from mid September through October – a considerable portion of the air-conditioning season. The atrium assists here. The hot air building up at top of the atrium creates a thermal chimney effect, pulling air from the offices into the atrium and out the ridge vent. Winds which are consistent in the swing seasons come out of the northwest and southwest to provide good cross ventilation through the operable windows on the outside and atrium walls. July and August are hot and humid. Because these are one-story buildings they use spray system on the roof to achieve evaporative heat loss. When the building is shut during the day in the cooling season, return air from the offices is circulated through the rock bed for pre-cooling and then goes to the air-conditioning unit, which, if the air is cool enough, simply circulates it. (The American Institute of Architects, 1982, p. 40)
3.3.2  Case Study # 2 – Terman Engineering Center, Palo Alto, California

Architects: Harry Weese & Associates

Gross square footage: 152,000 square feet

Program: Classrooms, offices, laboratories, lecture halls and a library.

Stanford University’s Terman Engineering Center uses natural ventilation with a high degree of control flexibility to handle the warm and somewhat humid climate of Palo Alto, California.

![Terman engineering center](image)

Figure 3: Terman engineering center

The building uses a number of energy-conserving features, primarily designed for natural ventilation. Ventilation is enhanced by the use of fully operable perimeter windows, narrow building sections that aid in cross ventilation, and operable skylight vents. Temperatures of the outside air flowing through the building are lowered by a water-pond and a fountain in the courtyard. Operable glazing for the perimeter spaces consists of floor-to-ceiling French doors to provide shade, with a small balcony for each office. Each window is provided with an operable louvered shutter that moves on a
standard hanging track commonly used as barn door hardware. The shutters are located on the exterior of the glazing to block the sun before it is transmitted through the glass. The siting and the quantity of wall openings all respond to the requirements for natural ventilation. The shaded pond cools the prevailing wind, the L-shaped, above ground portion of the louvers, and vents make the building entirely permeable to it. The system is further enhanced by louvers built into the interior doors which allow air to circulate through the rooms and enter the corridor ventilator shafts and airwells. These airwells are simply openings in the floor to levels below and are located alongside the corridors. Outside air first enters the perimeter rooms through the exterior windows and is then drawn to the corridor shafts. Warm air’s tendency to rise to the high points of the building [in this case the roof skylights above the corridors] increases the air flows throughout, pulling more and more outside air in through the windows. The warm air is vented through skylight vents. These are awning type windows located in high clerestories at the opposite sides of the building. This provides the flexibility of always being able to the leeward side, where negative air pressure accelerates the rate at which air is exhausted. The traditional architecture of warm climates clearly provided a wealth of information from which the designers of this building developed their solutions. The floor-to-ceiling openings and sliding shutters are similar to examples of European domestic architecture dating from the early 13th and 14th centuries. Raising the building partially off the ground to provide greater ventilation is common in the tropical regions of Africa, South America, and Southeast Asia. This and the airwells, used most notably in the architecture of Islam, have been found over time to be effective answers to hot climates. (The American Institute of Architects, 1982, pp. 50-51)
3.3.3  Case Study #3 – Camp Arroyo, Livermore, California

Architects: Siegel & Strain Architects

Gross square footage: 20,000 square feet [1,860 square meters]

Completed: July 2001

Program: Cabins, dining hall, kitchen, swimming pool with bathhouses

Responding to the hot, dry climate of the hills of California’s East Bay, the Architects selected three structural systems for the design of an educational camp. The program included a dining hall to seat 200 campers, served by a commercial kitchen, two bathhouses adjacent to the swimming pool; and cabins to house 144 campers and staff. The camp is little used during the peak heating months of December and January, and is used intensively during the peak cooling months.
The normal temperature and dew points; high, average and low temperatures shown for each month don’t reflect the extremes that are often experienced in Livermore. Siegel & Strain focused first on building orientation and form for maximum energy efficiency. For the dining hall, thermal performance to keep out the summer heat was a high priority, and the client had interest in straw bale construction. The building was made of straw bale walls, coated on either side with 1 ½ inches of gunite and a layer of plaster, giving them significant thermal mass in addition to the thermal resistance of the bales. Overhangs in the building design were carefully sized to keep the summer sun off the south facing windows. Inside, placards explain how to manually control the windows and shutters to maintain comfort during different weather conditions. Performance issues continue to plague some of the mechanical systems in the dining hall and cabins. Fortunately, the real success of the design is that those systems are hardly needed, even on hottest summer days. Dr. Gail Brager’s Sustainable Design for Hot Climates class from the University of California at Berkeley’s College of Environmental Design spent 19 days studying the buildings in 2002. With the support from the architects and the Pacific Energy Center, they tracked temperatures indoors and out, on various surfaces and in the middle of spaces. Their results show that even though the evaporative cooler in the dining hall wasn’t functioning properly; conditions remained comfortable indoors through several very hot afternoons. (Oehlkers, 2008, pp. 37-40)
Figure 6: Cross-ventilation and Stack ventilation in cabins

Figure 7: Cross-ventilation and Stack ventilation in dining hall

Figure 8: Ventilation in bathhouse
3.3.4 Case Study # 4 – Lillis Business Complex, University of Oregon, Eugene, Oregon

Architects: SRG Partnership

Gross square footage: 137,000 square feet [12,700 square meters]

Completed: October 2003

Program: A four-story addition connecting three preexisting buildings, consisting of an atrium/thoroughfare, a café, public meeting rooms, classrooms and offices.

As the scope of The Lillis Business Complex project grew, so did the project teams green aspirations; faculty and students from the College of Business identified sustainability as a key business strategy for companies of the future. A multidisciplinary design team worked collaboratively on the project. Eugene’s relatively mild climate makes it ideal for natural ventilation and night flushing. The building uses different ventilation strategies in different locations including 100% natural ventilation [no mechanical cooling or ventilation air] in the atrium and faculty offices on the north, hybrid natural and mechanical ventilation and cooling in the classrooms, and 100 percent mechanical ventilation and cooling in the faculty offices on the south.
Figure 10: Atrium Ventilation Diagram – Air enters through inlets in the classrooms and exits through outlets at the sides of the atrium.

Figure 11: Heating and Cooling Degree Days

Figure 12: Temperatures and Dew Points

Figure 13: Cool nighttime air is drawn through the outside air inlets and under the raised concrete floors, cooling the slabs at night so they can absorb heat during the day.
Extensive computer modeling revealed that the thermal mass needed for the night flushing strategy could be met with a steel structure by adding thin slabs in key locations. Without this modeling, a concrete structure might have been selected, adding more than a million dollars to the cost. Mass was added to selected indoor surfaces, and special plenums were created to maximize the contact between ventilation air and the surfaces of the thermal storage mass. While most of the occupants are thrilled with the building, the natural ventilation and night flushing strategies have been especially challenging for a commissioning process that typically focuses on mechanical equipment. To some extent, complaints about comfort are exacerbated by a design decision to provide offices on the south side of the corridor with mechanical cooling and fixed windows, while the offices on the north got operable windows but no air-conditioning. Anticipating that the stack effect in the atrium may not consistently provide enough pressure differentials to drive the natural ventilation process, the design team identified smoke evacuation fans in the atrium roof as a means of enhancing the airflow. The fans were outfitted with variable-speed drives so that they could be operated at a low speed to improve the ventilation without a large energy penalty. Unfortunately the control on those drivers was not configured in a way that activates the fans appropriately; once the control strategy for those fans is refined, comfort on the upper floors should improve. Similarly, the fourth-floor auditorium is being retrofitted with ceiling fans to alleviate summertime discomfort: “We thought that the stack effect was going to be so successful that we wouldn’t need those fans.” Mostly, though, the university’s experience with the building has been overwhelmingly positive. (Oehlkers, 2008, pp. 42-47) (Kwok A., Grondzik W., 2007, pp. 315-322)
3.3.5  Case Study # 5 – Sidwell Friends Middle School, Washington DC

Architects: Kieran Timberlake Associates

Gross square footage: 72,500 square feet [6,736 square meters]

Completed: September 2006

Program: Classrooms, library, art/music rooms, science labs, constructed wetland, rooftop container garden.

“We started out designing a building, which turned into a green building, and that green building ended up transforming the whole school, culturally and operationally,” says Mike Saxenin, assistant head of the school and its chief financial officer. To create a new middle school design, the design team renovated an existing 33,000 square foot building and expanded it with a 39,000 square foot addition. The old and new wings meet to form a U-shaped courtyard. The primary entrance leads through the courtyard into a spacious lobby, which together with administrative offices, connects the old and new parts of the building. Energy-use reductions were achieved with a highly efficient building envelope, lighting controls, and passive strategies to minimize heating and cooling loads. Solar chimneys exhaust hot air during the cooling season without fans.

Figure 15: Heating and Cooling Degree Days

Figure 14: Temperature and Dew Points
Solar chimneys designed for passive ventilation serve the specialty classrooms in the addition. South-facing glazing at the tops of the shafts heat the air within, creating convection current that draws cooler air in through north-facing open windows. Portals in the shaft-ways within the building demonstrate the operation and effectiveness of the passive cooling systems with the breeze. The solar chimneys are also intended to respond to both passive and active systems to the local climate.

Figure 16: Solar Chimneys designed for passive ventilation.

The school’s commitment to using this project as a learning opportunity extends far beyond the students. But it will be hard to measure the long-term benefits of providing students with such a deep connection to natural systems, which is so rare in the urban setting. (Oehlkers, 2008, pp. 48-53)
3.3.6 Case Study # 6 – Merril Hall University of Washington, Seattle

Architects: The Miller/Hull Partnership

Gross square footage: 19,670 square feet [1,830 square meters]

Completed: January 2005

Program: Offices, library, labs, herbarium, greenhouse [unconditioned]

The Merril Complex is situated at the edge of campus, between residential neighborhood and a nature preserve. The academic and outreach programs run by the center attract some 65,000 people a year. The center convinced the University, but was told that it would have to raise all the money for sustainability equipment, materials, and systems.

The greenhouse which opens to the lobby of the new building off of its main entrance is a new and much-needed informal goal, since one weakness of the old facility was a somewhat unidentified set of entry points. Early on it was determined that passive ventilation would be sufficient for cooling most spaces although not the library. High-efficiency condensing boilers and a water-cooled chiller were selected to keep energy use low, and administrative staff agreed to open offices for the light and air benefits. The building has high windows in the offices that stay open full-time in warm
weather, as well as transom windows. It makes a noticeable difference to have these open. The strategies of cross ventilation and stack ventilation both are incorporated in the building to make the impact of natural ventilation. Seattle’s relatively mild temperatures make natural ventilation a viable cooling strategy for most spaces.

The building can asset the program and to the educational process that they nurture – learning how urban and natural environments relate. This building is that process in real time. (Oehlkers, 2008, pp. 54-57)
Case Study # 7 – Global Ecology Center, Stanford, California

Architects: EHDD Architecture

Gross square footage: 10,890 square feet [1,000 square meters]

Completed: March 2004

Program: Offices and labs

Rather than clearing a mature oak forest from the site to create a one-story structure, the designers chose to tuck the building into a previously paved utility area at the back of the property, creating a new core for the campus. A two-story building better accommodated the area’s smaller size.

The program called for roughly equivalent amounts of lab and office space. Designers put the labs on the first floor and offices on the floor above to provide
enhanced interaction and flexibility. This separation also saves energy because it lets
large amount of outside air into the lab zone without over-ventilating the offices. An
evaporative downdraft cool tower cools the lobby, working in a similar way to the
“katabatic” winds that form as the temperature drops and moves air down the faces of
glaciers. And instead of a large chiller, water is cooled by spraying it onto the roof at
night, where it releases its heat through night-sky radiation; the cooled water is then
stored in an insulated tank until it is needed. Radiant heating and cooling is delivered
throughout the building via water pipes in the slab floors; air distribution is used
exclusively for ventilation. Labs are typically ventilated by a mechanical system that can
supply 100 percent outdoor air. When the air supply is also the delivery mechanism for
heating and cooling, outside air temperatures can mean huge expenditures of energy to
cool or heat air to comfortable levels. The department’s water based system saves energy
by separating heating and cooling from ventilation requirements.

Placing several heavy-duty freezers for the labs in a semi-conditioned warehouse
next door, instead of in the labs themselves, is another example of how the building
program was developed with sustainability in mind. These deep-freezers produce a large
amount of heat as they maintain temperatures as low as –80 degree Celsius, so keeping them out of the occupied building reduced the cooling load significantly.

The designers were sold on open offices as a way to optimize natural ventilation. The natural ventilation took some teamwork to figure out. For example, the windows were kept closed on really hot days; because the radiant cooling in the slab couldn’t keep the space comfortable with the windows open. It is thus possible to design a building that uses significantly less energy but is also very comfortable. (Oehlkers, 2008, pp. 142-147)
3.4 REFLECTION ON CASE STUDIES

I indulged myself on gaining understanding about ‘Direct Passive Cooling Strategies’. These strategies could be effective as well as affective to the urban environment and its inhabitants. I diverted myself to the aspects of the direct cooling techniques to understand the roles it plays on the ventilation aspect of a building in a particular climatic context. The precedent studies helped me to understand the installations of these type of systems in different ways. The outlook for all case studies in applying the strategies was distinctive. The precedent studies carried out have their own perspectives in Passive Cooling Strategy applications and justice in approaching the project goals. All of the case studies focused on different ways of implications of the cooling techniques to reflect the optimum environment for the inhabitants. An optimum environment reflects individuals’ needs for happiness, satisfaction, comfort and leisure that challenge their capabilities. The well designed technique might do justice to bring multiple goals together on the same platform. They are aesthetic environment, a suitable and sustainable climate, low cost of living, conservation of reserves, reduced pollution and minimizing the cost consumption.
4.0 CONCLUSIONS

4.1 INTRODUCTION

This section develops conclusions based on the information described in the earlier sections. Many of the observations and conclusions are based on literature review, case studies and interviews. It was not possible to reach a final conclusion about the feasibility, performance and economics of passive cooling systems in non-residential buildings in the United States and many creative design opportunities remain. Emphasis is placed on systems whose elements can serve cooling function. For many advanced heating systems there does not exist a well-defined cooling system employing some or all of the same elements. As in case of passive space heating, roles for passive cooling in more general energy management schemes for large-scale commercial and industrial buildings remain to be identified and evaluated.

4.1.1 SIGNIFICANCE

I have studied co-relation between two different variables of direct cooling technology and climate consideration.
**Direct cooling technology** –

Direct cooling techniques can be used to reduce, and in some cases eliminate, mechanical air conditioning requirements in areas where cooling is a dominant problem. The cost and energy effectiveness of these options are both worth considering by designers and builders. In many parts of the southwest, summer cooling is as important as winter heating. In the arid part of the country, cooling is the primary design consideration. Direct cooling has four potential components – keeping heat out, providing ventilation, underground construction and evaporative cooling. The direct cooling strategies I explored are cross ventilation, stack ventilation, night time ventilation of buildings and cool towers.

**Climate** –

Climate encompasses the statistics of temperature, humidity, atmospheric pressure, wind, rainfall, atmospheric particle count and other meteorological elements in a given region over long periods of time. Climate must be contrasted to weather, which is the present condition of these same elements and their variations over periods of up to two weeks. The climate of a location is affected by its latitude, terrain, and altitude, as well as nearby water bodies and their currents. Climates can be classified according to the average and the typical ranges of different variables, most commonly temperature and precipitation.

For the United States, this work predominantly considers 5 climatic variations – Mediterranean climate, humid sub-tropical climate, humid continental climate, semi-arid climate and desert climate.
4.1.2 CORRELATION

Climate –

There is a **strong positive correlation** between the direct cooling strategies and the climate in which these strategies are used.

Cultural issues –

There is a **weak positive correlation** between the strategy of cross ventilation or stack ventilation and the nationality or the belief of a particular person. But some religions emphasize natural ventilation and hence a weak positive correlation.

Economic-related issues –

There is a **strong positive correlation** between the use of a correct cooling strategy and HVAC costs and reflecting a stable economic condition of the building.

Political/Organizational issues –

Since there is a positive correlation of the economic aspect, the political aspects too is important to consider. The laws and by-laws of government keep changing according to the will of the ruling or governing organization. Hence a **weak positive correlation** can be established between the factors of the rules created by the governing party and the design techniques and limitations developed in the passive ventilation techniques.

Intellectual/ Theoretical issues –

There are a lot of theories established concerning climate and cooling strategies, which have been followed over time. But since there has now been such a shift in climatic conditions, these theories need to be researched upon more and is it possible for us to
come up with new technologies in this sector, respecting that the old strategies work even today. So there is definitely a strong positive correlation between a particular type of building in a particular climate and the design of the same kind of building in a different climate or the design of a similar building in the same climate.

**Technological issues** –

Technological issue always has been a major area of concern when it comes to climate and ventilation strategies. Since different strategies are used in different areas to suit the climate has not heard of any sustainable technology that has come up for a unanimous usage in all climates like the mechanical ventilation techniques. There is a strong positive correlation between the use of cooling towers in a desert climate and a strong negative correlation using the cooling tower in a humid-subtropical climate.

**Aesthetics of passive cooling** –

There is a weak negative correlation between the factors of the color of a particular room in the building and the wind direction [wind flow] in the building.

4.1.3 RESULTS

**Climate** –

There is a strong positive correlation between the direct cooling strategies and climate.

After analyzing the direct cooling strategies and the varied climatic conditions in the United States the patterns shown in the table should help designers and architects to apply direct cooling strategies under different climatic conditions.
### DIRECT COOLING STRATEGIES ACROSS THE CLIMATES

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mediterranean climate [warm to hot, dry summers]</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe [+ve]</td>
<td>Yes</td>
</tr>
<tr>
<td>Humid continental climate [warm to hot, humid summers]</td>
<td>Maybe [-ve]</td>
<td>Maybe [-ve]</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

*Figure 1: Table showing different direct cooling techniques across five climates of the United States*
Figure 2: Graph showing the different direct cooling strategies across five different climates in the United States
4.2 PREREQUISITES FOR PASSIVE COOLING

The use of passive cooling in a building will lead to –

- Shallow plans and operable windows for better natural ventilation
- More control given to occupants in order to maximize their ‘adaptive opportunities’ for moderating their immediate environment
- Connected indoor and outdoor climates where the seasons are reflected in the indoor temperatures of the building
- Lower energy use resulting from the building itself to playing a greater role in indoor climate control
- Healthier indoor environments as fresher, cleaner air is reintroduced through open windows.
- Comfort as a goal that occupants seek, and the opportunity for occupants to create their own comfort in partnership with the building.
- The temperature that the building occupants find comfortable will be close to the temperature which they would experience in buildings with local culture equivalent to air-conditioning in the United States.
- The changes in building temperatures within a day, and from day to day will be kept within the range of comfort.

The time has come to re-evaluate the 20th century approach to comfort standards and to identify their weaknesses and build on their strengths in order to enable passive buildings to emerge. Applying the insights of the adaptive approach to the thermal design of buildings will assist the evolution of a truly 21st century building paradigm. This will enable designers to create buildings that remain comfortable for their occupants in the increasingly extreme weather conditions.
5.0 GLOSSARY

Air Changes

A measure of the air exchange in a building due to infiltration or ventilation. One air change occurs when the building’s entire volume of air has been replaced.

Ambient Temperature

Surrounding air temperature, as in a room or around a building, in contrast to a local or modified temperature.

ASHRAE

American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Atrium

A usually large and multistoried, glass-roofed room used to bring daylight to the interior of thick buildings where sidelight alone cannot penetrate. The atrium may be enclosed on two, three, or four sides by the rooms it helps light.
**Comfort Zone**

On the bioclimatic or psychometric chart, the area of combined temperatures and humidity that 80% of the people find comfortable. People are assumed to be in the shade, fully protected from wind, engaged in light activity, and wearing moderate levels of clothing that increase slightly in winter.

**Conditioned and Unconditioned Spaces**

Conditioned spaces need treatment such as heat addition, heat removal, moisture removal, or pollution removal. Unconditioned spaces do not need or do not have such treatment and no effort is made to control infiltration.

**Cooling Degree Days**

*See Degree Days*

**Cool Tower**

*See Downdraft Evaporative Cool Tower*

**Cross Ventilation**

Ventilative cooling of people and spaces driven by the force of wind. When outside air is cooler than inside air, heat can be transferred from a space to the ventilation air. Cross-ventilation can also remove heat from people by convection and by increasing the rate of perspiration evaporation. The cooling rate from cross-ventilation is determined by wind speed, opening sizes and the temperature difference between the inside and outside. *See also stack ventilation.*
**Degree Days [DD]**

The difference, measured in degrees F or C, between a base temperature and the average outdoor temperature for a single day. For heating degree days, average outdoor temperature is always below the base, and for cooling degree days, outdoor temperature is always above the base.

**Direct Gain**

The transmission of sunlight through glazing directly into the space to be heated, where it is converted to heat by absorption on interior mass surfaces.

**Diurnal**

Relating to a 24-hour cycle. A diurnal temperature swing is the cycle of temperature over the course of one 24-hour period.

**Downdraft Evaporative Cool Tower**

A cooling system that humidifies and cools warm dry air by passing it through a wetted pad at the top of the tower. The cooled air, being denser, falls down the tower and into the occupied space below, drawing in more air through the pads in the process. Thus, no distribution fans are required.

**Dry Bulb Temperature**

The air temperature measured using a conventional thermometer.

**Earth Air Heat Exchanges**

A strategy of pretempering fresh air for ventilation, and in some cases, providing building cooling, by passing incoming air through buried ducts.
Earth Contact

The strategy of placing building surfaces in contact with the ground to reduce the temperature difference between inside and outside, reduce infiltration, and/or use the subsurface soil temperatures to cool the building.

Earth Tubes

*See Earth Air Heat Exchangers.*

Envelope Heat Gain or Loss

Heat transferred through the building skin or via infiltration/ventilation.

Evaporative Cooling

A heat removal process in which water vapor is added to air, increasing its relative humidity while lowering its temperature. The total amount of heat in the air stays constant, but is transferred from sensible heat to latent heat in the moisture. In the process of shifting from liquid to vapor, the water must absorb large amounts of heat.

Evaporative Cooling, Direct

A cooling process where warm, dry air is moved through a wet medium to evaporate moisture into the air. The cooler, more humid air is then used to cool the space.

Evaporative Cooling, Indirect

A cooling process where the evaporative process is remote from the conditioned space. The cooled air is then used to lower the temperature of building surface or is passed through a heat exchanger to cool indoor air. The indirect evaporative process has the advantage of lowering
temperatures without adding humidity to the air, thus extending the climatic conditions and regions in which evaporative cooling is effective.

**Floor Area, Conditioned**

The portion of a building that is heated and/or cooled. Does not include attics, unheated basements, outdoor spaces, garages, unheated buffer zones, etc.

**Heat Gain**

The amount of heat that is introduced into a space, either from incoming radiation, air infiltration, ventilation, or from internal sources such as occupants, lights, and equipment.

**Heating Degree Days**

*See Degree Days.*

**Heat Island**

The increased temperatures, relative to surrounding open land, found in center cities and areas of high development density. Heat islands are caused by concentrations of heat sources, decreased vegetation cover, increased massive and dark surfaces, decreased wind flows, and narrow sky view angles.

**HVAC**

Mechanical systems for heating, ventilating and air-conditioning that control temperature, humidity, and air quality.

**Hybrid System**

A solar heating or cooling system that combines passive and active elements.
**Indirect Gain**

The transfer of solar heat into the space to be heated from a collector that is coupled to the space by an uninsulated, conductive, or convective medium; for example, thermal storage walls and roof ponds.

**Infiltration**

Unintruded air exchange between interior spaces and the outdoors, resulting in heat loss or gain. It is driven by the difference in pressure between inside and outside buildings exposed to higher wind speeds and buildings with looser construction have increased rates of infiltration. Heat transfer from infiltration is proportional to the volume of air entering and to the temperature difference between inside and outside.

**Insulation**

Any material with high thermal resistance used to slow the transfer of heat via conduction. May also refer to materials used to reflect radiant heat.

**Internal Heat Gain**

Heat generated inside a building by sources other than the space-heating equipment, usually by appliances, lights, and people.

**Latitude**

The angular distance north or south of the earth’s equator, measured in degrees along a meridian. The equator is 0 degrees; the North Pole is 90 degrees North Latitude. Latitudes farther from the equator have lower sun angles, less radiation and illuminance per hour, and more variation in sun path between summer and winter.
Longitude

Angular distance on the earth’s surface, measured east or west from the prime meridian [0°] at Greenwich, England, to the meridian passing through a position, expressed in degrees.

Mass, Thermal

*See Thermal Mass.*

Mean Radiant Temperature

The weighted average temperature of surrounding surfaces, based on the angular size between a person and those surfaces. A lower room surface MRT, such as with earth contact, can give the perception of comfort at higher air temperatures than when the surfaces are near the temperature of the indoor air. Similarly in a passively heated building, a person will feel comfortable in a room with warm thermal mass at lower air temperatures than if in a room with no MRT difference.

Night Ventilation of Mass

A cooling process where a building is closed during the hot daytime hours, its heat gains are stored during that time in the building’s structure or other thermal mass, and then at night the building is opened, and cooler outdoor air is used to flush heat from the mass, lowering its temperature to prepare for another cycle.

Night Sky Radiation

A reversal of the day-time insolation principle. Just as the sun radiates energy during the day through the void of space, so heat energy can travel unhindered at night, from the earth’s surface
back into space. On a clear night, any warm object can cool itself by radiating long-wave heat energy to the cooler sky. On a cloudy night, the cloud cover acts as an insulator and prevents the heat from traveling to a cooler sky.

**Passive System**

A system that uses non-mechanical, non-electrical means to satisfy evaporative or cooling loads. Purely passive systems use radiation, conduction, and natural convection to distribute heat and provide light.

**Relative Humidity**

The percentage of water vapor in the atmosphere relative to the maximum amount of water vapor that can be held by the air at a given temperature.

**Solar Gain**

Heat transferred to a space by solar radiation through glazing.

**Stack Ventilation**

The process of natural ventilation induced by the chimney effect, where a pressure differential occurs across the section of a room. Air in the room absorbs heat in the space, expands, and loses density, thus rising to the top of the space. When it exits through high outlet openings, a lower pressure is created low in the space, drawing in cooler outside air from low inlets.

**Thermal Mass**

Materials with high heat capacity, such as masonry or water, used to store heat or cool when there is an excess of a resource for use later when there is a need.
Ventilation, Natural

Air flow through and within a space stimulated by either the distribution of pressure gradients around a building or thermal forces caused by temperature gradients between indoor and outdoor air.

Wet-Bulb Temperature

The air temperature measured using a thermometer with a wetted bulb moved rapidly through the air to promote evaporation. The evaporating moisture, changing phase, lowers the temperature measured, relative to that measured with a dry bulb. Wet-bulb temperature accounts for the effects of moisture in the air. It can be used, along with the dry-bulb temperature to determine relative humidity.

Windward

The upwind side of a building or obstruction that faces the direction, from which the wind blows, usually subjected to higher pressure.
6.0 LITERATURE CITED


