# POTENTIAL ENERGY COST SAVINGS BY USE OF BUILDING ROOFS AS THERMAL STORAGE OF A MULTI-STORIED BUILDING

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STORAGE OF A MULTI-STORIED BUILDING

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ABSTRACT

The thermal mass of a building has been used for more than two decades to shift the peak cooling load occurring during the day time to evening or night time. This is typically accomplished by use of concrete slabs embedded with pipes carrying hot or chilled water to meet the heating or cooling load, respectively. The water temperature drops across the coils and the frequency and intensity of room air circulation can be varied, along with controlling the gains through the windows, to shift the peak load hours to the nighttime when energy costs are cheaper and electric demands are lower.

This thesis deals with the transient finite element heat transfer analysis of a concrete slab embedded with pipes circulating heated or chilled water of a multi-storied office building. A hypothetical office building in Chattanooga, Tennessee, USA is analyzed with weather data of that locale. The electrical power consumption of such a system operating at milder conditions of evening or night hours is estimated by use of hourly weather data. The estimated electric power consumption is then compared to the traditional method of operations. The influence of the wall envelope, including the size and orientation of windows, is considered in reducing the energy gain or loss from the space. The results presented in this thesis identify the potential energy cost savings resulting from use of such a system as well as challenges involved compared to traditional buildings in commercial applications.

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NOMENCLATURE

$k$, thermal conductivity

$\propto$, thermal diffusion

$W$, slab thickness

$L$, slab length

$r$, pipe radius

$h_a$, convection heat transfer for air

$h_w$, convection heat transfer for water

$x$, special variable

$y$, special variable

$t$, time

$m$, row parameter

$n$, column parameter

$p$, step parameter

$F_o$, Fourier number

$B_i$, biot number

$A_{floor}$, area of floor

$A_{ceiling}$, area of ceiling

$Q$, heat transfer

$Q_{CL}$, heat of cooling load

$Q_{floor}$, heat of floor

$Q_{ceiling}$, heat of ceiling

ρ, density

V, velocity

$W_i$, weighting function

q, heat flux

ds, differential length

$q_e$, heat flux at node e

$q_w$, heat flux at node w

$q_n$, heat flux at node n

$T_E$, temperature flux at node E

$T_P$, temperature flux at node P

$T_W$, temperature flux at node W

$T_S$, temperature flux at node S

$T_{space}$, temperature of space

$T_{high}$, highest daily temperature point

$T_{low}$, lowest daily temperature point

A, temperature amplitude

$T_a$, air temperature

$T_w$, water temperature

# CHAPTER I

# INTRODUCTION

Energy use in commercial and residential buildings accounts for 30% of the world's primary energy consumption (Yang and Li, 2008). In light of this significant figure, the use of thermal masses to heat and cool non residential buildings began to be explored as early as the late twentieth century by European engineers. In an early Swiss design heat was stored in the concrete mass of the structure during the day and discharged at night through the use of a system of water piping. The pipes were embedded in a slab and coupled with air/water heat exchangers (Zhou et al, 2008). A similar system was installed in the mid-nineties in the exhibition rooms of the Groninger Museum in The Netherlands.

One limitation of the thermal slab method (hydronic method) is the impossibility of individual room control. Such systems are also unsuitable in climates with high cooling requirements (loads) in summer and high heating requirements in winter due to the high potential for under-cooling and risk of condensation. The suspended ceilings common in commercial buildings cannot be installed as much of the heat transfer between the slab and the climate-controlled space will occur through the ceiling surface (Olesen et al, 2002). In addition, a heavy, reinforced concrete wall with external polystyrene insulation and stucco is the most desirable type of external wall for buildings in which a thermal slab is the desired heating and cooling mechanism (Zhou et al., 2008). Finally, though the cost for energy transport is reduced, the need to reheat the water can limit the energy savings in this model over conventional HVAC or hybrid methods (Olesen et al, 2002).

Simmonds considered several factors in determining comfort level using the hydronic systems: dry bulb air temperature, radiant temperature (from the radiant system), air speed and relative humidity (Simmonds, 1994). He suggested that the dry-bulb air temperature (ambient room temperature) be kept between 18°C and 25°C. The heat convection coefficient used to calculate the heat transfer from the slab to the space is dependent on air speed (velocity).

In climates where solar heat gains preclude the use of a purely hydronic system, a hybrid system using slabs to transfer the peak cooling load to the cooler evening hours can be implemented successfully. Such is the example set forth in the hybrid conditioning system (radiant cooling floors and variable-volume displacement conditioning system) used in the International Airport in Bangkok (Simmonds et al, 2000).

In their 2008 analysis, Li and Yang quantified the relationship between the use of thermal mass and the reduction of cooling load including the time constant τ and the convective heat transfer factors (both interior number $A_i$ and exterior number$A_o$), the outdoor air temperature, and the indoor heat gain. They noted that with a time constant between 400 and 1000 hours, an increase of that time constant can effectively reduce the cooling load by as much as 60%. It can thus be inferred that the thermal mass of a slab can be used to reduce the cooling load.

## Purpose of this Analysis

The analysis set forth in this thesis focuses on transient numerical finite element analysis of a hydronic system to control temperature in a two story office building. The commercial building is considered to be of typical size and is located in Chattanooga, Tennessee, a large metropolitan area in the Southeastern region of the United States. The electrical power consumption of a system operating in milder weather conditions and during evening hours was estimated using the hourly weather data in TABLER software. Transient thermal analysis of the roof structure as well as Finite Element Analysis (ANSYS) was carried out to estimate the thermal capacity.

As in previous designs, the system discussed in this thesis consists of a concrete slab embedded with a pipe circulating either heated or chilled water. A model will be created in the specified locale. In addition, favorable dimensions for the model will be explored. Results will indicate if it is possible to shift the maximum heating or cooling load from the hours of peak electric demand to off-peak hours. Furthermore, simulation results will determine if a hydronic heating and cooling system is indeed an energy cost saving substitute for commercial building applications in the identified locale.

# CHAPTER II

## THEORY AND ANALYSIS

To analyze and simulate the physical heat transfer in the slab (for the general expression of the heat condition), Equation (2.1) was employed.

$$\frac{\partial T}{\partial x^2} + \frac{\partial T}{\partial y^2} + \frac{\partial T}{\partial z^2} + \frac{\dot{Q}}{k} = \frac{1}{\propto}\frac{\partial T}{\partial t} \qquad (2.1)$$

For transient conduction with two dimensional effects, constant properties, and no heat generation, Equation 2.1 can be reduced to Equation 2.2.

$$\frac{\partial T}{\partial x^2} + \frac{\partial T}{\partial y^2} = \frac{1}{\propto}\frac{\partial T}{\partial t} \qquad (2.2)$$

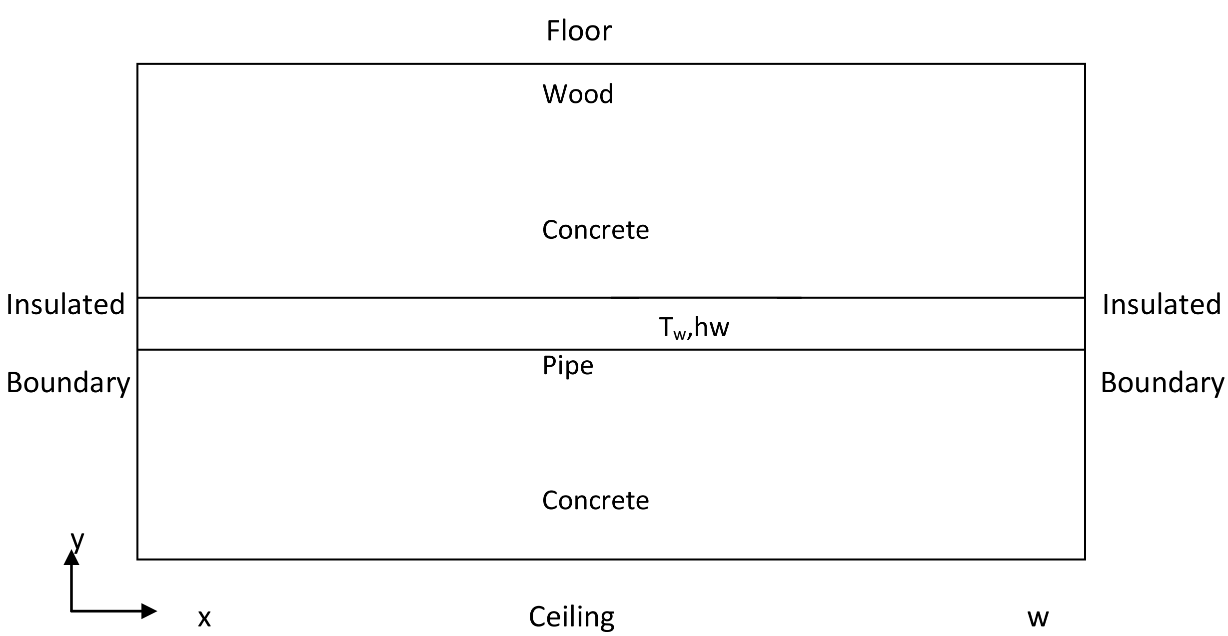


Figure 2.1 Cross Section of Insulated Concrete Slab

This differential equation was used to compute the spatial temperature distribution in the two dimensional slab model. The slab model is a 150 mm thick concrete slab covered with 20 mm of parquet flooring (oak wood). As depicted in Figure 2.1, the concrete slab contains a 20 mm pipe that carries hot or cold water used to heat or cool the slab as needed.

The solution of equation 2.2 requires boundary conditions; for the slab model the boundary conditions are as follows:

1. Convective surface condition at the floor surface:

$$y = l\,, \qquad k\frac{\partial T}{\partial y} = h_a[T_a - T(y,t)] \qquad (2.3)$$

2. Convective surface condition at the ceiling surface:

$$y = 0, \qquad k\frac{\partial T}{\partial y} = h_a[T_a - T(y,t)] \qquad (2.4)$$

3. Convective surface condition in the pipe:

$$y = r, \qquad k\frac{\partial T}{\partial y} = h_w[T_w - T(x,t)] \qquad (2.5)$$

4. Insulated boundary condition:

$$x = 0, \qquad \left.\frac{\partial y}{\partial x}\right|_{x=0} = 0, \qquad (2.6)$$

5. Insulated boundary condition:

$$x = w, \qquad \left.\frac{\partial y}{\partial x}\right|_{x=0} = 0 \qquad (2.7)$$

The solution of the differential equation with the above boundary conditions was approximated using numerical analysis.

$$\left.\frac{\partial^2 T}{\partial x^2}\right|_{m,n} = \frac{T_{m+1,n} + T_{m-1,n} - 2T_{m,n}}{\Delta x^2} \quad (2.8)$$

$$\left.\frac{\partial^2 T}{\partial y^2}\right|_{m,n} = \frac{T_{m+1,n} + T_{m-1,n} - 2T_{m,n}}{\Delta y^2} \quad (2.9)$$

To obtain the finite difference form, the central-difference form of Equations 2.8 and 2.9 were discretized in time using the integer p, as: t = p$\Delta$t.

$$\left.\frac{\partial T}{\partial t}\right|_{m,n} = \frac{T_{m,n}^{p+1} - T_{m,n}^{p}}{\Delta t} \quad (2.10)$$

Hence, the time derivative is in terms of the difference in temperatures at two points in time (p+1), new, and (p), previous, separated by the time interval $\Delta$t. Using the Explicit Method, the temperatures are evaluated at (p).

Substituting Equations 2.8, 2.9 and 2.10 into Equation 2.2 and evaluating the term on the right side at p gives:

$$\frac{1}{\propto}\frac{T_{m,n}^{p+1} + T_{m,n}^{p}}{\Delta t} = \frac{T_{m+1,n} + T_{m-1,n} - 2T_{m,n}}{\Delta x^2} + \frac{T_{m+1,n} + T_{m-1,n} - 2T_{m,n}}{\Delta y^2} \quad (2.11)$$

Then, solving for the new nodal temperature at $p + 1$ for $\Delta x = \Delta y$

$$T_{m,n}^{p+1} = Fo\left(T_{m+1,n}^{p} + T_{m-1,n}^{p} + T_{m,n+1}^{p} + T_{m,n-1}^{p}\right) + (1 - 4Fo)T_{m,n}^{p} \quad (2.12)$$

with the Fourier number:

$$Fo = \frac{\propto \Delta \boldsymbol{t}}{(\Delta \boldsymbol{x})^{\mathbf{2}}} \quad (2.13)$$

The equations are explicit since the unknown nodal temperatures at time p+1 are determined with known temperatures at time p for each time step. Initial conditions must be known so that the temperature of each node can be known at time t=0 when p=0.

Consequentially, the temperatures at t=Δt for p=1 are determined and the calculations proceed for t=2Δt for p=2 and so forth. Accuracy is increased by decreasing the size of the time step Δt and the size of Δx, at the expense of increasing calculation time.

Stability requires that the coefficient for $T_0^p \geq 0$, so the stability criterion for 2-D interior node is expressed as (Incropera et. al, 2007):

$$Fo \leq \frac{1}{4} \qquad (2.14).$$

The finite difference form for a nodal convective boundary condition is:

$$T_{m,n}^{p+1} = Fo\left(2T_{m-1,n}^{p} + T_{m,n+1}^{p} + T_{m,n-1}^{p} + 2BiT_{\infty}\right) + (1 - 4Fo - 2BiFo)T_{m,n}^{p} \qquad (2.15)$$

And the stability criterion for 2-D node is:

$$Fo(1 + Bi) \leq \frac{1}{2} \qquad (2.16).$$

where:

$$Bi = \frac{h\Delta x}{k} \qquad (2.17)$$

The space temperature was evaluated using the heat convection relation:

$$Q = A_{floor}h_a(T_s - T_{\infty}) \qquad (2.19)$$

where:

$h_a$ = heat convection coefficient

$A_{floor}$ = Area of the floor

$T_s$ = Floor surface temperature

$T_{\infty}$ = Space temperature

To find the behavior of the space temperature, the inside space of the building was defined as a closed system as illustrated in Figure 2.2. The energy balance for this system resulted in the following equation (2.20)

$$Q_{c.l} = Q_{floor} + Q_{ceiling} \qquad (2.20)$$

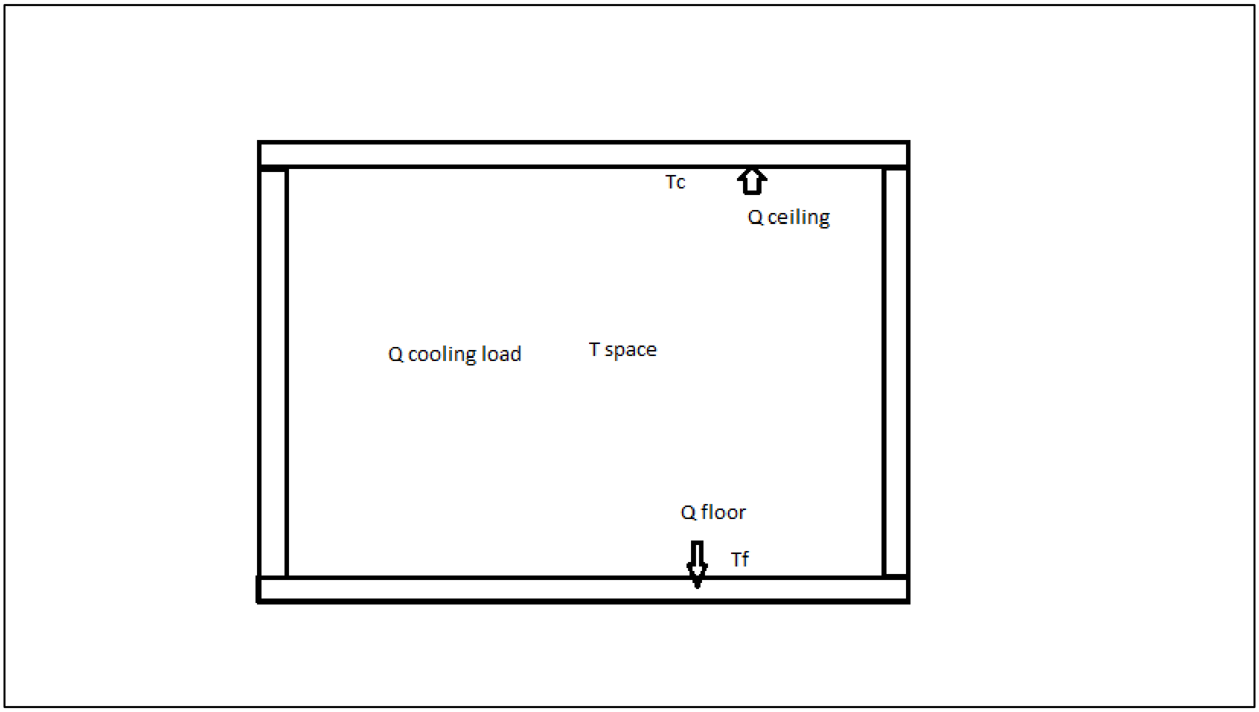


Figure 2.2 The Inside Space of an Office Building Defined as a Closed System

Substituting Equation 2.19 for $Q_{floor}$ and $Q_{ceiling}$ in Equation 2.20 and solving for $T_{space}$ as follows:

$$Q_{c.l} = A_{floor}h_a(T_s - T_\infty) + A_{floor}h_a(T_s - T_\infty)$$

$$A_{ceiling} = A_{floor}$$

$$T_{space} = T_\infty$$

$$T_\infty = \frac{Q_{c.l} + hA_{floor}(T_{ceiling} + T_{floor})}{2hA_{floor}}$$

where $T_{ceiling}$ *and* $T_{floor}$ values were generated from a simulation.

As the Finite Difference Method is not sufficient to solve complicated geometry problems, the Finite Element Method using ANSYS will be employed to solve the problem at hand.

## CHAPTER III

## FINITE ELEMENT ANALYSIS

The Finite Element Analysis (FEA) is a modern numerical method for solving engineering physics problems, such as structural analysis, heat transfer, and heat flow. In situations where ordinary differential equations cannot be solved in closed form, numerical methods, such as FEA, allow for the formulation of simultaneous algebraic equations yielding approximate values of the unknowns at distinct number of points in the continuum. It is from this process (division of a model into discrete units) that the name Finite Element Analysis is derived.

This process, known as discretization, is the heart of FEA. Discretization involves modeling an object by first dividing it into discrete units with interconnected nodal points (points common to two or more elements), boundary lines, or surfaces. These nodal points, or nodes, are then used to make a mesh. Equations are formulated for each element and then combined to represent the object as a whole. In FEA, heat transfer problems, such as those pertaining to this thesis, the nodal unknowns will be temperatures.

By its nature, Finite Element Analysis is well suited to automated computational analysis, with solid modeling both enhancing and simplifying mesh formation. In fact, though it has its roots in matrix methods, FEA was not able to be widely implemented until the advent of modern computing in the latter half of the twentieth century. There are numerous commercially available applications for performing FEA, with ANSYS being the one selected for this study.

ANSYS Mechanical, and the related APDL solver, was the platform used to perform FEA in this study. Continuous partial differential equations (the governing equations) were discretized into a system of linear algebraic equations that can be solved on a computer.

## Finite Element Method

In considering an isotropic body with temperature-dependent heat transfer, the equation of heat transfer has the following form

$$-\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)+Q = \rho c\frac{\partial T}{\partial t} \qquad 3.1$$

Where $q_X$, $q_Y$ and $q_Z$ are components of heat flux; $Q = Q(x, y, z, t)$ is the heat-generation rate per unit volume; ρ is material density; $c$ is heat capacity; $T$ is temperature and $t$ is time. The differential form of Fourier's law can be expressed as follows:

$$q_x = -k\frac{\partial T}{\partial x} \qquad 3.2$$

$$q_y = -k\frac{\partial T}{\partial y} \qquad 3.3$$

$$q_z = -k\frac{\partial T}{\partial z} \qquad 3.4$$

where $k$ is the thermal-conductivity coefficient. Substituting equations 3.2, 3.3 and 3.4 into equation 3.1 gives the following heat transfer equation (3.5):

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q=\rho c\frac{\partial T}{\partial t} \qquad 3.5$$

*Boundary Conditions*

It is assumed that the boundary conditions can be of the following types:

1. Specified temperature
   $T_s = T_1(x, y, z, t)$ on $S_1$ .

2. Specified heat flow
   $q_x n_x + q_y n_y + q_z n_z = -q_s$ on $S_2$ .

3. Convection boundary conditions
   $q_x n_x + q_y n_y + q_z n_z = h(T_s - T_e)$ on $S_3$ ,

4. Radiation
   $q_x n_x + q_y n_y + q_z n_z = \sigma \varepsilon T^4 - \alpha q_r$ on $S_4$,

where $h$ is the convection coefficient; $T_s$ is an unknown surface temperature; $T_e$ is a convective exchange temperature; σ is the Stefan–Boltzmann constant; ε is the surface emission coefficient; α is the surface absorption coefficient; and $q_r$ is the incident radiant heat flow per unit surface area. For transient problems, it is necessary to specify an initial temperature field for a body at the time $t$ = 0:

$$T(x, y, z, 0) = T_0(x, y, z).$$

# CHAPTER IV

# RESULTS AND DISCUSSION

## Establishment of the Model

To investigate the feasibility for concrete to be used as thermal mass in a single story office building, a model consisting of a concrete slab 203 mm thick by 75 mm width and 1 m deep with a 20mm diameter embedded pipe was used. As depicted in Figure 4.1, the model also has a 20 mm thick layer of insulation (wood). The material properties of each layer are listed in Table 1. In this study, floor temperature measurements were taken at the top surface of the wood, while ceiling temperatures were taken at the bottom of the model.

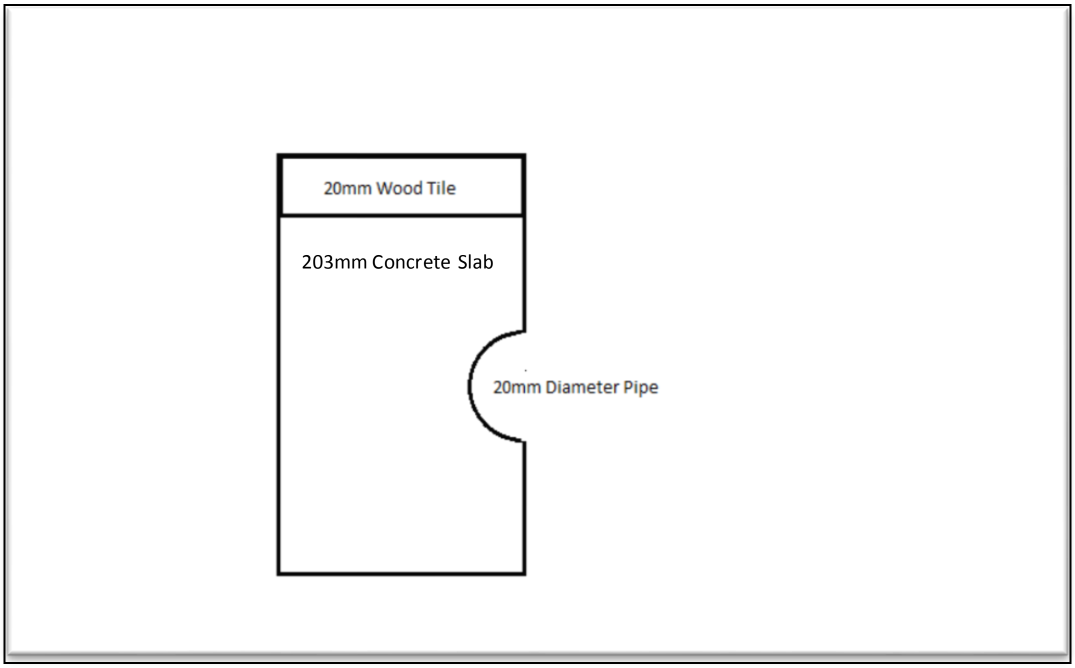


Figure 4.1 A Cross Section of the Slab

Table 1

Materials Properties of Slab Components

| | Density $[\frac{kg}{m^{\wedge}3}]$ | Thermal Conductivity $[\frac{1.4W}{m°C}]$ | Specific Heat $[\frac{J}{kg°C}]$ |
|---|---|---|---|
| **Concrete** | 2400 | 2.1 | 1008 |
| **Wood** | 2000 | 1.4 | 1008 |

Thermal Analysis and Results

*Steady State Analysis*

To conduct the thermal simulation on the model, the Finite Element Method was used to simulate the physical phenomenon. The initial and boundary conditions were defined as follows: the space temperature in the model was initially is set to 24° C. The floor and ceiling were defined with a convective boundary condition with an air temperature of 24°C and convective heat transfer coefficient of $10\ wm^{-1}k^{-1}$. The pipe conditions were allowed to be as follows: water temperature of 10°C and heat transfer coefficient of $3000\ wm^{-1}k^{-1}$.

In the first steady state heat transfer simulation, the temperature of the floor dropped from 24°C to 20°C and that of the ceiling dropped from 24°C to 11.119°C. The following figure (4.2) illustrates these variations in the model temperature of the model composite in space distribution. The difference in temperature in the floor and the ceiling resulted from the added layers of insulation and screen.

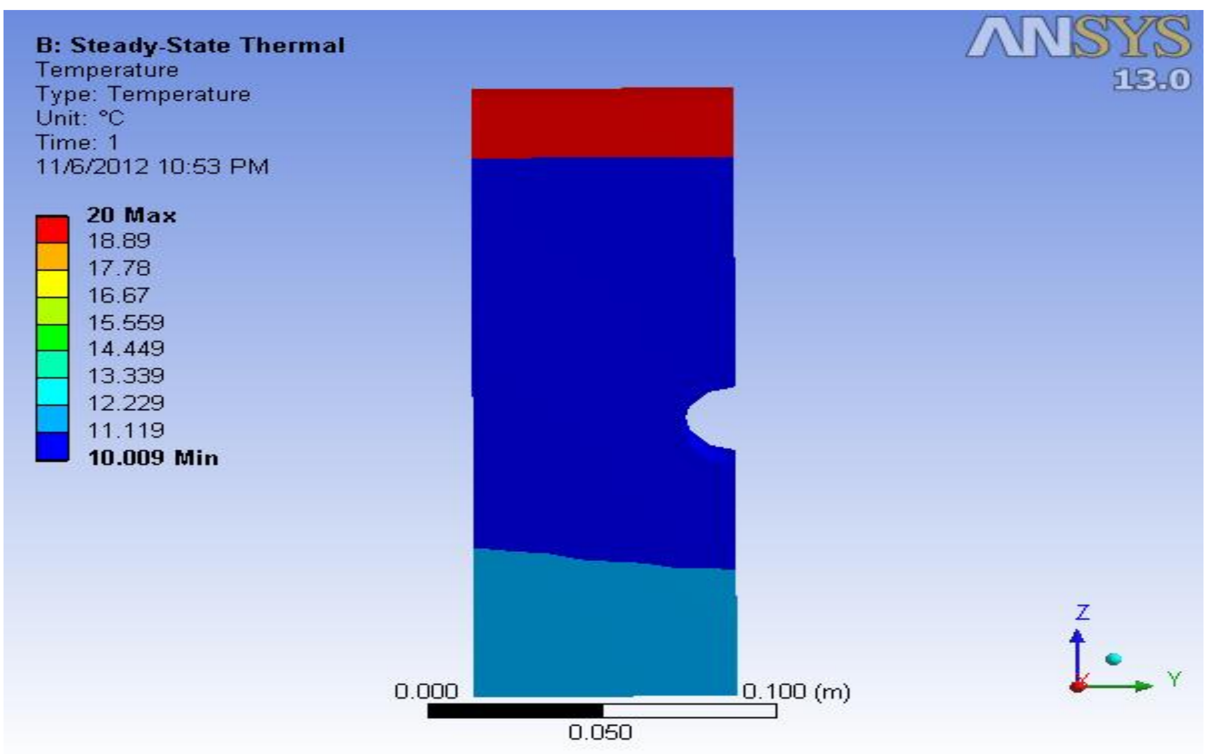


Figure 4.2 Steady State Special Distribution of Temperature

In addition, Figure 4.3 shows the heat flux distribution in the slab during the simulation. The maximum value of the heat flux 83.218 w/m^2 occurs at the bottom of the pipe surface. This is due to the material with lower thermal conductivity located at the top of the slab. This material acts as barrier and reduces the heat flow. Consequently, the minimum heat flux occurs at the floor surface while the ceiling has an average value of 46.232 w/m^2.

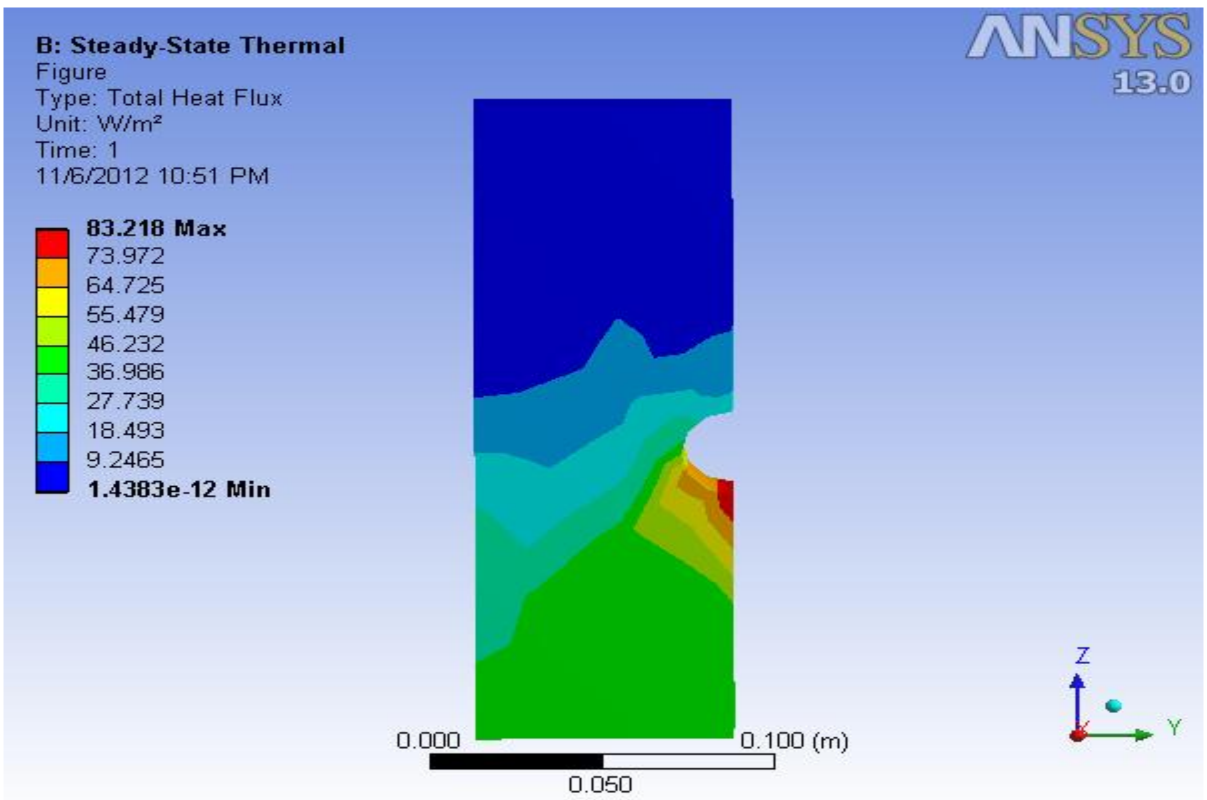


Figure 4.3 Steady State Spatial Distribution of Heat Flux

*Transient Analysis*

In the second part of this simulation, the initial conditions in the slab composite were matched to the temperature distribution of the previous simulation. The water in the pipe is turned off thus allowing it, at this point, be treated as an insulted boundary. The room air temperature is considered to be 18°C and the heat convection coefficient 10w/mk. In this particular case, the heat transfer occurs from the room to the slab composite. As demonstrated in Figure 4.4, 4.5, 4.6, and 4.7, the concrete mass has the ability to store heat energy; consequentially, it is feasible to use it as a thermal storage mass in a hydronic heating and cooling system.

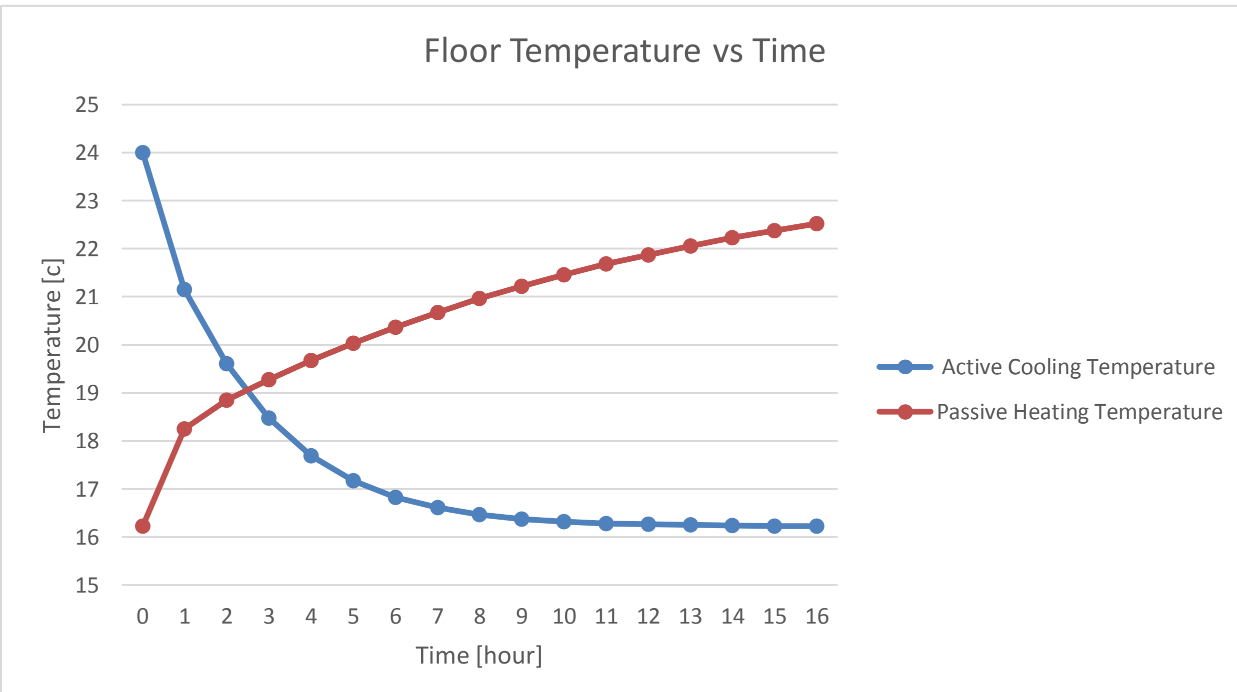


Figure 4.4 Active Cooling and Passive Heating of the Slab

Cooling the slab actively for 16 hours resulted in a temperature drop of the model floor from 24°C to 16.228°C. In the same period of time, the slab temperature increased passively from16.225°C to 22.518°C (Figure 4.4). Conversely, heating the slab actively for 16 hours resulted in an increase of the temperature of the model floor from 18°C to 23.792°C. In this same time period, the slab temperature decreased passively from 23.597°C to 20.965°C as shown in Figure 4.5.

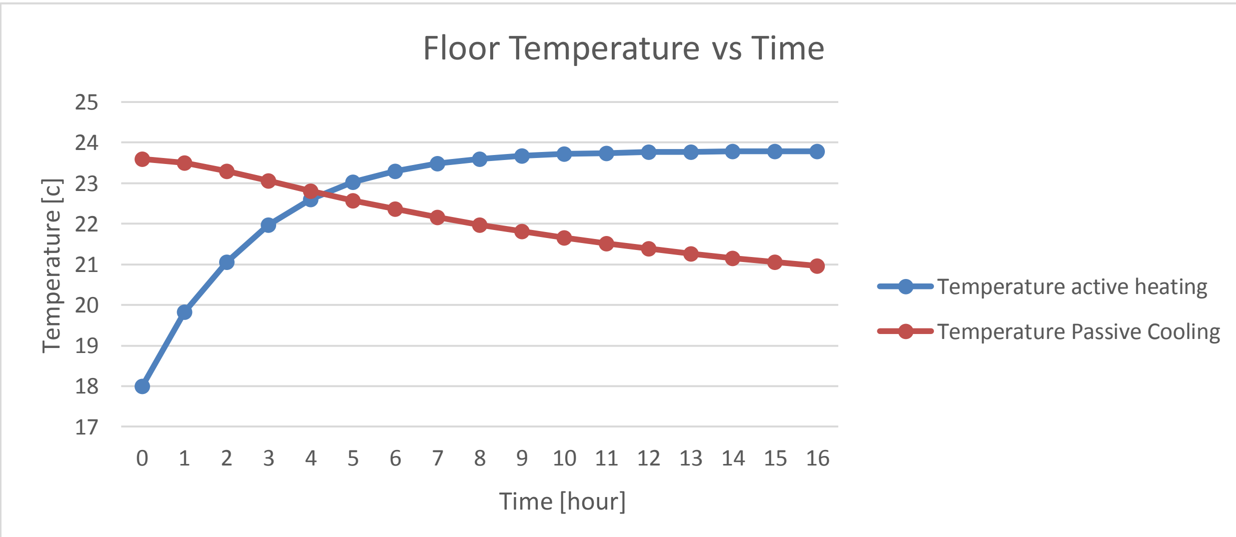


Figure 4.5 Active Heating and Passive Cooling of the Slab

As the 16 hour active cooling process starts, the heat flux of the slab decreases rapidly from 56.554 $\frac{W}{m^2.k}$ to 14.929$\frac{W}{m^2.k}$. As illustrated in Figure 4.6, it increases from 42.765$\frac{W}{m^2.k}$ to 67.97$\frac{W}{m^2.k}$ in the same time period. The time constant $\tau$, that is the length of time it takes for the heat to charge and discharge to and from the slab, is defined as the average time in hours per watt of heat. The average time constant for the active cooling process is 0.024 hr/w and that of passive heating process is 0.0396 hr/w. The time constant indicates that the slab passively releases the same amount of heat as what was charged; however, the heat discharge takes a longer period of time.

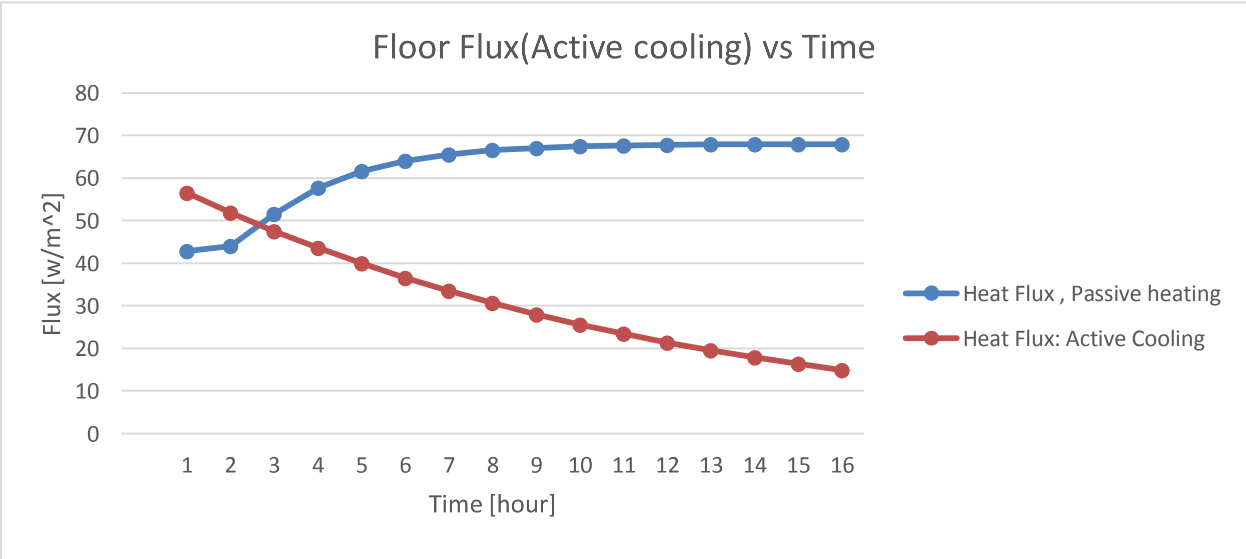


Figure 4.6 Heat Flux of the Slab during Active Cooling and Passive Heating

As the 16 hour active heating process begins, the heat flux of the slab increases rapidly from 18 $\frac{W}{m^2.k}$ to 27.972$\frac{W}{m^2.k}$. By contrast, during the 16 hour passive cooling period, the heat flux only decreases from 27.972$\frac{W}{m^2.k}$ to 20.992$\frac{W}{m^2.k}$ (Figure 4.7). The average time constant for the active heating process is 0.100 hr/w and that of the passive cooling process is 0.143 hr/w. Again, it is noted that the time constant indicates that a longer period of time is required for the slab to passively release the same amount of heat as was actively gained.

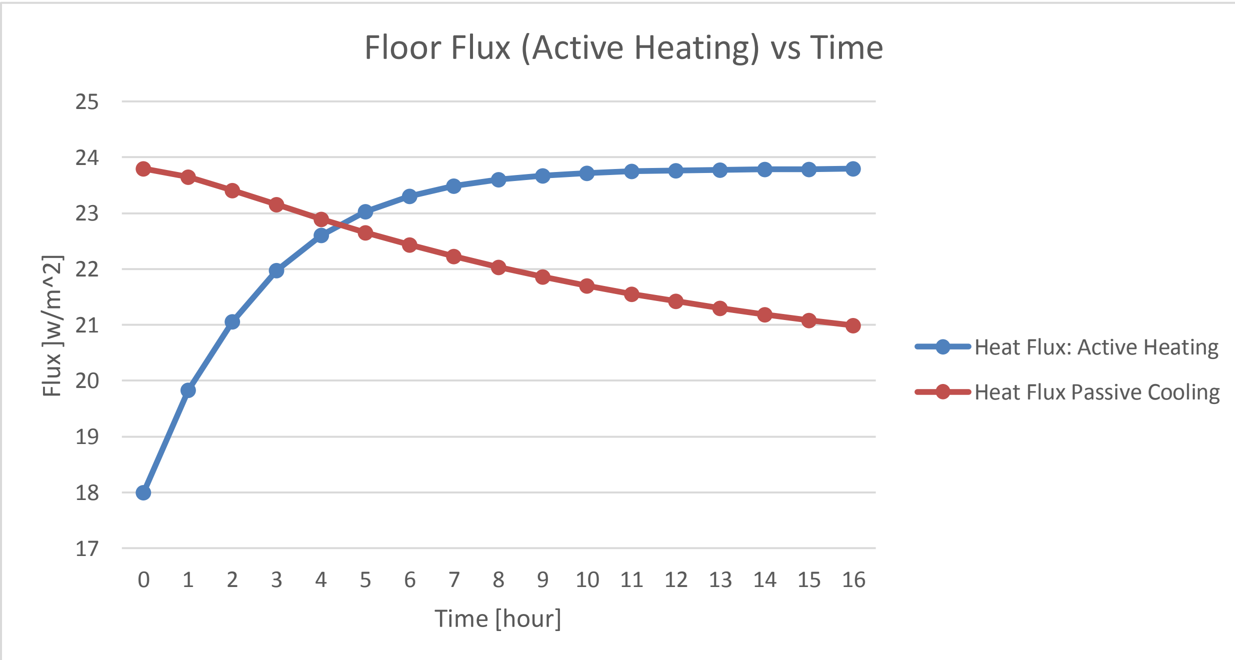


Figure 4.7    Heat Flux of the Slab During Active Heating and Passive Cooling

Determination of Slab and Pipe Dimensions

The specific dimensions for the analysis of the slab and pipe were based on the test space and boundary conditions set by Bjarne Olesen in his similar study of slab heating and cooling systems (2002).  Analyses were then performed on slabs with thicknesses ranging from 110mm to 190mm (Figure 4.8) and pipe diameters ranging from 10mm to 70mm.

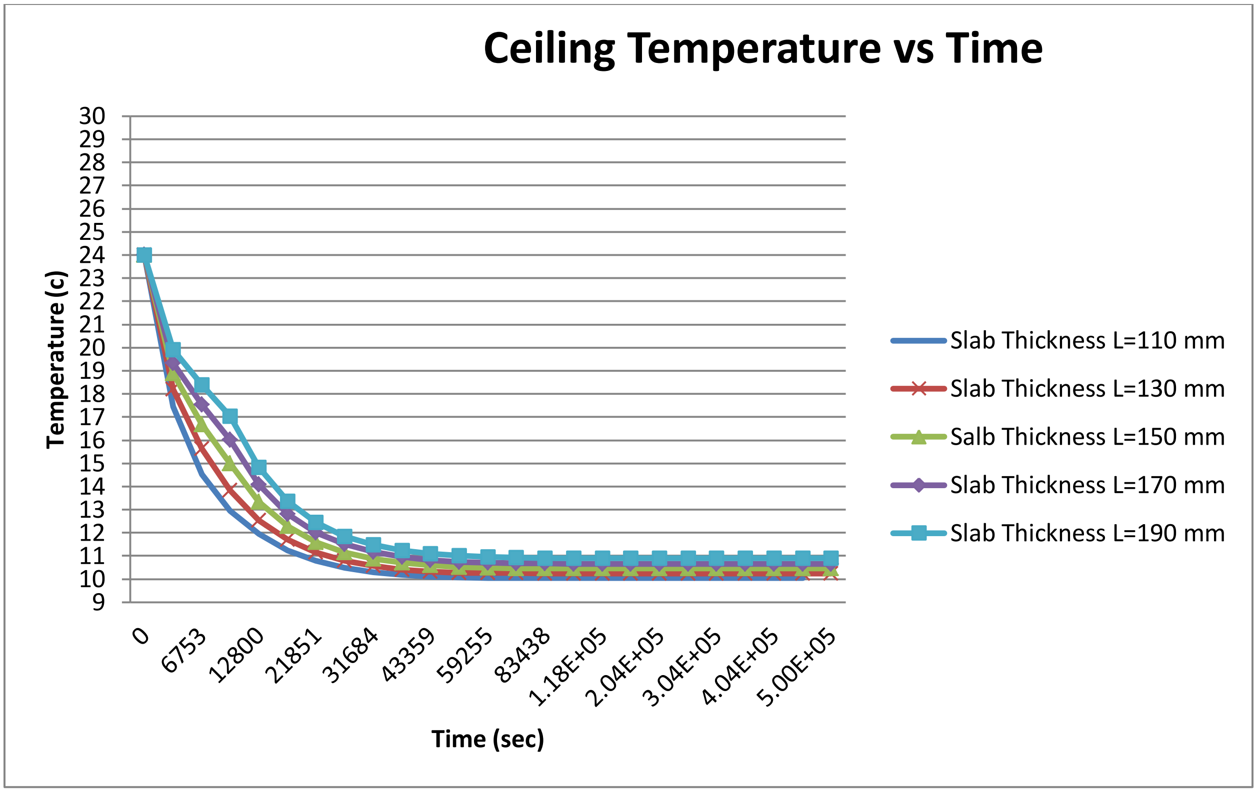


Figure 4.8 The Effects of Increasing Slab Thickness on Floor Temperature

To investigate the effect of the slab thickness L and the pipe diameter D on the energy storage capacity of the concrete mass, the simulation above was repeated, once with a constant slab thickness L and varying values for diameter D and again with a constant diameter D and differing values for slab thickness L. Figure 4.8, above, suggests that as the slab thickness increases, it takes a longer period of time for the floor temperature to reach the specified value. Figure 4.9, on the other hand, shows that as the pipe diameter increases, the floor temperature takes less time to reach the specified value. For example, the temperature of the ceiling dropped from 24°C to 14.98°C in 13333 seconds (3.70 hours) for a pipe of 10mm diameter and from 24°C to 14.98°C in 10000 second (2.77 hours) for a pipe of 30mm diameter.

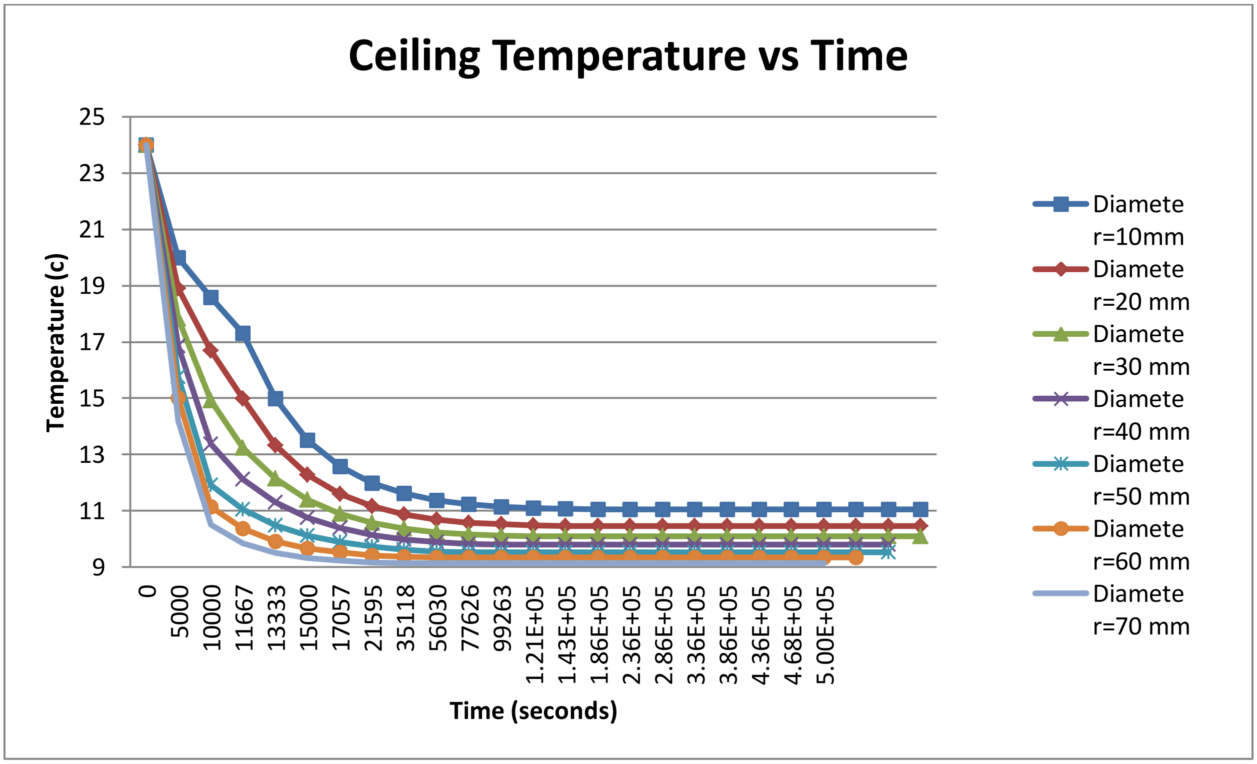


Figure 4.9 The Effects of Increasing Pipe Diameter on Floor Temperature

The more material that is in the slab, the greater the thermal storage. However, too large slab thickness introduces a negative effect in terms of weight and cost. Slab thickness most therefore be limited to those sizes generally used in commercial applications. Based on the above considerations, a slab thickness of 203.2mm was used.

The above trends also show that by allowing for a greater amount of material in the slab, limiting pipe diameter produces greater heat storage capability. Olesen, et al (2002) demonstrated that 20mm pipe diameter yielded suitable results. A pipe diameter of 20mm was chosen for this analysis as well.

Implementation of Hydronic Technique in a Hypothetical Example

To implement the thermal mass technique, the following model was used:

> A 70' x 70' office building located in Chattanooga, Tennessee was modeled. The building's 15 occupants perform office work between 8:00AM-6:00PM. The building is covered with a roof No. 9. The South and North facing walls are composed of insulated brick wall (Group B), each with a window area of 100 $ft^2$. The east and west facing walls are adjacent to the conditioned space. The height of the building is 10'and it has 2w/ft^2 of lighting; a machine attached to a 3 hp motor operates continuously. An infiltration of 0.3 ACH is assumed along with a ventilation requirement of 15 cfm/occupant. The peak cooling load occurs at 3:00 pm in July. (Dhamshala, 2011)

*Location and Implementation*

The city of Chattanooga is located in the southeastern United States and is characterized by mild weather. The following group of figures (4.10 and 4.11) illustrates the extremes of daily variation in this city. In these and all subsequent figures, the time recorded as 1 stands for 01:00, or 1:00 a.m., while 13 stands for 13:00, or 1:00 p.m., and so forth.

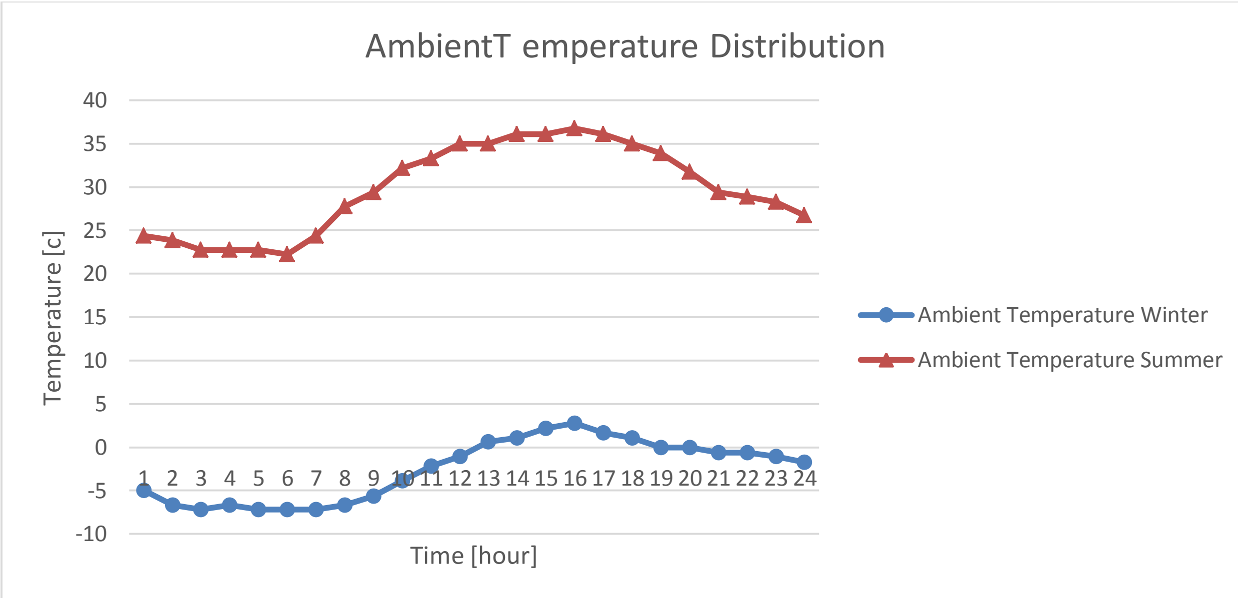


Figure 4.10 Daily Variations of Ambient Temperature in Chattanooga, TN

The variations of ambient temperature during summer and winter are shown in Figure 4.10, while Figure 4.11 illustrates the variation of the heating and cooling loads during summer and winter. The average ambient temperature in the summer is 27°C and the minimum and maximum summer temperatures are 21°C and 32°C, respectively. The average temperature in the winter is -1°C and the minimum and maximum winter temperatures are 5°C and 10°C, respectively.

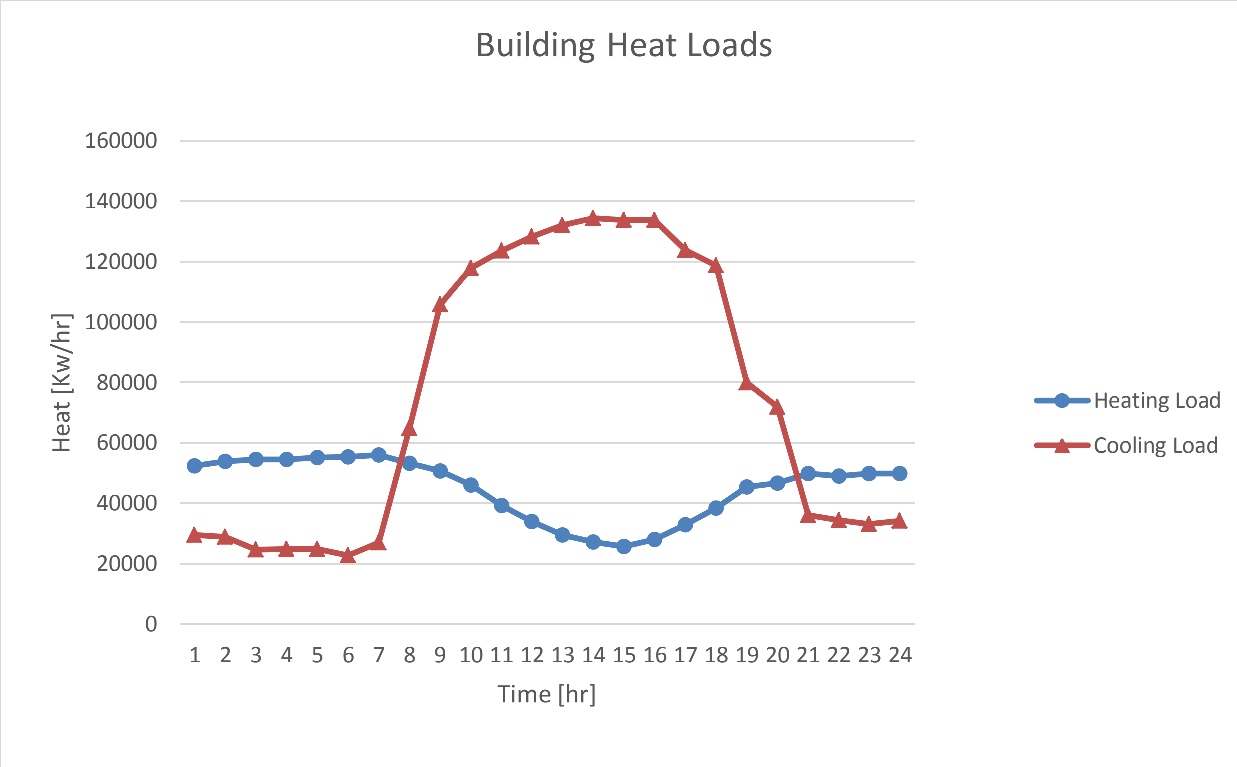


Figure 4.11 Daily Variations in Heating and Cooling Loads in Chattanooga, TN

Figure 11 shows the variation of the heating and cooling loads during summer and winter. In the winter, the required heat load increases from 52306 KW/hr to 55876 KW/hr between 1:00 and 7:00 and then decreases to 25690 KW/hr at 15:00. This decrease is due to the increase of the ambient temperature as well as the additional heat contributed by occupants, lights and equipment. The required heating load increases from 16:00 until 24:00 to reach a maximum value of 49729 KW/hr. On the contrary, the cooling load decreases from 29485 KW/hr to 27009 KW/hr between 1:00 and 7:00. It then increases to a maximum value of 134444 KW/hr at approximately 14:00 as a result of the heat added by occupants, lights and equipment. It decreases again to 34157 KW/hr by midnight

*Cooling*

The slab's heat removal capacity was calculated and simulated for different values for both the water pipe temperature and the heat convection coefficient. This was then plotted along with the building's cooling load against time as depicted in Figure 4.12. These simulations were done with two modes: radiation and no radiation. The general pattern of the slab capacity curves as follows. During the process of active cooling, the slab capacity starts increasing from a minimum value at 19:00 until it reaches a maximum value at 7:00. After 7:00, the slab capacity decreases again to reach the minimum value at 19:00. This is due to stopping active cooling, and the building normal operation.

Figure 4.12 is significant in that it is necessary in the design of the hybrid system. The area under each curve of the slab capacity curves represents the total heat that can be removed. The area under the heat extracted, on the other hand, represents the total amount of heat needing to be removed. In the hybrid system, an air conditioning unit is used primarily for ventilation, air quality control and as an auxiliary cooling mechanism during extreme weather conditions. The areas described above help in sizing the air conditioning unit. Since the heat convection coefficient depends on the velocity of the air flow, it can be used to optimize the blower fan thus directing the flow to the radiant surface. The data concerning pipe water temperature and heat extracted can be used to size and optimize the chiller.

After carefully comparing the slab heat capacity curves, the curve number 11 was found to meet the requirement. The choice was made mainly by matching the area under slab capacity curves to the heat extracted curve. The area under the heat extracted curve was calculated by numerical integration to be 341480W while the area under curve 11 was evaluated in similar manor and found to be 322310W. The differences in the value can be easily accommodated by a modest auxiliary air conditioning system. These two curve are shown in Figure 4.13.

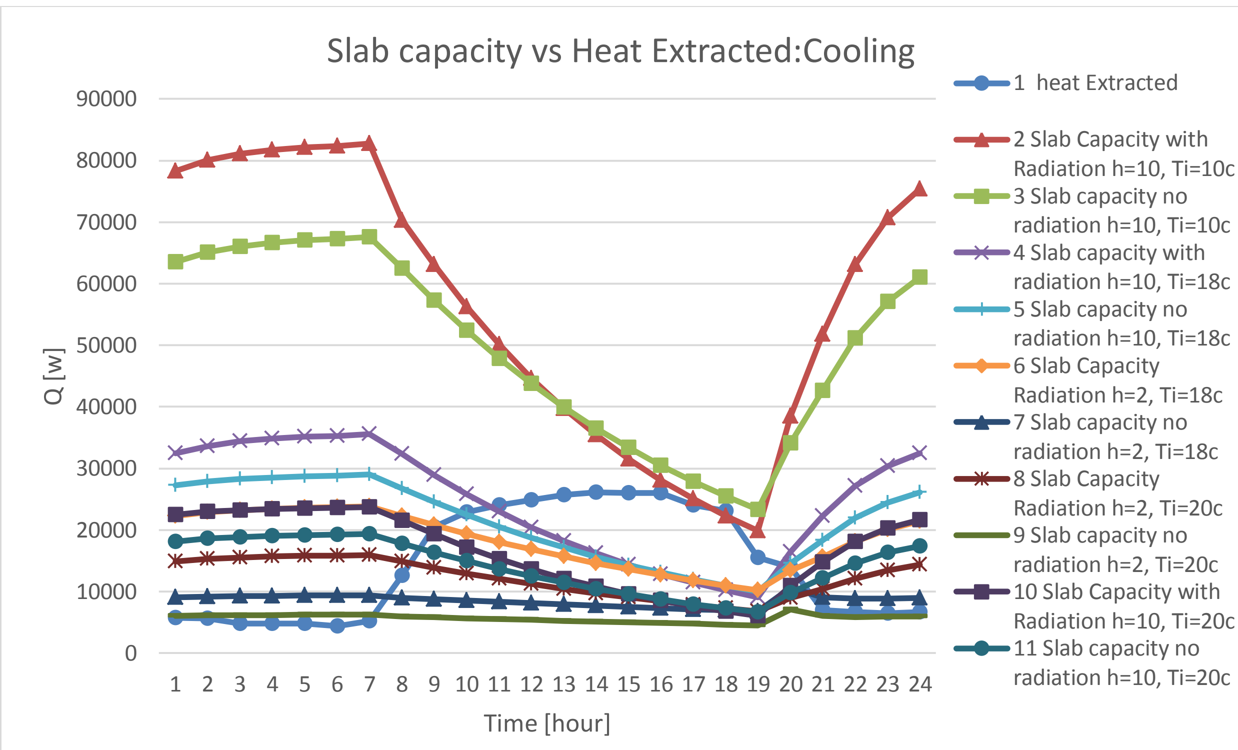


Figure 4.12 Slab capacity (with different values Ti and h) and Heat Extracted vs Time

As shown in Figure 4.13, the slab heat extraction capacity increases from 18145W to 19325W between 1:00 and 7:00 as a result of actively cooling the slab during this time.

After 7:00, the heat extraction capacity begins decreasing until it reaches 6664 W at 19:00. It then increases to 17439 at approximately 24:00. Between, 9:00 and about 8:30, the slab capacity is less than the heat extracted. The difference between the two curves during this time interval is 13932W, which can be accomodated easily by a small air conditioning unit.

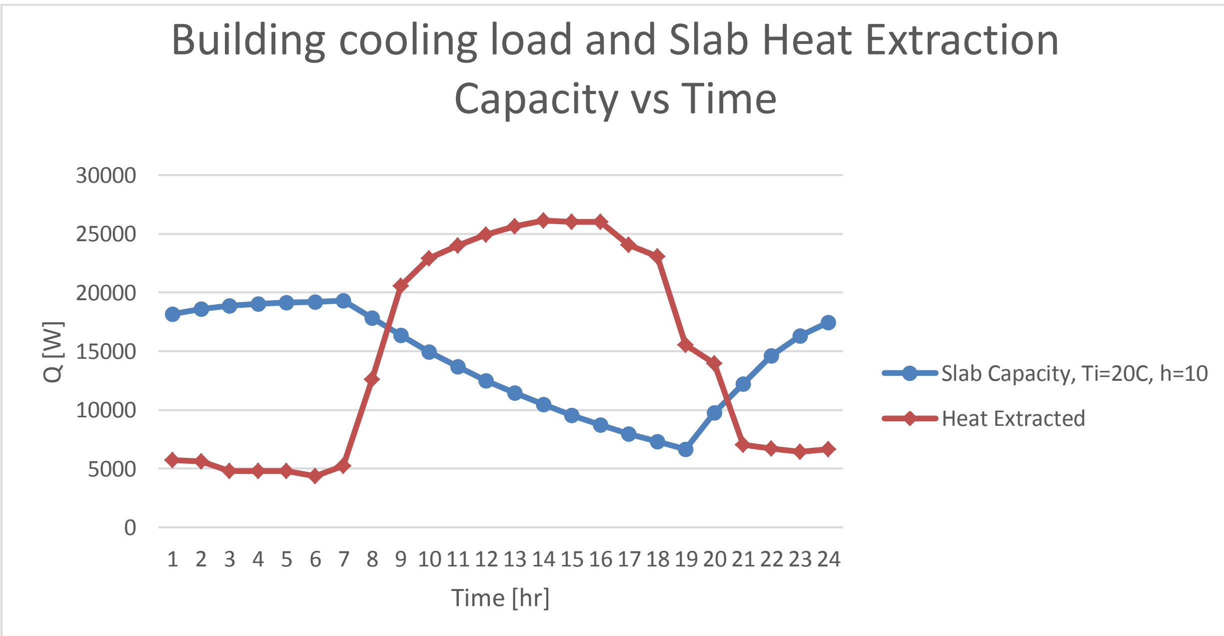


Figure 4.13 Simulation of the Building's Cooling Load and Slab Heat Extraction Capacity

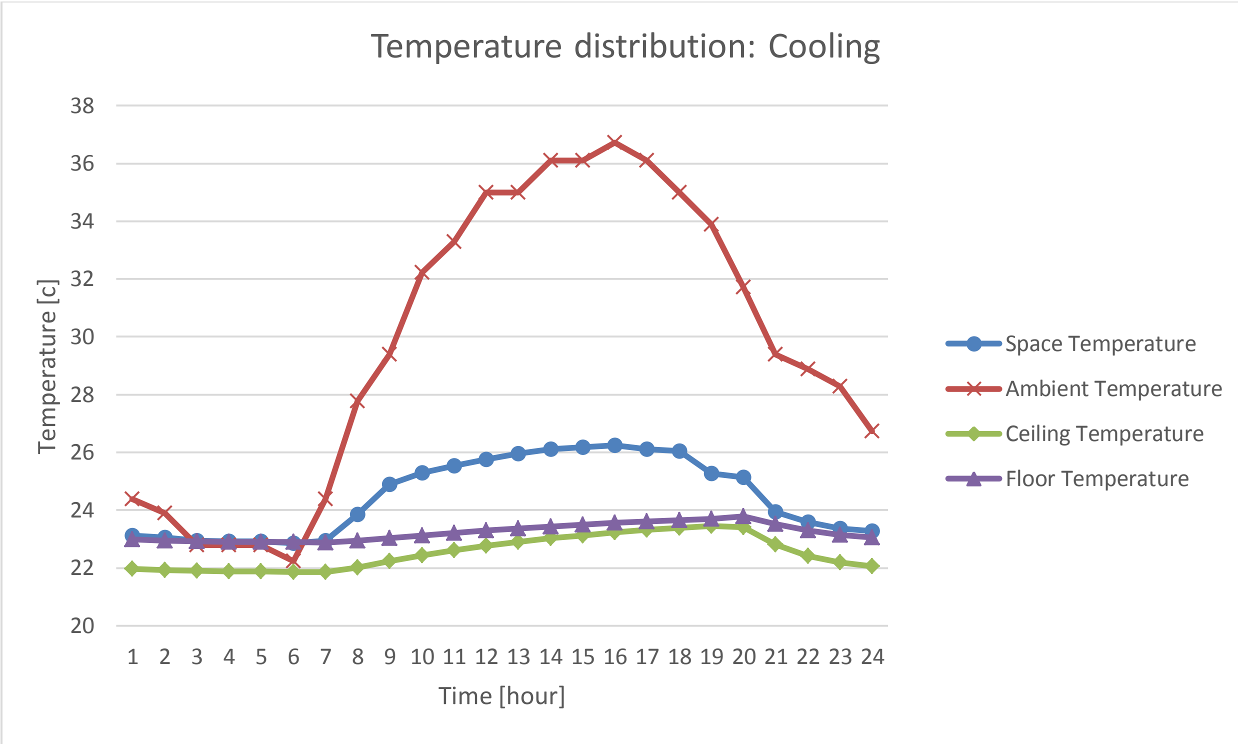


Figure 4.14 Temperature Distribution in an Office Building Using a Hydronic Cooling System

The above figure (4.14) shows the temperature distributions of the space (room) in addition to the ambient, ceiling and floor temperature distributions. The outside temperature distribution of July 1 for the metro area of Chattanooga, Tennessee is graphed as ambient temperature. The floor and the ceiling temperature begin to decrease as the process of active cooling starts at 20:00 and reach their minimum values at 7:00, at which point the active cooling process stops. After the building begins operation at 7:00, the cooling load once again increases. As previously discussed, this is due to the added heat load produced by occupants, lights, equipment, ventilation, and the rise of the outside temperature.

The space temperature follows the same pattern as the ambient, floor, and ceiling temperature because it is dependent on them; therefore, the temperature drops from 23.94°C to 22.88°C during the slab's active cooling period between 21:00 and 7:00. It increases afterward to reach 26.24°C at 16:00, then decreases slowly to 23.93°C at 21:00.

Additionally, Figure 4.14 shows that during the cooling season, the space temperature range from 24.88°C at 9:00 to 25.13°C at 20:00; that is, it stays within the range of human comfort.

*Heating*

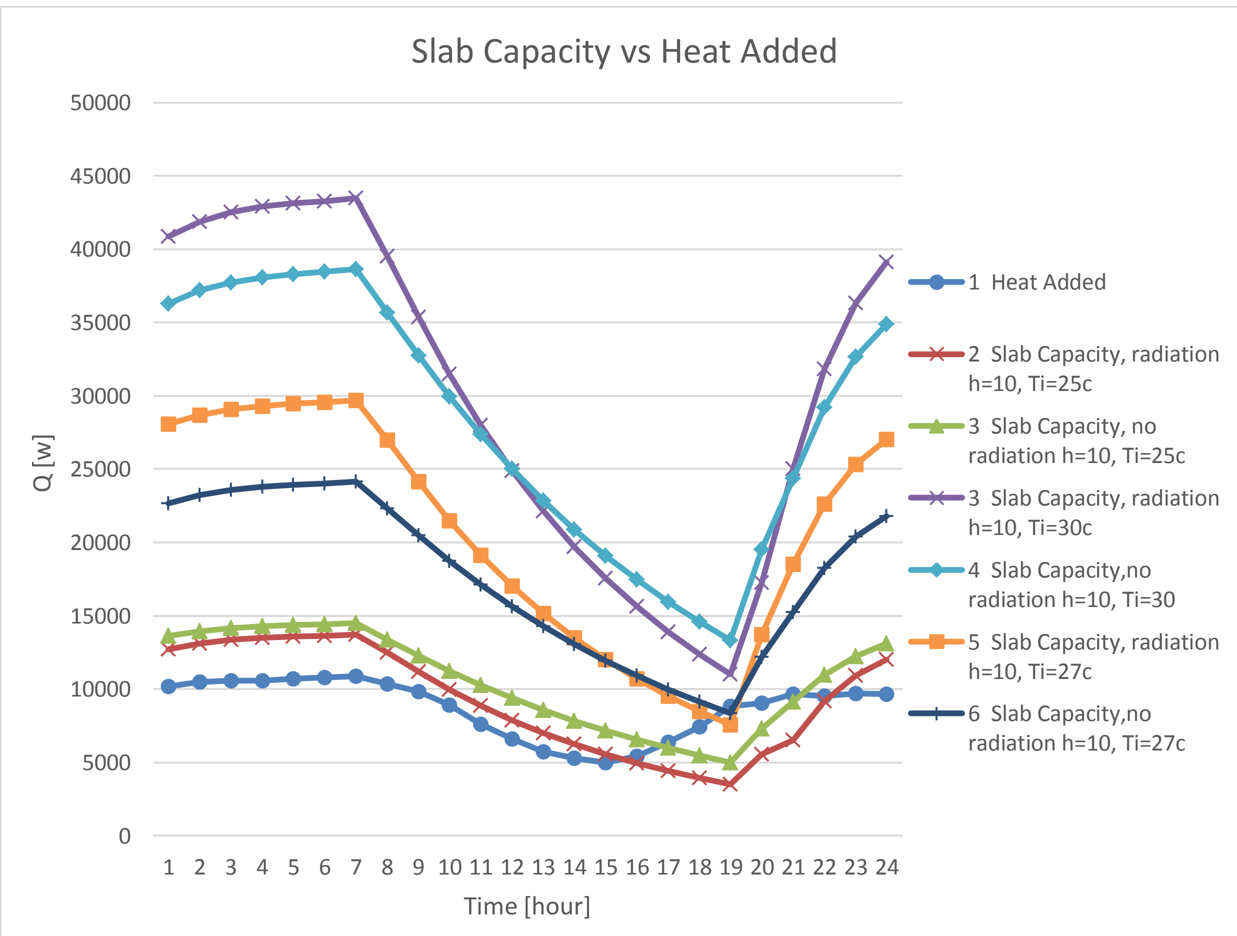


Figure 4.15 Simulation of Building's Heating Load and Slab's Heat Adding Capacity

The building heating load was calculated and simulated for different values for both the water pipe temperature and heat convection coefficient. This was then plotted along with the building's heat load against time as depicted in Figure 4.15, above. The general pattern of the slab capacity curves is as follows. During the period of active heating, the slab capacity begins to increase from a minimum value at 19:00 until it reaches a maximum value at 7:00. After 7:00, the slab capacity decreases to again reach the minimum value at 19:00. The matching curve for the slab capacity to the heat added curve is curve number 3 and follows the same reasoning as the previous discussion concerning the heat extracted. The matching slab capacity for heat added and the heat needed curves are shown in Figure 4.16.

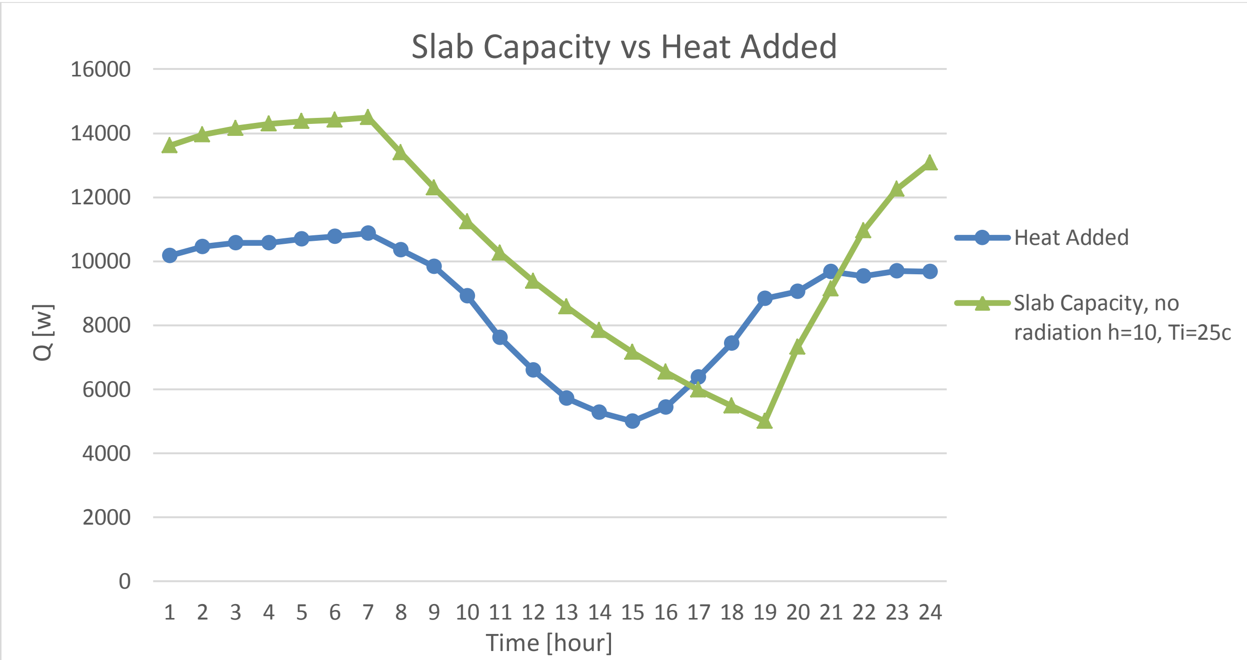


Figure 4.16. Slab Capacity vs Heat Added

Figure 4.17 illustrates the temperature distributions of the space (room), ambient, ceiling and floor temperatures, where ambient temperature is defined as the outside temperature distribution of January 1 for the metro area of Chattanooga, Tennessee. In the seasons during which heating is necessary, the ambient temperature decreases slowly from -5°C to -7.2°C between 1:00 and 7:00. It then increases to 2.8°C 16:00 at which point it begins to drops to -1.7°C at midnight. The floor and the ceiling temperatures increase as the process of active heating take place at 1:00, reaching their maximum values of 23.31°C and 23.89°C respectively at 7:00 when the active heating process is then terminated. After 7:00, both the floor and the ceiling temperature decrease slowly to 22.89°C and 22.99°C respectively. At 19:00, these temperature then increases again to 23.28°C and 23.86°C respectively. As previously observed, the space temperature follows the same pattern as the floor and ceiling temperatures because it depend on them—the temperature rises from 23.79°C to 24.84°C during the slab's active heating period between 19:00 and 7:00. It then drops back to 23.64°C at 15:00.

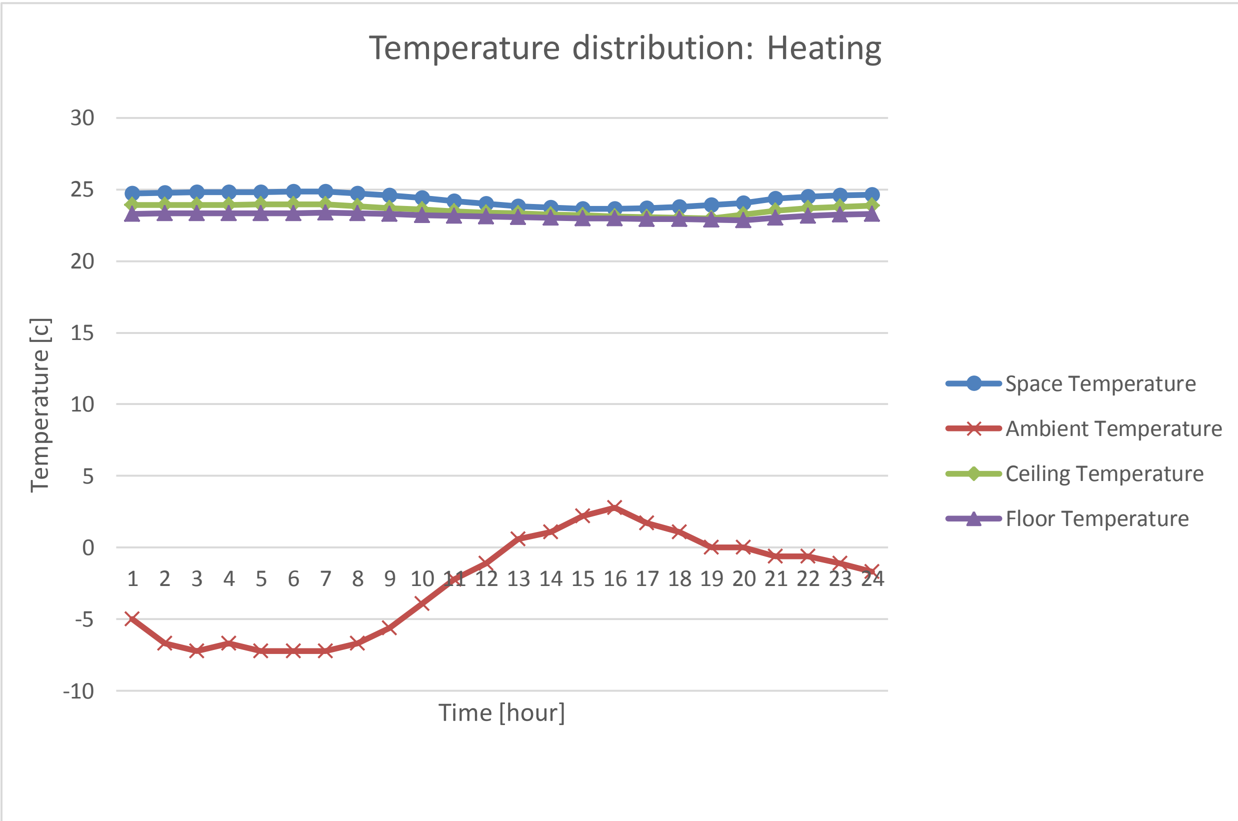


Figure 4.17 Temperature Distribution in an Office Building Using a Hydronic Heating System

Furthermore, Figure 4.17 shows that during the heating season, the space temperature ranges from 23.64°C at 15:00 to 24.84°C at 7:00; that is, it stays within the range of human comfort.

## Economic Merit

The space temperature results presented in Figures 4.15 and 4.17 above show that the technique of using a slab (embedded with a pipe) for thermal storage is adequate to keep the conditioned space comfortable during most of the building operation period. One exception is the period between 13:00 and 18:00 for the cooling season where the space temperature ranges from 25.9°C and 26.05°C. During this time, the auxiliary air conditioning system can provide the necessary cooling. To show the economic benefits of using the slab technique, the operational costs of the embedded slab technique versus a conventional air conditioning system were compared.

Table 4.2

Chiller Efficiency Analysis Data

| **Chiller Efficincy vs Chiller Evaperator Leaving Temperature, 70ton unit** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **ELWT** | **65F** | **70F** | **75F** | **85F** | **95F** | **105F** | **115F** |
| **40** | 5.417 | 4.929 | 4.500 | 3.761 | 3.212 | 2.729 | 2.304 |
| **42** | 5.469 | 4.993 | 4.571 | 3.844 | 3.289 | 2.800 | 2.370 |
| **44** | 5.499 | 5.043 | 4.635 | 3.926 | 3.369 | 2.870 | 2.432 |
| **46** | 5.578 | 5.126 | 4.718 | 4.005 | 3.448 | 2.938 | 2.499 |
| **48** | 5.630 | 5.188 | 4.788 | 4.088 | 3.520 | 3.005 | 2.565 |
| **50** | 5.641 | 5.220 | 4.836 | 4.167 | 3.590 | 3.071 | 2.632 |
| **52** | 5.695 | 5.285 | 4.904 | 4.241 | 3.664 | 3.135 | 2.696 |
| **54** | 5.734 | 5.335 | 4.962 | 4.315 | 3.734 | 3.198 | 2.762 |
| **56** | 5.770 | 5.382 | 5.018 | 4.386 | 3.802 | 3.259 | 2.827 |
| **58** | 5.805 | 5.428 | 5.073 | 4.457 | 3.868 | 3.319 | 2.893 |
| **60** | 5.839 | 5.472 | 5.125 | 4.525 | 3.933 | 3.378 | 2.958 |
| **62** | 5.870 | 5.514 | 5.175 | 4.592 | 3.997 | 3.436 | 3.024 |
| **64** | 5.901 | 5.555 | 5.224 | 4.657 | 4.060 | 3.492 | 3.089 |
| **66** | 5.929 | 5.594 | 5.270 | 4.721 | 4.121 | 3.548 | 3.155 |
| **68** | 5.957 | 5.631 | 5.316 | 4.784 | 4.181 | 3.602 | 3.220 |
| **70** | 5.984 | 5.667 | 5.359 | 4.845 | 4.240 | 3.655 | 3.286 |
| **72** | 6.009 | 5.702 | 5.402 | 4.905 | 4.297 | 3.708 | 3.351 |

In analyzing the chiller experimental data given by Trane Inc., a unit size 70 tons was considered. Data points were collected for the water temperature leaving the evaporator (chiller operating temperature), air temperature entering condenser (set room temperature), load output in tons and power required. The coefficient of performance was calculated for these data points and presented in Table 4.2. Figure 4.18 exhibits the behavior of these data. The figure (4.18) suggests that for each specific condenser air temperature curve modeled, the coefficient of performance of the chiller increases as the temperature of the water leaving the evaporator increases. In addition, the coefficient of performance increases as the temperature of the water leaving the condenser decreases. It appears from this analysis, that decreasing the gap between the water temperature leaving the evaporator and the air temperature entering the condenser increases the coefficient of performance.

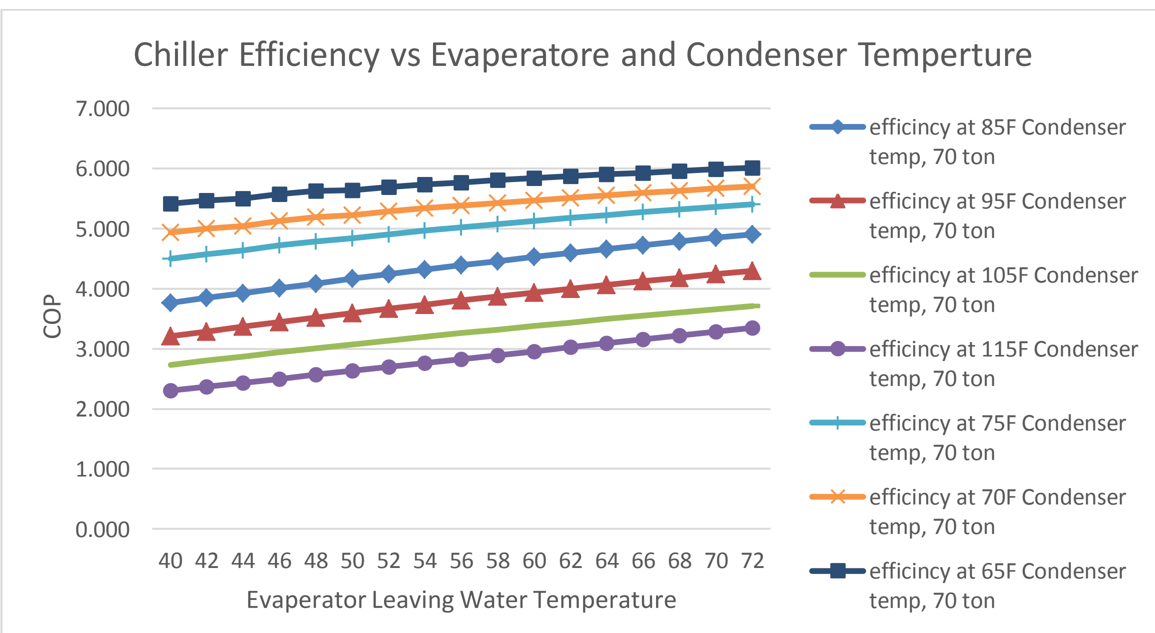


Figure 4.18 Chiller Efficiency Analysis Data (using data from Table 4.2)

The coefficient of performance (COP) is defined as the heat obtained per work input. A typical air conditioning system of 70 ton capacity operates with a COP of 3.289 as demonstrated by the highlighted cells (Table 4.2). In comparison, a chiller with 70 tons capacity operates on a typical COP of 5.359. This analysis showed that using a chiller offers about 62% cost savings over using the same technique with a conventional air conditioning system.

In the hypothetical building data, cooling and heating using a conventional air conditioning system ($3595 AC plus half of the demand costs) represent about 38% of the total utility costs ($11135). On the contrary, the slab technique using only a chiller and small air conditioning unit represent only 22.58% of the total utility costs. Demand is not included as the system is actively run during off peak hours. Therefore, the slab technique hybrid system offered an overall cost savings of 14.86% over a conventional system. A breakdown of the utility costs in the model building, as derived the data in Appendix 1, is presented in Table 4.3.

Table 4.3

Conventional Systems Costs in a Hypothetical Building

| **Building utility cost breakdown** | **Cost (in USD)** |
|---|---:|
| Air conditioning | 3495 |
| Equipment | 1518 |
| Auxiliary | 694 |
| Lights | 3014 |
| Demand | 1563 |
| Water heater | 58 |
| Telecomunication | 10338 |
| Heat | 797 |
| Total | 11135 |

# CHAPTER V

# CONCLUSION

## Cost Savings

The objective of this work was to investigate the feasibility of reducing the energy consumption in buildings by means of using the thermal mass of the building. Pipes for transporting cool or hot water are embedded in a concrete slab beneath the surface flooring. In what is called the hydronic system, hot or cold water runs through these pipes to store energy in the slab during night time when the energy costs of electrical power are significantly lower than during the day. The Finite Element Method was used in ANSYS to model a concrete slab with a pipe embedded in it. This slab technique was then implemented in a hypothetical building located in metropolitan Chattanooga, Tennessee, USA.

The results of the simulations show that the technique helped to reduce the cost of heating and cooling the building by 14.8%. As such, the cost savings are particularly high in areas where the charge for electricity is based on on-peak usage and off-peak usage. For example, the largest power company providing service in Atlanta, Georgia Power has costs savings of more than 50% during off-peak times (14:00-19:00), while the Tennessee Valley Authority, currently largest power company in the United States, is moving toward a peak hour surcharge for power consumption during the hours of noon to 20:00 (Connolly, 2010). Using the method described in this paper, active cooling of the slab only occurs during off peak hours. This method results in vastly improved operational costs over a conventional system which requires operation during both on-peak and off-peak times.

Further Study

Further study would likely consider the interior walls and the building envelope as means of thermal storage instead of the floor and ceiling alone.   Other considerations to be taken into account include the minimum slab thickness and pipe diameters necessary to produce optimum results.

Although implementing a hydronic system obviously has associated costs, it is important to note that this expenditure can be recouped elsewhere.   The costs savings of avoiding the instillation of a large air duct system versus small one are gained immediately. Additional savings can be explored by designing the embedded hydronic pipe as a foundation for a sprinkler system, thus rendering a separate fire protection system unnecessary.

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APPENDIX A

TABLER DATA

CHATTANOOGA TN 35 2 85 12 75
Time 12:55:52 PM Date: 11/30/2012

**(TABLER)Transient Analysis of Building Loads and Energy Requirements Zone:1**

| Envelop: | Roof | East Wall | South Wall | West Wall | North Wall | Floor | NE Wall | SE Wall | SW Wall | NW Wall |
|---|---|---|---|---|---|---|---|---|---|---|
| *Area(ft^2):* | *4900* | *700* | *500* | *700* | *500* | *4900* | *0* | *0* | *0* | *0* |
| *Glass Area (ft^2):* | *0* | *0* | *200* | *0* | *200* | *0* | *0* | *0* | *0* | *0* |
| *U-Factor(Btu/hr.ft^2.F):* | *0.036* | *0.038* | *0.038* | *0.038* | *0.038* | *0.04* | | | | |
| *Type:* | *17* | *31* | *31* | *31* | *31* | *6* | | | | |

*No of Occupants (day) = 10 (night) = 0 (holidays) = 0 Renw System:1 Mode:1 Life(yrs): Util P.Fac:2 Cap Cost:5 Payback =*
*Equip Elec Load, kW (day) = 5 (night) = 0 (holidays) = 0 No hrs/yr: Heat Eqpmt on: 0 Cool Eqpmt on: 0 Eqpmt Off: 0*
*Elec. Lights,W/ft^2 = 2 (night) = 0.01 (holidays) = 0.01 DCV System:Off Zc = Energy Recovery System: Off Sen.Eff: 0.85 Lat.Eff: 0.85*
*Infiltration,fraction of ACH = 0.3 Ventilation,cfm/person = 15 Hot Water Cons,gal/person/day = 2 U- of Glass(Btu/hr.ft^2.F) = 0.8*
*S.C of Glass = 0.85 Elec Power Cost,cents/kWh = 12 Gas Fuel Cost, cents/therm = 90 Economiser: Off Elec kW limit: 10 kW cost:10*
*Wint:Therm set = 72 F N. Setback = 72 F Throtl Range = F :Sum: Thrm set = 76 F N.Setback = 76 F Throtl Range = F*

**Pk H/lat.Load,tons = -4.47/1.1 in Month = 12 on Day = 20 at hr = 7 : Peak C/maxll, tons = 10.22/1.7 in month = 6 on Day = 28 at hr = 16**

**Approx Recommended Cap of Heating Eqpmt, tons = 7 : Approx Recommended Cap of Cooling Eqpmnt, tons = 12**

| On the Peak Heating Day : | | | | | | On the Peak Cooling Day | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time hr | A.Temp (deg F) | S.Load (Btu/hr) | H.Added (Btu/hr) | S.Flux (W/m^2) | S.Temp (deg F) | Time hr | A.Temp (deg F) | S.Load (Btu/hr) | Heat Extr (Btu/hr) | S.Temp (deg F) | S.Flux (W/m^2) |
| 1 | 23 | -50767 | -49579.6 | 0 | 72.2 | 1 | 75.9 | 33741 | 27948 | 75.1 | 0 |
| 2 | 19.94 | -52215 | -51006.9 | 0 | 72.2 | 2 | 75 | 32595 | 27399 | 75.1 | 0 |
| 3 | 19.04 | -52733 | -51584.3 | 0 | 72.2 | 3 | 73 | 28592 | 23336 | 75.2 | 0 |
| 4 | 19.94 | -52665 | -51564.4 | 0 | 72.2 | 4 | 73 | 27791 | 23490 | 75.2 | 0 |
| 5 | 19.04 | -53109 | -52125 | 0 | 72.2 | 5 | 73 | 26994 | 23484 | 75.2 | 0 |
| 6 | 19.04 | -53344 | -52513 | 0 | 72.2 | 6 | 72 | 24487 | 21387 | 75.2 | 0 |
| 7 | 19.04 | -53601 | -52963.4 | 0 | 72.2 | 7 | 75.9 | 27784 | 25601 | 75.1 | 0 |
| 8 | 19.94 | -51244 | -50438.7 | 0 | 72.2 | 8 | 82 | 59095 | 61493 | 74.6 | 0 |
| 9 | 21.92 | -49233 | -47951.2 | 0 | 72.2 | 9 | 84.9 | 93595 | 100231 | 74.1 | 0 |
| 10 | 24.98 | -45772 | -43481.7 | 0 | 72.1 | 10 | 90 | 104603 | 111714 | 73.9 | 0 |
| 11 | 28.04 | -40132 | -37103.6 | 0 | 72 | 11 | 91.9 | 110586 | 117038 | 73.9 | 0 |
| 12 | 30.02 | -35577 | -32202.5 | 0 | 71.9 | 12 | 95 | 114923 | 121471 | 73.8 | 0 |
| 13 | 33.08 | -31176 | -27872.9 | 0 | 71.9 | 13 | 95 | 118967 | 125092 | 73.8 | 0 |
| 14 | 33.98 | -29313 | -25751.3 | 0 | 71.9 | 14 | 97 | 121328 | 127436 | 73.7 | 0 |
| 15 | 35.96 | -28324 | -24351.2 | 0 | 71.8 | 15 | 97 | 121774 | 126794 | 73.7 | 0 |
| 16 | 37.04 | -29574 | -26518.4 | 0 | 71.9 | 16 | 98.1 | 122673 | 126785 | 73.7 | 0 |
| 17 | 35.06 | -33778 | -31103.3 | 0 | 71.9 | 17 | 97 | 115210 | 117267 | 73.9 | 0 |
| 18 | 33.98 | -37902 | -36287 | 0 | 72 | 18 | 95 | 110894 | 112504 | 73.9 | 0 |
| 19 | 32 | -43830 | -43049.3 | 0 | 72.1 | 19 | 93 | 79485 | 75741 | 74.4 | 0 |
| 20 | 32 | -44980 | -44119.3 | 0 | 72.1 | 20 | 89.1 | 72553 | 68066 | 74.6 | 0 |
| 21 | 30.92 | -47616 | -47124.2 | 0 | 72.2 | 21 | 84.9 | 42026 | 34165 | 75 | 0 |
| 22 | 30.92 | -47687 | -46438.1 | 0 | 72.1 | 22 | 84 | 39753 | 32622 | 75 | 0 |
| 23 | 30.02 | -48048 | -47277.6 | 0 | 72.2 | 23 | 82.9 | 38192 | 31372 | 75.1 | 0 |
| 24 | 28.94 | -48535 | -47136.5 | 0 | 72.2 | 24 | 80.1 | 37804 | 32377 | 75.1 | 0 |

**Utility Cost Analysis**

| | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec | t.year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ac: | 0 | 0 | 0 | 231 | 453 | 634 | 715 | 680 | 498 | 284 | 0 | 0 | 3495 |
| eqp: | 126 | 120 | 132 | 126 | 132 | 126 | 126 | 138 | 114 | 138 | 126 | 114 | 1518 |
| aux: | 69 | 58 | 59 | 53 | 53 | 58 | 63 | 61 | 45 | 53 | 54 | 68 | 694 |
| lit: | 250 | 238 | 262 | 250 | 262 | 250 | 250 | 274 | 227 | 274 | 250 | 227 | 3014 |
| edmd: | 75 | 75 | 75 | 165 | 166 | 178 | 177 | 173 | 167 | 162 | 75 | 75 | 1563 |
| wat: | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 58 |
| telc: | 526 | 497 | 533 | 831 | 1070 | 1249 | 1335 | 1330 | 1054 | 915 | 510 | 488 | 10338 |
| heat: | 169 | 133 | 96 | 54 | 15 | 0 | 0 | 0 | 4 | 54 | 97 | 175 | 797 |
| RevRn: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| tuty: | 695 | 630 | 629 | 885 | 1085 | 1249 | 1335 | 1330 | 1058 | 969 | 607 | 663 | 11135 |

Pk kW Dem: 27.82 kWh. Conp/yr: 77799 kWh Cost/yr,$: 8776 therms/yr: 0 GasCost,$: 0 E.D.Cost,$/yr: 1563

\# Solar Collectors = 50 Diam of Storg Tank(m) = 1.5 Cap C. S. Tank($) = Cap C. Sol Coll($) = 1500

Ast= 17.68 Vst = 5.3 Mcp = 21427.88 # hrs of highTemp in S.Tank = 0 # hrs of heating = 0 # hrs of cooling = 0 # hrs of auxheat= 0

# APPENDIX B

# ANSYS GENERATED DATA

Data used to calculate T space: COOLING

| h= | 10 | A= | 455.22 | | |
|---|---|---|---|---|---|
| Time [hour] | T out [C] | T Floor [C] | T Ceiling [C] | 70% Heat extr | T space [C] |
| 1 | 24.38889 | 22.986 | 21.973 | 5733.221667 | 23.10921988 |
| 2 | 23.88889 | 22.947 | 21.927 | 5620.600417 | 23.0543499 |
| 3 | 22.77778 | 22.923 | 21.899 | 4787.121111 | 22.93680303 |
| 4 | 22.77778 | 22.908 | 21.882 | 4818.7125 | 22.92427293 |
| 5 | 22.77778 | 22.899 | 21.872 | 4817.481667 | 22.91463774 |
| 6 | 22.22222 | 22.893 | 21.866 | 4387.305417 | 22.86138847 |
| 7 | 24.38889 | 22.885 | 21.858 | 5251.760694 | 22.94833765 |
| 8 | 27.77778 | 22.938 | 22.012 | 12614.60569 | 23.86055047 |
| 9 | 29.38889 | 23.024 | 22.225 | 20561.27597 | 24.88288891 |
| 10 | 32.22222 | 23.118 | 22.427 | 22916.88583 | 25.28962203 |
| 11 | 33.27778 | 23.21 | 22.605 | 24009.04528 | 25.54458155 |
| 12 | 35 | 23.294 | 22.761 | 24918.42597 | 25.7644652 |
| 13 | 35 | 23.37 | 22.899 | 25661.23389 | 25.953053 |
| 14 | 36.11111 | 23.439 | 23.021 | 26142.07944 | 26.10136763 |
| 15 | 36.11111 | 23.5 | 23.129 | 26010.38028 | 26.17140219 |
| 16 | 36.72222 | 23.555 | 23.225 | 26008.53403 | 26.2466994 |
| 17 | 36.11111 | 23.604 | 23.31 | 24056.02208 | 26.09924134 |
| 18 | 35 | 23.647 | 23.386 | 23078.94556 | 26.05142219 |
| 19 | 33.88889 | 23.686 | 23.453 | 15537.42458 | 25.27608413 |
| 20 | 31.72222 | 23.779 | 23.415 | 13962.98361 | 25.13065226 |
| 21 | 29.38889 | 23.51 | 22.811 | 7008.570139 | 23.93030033 |
| 22 | 28.88889 | 23.294 | 22.42 | 6692.040833 | 23.5920337 |
| 23 | 28.27778 | 23.145 | 22.188 | 6435.617222 | 23.3733689 |
| 24 | 26.72222 | 23.047 | 22.053 | 6641.781806 | 23.2795134 |

Simulation Data for cooling

| | | | | | | |
|---|---|---|---|---|---|---|
| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 10 |
| wood pine emissivity = | | 0.95 | h room = | 10 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 0 |
| 1 | 23.228 | 21.952 | 11.747 | 72.745 | 84.492 | 924.12 |
| 2 | 22.284 | 19.835 | 26.844 | 86.942 | 113.786 | 580.5 |
| 3 | 21.525 | 18.459 | 38.855 | 99.922 | 138.777 | 437.77 |
| 4 | 20.999 | 17.641 | 47.078 | 108.31 | 155.388 | 369.08 |
| 5 | 20.656 | 17.162 | 52.411 | 113.29 | 165.701 | 329.42 |
| 6 | 20.439 | 16.881 | 55.794 | 116.21 | 172.004 | 306.15 |
| 7 | 20.302 | 16.716 | 57.916 | 117.93 | 175.846 | 292.37 |
| 8 | 20.217 | 16.617 | 59.24 | 118.94 | 178.18 | 284.15 |
| 9 | 20.165 | 16.559 | 60.062 | 119.54 | 179.602 | 279.22 |
| 10 | 20.132 | 16.523 | 60.572 | 119.9 | 180.472 | 276.24 |
| 11 | 20.112 | 16.502 | 60.887 | 120.12 | 181.007 | 274.45 |
| 12 | 20.099 | 16.489 | 61.082 | 120.25 | 181.332 | 273.35 |
| 13 | 20.091 | 16.481 | 61.202 | 120.33 | 181.532 | 272.69 |
| 14 | 20.087 | 16.476 | 61.276 | 120.38 | 181.656 | 272.28 |
| 15 | 20.084 | 16.473 | 61.321 | 120.4 | 181.721 | 272.04 |
| 16 | 20.082 | 16.472 | 61.349 | 120.42 | 181.769 | 271.89 |
| Total | | | 837.636 | 1795.629 | 2633.27 | 5715.72 |
| discharging with radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 20.082 | 16.472 | 61.349 | 120.42 | 181.769 | |
| 1 | 19.847 | 16.816 | 54.158 | 100.27 | 154.428 | |
| 2 | 20.084 | 17.487 | 50.167 | 88.457 | 138.624 | |
| 3 | 20.387 | 18.141 | 45.416 | 78.215 | 123.631 | |
| 4 | 20.687 | 18.725 | 40.74 | 69.396 | 110.136 | |
| 5 | 20.964 | 19.24 | 36.41 | 61.689 | 98.099 | |
| 6 | 21.216 | 19.693 | 32.482 | 54.898 | 87.38 | |
| 7 | 21.441 | 20.094 | 28.951 | 48.884 | 77.835 | |
| 8 | 21.643 | 20.45 | 25.789 | 43.545 | 69.334 | |
| 9 | 21.824 | 20.766 | 22.964 | 38.797 | 61.761 | |
| 10 | 21.984 | 21.046 | 20.442 | 34.571 | 55.013 | |
| 11 | 22.128 | 21.296 | 18.194 | 30.809 | 49.003 | |
| 12 | 22.255 | 21.519 | 16.189 | 27.457 | 43.646 | |
| 13 | 22.369 | 21.717 | 14.402 | 24.472 | 38.874 | |
| 14 | 22.47 | 21.893 | 12.811 | 21.812 | 34.623 | |
| 15 | 22.561 | 22.05 | 11.393 | 19.443 | 30.836 | |
| 16 | 22.641 | 22.189 | 10.129 | 17.332 | 27.461 | |
| Total | | | 501.986 | 880.467 | 1382.45 | |

| | | | |
|---|---|---|---|
| T room = | 24 | T pipe = | 10 |
| h room = | 10 | h pipe = | 4300 |

| charging without radiation | | | | | | |
|---|---|---|---|---|---|---|
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 0 |
| 1 | 23.021 | 21.713 | 9.3871 | 65.605 | 74.9921 | 922.16 |
| 2 | 21.792 | 19.307 | 22.059 | 71.668 | 93.727 | 574.43 |
| 3 | 20.776 | 17.69 | 32.433 | 79.895 | 112.328 | 418.33 |
| 4 | 20.054 | 16.692 | 39.718 | 85.803 | 125.521 | 335.63 |
| 5 | 19.572 | 16.087 | 44.563 | 89.52 | 134.083 | 289.52 |
| 6 | 19.258 | 15.721 | 47.714 | 91.793 | 139.507 | 261.56 |
| 7 | 19.056 | 15.497 | 49.742 | 93.178 | 142.92 | 244.48 |
| 8 | 18.927 | 15.36 | 51.039 | 94.023 | 145.062 | 233.98 |
| 9 | 18.844 | 15.276 | 51.866 | 94.54 | 146.406 | 227.5 |
| 10 | 18.792 | 15.224 | 52.392 | 94.858 | 147.25 | 223.49 |
| 11 | 18.759 | 15.192 | 52.725 | 95.054 | 147.779 | 220.99 |
| 12 | 18.738 | 15.172 | 52.936 | 95.176 | 148.112 | 219.44 |
| 13 | 18.724 | 15.159 | 53.07 | 95.251 | 148.321 | 218.47 |
| 14 | 18.716 | 15.151 | 53.155 | 95.299 | 148.454 | 217.86 |
| 15 | 18.711 | 15.146 | 53.208 | 95.328 | 148.536 | 217.48 |
| 16 | 18.707 | 15.143 | 53.242 | 95.346 | 148.588 | 217.24 |
| Total | | | 719.2491 | 1432.337 | 2151.5861 | 5042.56 |

| discharging without radiation | | | | | |
|---|---|---|---|---|---|
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 18.707 | 15.143 | 53.242 | 95.346 | 148.588 |
| 1 | 18.899 | 15.63 | 51.418 | 85.778 | 137.196 |
| 2 | 19.219 | 16.321 | 48.182 | 77.736 | 125.918 |
| 3 | 19.58 | 16.996 | 44.524 | 70.563 | 115.087 |
| 4 | 19.939 | 17.614 | 40.908 | 64.266 | 105.174 |
| 5 | 20.278 | 18.173 | 37.492 | 58.628 | 96.12 |
| 6 | 20.593 | 18.68 | 34.32 | 53.529 | 87.849 |
| 7 | 20.883 | 19.14 | 31.398 | 48.898 | 80.296 |
| 8 | 21.15 | 19.559 | 28.714 | 44.679 | 73.393 |
| 9 | 21.394 | 19.942 | 26.255 | 40.831 | 67.086 |
| 10 | 21.617 | 20.291 | 24.004 | 37.318 | 61.322 |
| 11 | 21.822 | 20.61 | 21.944 | 34.11 | 56.054 |
| 12 | 22.009 | 20.901 | 20.06 | 31.178 | 51.238 |
| 13 | 22.18 | 21.168 | 18.338 | 28.499 | 46.837 |
| 14 | 22.336 | 21.411 | 16.763 | 26.051 | 42.814 |
| 15 | 22.479 | 21.633 | 15.323 | 23.813 | 39.136 |
| 16 | 22.61 | 21.837 | 14.007 | 21.767 | 35.774 |
| Total | | | 526.892 | 842.99 | 1369.882 |

| | | | | | |
|---|---|---|---|---|---|
| concrete emissivity = | 0.85 | T room = | 24 | T pipe = | 18 |
| wood pine emissivity = | 0.95 | h room = | 10 | h pipe = | 4300 |

Charging with radiation

| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
|---|---|---|---|---|---|---|
| 0 | 24 | 24 | 0 | 0 | 0 | 0 |
| 1 | 23.669 | 23.122 | 5.0343 | 31.176 | 36.2103 | 396.05 |
| 2 | 23.265 | 22.217 | 11.511 | 37.318 | 48.829 | 248.8 |
| 3 | 22.941 | 21.629 | 16.667 | 42.945 | 59.612 | 187.73 |
| 4 | 22.716 | 21.281 | 20.198 | 46.576 | 66.774 | 158.37 |
| 5 | 22.57 | 21.077 | 22.487 | 48.733 | 71.22 | 141.44 |
| 6 | 22.478 | 20.958 | 23.939 | 49.996 | 73.935 | 131.52 |
| 7 | 22.42 | 20.887 | 24.849 | 50.736 | 75.585 | 125.65 |
| 8 | 22.383 | 20.846 | 25.416 | 51.173 | 76.589 | 122.16 |
| 9 | 22.361 | 20.821 | 25.769 | 51.433 | 77.202 | 120.06 |
| 10 | 22.347 | 20.806 | 25.987 | 51.588 | 77.575 | 118.8 |
| 11 | 22.339 | 20.797 | 26.122 | 51.681 | 77.803 | 118.04 |
| 12 | 22.333 | 20.792 | 26.205 | 51.737 | 77.942 | 117.57 |
| 13 | 22.33 | 20.788 | 26.256 | 51.771 | 78.027 | 117.29 |
| 14 | 22.328 | 20.786 | 26.288 | 51.792 | 78.08 | 117.12 |
| 15 | 22.327 | 20.785 | 26.307 | 51.804 | 78.111 | 117.02 |
| 16 | 22.326 | 20.784 | 26.319 | 51.812 | 78.131 | 116.95 |
| Total | | | 359.3543 | 772.271 | 1131.63 | 2454.57 |

discharging with radiation

| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
|---|---|---|---|---|---|
| 0 | 22.326 | 20.784 | 26.319 | 51.812 | 78.131 |
| 1 | 22.405 | 21.015 | 25.129 | 45.92 | 71.049 |
| 2 | 22.534 | 21.335 | 23.101 | 40.563 | 63.664 |
| 3 | 22.676 | 21.638 | 20.866 | 35.821 | 56.687 |
| 4 | 22.814 | 21.905 | 18.708 | 31.743 | 50.451 |
| 5 | 22.94 | 22.14 | 16.717 | 28.187 | 44.904 |
| 6 | 23.055 | 22.347 | 14.915 | 25.059 | 39.974 |
| 7 | 23.157 | 22.53 | 13.295 | 22.293 | 35.588 |
| 8 | 23.249 | 22.692 | 11.846 | 19.84 | 31.686 |
| 9 | 23.332 | 22.836 | 10.552 | 17.66 | 28.212 |
| 10 | 23.405 | 22.964 | 9.3975 | 15.722 | 25.1195 |
| 11 | 23.47 | 23.078 | 8.3684 | 13.998 | 22.3664 |
| 12 | 23.528 | 23.179 | 7.4515 | 12.463 | 19.9145 |
| 13 | 23.58 | 23.269 | 6.6348 | 11.096 | 17.7308 |
| 14 | 23.626 | 23.35 | 5.9074 | 9.8796 | 15.787 |
| 15 | 23.667 | 23.421 | 5.2597 | 8.7963 | 14.056 |
| 16 | 23.704 | 23.484 | 4.6829 | 7.8317 | 12.5146 |
| Total | | | 229.1502 | 398.6846 | 627.835 |

| | | | | | | |
|---|---|---|---|---|---|---|
| T room = | | 24 | T pipe = | | 18 | |
| h room= | | 10 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | |
| 1 | 23.58 | 23.02 | 4.0232 | 28.116 | 32.1392 | 395.21 |
| 2 | 23.054 | 21.989 | 9.4541 | 30.715 | 40.1691 | 246.18 |
| 3 | 22.618 | 21.296 | 13.9 | 34.241 | 48.141 | 179.29 |
| 4 | 22.309 | 20.868 | 17.022 | 36.773 | 53.795 | 143.84 |
| 5 | 22.102 | 20.609 | 19.098 | 38.366 | 57.464 | 124.08 |
| 6 | 21.968 | 20.452 | 20.449 | 39.34 | 59.789 | 112.1 |
| 7 | 21.881 | 20.356 | 21.318 | 39.934 | 61.252 | 104.78 |
| 8 | 21.826 | 20.297 | 21.874 | 40.295 | 62.169 | 100.28 |
| 9 | 21.79 | 20.261 | 22.228 | 40.517 | 62.745 | 97.5 |
| 10 | 21.768 | 20.239 | 22.453 | 40.653 | 63.106 | 95.78 |
| 11 | 21.754 | 20.225 | 22.596 | 40.738 | 63.334 | 94.711 |
| 12 | 21.745 | 20.216 | 22.687 | 40.79 | 63.477 | 94.045 |
| 13 | 21.739 | 20.211 | 22.744 | 40.822 | 63.566 | 93.629 |
| 14 | 21.735 | 20.208 | 22.781 | 40.842 | 63.623 | 93.369 |
| 15 | 21.733 | 20.206 | 22.803 | 40.855 | 63.658 | 93.206 |
| 16 | 21.732 | 20.204 | 22.818 | 40.863 | 63.681 | 93.104 |
| Total | | | 308.2483 | 613.86 | 922.1083 | 2161.104 |
| discharging without radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 21.732 | 20.204 | 22.818 | 40.863 | 63.681 | |
| 1 | 21.814 | 20.413 | 22.036 | 36.762 | 58.798 | |
| 2 | 21.951 | 20.709 | 20.65 | 33.316 | 53.966 | |
| 3 | 22.106 | 20.998 | 19.082 | 30.241 | 49.323 | |
| 4 | 22.26 | 21.263 | 17.532 | 27.543 | 45.075 | |
| 5 | 22.405 | 21.503 | 16.068 | 25.126 | 41.194 | |
| 6 | 22.54 | 21.72 | 14.709 | 22.941 | 37.65 | |
| 7 | 22.664 | 21.917 | 13.456 | 20.956 | 34.412 | |
| 8 | 22.779 | 22.097 | 12.306 | 19.148 | 31.454 | |
| 9 | 22.883 | 22.261 | 11.252 | 17.499 | 28.751 | |
| 10 | 22.979 | 22.41 | 10.287 | 15.994 | 26.281 | |
| 11 | 23.067 | 22.547 | 9.4047 | 14.618 | 24.0227 | |
| 12 | 23.147 | 22.672 | 8.5973 | 13.362 | 21.9593 | |
| 13 | 23.22 | 22.786 | 7.8591 | 12.214 | 20.0731 | |
| 14 | 23.287 | 22.89 | 7.1842 | 11.165 | 18.3492 | |
| 15 | 23.348 | 22.986 | 6.5672 | 10.205 | 16.7722 | |
| 16 | 23.404 | 23.073 | 6.0031 | 9.3287 | 15.3318 | |
| Total | | | 225.8116 | 361.2817 | 587.0933 | |

| | | | | | |
|---|---|---|---|---|---|
| concrete emissivity = | 0.85 | T room = | 24 | T pipe = | 10 |
| wood pine emissivity = | 0.95 | h room = | 2 | h pipe = | 4300 |

Charging with radiation

| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
|---|---|---|---|---|---|---|
| 0 | 24 | 24 | 0 | 0 | 0 | 920.89 |
| 1 | 22.898 | 21.549 | 7.996 | 60.901 | 68.897 | 570.3 |
| 2 | 21.485 | 18.921 | 19.065 | 60.563 | 79.628 | 410.38 |
| 3 | 20.288 | 17.099 | 28.211 | 64.29 | 92.501 | 314.44 |
| 4 | 19.416 | 15.939 | 34.712 | 67.54 | 102.252 | 257.65 |
| 5 | 18.821 | 15.213 | 39.102 | 69.738 | 108.84 | 225.26 |
| 6 | 18.425 | 14.76 | 42.008 | 71.144 | 113.152 | 204.93 |
| 7 | 18.165 | 14.476 | 43.914 | 72.032 | 115.946 | 192.11 |
| 8 | 17.995 | 14.298 | 45.157 | 72.59 | 117.747 | 184 |
| 9 | 17.885 | 14.185 | 45.966 | 72.94 | 118.906 | 178.86 |
| 10 | 17.813 | 14.114 | 46.49 | 73.161 | 119.651 | 175.59 |
| 11 | 17.766 | 14.068 | 46.83 | 73.301 | 120.131 | 173.5 |
| 12 | 17.736 | 14.039 | 47.05 | 73.389 | 120.439 | 172.17 |
| 13 | 17.717 | 14.021 | 47.192 | 73.445 | 120.637 | 171.32 |
| 14 | 17.704 | 14.009 | 47.284 | 73.481 | 120.765 | 170.78 |
| 15 | 17.696 | 14.002 | 47.343 | 73.504 | 120.847 | 170.43 |
| 16 | 17.691 | 13.997 | 47.381 | 73.518 | 120.899 | |
| Total | | | 635.701 | 1125.537 | 1761.24 | 4492.61 |

discharging with radiation

| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
|---|---|---|---|---|---|
| 0 | 17.691 | 13.997 | 47.381 | 73.518 | 120.899 |
| 1 | 17.871 | 14.422 | 46.148 | 66.852 | 113 |
| 2 | 18.177 | 15.04 | 43.878 | 61.851 | 105.729 |
| 3 | 18.529 | 15.661 | 41.263 | 57.397 | 98.66 |
| 4 | 18.885 | 16.243 | 38.63 | 53.434 | 92.064 |
| 5 | 19.227 | 16.783 | 36.093 | 49.815 | 85.908 |
| 6 | 19.55 | 17.283 | 33.689 | 46.45 | 80.139 |
| 7 | 19.853 | 17.747 | 31.428 | 43.316 | 74.744 |
| 8 | 20.137 | 18.178 | 29.308 | 40.393 | 69.701 |
| 9 | 20.402 | 18.579 | 27.324 | 37.665 | 64.989 |
| 10 | 20.649 | 18.952 | 25.47 | 35.119 | 60.589 |
| 11 | 20.88 | 19.3 | 23.738 | 32.742 | 56.48 |
| 12 | 21.095 | 19.624 | 22.122 | 30.522 | 52.644 |
| 13 | 21.295 | 19.925 | 20.613 | 28.45 | 49.063 |
| 14 | 21.481 | 20.206 | 19.205 | 26.517 | 45.722 |
| 15 | 21.655 | 20.467 | 17.892 | 24.712 | 42.604 |
| 16 | 21.817 | 20.711 | 16.668 | 23.028 | 39.696 |
| Total | | | 520.85 | 731.781 | 1252.63 |

| | | | | | | |
|---|---|---|---|---|---|---|
| T room= | | 24 | T pipe = | | 10 | |
| h room= | | 2 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | |
| 1 | 22.428 | 21.21 | 2.6375 | 51.921 | 54.5585 | 917.56 |
| 2 | 20.289 | 18.138 | 7.3082 | 39.419 | 46.7272 | 559.39 |
| 3 | 18.369 | 15.904 | 11.369 | 33.84 | 45.209 | 389.05 |
| 4 | 16.89 | 14.407 | 14.37 | 31.089 | 45.459 | 281.84 |
| 5 | 15.822 | 13.42 | 16.493 | 29.562 | 46.055 | 210.45 |
| 6 | 15.07 | 12.771 | 17.972 | 28.666 | 46.638 | 162.19 |
| 7 | 14.548 | 12.342 | 18.996 | 28.121 | 47.117 | 129.43 |
| 8 | 14.188 | 12.058 | 19.701 | 27.779 | 47.48 | 107.15 |
| 9 | 13.941 | 11.87 | 20.185 | 27.559 | 47.744 | 92.009 |
| 10 | 13.771 | 11.744 | 20.517 | 27.415 | 47.932 | 81.714 |
| 11 | 13.655 | 11.659 | 20.744 | 27.32 | 48.064 | 75.631 |
| 12 | 13.576 | 11.603 | 20.899 | 27.257 | 48.156 | 71.892 |
| 13 | 13.522 | 11.565 | 21.004 | 27.214 | 48.218 | 69.378 |
| 14 | 13.486 | 11.539 | 21.076 | 27.185 | 48.261 | 67.684 |
| 15 | 13.46 | 11.522 | 21.125 | 27.166 | 48.291 | 66.541 |
| 16 | 13.443 | 11.511 | 21.159 | 27.152 | 48.311 | 65.77 |
| Total | | | 275.5557 | 488.665 | 764.2207 | 3347.679 |
| discharging without radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 13.443 | 11.511 | 21.159 | 27.152 | 48.311 | |
| 1 | 13.538 | 11.697 | 21.004 | 25.154 | 46.158 | |
| 2 | 13.718 | 11.982 | 20.632 | 24.186 | 44.818 | |
| 3 | 13.937 | 12.282 | 20.18 | 23.453 | 43.633 | |
| 4 | 14.17 | 12.578 | 19.706 | 22.857 | 42.563 | |
| 5 | 14.406 | 12.865 | 19.231 | 22.283 | 41.514 | |
| 6 | 14.64 | 13.144 | 18.763 | 21.727 | 40.49 | |
| 7 | 14.869 | 13.414 | 18.303 | 21.186 | 39.489 | |
| 8 | 15.094 | 13.677 | 17.852 | 20.66 | 38.512 | |
| 9 | 15.314 | 13.934 | 17.412 | 20.148 | 37.56 | |
| 10 | 15.528 | 14.183 | 16.981 | 19.649 | 36.63 | |
| 11 | 15.738 | 14.426 | 16.562 | 19.162 | 35.724 | |
| 12 | 15.942 | 14.664 | 16.152 | 18.687 | 34.839 | |
| 13 | 16.141 | 14.895 | 15.752 | 18.225 | 33.977 | |
| 14 | 16.336 | 15.12 | 15.362 | 17.773 | 33.135 | |
| 15 | 16.526 | 15.34 | 14.982 | 17.333 | 32.315 | |
| 16 | 16.711 | 15.555 | 14.611 | 16.904 | 31.515 | |
| Total | | | 304.644 | 356.539 | 661.183 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 10 |
| wood pine emissivity = | | 0.95 | h room = | 5 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | |
| 1 | 23.05 | 21.716 | 9.7226 | 65.694 | 75.4166 | 922.27 |
| 2 | 21.858 | 19.305 | 22.709 | 71.549 | 94.258 | 574.73 |
| 3 | 20.872 | 17.677 | 33.268 | 79.453 | 112.721 | 418.84 |
| 4 | 20.171 | 16.669 | 40.655 | 85.129 | 125.784 | 335.06 |
| 5 | 19.702 | 16.057 | 45.555 | 88.705 | 134.26 | 288.65 |
| 6 | 19.397 | 15.684 | 48.737 | 90.895 | 139.632 | 260.46 |
| 7 | 19.2 | 15.457 | 50.782 | 92.232 | 143.014 | 243.2 |
| 8 | 19.075 | 15.318 | 52.089 | 93.048 | 145.137 | 232.59 |
| 9 | 18.995 | 15.232 | 52.921 | 93.549 | 146.47 | 226.03 |
| 10 | 18.944 | 15.179 | 53.45 | 93.857 | 147.307 | 221.96 |
| 11 | 18.912 | 15.146 | 53.786 | 94.047 | 147.833 | 219.44 |
| 12 | 18.892 | 15.125 | 53.998 | 94.165 | 148.163 | 217.86 |
| 13 | 18.879 | 15.112 | 54.133 | 94.239 | 148.372 | 216.87 |
| 14 | 18.871 | 15.104 | 54.218 | 94.284 | 148.502 | 216.26 |
| 15 | 18.866 | 15.099 | 54.271 | 94.313 | 148.584 | 215.87 |
| 16 | 18.862 | 15.096 | 54.305 | 94.331 | 148.636 | 215.63 |
| Total | | | 734.5996 | 1419.49 | 2154.09 | 5025.72 |
| discharging with radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 18.862 | 15.096 | 54.305 | 94.331 | 148.636 | |
| 1 | 19.051 | 15.586 | 52.439 | 84.908 | 137.347 | |
| 2 | 19.366 | 16.283 | 49.138 | 77.057 | 126.195 | |
| 3 | 19.72 | 16.966 | 45.407 | 70.025 | 115.432 | |
| 4 | 20.072 | 17.591 | 41.717 | 63.83 | 105.547 | |
| 5 | 20.403 | 18.157 | 38.23 | 58.265 | 96.495 | |
| 6 | 20.711 | 18.669 | 34.99 | 53.219 | 88.209 | |
| 7 | 20.994 | 19.135 | 32.003 | 48.625 | 80.628 | |
| 8 | 21.254 | 19.56 | 29.258 | 44.433 | 73.691 | |
| 9 | 21.492 | 19.946 | 26.742 | 40.604 | 67.346 | |
| 10 | 21.709 | 20.299 | 24.437 | 37.105 | 61.542 | |
| 11 | 21.908 | 20.621 | 22.328 | 33.905 | 56.233 | |
| 12 | 22.09 | 20.915 | 20.398 | 30.98 | 51.378 | |
| 13 | 22.256 | 21.183 | 18.634 | 28.305 | 46.939 | |
| 14 | 22.407 | 21.428 | 17.022 | 25.86 | 42.882 | |
| 15 | 22.546 | 21.652 | 15.547 | 23.624 | 39.171 | |
| 16 | 22.672 | 21.856 | 14.2 | 21.58 | 35.78 | |
| Total | | | 536.795 | 836.656 | 1373.45 | |

| T room = | | 24 | T pipe = | | 10 | |
|---|---|---|---|---|---|---|
| h room= | | 5 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 919.62 |
| 1 | 22.718 | 21.421 | 5.9411 | 57.368 | 63.3091 | 566.25 |
| 2 | 21.041 | 18.635 | 14.71 | 52.61 | 67.32 | 402.62 |
| 3 | 19.594 | 16.675 | 22.156 | 53.385 | 75.541 | 302.81 |
| 4 | 18.522 | 15.407 | 27.564 | 54.908 | 82.472 | 238.53 |
| 5 | 17.776 | 14.6 | 31.292 | 56.103 | 87.395 | 199.15 |
| 6 | 17.272 | 14.087 | 33.808 | 56.922 | 90.73 | 176.45 |
| 7 | 16.934 | 13.761 | 35.491 | 57.46 | 92.951 | 161.9 |
| 8 | 16.709 | 13.552 | 36.609 | 57.807 | 94.416 | 152.53 |
| 9 | 16.56 | 13.418 | 37.351 | 58.031 | 95.382 | 146.49 |
| 10 | 16.462 | 13.332 | 37.841 | 58.174 | 96.015 | 142.57 |
| 11 | 16.397 | 13.276 | 38.164 | 58.266 | 96.43 | 140.04 |
| 12 | 16.354 | 13.24 | 38.377 | 58.325 | 96.702 | 138.39 |
| 13 | 16.326 | 13.216 | 38.517 | 58.363 | 96.88 | 137.32 |
| 14 | 16.308 | 13.201 | 38.609 | 58.387 | 96.996 | 136.62 |
| 15 | 16.296 | 13.191 | 38.669 | 58.403 | 97.072 | 136.17 |
| 16 | 16.288 | 13.185 | 38.709 | 58.413 | 97.122 | |
| Total | | | 513.8081 | 912.925 | 1426.7331 | 4097.46 |

| discharging without radiation | | | | | |
|---|---|---|---|---|---|
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 16.288 | 13.185 | 38.709 | 58.413 | 97.122 |
| 1 | 16.451 | 13.538 | 37.956 | 53.499 | 91.455 |
| 2 | 16.738 | 14.06 | 36.501 | 50.129 | 86.63 |
| 3 | 17.074 | 14.592 | 34.796 | 47.19 | 81.986 |
| 4 | 17.419 | 15.1 | 33.055 | 44.626 | 77.681 |
| 5 | 17.757 | 15.577 | 31.355 | 42.232 | 73.587 |
| 6 | 18.082 | 16.027 | 29.722 | 39.979 | 69.701 |
| 7 | 18.392 | 16.451 | 28.165 | 37.853 | 66.018 |
| 8 | 18.687 | 16.852 | 26.684 | 35.845 | 62.529 |
| 9 | 18.967 | 17.231 | 25.277 | 33.946 | 59.223 |
| 10 | 19.233 | 17.589 | 23.944 | 32.15 | 56.094 |
| 11 | 19.485 | 17.928 | 22.68 | 30.449 | 53.129 |
| 12 | 19.723 | 18.249 | 21.482 | 28.839 | 50.321 |
| 13 | 19.949 | 18.553 | 20.347 | 27.314 | 47.661 |
| 14 | 20.163 | 18.841 | 19.272 | 25.87 | 45.142 |
| 15 | 20.366 | 19.114 | 18.253 | 24.502 | 42.755 |
| 16 | 20.558 | 19.372 | 17.288 | 23.207 | 40.495 |
| Total | | | 465.486 | 636.043 | 1101.529 |

| | | | | | | |
|---|---|---|---|---|---|---|
| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 18 |
| wood pine emissivity = | | 0.95 | h room = | 2 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 394.67 |
| 1 | 23.528 | 22.949 | 3.4269 | 26.101 | 29.5279 | 244.44 |
| 2 | 22.924 | 21.826 | 8.1896 | 26.049 | 34.2386 | 175.95 |
| 3 | 22.414 | 21.05 | 12.14 | 27.772 | 39.912 | 134.91 |
| 4 | 22.044 | 20.557 | 14.952 | 29.259 | 44.211 | 110.94 |
| 5 | 21.792 | 20.249 | 16.853 | 30.261 | 47.114 | 97.184 |
| 6 | 21.625 | 20.058 | 18.11 | 30.901 | 49.011 | 88.572 |
| 7 | 21.516 | 19.938 | 18.933 | 31.304 | 50.237 | 83.155 |
| 8 | 21.444 | 19.863 | 19.47 | 31.556 | 51.026 | 79.735 |
| 9 | 21.398 | 19.816 | 19.818 | 31.715 | 51.533 | 77.57 |
| 10 | 21.368 | 19.786 | 20.044 | 31.815 | 51.859 | 76.196 |
| 11 | 21.348 | 19.767 | 20.19 | 31.878 | 52.068 | 75.322 |
| 12 | 21.336 | 19.755 | 20.284 | 31.917 | 52.201 | 74.765 |
| 13 | 21.328 | 19.747 | 20.345 | 31.943 | 52.288 | 74.41 |
| 14 | 21.322 | 19.743 | 20.384 | 31.959 | 52.343 | 74.183 |
| 15 | 21.319 | 19.739 | 20.409 | 31.969 | 52.378 | 74.038 |
| 16 | 21.317 | 19.737 | 20.426 | 31.975 | 52.401 | |
| Total | | | 273.9745 | 488.374 | 762.349 | 1541.37 |

| | | | | | |
|---|---|---|---|---|---|
| discharging with radiation | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 21.317 | 19.737 | 20.426 | 31.975 | 52.401 |
| 1 | 21.394 | 19.921 | 19.882 | 29.045 | 48.927 |
| 2 | 21.525 | 20.186 | 18.885 | 26.821 | 45.706 |
| 3 | 21.676 | 20.453 | 17.739 | 24.842 | 42.581 |
| 4 | 21.827 | 20.702 | 16.587 | 23.086 | 39.673 |
| 5 | 21.974 | 20.933 | 15.48 | 21.485 | 36.965 |
| 6 | 22.111 | 21.147 | 14.434 | 20.004 | 34.438 |
| 7 | 22.241 | 21.345 | 13.452 | 18.628 | 32.08 |
| 8 | 22.362 | 21.529 | 12.533 | 17.349 | 29.882 |
| 9 | 22.475 | 21.7 | 11.674 | 16.158 | 27.832 |
| 10 | 22.58 | 21.86 | 10.873 | 15.049 | 25.922 |
| 11 | 22.678 | 22.008 | 10.126 | 14.016 | 24.142 |
| 12 | 22.769 | 22.145 | 9.4293 | 13.053 | 22.4823 |
| 13 | 22.854 | 22.274 | 8.7803 | 12.156 | 20.9363 |
| 14 | 22.934 | 22.393 | 8.1756 | 11.32 | 19.4956 |
| 15 | 23.007 | 22.504 | 7.6123 | 10.542 | 18.1543 |
| 16 | 23.076 | 22.608 | 7.0875 | 9.8162 | 16.9037 |
| Total | | | 223.176 | 315.3452 | 538.521 |

| | | | | | | |
|---|---|---|---|---|---|---|
| T room = | | 24 | T pipe = | | 18 | |
| h room= | | 2 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 393.24 |
| 1 | 23.326 | 22.804 | 1.1306 | 22.252 | 23.3826 | 239.74 |
| 2 | 22.41 | 21.488 | 3.1322 | 16.894 | 20.0262 | 166.73 |
| 3 | 21.587 | 20.53 | 4.8723 | 14.503 | 19.3753 | 120.79 |
| 4 | 20.953 | 19.889 | 6.1585 | 13.324 | 19.4825 | 90.193 |
| 5 | 20.495 | 19.466 | 7.0683 | 12.669 | 19.7373 | 69.512 |
| 6 | 20.173 | 19.188 | 7.7025 | 12.285 | 19.9875 | 55.47 |
| 7 | 19.949 | 19.004 | 8.1411 | 12.052 | 20.1931 | 45.923 |
| 8 | 19.795 | 18.882 | 8.4432 | 11.905 | 20.3482 | 39.433 |
| 9 | 19.689 | 18.801 | 8.6508 | 11.811 | 20.4618 | 35.02 |
| 10 | 19.616 | 18.747 | 8.793 | 11.75 | 20.543 | 32.413 |
| 11 | 19.567 | 18.711 | 8.8902 | 11.709 | 20.5992 | 30.811 |
| 12 | 19.533 | 18.687 | 8.9565 | 11.682 | 20.6385 | 29.733 |
| 13 | 19.51 | 18.671 | 9.0018 | 11.663 | 20.6648 | 29.007 |
| 14 | 19.494 | 18.66 | 9.0327 | 11.651 | 20.6837 | 28.518 |
| 15 | 19.483 | 18.652 | 9.0537 | 11.642 | 20.6957 | 28.187 |
| 16 | 19.476 | 18.647 | 9.068 | 11.637 | 20.705 | |
| Total | | | 118.0954 | 209.429 | 327.5244 | 1434.72 |
| discharging without radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 19.476 | 18.647 | 9.068 | 11.637 | 20.705 | |
| 1 | 19.516 | 18.727 | 9.0018 | 10.78 | 19.7818 | |
| 2 | 19.593 | 18.849 | 8.8425 | 10.366 | 19.2085 | |
| 3 | 19.687 | 18.978 | 8.6484 | 10.051 | 18.6994 | |
| 4 | 19.787 | 19.105 | 8.4454 | 9.7959 | 18.2413 | |
| 5 | 19.888 | 19.228 | 8.2421 | 9.55 | 17.7921 | |
| 6 | 19.988 | 19.347 | 8.0412 | 9.3116 | 17.3528 | |
| 7 | 20.087 | 19.463 | 7.844 | 9.0799 | 16.9239 | |
| 8 | 20.183 | 19.576 | 7.6509 | 8.8544 | 16.5053 | |
| 9 | 20.277 | 19.686 | 7.4621 | 8.6348 | 16.0969 | |
| 10 | 20.369 | 19.793 | 7.2778 | 8.4208 | 15.6986 | |
| 11 | 20.459 | 19.897 | 7.0978 | 8.2122 | 15.31 | |
| 12 | 20.547 | 19.999 | 6.9223 | 8.0088 | 14.9311 | |
| 13 | 20.632 | 20.098 | 6.751 | 7.8105 | 14.5615 | |
| 14 | 20.715 | 20.194 | 6.5839 | 7.6171 | 14.201 | |
| 15 | 20.797 | 20.289 | 6.421 | 7.4285 | 13.8495 | |
| 16 | 20.876 | 20.381 | 6.262 | 7.2446 | 13.5066 | |
| Total | | | 130.5622 | 152.8031 | 283.3653 | |

| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 20 |
|---|---|---|---|---|---|---|
| wood pine emissivity = | | 0.95 | h room = | 2 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 263.11 |
| 1 | 23.685 | 23.3 | 2.2846 | 17.4 | 19.6846 | 162.96 |
| 2 | 23.283 | 22.551 | 5.4629 | 17.382 | 22.8449 | 117.31 |
| 3 | 22.943 | 22.034 | 8.1013 | 18.552 | 26.6533 | 89.963 |
| 4 | 22.698 | 21.706 | 9.9809 | 19.558 | 29.5389 | 74.046 |
| 5 | 22.53 | 21.502 | 11.251 | 20.236 | 31.487 | 64.897 |
| 6 | 22.419 | 21.375 | 12.091 | 20.669 | 32.76 | 59.172 |
| 7 | 22.346 | 21.296 | 12.641 | 20.941 | 33.582 | 55.574 |
| 8 | 22.299 | 21.246 | 12.999 | 21.112 | 34.111 | 53.303 |
| 9 | 22.268 | 21.214 | 13.232 | 21.219 | 34.451 | 51.867 |
| 10 | 22.248 | 21.195 | 13.382 | 21.287 | 34.669 | 50.955 |
| 11 | 22.235 | 21.182 | 13.48 | 21.329 | 34.809 | 50.376 |
| 12 | 22.227 | 21.174 | 13.543 | 21.356 | 34.899 | 50.007 |
| 13 | 22.222 | 21.169 | 13.583 | 21.373 | 34.956 | 49.772 |
| 14 | 22.218 | 21.166 | 13.609 | 21.384 | 34.993 | 49.621 |
| 15 | 22.216 | 21.164 | 13.626 | 21.391 | 35.017 | 49.525 |
| 16 | 22.215 | 21.162 | 13.637 | 21.395 | 35.032 | |
| Total | | | 182.9037 | 326.584 | 509.488 | 1029.348 |

| discharging with radiation | | | | | |
|---|---|---|---|---|---|
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 22.215 | 21.162 | 13.637 | 21.395 | 35.032 |
| 1 | 22.266 | 21.285 | 13.272 | 19.429 | 32.701 |
| 2 | 22.353 | 21.462 | 12.603 | 17.933 | 30.536 |
| 3 | 22.454 | 21.64 | 11.835 | 16.602 | 28.437 |
| 4 | 22.555 | 21.806 | 11.063 | 15.421 | 26.484 |
| 5 | 22.652 | 21.96 | 10.322 | 14.346 | 24.668 |
| 6 | 22.744 | 22.102 | 9.6219 | 13.352 | 22.9739 |
| 7 | 22.83 | 22.234 | 8.9648 | 12.429 | 21.3938 |
| 8 | 22.911 | 22.357 | 8.3503 | 11.572 | 19.9223 |
| 9 | 22.986 | 22.471 | 7.7765 | 10.774 | 18.5505 |
| 10 | 23.056 | 22.577 | 7.2414 | 10.032 | 17.2734 |
| 11 | 23.121 | 22.675 | 6.7425 | 9.341 | 16.0835 |
| 12 | 23.182 | 22.767 | 6.2776 | 8.6973 | 14.9749 |
| 13 | 23.239 | 22.852 | 5.8446 | 8.0978 | 13.9424 |
| 14 | 23.291 | 22.932 | 5.4412 | 7.5395 | 12.9807 |
| 15 | 23.34 | 23.006 | 5.0656 | 7.0196 | 12.0852 |
| 16 | 23.386 | 23.075 | 4.7157 | 6.5353 | 11.251 |
| Total | | | 148.7741 | 210.5155 | 359.29 |

| | | | | | | |
|---|---|---|---|---|---|---|
| T room = | | 24 | T pipe = | | 20 | |
| h room= | | 2 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 262.16 |
| 1 | 23.551 | 23.203 | 0.75371 | 14.835 | 15.58871 | 159.82 |
| 2 | 22.94 | 22.325 | 2.0882 | 11.262 | 13.3502 | 111.16 |
| 3 | 22.391 | 21.687 | 3.2482 | 9.6685 | 12.9167 | 80.525 |
| 4 | 21.969 | 21.259 | 4.1057 | 8.8827 | 12.9884 | 60.129 |
| 5 | 21.663 | 20.977 | 4.7124 | 8.4464 | 13.1588 | 46.341 |
| 6 | 21.449 | 20.792 | 5.135 | 8.1903 | 13.3253 | 36.98 |
| 7 | 21.299 | 20.669 | 5.4275 | 8.0346 | 13.4621 | 30.615 |
| 8 | 21.197 | 20.588 | 5.6288 | 7.9369 | 13.5657 | 26.288 |
| 9 | 21.126 | 20.534 | 5.7672 | 7.8744 | 13.6416 | 23.347 |
| 10 | 21.078 | 20.498 | 5.862 | 7.8332 | 13.6952 | 21.609 |
| 11 | 21.044 | 20.474 | 5.9268 | 7.8059 | 13.7327 | 20.541 |
| 12 | 21.022 | 20.458 | 5.9711 | 7.7879 | 13.759 | 19.822 |
| 13 | 21.006 | 20.447 | 6.0012 | 7.7755 | 13.7767 | 19.338 |
| 14 | 20.996 | 20.44 | 6.0218 | 7.7673 | 13.7891 | 19.012 |
| 15 | 20.989 | 20.435 | 6.0359 | 7.7617 | 13.7976 | 18.791 |
| 16 | 20.984 | 20.432 | 6.0454 | 7.7578 | 13.8032 | |
| Total | | | 78.73091 | 139.6201 | 218.35101 | 956.478 |

| | | | | | |
|---|---|---|---|---|---|
| discharging without radiation | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 20.984 | 20.432 | 6.0454 | 7.7578 | 13.8032 |
| 1 | 21.011 | 20.485 | 6.0012 | 7.187 | 13.1882 |
| 2 | 21.062 | 20.566 | 5.895 | 6.9103 | 12.8053 |
| 3 | 21.125 | 20.652 | 5.7656 | 6.7008 | 12.4664 |
| 4 | 21.192 | 20.737 | 5.6303 | 6.5306 | 12.1609 |
| 5 | 21.259 | 20.819 | 5.4947 | 6.3666 | 11.8613 |
| 6 | 21.326 | 20.898 | 5.3608 | 6.2077 | 11.5685 |
| 7 | 21.391 | 20.975 | 5.2293 | 6.0533 | 11.2826 |
| 8 | 21.455 | 21.051 | 5.1006 | 5.903 | 11.0036 |
| 9 | 21.518 | 21.124 | 4.9747 | 5.7566 | 10.7313 |
| 10 | 21.579 | 21.195 | 4.8519 | 5.6139 | 10.4658 |
| 11 | 21.639 | 21.265 | 4.7319 | 5.4748 | 10.2067 |
| 12 | 21.698 | 21.332 | 4.6149 | 5.3392 | 9.9541 |
| 13 | 21.755 | 21.399 | 4.5007 | 5.207 | 9.7077 |
| 14 | 21.81 | 21.463 | 4.3893 | 5.0781 | 9.4674 |
| 15 | 21.864 | 21.526 | 4.2807 | 4.9524 | 9.2331 |
| 16 | 21.917 | 21.587 | 4.1747 | 4.8298 | 9.0045 |
| Total | | | 87.0417 | 101.8689 | 188.9106 |

| | | | | | | |
|---|---|---|---|---|---|---|
| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 20 |
| wood pine emissivity = | | 0.95 | h room = | 10 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 264.03 |
| 1 | 23.779 | 23.415 | 3.3562 | 20.784 | 24.1402 | 165.87 |
| 2 | 23.51 | 22.811 | 7.6749 | 24.888 | 32.5629 | 125.17 |
| 3 | 23.294 | 22.42 | 11.114 | 28.65 | 39.764 | 105.61 |
| 4 | 23.145 | 22.188 | 13.469 | 31.078 | 44.547 | 94.338 |
| 5 | 23.047 | 22.053 | 14.996 | 32.519 | 47.515 | 87.732 |
| 6 | 22.986 | 21.973 | 15.964 | 33.363 | 49.327 | 83.827 |
| 7 | 22.947 | 21.927 | 16.571 | 33.857 | 50.428 | 81.5 |
| 8 | 22.923 | 21.899 | 16.949 | 34.149 | 51.098 | 80.106 |
| 9 | 22.908 | 21.882 | 17.184 | 34.322 | 51.506 | 79.267 |
| 10 | 22.899 | 21.872 | 17.329 | 34.426 | 51.755 | 78.76 |
| 11 | 22.893 | 21.866 | 17.419 | 34.488 | 51.907 | 78.452 |
| 12 | 22.89 | 21.863 | 17.474 | 34.525 | 51.999 | 78.265 |
| 13 | 22.888 | 21.861 | 17.509 | 34.548 | 52.057 | 78.151 |
| 14 | 22.886 | 21.859 | 17.53 | 34.562 | 52.092 | 78.082 |
| 15 | 22.885 | 21.858 | 17.543 | 34.57 | 52.113 | 78.039 |
| 16 | 22.885 | 21.858 | 17.55 | 34.575 | 52.125 | |
| Total | | | 239.6321 | 515.304 | 754.936 | 1373.169 |

| | | | | | |
|---|---|---|---|---|---|
| discharging with radiation | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 22.885 | 21.858 | 17.55 | 34.575 | 52.125 |
| 1 | 22.938 | 22.012 | 16.756 | 30.639 | 47.395 |
| 2 | 23.024 | 22.225 | 15.402 | 27.058 | 42.46 |
| 3 | 23.118 | 22.427 | 13.911 | 23.89 | 37.801 |
| 4 | 23.21 | 22.605 | 12.47 | 21.166 | 33.636 |
| 5 | 23.294 | 22.761 | 11.142 | 18.793 | 29.935 |
| 6 | 23.37 | 22.899 | 9.94 | 16.705 | 26.645 |
| 7 | 23.439 | 23.021 | 8.86 | 14.859 | 23.719 |
| 8 | 23.5 | 23.129 | 7.8937 | 13.223 | 21.1167 |
| 9 | 23.555 | 23.225 | 7.0308 | 11.769 | 18.7998 |
| 10 | 23.604 | 23.31 | 6.2612 | 10.477 | 16.7382 |
| 11 | 23.647 | 23.386 | 5.5753 | 9.327 | 14.9023 |
| 12 | 23.686 | 23.453 | 4.9642 | 8.3037 | 13.2679 |
| 13 | 23.72 | 23.513 | 4.4199 | 7.3928 | 11.8127 |
| 14 | 23.751 | 23.567 | 3.9352 | 6.5819 | 10.5171 |
| 15 | 23.778 | 23.614 | 3.5036 | 5.8599 | 9.3635 |
| 16 | 23.803 | 23.657 | 3.1192 | 5.2171 | 8.3363 |
| Total | | | 152.7341 | 265.8364 | 418.571 |

| T room = | | 24 | T pipe = | | 20 | |
|---|---|---|---|---|---|---|
| h room= | | 10 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 24 | 24 | 0 | 0 | 0 | 263.48 |
| 1 | 23.72 | 23.346 | 2.6821 | 18.744 | 21.4261 | 164.12 |
| 2 | 23.369 | 22.659 | 6.3028 | 20.477 | 26.7798 | 119.52 |
| 3 | 23.079 | 22.197 | 9.2666 | 22.827 | 32.0936 | 95.895 |
| 4 | 22.873 | 21.912 | 11.348 | 24.515 | 35.863 | 82.72 |
| 5 | 22.735 | 21.739 | 12.732 | 25.577 | 38.309 | 74.731 |
| 6 | 22.645 | 21.634 | 13.633 | 26.227 | 39.86 | 69.85 |
| 7 | 22.587 | 21.571 | 14.212 | 26.623 | 40.835 | 66.851 |
| 8 | 22.55 | 21.532 | 14.583 | 26.864 | 41.447 | 65 |
| 9 | 22.527 | 21.507 | 14.819 | 27.011 | 41.83 | 63.854 |
| 10 | 22.512 | 21.493 | 14.969 | 27.102 | 42.071 | 63.141 |
| 11 | 22.503 | 21.483 | 15.064 | 27.158 | 42.222 | 62.697 |
| 12 | 22.497 | 21.478 | 15.125 | 27.193 | 42.318 | 62.42 |
| 13 | 22.493 | 21.474 | 15.163 | 27.215 | 42.378 | 62.246 |
| 14 | 22.49 | 21.472 | 15.187 | 27.228 | 42.415 | 62.137 |
| 15 | 22.489 | 21.47 | 15.202 | 27.237 | 42.439 | 62.069 |
| 16 | 22.488 | 21.47 | 15.212 | 27.242 | 42.454 | |
| Total | | | 205.5005 | 409.24 | 614.7405 | 1440.731 |

| discharging without radiation | | | | | |
|---|---|---|---|---|---|
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 22.488 | 21.47 | 15.212 | 27.242 | 42.454 |
| 1 | 22.543 | 21.608 | 14.691 | 24.508 | 39.199 |
| 2 | 22.634 | 21.806 | 13.766 | 22.21 | 35.976 |
| 3 | 22.737 | 21.999 | 12.721 | 20.161 | 32.882 |
| 4 | 22.84 | 22.175 | 11.688 | 18.362 | 30.05 |
| 5 | 22.937 | 22.335 | 10.712 | 16.751 | 27.463 |
| 6 | 23.027 | 22.48 | 9.8057 | 15.294 | 25.0997 |
| 7 | 23.11 | 22.611 | 8.9707 | 13.971 | 22.9417 |
| 8 | 23.186 | 22.731 | 8.2041 | 12.765 | 20.9691 |
| 9 | 23.255 | 22.841 | 7.5015 | 11.666 | 19.1675 |
| 10 | 23.319 | 22.94 | 6.8583 | 10.662 | 17.5203 |
| 11 | 23.378 | 23.031 | 6.2698 | 9.7456 | 16.0154 |
| 12 | 23.431 | 23.115 | 5.7316 | 8.908 | 14.6396 |
| 13 | 23.48 | 23.191 | 5.2394 | 8.1426 | 13.382 |
| 14 | 23.525 | 23.26 | 4.7895 | 7.443 | 12.2325 |
| 15 | 23.565 | 23.324 | 4.3781 | 6.8036 | 11.1817 |
| 16 | 23.603 | 23.382 | 4.0021 | 6.2191 | 10.2212 |
| Total | | | 150.5408 | 240.8539 | 391.3947 |

Table used to generate slab cooling graph

| concrete em =0.85<br>wood em =0.95 | T room =24<br>h pipe = 4300 | T pipe = 10<br>h room =10 | T pipe = 10<br>h room =10 |
|---|---|---|---|
| Time[h] | 70% Heat extr | slab capacity+ radiation | slab capacity no radiation |
| 1 | 5733.221667 | 78299.66088 | 63506.37654 |
| 2 | 5620.600417 | 80048.61612 | 65060.0424 |
| 3 | 4787.121111 | 81111.0996 | 66035.12364 |
| 4 | 4818.7125 | 81758.42244 | 66646.93932 |
| 5 | 4817.481667 | 82154.46384 | 67031.145 |
| 6 | 4387.305417 | 82398.00654 | 67271.95638 |
| 7 | 5251.760694 | 82744.88418 | 67640.22936 |
| 8 | 12614.60569 | 70298.71416 | 62454.36312 |
| 9 | 20561.27597 | 63104.41728 | 57320.39196 |
| 10 | 22916.88583 | 56279.30382 | 52389.90414 |
| 11 | 24009.04528 | 50136.10992 | 47877.30828 |
| 12 | 24918.42597 | 44656.62678 | 43755.7464 |
| 13 | 25661.23389 | 39777.1236 | 39990.62178 |
| 14 | 26142.07944 | 35432.0487 | 36552.34512 |
| 15 | 26010.38028 | 31562.22348 | 33409.96146 |
| 16 | 26008.53403 | 28114.84242 | 30538.88892 |
| 17 | 24056.02208 | 25043.01786 | 27915.00084 |
| 18 | 23078.94556 | 22307.14566 | 25516.90188 |
| 19 | 15537.42458 | 19868.53212 | 23324.56236 |
| 20 | 13962.98361 | 38462.44824 | 34137.90376 |
| 21 | 7008.570139 | 51797.66292 | 42666.40494 |
| 22 | 6692.040833 | 63174.06594 | 51133.95216 |
| 23 | 6435.617222 | 70735.72536 | 57139.66962 |
| 24 | 6641.781806 | 75430.40922 | 61037.26326 |

| concrete em =0.85<br>wood em =0.95 | T room = 24<br>h pipe = 4300 | T pipe =  18c<br>h room =10 | T pipe=     18c<br>h room = 10 |
|---|---|---|---|
| Time[h] | 70% Heat extr | slab capacity+ radiation | slab capacity no radiation |
| 1 | 5733.221667 | 32420.7684 | 27217.14858 |
| 2 | 5620.600417 | 33656.6907 | 27883.13544 |
| 3 | 4787.121111 | 34407.8037 | 28300.57218 |
| 4 | 4818.7125 | 34864.84458 | 28562.7789 |
| 5 | 4817.481667 | 35143.89444 | 28727.11332 |
| 6 | 4387.305417 | 35313.6915 | 28830.90348 |
| 7 | 5251.760694 | 35566.79382 | 28988.86482 |
| 8 | 12614.60569 | 32342.92578 | 26766.02556 |
| 9 | 20561.27597 | 28981.12608 | 24566.40252 |
| 10 | 22916.88583 | 25805.05614 | 22452.81606 |
| 11 | 24009.04528 | 22966.30422 | 20519.0415 |
| 12 | 24918.42597 | 20441.19888 | 18752.33268 |
| 13 | 25661.23389 | 18196.96428 | 17139.033 |
| 14 | 26142.07944 | 16200.36936 | 15665.03064 |
| 15 | 26010.38028 | 14424.10092 | 14318.48988 |
| 16 | 26008.53403 | 12842.66664 | 13088.03022 |
| 17 | 24056.02208 | 11434.89879 | 11963.63682 |
| 18 | 23078.94556 | 10181.63261 | 10935.61349 |
| 19 | 15537.42458 | 9065.47869 | 9996.312546 |
| 20 | 13962.98361 | 16483.65277 | 14630.40662 |
| 21 | 7008.570139 | 22227.93738 | 18285.7777 |
| 22 | 6692.040833 | 27136.57464 | 21914.74602 |
| 23 | 6435.617222 | 30396.86028 | 24488.5599 |
| 24 | 6641.781806 | 32420.7684 | 26158.76208 |

| concrete em =0.85<br>wood em =0.95 | h pipe = 4300<br>T room = 24 c | T pipe = 10<br>h room =10 | T pipe = 10<br>h room =10 | T pipe = 10<br>h room =5 |
|---|---|---|---|---|
| Time | 70% Heat extr | slab capacity+ radiation | slab capacity no radiation | slab capacity+ radiation |
| 1 | 5733.221667 | 52780.93812 | 21448.60074 | 63563.27904 |
| 2 | 5620.600417 | 53600.78934 | 21613.8456 | 65102.83308 |
| 3 | 4787.121111 | 54128.38932 | 21734.02368 | 66069.26514 |
| 4 | 4818.7125 | 54467.52822 | 21819.60504 | 66676.0734 |
| 5 | 4817.481667 | 54686.03382 | 21879.69408 | 67057.09254 |
| 6 | 4387.305417 | 54826.24158 | 21921.57432 | 67296.53826 |
| 7 | 5251.760694 | 51439.86 | 21012.04476 | 67662.07992 |
| 8 | 12614.60569 | 48129.95538 | 20402.04996 | 62523.10134 |
| 9 | 20561.27597 | 44912.0052 | 19862.61426 | 57446.4879 |
| 10 | 22916.88583 | 41909.37408 | 19375.52886 | 52546.95504 |
| 11 | 24009.04528 | 39107.03976 | 18898.00308 | 48047.10534 |
| 12 | 24918.42597 | 36480.87558 | 18431.8578 | 43926.4539 |
| 13 | 25661.23389 | 34024.96368 | 17976.18258 | 40154.50098 |
| 14 | 26142.07944 | 31729.28922 | 17531.43264 | 36703.47816 |
| 15 | 26010.38028 | 29584.29258 | 17098.0632 | 33545.61702 |
| 16 | 26008.53403 | 27581.32458 | 16674.7086 | 30657.24612 |
| 17 | 24056.02208 | 25710.8256 | 16262.27928 | 28015.14924 |
| 18 | 23078.94556 | 23964.60168 | 15859.40958 | 25598.38626 |
| 19 | 15537.42458 | 22334.45886 | 15467.00994 | 23388.29316 |
| 20 | 13962.98361 | 36248.25816 | 21271.15598 | 34331.14465 |
| 21 | 7008.570139 | 42108.30522 | 20580.04098 | 42908.12676 |
| 22 | 6692.040833 | 46547.15544 | 20693.84598 | 51312.85362 |
| 23 | 6435.617222 | 49546.1448 | 20965.1571 | 57259.39248 |
| 24 | 6641.781806 | 51509.05344 | 21230.55036 | 61117.8372 |

| concrete em =0.85<br>wood em =0.95 | h pipe = 4300<br>T room = 24 c | T pipe = 10<br>h room =5 | T pipe = 10<br>h room =2 | T pipe = 10<br>h room =2 |
|---|---|---|---|---|
| Time | 70% Heat extr | slab capacity no radiation | slab capacity+ radiation | slab capacity no radiation |
| 1 | 5733.221667 | 41302.1106 | 51509.05344 | 21230.55036 |
| 2 | 5620.600417 | 42313.15422 | 52780.93812 | 21448.60074 |
| 3 | 4787.121111 | 42980.05152 | 53600.78934 | 21613.8456 |
| 4 | 4818.7125 | 43419.79404 | 54128.38932 | 21734.02368 |
| 5 | 4817.481667 | 43707.9483 | 54467.52822 | 21819.60504 |
| 6 | 4387.305417 | 43896.8646 | 54686.03382 | 21879.69408 |
| 7 | 5251.760694 | 44211.87684 | 55035.64278 | 21992.13342 |
| 8 | 12614.60569 | 41632.1451 | 51439.86 | 21012.04476 |
| 9 | 20561.27597 | 39435.7086 | 48129.95538 | 20402.04996 |
| 10 | 22916.88583 | 37321.66692 | 44912.0052 | 19862.61426 |
| 11 | 24009.04528 | 35361.94482 | 41909.37408 | 19375.52886 |
| 12 | 24918.42597 | 33498.27414 | 39107.03976 | 18898.00308 |
| 13 | 25661.23389 | 31729.28922 | 36480.87558 | 18431.8578 |
| 14 | 26142.07944 | 30052.71396 | 34024.96368 | 17976.18258 |
| 15 | 26010.38028 | 28464.45138 | 31729.28922 | 17531.43264 |
| 16 | 26008.53403 | 26959.49406 | 29584.29258 | 17098.0632 |
| 17 | 24056.02208 | 25535.11068 | 27581.32458 | 16674.7086 |
| 18 | 23078.94556 | 24185.38338 | 25710.8256 | 16262.27928 |
| 19 | 15537.42458 | 22907.12562 | 23964.60168 | 15859.40958 |
| 20 | 13962.98361 | 28819.5685 | 31363.29234 | 24836.12037 |
| 21 | 7008.570139 | 30645.4104 | 36248.25816 | 21271.15598 |
| 22 | 6692.040833 | 34387.77402 | 42108.30522 | 20580.04098 |
| 23 | 6435.617222 | 37542.90384 | 46547.15544 | 20693.84598 |
| 24 | 6641.781806 | 39783.9519 | 49546.1448 | 20965.1571 |

| concrete em =0.85<br>wood em =0.95 | h pipe = 4300<br>T room = 24 c | Ti=18 h=2 | Ti=18 h=2 | Ti=20 h=2 | Ti=20 h=2 |
|---|---|---|---|---|---|
| Time[h] | 70% Heat extr | slab capacity+ radiation | slab capacity no radiation | slab capacity+ radiation | slab capacity no radiation |
| 1 | 5733.221667 | 22310.78742 | 9098.70975 | 14913.0072 | 6065.943066 |
| 2 | 5620.600417 | 22868.88714 | 9192.302982 | 15287.19804 | 6128.217162 |
| 3 | 4787.121111 | 23228.05572 | 9262.907604 | 15528.00942 | 6175.377954 |
| 4 | 4818.7125 | 23458.85226 | 9314.620596 | 15682.78422 | 6209.929152 |
| 5 | 4817.481667 | 23607.25398 | 9351.58446 | 15782.02218 | 6234.328944 |
| 6 | 4387.305417 | 23702.39496 | 9377.167824 | 15845.75298 | 6251.399694 |
| 7 | 5251.760694 | 23853.98322 | 9425.3301 | 15947.26704 | 6283.492704 |
| 8 | 12614.60569 | 22272.54894 | 9005.070996 | 14886.14922 | 6003.532404 |
| 9 | 20561.27597 | 20806.28532 | 8744.09337 | 13900.59792 | 5829.228666 |
| 10 | 22916.88583 | 19383.72282 | 8512.340868 | 12945.09114 | 5674.954608 |
| 11 | 24009.04528 | 18059.94306 | 8303.804586 | 12056.04648 | 5535.884898 |
| 12 | 24918.42597 | 16827.2073 | 8099.319762 | 11229.36696 | 5399.500986 |
| 13 | 25661.23389 | 15676.86636 | 7899.341616 | 10458.17876 | 5266.21257 |
| 14 | 26142.07944 | 14603.4576 | 7704.097758 | 9738.885636 | 5136.065172 |
| 15 | 26010.38028 | 13602.88404 | 7513.542666 | 9069.029406 | 5009.058792 |
| 16 | 26008.53403 | 12669.68304 | 7327.630818 | 8444.55861 | 4885.102386 |
| 17 | 24056.02208 | 11800.21284 | 7146.316692 | 7863.197148 | 4764.241476 |
| 18 | 23078.94556 | 10989.92124 | 6969.4182 | 7321.53087 | 4646.293974 |
| 19 | 15537.42458 | 10234.39261 | 6796.935342 | 6816.873978 | 4531.305402 |
| 20 | 13962.98361 | 13441.69064 | 10644.22717 | 8960.823612 | 7096.292566 |
| 21 | 7008.570139 | 15586.09549 | 9116.326764 | 10399.45538 | 6077.278044 |
| 22 | 6692.040833 | 18168.74064 | 8820.024066 | 12133.11523 | 5879.940174 |
| 23 | 6435.617222 | 20125.73142 | 8868.82365 | 13446.69806 | 5912.579448 |
| 24 | 6641.781806 | 21447.23508 | 8984.813706 | 14333.51214 | 5990.148936 |

| concrete em =0.85<br>wood em =0.95 | T room =24<br>h pipe =4300 | T pipe =20<br>h room =10 | T pipe =20<br>h room =10 |
|---|---|---|---|
| Time | 70% Heat extr | slab capacity+ radiation | slab capacity no radiation |
| 1 | 5733.221667 | 22454.63694 | 18145.0692 |
| 2 | 5620.600417 | 22955.83416 | 18588.9087 |
| 3 | 4787.121111 | 23260.83156 | 18867.50334 |
| 4 | 4818.7125 | 23446.56132 | 19041.8526 |
| 5 | 4817.481667 | 23559.9111 | 19151.56062 |
| 6 | 4387.305417 | 23629.10454 | 19220.29884 |
| 7 | 5251.760694 | 23728.3425 | 19325.90988 |
| 8 | 12614.60569 | 21575.1519 | 17844.16878 |
| 9 | 20561.27597 | 19328.6412 | 16376.99472 |
| 10 | 22916.88583 | 17207.77122 | 14968.54404 |
| 11 | 24009.04528 | 15311.77992 | 13679.361 |
| 12 | 24918.42597 | 13627.0107 | 12501.70686 |
| 13 | 25661.23389 | 12129.3369 | 11425.88543 |
| 14 | 26142.07944 | 10797.36318 | 10443.52067 |
| 15 | 26010.38028 | 9612.744174 | 9545.553702 |
| 16 | 26008.53403 | 8558.044956 | 8725.42935 |
| 17 | 24056.02208 | 7619.563404 | 7975.590966 |
| 18 | 23078.94556 | 6783.825006 | 7290.530388 |
| 19 | 15537.42458 | 6039.813438 | 6664.238712 |
| 20 | 13962.98361 | 10989.10184 | 9753.589242 |
| 21 | 7008.570139 | 14823.28334 | 12190.70056 |
| 22 | 6692.040833 | 18101.36808 | 14609.64859 |
| 23 | 6435.617222 | 20278.68534 | 16325.55486 |
| 24 | 6641.781806 | 21629.7783 | 17439.02298 |

Data used to calculate T space: Heating

| h= | 10 | A= | 455.22 | | |
|---|---|---|---|---|---|
| Time [hour] | T out [C] | T Floor [C] | T Ceiling [C] | 70% Heat Add | T space [C] |
| 1 | -5 | 23.31 | 23.896 | 10170.70406 | 24.72011964 |
| 2 | -6.7 | 23.329 | 23.916 | 10463.49879 | 24.77177934 |
| 3 | -7.2 | 23.34 | 23.928 | 10581.94599 | 24.79628922 |
| 4 | -6.7 | 23.348 | 23.935 | 10577.86372 | 24.80334084 |
| 5 | -7.2 | 23.352 | 23.94 | 10692.86458 | 24.82047219 |
| 6 | -7.2 | 23.355 | 23.942 | 10772.45847 | 24.83171454 |
| 7 | -7.2 | 23.359 | 23.946 | 10864.85303 | 24.84586288 |
| 8 | -6.7 | 23.326 | 23.834 | 10346.93888 | 24.71647674 |
| 9 | -5.6 | 23.275 | 23.707 | 9836.655889 | 24.57142879 |
| 10 | -3.9 | 23.22 | 23.591 | 8919.787625 | 24.38522273 |
| 11 | -2.2 | 23.168 | 23.488 | 7611.391278 | 24.1640124 |
| 12 | -1.1 | 23.119 | 23.397 | 6605.985069 | 23.98358159 |
| 13 | 0.6 | 23.075 | 23.317 | 5717.815736 | 23.82402774 |
| 14 | 1.1 | 23.035 | 23.247 | 5282.593069 | 23.72122418 |
| 15 | 2.2 | 22.999 | 23.184 | 4995.378111 | 23.64017736 |
| 16 | 2.8 | 22.968 | 23.129 | 5439.955111 | 23.64600836 |
| 17 | 1.7 | 22.94 | 23.08 | 6380.496403 | 23.7108146 |
| 18 | 1.1 | 22.914 | 23.036 | 7443.874861 | 23.7926129 |
| 19 | 0 | 22.892 | 22.997 | 8831.085569 | 23.91447996 |
| 20 | 0 | 22.856 | 23.231 | 9050.584181 | 24.03758903 |
| 21 | -0.6 | 23.036 | 23.529 | 9667.006028 | 24.34429496 |
| 22 | -0.6 | 23.155 | 23.703 | 9526.260236 | 24.47533586 |
| 23 | -1.1 | 23.231 | 23.803 | 9698.474333 | 24.58225134 |
| 24 | -1.7 | 23.28 | 23.861 | 9669.529236 | 24.6325721 |

## Simulation Data for Heating

| | | | | | | |
|---|---|---|---|---|---|---|
| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 25 |
| wood pine emissivity = | | 0.95 | h room = | 10 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 22 | 22 | 0 | 0 | 0 | |
| 1 | 22.591 | 22.739 | 2.1233 | 10.101 | 12.2243 | 195.75 |
| 2 | 22.856 | 23.231 | 1.9096 | 12.414 | 14.3236 | 119.54 |
| 3 | 23.036 | 23.529 | 4.7762 | 15.358 | 20.1342 | 85.246 |
| 4 | 23.155 | 23.703 | 6.6922 | 17.321 | 24.0132 | 67.78 |
| 5 | 23.231 | 23.803 | 7.9262 | 18.493 | 26.4192 | 58.619 |
| 6 | 23.28 | 23.861 | 8.7072 | 19.18 | 27.8872 | 53.263 |
| 7 | 23.31 | 23.896 | 9.1968 | 19.583 | 28.7798 | 50.101 |
| 8 | 23.329 | 23.916 | 9.502 | 19.821 | 29.323 | 48.22 |
| 9 | 23.34 | 23.928 | 9.6914 | 19.961 | 29.6524 | 47.094 |
| 10 | 23.348 | 23.935 | 9.8087 | 20.045 | 29.8537 | 46.417 |
| 11 | 23.352 | 23.94 | 9.8812 | 20.096 | 29.9772 | 46.008 |
| 12 | 23.355 | 23.942 | 9.926 | 20.126 | 30.052 | 45.76 |
| 13 | 23.357 | 23.944 | 9.9535 | 20.145 | 30.0985 | 45.61 |
| 14 | 23.358 | 23.945 | 9.9705 | 20.156 | 30.1265 | 45.518 |
| 15 | 23.358 | 23.945 | 9.9809 | 20.163 | 30.1439 | 45.462 |
| 16 | 23.359 | 23.946 | 9.9874 | 20.167 | 30.1544 | 45.428 |
| Total | | | 130.0331 | 293.13 | 423.1631 | 1045.816 |
| discharging with radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 23.359 | 23.946 | 9.9874 | 20.167 | 30.1544 | |
| 1 | 23.326 | 23.834 | 9.5289 | 17.881 | 27.4099 | |
| 2 | 23.275 | 23.707 | 8.7471 | 15.799 | 24.5461 | |
| 3 | 23.22 | 23.591 | 7.8851 | 13.962 | 21.8471 | |
| 4 | 23.168 | 23.488 | 7.0528 | 12.384 | 19.4368 | |
| 5 | 23.119 | 23.397 | 6.2856 | 11.01 | 17.2956 | |
| 6 | 23.075 | 23.317 | 5.5911 | 9.8023 | 15.3934 | |
| 7 | 23.035 | 23.247 | 4.9673 | 8.7354 | 13.7027 | |
| 8 | 22.999 | 23.184 | 4.4092 | 7.7899 | 12.1991 | |
| 9 | 22.968 | 23.129 | 3.911 | 6.9503 | 10.8613 | |
| 10 | 22.94 | 23.08 | 3.4667 | 6.204 | 9.6707 | |
| 11 | 22.914 | 23.036 | 3.0707 | 5.5402 | 8.6109 | |
| 12 | 22.892 | 22.997 | 2.7179 | 4.9494 | 7.6673 | |
| 13 | 22.872 | 22.962 | 2.4037 | 4.4236 | 6.8273 | |
| 14 | 22.854 | 22.931 | 2.1238 | 3.9555 | 6.0793 | |
| 15 | 22.838 | 22.903 | 1.8746 | 3.5388 | 5.4134 | |
| 16 | 22.824 | 22.879 | 1.6527 | 3.1677 | 4.8204 | |
| Total | | | 85.6756 | 156.2601 | 241.9357 | |

| T room = | 24 | T pipe = | 25 |
|---|---|---|---|
| h room = | 10 | h pipe = | 4300 |

charging without radiation

| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
|---|---|---|---|---|---|---|
| 0 | 22 | 22 | 0 | 0 | 0 | 197.61 |
| 1 | 22.225 | 22.609 | 2.0116 | 14.058 | 16.0696 | 123.09 |
| 2 | 22.492 | 23.105 | 4.7271 | 15.358 | 20.0851 | 89.643 |
| 3 | 22.707 | 23.427 | 6.95 | 17.121 | 24.071 | 71.922 |
| 4 | 22.858 | 23.624 | 8.5111 | 18.387 | 26.8981 | 62.04 |
| 5 | 22.959 | 23.743 | 9.5493 | 19.183 | 28.7323 | 56.048 |
| 6 | 23.025 | 23.815 | 10.225 | 19.67 | 29.895 | 52.387 |
| 7 | 23.067 | 23.859 | 10.659 | 19.967 | 30.626 | 50.138 |
| 8 | 23.094 | 23.886 | 10.937 | 20.148 | 31.085 | 48.75 |
| 9 | 23.111 | 23.903 | 11.114 | 20.259 | 31.373 | 47.89 |
| 10 | 23.122 | 23.913 | 11.227 | 20.327 | 31.554 | 47.356 |
| 11 | 23.129 | 23.919 | 11.298 | 20.369 | 31.667 | 47.023 |
| 12 | 23.133 | 23.923 | 11.343 | 20.395 | 31.738 | 46.815 |
| 13 | 23.136 | 23.926 | 11.372 | 20.411 | 31.783 | 46.685 |
| 14 | 23.138 | 23.927 | 11.39 | 20.421 | 31.811 | 46.603 |
| 15 | 23.139 | 23.928 | 11.402 | 20.427 | 31.829 | 46.552 |
| 16 | 23.14 | 23.929 | 11.409 | 20.431 | 31.84 | |
| Total | | | 154.1251 | 306.932 | 461.0571 | 1080.552 |

discharging without radiation

| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
|---|---|---|---|---|---|
| 0 | 23.14 | 23.929 | 11.409 | 20.431 | 31.84 |
| 1 | 23.096 | 23.801 | 11.018 | 18.381 | 29.399 |
| 2 | 23.026 | 23.648 | 10.325 | 16.658 | 26.983 |
| 3 | 22.948 | 23.503 | 9.5409 | 15.121 | 24.6619 |
| 4 | 22.871 | 23.371 | 8.766 | 13.771 | 22.537 |
| 5 | 22.798 | 23.251 | 8.0339 | 12.563 | 20.5969 |
| 6 | 22.73 | 23.142 | 7.3543 | 11.471 | 18.8253 |
| 7 | 22.668 | 23.043 | 6.728 | 10.478 | 17.206 |
| 8 | 22.611 | 22.953 | 6.153 | 9.5741 | 15.7271 |
| 9 | 22.559 | 22.871 | 5.6261 | 8.7495 | 14.3756 |
| 10 | 22.511 | 22.796 | 5.1437 | 7.9968 | 13.1405 |
| 11 | 22.467 | 22.728 | 4.7023 | 7.3092 | 12.0115 |
| 12 | 22.427 | 22.665 | 4.2987 | 6.681 | 10.9797 |
| 13 | 22.39 | 22.608 | 3.9296 | 6.1069 | 10.0365 |
| 14 | 22.357 | 22.556 | 3.5921 | 5.5823 | 9.1744 |
| 15 | 22.326 | 22.508 | 3.2836 | 5.1027 | 8.3863 |
| 16 | 22.298 | 22.464 | 3.0016 | 4.6644 | 7.666 |
| Total | | | 112.9058 | 180.6409 | 293.5467 |

| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 30 |
|---|---|---|---|---|---|---|
| wood pine emissivity = | | 0.95 | h room = | 10 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 22 | 22 | 0 | 0 | 0 | 525.79 |
| 1 | 22.888 | 23.666 | 2.289 | 35.599 | 37.888 | 326.86 |
| 2 | 23.495 | 24.88 | 11.493 | 43.451 | 54.944 | 240.19 |
| 3 | 23.94 | 25.626 | 18.666 | 51.235 | 69.901 | 199.92 |
| 4 | 24.241 | 26.062 | 23.532 | 56.293 | 79.825 | 176.74 |
| 5 | 24.435 | 26.315 | 26.679 | 59.297 | 85.976 | 163.18 |
| 6 | 24.558 | 26.463 | 28.672 | 61.053 | 89.725 | 155.18 |
| 7 | 24.635 | 26.549 | 29.921 | 62.082 | 92.003 | 150.42 |
| 8 | 24.683 | 26.6 | 30.699 | 62.688 | 93.387 | 147.58 |
| 9 | 24.713 | 26.631 | 31.182 | 63.048 | 94.23 | 145.86 |
| 10 | 24.731 | 26.649 | 31.481 | 63.262 | 94.743 | 144.83 |
| 11 | 24.742 | 26.66 | 31.665 | 63.39 | 95.055 | 144.2 |
| 12 | 24.749 | 26.667 | 31.779 | 63.468 | 95.247 | 143.82 |
| 13 | 24.754 | 26.671 | 31.849 | 63.515 | 95.364 | 143.59 |
| 14 | 24.756 | 26.673 | 31.892 | 63.543 | 95.435 | 143.45 |
| 15 | 24.758 | 26.675 | 31.919 | 63.56 | 95.479 | 143.36 |
| 16 | 24.759 | 26.676 | 31.935 | 63.571 | 95.506 | |
| Total | | | 425.653 | 939.055 | 1364.708 | 2569.18 |

| discharging with radiation | | | | | |
|---|---|---|---|---|---|
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 24.759 | 26.676 | 31.935 | 63.571 | 95.506 |
| 1 | 24.656 | 26.324 | 30.477 | 56.312 | 86.789 |
| 2 | 24.496 | 25.922 | 27.994 | 49.693 | 77.687 |
| 3 | 24.322 | 25.555 | 25.259 | 43.855 | 69.114 |
| 4 | 24.155 | 25.23 | 22.621 | 38.846 | 61.467 |
| 5 | 24.001 | 24.944 | 20.191 | 34.487 | 54.678 |
| 6 | 23.861 | 24.693 | 17.991 | 30.659 | 48.65 |
| 7 | 23.736 | 24.47 | 16.017 | 27.279 | 43.296 |
| 8 | 23.624 | 24.273 | 14.252 | 24.285 | 38.537 |
| 9 | 23.524 | 24.098 | 12.676 | 21.628 | 34.304 |
| 10 | 23.435 | 23.942 | 11.272 | 19.266 | 30.538 |
| 11 | 23.356 | 23.804 | 10.02 | 17.167 | 27.187 |
| 12 | 23.285 | 23.681 | 8.9056 | 15.299 | 24.2046 |
| 13 | 23.222 | 23.571 | 7.913 | 13.637 | 21.55 |
| 14 | 23.166 | 23.473 | 7.0292 | 12.158 | 19.1872 |
| 15 | 23.116 | 23.386 | 6.2422 | 10.842 | 17.0842 |
| 16 | 23.071 | 23.309 | 5.5416 | 9.6698 | 15.2114 |
| Total | | | 276.3366 | 488.6538 | 764.9904 |

| | | | | | | |
|---|---|---|---|---|---|---|
| T room = | | 24 | T pipe = | | 30 | |
| h room = | | 10 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 22 | 22 | 0 | 0 | 0 | 526.95 |
| 1 | 22.599 | 23.623 | 5.3643 | 37.489 | 42.8533 | 328.25 |
| 2 | 23.311 | 24.946 | 12.606 | 40.953 | 53.559 | 239.05 |
| 3 | 23.885 | 25.804 | 18.533 | 45.654 | 64.187 | 191.79 |
| 4 | 24.289 | 26.33 | 22.696 | 49.03 | 71.726 | 165.44 |
| 5 | 24.557 | 26.648 | 25.465 | 51.154 | 76.619 | 149.46 |
| 6 | 24.732 | 26.841 | 27.265 | 52.454 | 79.719 | 139.7 |
| 7 | 24.845 | 26.958 | 28.424 | 53.245 | 81.669 | 133.7 |
| 8 | 24.917 | 27.03 | 29.165 | 53.727 | 82.892 | 130 |
| 9 | 24.963 | 27.074 | 29.638 | 54.023 | 83.661 | 127.71 |
| 10 | 24.992 | 27.101 | 29.938 | 54.205 | 84.143 | 126.28 |
| 11 | 25.011 | 27.118 | 30.129 | 54.317 | 84.446 | 125.39 |
| 12 | 25.022 | 27.129 | 30.249 | 54.386 | 84.635 | 124.84 |
| 13 | 25.03 | 27.135 | 30.326 | 54.429 | 84.755 | 124.49 |
| 14 | 25.034 | 27.139 | 30.374 | 54.456 | 84.83 | 124.27 |
| 15 | 25.037 | 27.142 | 30.405 | 54.473 | 84.878 | 124.14 |
| 16 | 25.039 | 27.143 | 30.424 | 54.484 | 84.908 | |
| Total | | | 411.0013 | 818.479 | 1229.48 | 2881.46 |

| | | | | | |
|---|---|---|---|---|---|
| discharging without radiation | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 25.039 | 27.143 | 30.424 | 54.484 | 84.908 |
| 1 | 24.923 | 26.801 | 29.382 | 49.016 | 78.398 |
| 2 | 24.735 | 26.394 | 27.533 | 44.421 | 71.954 |
| 3 | 24.527 | 26.008 | 25.443 | 40.322 | 65.765 |
| 4 | 24.322 | 25.655 | 23.376 | 36.724 | 60.1 |
| 5 | 24.128 | 25.335 | 21.424 | 33.502 | 54.926 |
| 6 | 23.948 | 25.045 | 19.611 | 30.588 | 50.199 |
| 7 | 23.782 | 24.782 | 17.941 | 27.941 | 45.882 |
| 8 | 23.629 | 24.542 | 16.408 | 25.531 | 41.939 |
| 9 | 23.49 | 24.323 | 15.003 | 23.332 | 38.335 |
| 10 | 23.362 | 24.123 | 13.717 | 21.325 | 35.042 |
| 11 | 23.245 | 23.94 | 12.54 | 19.491 | 32.031 |
| 12 | 23.138 | 23.774 | 11.463 | 17.816 | 29.279 |
| 13 | 23.041 | 23.621 | 10.479 | 16.285 | 26.764 |
| 14 | 22.951 | 23.482 | 9.579 | 14.886 | 24.465 |
| 15 | 22.87 | 23.355 | 8.7563 | 13.607 | 22.3633 |
| 16 | 22.795 | 23.238 | 8.0042 | 12.438 | 20.4422 |
| Total | | | 301.0835 | 481.709 | 782.7925 |

| concrete emissivity = | | 0.85 | T room = | 24 | T pipe = | 27 |
|---|---|---|---|---|---|---|
| wood pine emissivity = | | 0.95 | h room = | 10 | h pipe = | 4300 |
| Charging with radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 22 | 22 | 0 | 0 | 0 | 330.03 |
| 1 | 22.297 | 22.926 | 4.1818 | 25.933 | 30.1148 | 207.31 |
| 2 | 22.639 | 23.65 | 9.5727 | 31.065 | 40.6377 | 156.41 |
| 3 | 22.907 | 24.1 | 13.871 | 35.797 | 49.668 | 131.99 |
| 4 | 23.089 | 24.364 | 16.816 | 38.854 | 55.67 | 117.91 |
| 5 | 23.208 | 24.518 | 18.726 | 40.668 | 59.394 | 109.68 |
| 6 | 23.283 | 24.608 | 19.936 | 41.729 | 61.665 | 104.81 |
| 7 | 23.33 | 24.661 | 20.695 | 42.351 | 63.046 | 101.92 |
| 8 | 23.359 | 24.692 | 21.168 | 42.718 | 63.886 | 100.18 |
| 9 | 23.377 | 24.71 | 21.462 | 42.935 | 64.397 | 99.138 |
| 10 | 23.388 | 24.721 | 21.643 | 43.065 | 64.708 | 98.507 |
| 11 | 23.395 | 24.728 | 21.756 | 43.143 | 64.899 | 98.125 |
| 12 | 23.4 | 24.732 | 21.825 | 43.19 | 65.015 | 97.893 |
| 13 | 23.402 | 24.735 | 21.867 | 43.218 | 65.085 | 97.751 |
| 14 | 23.404 | 24.736 | 21.894 | 43.235 | 65.129 | 97.665 |
| 15 | 23.405 | 24.737 | 21.91 | 43.246 | 65.156 | 97.612 |
| 16 | 23.405 | 24.738 | 21.92 | 43.252 | 65.172 | |
| Total | | | 299.2435 | 644.399 | 943.6425 | 2046.931 |
| discharging with radiation | | | | | | |
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf | |
| 0 | 23.405 | 24.738 | 21.92 | 43.252 | 65.172 | |
| 1 | 23.335 | 24.497 | 20.925 | 38.313 | 59.238 | |
| 2 | 23.225 | 24.223 | 19.233 | 33.814 | 53.047 | |
| 3 | 23.106 | 23.972 | 17.369 | 29.842 | 47.211 | |
| 4 | 22.991 | 23.749 | 15.569 | 26.432 | 42.001 | |
| 5 | 22.886 | 23.554 | 13.911 | 23.463 | 37.374 | |
| 6 | 22.79 | 23.381 | 12.411 | 20.854 | 33.265 | |
| 7 | 22.705 | 23.229 | 11.063 | 18.549 | 29.612 | |
| 8 | 22.628 | 23.094 | 9.8574 | 16.506 | 26.3634 | |
| 9 | 22.559 | 22.974 | 8.7812 | 14.692 | 23.4732 | |
| 10 | 22.498 | 22.867 | 7.8214 | 13.08 | 20.9014 | |
| 11 | 22.444 | 22.772 | 6.9661 | 11.646 | 18.6121 | |
| 12 | 22.395 | 22.688 | 6.2041 | 10.37 | 16.5741 | |
| 13 | 22.352 | 22.612 | 5.5253 | 9.2347 | 14.76 | |
| 14 | 22.314 | 22.545 | 4.9207 | 8.2236 | 13.1443 | |
| 15 | 22.279 | 22.486 | 4.3823 | 7.3234 | 11.7057 | |
| 16 | 22.249 | 22.433 | 3.9029 | 6.5219 | 10.4248 | |
| Total | | | 190.7624 | 332.1166 | 522.879 | |

| T room = | | 24 | T pipe = | | 27 | |
|---|---|---|---|---|---|---|
| h room = | | 10 | h pipe = | | 4300 | |
| charging without radiation | | | | | | |
| Time | T floor | T ceiling | q floor | q ceiling | qc + qf | q pipe surface |
| 0 | 22 | 22 | 0 | 0 | 0 | |
| 1 | 22.374 | 23.014 | 3.3526 | 23.43 | 26.7826 | 329.34 |
| 2 | 22.819 | 23.841 | 7.8785 | 25.596 | 33.4745 | 205.15 |
| 3 | 23.178 | 24.378 | 11.583 | 28.534 | 40.117 | 149.4 |
| 4 | 23.43 | 24.706 | 14.185 | 30.644 | 44.829 | 119.87 |
| 5 | 23.598 | 24.905 | 15.915 | 31.971 | 47.886 | 103.4 |
| 6 | 23.708 | 25.026 | 17.041 | 32.784 | 49.825 | 93.414 |
| 7 | 23.778 | 25.099 | 17.765 | 33.278 | 51.043 | 87.313 |
| 8 | 23.823 | 25.144 | 18.228 | 33.579 | 51.807 | 83.564 |
| 9 | 23.852 | 25.171 | 18.524 | 33.764 | 52.288 | 81.25 |
| 10 | 23.87 | 25.188 | 18.711 | 33.878 | 52.589 | 79.817 |
| 11 | 23.882 | 25.199 | 18.83 | 33.948 | 52.778 | 78.926 |
| 12 | 23.889 | 25.205 | 18.906 | 33.991 | 52.897 | 78.371 |
| 13 | 23.894 | 25.209 | 18.954 | 34.018 | 52.972 | 78.024 |
| 14 | 23.897 | 25.212 | 18.984 | 34.035 | 53.019 | 77.808 |
| 15 | 23.898 | 25.214 | 19.003 | 34.046 | 53.049 | 77.672 |
| 16 | 23.9 | 25.215 | 19.015 | 34.053 | 53.068 | 77.587 |
| Total | | | 256.8751 | 511.549 | 768.4241 | 1471.566 |

| discharging without radiation | | | | | |
|---|---|---|---|---|---|
| Time | T floor | Tceiling | q floor | q ceiling | qc + qf |
| 0 | 23.9 | 25.215 | 19.015 | 34.053 | 53.068 |
| 1 | 23.827 | 25.001 | 18.364 | 30.635 | 48.999 |
| 2 | 23.709 | 24.746 | 17.208 | 27.763 | 44.971 |
| 3 | 23.579 | 24.505 | 15.902 | 25.201 | 41.103 |
| 4 | 23.451 | 24.284 | 14.61 | 22.952 | 37.562 |
| 5 | 23.33 | 24.085 | 13.39 | 20.938 | 34.328 |
| 6 | 23.217 | 23.903 | 12.257 | 19.118 | 31.375 |
| 7 | 23.114 | 23.739 | 11.213 | 17.463 | 28.676 |
| 8 | 23.018 | 23.589 | 10.255 | 15.957 | 26.212 |
| 9 | 22.931 | 23.452 | 9.3768 | 14.583 | 23.9598 |
| 10 | 22.851 | 23.327 | 8.5728 | 13.328 | 21.9008 |
| 11 | 22.778 | 23.213 | 7.8372 | 12.182 | 20.0192 |
| 12 | 22.711 | 23.108 | 7.1645 | 11.135 | 18.2995 |
| 13 | 22.65 | 23.013 | 6.5493 | 10.178 | 16.7273 |
| 14 | 22.595 | 22.926 | 5.9869 | 9.3038 | 15.2907 |
| 15 | 22.543 | 22.847 | 5.4727 | 8.5045 | 13.9772 |
| 16 | 22.497 | 22.774 | 5.0026 | 7.7739 | 12.7765 |
| Total | | | 188.1768 | 301.0682 | 489.245 |

Table used to generate Heat Graphs

| concrete em =0.85<br>wood em =0.95 | h pipe = 4300<br>T room = 22c | T pipe = 25<br>h room =10 | T pipe = 25<br>h room =10 | T pipe = 27<br>h room =10 |
|---|---|---|---|---|
| Time | 70% Heat Added | slab +radiation | slab no radiation | slab + radiation |
| 1 | 10170.70406 | 12694.81118 | 13608.8019 | 28071.14 |
| 2 | 10463.49879 | 13101.14056 | 13941.56772 | 28699.8 |
| 3 | 10581.94599 | 13348.41606 | 14150.5137 | 29082.18 |
| 4 | 10577.86372 | 13498.36553 | 14281.61706 | 29314.8 |
| 5 | 10692.86458 | 13590.00131 | 14364.01188 | 29456.38 |
| 6 | 10772.45847 | 13646.22098 | 14415.45174 | 29543.32 |
| 7 | 10864.85303 | 13726.88597 | 14494.2048 | 29667.6 |
| 8 | 10346.93888 | 12477.53468 | 13383.01278 | 26966.32 |
| 9 | 9836.655889 | 11173.87564 | 12283.20126 | 24148.06 |
| 10 | 8919.787625 | 9945.236862 | 11226.59012 | 21491.39 |
| 11 | 7611.391278 | 8848.020096 | 10259.29314 | 19119.7 |
| 12 | 6605.985069 | 7873.303032 | 9376.120818 | 17013.39 |
| 13 | 5717.815736 | 7007.383548 | 8569.653066 | 15142.89 |
| 14 | 5282.593069 | 6237.743094 | 7832.51532 | 13479.97 |
| 15 | 4995.378111 | 5553.274302 | 7159.290462 | 12001.15 |
| 16 | 5439.955111 | 4944.280986 | 6544.060632 | 10685.47 |
| 17 | 6380.496403 | 4402.296054 | 5981.81841 | 9514.735 |
| 18 | 7443.874861 | 3919.853898 | 5467.87503 | 8472.6 |
| 19 | 8831.085569 | 3490.308306 | 4998.179034 | 7544.862 |
| 20 | 9050.584181 | 5564.745846 | 7315.203312 | 13708.86 |
| 21 | 9667.006028 | 6520.389192 | 9143.139222 | 18499.09 |
| 22 | 9526.260236 | 9165.490524 | 10957.60062 | 22609.87 |
| 23 | 9698.474333 | 10931.2889 | 12244.55308 | 25342.1 |
| 24 | 9669.529236 | 12026.54822 | 13079.51761 | 27037.34 |

| concrete em =0.85<br><br>wood em =0.95 | h pipe = 4300<br><br>T room = 22c | T pipe = 27<br><br>h room =10 | T pipe = 30<br><br>h room =10 | T pipe = 30c<br>h room =10 |
|---|---|---|---|---|
| Time | 70% Heat Added | slab,no radiation | slab + radiation | slab, no radiation |
| 1 | 10170.70406 | 22681.3365 | 40844.6145 | 36289.68 |
| 2 | 10463.49879 | 23235.79446 | 41881.60566 | 37177.36 |
| 3 | 10581.94599 | 23583.58254 | 42511.63014 | 37734.1 |
| 4 | 10577.86372 | 23802.54336 | 42895.3806 | 38084.16 |
| 5 | 10692.86458 | 23939.56458 | 43128.90846 | 38303.58 |
| 6 | 10772.45847 | 24025.60116 | 43270.9371 | 38441.51 |
| 7 | 10864.85303 | 24157.61496 | 43474.3312 | 38651.82 |
| 8 | 10346.93888 | 22305.32478 | 39506.3528 | 35688.34 |
| 9 | 9836.655889 | 20471.69862 | 35363.1224 | 32754.9 |
| 10 | 8919.787625 | 18710.90766 | 31460.6928 | 29937.54 |
| 11 | 7611.391278 | 17098.97364 | 27979.7784 | 27358.72 |
| 12 | 6605.985069 | 15626.79216 | 24889.4256 | 25003.41 |
| 13 | 5717.815736 | 14282.5275 | 22145.48 | 22851.59 |
| 14 | 5282.593069 | 13053.88872 | 19708.3392 | 20886.4 |
| 15 | 4995.378111 | 11932.22664 | 17542.0424 | 19091.47 |
| 16 | 5439.955111 | 10906.98016 | 15615.1808 | 17450.86 |
| 17 | 6380.496403 | 9969.682176 | 13900.8976 | 15951.82 |
| 18 | 7443.874861 | 9113.140224 | 12375.5224 | 14581.15 |
| 19 | 8831.085569 | 8330.29839 | 11017.93392 | 13328.39 |
| 20 | 9050.584181 | 12191.97517 | 17247.37536 | 19507.68 |
| 21 | 9667.006028 | 15238.26189 | 25011.60768 | 24381.13 |
| 22 | 9526.260236 | 18262.06074 | 31820.33322 | 29219.21 |
| 23 | 9698.474333 | 20407.05738 | 36337.9365 | 32651.11 |
| 24 | 9669.529236 | 21798.66492 | 39137.99472 | 34878.5 |

# APPENDIX C

# CHILLER PERFORMANCE DATA

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Condenser Entering Air Temperature | | | | | | | | | | | | |
| | 85 | | | | 95 | | | 105 | | | 115 | | |
| Evaper | unit size | tons | Kw input | EER | tons | Kw input | EER | tons | Kw input | EER | tons | Kw input | EER |
| 40 | 70 | 68.7 | 64.3 | 11.2 | 64.6 | 70.8 | 9.7 | 60.4 | 77.9 | 8 | 55.5 | 84.8 | 7.1 |
| | 80 | 78.8 | 75.6 | 11.2 | 74.4 | 83.1 | 9.7 | 69.8 | 91.3 | 8 | 65 | 100.4 | 7.2 |
| | 90 | 89.9 | 88.9 | 10.9 | 84.8 | 97 | 9.5 | 79.5 | 106.1 | 8 | 73.9 | 116.4 | 7 |
| | 100 | 99.9 | 101.7 | 10.6 | 94.2 | 110.5 | 9.3 | 88.2 | 120.5 | 8 | 81.9 | 131.9 | 6.9 |
| | 110 | 108 | 110.7 | 10.6 | 102 | 120.3 | 9.3 | 95.2 | 131.2 | 8 | 88.4 | 143.6 | 6.9 |
| | 125 | 119 | 122 | 10.8 | 112 | 132.3 | 9.4 | 105 | 144.1 | 8 | 97.5 | 157.5 | 7 |
| | | | | | | | | | | | | | |
| 42 | 70 | 71.1 | 65.1 | 11.5 | 66.9 | 71.6 | 10 | 62.6 | 78.7 | 9 | 57.1 | 84.8 | 7.3 |
| | 80 | 81.6 | 76.8 | 11.4 | 77.1 | 84.2 | 9.9 | 72.3 | 92.5 | 9 | 67.4 | 101.6 | 7.3 |
| | 90 | 93 | 90.3 | 11.1 | 87.8 | 98.4 | 9.7 | 82.3 | 107.5 | 8 | 76.5 | 117.8 | 7.2 |
| | 100 | 103 | 103.3 | 10.8 | 97.4 | 112 | 9.5 | 91.2 | 122.1 | 8 | 84.7 | 133.5 | 7.1 |
| | 110 | 111 | 112.4 | 10.8 | 105 | 121.9 | 9.5 | 98.4 | 132.9 | 8 | 91.5 | 145.3 | 7 |
| | 125 | 123 | 124 | 11 | 116 | 134.2 | 9.6 | 109 | 146.1 | 8 | 101 | 159.5 | 7.1 |
| | | | | | | | | | | | | | |
| 44 | 70 | 73.5 | 65.9 | 11.8 | 69.3 | 72.4 | 10 | 64.9 | 79.6 | 9 | 58.6 | 84.8 | 7.5 |
| | 80 | 84.5 | 78 | 11.7 | 79.8 | 85.4 | 10 | 74.9 | 93.7 | 9 | 69.9 | 102.8 | 7.5 |
| | 90 | 96.1 | 91.7 | 11.3 | 90.8 | 99.8 | 9.9 | 85.1 | 108.9 | 9 | 79.2 | 119.2 | 7.4 |
| | 100 | 107 | 104.9 | 11 | 101 | 113.6 | 9.7 | 94.3 | 123.7 | 8 | 87.6 | 135.1 | 7.2 |
| | 110 | 115 | 114.2 | 11 | 109 | 123.7 | 9.7 | 102 | 134.6 | 8 | 94.6 | 147.1 | 7.2 |
| | 125 | 127 | 126 | 11.1 | 120 | 136.2 | 9.8 | 112 | 148.1 | 9 | 104 | 161.5 | 7.3 |
| | | | | | | | | | | | | | |
| 46 | 70 | 76 | 66.8 | 12 | 71.7 | 73.2 | 11 | 67.2 | 80.5 | 9 | 60.2 | 84.8 | 7.7 |
| | 80 | 87.4 | 79.2 | 11.9 | 82.6 | 86.6 | 10 | 77.6 | 94.9 | 9 | 72.4 | 104.1 | 7.7 |
| | 90 | 99.4 | 93.1 | 11.6 | 93.8 | 101.2 | 10 | 88 | 110.4 | 9 | 81.7 | 120.4 | 7.5 |
| | 100 | 110 | 106.6 | 11.2 | 104 | 115.3 | 9.9 | 97.4 | 125.3 | 9 | 90.6 | 136.7 | 7.4 |
| | 110 | 119 | 116 | 11.2 | 112 | 125.5 | 9.9 | 105 | 136.4 | 9 | 97.7 | 148.9 | 7.4 |
| | 125 | 131 | 128 | 11.3 | 124 | 138.3 | 10 | 116 | 150.1 | 9 | 107 | 162.1 | 7.4 |
| | | | | | | | | | | | | | |
| 48 | 70 | 78.5 | 67.6 | 12.3 | 74.1 | 74.1 | 11 | 69.5 | 81.4 | 9 | 61.8 | 84.8 | 7.9 |
| | 80 | 90.4 | 80.4 | 12.1 | 85.4 | 87.9 | 11 | 80.3 | 96.2 | 9 | 74.4 | 104.7 | 7.9 |
| | 90 | 103 | 94.6 | 11.8 | 96.9 | 102.7 | 10 | 90.9 | 111.8 | 9 | 82.9 | 120.1 | 7.7 |
| | 100 | 114 | 108.3 | 11.4 | 107 | 117 | 10 | 101 | 127 | 9 | 92 | 136.7 | 7.5 |
| | 110 | 122 | 117.8 | 11.4 | 116 | 127.3 | 10 | 108 | 138.3 | 9 | 99.4 | 148.9 | 7.5 |
| | 125 | 136 | 130.2 | 11.5 | 128 | 140.4 | 10 | 120 | 152.2 | 9 | 107 | 162.1 | 7.5 |
| | | | | | | | | | | | | | |
| 50 | 70 | 81.1 | 68.5 | 12.6 | 76.5 | 75 | 11 | 71.8 | 82.3 | 10 | 63.4 | 84.8 | 8.1 |
| | 80 | 93.4 | 81.7 | 12.4 | 88.3 | 89.1 | 11 | 83 | 97.4 | 9 | 75.9 | 104.8 | 8 |
| | 90 | 106 | 96.2 | 12 | 100 | 104.2 | 11 | 93.9 | 113.3 | 9 | 84.3 | 120 | 7.8 |
| | 100 | 117 | 110.1 | 11.6 | 111 | 118.7 | 10 | 104 | 128.7 | 9 | 93.4 | 136.5 | 7.6 |
| | 110 | 126 | 119.7 | 11.6 | 119 | 129.2 | 10 | 112 | 140.1 | 9 | 101 | 148.7 | 7.6 |
| | 125 | 140 | 132.3 | 11.7 | 132 | 142.6 | 10 | 124 | 154.3 | 9 | 108 | 158.5 | 7.7 |

VITA

Ahmad Shelbaya graduated from the University of Florida in 2009 with Bachelor of Engineering degrees in Aerospace Engineering and Mechanical Engineering. His work experience at the University included extensive labwork as well as a position as a laboratory teaching assistant. His main interests during his undergraduate years were 3D CAD design, dynamic analysis, Finite Element Analysis, modeling and control systems.

Subsequent to earning his Bachelors' degrees, Ahmad pursued a Masters in Mechanical Engineer from the University of Tennessee at Chattanooga where he was pleased to choose the energy concentration under the experienced advisement of Dr. Prakash Dhamshala, Ph.D. P.E. Ahmad has actively used his extensive undergraduate design and analysis experience in heat transfer and thermodynamics applications. He also served as a graduate assistant in the department of Mechanical Engineering.

Prior to and intermittently during his Master's program, Ahmad accepted a position as a construction project manager. He was successful in this role which included management of all phases of construction.

Ahmad currently resides in Atlanta, Georgia with his wife. His personal hobbies include physical fitness, home-remodeling, and building computers.