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Design of a Thermally Homeostatic Building and Modeling of Its Natural Radiant Cooling Using Cooling Tower

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Abstract Thermal Homeostasis in Buildings (THiB) is a new concept consisting of two steps: thermal autonomy (architectural homeostasis) and thermal homeostasis (mechanical homeostasis). The first step is based on the architectural requirement of a building's envelope and its thermal mass, while the second one is based on the engineering requirement of hydronic equipment. Previous studies of homeostatic building were limited to a TABS-equipped single room in a commercial building. Here we investigate the possibility of thermal homeostasis in a small TABS-equipped building, and focus on the possibility of natural summer cooling in Paso Robles, CA, by using cooling tower alone. By showing the viability of natural cooling in one special case, albeit a case in one of the most favorable locations climatically, a case is made that the use of cooling tower in thermally homeostatic buildings should not be overlooked for general application in wider regions of other climatic zones.

Keywords: *thermally homeostatic building, building design, building energy modeling, TABS, cooling tower, hydronic radiant cooling, small commercial building*

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1. Introduction

Thermal Homeostasis in Buildings (THiB) is a new concept developed in two recently published articles [1,2]. Its development consists of two steps: thermal autonomy (architectural homeostasis) first and then thermal homeostasis (mechanical homeostasis). This new approach was called process assumption-based (dynamic) design method [1]. Thermal autonomy [1] is an "architectural" step that determines a building's passive features for keeping indoor operative temperature within a prescribed temperature range without HVAC equipment; a building that meets a constraint of a maximum indoor operative temperature variation under a given ambient temperature amplitude was called thermally autonomous building. The mechanical step engineers a building's active features for keeping indoor operative temperature at desirable temperature level with heat extraction equipment (i.e., heat pump, cooling tower, solar thermal panel, etc.) through thermally activated building systems (TABS). The possibility of achieving thermal homeostasis in an office building was investigated by applying a cooling tower in one summer in seven selected U.S. cities [2]. Instead of sizing equipment as a function of design peak hourly temperature as it is done in heat balance design approach of selecting HVAC equipment, it was shown that the conditions of using cooling tower depend on both "design-peak" daily-mean temperature and the diurnal temperature amplitude. The study indicated that homeostatic building with natural cooling (by cooling tower alone) is possible in locations of special meso-scale climatic condition, such as Sacramento, CA. In other locations the use of cooling tower alone can only achieve homeostasis partially.

The investigation in the previous articles [1,2] was a modeling study using an RC model that was built in Matlab/Simulink originally developed in Ref. [3]. It was applied to a TABS-equipped room in a large multi-story building located in Zürich, Switzerland, the design of which was already done. [4,5] In this paper, instead of a single room, a small commercial building in Paso Robles, California, is designed in Autodesk Revit, and then an RC model of the building is built to investigate the building thermal behavior. Here is the structure of this paper: the special geographical and climatic conditions of Paso Robles are introduced in Section 2; the detailed design of the building in Autodesk Revit is presented in Section 3; Section 4 models the building system in Simulink; the simulation results are in Section 5; after the discussions in Section 6, main conclusions are summarized at the end of this paper.

2. Special Geographical And Climatic Conditions Of Paso Robles

Large diurnal temperature amplitude is preferred for buildings to achieve thermal homeostasis and Paso Robles is an ideal location for thermally homeostatic buildings.

Paso Robles is located at 35°37′36″N and 120°41′24″W, approximately halfway between Los Angeles and San Francisco [6,7]. It is at the southern end of the Salinas River Valley [8], which is "approximately 75 km in length and 20-30 km in width, oriented in a NW-SE direction. The valley opens into Monterey Bay on the Pacific coast in the northwest and in the southeast it gradually merges into the coastal mountains. It is bounded by the Gabilan mountain range on the east and Sierra de Salinas Mountain on the west (Figure 1). Elevations of the surrounding mountains are typically near 900-1000 m above mean sea level. Fremont Peak (960.61 m) is NE of the city of Salinas within a distance of 15 km. Mt. Toro (1056.36 m) is WSW of Salinas within a distance of 10 km. North Chalone Peak (1001.21 m) is SSE of Salinas at a distance of ~40 km." [8]

"Typical daytime up-valley and nighttime down-valley winds prevail in the Salinas Valley. However, since it is a coastal valley this diurnal pattern is strongly influenced by the coastal winds and the land and sea breeze systems. During nighttime in the northern part of the valley, the land breeze regime results in the winds descending down the mountain slopes toward the Pacific Ocean. In the middle and southern part of the valley, the down-valley wind blows towards Monterey Bay (Figure 1). However, nighttime meteorological data for the study period shows significant periods of up-valley flows." [8]

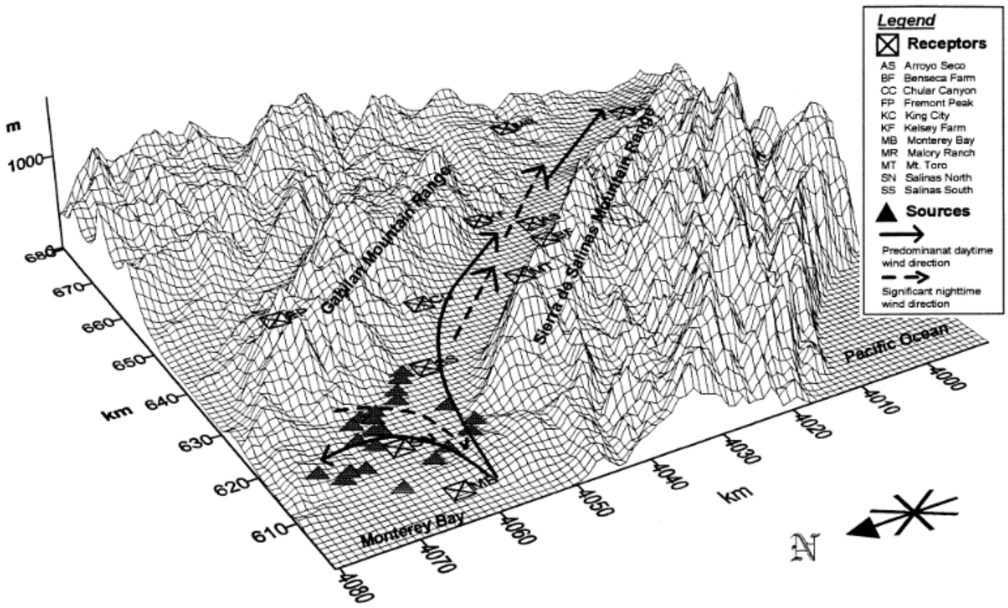

Figure 1. 3D view showing the sources, receptors and the main wind patterns in the Salinas river valley, CA [8]

Due to its special geographical condition, the Paso Robles area consists of two different climate types and classifications [6]: KCC type *BSk* and KCC type *Csb*. The types are based on the Köppen climate classification (KCC) system. The type *BSk* is a semi-arid, dry, steppe-type climate, and the type *Csb* is the typical, coastal Californian & "Mediterranean" type. The primary climate of the area is defined by long, hot, dry summers and brief, cool, sometimes rainy winters.

The long-lasting, mild autumns and occasional early springs give Paso Robles a unique climate. Summers are usually very hot, with daily temperatures frequently exceeding 100°F (38°C) and even exceeding 110°F (43°C) occasionally. The diurnal temperature swing in summers of Paso Robles is unusually very large: as much as 50°F (28°C). Winters in Paso Robles are often very cool and moist. The lowest temperature can reach to 25°F (-4°C).

According to a minimum 30-year weather record of Paso Robles, [9] the hottest month is July and the coldest month is December. In July, the average high and low temperatures are 93°F (34°C) and 54°F (12°C), respectively; the monthly mean temperature is 74°F (23°C); and the record high temperature is 115°F (46°C) occurred in 1961. In December, the average high and low temperatures are 59°F (15°C) and 34°F (1°C), respectively; the monthly mean temperature is 47°F (8°C); and the record low temperature is 8°F (-13°C) occurred in 1990.

Extending the record period, according to Ref. [10], the all-time record high temperature is 117°F (47°C) on August 13, 1933, and the record low temperature is 0°F (-18°C) on January 6, 1913. On average, there are 81.0 days with high temperatures of 90°F (32°C) or higher and 64.0 days with low temperatures of 32°F (0°C) or lower. At the Paso Robles FAA Airport [11], the record high temperature is 115°F (46°C) on June 15, 1961 and July 20, 1960, and the record low temperature is 8°F (-13°C) on December 22, 1990. There is an average of 86.7 days with highs of 90°F (32°C) or higher and an average of 53.6 days with lows of 32°F (0°C) or lower.

In summer time, Paso Robles has large diurnal temperature amplitudes because of the sea breeze from the Monterey Bay, which is critical for thermally homeostatic buildings. The real-time hour-by-hour dry-bulb temperatures of Paso Robles were requested by email from the website of the U.S. Department of Energy (DOE) [12]. In the four summer months from June to September in 2007, the amplitude distribution of the dry-bulb temperatures in Paso Robles is shown in Figure 2. As seen from the figure, nearly two thirds of the amplitudes are equal or greater than 20°C. This is the main reason that Paso Robles is selected as the building location.

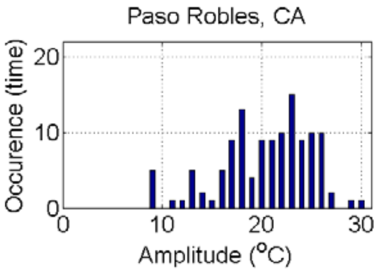

Figure 2. Amplitude distribution of dry-bulb ambient temperatures in Paso Robles (summer, 2007)

3. Design Of A Small Commercial Building In Autodesk Revit

The designed building is a stand-alone, one-story, south-facing, small commercial building located in Paso Robles, which is in Climate Zone 3 [13]. The building has a large lobby, a waiting room, a reception room, three offices and two restrooms. The total cooled and heated floor area is 2310 ft^2 (214.6 m^2). Figure 3 shows its main dimensions.

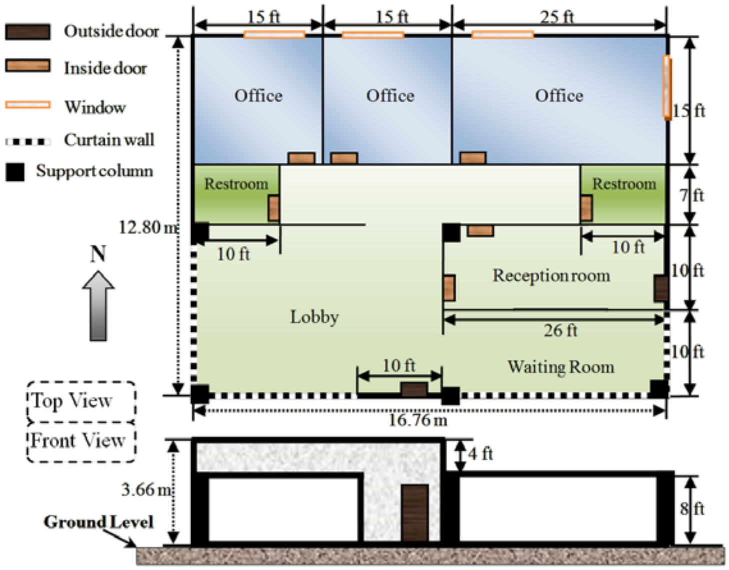

Figure 3. Schematic of the small commercial building

The small commercial building can be divided into two zones: the Front Zone (consisting of the lobby, the waiting room, the reception room and the two restrooms) and the Office Zone (consisting of the three offices). In the exterior walls of the front zone, large curtain walls are installed, which means that this zone is almost transparent to the outdoor environment.

The small commercial building is designed in the Autodesk Revit 2013. The configurations of the building are as follows.

3.1. Exterior Walls

The exterior walls are selected as "Basic Wall: CW 102-85-100p." The *U*-Factor of this kind of wall is 0.3463 W/m^2-K, which meets the Climate Zone 3's requirement (maximum 0.701 W/m^2-K for mass walls) in the ASHRAE Standard 90.1-2010 [13]. However, in this investigation, the *U*-Factors of the building envelope are expected to be as close as the values recommended by the Standard 90.1. Therefore, the insulation thickness will be modified and the differences of the building *U*-Factors and the recommended values will be smaller than 5%. After change the air layer thickness from 0.050 m to 0.014 m, the *U*-Factor of the wall becomes 0.6907 W/m^2-K (corresponding *R*-value is 1.4477 m^2-K/W). The thickness of the concrete in the walls is 0.100 m, which is exactly the recommended thickness for exterior walls in Ref. [1]. From exterior side to interior side, the exterior walls consist: 0.102m common brick, 0.014m air, 0.035m cavity fill, vapor retarder membrane layer, 0.100m concrete masonry units, and 0.012m gypsum wall board. The total thickness of the walls is 0.263m.

3.2. Floor

Below the ground level, the floor is selected as "Floor: Concrete Domestic 425mm 2," whose *U*-Factor is 0.6084 W/m^2-K that does not meet the Zone 3's requirement (maximum 0.606 W/m^2-K for mass floors). After adding a 0.005 m thick carpet, the *U*-Factor changed to 0.5790 W/m^2-K (corresponding *R*-value is 1.7270 m^2-K/W). The new floor type is renamed as "Floor: Concrete Domestic 430mm 2." It consists: 0.005m carpet, 0.050m sand/cement screed concrete, 0.175m cast-in-situ concrete, damp-proofing membrane layer, 0.050m rigid insulation, and 0.150m site-hardcore. For thermal protection purpose, the exterior walls are extended to the bottom of the floor.

3.3. Foundation walls

Below the exterior walls, there are 3 ft (0.914 m) depth foundation walls, which are selected as "Basic Wall: Foundation - 300mm Concrete." As its name implies, the walls are constructed by 0.300m-thick cast-in-situ concrete. The thermal resistance of the concrete walls is 0.2868 m^2-K/W.

3.4. Roofs

There are two roofs in the building: the upper level roof, which covers the lobby area, and the lower level roof, which covers other areas of the building. The two roofs have a 2 ft (0.610 m) extension from the outside surface of the exterior walls. The roofs have the same roof type—"Basic Roof: Warm Roof - Concrete." The *U*-Factor of this roof type is 0.5861 W/m^2-K, which does not meet the Zone 3's requirement (maximum 0.273 W/m^2-K for insulation entirely above deck roofs). The concrete thickness is 0.225m but is expected to be 0.250m for a TABS-equipped building.

Two modifications are made: the cast-in-situ concrete layer is changed from 0.175m to 0.200m; and the rigid insulation layer is thickened from 0.050m to 0.118m.

Now the *U*-Factor of the new roof type becomes 0.2723 W/m^2-K (corresponding *R*-value is 3.6731 m^2-K/W). The new roof type is renamed as "Basic Roof: Warm Roof – Concrete 250mm." It consists: 0.038m tile roofing, 0.118m rigid insulation, 0.020m asphalt-bitumen, roofing felt membrane layer, 0.050m sand/cement screed concrete, and 0.200m cast-in-situ concrete.

3.5. Interior walls

The type of the interior walls is selected as "Basic Wall: Interior – Blockwork 190," which is made of 0.190m concrete masonry units with 0.012m gypsum wall board on both sides.

3.6. Doors

There are two exterior doors (south and east) and seven interior doors in the building. All the doors are selected as "M_Single-Flush 0915 × 2134 mm," whose *U*-Factor is 3.7021 W/m^2-K (Zone 3's requirement is maximum *U*-3.975 for swinging opaque doors).

3.7. Windows

In the office zone, there are four exterior windows (three in the north wall and one in the east wall). All the windows are the type "M_Fixed 2134 × 1524 mm 2," which is modified from the basic "M_Fixed" window type. According to the Standard 90.1 [13], in Zone 3 for nonmetal framing vertical glazing that is 0%-40% of wall area, the assembly maximum *U*-Factor is 3.69 W/m^2-K and the assembly maximum SHGC (solar heat gain coefficient) is 0.25. The following glazed panel meets these two requirements: "Double glazing - 1/4 in thick - gray/low-E (e = 0.05) glass," whose *U*-Factor is 1.9873 W/m^2-K that is much smaller than the recommended value and the SHGC is 0.24. The visual light transmittance of this glazed panel is 0.35.

3.8. Curtain Walls

In Revit, no detailed thermal properties of the curtain wall type are presented. According to Ref. [14], "A standard clear insulated double glazing unit has a *U*-Factor of 2.76 W/m^2-K at center-of-glass. When the edge-of-glass and frame are taken into account, the overall *U*-Factor will become even higher." Comparing to other building components, curtain wall has a higher *U*-Factor, which may "lead to a number of potential problems, such as high-energy consumption, thermal discomfort to occupant in the perimeter zones, and condensation risk." [14] However, "the typically large continuous span of glazing in curtain walls can provide occupants with pleasant view, contact with outdoors and natural lighting." [14] Many architects prefer large glazing in their designs. The Zone 3's requirements of metal framing curtain wall are: maximum *U*-Factor is 3.41 W/m^2-K and maximum SHGC is 0.25, which are almost the same as that of nonmetal framing vertical glazing (windows). Therefore, the glazed panels of the curtain walls in the designed building are selected the same as the glazed panels of the windows.

Under the lower level roof, the length of the east-facing curtain wall is 2.743 m and the length of the south-facing curtain wall is 7.010 m; under the upper level roof, the south-facing curtain wall is 5.486 m and the west-facing curtain wall is 5.486 m. Notice that between the upper and lower roofs, there is standard exterior wall, rather than curtain wall. Therefore, including the windows and the curtain walls, the total WWR (window to wall ratio) is 35.2% (25.7% east, 59.0% south, 34.6% west and 18.9% north) and people outside of the building can see most of the front zone through the curtain walls. In Paso Robles, the hottest month is July, and in this month the ambient mean temperature is 23°C with mean peak-to-peak amplitude of 22°C. According to Ref. [15], when the ambient temperature is 22°C and the exterior wall *U*-Factor is 0.691 W/m^2-K, the recommended maximum WWR is about 33% for thermally autonomous buildings. Our design is very close to the recommended value.

3.9. Roof Support Column

Because the curtain walls cannot support the roofs, five roof support columns are added between the foundation and the roofs: four columns supporting the upper level roof are at the corners of the roof and one column supporting the lower level roof is at the southeast corner of the building. The columns are selected as "M_Rectangular Column 610 × 610 mm" and the material is sand/cement screed concrete. These support columns are assumed to be well-insulated to avoid thermal bridge and are not considered in the building models in Section 4 and 5.

The southeast view of the designed small commercial building is shown in Figure 4. Some thermal and physical properties of the materials used in the building are summarized in Table 1.

Table 1. Thermal properties of materials in the building

Category	Material	Conductivity	Capacity	Density
		k (W/m K)	*C* (kJ/kgK)	*ρ* (kg/m^3)
Brick	Common brick	0.540	0.840	1550
Concrete	Concrete masonry units	1.300	0.840	1800
	Sand/cement screed concrete	1.046	0.657	2300
	Cast-in-situ concrete	1.046	0.657	2300
Insulation	Rigid insulation	0.035	1.470	23
Membrane	Vapour retarder	0.167	1.674	1500
	Damp-proofing	1.150	0.840	2330
	Roofing felt	0.500	1.000	1700
Curtain wall		0.391	—	—
Misc.	Gypsum wall board	0.650	0.840	1100
	Carpet	0.060	1.360	190
	Tile roofing	0.840	0.800	1900
	Asphalt-bitumen	1.150	0.840	2330
	Cavity fill	0.058	0.840	350
	Air	0.025	0.001	1.2
	Site-hardcore	No thermal properties are presented.		

Figure 4. Southeast view of the small commercial building

4. Modeling of the Building in Simulink And Cooling Tower Cooling

4.1. One-zone Model

The small commercial building is modeled by the RC (resistor-capacitor) method used in Refs. [1,2,3,15] in Matlab and Matlab/Simulink, as shown in Figure 5. In this one-zone model, the building envelope (including roofs, exterior walls, windows, curtain walls and doors) is connected to the outdoor air and indoor air with surface thermal resistors; the floor is connected to the indoor air and the earth; inside of the building, there are internal walls and other interior thermal mass (assumed as wood with dimensions of 0.1m × floor area); the indoor air is considered as a small capacitor and its temperature is assumed to be uniform; the internal heat gain is put into the indoor air directly; the solar energy gain is calculated according to the solar geometry on July 15 in Paso Robles, and its distribution is 80% on the floor surface and 20% on the upward surface of other interior thermal mass; the ambient mean dry-bulb temperature is 23°C with the peak-to-peak amplitude of 22°C; the simulation time step is 60 seconds.

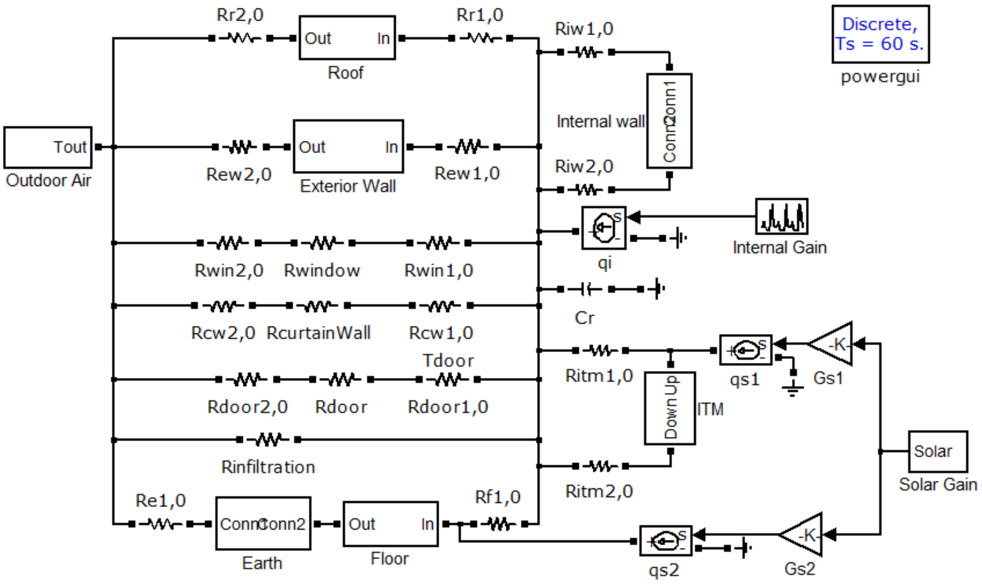

Figure 5. Model of the small partially homeostatic building in Simulink

In order to maintain the operative temperature level, as suggested in Ref. [2], a hydronic system—a cooling tower (CT) combined with thermally active building slabs (TABS)—can be used for summer cooling of a partially homeostatic building in locations with large diurnal temperature variation. The TABS was reviewed in detail in Ref. [16]. The one-zone model in Figure 5 is modified by adding a wet cooling tower and TABS, as shown in Figure 6.

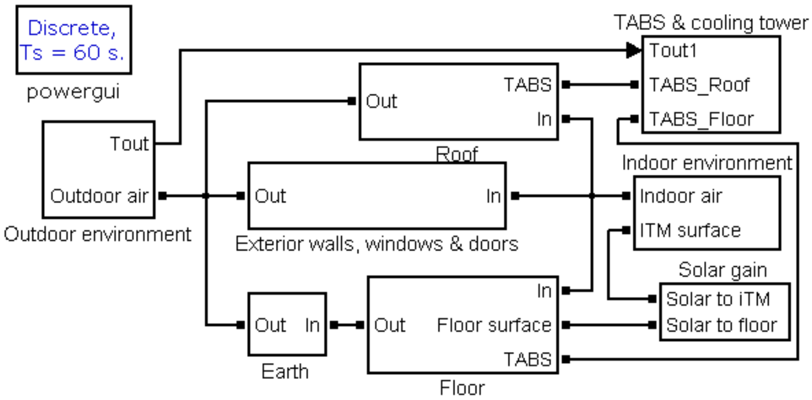

Figure 6. Model of the small homeostatic building in Simulink: one zone

Notice that the detailed components are hidden in the corresponding subsystems in order to make the figure more clearly. The hydronic system works in the nighttime from 8:00PM to 4:00AM to cool down the water in the system by the cold ambient air in the cooling tower. The cold water from the cooling tower is split into two branches: one goes to the pipes embedded in the roof concrete slabs, and the other goes to the floor. Thus the coldness is stored into the large amounts of building thermal mass in the nighttime. Then the water in the two branches is mixed together and goes back to the cooling tower. When the hydronic system does not need to work, the water pump is off and the water in the system is still. In the daytime, the stored coldness is released from the building thermal mass and the indoor environment is thus maintained in the comfortable zone.

Detailed modeling of the hydronic system can be found in Ref. [2]. Here only the two most important parameters of cooling tower, which will be used and discussed later, are defined:

Effectiveness ε (or thermal efficiency), which is between 0 and 1:

$$\varepsilon = \frac{T_{win} - T_{wout}}{T_{win} - T_{wbin}} = \frac{1 - \exp\left[-NTU\left(1 - \dot{C}_w/\dot{C}_a\right)\right]}{1 - \left(\dot{C}_w/\dot{C}_a\right)\exp\left[-NTU\left(1 - \dot{C}_w/\dot{C}_a\right)\right]} \quad (1)$$

where T_{win} is the cooling tower inlet water temperature, T_{wout} is the outlet water temperature, T_{wbin} is the wet-bulb temperature of the inlet air, $NTU = UA_e/\dot{C}_w$ is the Number of Transfer Units, U is the cooling tower overall heat transfer coefficient, and $A_e = A\bar{c}_{pe}/c_p$ is the equivalent heat transfer surface area, A is the heat transfer surface area, $\bar{c}_{pe}$ is the mean specific heat of the moist air treated as an equivalent ideal gas, c_p is the specific heat of moist air, $\dot{C}_w = \dot{m}_w c_{pw}$ and $\dot{C}_a = \dot{m}_a \bar{c}_{pe}$, $\dot{m}_w$ is the mass flow rate of water, $\dot{m}_a$ is the mass flow rate of air, c_{pw} is the specific heat of water, and $\bar{c}_{pe}$ is the mean specific heat of the moist air treated as an equivalent ideal gas.

Approach is an important indicator of cooling tower performance and defined as “the difference between the cooling tower outlet cold-water temperature and ambient wet bulb temperature” [17]. Lower approach means better cooling tower performance. “As a general rule, the closer the approach to the wet bulb, the more expensive the cooling tower due to increased size. Usually a 2.8°C approach to the design wet bulb is the coldest water temperature that cooling tower manufacturers will guarantee.” [17] In this paper, the minimum approach of the wet cooling tower will be kept at 2.8°C.

4.2. Two-zone Model

It is better to model the building into two zones: the Front Zone (the lobby, waiting room, reception room and restrooms) and the Office Zone (the three offices). The zones are separated by the internal walls and doors. As the envelopes of these two zones are quite different, the thermal behavior of the zones should be different. For the hydronic system, the only difference in the two-zone model is that the cold water from the cooling tower is divided into four branches to go to the roof and the floor of each zone. The two-zone model is shown in Figure 7.

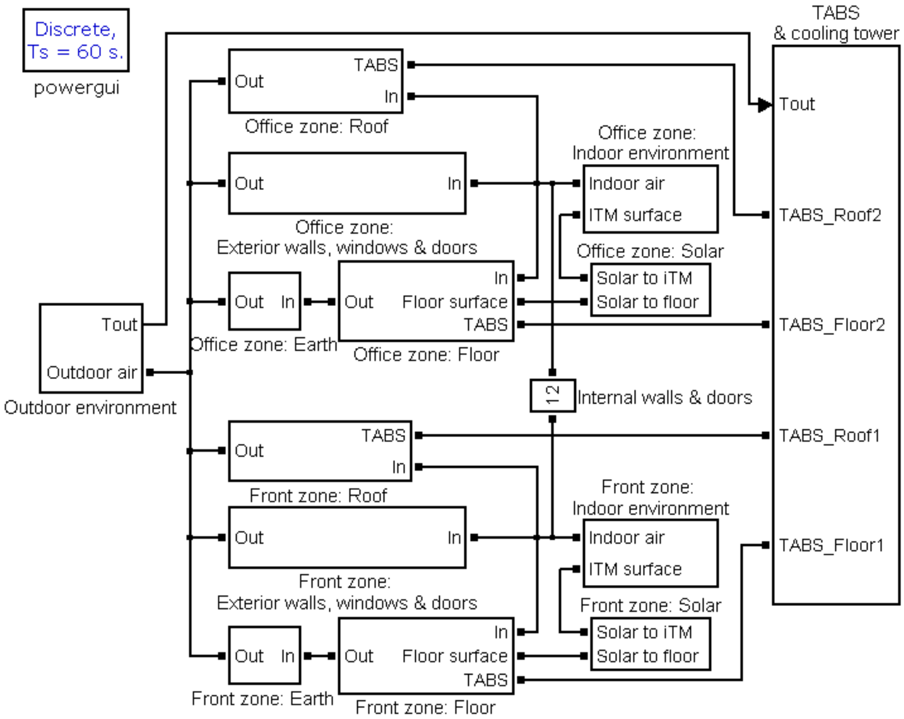

Figure 7. Model of the small homeostatic building in Simulink: two zones

From the energy gain point of view, buildings can be divided into two types [18]: internally load dominated buildings and envelope (externally) load dominated buildings. Commercial and office buildings usually belongs to the first type, which have a large amount of internal heat gains (produced by people, lights and equipment in buildings) and solar energy gains (through windows and curtain walls). In this type of building, cooling is much more important than heating. In the previous papers [1,2,3,15], all the windows and curtain walls are assumed to have good shading devices and only 8% of solar energy goes into the building. The solar energy gain and the internal heat gain are shown in Figure 8 (a). With good shading devices, the designed building belongs to a moderately internally-load-dominated building type. However, the assumption of the building with good shading may not be practical when occupants of the building choose to take advantage of the large fenestration for aesthetics and natural lighting. If the shading devices are removed and all the available solar energy enters the building, the building becomes a strongly internally-load-dominated one, as shown in Figure 8 (b).

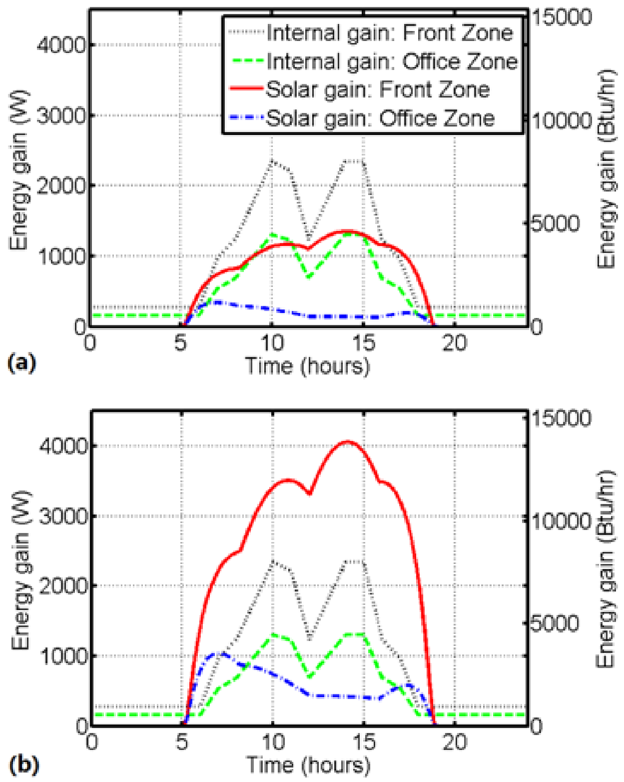

Figure 8. Solar energy gain and internal heat gain of the small commercial building: (a) with shading and (b) without shading

5. Simulation Results

5.1. One-zone Cases

Using the one-zone model, simulation results show that with good shading the mean value of the indoor operative temperature is 28.59°C (without cooling process) and the variation is 1.84°C, which is smaller than the 2°C constraint [1]. Therefore, the designed building is a good thermally autonomous building as the operative temperature range is well maintained. Actually this 2°C per day constraint is pretty strict, as mentioned in Ref. [19] "people find temperature drifts within the comfort zone acceptable up to a rate of 4 K/h (7.2°F/h)." If there is no shading device for the building, the operative temperature variation increases to 2.31°C, while the mean value increases to 32.09°C, because of the bigger influence of the solar energy gain.

Because the diurnal ambient temperature variation is big (which means low nighttime temperature) and the mean value is not high (23°C), a very small cooling tower with effectiveness of 0.031 can cool the indoor operative temperature to the most comfortable summer temperature with the mean value of 25.25°C. Comparing with the previous case without cooling (the hydronic system), the operative temperature variation only increases from 1.84°C to 1.87°C. If there is no shading device, the cooling tower effectiveness should be increased to 0.072 in order to reach the 25.25°C mean operative temperature, while the variation becomes 2.46°C due to the larger solar gain variation.

The simulation results using the one-zone model are summarized in Table 2. Several conclusions are as follows: due to the large fenestration area in the building envelope, shading effects are big on the operative temperature (both variation and mean value) and the cooling tower effectiveness; the hydronic system can keep the operative temperature level in the comfortable range almost without enlarging the operative temperature range.

Table 2. Summarization of the one-zone cases

T_{out} (°C)	Shade/Cool	ΔT_{op} (°C)	Mean T_{op} (°C)	Required CT ε
23.00 ± 11.00	Yes / No	1.84	28.59	NA (not available)
	No / No	2.31	32.09	NA
	Yes / Yes	1.87	25.25	0.031
	No / Yes	2.46	25.25	0.072

5.2. Two-zone Cases

Table 3 summarizes the simulation results of the two-zone model. It can be seen that the indoor operative temperature variation in the Front zone in each case is much bigger than that in the Office zone, and the corresponding mean operative temperature in the Front zone is a little higher than that in the Office zone. The results are expected, because the fenestration area in the Front zone is much larger than that in the Office zone and thus the effect of the solar energy gain should be bigger in the Front zone.

Table 3. Summarization of the two-zone cases

T_{out} (°C)	Shade/Cool	Front zone (°C)		Office zone (°C)		
		ΔT_{op}	Mean T_{op}	ΔT_{op}	Mean T_{op}	CT ε
23.00 ± 11.00	Yes / No	2.06	28.20	1.41	27.71	NA
	No / No	2.72	31.75	1.59	30.06	NA
	Yes / Yes	2.12	25.25	1.47	24.92	0.031
	No / Yes	2.90	25.24	1.74	24.14	0.074

5.3. Two Worst Cases

The hour-by-hour real-time weather data of Paso Robles were requested by email from the website of the U.S. Department of Energy (DOE). [12] The data were collected by the National Weather Service (NWS) from weather stations and stored in a database at the National Renewable Energy Laboratory (NREL). [20] The dry-bulb temperatures in the four summer months from June to September in 2007 are presented in Figure 9.

Analyzing the ambient temperature data, it can be found that in 2007, the mean ambient temperature is from 12.75°C to 29.70°C and the peak-to-peak diurnal amplitude is from 8.90°C to 30.00°C. Therefore, for controlling the operative temperature range, the worst case is 29.70 ± 15.00°C (big amplitude), and for maintaining the operative temperature level, the worst case is 29.70 ± 4.45°C (high mean temperature and small amplitude). Although these worst values may not occur simultaneously, the first worst case may be taken for the simulation of the system without hydronic system (the first two cases in Table 4), and the second worst case may be taken for the simulation of the system with hydronic system (the last two cases in Table 4). The first case is used to test the thermal autonomy of the building and the second one is to test its thermal homeostasis. In Worst case 2, the minimum cooling tower approach is 2.8°C following Ref. [2]. As shown in Table 4, except the operative temperature range in the Office zone, others cannot be well maintained under these worst conditions. Therefore, several possible methods that may improve the system performance will be investigated in the following two sub-sections.

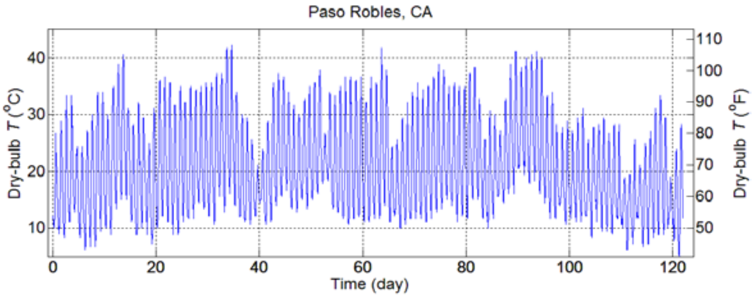

Figure 9. Dry bulb temperatures of Paso Robles in the summer of 2007

Table 4. Summarization of the two-zone cases: worst cases

T_{out} (°C)	Shade/Cool	Front zone (°C)		Office zone (°C)		
		ΔT_{op}	Mean T_{op}	ΔT_{op}	Mean T_{op}	CT ε
Worst case 1: 29.70 ± 15.00	Yes / No	2.47	34.90	1.67	34.41	NA
	No / No	3.12	38.45	1.85	36.76	NA
Worst case 2: 29.70 ± 4.45	Yes / Yes	1.67	26.43	1.25	25.98	0.319
	No / Yes	2.46	27.93	1.48	26.76	0.359

5.4. Heat Distribution Between Zones with Hydronic System in Daytime

It is expected that the TABS system can distribute heat effectively between zones and thus reduce the difference of the operative temperatures. Therefore, instead of shutting down the hydronic system in the daytime, the water in the four branches of the TABS system is circulated in order to distribute heat between the two zones. The results under the worst condition for controlling of the operative temperature level are given in Table 5. However, comparing with the corresponding results in Table 4, there is almost no change of both the operative temperature level and range, although the corresponding cooling tower effective can be a little higher. The results show that the heat cannot be distributed effectively because of the building thermal inertia due to the large amount of the thermal mass in the floors and roofs, as well as the thermal resistance due to the water pipes, the concrete, the carpet on the floor, and the convection on the surfaces.

Table 5. Summarization of the two-zone cases with daytime hydronic circulation

T_{out} (°C)	Shade/Cool	Front zone (°C)		Office zone (°C)		
		ΔT_{op}	Mean T_{op}	ΔT_{op}	Mean T_{op}	CT ε
Worst case 2: 29.70 ± 4.45	Yes / Yes	1.67	26.41	1.25	26.04	0.321
	No / Yes	2.45	27.84	1.50	26.95	0.365

5.5. Heat Distribution Between Zones with Internal Ventilation

It may be better to distribute heat through internal ventilation between the two zones, such as open all the internal doors or add a fan to circulate the interior air forcedly. Manipulating the indoor air temperatures of the two zones to be equal in the model, the simulation results are shown in Table 6. Comparing with the corresponding results in Table 5, there is some improvement, especially the operative temperature range: the range difference of the two zones is reduced from 0.42°C to 0.11°C in the case with shading and from 0.95°C to 0.22°C in the case without shading. With internal ventilation, the corresponding cooling tower effective can be even higher while the minimum cooling tower approach is kept at 2.8°C. However, the mean operative temperatures in the zones are still higher than 25.25°C even when the cooling tower works fully.

Table 6. Summarization of the two-zone cases with daytime hydronic circulation and internal ventilation

T_{out} (°C)	Shade/Cool	Front zone (°C)		Office zone (°C)		
		ΔT_{op}	Mean T_{op}	ΔT_{op}	Mean T_{op}	CT ε
Worst case 2: 29.70 ± 4.45	Yes / Yes	1.56	26.30	1.45	26.22	0.323
	No / Yes	2.18	27.56	1.96	27.43	0.370

5.6. Effects of Ambient Temperature Variation on the System

With both daytime hydronic circulation and internal ventilation, the simulation results are summarized in Table 7. In these cases, there is no shading device; the mean operative temperature in the Front zone is maintained at the optimal value of 25.25°C; the minimum cooling tower approach is kept at 2.8°C; the peak-to-peak diurnal amplitudes of the ambient temperature are from 2°C to 30°C with a 4°C step (the first row in Table 7); the maximum mean values of the ambient temperature that the cooling tower can maintain the optimal operative temperature are calculated (the second row); the operative temperature variations in the two zones are given in the following two rows; the mean operative temperatures in the Office zone and the cooling tower effectiveness are recorded in the last two rows for reference purpose only. From the table, with the increase of the ambient temperature amplitude, the maximum mean ambient temperatures increase steadily. This means that the cooling tower can manage the indoor thermal homeostasis under higher ambient temperature if the amplitude is larger.

The architect J.M. Fitch [21] said that "the central paradox [challenge] of architecture [is] how to provide a stable, predetermined internal environment in an external environment that is in constant flux across time and space…" We argued [2] that the "'external environment that is in constant flux across time and space' is both a challenge and an opportunity": a challenge for controlling the operative temperature range (the operative temperature ranges of the two zones increase steadily) and an opportunity for maintaining the operative temperature level (the cooling tower works well under higher ambient temperature). Notice that there is almost no change of the cooling tower effectiveness. That is to say, the cooling tower size does not need to be increased with higher mean ambient temperature if the amplitude is larger.

Table 7. Summarization of the two-zone cases in the design day

ΔT_{out} (°C)	2	6	10	14	18	22	26	30
Max mean T_{out} (°C)	25.99	26.79	27.60	28.40	29.21	30.01	30.81	31.63
Front ΔT_{op} (°C)	1.87	2.05	2.24	2.42	2.61	2.80	2.99	3.19
Office ΔT_{op} (°C)	1.69	1.85	2.01	2.17	2.34	2.50	2.67	2.83
Office mean T_{op} (°C)	25.15	25.13	25.12	25.10	25.09	25.08	25.07	25.06
CT effectiveness	0.370	0.370	0.371	0.371	0.372	0.372	0.372	0.373

5.7. Summarization of the Building Cooling

In Figure 10, the red line is the maximum mean ambient temperatures from Table 7 against the ambient temperature amplitudes; the blue crosses are the daily mean ambient temperatures vs. temperature amplitudes from the real-time weather data of Paso Robles in the four summer months in 2007. Clearly, there is only one day above the red line, which means that only this day the cooling tower alone cannot maintain the optimal mean operative temperature. In Ref. [2], the most favorable location, Sacramento, CA, has four days that the cooling tower alone cannot meet the cooling requirement. The result in Paso Robles is even better.

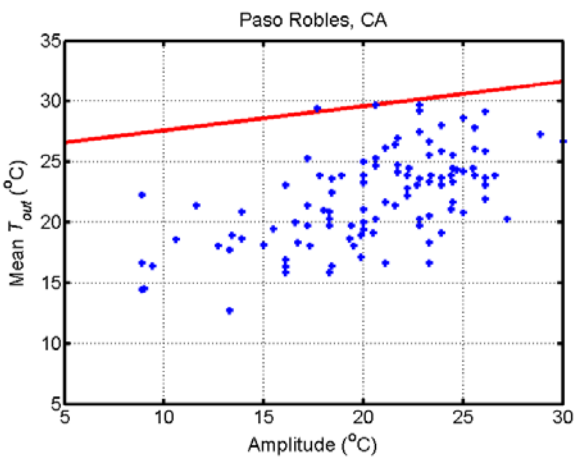

Figure 10. Daily distribution of dry-bulb temperatures vs. temperature amplitudes of Paso Robles in the summer of 2007

6. Discussions

This paper investigated the possibility of whether cooling tower alone can maintain the summer thermal homeostasis in a small commercial building located in Paso Robles, which is one of the most favorable locations for thermally homeostatic buildings. In reality, there are many other factors should be considered, including but not limited to:

(1) The investigation focuses on a certain type of buildings: small commercial building with large fenestration area, heavy thermal mass and hydronic system; the thermal behavior of other kinds of buildings may be different.

(2) The design of the building in fact is not good since there are large glazing area in the south and west walls. In building designs, this should be avoided from thermal comfort and building cooling energy consumption point of view. Here we intentionally designed the building this way. If the building with this "bad" design can be managed, it can be managed more easily with good designs.

(3) The on-off control of the cooling tower is too simplistic for the cooling operation in the whole summer. In fact, as the design day is chosen as the hottest day in the summer, the indoor temperature will be too low in other days if the cooling tower is always on in the nighttime. Control strategy should be carefully designed for maintaining the comfortable level in the whole summer.

(4) As cooling tower of effectiveness 0.370 can maintain 25.25°C even on the hottest design day, it is possible to maintain the indoor comfort with a smaller cooling tower and a thermal energy storage tank for storing the extra coolness in other days.

(5) The continual operation of such a smaller cooling tower over the whole summer has been studied in another paper [22] for Paso Robles as well as the three cities of Sacramento, CA, Albuquerque, NM, and Atlanta, GA.

(6) Paso Robles is one of the most favorable locations for thermally homeostatic buildings; in other non-favorable locations, such as Atlanta GA [2], composite heat extraction systems (CHESS) will be investigated for achieving full thermal homeostasis in the whole year [23].

(7) The proposed building system is more flexible for cooling than conventional buildings: instead of maintaining heat balance on hourly basis, our approach maintains a building's heat balance by recharging its thermal condition on daily basis. Therefore, the cooling operation using heat pump can take place at any favorable time interval during one-day period. Thus building cooling can be powered at times that the whole sale power cost is almost ridiculously low.

(8) The internal heat gain in the building is fixed with a certain pattern and the selected values are moderate; different pattern or values may affect the indoor temperature variation.

7. Conclusion

The development of a thermally homeostatic building consists of two steps: thermal autonomy first, which is based on the architectural requirement of a building's envelope and its thermal mass, and then thermal homeostasis, which is based on the engineering requirement of hydronic equipment. This paper focuses on the possibility of natural summer cooling in Paso Robles, CA, by using cooling tower alone. By showing the viability of natural cooling in one special case, albeit a case in one of the most favorable locations climatically, a case is made that the use of cooling tower in thermally homeostatic buildings should not be overlooked for general application in wider regions of other climatic zones. This paper is limited to answering the question of possibility, rather than providing any details of continual operation of a cooling tower. Some of the operation details are provided in future paper. In the general applications to other climatic zones, composite heat extraction system (CHES) is proposed for achieving full thermal homeostasis. In other words, building thermal mass and the generalized concept of heat extraction are keys to homeostasis in buildings.

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