American Journal of Mechanical Engineering, 2015, Vol. 3, No. 5, 142-146
Available online at http://pubs.sciepub.com/ajme/3/5/1

DOI:10.12691/ajme-3-5-1

PWM Control of a Cooling Tower in a Thermally Homeostatic Building

Peizheng Ma[1,*], Lin-Shu Wang[1], Nianhua Guo[2]

[1]Department of Mechanical Engineering, Stony Brook University, Stony Brook, United States
[2]Department of Asian and Asian American Studies, Stony Brook University, Stony Brook, United States
*Corresponding author: peizheng.ma@alumni.stonybrook.edu

Received August 20, 2015; Revised August 30, 2015; Accepted September 02, 2015

Abstract Thermal Homeostasis in Buildings (THiB) is a new concept of building conditioning. Since summer cooling is the more challenging of building conditioning, several earlier papers focused on the study of natural summer cooling by using cooling tower (CT). The goal was to show the possibility and conditions of natural cooling, i.e., under what extreme day by day conditions that it is still possible for natural cooling to keep indoor temperature from exceeding a given maximum value: since no consideration was given to limiting indoor temperature above a minimum, in fact CT overcooling would be the problem for most part of the summer. This paper presents a fuller consideration of continual operation of a CT throughout the whole summer with pulse-width modulation (PWM) control of the tower operation. The goal here is to find to what extent the indoor temperature can be kept within the comfort zone. To put it another way, determine whether hours or percentile of hours out of total annual hours that the operative temperatures are out of the comfort zone are acceptable or not in a small sample of cities.

Keywords: *thermally homeostatic building, building energy modeling, PWM control, cooling tower, hydronic radiant cooling, small commercial building*

Cite This Article: Peizheng Ma, Lin-Shu Wang, and Nianhua Guo, “PWM Control of a Cooling Tower in a Thermally Homeostatic Building.” *American Journal of Mechanical Engineering*, vol. 3, no. 5 (2015): 142-146. doi: 10.12691/ajme-3-5-1.

1. Introduction

Thermally homeostatic building is a new building concept developed in two recently articles [1,2]. The two papers proposed a two-step process assumption-based (dynamic) design method for the development of a thermally homeostatic building: first thermal autonomy [1] and then thermal homeostasis [2]. Using Autodesk Revit, Ref. [3] designed such a building located in Paso Robles, California, [4] which has a special climate with very large diurnal temperature swing in summers because of the sea breeze from the Monterey Bay. This kind of climate is preferred by thermally homeostatic buildings for achieving summer homeostasis by natural cooling (i.e., using cooling tower [CT] alone). The designed building is a stand-alone, one-story, south-facing, small commercial building equipped with Thermally Activated Building Systems (TABS) [5,6,7,8] and CT. The total floor area of the building is 2310 ft^2 (214.6 m^2). In Ref. [3], we investigated the possibility of natural cooling. This paper continues the investigation by applying a PWM (pulse-width modulation) control for the CT.

2. The Building In Paso Robles And Its RC Model

2.1. The Building Designed in Autodesk Revit

The designed 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 (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 south view (rendered in Revit) and the final floor plan of the building are shown in Figure 1 and Figure 2, respectively.

Figure 1. South view of the small commercial building

The envelope thermal insulation level of the building meets the Climate Zone 3’s requirements provided in the 2010 version of the *ANSI/ASHRAE/IES Standard 90.1* [9]. The configurations of the building [3] are listed in Table 1.

2.2. Weather Data Of Paso Robles

The real-time hour-by-hour weather data of Paso Robles were requested by email from the website of the

U.S. Department of Energy (DOE) [10]. The outdoor dry-bulb temperatures in the four summer months from June to September in 2007 are shown in Figure 3. It can be seen that the diurnal temperature variations in Paso Robles were pretty large in this duration. Analyzing the data, it shows that in 2007, the mean values of the diurnal ambient temperature was from 12.75 °C to 29.70 °C and the peak-to-peak diurnal amplitude was from 8.90 °C to 30.00 °C. The real-time weather data also includes the cloudiness of Paso Robles: the sky was clear in 89.7 % of the total 2928 summer hours, and the cloudy hours usually occurred in the early morning before sunrise. Therefore, in the modeling, the sky will be assumed to be clear in the whole summer.

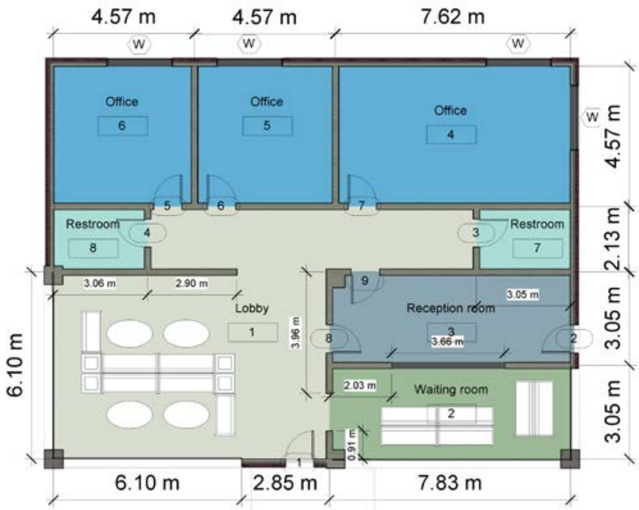

Figure 2. Floor plan of the small commercial building

Table 1. Configurations of the building

Components	U W/m²K	R m²K/W	Materials
Exterior walls	0.6907	1.4477	0.102m common brick; 0.014m air; 0.035m cavity fill; vapor retarder membrane layer; 0.100m concrete masonry units; 0.012m gypsum wall board.
Floor	0.5790	1.7270	0.005m carpet; 0.050m sand/cement screed concrete; 0.175m cast-in-situ concrete; damp-proofing membrane layer; 0.050m rigid insulation; 0.150m site-hardcore.
Roofs	0.2723	3.6731	0.038m tile roofing; 0.118m rigid insulation; 0.020m asphalt-bitumen; roofing felt membrane layer; 0.050m sand/cement screed concrete; 0.200m cast-in-situ concrete.
Interior walls	5.4622	0.1831	0.012m gypsum wall board; 0.190m concrete masonry units; 0.012m gypsum wall board.
Doors	3.7021	0.2701	“M_Single-Flush 0915 × 2134 mm”.
Windows	1.9873	0.5032	“M_Fixed 2134 × 1524 mm”; Panels: “Double glazing - 1/4 in thick - gray/low-E (e = 0.05) glass”.
Curtain walls	1.9873	0.5032	Panels: “Double glazing - 1/4 in thick - gray/low-E (e = 0.05) glass”.
Roof support columns	-	-	“M_Rectangular Column 610 × 610 mm”: Insulated sand/cement screed concrete.

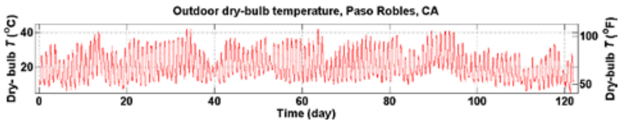

Figure 3. Outdoor dry-bulb temperatures of Paso Robles in the summer of 2007

2.3. Modeling Of The Building System

The RC model of the building is the same model built in Matlab/Simulink in Ref. [3], which followed Refs. [1,2,11,12]. Here we briefly describe the procedure and conditions of the modeling. The building was modeled as two zones, which were separated by interior walls and doors; the envelope was connected to the outdoor and indoor air with surface thermal resistors, except the floor was connected to the earth and the indoor air; interior thermal mass [13] was surrounded by the indoor air; the indoor air was modeled as a small capacitor and its temperature was assumed to be uniform due to internal ventilation; the internal heat gains from people, lighting and equipment were scheduled with moderate values and were transferred into the indoor air directly; there was no shading device for the building and the solar energy gains from the glazing were distributed on the floors (80%) and the interior thermal mass (20%); the indoor operative temperature was calculated by combining the indoor air temperature and the mean radiant temperature; the CT worked in the nighttime for cooling down the water by the cold ambient air; the cold water from the CT was divided into four branches and delivered into the TABS systems in the roof and the floor of each zone; after circulating, the water was then mixed and delivered back to the CT; in the daytime the CT was off, but the water in the TABS systems was circulated between the zones.

3. Cooling Tower Cooling Performance In Paso Robles

Because of the larger curtain walls and windows, the designed building has a high WWR (window to wall ratio) [12] of 35.2% (25.7% east, 59.0% south, 34.6% west and 18.9% north). Therefore, the building has a large amount of solar energy gains, and in Ref. [3] we assumed that it has good shading devices and only 8% of solar energy goes into the building interior. Under this assumption in the hottest summer day, the operative temperature variation could be kept in a 2 °C constraint and the operative temperature level could be maintained in the comfort zone (mean value of 25.25 °C was assumed) with a CT only. However, if there is no shading device, the building could possibly not be well maintained with CT alone [3]. Rather than modeling the building’s thermal behavior in a design summer day, this paper will investigate the building’s thermal behavior in the whole summer from June 1st to September 31st. A PWM control for the CT will be applied to maintain the thermal homeostasis of the building.

3.1. Simple on-off Control of Cooling Tower

First, a simple on-off control of the CT was applied: the CT worked in the whole nighttime from 8:00PM to

4:00AM the next morning. Based on the calculation in Ref. [3], the CT effectiveness (or thermal efficiency) was kept at 0.370, in this case the CT approach, which was defined as "the difference between the cooling tower outlet cold-water temperature and ambient wet bulb temperature" [14], was around its minimum value guaranteed by manufacturers (2.8 °C). With simulation time step of 60 seconds, the operative temperatures of the two zones are calculated and shown in Figure 4. The two operative temperatures almost coincide with each other, with a maximum difference of 0.53 °C. The temperature in the front zone is the higher one because of the much larger glazing area in this zone. Comparing to Figure 3, it is safe to say that the trend of the operative temperatures are following that of the outdoor ambient temperature. As the comfort range of operative temperature in summer is 24.5 - 26.0 °C for a maximum 6% dissatisfied permissible rate and is 23.5 - 27.0 °C for a maximum 10% dissatisfied permissible rate [15], in most time of the summer the two zones were too cold if such a CT worked in this simple on-off control mode (from 8:00PM to 4:00AM with effectiveness of 0.370 and minimum approach of 2.8 °C). Therefore, a better control strategy should be applied. Notice that due to coolness storage in the large building thermal mass, the CT has no difficulty to maintain operative temperatures under 27 °C even during worst days in early September with high ambient temperature (from day 90 to 100), and in fact overcooling is the problem throughout the summer.

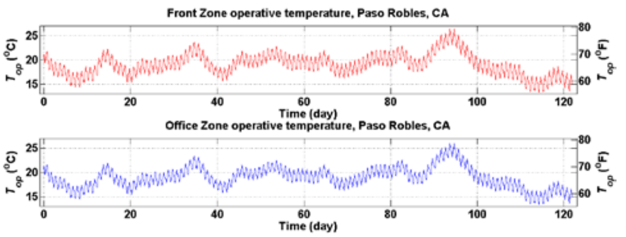

Figure 4. Operative temperatures in the summer of 2007 while cooling tower worked fully

3.2. PWM Control of Cooling Tower

Keeping the CT effectiveness at 0.370, a PWM control is applied to the CT. Since in the daytime, the outdoor temperature is too high, the CT should not be turned on. A quick simulation showed that if the CT was on in the daytime, heat rather than coolness was delivered into the building. Therefore, the CT is only allowed to be on in the nighttime from 8:00PM to 8:00AM in the next morning. In order to avoid frequent on-off switching of the CT, a deadband should be set. The indoor air temperature T_{in} is used as the feedback signal of the PWM control: once T_{in} is above the upper temperature of the deadband, the CT is switched on; the CT is off once T_{in} is below the lower temperature of the deadband; if T_{in} is in the deadband interval, no action occurs.

Of course, we can use the indoor operative temperature T_{op} as the feedback signal; however, T_{op} in the two zones are not identical, and T_{op} are calculated by combining the indoor air temperature and the mean radiant temperature. "Mean radiant temperature can be calculated from measured surface temperatures and the corresponding angle factors between the person and surfaces." [16] And "the instrument most commonly used to determine the mean radiant temperature is a black globe thermometer." [16] For simplicity, here Tin is used as the feedback signal.

With the mean value of 25.25 °C, the deadband interval is set to be 0 (no deadband), 1 and 2 °C. The operative temperatures of the two zones and the PWM are shown in Figure 5, Figure 6 and Figure 7, respectively. Since the difference of the operative temperatures in the two zones is not big, the two temperatures are plotted in one sub-figure. Details of the operative temperatures are summarized in Table 2. From the figures and the table, with higher deadband interval, the operative temperatures' mean values are lower and variations are larger, and the on-off switching of the CT is fewer. Detailed simulation results tell that for the deadband interval of 0, 1 and 2 °C, the CT-switch-on times are 96, 90 and 60, respectively, and the CT-on durations are 15863, 17689 and 17992 minutes, respectively. Balancing the factors above, the deadband interval of 1 °C should be the best choice for the PWM control of the CT.

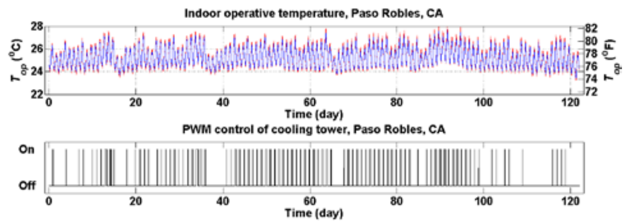

Figure 5. Operative temperatures and PWM when cooling tower deadband interval is 0 °C

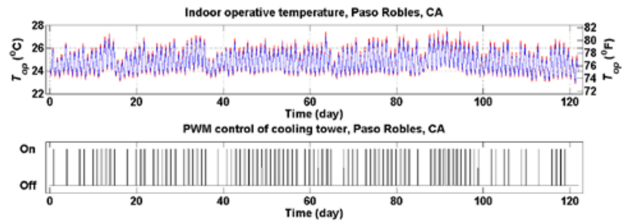

Figure 6. Operative temperatures and PWM when cooling tower deadband interval is 1 °C

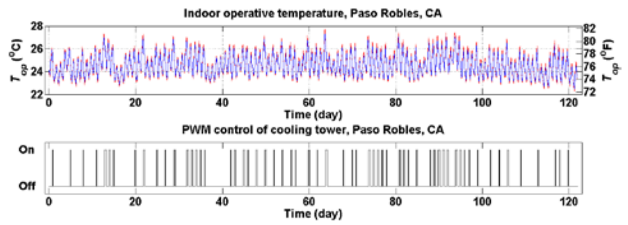

Figure 7. Operative temperatures and PWM when cooling tower deadband interval is 2 °C

Table 2. Operative temperatures of the two zones while cooling tower was controlled by PWM

	Front zone T_{op} (°C)				Office zone T_{op} (°C)			
Bandwidth (°C)	Min	Mean	Max	Δ	Min	Mean	Max	Δ
0	23.22	25.65	28.08	4.86	23.43	25.56	27.68	4.25
1	22.86	25.35	27.83	4.97	23.06	25.25	27.43	4.37
2	22.30	25.00	27.70	5.40	22.50	24.90	27.31	4.82

3.3. PWM Control of a Smaller Cooling Tower

Even in the case with the 2 °C deadband interval, only in about 10% of the whole summer duration, the CT is on.

Therefore, rather than a big CT with effectiveness of 0.370, a smaller CT may also work well because of the coolness storage in the building thermal mass. Table 3 summarizes the operative temperatures of the two zones with smaller CTs. In these cases, the CTs are still controlled by PWM with a deadband interval of 1 °C. The CT effectiveness is divided by two in each of following cases, 0.370/2=0.185. The exciting result is that when the effectiveness is 0.185, in both zones the mean operative temperatures only increase by 0.12 °C and the variations are just 0.09 °C larger. These tiny differences should not be noticeable by occupants in the building. Therefore, a smaller CT does work well. For the case with CT effectiveness of 0.185, the CT is switched on 101 times, and the duration is 25790 minutes (14.7% of the whole summer).

Table 3. Operative temperatures of the two zones with smaller cooling towers

	Front zone T_{op} (°C)				Office zone T_{op} (°C)			
CT effectiveness	Min	Mean	Max	Δ	Min	Mean	Max	Δ
0.370	22.86	25.35	27.83	4.97	23.06	25.25	27.43	4.37
0.370/2	22.94	25.47	28.00	5.06	23.14	25.37	27.60	4.46
0.370/4	22.97	26.11	29.24	6.26	23.18	26.01	28.85	5.67

4. Cooling Tower Cooling Performance in Other Three Cities

Ref. [2] investigated the possibility of using CT alone for maintaining partial summer thermal homeostasis of an identical building located in seven U.S. cities. From easy to hard in maintaining homeostasis, the cities are: Sacramento CA, Valentine NE, Fullerton CA, Albuquerque NM, Springfield IL, Wilmington DE, and Atlanta GA. Here Sacramento, Albuquerque and Atlanta are selected to investigate the CT cooling performance in the whole summer of 2007.

Based on the simulation results in Section 3, the deadband interval is chosen as 1 °C and the CT effectiveness is selected as 0.185. Again, the real-time hour-by-hour weather data of the cities were requested by email from the DOE's website. The sky is still assumed to be clear in the summer, which means our simulation is conservative.

The outdoor temperatures, the operative temperatures of the two zones, and the PWM control of Paso Robles and the three cities are shown in Figure 8, Figure 9, Figure 10 and Figure 11.

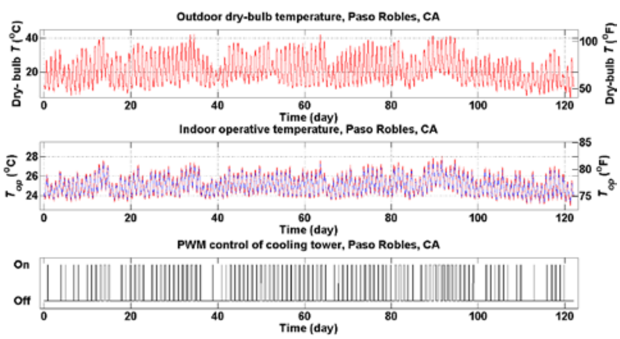

Figure 8. Temperatures and PWM control in Paso Robles, CA

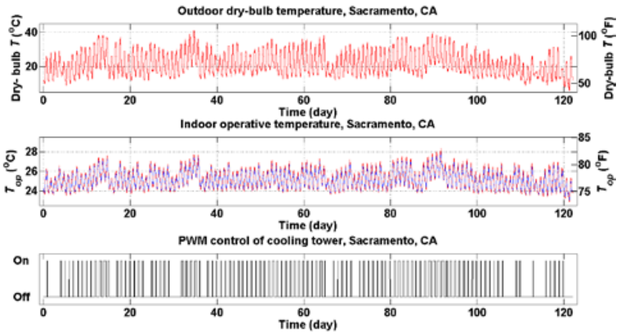

Figure 9. Temperatures and PWM control in Sacramento, CA

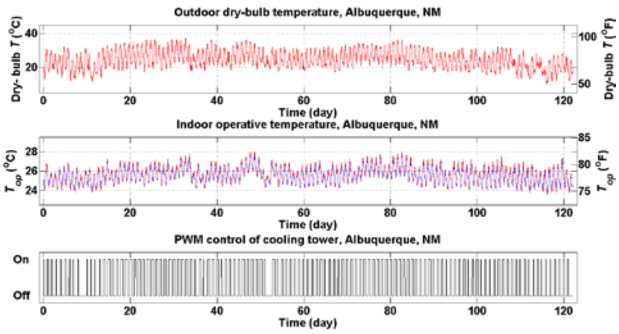

Figure 10. Temperatures and PWM control in Albuquerque, NM

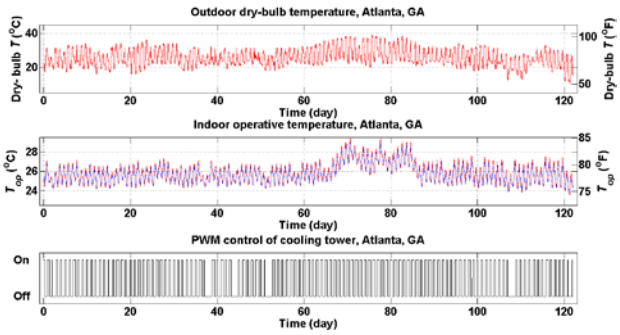

Figure 11. Temperatures and PWM control in Atlanta, GA

The operative temperatures are summarized in Table 4. Analyzing the simulation results, the CT-switch-on times are 101, 105, 120 and 119, respectively, and the CT-on durations are 25790, 30744, 58637 and 63959 minutes, respectively. These results confirmed that the degree of difficulty of using cooling tower alone for partial thermal homeostasis as reported in Ref. [2] is correct.

Table 4. Operative temperatures of the two zones of the building located in different cities

	Front zone T_{op} (°C)				Office zone T_{op} (°C)			
City	Min	Mean	Max	Δ	Min	Mean	Max	Δ
Paso Robles	22.94	25.47	28.00	5.06	23.14	25.37	27.60	4.46
Sacramento	22.83	25.58	28.33	5.50	23.02	25.49	27.96	4.94
Albuquerque	23.51	25.72	27.92	4.41	23.65	25.65	27.65	4.01
Atlanta	23.57	26.50	29.43	5.86	23.71	26.41	29.10	5.39

In the Heat Balance design method [16,17], the design of HVAC equipment is based on fixed climatic design [peak] conditions, which for annual cooling is the design condition for 0.4%, 1% or 2% in annual cumulative frequency of occurrence (exceeding the design condition) [16]. There are 365 × 24 h = 8760 h in one year. The 0.4%, 1%, and 2% design conditions are the three dry-bulb temperatures values that the instantaneous hourly temperature in the hottest months exceeded the corresponding value for a duration of 35 h (0.4% of 8760 h), 88 h (1%), or 175 h (2%) per year, respectively, for the period of record. Although it is in a different context, we may borrow the design condition concept of permitting 2% of hours outside of acceptable range of the comfort zone to see in which locations and in what sense natural cooling is possible. The details are in Table 5.

Table 5. Hours that the operative temperatures are out of the comfort zone

T (°C) / City	Hours of front zone T_{op}				Hours of office zone T_{op}			
	<23.5	>27.0	<24.5	>26.0	<23.5	>27.0	<24.5	>26.0
Paso Robles	42.5	61.0	1029.1	522.5	15.9	17.8	967.9	391.8
Sacramento	15.0	87.0	870.7	599.8	7.4	32.8	800.9	485.2
Albuquerque	0.0	138.9	287.1	946.0	0.0	68.0	238.0	785.3
Atlanta	0.0	347.0	156.5	1169.5	0.0	274.9	114.0	1020.9

As mentioned in Section 3.1, the comfort range of operative temperature in summer is 24.5 - 26.0 °C for a maximum 6% dissatisfied permissible rate (DPR) and is 23.5-27.0 °C for a maximum 10% dissatisfied permissible rate. So with the data in Table 5, the percentages (over 8760 h) are calculated in Table 6. Therefore, if allowing a maximum 10% DPR, the building in the cities except Atlanta is well maintained by the cooling tower alone (less than 175 hours are out of the comfort zone). But if allowing a maximum 6% DPR, no natural cooling is possible and a better control strategy or more versatile cooling equipment should be applied, which will be investigated in the future.

Table 6. Percentages that the operative temperatures are out of the comfort zone

	Front zone		Office zone	
City	6% DPR	10% DPR	6% DPR	10% DPR
Paso Robles, CA	17.71%	1.18%	15.52%	0.38%
Sacramento, CA	16.79%	1.16%	14.68%	0.46%
Albuquerque, NM	14.08%	1.59%	11.68%	0.78%
Atlanta, GA	15.14%	3.96%	12.96%	3.14%

5. Conclusion

By studying continual operation of a cooling tower throughout the whole summer with its control by pulse-width modulation (PWM), we gain a better understanding of how well the cooling tower works in summer in a number of cities. The goal here is to find which locations and to what extent the indoor temperature can be kept within the comfort zone. To put it another way, determine whether percentile of hours out of total annual hours that the operative temperatures are out of the comfort zone are acceptable or not. Our finding shows that natural cooling (using cooling tower alone) is not possible in Atlanta, GA, while it results in acceptable indoor condition on the basis of comfort zone for a maximum 10% dissatisfied permissible rate (10% DPR) in a number of locations with dry climate or large outdoor temperature amplitude. On the basis of 6% DPR, however, results of natural cooling at none of the locations (even those with favorable climate) are acceptable. This suggests a strong motivation to investigate the application of composite heat extraction system (CHES) [18,19] that is made of parallel thermal-charging circuits of cooling tower and heat pump. Our finding does suggest that with such parallel circuits, the cooling tower circuit, even though it cannot work by itself for the whole summer, can carry significant cooling function even in Atlanta, GA. The system innovation by combining cooling tower and heat pump is expected to be the transformation of cooling tower from a marginal and unreliable device that may work under goldilocks conditions into one of the principal partner of the cooling system carrying heavy load under much wider conditions.

References

[1] Wang, L.-S., Ma, P., Hu, E., Giza-Sisson, D., Mueller, G., Guo, N., "A study of building envelope and thermal mass requirements for achieving thermal autonomy in an office building," *Energy and Buildings* 78. 79-88. Aug.2014.

[2] Ma, P., Wang, L.-S., Guo, N., "Modeling of hydronic radiant cooling of a thermally homeostatic building using a parametric cooling tower," *Applied Energy* 127. 172-181. Aug.2014.

[3] Ma, P., Wang, L.-S., Guo, N., "Design of a Thermally Homeostatic Building and Modeling of Its Natural Radiant Cooling Using Cooling Tower," *American Journal of Mechanical Engineering* 3 (4). 105-114. July.2015.

[4] PRcity.com, "Paso Robles," [Online]. Available: http://www.prcity.com. [Accessed Aug. 20, 2015]

[5] Gwerder, M., Lehmann, B., Tötli, J., Dorer, V., Renggli, F., "Control of thermally activated building systems TABS," *Applied Energy* 85 (7). 565-581. Jul.2008.

[6] Lehmann, B., Dorer, V., Gwerder, M., Renggli, F., Tötli, J., "Thermally activated building systems (TABS): Energy efficiency as a function of control strategy, hydronic circuit topology and (cold) generation system," *Applied Energy* 88 (1). 180-191. Jan.2011.

[7] Olesen, B.W., "Thermo active building systems - Using building mass to heat and cool," *ASHRAE Journal* 54 (2). 44-52. Feb.2012.

[8] Ma, P., Wang, L.-S., Guo, N., "Energy storage and heat extraction – From thermally activated building systems (TABS) to thermally homeostatic buildings," *Renewable and Sustainable Energy Reviews* 45. 677-685. May.2015.

[9] ASHRAE Inc., *ANSI/ASHRAE/IES Standard 90.1-2010: Energy Standard for Buildings Except Low-Rise Residential Buildings*, S-I ed. 2010.

[10] U.S. Department of Energy, "Real-Time Weather Data," [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_download.cfm. [Accessed Aug. 20, 2015].

[11] Ma, P., Wang, L.-S., Guo, N., "Modeling of TABS-based thermally manageable buildings in Simulink," *Applied Energy* 104. 791-800. Apr.2013.

[12] Ma, P., Wang, L.-S., Guo, N., "Maximum window-to-wall ratio of a thermally autonomous building as a function of envelope *U*-value and ambient temperature amplitude," *Applied Energy* 146. 84-91. May.2015.

[13] Ma, P., Wang, L.-S., "Effective heat capacity of interior planar thermal mass (iPTM) subject to periodic heating and cooling," *Energy and Buildings* 47. 44-52. Apr.2012.

[14] United Nations Environment Programme, *Electrical Energy Equipment: Cooling Towers*, 2006.

[15] Lehmann, B., Dorer, V., Koschenz, M., "Application range of thermally activated building systems tabs," *Energy and Buildings* 39 (5). 593-598. May.2007.

[16] ASHRAE, Inc., *2009 ASHRAE Handbook—Fundamentals*, I-P & S-I ed., 2009.

[17] Watson R.D., Chapman K.S., *Radiant Heating and cooling Handbook*, 1st ed., McGraw-Hill Education: New York, U.S.A., p.5.251. Jan.2002.

[18] Wang, L.-S., Ma, P., "Low-grade heat and its definitions of Coefficient-of-Performance (COP)," *Applied Thermal Engineering* 84. 460-467. Jun.2015.

[19] Wang, L.-S., Ma, P., "The Homeostasis Solution – Mechanical homeostasis in architecturally homeostatic buildings," *Applied Energy* [submitted in June 2015, APEN-D-15-03388].