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Design of an ice thermal energy storage system for a building of hospitality operation

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ABSTRACT

Large chunk of cooling load is typically demanded during hospitality operation. In the pursuit of reducing its energy cost, a multi-functional commercial building incorporates ice thermal energy storage (TES) concept for storing harvested ice at off-peak hours and thawing the storage medium at peak hours. Ice built during off-peak hours is used to relief the cooling burden of hospitality operation at peak hours. The refrigeration cycle of water chilling would operate under two modes, the ice mode for thermal storage, and the chill water mode for instantaneous air cooling. The TES design uses a partial storage approach to satisfy off-peak hour cooling demands. Two screw chillers are integrated with each other for the implementation to allow feeding chill water to the air-handler coils while producing ice for storage at the same time. Not only does the TES system take advantage of the electric rate structure, super-cooled air also makes humidity levels to be lower than buildings with conventional cooling systems. Cool air is introduced to VAV (variable air volume) terminal boxes and is mixed with induced plenum air to bypass any reheat, yielding additional saving. The TES system saves electricity cost while providing thermal comfort to occupants. Indoor air quality may have been sacrificed when only 5 L/s per person of fresh ventilation is introduced into the building.

1. Preface

Energy management is of considerable concern for officials of commercial or institutional buildings in Taiwan. The island's subtropical climate demands large chunks of cooling loads during daylight hours across all commercial buildings and households. With limited natural energy resources, higher electricity rates during daylight peak hours are prevalent throughout Taiwan in hopes to reduce its peak demands and possible blackouts. This paper offers an alternative approach to energy management operation for commercial or institutional buildings by ways of ice thermal energy storage (TES) during nighttime off-peak hours. Load shift from expensive on-peak hours to cheaper off-peak hours has been an attractive option of peak demand management for decades (Hasnain, 1998; Parameshwaran et al., 2012; Yau and Rismanchi, 2012; Hajiah and Krarti, 2012; Sun et al., 2013). During daylight peak-hours, ice built from the previous night is released to chill water for cooling in peak-hours, thereby reducing the peak cooling load. Reduction of the peak cooling load can be met by operation strategies of full-storage, partial storage, or partial-storage demand-limiting (Dincer, 2002). In hospitality operations, it is expected that high electric demands from equipment other than air-conditioning systems would coincide with high cooling requirements in the afternoon hours. Optimal TES provides an effective method to limit the electric demand (Kintner-Meyer and Emery, 1995). The degree of savings varied across building operations, climates, and time-dependent rate structures (Fiorino, 1994; Lemort, 2006; Habeebullah, 2007; Ehyaei et al., 2010; Vetterli and Benz, 2012; Nassif et al., 2013; Rismanchi et al., 2013; Sebzali et al., 2013; Lin et al., 2014).

A multi-functional commercial building, situated in the heart of Taipei City, is used for the case study. The building has a gross space of 15,110 m^2. The total conditioned space is 5950 m^2 where hospitality operation is expected to demand high electricity consumption. The unconditioned spaces are mostly underground parking lots that are ventilated with outside air. Due to the fact that space is much more precious in Taipei City than in other parts of Taiwan, the challenge was to design a ventilation system that would reduce its peak demand and fit within the limited space. Because of this challenge, a unique system of air-conditioning was envisioned and subsequently installed in this building.

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Nomenclature

A	surface area of a wall or roof [m^2]
b_n, c_n, d_n	conduction transfer function coefficients of a wall or roof
EFT	entering fluid temperature [°C]
EWT	entering water temperature [°C]
F	airflow rate [L/s]
GPM	gallons per minute
LFT	leaving fluid temperature [°C]
LWT	leaving water temperature [°C]
NTU	number of transfer units
OA	outside air
Q	cooling load of the space at calculation hour, (θ) for the current, ($\theta - 1$) for the previous hour etc. [W]
$\dot{q}$	heat gain through wall or roof at calculation hour, (θ) for the current hour, ($\theta - 1$) for the previous hour, ($\theta - 2$) for 2 h ago etc. [W/h]
RA	return air
SA	supply air
SC	shading coefficient
SHGF	solar heat gain factor by orientation, latitude, month, and hour
T	solar-air temperature, (θ) for the current hour, ($\theta - 1$) for the previous hour etc. [°C]
T_o, T_i	outside, inside air temperature [°C]
T_{room}	constant indoor temperature to be maintained at a particular room [°C]
U	unit conductance or U-value [W/(m^2 °C)]
v_0 and v_1	RTF weighting factors due to heat gain components
w_1	RTF weighting factor due to room air-circulation types

2. Building description

The building has three underground floors, and four floors that are above ground, with a flattop-roof. All three basements are 75.6 m by 45.3 m (3425 m^2), including unconditioned parking lots and conditioned space in the first basement (1B). The total underground conditioned space takes up 1210 m^2. Most of the cooling equipment is housed in the lowest basement floor. All underground parking spaces are ventilated with unconditioned outside air.

The first floor is occupied by various catering services around the peripheral. A spacious dining area in the center of the first floor takes up approximately 336 m^2 (24 m by 14 m) of the total first floor space (1350 m^2). The ceiling of the dining area is elevated to the second floor, taking away the same amount of floor space from the second floor. The design is advantageous in buildings of hot climate because the conditioned cold air is heavier and stays in the first floor occupied space. No heating is required in winter where heated hot air would have stayed near the elevated ceiling due to air density differential. Nevertheless, the cooling load calculation still treats the elevated ceiling spaces as if there were two separate floor zones. Although the third floor has an identical gross area of 1350 m^2 as the first and second floors, two terraces reduce the conditioning space down to 1070 m^2. The conditioned space in the fourth floor is identical to the third floor at 1070 m^2, but a reduced gross area without the two terraces.

3. Cooling load calculation

Cooling load of the building envelope is the combination of the temperature differential between inside and outside temperatures and solar heat gains. Other than the driving force resulted from the temperature differential between inside and outside of the building, the load is dependent on thermal characteristics of the construction, walls, roof, floor, fenestration, and interior generation from occupants and equipment. The driving force due to external solar radiation and internal operating schedule makes the load transient and difficult to predict. Fortunately, with the aid of computers and TMY (typical meteorological year) weather data, the task can be accomplished where a typical hourly outdoor data is shown in Table 1.

A number of researchers had proposed different ways of predicting annual energy consumption in subtropical climate (Li et al., 2003; Mui and Wong, 2007). The transfer function method (TFM) is particularly well suited for use with a computer, taking into accounts of the transient effect to predict the hourly cooling load due to different types of walls, roofs, and fenestration (Stephenson and Mitalas, 1967; Al-Rabghi and Al-Johani, 1997). The method describes the heat flux at the inside of a wall or roof as a function of previous values of the heat flux and previous values of inside and outside temperatures. The TFM uses fixed, combined convection and radiation coefficients on the inside and outside surfaces, so that the conduction transfer functions are driven by solar-air temperature on the outside and by room temperature on the inside. The simulation used Songshan (Taipei City) Airport TMY data for outdoor conditions to calculate the required cooling loads. It is noted that there are no heating load for the building. The VAV (variable air volume) ventilation system used in this building would bypass any reheat in space zone's terminal boxes. The cooling TFM assumes constant indoor and outdoor surface heat transfer coefficients (Mitalas, 1972). The heat gain through a wall or roof is calculated from

$$
\begin{aligned}
\dot{q}(\theta) &= A[b_0T(\theta) + b_1T(\theta-1) + b_2T(\theta-2) + b_3T(\theta-3) + \cdots] \\
&\quad - [d_1\dot{q}(\theta-1) + d_2\dot{q}(\theta-2) + d_3\dot{q}(\theta-3) + \cdots] \\
&\quad - AT_{room}(\theta)[c_0(\theta) + c_1(\theta-1) + c_2(\theta-2) + c_3(\theta-3) + \cdots] \qquad (1)
\end{aligned}
$$

Specific conduction transfer function (CTF) coefficients for different constructions can be calculated using the software produced by Spitler et al. (1993). ASHRAE (2013) listed various groups of the walls and roofs for engineers to identify the CTF coefficients. The composition of the building envelope wall is granite, lightweight concrete, and insulation finishes. The civil/architectural engineers have indicated that the exterior stone has a similar thermal characteristic of a face brick. From ASHRAE Wall Group #17, the CTF coefficients of the building envelope walls were found, as shown in Table 2. Also included in this Table are the CTF coefficients for the building's flattop-roof, adapted from ASHRAE Roof Group #1, steel deck with insulations.

The actual cooling load depends on the magnitude and the nature of the heat gain calculated by Eq. (1). Stephenson and Mitalas (1967) related heat gains to the corresponding cooling load by a room transfer function (RTF). The heat storage characteristics of the enclosed space would be represented by three weighting factors, v_0, v_1, and w_1. Using the heat gains $\dot{q}(\theta)$ and $\dot{q}(\theta-1)$, the corresponding cooling load can be related to the current value of $Q(\theta)$ and the preceding values of the cooling load and heat gain.

$$
Q(\theta) = v_0\dot{q}(\theta) + v_1\dot{q}(\theta-1)w_1Q(\theta-1) \qquad (2)
$$

According to ASHRAE (2013), w_1 is depended on the room envelope construction and the room air-circulation type. For example, a light construction mass with very high air-circulation would render $w_1 = -0.73$. A heavy construction mass with low air-circulation would render $w_1 = -0.98$. For this building, both the construction mass and the air-circulation may be considered as medium, then $w_1 = -0.94$. The weighting factors v_0 and v_1 are related with the heat