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Retrofitting Building Fire Service Water Tanks as Chilled Water Storage for Power Demand Limiting

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Abstract:

Peak demand cost usually contributes a large proportion of the total electricity bills in buildings. Using existing building facilities for power demand limiting has been verified as effective measures to reduce monthly peak demands and associated costs. Fire service water tanks exist in most commercial buildings. This paper presents a comprehensive study on how to effectively retrofit existing building fire service water tanks as chilled water storage for power demand limiting. Important technical and economic factors that may affect the implementation of the proposed retrofitting are addressed. Two retrofitting schemes, i.e. a small ΔT (storage temperature difference) scheme and a large ΔT scheme are proposed for integrating the chilled water storage system into an existing all-air system and an existing air-water air conditioning system respectively. Two optimal demand limiting control strategies, i.e. time-based control and demand-based control, are proposed for maximizing the monthly peak demand reduction of buildings with regulate and variable peak occurring time respectively. The cost-effectiveness of different retrofitting schemes in three real buildings in Hong Kong are analysed. Results show that substantial cost savings can be achieved with short payback periods (0.7~2.6 years) for the retrofits in these three buildings.

Keywords: *chilled water storage; fire service water tank retrofitting; air-conditioning system; power demand limiting; temperature and humidity independent control*

1. Introduction

A large proportion of the electricity peak demand and energy consumption is contributed by buildings [1]. Every electric bill of commercial buildings generally includes charges for both electricity consumption (i.e. kWh) and electricity peak demand (i.e. kVA). The peak demand in commercial buildings usually lasts for relatively a short period (e.g. 15 or 30 min) but its cost can contributes a great part to the overall electricity bill, sometimes even exceeding 50% [2]. Therefore, peak demand management is usually performed in buildings to reduce the peak demand which results in substantial saving of peak demand cost. Various peak demand control methods and strategies using diverse energy storage facilities such as building thermal mass, thermal energy storage system (TES) and phase change material (PCM) are employed in different buildings [3-8].

Among available TES techniques, chilled water storage (CWS) and ice storage are the most commonly used techniques worldwide. Compared to the ice storage system, the CWS system has many attractive advantages such as simple system configuration, easy control strategy and low initial and operating cost [9]. However, the volumetric thermal storage density (e.g., the storage capacity of each cubic of water) of the CWS system is much less than that of the ice storage system. For storing the same amount of cold energy, the required volume for a chilled water storage is about 5 to 8 times of that of an ice storage system [10]. The requirement of large storage tank and consequently high storage construction cost are the main obstacle to apply the chilled water storage system in buildings.

Fortunately, some practical measures, such as retrofitting an existing water tank (e.g., a fire service water tank) as a CWS tank and/or revising the configuration of air-conditioning systems to allow larger storage temperature difference of the CWS, can be used to facilitate the application of chilled water storage systems in practices [11]. Constructing a fire service water tank in a commercial building is usually mandatorily required by fire authorities. From the perspective of maximizing the use of building facilities, the fire service water tank could be designed or retrofitted as a dual-function water tank that can serve the dual function of emergency fire service and chilled-water storage, without adversely impacting either function. This idea is not new at all and the technical feasibility of using fire service water tank as a dual-function tank has been verified by some real applications worldwide. For instance, Hussain and Peters described how an existing fire service water storage pond was successfully retrofitted as a stratified chilled water thermal energy storage reservoir [12]. Holness illustrated a combined CWS and fire service storage system in a truck assembly plant in South Carolina [13]. In China, projects and studies on retrofitting existing large volume fire service storage tanks for CWS are found in several types of buildings, including commercial buildings and high rise office buildings [14][15]. In Singapore, the application of retrofitting an existing 205 m^3 sprinkler tank in a retail mall as a CWS system was approved by the local fire authority [16]. In above mentioned projects, the tanks serve the cooling demands of buildings while remaining continuously available for fire service. In addition, the water in tanks is maintained in a flowing and low-temperature condition that can effectively prevent water corruption and breeding algae in the water tank [14].

Although the principle of retrofitting fire service storage tanks for conventional CWS (i.e., the applications of previous studies for general load shifting purpose) and for power demand limiting (i.e., using CWS for peak demand reduction in this study) are the same, the applicability and the cost-effectiveness as well as the associated technical requirements for achieving the two application purposes are different. The aim of conventional CWS is to shift the cooling from the high electricity price period to the low electricity price period and the cost saving is only contributed by the difference of the time-based electricity price (e.g. time of use (TOU) pricing structures). The aim of demand limiting is to reduce the monthly peak demand of each month and the cost saving is mainly contributed by the reduction of peak demand charges. For achieving a substantial cost saving, a huge amount of cooling shifting capacity (i.e. cooling storage capacity) is required for conventional CWS, which indicates that the volume of the storage water tank must be large enough. In contrast, the same amount of cost saving can be achieved by much less cooling shifting capacity and the required volume of storage tank is much smaller. For instance, up to about 7% of total building electricity cost reduction can be obtained by implementing demand limiting control even when the proportion of the stored cooling is very limited, e.g., only accounting for 3~5% of the daily cooling load [4]. Compared to the retrofitting purpose for conventional CWS, the low requirement on the tank volume enables the retrofitting for demand limiting with better cost-effectiveness, and makes it to be applicable in more existing buildings since not all buildings have large fire service water tanks. In addition, the control requirement of cooling discharging for demand limiting is more complicated than that for conventional CWS. For the later application, the stored chilled water is used in the high price period, which is generally fixed for all buildings under the same TOU price structure. However for demand limiting, the stored chilled water must be optimally used to offset the possible largest peak during the monthly peak demand period, which varies in each month and in each building. As a result, proper cold discharging control strategy is supposed to be developed for achieving effective monthly peak demand reduction.

Retrofitting fire service storage tanks for demand limiting might be a more applicable, more cost-effective and more challenging application compared to retrofitting them for conventional CWS as described above. However, there is no existing scientific study or real application project available so far. This paper therefore presents a comprehensive study on how to effectively retrofit existing building fire service water tanks as chilled water storage for power demand limiting. Two retrofitting schemes, i.e. a small ΔT (storage temperature difference) scheme and a large ΔT scheme are proposed for integrating the chilled water storage system into an existing all-air system and an existing air-water air conditioning system respectively. Two optimal demand limiting control strategies, i.e. time-based control and demand-based control, are proposed for achieving the maximum monthly peak demand reduction in buildings with regulate peak time and buildings with variable peak time respectively. The cost-effectiveness of the retrofits in three real buildings in Hong Kong are analysed. Results show that substantial cost savings can be achieved with short payback periods (0.7~2.6 years) when the proposed retrofits are implemented in these three case buildings. Some other important factors that may affect the implementation and the cost-effectiveness of the retrofitting are discussed as well.

2. Retrofitting fire service water tank for chilled water storage

2.1 Dual-function water tank

Fig.1 illustrates the configuration of a dual-function water tank. It is firstly a fire service water tank and therefore the original functions for emergency fire service must be guaranteed. For instance, the intake devices and suction pipes for fire pumps and fire trucks must be preserved and not be affected. In addition, when retrofitting the fire water tank for other usages (e.g., for chilled water storage), an essential prerequisite is to keep sufficient volume of water always being available for fire services. In this study, the dual-function water tank is completely separated from the air-conditioning system by heat exchangers. Only heat exchanging (i.e. cooling energy charging and discharging) is allowed through heat exchangers while the water within the tank can be only extracted for fire services. In addition to the basic requirements for waterproof, the water tank should also be well installed. For example, thickness of 100 mm foamed polyurethane is used for insulation material in [14].

Maintaining separation between the stored cold supply water and the warmer return water is essentially important for achieving effective cooling energy storage, which can be realized by various approaches such as flexible tank membranes, natural thermal stratification, compartmentalized tanks and multiple tanks [9]. In this study, the natural thermal stratification technique is selected for tank retrofitting. During the off-peak periods, the cold chilled water is charged and stored inside the tank in stratified layers. During the peak periods, cold chilled water is supplied from the bottom of the tank and returned to the top of the tank after being heated by the heat exchangers. Proper design of water diffusers is important for achieving good thermal stratification. The diffusers should introduce water to the tank uniformly and at a very low-velocity so that buoyancy forces create and maintain the thermocline [8].

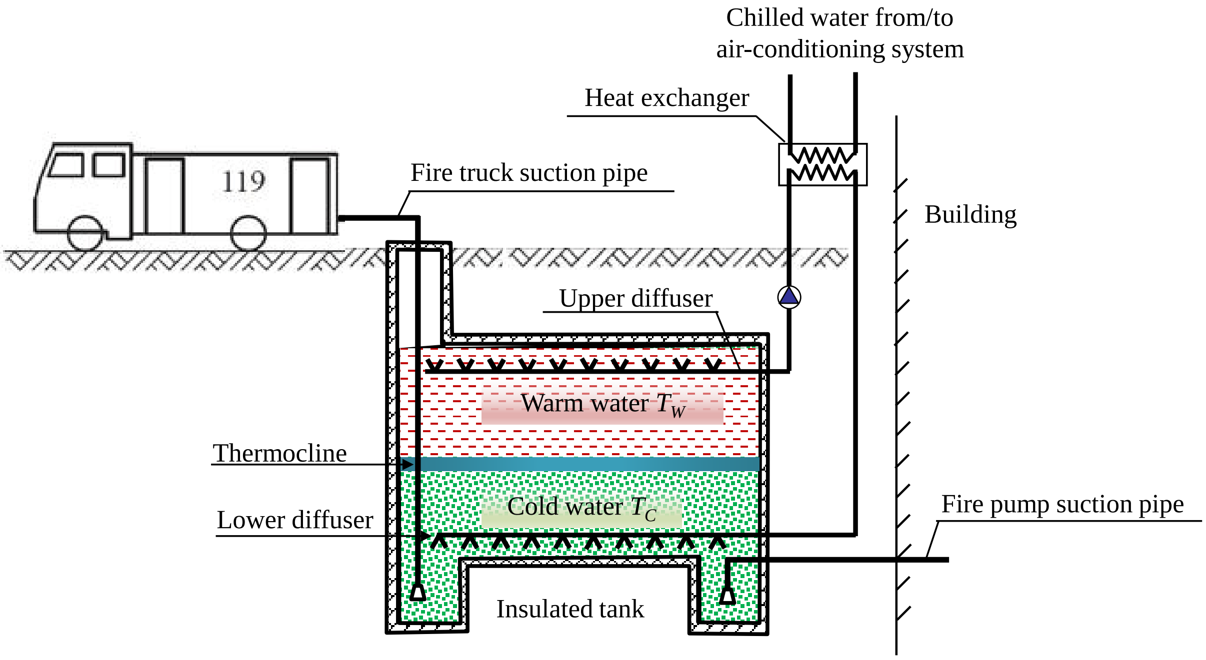


Fig.1. Configuration of the dual-function water tank

The cooling storage capacity of the water tank mainly depends on the tank volume and the temperature differential across the stratified storage tank, as shown in Eq. (1).

$$Q_S = \eta \cdot V_{tank} \cdot \Delta T \tag{1}$$

where, Q_s is the maximum storage capacity of the tank. η is the storage efficiency of the tank, generally is about 80%~90% [8]. V_{tank} is the effective volume of the water tank. ΔT is the temperature difference of the CWS, which equals the difference between the warm return water temperature (i.e. T_W) and the cold supply water temperature (i.e. T_C).

Generally, the cold supply water temperature is mainly determined by the outlet water temperature of chillers that typically ranges from 4°C to 6°C during cold charging periods. The warm return water temperature is mainly determined by the outlet water temperature of cooling coils. Depending on the type and configuration of air-conditioning systems, the cooling coil outlet temperature may have very different values. For instance, this temperature is typically about 12°C in a conventional air-conditioning system while it can be over 21 °C in a temperature and humidity independent control (THIC) air-conditioning system. This indicates the storage capacity of the same water tank can be very different when it is used in different air-conditioning systems.

In this study, two different configuration schemes are proposed for combining the CWS with existing air-conditioning systems. In the first combination scheme, the dual-function water tank is connected to an existing all-air system, which operates as a conventional air-conditioning system and the CWS has a small storage temperature difference (e.g., ΔT is about 5°C). In the second combination scheme, the tank is connected to an existing air-water system. It operates as a conventional system during normal operations while it can operate as a THIC system when discharging cooling energy during the demand limiting period. This enable the CWS to have a relatively large ΔT (e.g., 15°C).

2.2 Application in all-air systems with small ΔT

Fig.2 shows the schematic of combining the dual-function water tank with an existing all-air system for chilled water storage with small ΔT (i.e. 5°C). The retrofitted CWS system is connected to chillers through a heat exchanger (i.e. EX1) for charging cooling energy into the water tank during off-peak periods. On the other hand, the CWS is also connected to AHUs (air-handling units) through the other heat exchanger (i.e. EX2) for discharging cooling energy from the water tank during the demand limiting period.

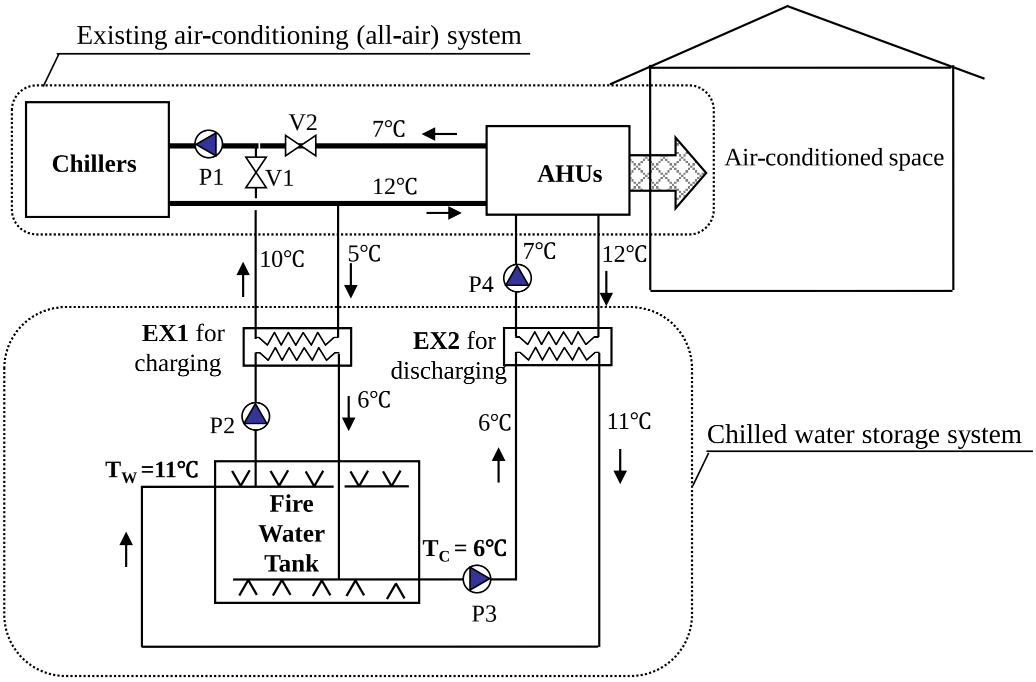


Fig.2. Schematic of combining the CWS with an all-air system (Small-ΔT Scheme)

The main supply and return water temperature of all water circulating loops in the combined system are marked in Fig.2. It shows that the ΔT of the CWS is only about 5°C, which indicates that each cubic meter water can provide up to 5.8 kWh of cooling according to Eq.(1). As aforementioned, the ΔT of a CWS is determined by the outlet water temperature of the cooling coils once the cooling charging temperature is given. In an all-air system, air is cooled and dehumidified by cooling coils of AHUs simultaneously, which requires the chilled water temperature to be lower than the dew-point temperature of the supply air. For this reason, the supply and return temperature (i.e. the the outlet water temperature of the cooling coils) of chilled water are usually set as 7°C and 12°C respectively.

Three different modes can be operated for the combined system, which are *normal operational mode*, *cold charging mode*, and *cold discharging mode* (also called demand limiting mode in this study). The specific operating status of key equipment and valves under these three modes are shown in Table 1. During normal operational hours (i.e. no-peak demand daytime), the system operates as a normal air-conditioning system in which all cooling is directly provided from chillers to AHUs. During the off-peak periods (e.g., nighttime), the system operates in *cold charging mode*: chillers are switch on to produce cold energy that is stored in the water tank with relative low-temperature about 6°C. During the peak demand hours, the system operates in cold discharging mode for demand limiting: the stored cold energy is extracted from the tank through heat exchangers (i.e. EX2) to handle the total cooling load (both the sensible and latent load) of AHUs. Parts or even all operating chillers can be shut down and the building power demand can be reduced significantly.

Table 1 Operation mode switch in the small ΔT application system

Operation mode	Chiller	AHUs	Pumps				Valves	
			P1	P2	P3	P4	V1	V2
Normal mode	7/12°C	ON	ON	OFF	OFF	OFF	OFF	ON
Cold charging	5/10°C	OFF	ON	ON	OFF	OFF	ON	OFF
Cold discharging	OFF	ON	OFF	OFF	ON	ON	OFF	OFF

2.3 Application in air-water systems with large ΔT

In principle, the above small-ΔT application scheme can also be used in an existing air-water or all-water system with minor revisions. However, a better combination scheme that enables the storage system with large ΔT (i.e. 15°C) is proposed for combining the CWS with an existing air-water system exclusively, as shown in Fig.3. In no-peak periods, the system operates as a typical air-water air-conditioning system, in which the space cooling load is mainly offset by FCUs (fan coil units) and the fresh air is handled by PAUs (primary air handling units). But in on-peak or demand limiting period, the system can be operated as a THIC air-conditioning system. Different from a conventional system in which air is cooled and dehumidified by cooling coils simultaneously, a THIC system regulates the indoor air temperature and humidity separately using a temperature control subsystem and a humidity control subsystem respectively [18].

In this study, FCUs can operate as the temperature control subsystem to handle all sensible cooling load and the PAUs can operate as the humidity control subsystem to handle all latent cooling load and fresh air load. The temperature control subsystem has no need for dehumidifying and therefore uses high temperature chilled water to cool down the indoor temperature. As marked in Fig.3, the supply and return temperature of the FCU cooling coils are 18 ◦C and 22 ◦C respectively. Considering 1°C temperature difference is lost by heat exchangers, the temperature of the warm return water of the tank can be up to 21°C. The ΔT of the CWS then can reach up to 15°C, providing 17.5 kWh of cooling per cubic meter of water. This indicates that the storage capacity of the dual-function water tank in the THIC system can be three times as that when the tank is used in the conventional air-conditioning system.

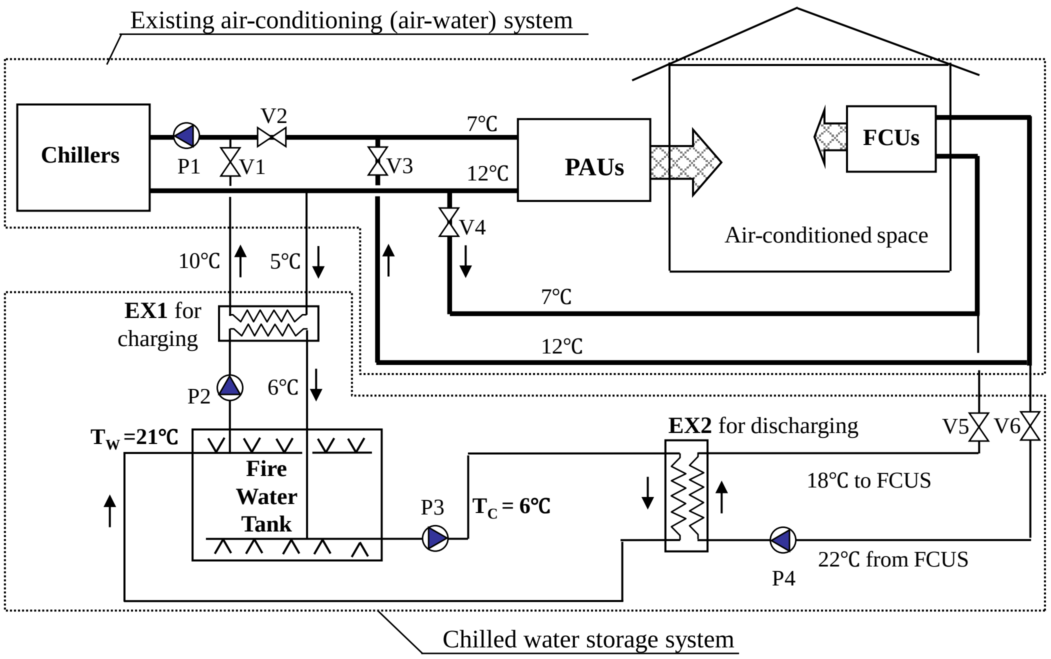


Fig.3. Schematic of combining the CWS with an air-water system (Large-ΔT Scheme)

Similar as in the small ΔT application system, the three operational modes i.e. *normal operational mode*, *cold charging mode* and *cold discharging mode*, can also be operated in the large ΔT application system. The switching among these three modes are shown in Table 2. During normal operational mode, the system operates as a normal air-water system, in which all chilled water (7/12°C) is directly provided from chillers to PAUs and FCUs. During the off-peak periods (e.g., nighttime), the system operates in cold charging mode. The supply and return water temperature of discharging chiller are about 5°C and 10°C respectively. During the on-peak hours, cold discharging mode is activated for demand limiting. In such a case, the air-conditioning system is operated as a THIC system.

It is worth noting that not all but only a part of the chiller power demand can be reduced during the cold discharging period. In the temperature control subsystem of the THIC system, the required cooling energy for offsetting all sensible cooling load of FCUs is provided from the CWS. Meanwhile in the humidity control subsystem, cooling energy is still provided from chillers. Moreover, in order to enhance the dehumidifying capacity of the PAU cooling coils to offset the additional latent load, which is supposed to be handled in FCUs during normal operation mode, the chiller supply/return water temperature should be decreased from the normal values (7/12°C) to lower values (e.g., 5/10°C). This may cause the cooling supply in the PAU side to be increased slightly. Nevertheless, compared to the normal operation mode, the total cooling supply from chillers is reduced significantly and a substantial power demand reduction is then achieved consequently.

Table 2 Operation mode switch in the large ΔT application system

Operating mode	Chillers	Cooling coils		Pumps				Valves					
		PAU	FCU	P1	P2	P3	P4	V1	V2	V3	V4	V5	V6
Normal mode	7/12°C	ON	ON	ON	OFF	OFF	OFF	OFF	ON	ON	ON	OFF	OFF
Cold charging	5/10°C	OFF	OFF	ON	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF	OFF
Cold discharging	5/10°C	ON	ON	ON	OFF	ON	ON	OFF	ON	OFF	OFF	ON	ON

3. CWS-based demand limiting for monthly cost saving

3.1 Electricity bill structure and cost saving

Monthly electricity bill usually consists of monthly peak demand cost and monthly energy consumption cost (the prices during on-peak and off-peak are different), as shown in Eq. (2).

$$C_{tot} = \alpha \cdot PD_{mon} + (\beta_{on} \cdot E_{on} + \beta_{off} \cdot E_{off}) \tag{2}$$

where, C_{tot} is the monthly electricity bill (HKD); α, β are the unit prices for electrical peak demand and energy consumption respectively; PD_{mon} is the monthly peak demand (kVA); E_{on} and E_{off} represent the monthly total building energy consumption (kWh) during on-peak and off-peak periods respectively.

Using the proposed CWS systems for demand limiting, the cost saving can be contributed from two parts: the saving due to the monthly peak demand reduction and the saving due to the shifting of energy consumption from on-peak periods with high price period to off-peak periods with low price (as conventional CWS), as shown in in Eq. (3).

$$C_{saving} = \alpha \cdot \Delta PD_{mon} + \Delta\beta \sum_{i=1}^{n} E_{shifted} \tag{3}$$

where, C_{saving} is the monthly electricity bill saving (HKD); ΔPD_{mon} is the monthly peak demand reduction (kVA); $\Delta\beta$ is the energy consumption price difference between on-peak and off-peak; $E_{shifted}$ is the shifted energy consumption (kWh). In Hong Kong and other areas, the unit price of the peak demand is much higher than that of energy consumption, for instance, according to one of the bill structure of China Light and Power (CLP) company in Hong Kong, α=117; $\Delta\beta$= 0.095 [6]. Hence, the monthly electricity bill saving is mainly contributed by the cost saving due to the peak demand reduction for most cases. Only when the value of $\Delta\beta$ and/or the amount of the shifted energy consumption are relatively large, the cost saving due to the energy shifting might be comparable.

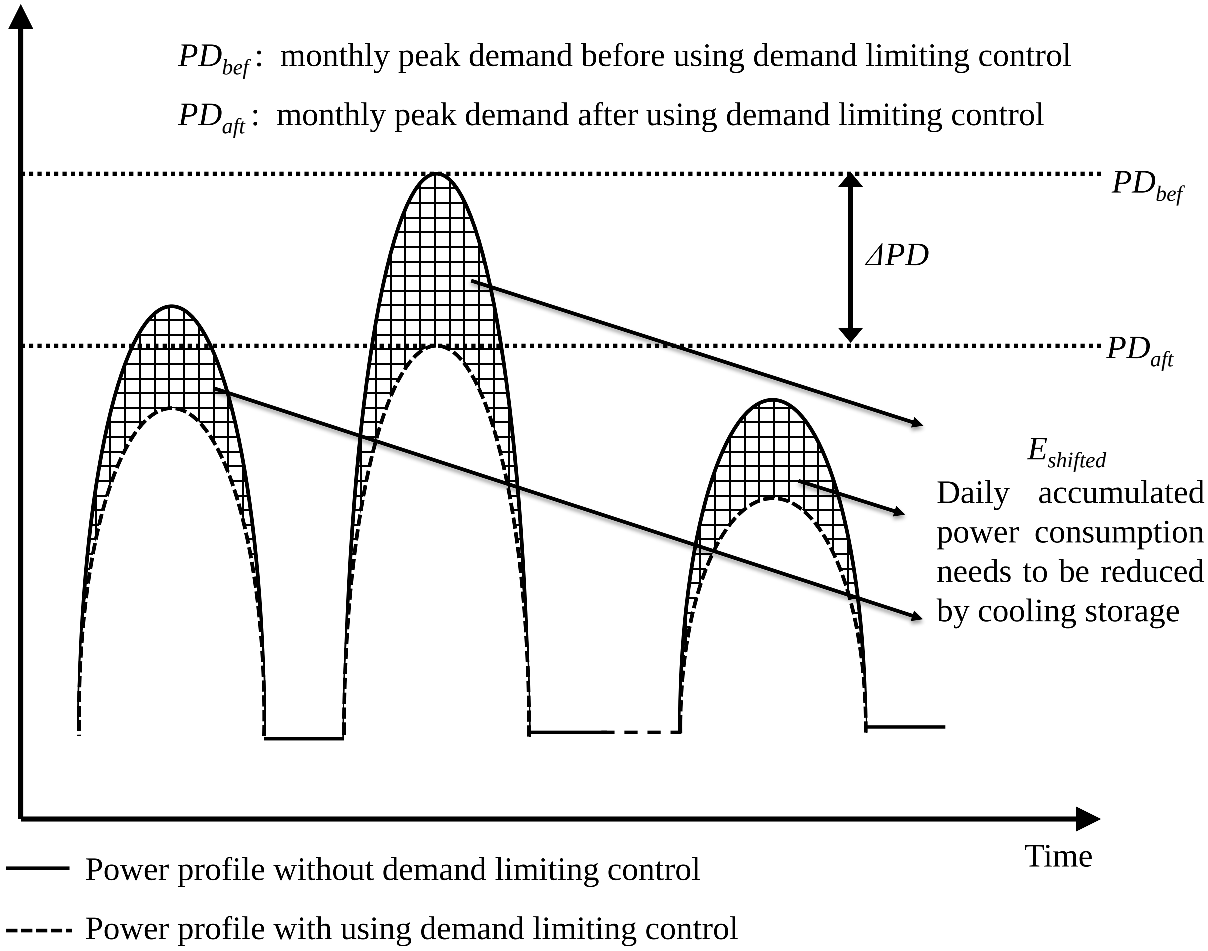


Fig.4 Daily demand limiting for peak demand reduction and energy consumption shifting

Daily peak demand limiting control through shifting part of energy consumption from on-peak to off-peak can certainly reduce the monthly peak demand, as shown in Fig.4, where the monthly peak demand without and with daily peak demand limiting control are represented by PD_{bef} and PD_{aft} respectively. It can be observed that a large amount of monthly peak demand reduction (i.e. ΔPD) is obtained by reducing daily peak demands. The magnitude of daily power reduction mainly determines by both the daily shifted power consumption $E_{shifted}$ (the area of shadows) and the shape of the power profiles determined by the electricity usage characteristics of the building.

When CWS is used in a building, power shifting can be realized by cooling energy shifting from the off-peak periods to on-peak periods. The amount of the daily shifted power consumption can be roughly estimated according to the cooling storage capacity of the tank

(Q_s) and the overall energy efficiency of the air-conditioning system, as shown in Eq.(4):

$$E_{shifted} = \frac{Q_S}{SCOP} \tag{4}$$

where, SCOP represents the "System Coefficient of Performance" of the entire air-conditioning system including all energy components such as chiller, pump, cooling tower and all fans. According to the field measurement data from real buildings, the SCOP can be estimated as 2.5 on annual average [19].

3.2 Cold discharging control for maximum peak demand reduction

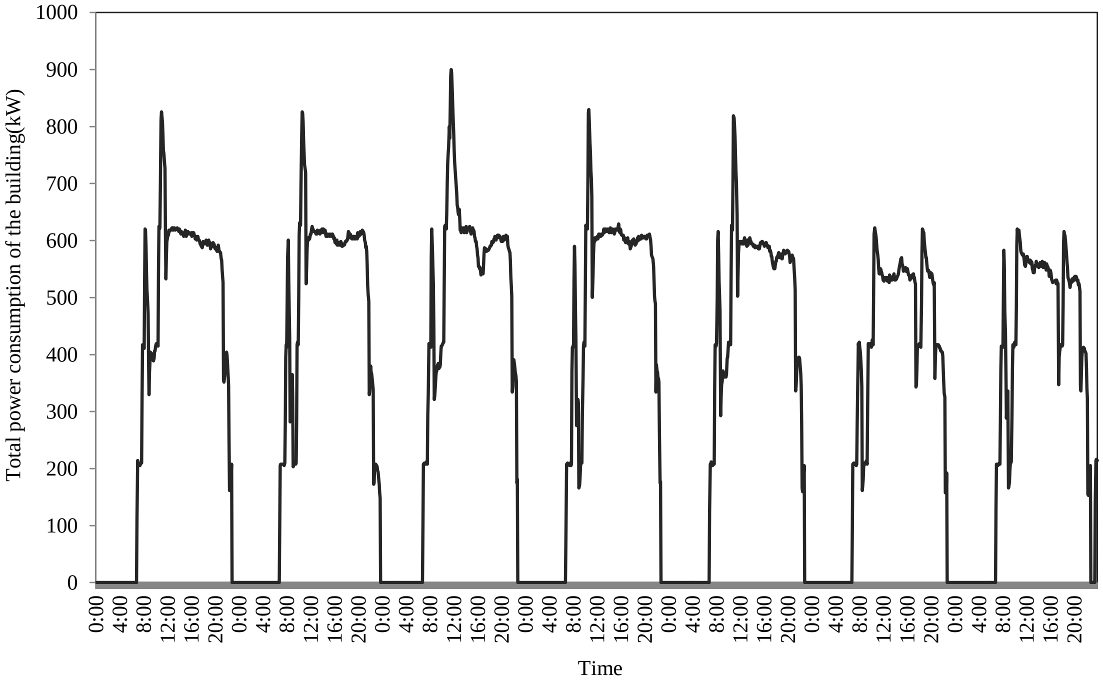


Fig.5 Power consumption patterns of a building in a week

In order to achieve the maximum monthly peak demand reduction, a demand limiting control strategy is needed to ensure that the stored cooling energy of the CWS is discharged in the most suitable time, particularly when the CWS has very limited storage capacity and can only maintain the discharging process for a short period of time (e.g., within one hour). Generally, the most effective way to reduce the monthly peak demand is to activate the demand limiting control when the building power demand is likely to reach its possible peak value in each month.

The difficulty of predicting the occurring time of peak demand varies from buildings to buildings. In this study, two demand limiting control strategies, i.e. time-based control and demand-based control are proposed for buildings with regulate peak time and buildings with variable peak time respectively.

Using the time-based control strategy, cold discharging mode is activated in some certain or pre-defined demand limiting periods when the daily peak is supposed to be occurred. In some buildings, particularly buildings with regulate usage characteristics, the power demand generally shows similar profile patterns and the peak occurring time is easy to be predicted. For example, the total building power consumption profile of a commercial building in Hong Kong is shown in Fig.5. The profile shape in the first five working days are similar and the occurring time of daily peak demands are concentrated within a certain short period of time, e.g., from 11:30 to 12:30. The demand limiting period in this building then can be defined as from 11:30 to 12:30.

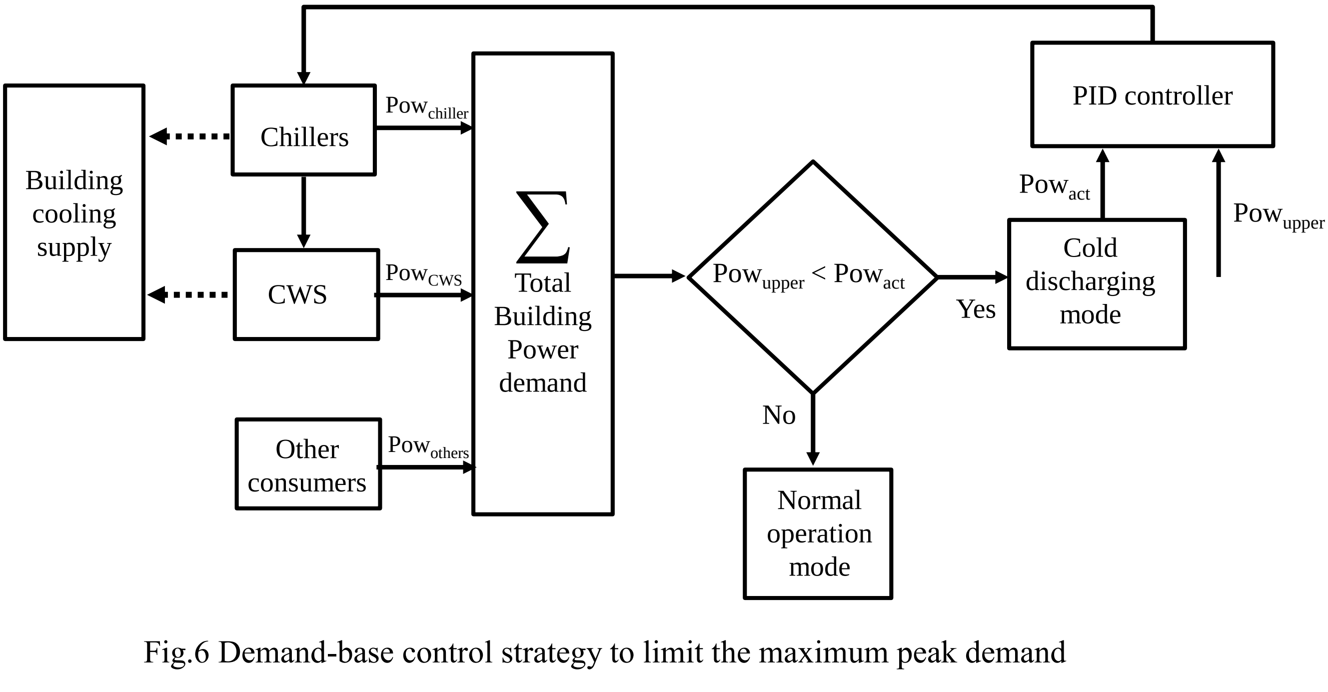


Fig.6 Demand-base control strategy to limit the maximum peak demand

In contrast, in some other buildings, the occurring time of peak demands varies greatly due to the uncertain weather conditions and variable occupant activities. In such cases, the demand-based control strategy is used to limit the actual building peak demand within the target set-point. As shown in Fig.6, when the actually measured total building power demand exceeds the peak demand set-point (i.e. Pow_{upper}), the cold discharging mode will be activated. The cooling supply from the operating chillers is then reduced until the upper limit of total building demand is achieved under the control of a PID controller. Meanwhile the cooling supply from the CWS system is increased correspondingly. In this control strategy, the peak demand set-point should be given a proper value, which can be determined by the historic data or predicted based on the optimal method introduced in [6].

4. Case studies and cost-effectiveness analysis

From above analysis, the monthly cost saving contributed by the proposed chilled water storage system are mainly determined by the cold storage capacity of the tank (or the volume of the fire service storage tank) and the building power profiles. Three buildings with different fire service tank sizes and different power profiles are used as the reference buildings for evaluating the effectiveness and cost-effectiveness of the proposed retrofitting. The three reference buildings are located in Hong Kong and their real-time total power consumptions are monitored with the sample interval of 5 minutes. The monitored power consumption profiles in a typical summer day are shown in Fig.7. The basic information about buildings and their fire service water tanks are described as follows.

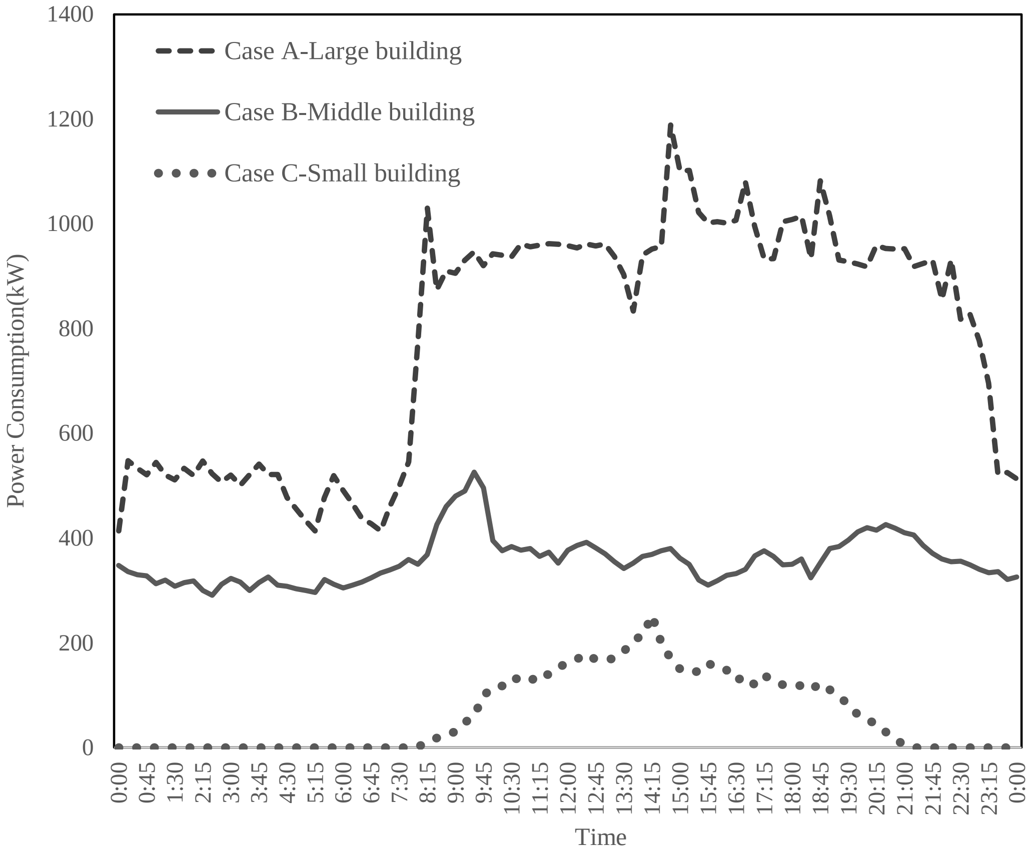


Fig.7. Power consumption profiles in a typical summer day for three reference buildings

4.1 Buildings and their fire service storage tanks

Case A - a large scale campus building

The Phase 5 building located in Hong Kong Polytechnic University campus is used as the large scale reference building in this study. It mainly consists of offices, classrooms and computer rooms. The total area is approximately 11,000 m^2, of which about 8500 m^2 is air-conditioned by an air-water system. In typical summer days, the maximum peak demand is about 1200 kVA and the daily power consumption is about 19,000 kWh, as shown by the power profile in Fig.5. The daily building cooling load in summer is about 12,650 kWh.

A fire service tank with a volume of 85 m^3 is available in this building, which can be retrofitted as a chilled water storage system and integrated within the existing air-conditioning system using the Large-ΔT application scheme (see Fig.3). Considering that the temperature difference of the CWS can reach up to 15°C and the overall storage efficiency of the tank (η) is about

90%, the maximum cooling storage capacity of this tank is calculated about 1340kWh. Since the tank can only provide a small portion (i.e. 10.6%) of the daily cooling load, all stored cooling energy should be used only when the peak demand occurs. The maximum daily shifted power consumption due to cold storage then can be estimated as 536 kWh using Eq. (4).

Case B - a middle scale hotel building

A typical hotel in Hong Kong is used as a middle scale reference building. The total floor area is about 5,300 m^2, of which about 4,000 m^2 is air-conditioned. The annual electrical energy consumption is about 1.9 million kWh. The peak demand in summer months is about 520 kVA. In this building, all guestrooms are served by a typical air-water system, in which FCUs are used to control the room temperature of individual rooms and the fresh air is provided from PAUs. The daily building cooling load in summer is about 5100 kWh.

A fire service tank with a volume of 125 m^3 has been constructed in this building, which can also be integrated with the existing air-conditioning system with large storage ΔT (15°C). Using the same calculation settings in Case A, the cooling storage capacity and the daily shifted power consumption are calculated as 1970 kWh and 788 kWh respectively.

Case C- a small scale office building

The Hong Kong Zero Carbon Building (ZCB) is introduced as an illustrative example of small scale office building for evaluating the economic performance of the demand limiting using the proposed chilled water storage. The Hong Kong ZCB is a three-story office building with the total net floor area of 1,520 m^2. The annual electrical consumption in this building is about 365,000kWh. The annual peak demand is about 250 kVA in summer. The air-conditioning system is typical all-air system. The peak cooling load is about 240 kW and the maximum daily building cooling load is about 1800 kWh.

In this building, a fire service water tank with a volume of 125 m^3 is constructed underground. Based on the configuration of the existing air-conditioning system (i.e., all-air system), the retrofitted water tank can only be used a small storage ΔT (5°C) tank. The maximum cooling storage capacity is calculated as 656 kWh. The maximum power reduction and daily shifted power consumption are estimated as 96 kW and 262 kWh respectively.

4.2 Cost-effectiveness

The economic performance of implementation of the proposed retrofitting can be evaluated by payback period, which are mainly determined by the annual cost saving due to demand limiting and the extra cost involved. The payback period in capital budgeting refers to the period of time required to recoup the funds expended in an investment. In this study, the simplest payback calculation method (e.g., the total extra cost divided by the annual cost saving) is used for determining the static payback period. The payback period of the retrofitting project in Case A, Case B and Case C building are about 0.70 year, 0.95 year and 2.58 years respectively. This indicates that the proposed retrofitting schemes are very cost-effective, particularly when the large ΔT application scheme is adopted.

The annual cost saving of the three retrofitting cases in the three reference buildings are summarized in Table 3. The annual cost saving is the sum of cost saving from both the monthly peak demand reduction and the accumulated shifted power consumption in twelve months. It is shown that substantial annual cost saving can be obtained for three buildings. Particularly for the large and middle scale buildings, an annual cost saving near 0.3 million HK$ can be achieved by demand limited control. The majority (90-95%) of cost savings in three buildings, indicated by the saving ratio (C_P / C_T) of peak reduction in the table, are contributed from the reduction of monthly peak demand. The cost saving calculation for the three buildings are based same methods and assumptions. Once the annual power profiles of these buildings are given from the monitored data, the magnitude of monthly power demand reduction in each month and the annual amount can be determined. As all peak information are already known, the stored cooling energy then can be discharged ideally to achieve the maximum peak demand reduction in each day based on the time-based demand limiting strategy. The annual shifted power consumption is estimated based on an assumption that the CWS system is fully used in every day, i.e. assuming the daily shifted power consumption $E_{shifted}$ is constant. This assumption is reasonable in the three buildings as the cold storage capacity of the CWS is much less than the daily cooling load and space cooling is needed throughout the year. In other cases, the annual shifted power consumption should be determined according to the actual usages of the CWS through dynamic simulations.

Table 3 Annual cost saving of three reference buildings using CWS

		Case A	Case B	Case C
Saving from Peak Reduction C_P	Maximum ΔPD (kVA)	254	195	96
	Annual ΔPD (kVA)	2,464	2,204	941
	Annual saving (HK$)	288,265	257,810	110,074
	Saving ratio (C_P /C_T)	94%	90%	92%
Saving from Power Shifting C_S	Daily $E_{shifted}$ (kWh/day)	536	788	262
	Annual $E_{shifted}$ (kWh)	195,640	287,620	95,630
	Annual saving (HK$)	18,586	27,324	9,085
	Saving ratio(C_S /C_T)	6%	10%	8%
Total Annual Saving (HK$) C_T		306,850	285,133	119,158

Table 4 Extra cost for tank retrofitting and additional equipment (HK$)

	Case A	Case B	Case C
Insulation	36,500	45,000	58,100
Pumps	51,400	75,500	42,600
Heat exchangers	42,900	63,100	131,000
Electric actuated valves	36,000	33,000	23,000
Water distributors & pipelines	28,000	30,000	25,000
Others (10%)	19,480	24,660	27,970
Total extra cost (HK$)	214,280	271,260	307,670

The extra costs involved in tank retrofitting are mainly caused by the thermal insulation of the chilled water tank and the use of additional equipment for cold charging and discharging. The break-down of extra cost in three reference buildings, which are based on the average quoted price of three Hong Kong-based suppliers, are summarized in Table 4. The total extra cost for tank retrofitting in three cases are different, as the tank volume and the application scheme of the CWS are different. The cost difference between Case A and Case B is apparent: using the same ΔT application scheme, the larger water tank needs more retrofitting cost. However, the total retrofitting cost of Case C is about 13.4% higher than that of Case B even these two buildings have the same volume of water tank (i.e. 125 m^3). This indicates that the retrofitting the water tank as a large ΔT tank is more cost-effective compared to as a small ΔT tank. Using the large ΔT application scheme, the required heat exchanger area and the amount of insulation materials as well as the pump size can be reduced greatly due to the higher water temperature within the tank.

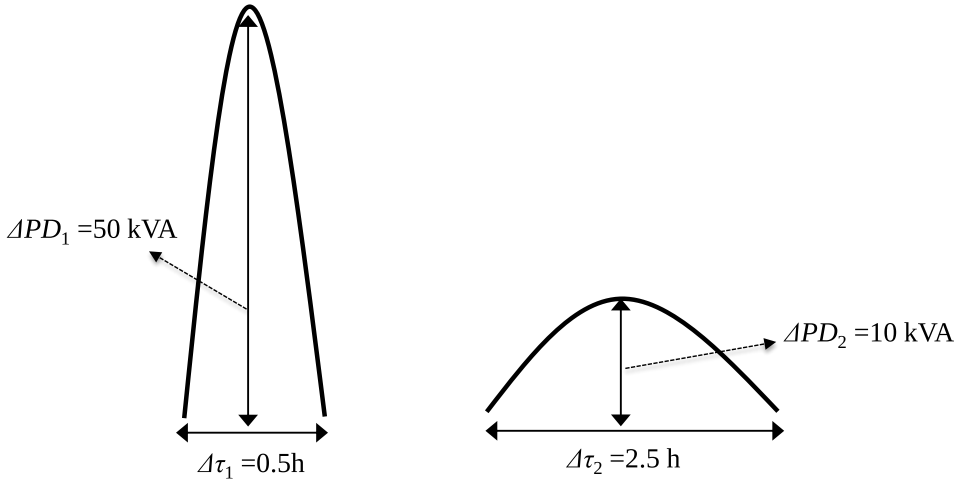
5. Discussion on applicable conditions

Although this study is based the situation in Hong Kong, in principle the proposed retrofitting schemes could be applied in buildings of any other regions or cities. In addition to the consideration of good data availability in these three buildings, the other reason why choose Hong Kong as the trial application city is the uniqueness of Hong Kong. The unique conditions (e.g., Hong Kong buildings have a relatively small size fire water tank required by the fire authorities while have relatively large building cooling load due to its subtropical climate and high density of occupants) bring more barriers to implement the proposed retrofits in Hong Kong. Such retrofits in Hong Kong buildings are verified to be feasible and cost-effective, the same performance, if not the better, of the retrofits in other places is expected, particularly for those places with preferable building conditions and more attractive electricity price structures.

5.1 Preferable building factors

The cooling storage capacity of the CWS is one of the most important building factors in determining the peak demand limiting performance. Generally, the larger storage capacity is more likely to contribute the more peak demand reduction. In a given building with the given configuration of the existing air-conditioning system, the maximum cooling storage capacity is mainly determined by the volume of the fire water tank. The requirement for the fire water tank volume varies greatly in different regions and countries. In Hong Kong, the required fire tank volume in a building is generally small (e.g., almost no larger than 125 m^3) according to the Code of Practice for Fire Safety in Buildings in Hong Kong [20]. Similar mandatory requirement (relatively small) for fire water tank installation can be found in the building fire service codes of the United Kingdom [21]. However, in some other countries such as in China and USA, the volume of fire service water tank can reach up to 500~1000 m^3 in many buildings [12] [15]. More effective peak demand reduction can be achieved when these large volume fire water tanks can retrofitted as proposed.

With the given cooling storage capacity, the shape of peak load profile is the other key building factor in determining the amount of peak demand reduction. A building with sharp peak profile has better demand limiting performance than that of a building with a rounded peak profile. As shown in Fig.8, a reduction of 50 kVA can be achieved under the sharp profile (i.e. high in magnitude but short in time) while only 10 kVA of peak demand can be reduced under the rounded profile (i.e. low in magnitude and long in time) through shifting the same among of power consumption. Generally, sharp peak profiles are usually caused by the sudden change of cooling load during the cool-down period at the start of the system operation or the occupant number is suddenly increased.



Sharp peak Rounded peak

Fig.8. Two different shapes of peak demand profile

5.2 Preferable electricity price structures

Another main factor affecting the cost-effectiveness of the retrofitting is the electricity price structure. The electricity price structure introduced in this study comprises of two items. One is monthly peak demand charge and the other is the overall energy consumption charge over a month. The demand charge during on-peak period and the energy charge in the electricity price structure decide the effectiveness of power demand limiting control. Generally, it is more favorable to use chilled water storage for limiting power demand when the demand charge is high and energy charge is low. Table 5 presents some typical time-of-use (TOU) plus peak demand charge electricity price structures in USA [4]. These structures are similar to that in Hong Kong. Compared with that in Hong Kong, the higher on-peak demand charges and lower energy charges even provide greater incentives to retrofit the fire service water tank for demand limiting in these regions. In China, there is a nationwide policy of TOU pricing for industrial customers [22]. For example, customers in Shanghai face a TOU rate with a 4.5-to-1 peak to off-peak price ratio. This indicates the cost saving through power shifting in Shanghai is much more effective compared to these regions with small TOU rate (e.g., the TOU rate in Hong Kong is less than 1.5.). Additionally, the monthly peak demand control in China is also very important based on the current peak demand charge policy. Customers need to submit their peak demand limit of each month to the power company in advance. The peak demand charging is then determined by the actual peak demand and the peak demand limit: when the actual peak does not exceed the peak limit, it is charged by the submitted peak; otherwise, the price of the exceeding demand is doubled. The predictability and controllability of the peak demand of a building can be greatly improved when the fire service water tank can be retrofitted as the CWS.

Table 5 Typical time-of-use plus peak demand charge electricity price structures in USA

Location	Energy consumption				Peak Demand			
	Summer		Winter		Summer		Winter	
	On-Peak ($/kWh)	Off-Peak ($/kWh)	On-Peak ($/kWh)	Off-Peak ($/kWh)	On-Peak ($/kVA)	Off-Peak ($/kVA)	On-Peak ($/kVA)	Off-Peak ($/kVA)
Atlanta	0.1074	0.0194	0.0194	0.0194	8.59	4.30	-	4.30
Phoenix	0.1062	0.0410	0.0968	0.0372	4.88	-	0.31	-
Los Angeles	0.1150	0.0595	0.1027	0.0638	28.13	7.87	-	7.87
New York	0.0052	0.0052	0.0052	0.0052	14.99	9.79	6.56	2.73

6. Conclusions

This paper presents a comprehensive technical and economic feasibility study on retrofitting an existing building fire service water tank as a chilled water storage (CWS) tank for building power demand limiting. Two combination schemes (i.e., the small ΔT scheme of 5°C and the large ΔT scheme of 15°C) that enable the retrofitted storage tank with different applicability and storage capacities are proposed for air-conditioning systems with different configurations. The small ΔT scheme has a broader applicability, which can be used in all-air systems as well as in air-water or all-water systems. But the cold storage capacity of the water tank using such a scheme is only about 5.8 kWh/ m^3. In contrast, the large ΔT scheme enables the water tank to have a much larger cold storage capacity, i.e., 17.5 kWh/ m^3. However, this scheme can only be used in air-water systems that are easily to be retrofitted as THIC air-conditioning systems.

The time-based demand limiting strategy is a simple and ideal control strategy that can be used in buildings with regulate peak demand occurring time. The demand-based control strategy is a more complicated and more realistic strategy, which can be used in buildings with variable peak demand occurring time.

The cost-effectiveness of the proposed retrofits is well verified in three reference buildings in Hong Kong. Results show that substantial annual cost savings can be obtained in these three buildings and the majority (90-95%) of the savings are contributed from the reduction of monthly peak demand. The payback period of the retrofitting project in the large scale (11,000 m^2), middle scale (5,300m^2) and small scale (< 2000 m^2) building are about 0.70 year, 0.95 year and 2.58 years respectively. The total retrofitting cost of using the small ΔT scheme is about 13.4% higher than that of using the large ΔT application scheme when retrofitting existing fire service water tanks with the same volume.

The applicability of the proposed retrofits in other places rather than only in Hong Kong is also discussed. Analysis shows that the same or even better technical and economic performances are likely to be achieved in many other cities worldwide where there are similar or better application conditions compared with that in Hong Kong, such as buildings with larger volume of fire service tanks required by local fire authorities and more incentive electricity price structures. The application of the proposed retrofits to real buildings and the recommendation of using fire service water tanks for demand limiting at the design stage of new buildings are the key issues for the future works.

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