First of its kind in Hong Kong - innovative reuse of treated effluent and enhanced energy efficiency for air-conditioning systems

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ABSTRACT

In Hong Kong, air-conditioning (A/C) systems are major consumers of electricity. Although water-cooled air-conditioning systems (WACSs) are more energy efficient, the need for water towers, water treatment and other operation and maintenance (O&M) demands restrain their application in most buildings. This paper reviews a pilot application of treated effluent from sewage treatment works as a cooling medium for the Direct Expansion type of A/C system within the treatment Plant. The Drainage Services Department (DSD) installed a WACS with a self-assembled effluent-cooled condenser to study the energy efficiency, cooling performance and actual O&M requirements of the new system over a one-year pilot. It revealed that an energy saving of up to 27.6% per year could be achieved when compared with a conventional air-cooled air-conditioning system (AACS). This innovative effluent cooling A/C system achieves innovative reuse of treated effluent as well as reduction in carbon footprint as a result of higher energy efficiency for sustainable development.

KEYWORDS Wastewater treatment; sewage treatment works; treated effluent reuse; water-cooled air-conditioning system; building energy saving

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1. Introduction

In Hong Kong, air-conditioning (A/C) systems are the major contributors to the total electricity consumption in buildings. Similar to other industrial and commercial buildings, A/C systems for temperature, humidity and ventilation control of various equipment and administrative areas are installed in sewage treatment works (STWs) of the Drainage Services Department (DSD). These A/C systems account for a certain proportion of overall energy consumption.

Due to the scattered layout of various plant rooms, workshops, and buildings requiring air-conditioning and their staggered cooling loads, split-type direct expansion (DX) air-cooled air-conditioning systems (AACSs) are currently adopted in STWs of the DSD. However, AACSs are less energy efficient as compared with DX water-cooled air-conditioning systems (WACSs). With the rising concern of energy saving, greenhouse gas reduction and building sustainability, it is desirable to replace AACSs with more energy-efficient WCASs. However, the use of conventional WCASs with fresh water cooling towers is not an ideal option because they consume valuable fresh water resources.

The DSD has incorporated a concept of water resource management into facilities to improve utilisation rates of water and step up the harvesting and reuse of precious water resources so as to support sustainable development. The Department has made continuous efforts to promote the use of reclaimed water, treated effluent and harvested rainwater in facilities. To combine the concepts of effluent reuse and energy efficiency, the DSD has explored the feasibility of innovative reuse of treated effluent as a cooling medium for WACSs in its facilities.

This paper describes a pilot project conducted from 2021-2022 to study the use of ultraviolet-disinfected secondarily treated effluent, which would have been discharged into the sea, for cooling the refrigerant of A/C systems. Application of treated effluent as a cooling medium in the A/C system is the first of its kind in the STWs of the DSD. This pilot project will provide a baseline for further development of innovative reuse of effluent for cooling A/C systems in STWs and also wider use of treated effluent directly for district cooling in Hong Kong.

2. Project background

There are 2.8 million cubic metres of sewage treated by the DSD every day, of which about 20% is treated by secondary and tertiary STWs (Drainage Services Department, 2021). Treated effluent from secondary and tertiary STWs has high potential for non-potable applications in STWs, and the use of treated effluent is cheaper and consumes less energy when compared with reclaimed water and potable water. Reusing treated effluent not only could minimise pollution of the environment and avoid overloading of the ecosystem, but also relieve the demand on fresh water resources and reduce carbon emissions.

To enhance the energy efficiency of A/C systems and preserve the valuable fresh water resources, a trial project was initiated to study the reuse of ultraviolet-disinfected secondarily treated effluent as the cooling medium for the DX WACS with a once-through direct cooling system and variable refrigerant volume (VRV) control system. The aged and deteriorated DX AACSs at the Water Reclamation

Information Centre and Switchroom I of the Sha Tin STW were replaced with such effluent cooling A/C system which achieved a significant energy saving of 27.6% as presented in Section 5 below.

In this pilot project, a WACS with a self-assembled effluent-cooled condenser was installed to study the energy efficiency of the new system, the cooling performance of treated effluent, and the actual O&M requirements associated with the reuse of treated effluent as a cooling medium.

3. Literature review

3.1. Water-cooled air-conditioning system (WACS) vs. air-cooled air-conditioning system (AACS)

Air-conditioning (A/C) systems are indispensable in modern life in Hong Kong for indoor temperature, humidity and ventilation control. The use of A/C accounts for about 30% of the total electricity consumption in Hong Kong (Electrical and Mechanical Services Department, no date). In consideration of the scattered layout of plant rooms, workshops and buildings requiring A/C in STWs of the DSD as well as their staggered cooling loads, independent A/C systems are commonly adopted rather than central systems. The cooling of air is accomplished by direct expansion of refrigerant in cooling coils as indicated in a typical setup of a DX AACS in Figure 1 below (Saif M, 2022).

According to the different types of cooling medium for refrigerant in the reverse-Rankine cycle, A/C systems can be divided into two categories, namely air-cooled and water-cooled systems. Water-cooled condensers have a higher heat transfer coefficient than air-cooled condensers, which in turn require smaller heat exchange surfaces and lower compressor power consumption. Owing to the disadvantage of AACSs, their cooling performance drops significantly during summer in Hong Kong under the high ambient temperature (Chen, et al., 2008). The rated coefficient of performance (COP) of AACSs and WACSs is generally 2.8 and 4.7 respectively (Yik et al., 2001). Taking into account the seasonal fluctuation of outdoor ambient conditions, it is anticipated that the conversion of AACSs to WACSs in this pilot study could result in energy savings of 20-30%.

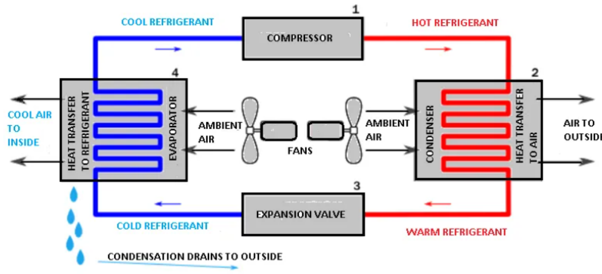

Figure 1. Typical setup and working principle of the direct expansion type of air-cooled A/C system.

3.2. Effluent-cooling vs. recirculating water-cooling tower

In Hong Kong, the WACS is dominated by recirculating water cooling tower systems and once-through seawater cooling systems.

In the traditional recirculating water-cooling tower system, consumption of valuable fresh water and the risk of legionnaires' disease infection are major concerns. In general, about 2% to 3% of the condenser water flow is also required as make-up water to compensate for water losses due to evaporation, drift and bleed-off from the cooling tower (Yik et al., 2001). During operation, water treatment (physical or chemical) is necessary to limit the growth of legionella associated with cooling towers, which adds to the operation costs for routine inspection and preventive maintenance. Apart from this, it is worth noting that the high humidity climatic conditions in Hong Kong sometimes affect the effectiveness of the evaporative cooling towers significantly.

On the other hand, the adoption of seawater cooling systems might not be versatile due to the lack of convenient and reliable seawater sources nearby. Fortunately, the STWs of the DSD produce substantial quantities of treated effluent every day, which makes it a perfect stable source for WACSs.

4. Pilot setup

From 2021-2022, a pilot project was initiated by the DSD to replace the aged and deteriorated DX ACCSs with higher-efficiency DX WACSs. In order to minimise the potential O&M burdens and scarce fresh water consumption associated with the cooling tower system, the project team decided to assemble an indirect-feed treated effluent cooling condenser (see Figure 3) for the factory assembled self-contained DX water-cooled A/C units (see Figure 2). Two units of cassette split type DX ACCSs and two units of ceiling mounted split-type DX ACCSs at the Water Reclamation Information Centre and Switchroom I of the Sha Tin STW were selected respectively for replacement.

This is now an effluent cooling A/C system which uses ultraviolet-disinfected secondarily treated effluent as the cooling agent for the DX WACS with once-through direct cooling and variable refrigerant volume (VRV) control systems.

4.1. Variable Refrigerant Volume (VRV) technology

The COP of a refrigeration system increases with capacity. Since the localised DX units are smaller in size, the COP is low. Due to the wide spectrum of thermal zones to be controlled, the conventional capacity control in a DX system is commonly achieved by cycling the compressor on and off in response to signals from a thermostat. Adopting the VRV control for A/C systems is a good solution to improve the COP.

VRV offers precise refrigerant flow control in relation to the evaporators so that the volume of refrigerant is accurately matched with the required cooling loads in the cooling space, hence saving more energy. It was reported that VRV systems can achieve 30% and higher heating, ventilation, and air conditioning (HVAC) energy cost savings relative to minimally coded conventional compliant systems (Thornton and Wagner, 2012). Thanks to the advancement of technologies, the latest VRV A/C systems can be equipped with full-coverage occupancy sensors to auto-tune indoor temperature and swing fan settings according to occupancy number and position. For instance, energy-saving mode or auto-off mode can be selected when there is no occupancy detected. These technologies further reduce the energy consumption of A/C systems.

Figure 2. Schematic diagram of the pilot effluent cooling A/C system setup.

4.2. Heat exchanger

Since this is saline effluent, indirect cooling of the VRV system was adopted to prevent coil corrosion. Separate plate-type heat exchangers (Hxs) made of titanium were therefore used wherein the effluent and condensing water inside the Hxs are totally independent during the heat exchange process. Plate-type Hxs were selected for the effluent cooling A/C system due to their following advantages over the shell and tube type of Hxs. Firstly, plate-type Hxs have higher heat thermal efficiency than tubular apparatuses do. The plate-type Hxs have higher heat transfer efficiency as well as larger heat exchange surfaces inside a compact unit. Secondly, they have lower fouling resistance. In general, the deposition fouling coefficient decreases as the flow velocity increases (Sung et al., 2008). Due to the comparatively higher turbulence, and no zone of low velocity for plate-type Hx, the risk of scaling on heat exchange surfaces is lower.

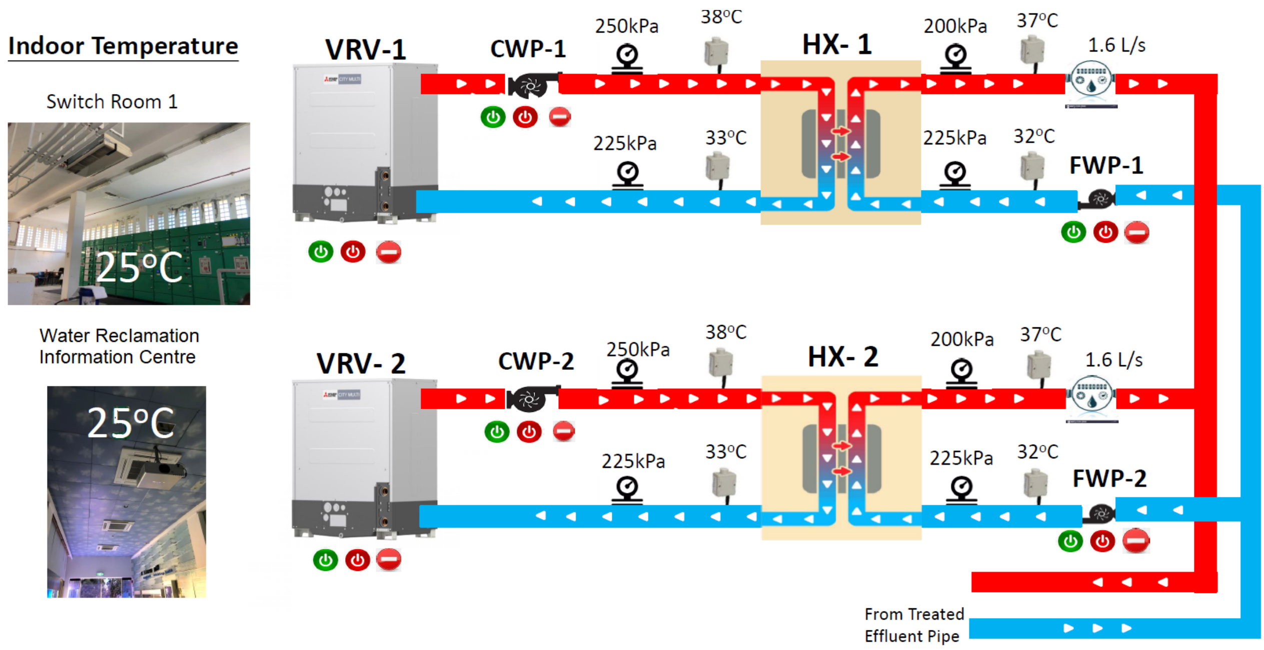

Figure 3. Schematic diagram of the assembled indirect-feed treated effluent cooling condenser.

However, the use of treated effluent may pose the risk of accelerated heat exchanger fouling. In this circumstance, it is important to quickly notice when exchanger performance is degrading. Condition monitoring of Hx with Internet of Things (IoT) technologies (e.g. smart digital sensors, real-time monitoring and alarm devices, etc.) was adopted to provide operating data for analysis. The result can alert operators before excessive fouling accumulates which would otherwise reduce the efficiency of the A/C system.

Figure 4. Pilot effluent cooling A/C system at the Sha Tin STW.

4.3. Treated effluent intake

In the sewage treatment process of the Sha Tin STW, the incoming sewage goes through preliminary treatment, primary treatment and secondary treatment before being discharged into Victoria Harbour via effluent export tunnels (see Figure 5). In line with the government's initiative to use reclaimed water under the Total Water Management Strategy, water reclamation facilities were installed and commissioned at the Sha Tin STW in 2011. Reclaimed water has wider non-potable applications than secondarily treated effluent; however, there are issues of extra space requirements and higher O&M cost. The ultraviolet-disinfected secondarily treated effluent, with the majority of impurities, nutrients and contaminants removed in the treatment process, makes it suitable for non-potable reuse within the STW.

In the pilot project, the ultraviolet-disinfected secondarily treated effluent was extracted for cooling the condensing water (primary water circuit) inside the Hx (see Figure 6). The closed loop condensing water in turn cools the refrigerant in the factory-assembled VRV outdoor unit (secondary water circuit). After absorbing heat inside the Hx, the treated effluent will only increase its temperature from 32°C (max. effluent temperature in summer) to 37.5°C with no deterioration in effluent quality. Therefore, the used treated effluent can return to its original effluent export route without disturbance to the overall sewage treatment system. This layout utilises the existing pumping systems in the Sha Tin STW; thus, less extra energy is consumed.

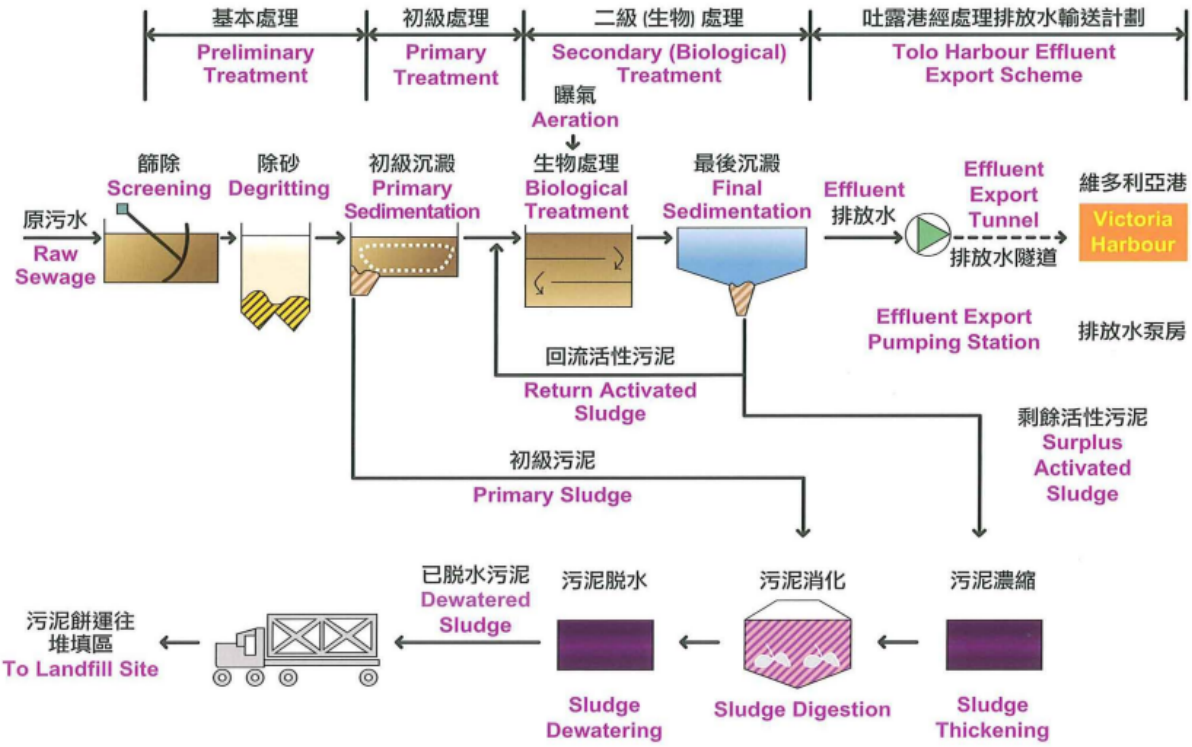

Figure 5. Sewage treatment process flowchart of the Sha Tin STW.

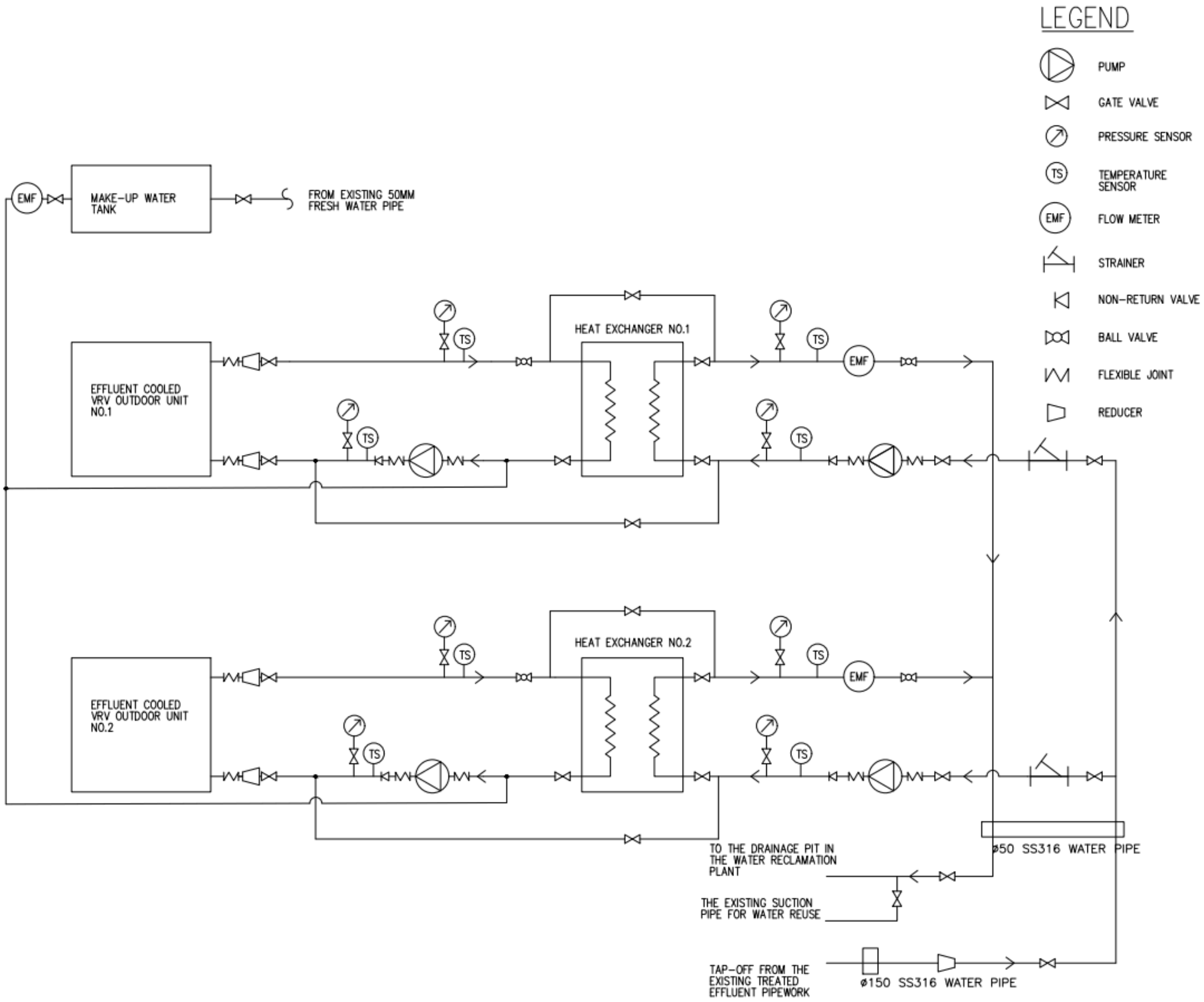

Figure 6. Piping and instrumentation diagram of the pilot setup.

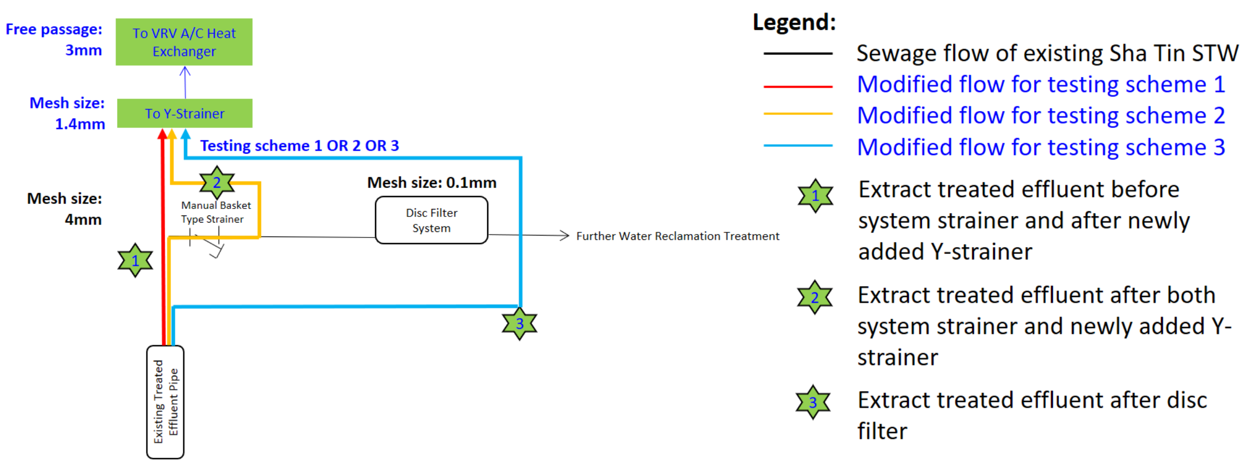

Figure 7. Details of three trial runs of the effluent cooling A/C system.

5. Pilot implementation

5.1. Screening trials

Three trial runs and one-year pilot operation were conducted from 2021-2022 to acquire actual system performance data and O&M experience. During the first trial run, the primary water circuit flow rate, the differential pressure across the Hx, and the treated effluent temperature before and after the Hx were monitored and examined. As shown in Figure 7, in the first trial run, the treated effluent passed through a 5-mm diameter manual Y-strainer (1.4mm mesh size) before entering the plate-type Hx with 3-mm free passage. The performance of the effluent cooling A/C system was successful. The room temperature was found to be satisfactory and in line with users' setting. However, the Y-strainer was blocked with debris after operation for 1.5 days. After an investigation and review of the collected debris composition and the treatment installations of the Sha Tin STW, it was suspected that leaves had fallen into open tanks along the treatment process, and the debris and scale that had accumulated inside the pipeline might be the causes of the blockage.

In the second trial run, treated effluent was extracted after both the existing 150-mm diameter system strainer (4-mm mesh size) and the 50-mm diameter Y-strainer (1.4-mm mesh size). It was observed that the Y-strainer was partially blocked after a trial run of 1 week. The flow rate of treated effluent in the secondary water circuit dropped to 40% of rated flow. As large foreign objects should have been screened by the 4-mm system strainer before the treated effluent entered the Y-strainer and there was no residue deposit on the plate surface of the Hx, it was a sensible conclusion that the 1.4-mm mesh size Y-strainer would be sufficient to screen the insoluble solids in the treated effluent. Apparently, the Y-strainer cleansing was demanding and a strainer with automatic flushing would be required. In order to make use of the existing resources, in the third trial run, the project team further modified the extraction point to the discharge of the existing disc filter (0.1-mm mesh size, with periodic automatic backwashing function) to the Hx via both the existing system strainer and Y-strainer. There was no further blockage of the Y-strainer nor the Hx after operation for one year.

5.2. Tangible benefits

In this pilot project, four units of aged split-type DX ACCSs at the Sha Tin STW were replaced with the effluent cooling A/C systems. Since all visits to the Sha Tin STW were suspended due to the COVID-19 pandemic from 2021-2022, the actual running hours of the A/C system at the Information Centre were considerably less than usual. For evaluation purposes, the rated power consumption of equipment and A/C running hours from past records were taken for energy saving calculation in this paper.

Under the same indoor cooling output and operation hours, the effluent cooling A/C systems' power consumption and energy efficiency ratio (EER) were compared with the rated values of AACSs before the upgrade. As shown in the summary in Table 3, an energy saving of up to 27.6% or 23,207.74 kWh per year can be achieved after the adoption of effluent cooling A/C systems, giving rise to a greenhouse gas reduction equivalent of 9.3 tonnes of CO_2, which is equivalent to the effect of planting 155 trees in urban area for 10 years (United States Environmental Protection Agency, no date).

Table 1. Specification of the AACSs before replacement.

	Information Centre	Switchroom
No. of Duty Indoor Unit	2	2
Cooling Capacity	13.19 kW	10.5 kW
Input Power	4.37 kW	3.80 kW
Type	4-way cassette	2-way suspended
EER	3.02	2.76

Table 2. Specification of the WACSs after replacement.

	Information Centre	Switchroom
No. of Duty Indoor Unit	2	2
Cooling Capacity	33.5/14 kW	28/11.2 kW
Input Power	6.04/0.11 kW	4.9/0.09 kW
Type	4-way cassette	4-way cassette
EER	5.54	5.71

Table 3. Power consumption of auxiliaries for the effluent-cooling condenser.

	Information Centre	Switchroom
Primary Circuit re-circulation pump	1.6 l/s 0.75kW	1.6 l/s 0.75kW
Secondary Circuit re-circulation pump	1.6 l/s 0.75kW	1.6 l/s 0.75kW

In addition to energy savings, the development of effluent cooling A/C systems helps promote the reuse of water resources that are readily available from treated effluent in the existing or new STWs. A maximum of 1,190 m^3 of fresh water per year can be preserved at the designated cooling load by changing the cooling agent from valuable fresh water in conventional WACSs to treated effluent. The arrangement of a one-outdoor unit and two-indoor unit of effluent cooling A/C system enables easier O&M.

Saving energy also depends on the cooling load required, the needs and habits of occupants, the operating schedules and the control of temperature settings. With the advancement of technologies, VRV control, smart digital sensors, and real-time monitoring devices are utilised to

Table 4. Summary table of the energy saving achieved by effluent cooling A/C systems.

Item	Location of Effluent Cooling A/C System	Cooling Capacity		Power Consumption (kW)		Energy Efficiency Ratio (EER)	Energy Efficiency Ratio (EER)	Normalised Power Consumption (kW)	Normalised Energy Efficiency Ratio (EER)	Energy Saving (kWh per year)	Energy Saving (normalised to cooling load)	Cost Saving (per year)	Carbon Saving (per year)
		Before upgrade	After upgrade	Before upgrade	After upgrade	Before upgrade	After upgrade	After upgrade	After upgrade				
1	Switchroom	21	28	7.6	6.58	2.76	4.26	5.36	3.92	19,666.20	29.5%	27,139.36	7,866.48
2	Information Centre	26.38	33.5	8.74	7.76	3.02	4.32	6.48	4.07	3,541.54	25.9%	4,887.33	1,416.62
				16.34				**11.83**		**23,207.74**	**27.6%**	**32,026.68**	**9,283.10**

Assumption:

(1) The actual cooling load is equal to the max cooling capacity of the A/C system before upgrade.

(2) The electricity tariff is HK$1.38 per kWh.

(3) Carbon emission of 0.4 kgCO2/kWh assumed in CLP Sustainability Report for 2020.

The operation schedule under remote mode is set as below: -

	Operation Day	Operation Hour
VRV 1 (To Switchroom)	Monday - Sunday	24-hour operation
VRV 2 (To Information Centre)	Monday - Friday	10:00 a.m. - 4:00 p.m.

Table 5. Comparison table of ACCS, WACS (cooling tower) and effluent cooling A/C systems.

	Existing Air-cooled A/C System	Water-cooled A/C System with Cooling Tower (Fresh water)	Treated Effluent cooling A/C System
Energy Efficiency Ratio (EER) (cooling output / input power)	2.5	4.50	4.50
Energy Saving (%)	0 (baseline)	27%	27%
Annual Fresh Water Consumption (m^3 per year)	0	1189 (make water quantity is assumed to be 2% of the cooling water rate)	0
Chemical Addition	Nil	Chlorine addition in the recirculating water circuit	Nil
Mechanical Configuration	4 indoor units plus	4 indoor units plus	4 indoor units plus
	4 outdoor units plus	2 outdoor units and 1 cooling water tower at rooftop	2 outdoor units and 2 heat exchangers

optimise the efficiency of A/C systems and assist predictive maintenance. For example, switching of A/C systems at the Water Reclamation Information Centre can be pre-set remotely at the control room to match the visiting tour schedule.

The capital costs for indoor and outdoor units of VRV A/C systems are similar for WACSs and AACSs. The extra cost for an effluent cooling A/C system over a conventional split-type AACS is mainly contributed by the effluent-cooled condenser (i.e. heat exchangers, pumps, strainers, sensors and control), in regard to which the equipment sizing correlates to the A/C system cooling demand. In this pilot, about HK$300,000 was spent on the additional equipment and installation works. Considering the cost saving due to lower consumption of electricity and fresh water, which is calculated conservatively in Table 4 (where the lower energy consumption of variable speed drive (VSD) pumps in actual operation and the longer A/C running hours for the Information Centre over the weekend are disregarded), the payback period for this project is around eight years as calculated by the following.

(1) Electricity cost saving
= 23,207.74 kWh/year x HK$1.38/kWh
= HK$32,026.7/year

*CLP non-residential tariff is taken as HK$1.38/kWh.

(2) Fresh water cost saving
= 1,190 m^3/year x HK$4.58/$m^3$
= HK$5,450.2/year

*WSD non-domestic suppliers for trade is taken as HK$4.58/$m^3$.

(3) Payback period

$$= \frac{\text{Extra cost for effluent cooling A/C}}{\text{Electricity and water costs saving}}$$

$$= \frac{\text{HK\$300,000}}{\text{HK\$32,026.7/year+HK\$5,450.2/year}}$$

= 8 years

6. Conclusion

This pilot project demonstrated that, with proper pre-filtration, the use of ultraviolet-disinfected treated effluent from a secondary treatment plant as the cooling medium for A/C systems is viable. Effluent cooling VRV A/C systems can achieve higher energy efficiency than AACSs and the system also preserves fresh water consumed over conventional WACSs. The concept of energy efficiency and effluent reuse provides favourable conditions for sustainable development and enhances environmental protection. This pilot project has also set an example and provided an essential reference for future construction and installation of effluent cooling A/C systems in existing and new STWs. Prior to conversion, it is recommended to conduct condition checking of insoluble solid characteristics in treated effluent. Suitably sized strainers with an automatic backwash function should be provided to maintain the system's efficiency and ease the O&M of the A/C system. Last but not least, although no biological fouling was observed during the operation of the system in the first year, bleach dosing in the effluent cooling system should be considered for hygiene purposes.

There are a number of secondary and tertiary STWs being operated in Hong Kong. More treatment works are also being constructed and conceived in the Sha Tin Cavern STW and the North Metropolis development. These all have very high potential for applying treated effluent as cooling medium for the A/C systems in their facilities. With the success of this pilot project, which is the first of its kind in the DSD, a baseline has been developed for future consideration of the wider use of effluent cooling A/C systems in STWs as well as district cooling in Hong Kong. Furthermore, the application also provides other latent benefits like reducing pumping energy, e.g. freshwater pumping and carbon footprint. Although immeasurable, these can enhance the living environment and the application is recommended to be included in future STW studies.

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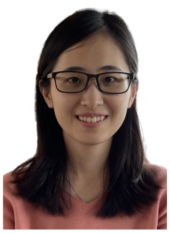

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