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A Case Study on the Application of Air- and Water-cooled Oil-free Chillers to Hospitals in Hong Kong

Francis W. H. Yik[a,*] DEng, PhD, CEng, FCIBSE
Joseph H. K. Lai[a] PhD, CEng, MCIBSE
N. K. Fong[a] PhD, MHKIE
Polly H. M. Leung[b] PhD
P. L. Yuen[c] BSc(Eng), MBA, FCIBSE

[a] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong SAR, China

[b] Department of Health Technology and Informatics, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong SAR, China

[c] Hospital Authority, Hospital Authority Building, 147B Argyle Street, Kowloon, Hong Kong SAR, China

* Corresponding Author; email: bewhyik@polyu.edu.hk, tel.: (852) 2766 5841.

Abstract

A comparison study on using air-cooled and water-cooled conventional and oil-free chillers in hospitals in Hong Kong is reported. The study commenced with a comprehensive literature review to reaffirm the effectiveness of recommended precaution measures for containing the risk of Legionnaires' disease (LD) associated with using cooling towers. Numerical performance models for oil-free chillers established for use in the study are presented. Based on recorded cooling demands of two existing hospitals, the life cycle energy consumption and cost of system options involving different combinations of heat rejection method and chiller type were evaluated, compared and discussed. The results show that water-cooled air-conditioning systems with conventional chillers and cooling towers are still more energy efficient than air-cooled systems with oil-free chillers. Water-cooled oil-free chillers may become an economically viable choice when their price is lowered in future. Pilot installation is recommendable, as it would allow the reliability and maintainability of the new oil-free chillers to be ascertained.

Practical Applications

Findings of the literature review reaffirmed the effectiveness of measures recommended in contemporary guidelines for LD prevention, which would ease the mind of owners, designers and operation and maintenance personnel in regard of using cooling towers in hospitals. The numerical models for oil-free chillers presented in the paper are useful for evaluation of the energy consumption of this new type of chiller and for comparison with other types of chiller. The study approach described in the paper, including the energy consumption prediction and life cycle cost evaluation methods, provides a useful framework for similar studies.

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Introduction

In lieu of air-cooled chillers, using water-cooled chillers together with cooling towers can lead to substantial energy saving[1] but is subject to the risk of legionnaires' disease (LD) given that the water temperature in cooling towers is ideal for legionellae to grow and proliferate.[2, 3] With a view to reducing energy consumption and the associated greenhouse gas emissions, the Hospital Authority of Hong Kong (HA) intends to widen application of water-cooled air-conditioning systems (WACS) to its hospitals but is concerned about the risk of nosocomial infection. Recently, air-cooled oil-free chillers, which are significantly more energy efficient than conventional chillers while running under part-load conditions, have emerged in the market[4] and have been adopted, as pilot installations, in a number of buildings in Hong Kong.[5, 6] Therefore, HA was keen to know whether air-cooled air-conditioning systems (AACS) with oil-free chillers could be a good substitute of WACS with cooling towers. The study reported in this paper was mainly meant to answer this question.

For reaffirming that the risk of LD associated with using cooling towers can be contained at or below an acceptable level by adequate system design and operation and maintenance (O&M), the study commenced with a comprehensive literature review of local and international regulatory controls, codes of practice and guidelines on prevention of LD. In this paper, a condensed summary of the literature review findings is first given, followed by a brief description of the characteristics of oil-free chillers. The mathematical models for air-cooled and water-cooled oil-free chillers, which were established from manufacturer's performance data to underpin energy simulation predictions, are presented. The methods used in the detailed energy simulation and life cycle cost (LCC) studies for four system options, and the findings of these studies, are then reported.

The risk of LD and measures for mitigation – literature review findings

The key findings of the comprehensive review of relevant international and local regulatory controls, codes of practice and guidelines on prevention of LD associated with using cooling towers (including Ref. 2, 3, 7 – 12 and many others) were as summarized below:

1. No evidence has been found that shows that the risk of WACS-mediated infectious diseases is unacceptably high and no international or national authorities have banned the use of evaporative cooling towers for healthcare facilities, including acute and non-acute hospitals.

2. According to Department of Health, the accumulated total number of reported LD cases in Hong Kong from 1997 to 2008 was 70 only, and all were sporadic cases (see http://www.healthyhk.gov.hk/phisweb/en/enquiry/index.html). With due consideration given to this risk, the Pilot Scheme for Wider Use of Fresh Water in Evaporative Cooling Towers for Energy-efficient Air Conditioning Systems, which was launched in 2000, has been made a standing scheme since 2008.[13]

3. Use of cooling towers does entail more stringent system design and O&M but relevant authorities in different countries and regions, including Hong Kong, have accepted that the risk of LD outbreak can be satisfactorily mitigated by closely adhering to the available design and O&M guidelines.

4. Full compliance with the comprehensive set of requirements stipulated in the codes of practice issued by the Electrical and Mechanical Services Department (EMSD)[12] will allow several lines of defence against LD to be put in place. The requirements

include:

i. Using only cooling towers with efficient drift eliminators;

ii. Elimination of any dead-legs in the piping system;

iii. Keeping minimum distances between cooling towers and nearby air intake and exhaust locations;

iv. Restricting access to cooling towers;

v. Application of water treatment, including dosing of chemicals or biocides and biodispersants;

vi. Alternate use of different chemicals / biocides;

vii. Regular water sample analyses;

viii. Periodic inspection and cleansing, prevention of stagnant water, keeping proper operational records, and annual audit by an independent party; and

ix. For healthcare settings, establishment of a water safety plan.

Since legionella is parasitic,[2, 3] use of biodispersants on top of biocides helps minimize microbial deposits which provide the bacteria with nutrients and shelter for growth and proliferation. Although the effectiveness of extensive environmental monitoring remains controversial, [2, 3] regular water sample analyses for detecting presence of legionellae can help verify whether or not the disinfection regime has been effective or requires improvement.

Having reaffirmed that the risk of nosocomial legionnellosis associated with using WACS can be kept under control through appropriate design and O&M practices, the key factor to be considered in making a choice between using AACS with oil-free chillers and WACS with conventional or oil-free chillers and cooling towers would boil down to the LCCs of the respective system options, taking into account the initial and replacement costs of the equipment and system components and, in the case of using a WACS, the water treatment costs and other associated costs for meeting the more stringent requirements.

Oil-free chillers and models for this type of chillers

General description

For conventional chillers, the use of lubricant for reducing friction and avoiding overheating at contacts between moving and stationary parts, especially those in the compressor, is indispensable.[4] However, presence of oil in the refrigerant is a significant cause of loss of efficiency and increased probability of failure. Recently, chillers that adopt a new type of bearing that does not require lubrication, referred to as 'oil-free' chillers, have emerged in the market, but 'oil-free' chiller is not a precise description for them; they may be more appropriately described as 'oil-free chillers with magnetic bearings', as there are other types of chillers that utilize other bearing designs, e.g. ceramic bearing, to do away with the need for lubricant.[14] Nevertheless, since the term 'oil-free' chiller is used in the market, it is used throughout this paper in making reference to this type of chiller.

The use of magnetic bearings for supporting the shaft that directly couples the motor with the compressor impeller and for fixing the axial position of the shaft offers the advantage that the shaft is suspended in air by magnetic flux such that it makes no contact with any other parts in the chiller and thus can run at very high speeds (e.g. up to 30,000rpm). This eliminates the need for lubricant as well as a gear chain to step up the rotational speed of the motor to that of the impeller, and the associated energy losses, too. However, a sophisticated control system, which includes sensors for detecting the axial and radial positions of the shaft (Figure 1), is needed to ensure the shaft will be held in position at all times. This makes repair and overhaul works very demanding tasks and, as yet, the reliability and maintainability of oil-free chillers and costs for their repair and overhaul are unknown.

Oil-free chiller models

For an evaluation of the economic viability of adopting oil-free chillers in lieu of conventional chillers, performance models for both types of chillers are needed. Models for conventional chiller types have been developed and incorporated into the air-conditioning plant energy simulation program BECON, which is the major simulation tool used in the present study. [15 – 17] Models for oil-free chillers, however, were unavailable but have to be developed for use in the study. For this purpose, the full- and part-load performance of oil-free chillers and their supply and installation costs were sourced from a supplier. Table 1 summarizes the coefficient of performance (COP; COP is defined as the cooling output per unit power input) of the air-cooled and water-cooled oil-free chillers over a range of condenser air/water inlet temperatures and loads on the chillers, from 100% down to 10% of their rated cooling outputs.

The full-load COP of the air-cooled oil-free chillers (2.9) is same as that assumed in this study for conventional air-cooled screw chillers, but the rated COP of the water-cooled oil-free chillers (5.4) is marginally lower than the assumed value for conventional water-cooled conventional screw chillers (5.5) (see further discussions in the next section). Nonetheless, the part-load COP values of both the air-cooled and the water-cooled oil-free chillers are superior to the corresponding types of conventional chillers, which imply that there will be energy saving by adopting oil-free chillers. However, the prices of the oil-free chillers are much higher, about double the prices of conventional chillers. Therefore, oil-free chillers will be more economical to use provided only that the achievable energy cost saving can payback the higher initial and replacement costs of chillers. Whether or not this is true is a question that will be addressed later.

Two oil-free chiller models have been established; one for air-cooled and the other for water-cooled oil-free chillers, and both of them are in the same mathematical form as other chiller models in BECON, which is a bi-quadratic equation as shown below.

$$w = C_0 + C_1 \cdot q + C_2 \cdot q^2 + C_3 \cdot T_{Ci} + C_4 \cdot T_{Ci}^2 + C_5 \cdot qT_{Ci} + C_6 \cdot q^2 T_{Ci} + C_7 \cdot qT_{Ci}^2 + C_8 \cdot q^2 T_{Ci}^2 \quad (1)$$

Where

q = the ratio of the actual load on the chiller to the rated cooling capacity of the chiller;

T_{Ci} = the condenser air/water inlet temperature, °C;

w = the ratio of the actual power demand, when it is outputting q with condenser air/water inlet temperature at T_{Ci}, to the rated power demand of the chiller; and

C_0 to C_8 = coefficients of the model.

The coefficients (C_0 to C_8) in the mathematical models (equation (1)) were evaluated by multiple linear regressions such that the models can best-fit the chiller manufacturer's performance data. Table 2 summarizes the model coefficients so obtained for the air-cooled and water-cooled oil-free chillers. Note should be taken that the air-cooled chiller model is based on the rated condenser air inlet temperature of 35°C and the water-cooled model on the rated condenser water inlet temperature of 32°C. The method given in Ref. 15 may be used to correct the model predictions for a chiller that is rated at other condenser air/water inlet temperatures. Comparison of the predictions of the air-cooled and water-cooled chiller models with the manufacturer's data showed that the models can yield predictions that match well with the manufacturer's data (Figure 2).

Energy and cost comparisons

The approach

Energy consumption prediction

The energy demand of the central air-conditioning plant of a building can be evaluated only if the building cooling load is known. A year-round hourly cooling load profile may be predicted by computer simulation but this has to be based on detailed characteristic data for the envelope and internal constructions of the building as well as the heat gains from occupants, lights and other loads in various air-conditioned spaces in the building. Furthermore, load profiles that represent typical conditions are often used to provide a simplified quantification of the variable heat gain intensities due to occupants, lights and appliances. Therefore, there will be uncertainties in the input data, and consequently in the predicted cooling loads, too.

To simplify the study, instead of carrying out detailed cooling load predictions, records of the year-round cooling load demands of two existing hospitals (denoted hereinafter as Hospital A and Hospital B) were collected from the O&M staff serving the two hospitals, and the records were used as the basis for prediction of the air-conditioning energy consumption of the hospitals. The energy consumption predictions covered a total of 8 cases for the two hospitals, which include cases with the following 4 system options for each hospital:

1. AACS with conventional screw chillers
2. WACS with conventional screw chillers
3. AACS with oil-free chillers

4. WACS with oil-free chillers

To cope with this series of simulation studies, the data input routine in the air-conditioning plant simulation program BECON was modified, and its chiller model library was expanded to include the oil-free chiller models, such that it can directly read the recorded hourly cooling loads and predict the annual air-conditioning energy use of the hospital concerned under each of the above 8 cases.

Since the COP values of chillers are highly influential to the energy consumption of the chillers, for providing a levelled platform for the comparison study, the minimum acceptable rated COP values for air-cooled and water-cooled chillers, as stipulated in the Code of Practice on Energy Efficiency of Air Conditioning Installations,[18] were adopted in the comparison study, except that the marginally lower COP value for the water-cooled oil-free chillers as given by the manufacturer (see discussions above) was retained. Part-load performances of the air-cooled and water-cooled chillers, and the cooling towers, were modelled using the respective equipment model established and incorporated into the model library of BECON.[15, 17]

In this study, comparison was made only on the energy consumption of those equipment in a system option that would be substituted when an alternative system option was adopted instead; the energy use of all other air-conditioning equipment, including the chilled water pumps and all air-side equipment, was assumed to be identical among the alternative system options and was excluded from the comparison. Therefore, only the energy consumption of the air-cooled chillers in an AACS was compared against the total energy consumption of the water-cooled chillers, the condenser water pumps and the cooling towers in the WACS that replaces the AACS.

Life cycle cost estimation

In the life cycle cost (LCC) analysis for the 8 cases, the analysis period (N) was taken as 60 years, which is the assumed useful life span of a hospital building. The life spans of chillers, pumps, cooling towers and condenser water pipes are much shorter. The assumed life spans of these equipments and components, and accordingly the number of times that they would need to be replaced within the life span of the hospital building, are summarized in Table 3. The rationale behind adopting 60 years as the analysis period includes:

1. The typical design service life for long life buildings, which includes healthcare buildings, is 50 to 99 years.[19] A building life span of 60 years is within this range.

2. Each system option involves equipments that have different life spans (Table 3), and thus their replacement would take place at different points in time within the life span of the building, whilst 60 years is the least common multiple of the life spans of the equipments involved (Figure 3).

Therefore, taking 60 years as the lifespan of a hospital building provided an equal basis for a fair comparison among the system options that were assessed. Otherwise, the LCC estimate could be unduly jacked up because some of the equipments would remain usable at the end of the time span covered by the analysis, in which case such equipments would be regarded as being disposed of before they would be due for replacement, while the increase in LCC so incurred would differ from one option to another.

It, however, does not mean that once a decision is made to adopt a particular option, the same option should necessarily be used throughout the life span of the building. When there is a need to make another decision, such as when the existing system has aged, whether or not to switch to another system option should be considered afresh, but should still be underpinned by LCC estimates for the alternatives estimated on an equal basis.

The life cycle costs of the AACS and the WACS were determined based on the following assumptions:

i. All monetary values are in constant dollars (i.e. with inflation already adjusted).

ii. According to the Water Supplies Department, for non-domestic supplies other than for construction or ocean-going shipping, the water tariff is at HK$4.58/m^3 and the sewage charge at HK$1.43/m^3, both determined based on the amount of water consumed, which need to be included as recurrent cost elements in cases where WACS is adopted.

iii. The price of everything except energy would only increase at a rate equal to the inflation rate and, therefore, their future prices would be same as their current prices when expressed in constant dollars.

iv. The price of electricity is HK$1/kWh and would increase at a real escalation rate (e) of 2% per annum.

v. The real discount rate (d) can be taken as 5% per annum.

Knowing the future cost for replacement of each equipment or component (C_{Rpl}), its life span (N_{Rpl}), the number of times that it would have to be replaced (T_R), and the real discount rate (d), the present value of the total replacement cost ($PV\{C_{TRpl}\}$) of that equipment or component through the life span of the hospital can be determined using equation (2).

$$PV\{C_{TRpl}\} = \sum_{i=1}^{T_R} \frac{C_{Rpl}}{(1+d)^{i \cdot N_{Rpl}}} \tag{2}$$

The life cycle maintenance cost ($LCC(M)$) and the life cycle water and sewage charges

(*LCC*(*WS*)), both in present values, were determined from the respective recurrent annual costs (*C*(*M*) and *C*(*WS*)) for the AACS and WACS, using equations (3) and (4). The life cycle water and sewage charges would need to be taken into account only for the WACS case but would be zero for the AACS case.

$$LCC(M) = C(M) \cdot USPWF_M \quad (3)$$

$$LCC(WS) = C(WS) \cdot USPWF_M \quad (4)$$

Where

$$USPWF_M = \frac{(1+d)^N - 1}{d(1+d)^N} \quad (5)$$

The annual total cost due to water and sewage charges on the water use (*C*(*WS*)) was determined based on the hourly water losses at the cooling towers of a WACS throughout a year, which include evaporation, drift and blow-down losses. The evaporation loss is proportional to the heat rejection rate, which equals the sum of the cooling output of and the power input to the operating chillers, and was determined from the predictions of the detailed energy simulation. The drift loss is proportional to the water recirculation rate through the operating cooling towers, which is dependent on the number of chillers being run and the condenser water flow rate through each of the running chillers, as ascertained from the simulation predictions. The blow-down loss was assumed to be 20% of the evaporation loss and, therefore, the cycle-of-concentration value would be about 6, which is the minimum value for fresh water cooling towers as recommended in EMSD's Code of Practice for Water-cooled Air Conditioning Systems (Part 3).[12]

The life cycle energy cost (*LCC*(*E*)), in present value, was determined from the recurrent annual energy cost (*C*(*E*)) for the AACS and WACS, using equation (6).

$$LCC(E) = C(E) \cdot USPWF_E \tag{6}$$

Where

$$USPWF_E = \frac{(1+e)}{(d-e)}\left[1-\left(\frac{1+e}{1+d}\right)^N\right] \tag{7}$$

Hospital A

Conventional screw chillers – energy consumption

Table 4 summarizes the characteristics of the air-cooled chillers, and the water-cooled chillers, cooling towers and condenser water pumps, that were used in the energy use predictions for the cases where Hospital A was assumed to be equipped with an AACS or a WACS with conventional screw chillers. Figure 4 shows the hourly cooling loads of the hospital ascertained from the collected records and the chiller energy use predicted for the AACS case. The results for the WACS case are shown in Figure 5. Table 5 summarizes the annual total cooling load and the predicted air-conditioning energy use of the two types of systems when applied to the hospital.

The simulation results summarized in Table 5 show that when Hospital A was equipped with a WACS instead of an AACS (both being newly installed, with conventional type screw chillers), the annual total energy use (i.e. total electricity consumption) of the chillers, the condenser water pumps and the cooling towers would be 29.5% less than the annual energy use of the chillers in the AACS. The difference in the peak power demand was even greater, by over 40%. This predicted energy saving compares well with the energy saving achieved in retrofit projects where AACS were replaced by WACS with cooling towers (24.1 to 37.2%), as reported by Tam et al.[20] It is possible to achieve a greater percentage energy saving in retrofit projects, as retrofit works typically involve replacement of worn out air-cooled chillers by brand-new water-cooled chillers.

Based on the predicted annual energy use of the AACS and WACS (Table 5), the respective annual and life cycle (for a life span of 60 years) equivalent CO_2 emissions incurred by generation of the electricity consumed by the two systems have been estimated, as shown in Table 6. This result shows that by adopting a WACS in lieu of an AACS for Hospital A, the greenhouse gas emissions over a life span of 60 years can be reduced by an equivalent amount of about 34,000 tonnes of carbon dioxide.

Conventional screw chillers – LCC estimation

For an estimation of the difference in the LCC that would arise if Hospital A was equipped with a WACS in lieu of an AACS, market prices of air-cooled and water-cooled chillers, condenser water pumps and cooling towers that are suitable for use in the hospital were sourced from three highly experienced practitioners in the contracting or O&M fields in the local building services industry. Table 7 summarizes the unit cost data obtained from the three sources. As expected, there are considerable variations in the costs provided by the three sources. In the LCC estimation, the median value among the cost data given by the three sources for each item was used. Table 8 shows the total initial equipment costs of the AACS and WACS determined from these median values.

Based on the assumption that replacement costs equal initial costs in constant dollars, the initial costs summarized in Table 8, and the life span and number of times of replacement of the equipment and system components as shown in Table 3, can be used to determine the life cycle equipment and component replacement costs of the AACS and WACS. The results so obtained are as shown in Table 9. Table 10 shows the life cycle costs of the AACS and WACS when applied to Hospital A.

Conventional chillers – Comparison of AACS and WACS

It can be seen from the results summarized in Table 10 that by adopting a WACS instead of an AACS for Hospital A, the life cycle cost saving, in present value, would amount to over HK$18.5 million, representing a saving of 20.9%, or HK$18,500 per ton of refrigeration (TR; 1TR = 3.517kW) based on the installed cooling capacity of the chiller plant, as compared to the case where an AACS was adopted. In the estimation, account has been taken of the higher maintenance cost for the WACS, which is incurred by the greater number of equipment to be maintained as compared to an AACS, the higher costs for water treatment, water sample analyses and system cleansing, as well as the additional water and sewage charges that would be required only in the case of using a WACS.

The results of the energy and cost analysis show that even though extra costs need to be spent on measures for minimizing the risk of outbreak of LD, the energy cost saving achievable by adopting WACS in lieu of AACS would be more than enough to offset the extra costs. Besides energy and cost savings, the benefits include also the associated reduction in greenhouse gas emissions.

Oil-free chillers – energy use and greenhouse gas emission predictions

Prediction of the energy use of the oil-free chillers for the case where Hospital A was assumed to be equipped with an AACS, and that of the oil-free chillers, the condenser water pumps and the cooling towers for the case where a WACS was used instead, was based on the assumption that the air-conditioning system in Hospital A was identical to the corresponding system in the cases studied earlier (Table 4), except that the conventional chillers were replaced by the oil-free chillers, and that the condenser water flow rate and heat rejection rate of the chillers in the WACS case had been adjusted to cope with the slightly different chiller COP value. The predicted annual total, maximum, minimum and average energy use values for these two cases (Hospital A with air-cooled and water-cooled oil-free chillers) are as summarized in Table 11. Table 12 shows the annual and life cycle greenhouse gas emissions estimated from the predicted energy use.

Oil-free chillers – LCC estimation

In estimating the life cycle costs (LCCs) for the two cases (Hospital A with AACS and WACS; both with oil-free chillers), the equipment costs were assumed to be identical to those of the corresponding cases studied earlier (Table 8), except the chiller costs. Due to lack of information, the maintenance costs for the chillers were also assumed to be identical to the earlier cases, but this may be an optimistic estimate given the much higher prices of oil-free chillers, unless the components of the oil-free chillers, although are more costly, are also more durable such that they would require less frequent replacement. Table 13 shows the total initial costs of the AACS and WACS for the current two cases with oil-free chillers.

The life cycle equipment and component replacement costs, and the overall LCCs taking into account also the life cycle energy, maintenance, water and sewage costs, for the two cases, which were estimated based on the same set of assumptions on the life span of the hospital building and the equipments, and the real interest and electricity price escalation rates, as before, are as shown in Tables 14 and 15.

LCC comparison between conventional and oil-free chillers

An overall comparison of the total intital costs, life cycle equipment and component replacement costs, life cycle energy and maintenance costs, life cycle water and sewage charges and overall life cycle costs for the four cases discussed above (Hospital A with AACS or WACS in conjunction with either conventional or oil-free chillers) is shown in Table 16.

This set of results, which are all based on the recorded hourly year-round cooling load for

Hospital A, shows that:

1. The LCC of using WACS would be much lower than using AACS no matter whether conventional chillers or oil-free chillers are used. Even water-cooled conventional chillers are compared to air-cooled oil-free chillers, there would still be substantial LCC saving.

2. When the same cooling medium (air or water) is used, using oil-free chillers could lead to substantial life cycle energy cost savings compared to using conventional chillers. However, this benefit would be largely offset by the very substantial increase in the initial and replacement costs of oil-free chillers. As a result, the net LCC savings are marginal: about 3 to 4% in the case of air-cooled chillers, but would be intangible in the case of water-cooled chillers.

Additionally, because oil-free chillers are relatively new products, their life span and the failure rates of their components remain largely unknown. Therefore, there can be large uncertainties in the estimates of life cycle replacement cost and annual maintenance cost. Extensive use of oil-free chillers is, therefore, considered premature, unless and until their reliability and the associated maintenance costs are ascertained and their prices drop significantly due to deeper market penetration. Nonetheless, it would be worthwhile to adopt this type of chillers as pilot installations such that their reliability and the required maintenance cost can be observed and compared against conventional chillers.

Hospital B

Compared to Hospital A, Hospital B is significantly bigger in size and, therefore, it is equipped with a central air-conditioning plant of a larger installed capacity (9,848kW vs. 3,517kW). The same series of comparison studies, as presented above, have been carried out on the basis of the cooling load profile of Hospital B. In the interest of brevity, detailed results for Hospital B are omitted. It, however, can be observed from the overall results for Hospital B (Table 17) that they were very similar to those of Hospital A (Table 16) except that the energy use and costs are all magnified. Therefore, the abovementioned observations made based on the results for Hospital A apply equally well to Hospital B.

Conclusion

Literature review showed that the risk of LD associated with use of cooling tower can be contained at or below an acceptable level by proper design and O&M practices, and thus should not be an obstacle to wider use of WACS. The decision on which system option to take, therefore, should be informed by the life cycle energy use, cost and incurred greenhouse gas emissions of each system option.

According to the performance data obtained from a manufacturer, oil-free chillers are significantly more energy efficient than conventional chillers under part-load operations. Nonetheless, use of air-cooled oil-free chillers remains significantly less energy efficient than using water-cooled chillers together with cooling towers even if only conventional chillers are used. Therefore, air-cooled oil-free chillers are not a good substitute of WACS with cooling towers. Water-cooled oil-free chillers, however, may become a viable option if their prices are lowered in future.

The benefits of using oil-free chillers are currently offset largely by their high initial costs, and potentially high component replacement costs as well. Their widespread application is, at this moment, premature, unless and until their reliability is well proven and there is a significant drop in their prices. Nevertheless, pilot installations are recommendable, which will help ascertain their reliability and maintainability.

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References

1. Yik FWH, Burnett J, Prescott I. Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods. Energy and Buildings 2001, 33(2): 151-166.

2. WHO. Legionella and the Prevention of Legionellosis. World Heath Organization, 2007.

3. McCoy WF. Preventing Legionellosis. ASHRAE Journal, June 2006.

4. McQuay. Efficient, quiet and oil-free – frictionless chiller technology sets new standard for efficiency and quiet operation. Bulletin, McQuay International, 2005 [available from: www.mcquay.com].

5. Newsletter Issue 156, April 2008. HK: Electrical and Mechanical Services Department, 2008.

6. Business Plus. HK: CLP Power Co. Ltd., 2009 [available from ba@clp.com.hk].

7. Australian/New Zealand Standard 3666.3:2000 Air-handling and water systems of buildings – Microbial control Part 3: Performance based maintenance cooling water systems (AS/NZS 3666.3), 2000.

8. ASHRAE Guideline 12-2000 – Minimizing the Risk of Legionellosis Associated with Building Water Systems. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2000.

9. The HSE Approved Code of Practice and Guidance 2000 – Legionnaires' disease, The control of legionella bacteria in water systems. UK: Health and Safety Executive, 2000.

10. CIBSE Technical Memorandum TM 13: Minimizing the Risk of Legionnaires' Disease. Chartered Institution of Building Services Engineers, 2002.

11. CDC Guidelines for Environmental Infection Control in Health-Care Facilities. US: Centres for Disease Control and Prevention, 2003.

12. Code of Practice for Water-cooled Air Conditioning Systems; Part 1: Design, Installation and Commissioning of Cooling Towers; Part 2: Operation and Maintenance of Cooling Towers; and Part 3: Water Treatment Methods for Cooling Towers. HK: Electrical and

Mechanical Services Department, 2006.

13. Scheme for Wider Use of Fresh Water in Evaporative Cooling Towers for Energy-efficient Air Conditioning Systems. HK: Electrical and Mechanical Services Department, 2008.

14. Trane introduces oil-free chiller. American Standard Companies, 2002.

15. Yik FWH, Lam VKC. Chiller models for plant design studies. Building Services Engineering Research and Technology 1998, 19(4): 233-241.

16. Yik FWH, Burnett J. BECON: A program for predicting building energy consumption for air-conditioning buildings. Transactions 1998, 5(3): 89-94. HK: The Hong Kong Institution of Engineers.

17. Underwood CP, Yik FWH. Modelling Methods for Energy in Buildings. Oxford: Blackwell Science, 2004.

18. Code of Practice on Energy Efficiency of Air Conditioning Installations. HK: Electrical and Mechanical Services Department, 2007.

19. CIB W080 / RILEM 175 SLM Service Life Methodologies: Prediction of Service Life for Buildings and Components. CIB, 2004

20. Tam LS, Lau KC, Shek LC. Achievements and participation of the pilot scheme for fresh water evaporative cooling towers. In: Proc. of Symposium on Solution, Breakthrough & Technical Approach for Wider User of Water-cooled Air Conditioning System in Hong Kong, 8 December 2006. Hong Kong Association of Energy Engineers, 2006; p.1-9.

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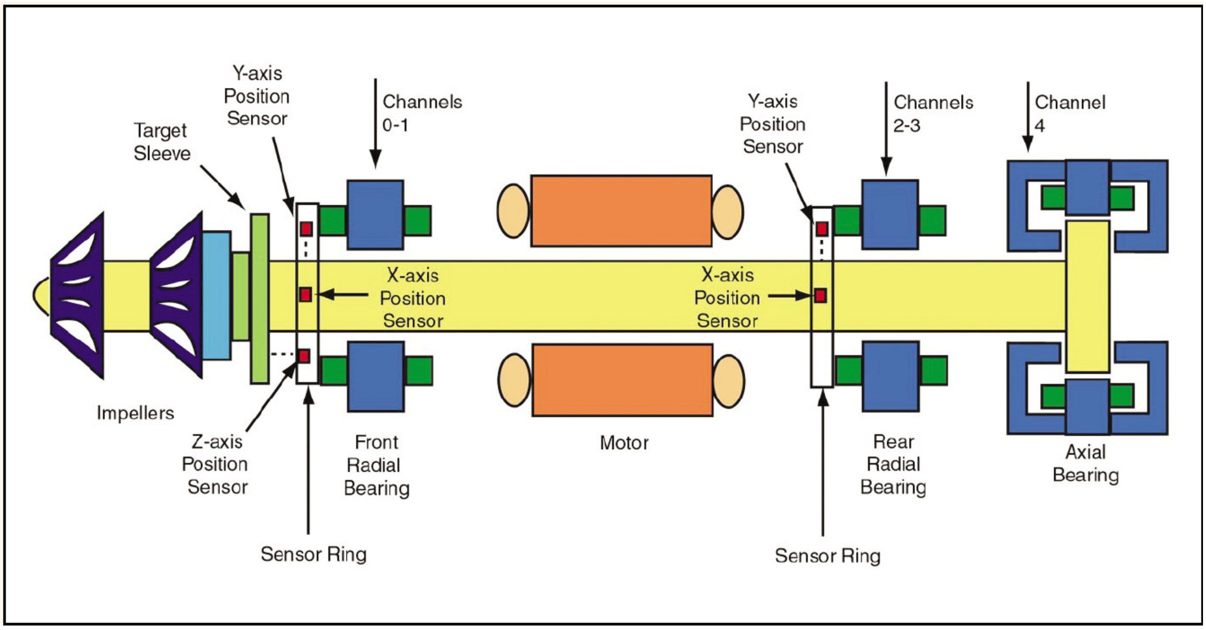
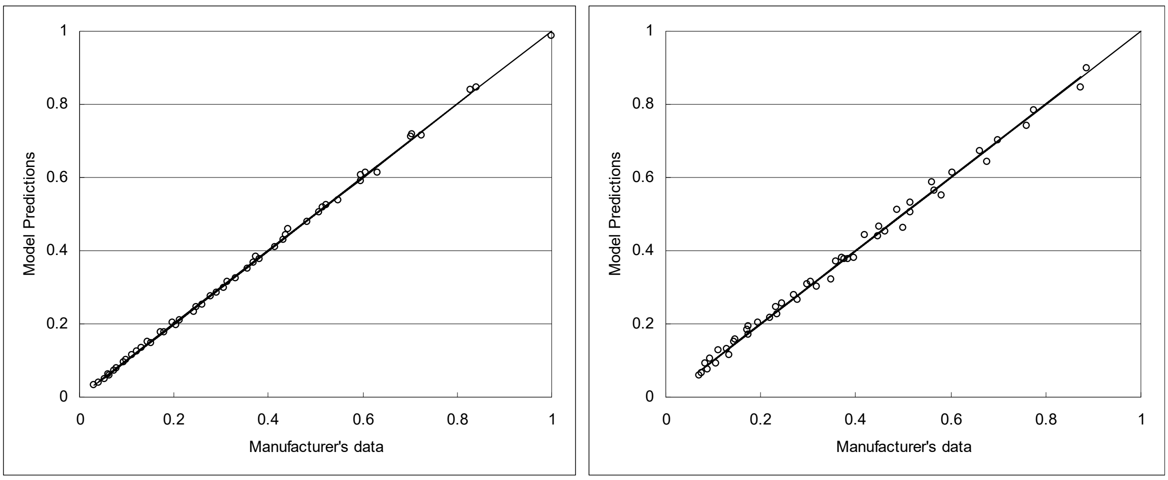


Figure 1 Schematic diagram for the motor/compressor design of an oil-free chiller with magnetic bearings (Source: Ref. 4)



(a) (b)

Figure 2 Comparison of oil-free chiller model predictions with manufacturer's data: (a) air-cooled chillers; (b) water-cooled chillers

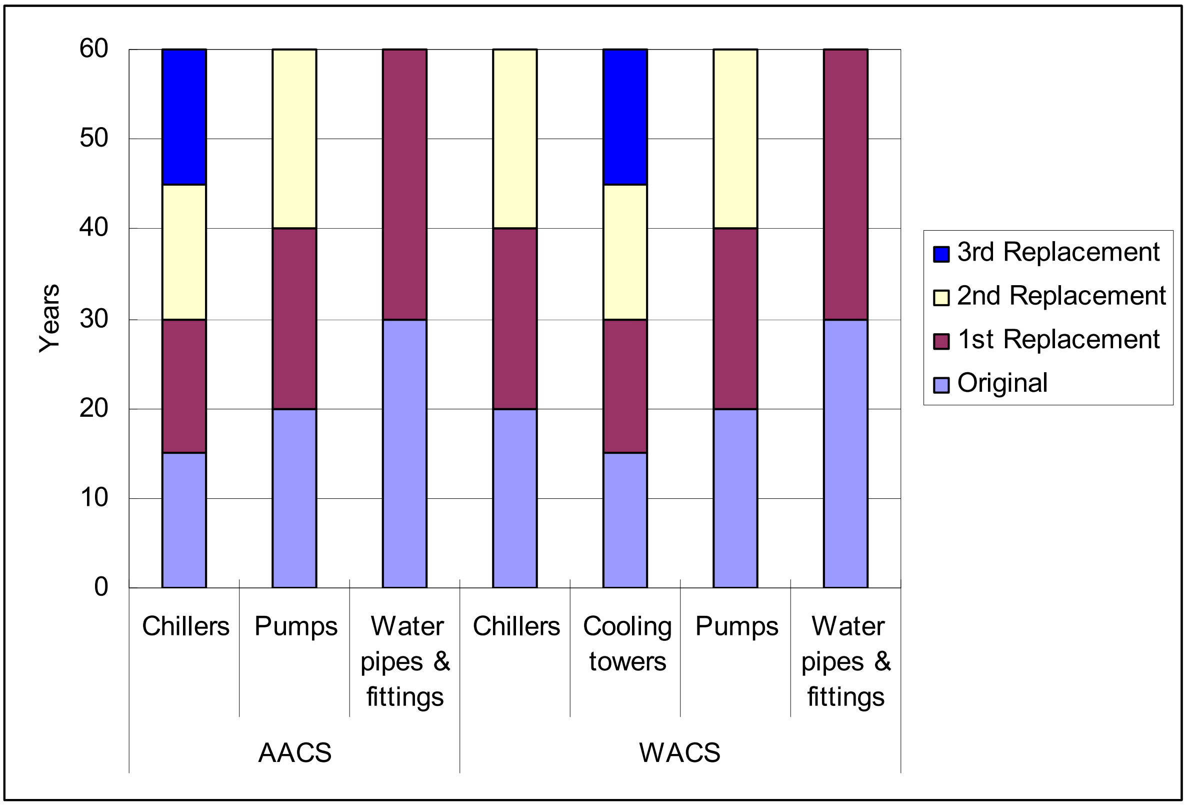


Figure 3 Life spans and time of replacement of major equipments in an AACS and a WACS

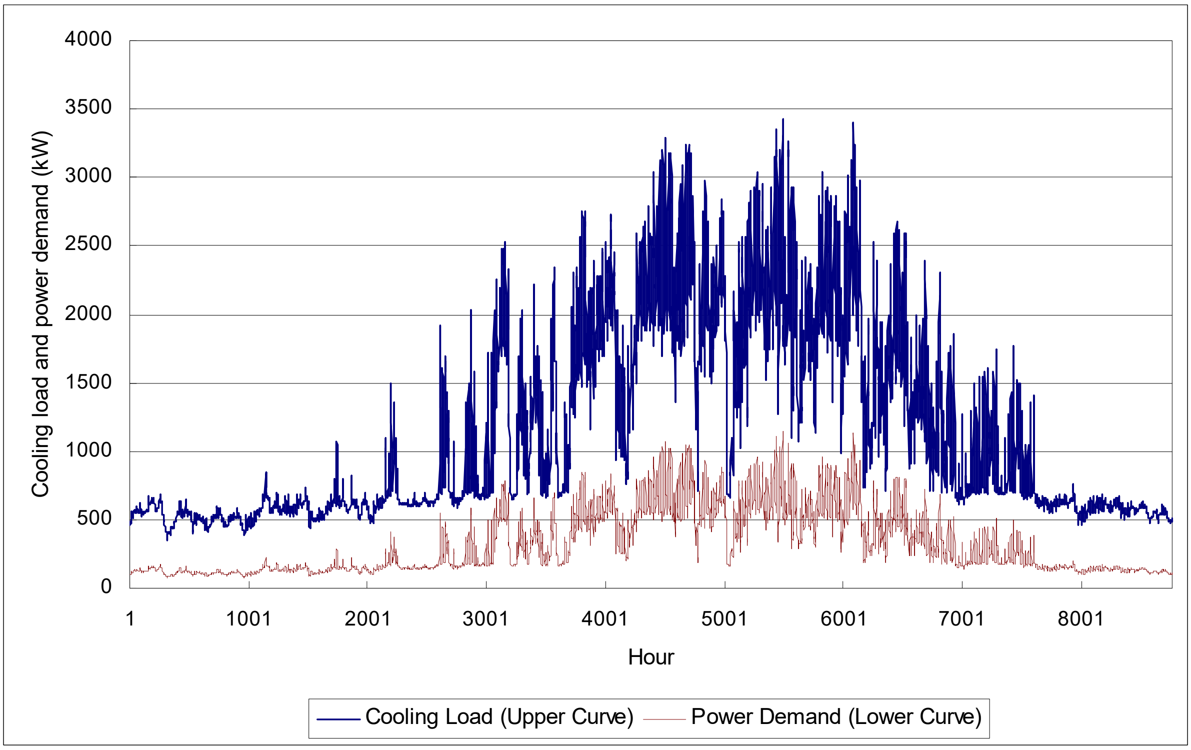


Figure 4 Cooling load and power consumption of chillers of Hospital A when equipped with an AACS with conventional screw chillers

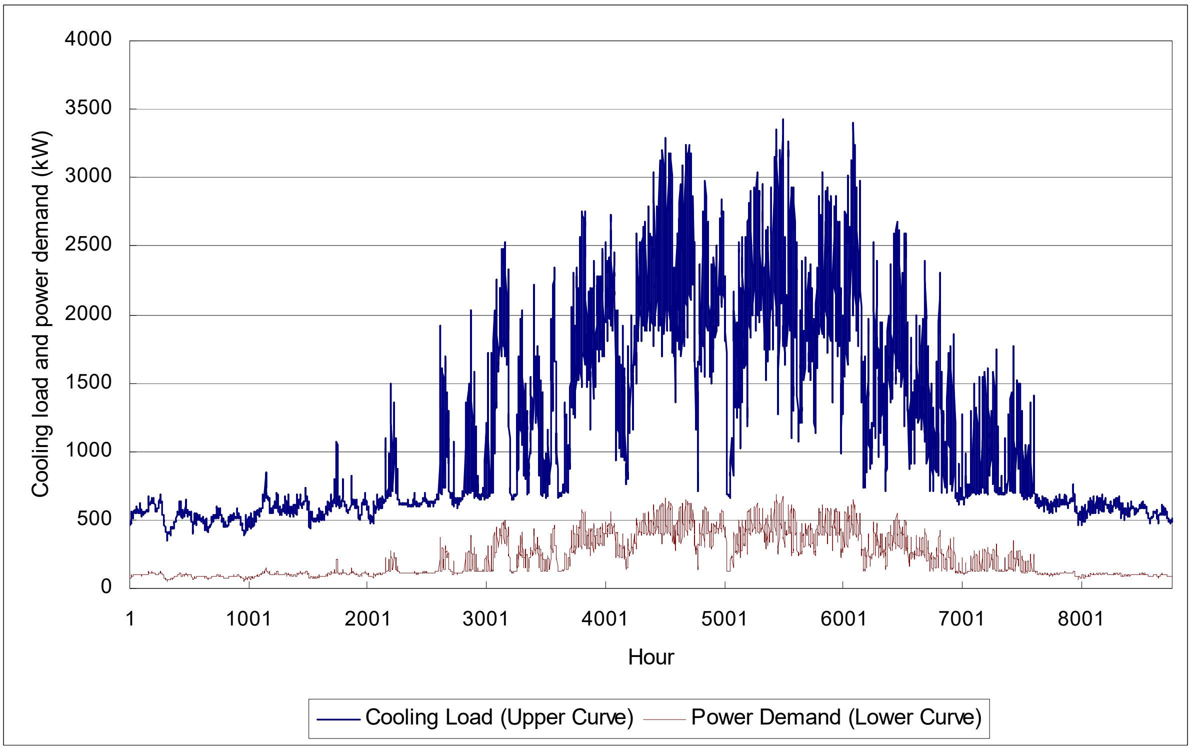


Figure 5 Cooling load and power consumption of chillers, condenser water pumps and cooling towers of Hospital A when equipped with a WACS with conventional screw chillers

Table 1 COP of oil-free chillers under full- and part-load conditions

	Air-cooled oil-free chillers					Water-cooled oil-free chillers				
Condenser air/water entering temperature, °C	35	30	25	20	15	32	27	22	17	12
At 100% rated cooling output	2.9	3.5	4.0	4.6	5.3	5.4	6.2	7.7	9.6	10.5
At 90% rated cooling output	3.1	3.7	4.3	5.0	5.9	5.5	6.4	8.1	10.0	10.9
At 80% rated cooling output	3.3	3.9	4.5	5.3	6.2	5.6	6.4	8.4	10.3	11.3
At 70% rated cooling output	3.4	4.0	4.7	5.5	6.5	5.7	6.5	8.2	10.1	10.9
At 60% rated cooling output	3.6	4.2	4.9	5.7	6.7	5.7	6.5	8.7	10.6	11.7
At 50% rated cooling output	3.8	4.4	5.2	6.0	7.1	6.0	6.8	9.1	11.0	12.4
At 40% rated cooling output	4.0	4.7	5.5	6.5	7.7	6.0	6.8	9.3	11.1	12.4
At 30% rated cooling output	4.4	5.1	6.0	7.2	8.8	6.0	6.9	9.4	11.3	12.6
At 20% rated cooling output	4.5	5.2	6.2	7.5	9.6	6.2	7.4	9.7	11.7	13.2
At 10% rated cooling output	3.9	4.6	5.6	7.0	9.2	4.1	5.1	6.1	7.0	7.6

Table 2 Model coefficients for air-cooled and water-cooled oil-free chillers

Coefficients	Air-cooled	Water-cooled
C_0	$6.99995066 \times 10^{-03}$	$4.83458462 \times 10^{-02}$
C_1	$-8.24899840 \times 10^{-03}$	$1.84132587 \times 10^{-01}$
C_2	$4.61093221 \times 10^{-01}$	$2.01874126 \times 10^{-01}$
C_3	$-5.40286041 \times 10^{-04}$	$-2.41712088 \times 10^{-03}$
C_4	$2.64142662 \times 10^{-05}$	$6.86373626 \times 10^{-05}$
C_5	$1.83275063 \times 10^{-02}$	$2.68319347 \times 10^{-03}$
C_6	$-1.98426216 \times 10^{-02}$	$-1.91225441 \times 10^{-03}$
C_7	$-1.39259848 \times 10^{-04}$	$4.31958042 \times 10^{-04}$
C_8	$6.01211703 \times 10^{-04}$	$1.23376623 \times 10^{-04}$

Table 3 Life spans and number of replacements of air-conditioning system equipments and components

	Life span (yrs)	No. of replacement(s)
Air-cooled chillers	15	3
Water-cooled chillers	20	2
Condenser water pumps	20	2
Cooling towers	15	3
Condenser water pipes and fittings	30	1

Table 4 Performance of major equipment in an AACS and a WACS for Hospital A (with conventional screw chillers)

General		Total
No. of chillers in the plant	4	
Rated cooling capacity of chiller	879 kW each	3517 kW
Chilled water supply temperature	7 °C	
Chilled water return temperature	12.5 °C	
Chilled water flow rate of chiller	38 kg/s each	152 kg/s
AACS		
Rated COP of chillers	2.9	
Rated power demand of chiller	303.2 kW each	1213 kW
WACS		
Condenser water supply temperature	32 °C	
Condenser water return temperature	37.5 °C	
Rated COP of chillers	5.5	
Rated power demand of chiller	160 kW each	639 kW
Rated heat rejection rate of chiller	1039 kW each	
Condenser water flow rate of chiller	45.0 kg/s each	180 kg/s
Condenser water pump pressure	200 kPa	
Condenser water pump efficiency	0.75	
Condenser water pump power demand	12.0 kW each	48 kW
Cooling tower power demand	5.5 kW each	22 kW

Table 5 Cooling load and annual energy use of chillers and heat rejection equipment of Hospital A when equipped with an AACS or a WACS with conventional type screw chillers

	Cooling load	Energy Use			
		AACS	WACS	WACS/AACS	%Saving
Annual Total (kWh)	10,012,923	2,736,980	1,930,725	0.71	29.46
Maximum (kW)	3,432	1,143	684	0.60	40.13
Minimum (kW)	352	75	54	0.71	28.53
Annual Average (kW)	1,143	312	220	0.71	29.46
Annual Average COP		3.66	5.19		

Table 6 Annual and life cycle greenhouse gas emissions due to energy consumption of chillers and heat rejection equipments of the AACS and WACS for Hospital A with conventional screw chillers

	AACS	WACS	Difference
Annual CO_2 (eqv.) emission*, Tonnes	1,941	1,369	572
Life cycle (60 yrs) CO_2 (eqv.) emission, Tonnes	116,464	82,156	34,308

* Calculated based on 197 Tons of CO_2 (eqv.) emission per TJ of electricity consumed.

Table 7 Unit prices of major components in the AACS and WACS in Hospital A with conventional screw chillers

	Source 1	Source 2	Source 3	Adopted
AACS				
Chiller unit cost (250TR) (HK$)	950,000	1,050,000	1,000,000	1,000,000
Water tank and accessories (HK$)	30,000			30,000
Maintenance (HK$/yr)	72,000	300,000	250,000	250,000
WACS				
Chiller unit cost (250TR) (HK$)	800,000	900,000	625,000	800,000
Condenser water pump unit cost (45kg/s) (HK$)	75,000	38,000	40,000	40,000
Cooling tower unit cost (45kg/s) (HK$)	80,000	90,000	200,000	90,000
Water tank and accessories (HK$)	160,000			160,000
Maintenance (HK$/yr)	180,000	390,000	350,000	350,000

Table 8 Initial costs of the AACS and WACS in Hospital A with conventional screw chillers

	AACS	WACS
No. of chillers / pumps / cooling towers	4	4
Chiller unit cost (250TR) (HK$)	1,000,000	800,000
Condenser water pump unit cost (45kg/s) (HK$)		40,000
Cooling tower unit cost (45kg/s) (HK$)		90,000
Total equipment cost (HK$)	4,000,000	3,720,000
Water tank and accessories	30,000	160,000
Condenser water piping system (HK$)		700,000
Total initial cost (HK$)	4,030,000	4,580,000

Table 9 Life cycle equipment and component replacement costs of the AACS and WACS for Hospital A with conventional screw chillers

AACS

Item	Replacement Cost (HK$)	Replacement Yr	Present Value (HK$)
Chillers	4,000,000	15	1,924,068
	4,000,000	30	925,510
	4,000,000	45	445,186
Water tank	30,000	30	6,941
Total			3,301,706

WACS

Item	Replacement Cost (HK$)	Replacement Yr	Present Value (HK$)
Chillers	3,200,000	20	1,206,046
	3,200,000	40	454,546
CW pumps	160,000	20	60,302
	160,000	40	22,727
Cooling towers	360,000	15	173,166
	360,000	30	83,296
	360,000	45	40,067
Water tank and pipes	860,000	30	198,985
Total			2,239,136

Table 10 Life cycle costs of the AACS and WACS for Hospital A with conventional screw chillers

	AACS	WACS	Difference	% Saving
Total initial cost (HK$)	4,030,000	4,580,000	-550,000	
Life cycle equip. & comp. replacement cost (HK$)	3,301,706	2,239,136	1,062,570	
Recurrent Cost				
Electricity (HK$/yr; Elec. Cost at HK$1/kWh)	2,736,980	1,930,725	806,254	
Maintenance (HK$/yr)	250,000	350,000	-100,000	
Water and sewage charges (HK$/yr)	0	139,761		
No. of years	60	60		
Real discount rate per yr (*d*)	0.05	0.05		
Real energy cost escalation rate per yr (*e*)	0.02	0.02		
USPWF (Energy)	28.03	28.03		
USPWF (Maintenance)	18.93	18.93		
Life cycle energy cost (HK$)	76,711,631	54,114,062	22,597,568	29.46
Life cycle maintenance cost (HK$)	4,732,322	6,625,251	-1,892,929	-40.00
Life cycle water and sewage charges (HK$)	0	2,645,571		
Life cycle cost (HK$)	88,775,658	70,204,020	18,571,639	20.92

Table 11 Cooling load and annual energy use of chillers and heat rejection equipment of Hospital A when equipped with an AACS or a WACS with oil-free chillers

	Cooling load	Energy Use			
		AACS	WACS	WACS/AACS	%Saving
Annual Total (kWh)	10,012,923	2,340,559	1,755,612	0.75	24.99
Maximum (kW)	3,432	1,121	687	0.61	38.72
Minimum (kW)	352	34	46	1.37	-37.16
Annual Average (kW)	1,143	267	200	0.75	24.99
Annual Average COP		4.28	5.70		

Table 12 Annual and life cycle greenhouse gas emissions due to energy consumption of chillers and heat rejection equipments of the AACS and WACS for Hospital A with oil-free chillers

	AACS	WACS	Difference
Annual CO_2 (eqv.) emission*, Tonnes	1,660	1,245	415
Life cycle (60 yrs) CO_2 (eqv.) emission, Tonnes	99,595	74,705	24,890

* Calculated based on 197 Tons of CO_2 (eqv.) emission per TJ of electricity consumed.

Table 13 Initial costs of the AACS and WACS in Hospital A with oil-free chillers

	AACS	WACS
No. of chillers / pumps / cooling towers	4	4
Chiller unit cost (250TR) (HK$)	2,150,000	1,600,000
Condenser water pump unit cost (45kg/s) (HK$)		40,000
Cooling tower unit cost (45kg/s) (HK$)		90,000
Total equipment cost (HK$)	8,600,000	6,920,000
Water tank and accessories	30,000	160,000
Condenser water piping system (HK$)		700,000
Total initial cost (HK$)	8,630,000	7,780,000

Table 14 Life cycle equipment and component replacement costs of the AACS and WACS for Hospital A with oil-free chillers

AACS			
Item	Replacement Cost (HK$)	Replacement Yr	Present Value (HK$)
Chillers	8,600,000	15	4,136,747
	8,600,000	30	1,989,846
	8,600,000	45	957,150
Water tank	30,000	30	6,941
Total			7,090,684

WACS			
Item	Replacement Cost (HK$)	Replacement Yr	Present Value (HK$)
Chillers	6400000	20	2,412,093
	6400000	40	909,092
CW pumps	160000	20	60,302
	160000	40	22,727
Cooling towers	360000	15	173,166
	360000	30	83,296
	360000	45	40,067
Water tank and pipes	860,000	30	198,985
Total			3,899,728

Table 15 Life cycle costs of the AACS and WACS for Hospital A with oil-free chillers

	AACS	WACS	Difference	% Saving
Total initial cost (HK$)	8,630,000	7,780,000	850,000	
Life cycle equip. & comp. replacement cost (HK$)	7,090,684	3,899,728	3,190,956	
Recurrent Cost				
Electricity (HK$/yr; Elec. Cost at HK$1/kWh)	2,340,559	1,755,612	584,947	
Maintenance (HK$/yr)	250,000	350,000	-100,000	
Water and sewage charges (HK$/yr)	0	137,886		
No. of years	60	60		
Real discount rate per yr (*d*)	0.05	0.05		
Real energy cost escalation rate per yr (*e*)	0.02	0.02		
USPWF (Energy)	28.03	28.03		
USPWF (Maintenance)	18.93	18.93		
Life cycle energy cost (HK$)	65,600,832	49,206,019	16,394,813	24.99
Life cycle maintenance cost (HK$)	4,732,322	6,625,251	-1,892,929	-40.00
Life cycle water and sewage charges (HK$)	0	2,610,081		
Life cycle cost (HK$)	86,053,839	70,121,079	15,932,760	18.51

Table 16 Comparison of LCC of AACS and WACS with conventional or oil-free chillers based on Hospital A

	With conventional chillers		With oil-free chillers	
	AACS	WACS	AACS	WACS
Initial cost (HK$)	4,030,000	4,580,000	8,630,000	7,780,000
Life cycle replacement cost (HK$)	3,301,706	2,239,136	7,090,684	3,899,728
Initial and life cycle replacement cost (HK$)	7,331,706	6,819,136	15,720,684	11,679,728
Life cycle energy cost (HK$)	76,711,631	54,114,062	65,600,832	49,206,019
Life cycle maintenance cost (HK$)	4,732,322	6,625,251	4,732,322	6,625,251
Life cycle water and sewage charges (HK$)	0	2,645,571	0	2,610,081
Life cycle cost (HK$)	88,775,658	70,204,020	86,053,839	70,121,079

Table 17 Comparison of LCC of AACS and WACS with conventional or oil-free chillers based on Hospital B

	With conventional chillers		**With oil-free chillers**	
	AACS	**WACS**	**AACS**	**WACS**
Initial cost	11,284,000	12,824,000	24,164,000	21,784,000
Life cycle replacement cost	9,244,776	6,269,580	19,853,916	10,919,239
Initial and life cycle replacement cost	20,528,776	19,093,580	44,017,916	32,703,239
Life cycle energy cost	258,987,184	181,450,122	222,674,971	166,736,705
Life cycle maintenance cost	13,250,503	18,550,704	13,250,503	18,550,704
Life cycle water and sewage charges	0	8,921,651	0	8,815,260
Life cycle cost	292,766,462	228,016,056	279,943,390	226,805,908