Study of Water Cooling Schemes for Commercial Air-Conditioning Applications

Apple L S Chan, MPhil, CEng, MInstE MASHRAE
Division of Building Science & Technology, City University of Hong Kong,
Tat Chee Avenue, Hong Kong SAR, China
bsapplec@cityu.edu.hk

T T Chow, PhD, MBA, CEng, MCIBSE, MIMechE, MASHRAE, FHKIE
Division of Building Science & Technology, City University of Hong Kong,
Tat Chee Avenue, Hong Kong SAR, China
bsttchow@cityu.edu.hk

Abstract: *For a number of years, the use of water-cooled air-conditioning systems was not encouraged for commercial applications in Hong Kong. This was mainly due to the scarcity in water supply. Central air-cooled air-conditioning systems with a relatively low coefficient of performance are thus widely applied in the city. With a raised concern about building sustainability and a surplus supply of potable water from the Mainland China, the local government policy has been revised recently and the possible use of various types of water-cooled air-conditioning systems is being actively considered. In many existing commercial buildings, a conversion of the air-cooled air-conditioning system by a suitable design of water-cooled system has to bring into a number of crucial considerations such as the availability of space, replacement cost, payback period, etc. This paper presents a case of investigating the performance of evaporative air-conditioning system under Hong Kong weather condition. The economic feasibility of modifying an existing air-cooled air-conditioning system to one using fresh-water cooling towers in an existing commercial building is discussed. The application of centralised condensing seawater supply and district cooling schemes, and the methodology and procedures leading to the final recommendation are addressed.*

Keywords: air-conditioning, cooling tower, district cooling scheme, life-cycle costing

Introduction

Comparing with an air-cooled air-conditioning (AC) system, a water-cooled AC system offers better coefficient of performance (COP) for the same application, i.e. less energy consumption for producing the same amount of cooling capacity (Goshayshi *et al* 1999). Some water-cooled AC systems use seawater as a means of condenser heat rejection; these include the once through seawater-cooled AC systems and the application of seawater cooling towers. Recent studies indicate that energy savings of around 20-30% are possible when compared with the air-cooled chiller schemes. In the past, potable water was a cherished resource in Hong Kong. For a number of years, one major source of potable water is from the Mainland China and the water from the Pearl River is delivered via lengthy pipelines across the territory to Hong Kong. The application of evaporative cooling by means of mechanical-draught fresh-water cooling tower in AC system had to be approved by the Water Supplies Department, since the device requires continuous supply of make-up water to compensate the evaporative loss. Only the applications to specific industrial processes were allowed with very stringent assessment criteria. According to the government statistics, there are only about one hundred numbers of evaporative-cooled AC systems in Hong Kong using the Government's main water supply. There are about another one hundred once-through seawater-cooled AC systems that serve public and commercial buildings. These are installed at buildings close to the seafront, and have dedicated seawater pumping stations and pipelines for AC heat rejection. In some other buildings near the seafront however, air-cooled heat-rejection systems are still used because the investments can be lowered. Hence the use of air-cooled AC systems has been dominating in the public and commercial sectors throughout the city.

With the growing concerns about energy saving, building sustainability and, at the same time, a record of over supply of potable water from the Mainland China, a wider use of evaporative-cooled and water-cooled AC systems has been called for. Building professionals urged the relaxation of using fresh-water cooling towers in newly designed AC systems. In 1999, a government study (HKSAR Government 1999) concluded that the economic and environmental benefits of adopting water-cooled AC systems on a wider basis in Hong Kong are substantial. Three different schemes of water-cooled AC systems with good potentials have been identified. These are:

1. Centralized piped seawater supply system that consists of a central supply of large quantity of seawater to a number of buildings via pumping station for condenser cooling.
2. Centralized piped supply system for cooling towers, that is a similar infrastructure arrangement to the above; however, this involves the supply of a much smaller amount of seawater or freshwater to the buildings.
3. District cooling scheme (DCS), that comprises a large central chiller plant located within close proximity of the buildings (or district) being served.

In a centralized piped seawater supply system, seawater is supplied to the air-conditioning plant of the individual building through an underground distribution piping network. It is a capital intensive infrastructure development. Energy and economic benefits must be justified before implementation. Other than the advantage of installing less number of seawater pumps because of the diversity factor, the economy of scale lies in the use of large seawater pumps. This is not so attractive as the use of huge chillers in DCS, of which the COP can be much higher than the medium-size chillers.

Technically speaking, the location, development and implementation of the above schemes will be largely dependent on the physical area or district where the scheme is to be employed. It will be much simple to implement these in new developing areas than in existing urban areas. In many existing commercial buildings, a conversion of the air-cooled AC system by a suitable design of water-cooled system has to bring into a number of crucial considerations such as the availability of space, replacement cost, payback period, etc. The methodology and procedures adopted to produce the final recommendation also have to be explored. In the role of a facilities manager, there is a need to study the technical feasibility and financial implication of modifying an existing air-cooled AC system, during the building retrofit work, to an evaporative AC system with cooling towers. In the following sections, a study of the said modification work based on real building data is first introduced. Then a methodology of evaluating DCS is discussed. Computer simulation has been found very useful in these analyses.

Modification of Existing Air-Cooled Air-Conditioning System

In this study, real data of an existing commercial building installed with an air-cooled air-conditioning plant was used. This is a 20-storey curtain wall commercial building with a window-to-wall ratio of 40%. There are ten nos. of chillers: two 100 TR, one 175 TR and seven 200 TR in the hydronic circuit with differential pressure bypass control. A building management system (BMS) is provided and recorded the operating data of the AC system, such as hourly chilled water flow rate, chilled water temperatures, electricity consumption of major equipment, etc.

A transient plant simulation program TRNSYS was used to model and simulate the operation of the AC system. The modelling flow chart is shown in Figure 1 below. A set of 8,760 measured hourly weather data for the year 1989 in Hong Kong was used for the simulations of respectively air-cooled and evaporative-cooled (with fresh-water cooling tower) AC plants. The year 1989 has been worked out to be the Test Reference Year (TRY) of Hong Kong, which represents the prevailing weather conditions regarding comparative energy study (Hui & Lam 1992). The evaporative-cooled AC plant configuration developed through TRNSYS is shown in Figure 2. With the hourly building cooling loads derived from the BMS recorded data, the monthly/annual electricity consumption of each AC plant was simulated. Economic analysis was then conducted. Life-cycle cost and pay back period were also determined.

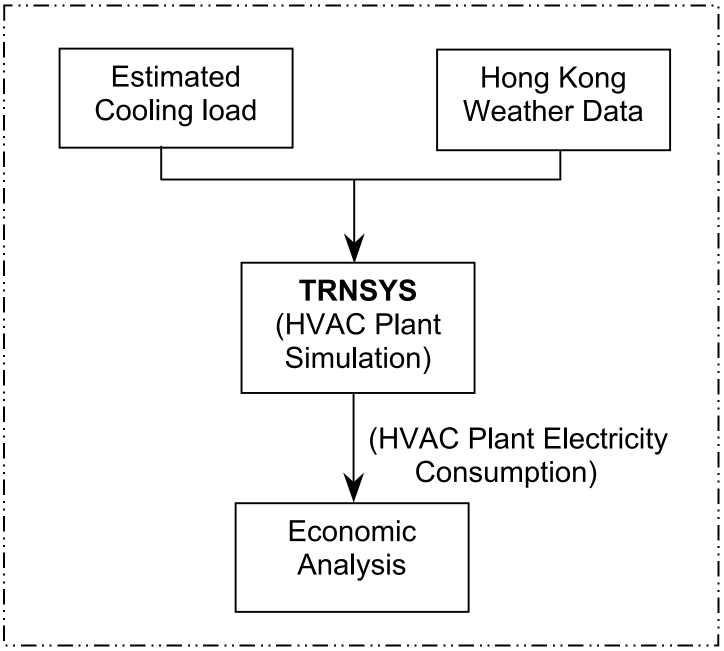

Figure 1 Modelling Flow Chart

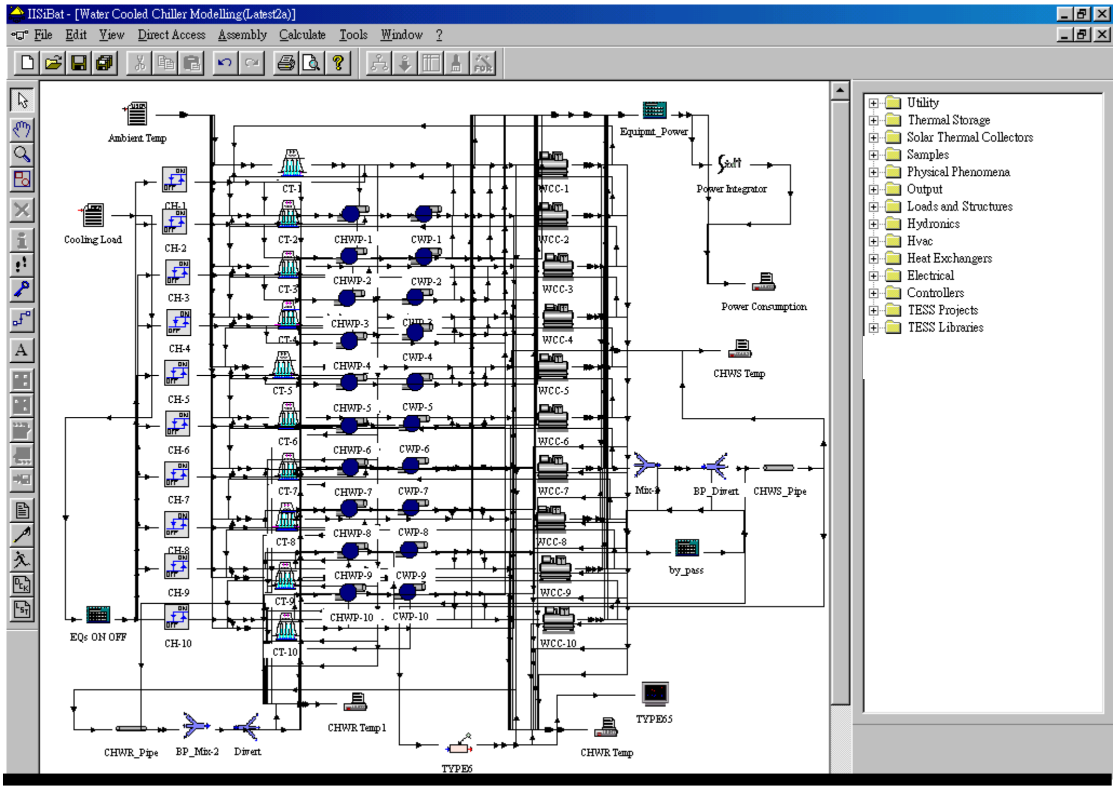

Figure 2 Air-Conditioning Plant Configuration in TRNSYS

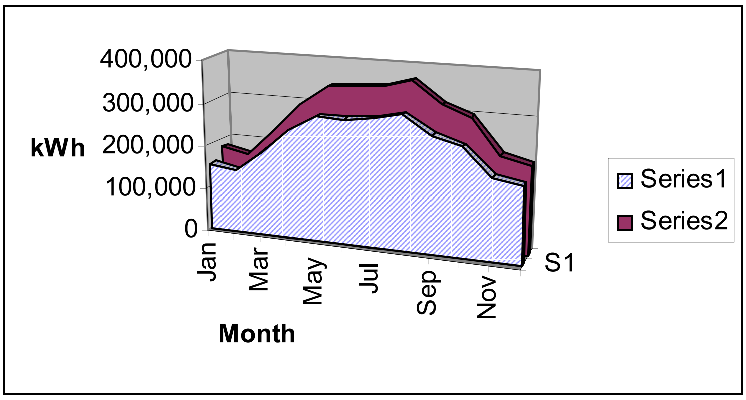

Figure 3 Simulated Monthly Electricity Consumptions of Air-Cooled and Water-Cooled Air-Conditioning Systems

Figure 3 shows the simulated monthly electricity consumptions of the two AC systems. Series 1 shows the electricity consumptions of the evaporative-cooled AC system and series 2 shows that of the air-cooled AC system. The evaporative-cooled AC is found more energy-efficient. The percentage in saving ranges from 12.35% in February to 17.1% in August. The annual saving is 15.6%.

Economic Feasibility Analysis

Life-cycle costing technique was used to investigate the economic feasibility of modifying an existing air-cooled air-conditioning system to an air-conditioning system with cooling tower in existing buildings (Charette 1980). Due to inflation and market discount rate, net present value (NPV) of the total electricity cost over the life cycle of the air-conditioning plant has to be calculated. This is expressed as:

$$\sum_{n=1}^{p}(EC)_n = EC\sum_{n=1}^{p}\left(\frac{1+i}{1+d}\right)^{n-1} \qquad (1)$$

where

EC = electricity cost in the first year
i = escalation rate of electricity cost
d = market discount rate
$\left(\frac{1+i}{1+d}\right)^{n-1}$ = discounting factor

and the pay back period is calculated by:

$$P = \left\{ \frac{\ln\left[\frac{1}{ID} - \frac{I \times (1/ID - 1)}{EC_1 - EC_2}\right]}{\ln(ID)} \right\} + 1 \qquad (2)$$

where

ID = $\left(\frac{1+i}{1+d}\right)$
I = investment for plant modification

An average escalation rate of electricity of 3.55% and a market discount rate of 5.69% (HKSAR Government 2000) were used. The electricity tariff in Hong Kong is about HK$0.95 per kWh (1 GBP = HK$12 approximately). Based on the simulated results, the annual saving in electricity cost was found HK$493,600 after the conversion. The life cycle of the modified plant is 25 years, and the corresponding cost is HK$3,800,000; these are provided by a licensed air-conditioning contractor firm. Based on the mentioned life-cycle model, the pay back period of the conversion is found about 8 years, and the net saving in electricity cost is HK$5,960,600 throughout its operating life. It can be seen that both the payback period and the net saving are reasonable, from the building owners point of view.

District Cooling Scheme

In a district cooling scheme, chilled water is circulating between a centralized chiller plant and a district comprising multiple buildings or facilities, through closed-loop underground piping network. The economical advantage of DCS mainly comes from the diversity factor in which the total installed cooling capacity at the centralised plant is smaller than the sum of individual plants at the consumer buildings based on conventional design. DCS thus offers massive and collective cooling energy production, which is higher in efficiency than individual cooling energy production. On the other hand, DCS consumers are not required to install their own chiller plants and thus can utilise building space more effectively. Moreover, operating cost advantage can be achieved by shifting power consumption of electric-type chillers from daytime to night by the use of thermal storage, hence cutting power consumption in the peak hours. A systematic approach to evaluate the feasibility of a DCS is illustrated below.

Thermal Load Modelling

The methodology for developing thermal load profiles, central plant design, and operation arrangements was introduced herewith, making reference to a new district in Hong Kong. The process is indicated in a flow chart shown in Figure 4.

In the process, the buildings to be served by the DCS are grouped into a number of categories, such as office, shopping arcade, hotel, hospital, etc. Of each category, model buildings are developed to represent the typical conditions within the district. These include the appropriate building materials, configuration, floor area, occupancy, operating schedule, etc. The hourly cooling load profiles of each model building during the whole year (or only the summer months for simplicity) are determined using a cooling load estimation tool, like the HEVACOMP or CARRIER software. The computation is based on the cooling load design weather data of Hong Kong. Three daily schedules are involved: weekday, weekend and holiday types. By these the normalized design load profiles of each category expressed in terms of cooling load intensity (*CLI*) in W/m^2 are determined. For a development site with n numbers of building categories, the hourly district cooling load profile, the *DCL* matrix (with elements in MW) can be determined as illustrated in Figure 5. A_1 to A_n in the equation represent the gross floor area of each building category. DCL_{max} is the peak value sorted from the *DCL* matrix elements and is the required cooling capacity of the DCS plant, i.e. the total installed capacity.

Figure 6 shows the weekday design cooling load profiles for different building types of the selected new district in Hong Kong. Based on the gross floor areas for each type of building, the peak cooling load without diversity is estimated as 261 MW, while the peak cooling load for the whole district is 193 MW when the DCS is applied. The corresponding diversity factor is 0.74.

Similarly, the 8,760 hourly thermal load profiles for various typical buildings in different categories during the Test Reference Year can be obtained through the use of a dynamic simulation program. In our case, the DOE-2 energy simulation software was used.

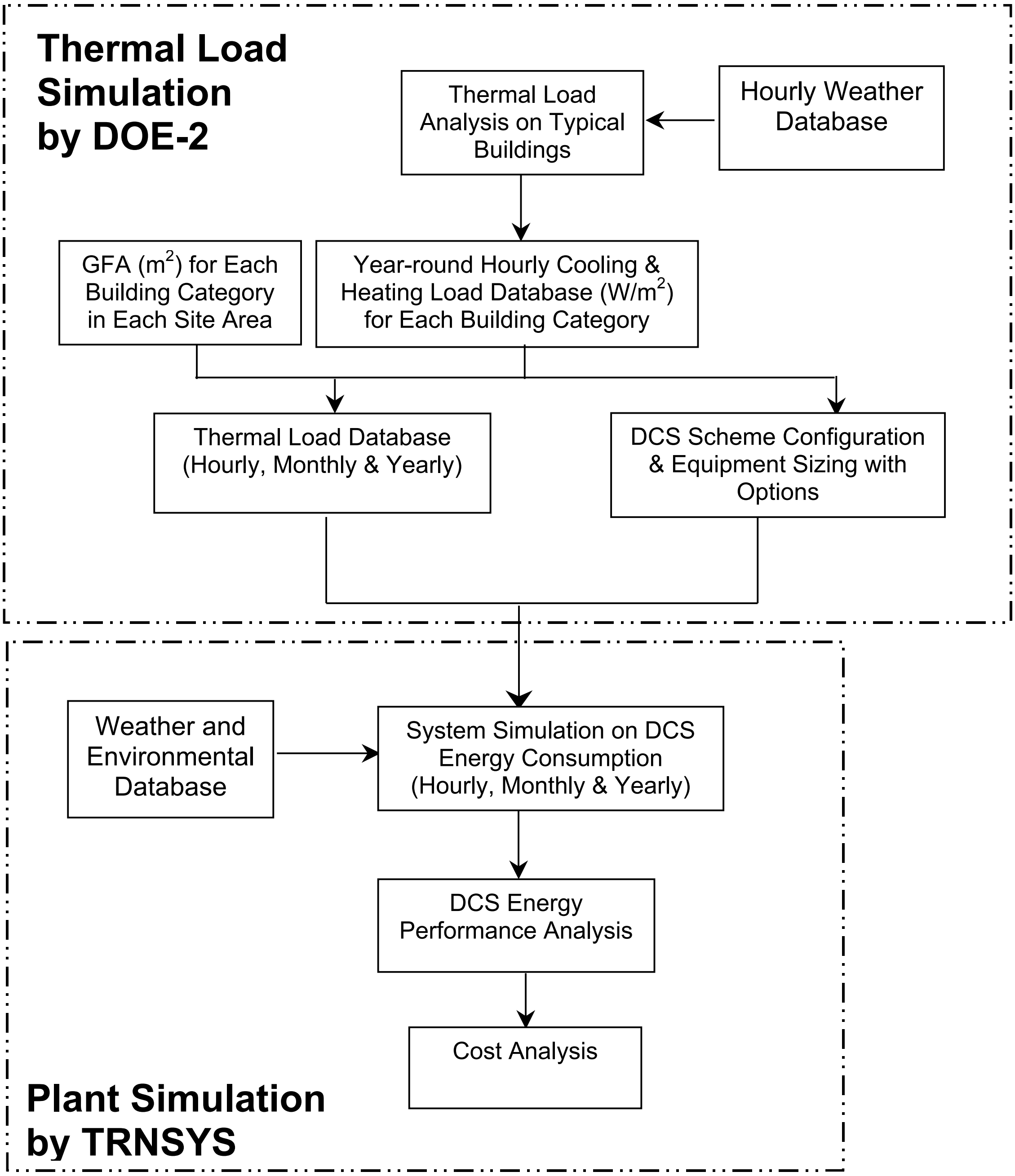

Figure 4 Thermal Load and Plant Simulation Modelling Flow Chart

$$\begin{bmatrix} CLI_{1,1} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ CLI_{1,8760} \end{bmatrix} \times A_1 + \begin{bmatrix} CLI_{2,1} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ CLI_{2,8760} \end{bmatrix} \times A_2 + \begin{bmatrix} CLI_{3,1} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ CLI_{3,8760} \end{bmatrix} \times A_3 + \dots\dots\dots\dots\dots\dots + \begin{bmatrix} CLI_{n,1} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ CLI_{n,8760} \end{bmatrix} \times A_n = \begin{bmatrix} DCL_{n,1} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ DCL_{n,8760} \end{bmatrix} \quad \Rightarrow DCL_{\max}$$

Figure 5 Determination of Hourly and Peak Cooling Loads in a District

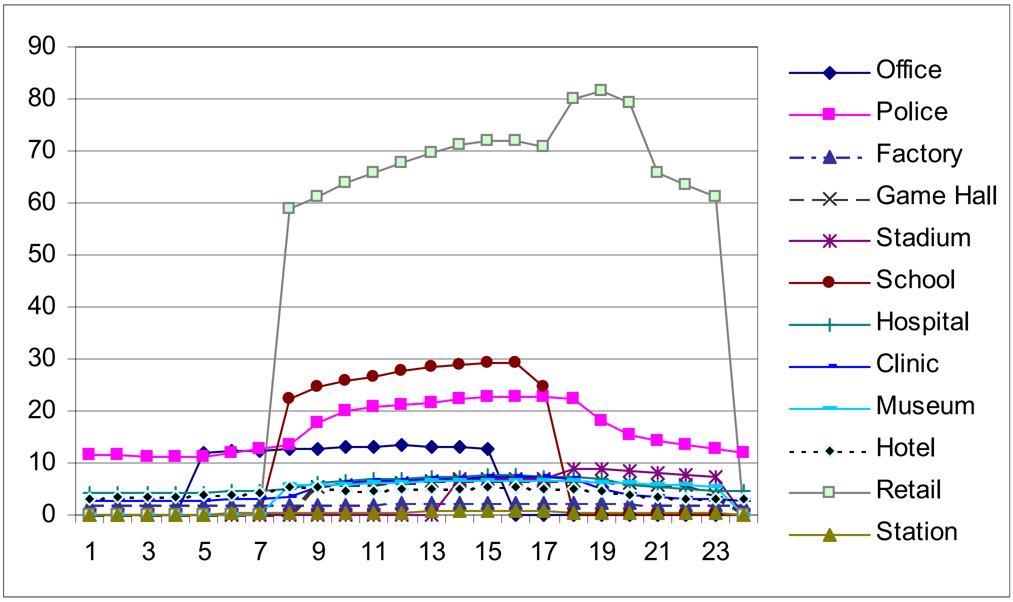

Figure 6 Weekday Cooling Load Profiles for Various Building Categories

Plant Modelling

In plant simulation, the TRNSYS software had been used for estimating the annual electricity consumption through a “quasi” steady-state simulation of discrete hourly data of the system operation. Figure 7 shows the proportion of the energy consumption at the four main system components, namely the chillers, the production pumps, the distribution pumps, and the seawater cooling pumps. In DCS, the chiller is the major power consumer and can consume up 70 to 80% of the total electric energy supply. The percentage shares of the distribution pumps and the seawater cooling pumps depend very much on the size of the distribution network as well as the seawater intake and discharge locations.

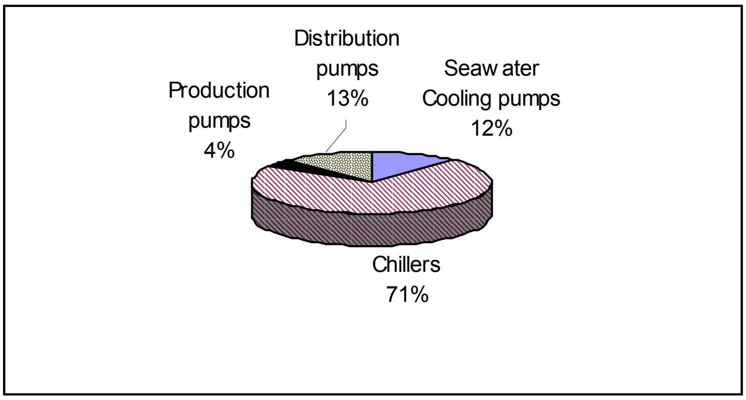

Figure 7 Percentage of Electricity Consumption in a DCS

System simulation exercises can be extended for a mix of central plant facilities and distribution loop configurations. The decision on potential DCS options must bring into consideration a series of plant operating strategies, as well as other physical constraints imposed by the civil work, the social, business and legal environment etc. The output of the energy model, i.e. year round hourly data of the electricity (and other fuels if any) consumption profiles, can be transferred to the cost model to analyse the annual operation costs under different tariff structure. The cost model thus needs to compare costs of each option with the revenue flows that could be expected by potential DCS operators. Costs and revenues are to be compared within the options for a regulatory framework to protect DCS customers.

Discussion and Conclusions

There is a global concern about energy conservation - the lesser we consume, the "greener" environment we can have due to lesser pollutants produced. Air-conditioning, the largest electricity-consuming item in commercial buildings, accounts for about 50 to 60% of the total building electricity consumption in Hong Kong (Chan 1994). In most commercial buildings in Hong Kong, air-cooled air-conditioning systems are installed. It is needed to look severely into the energy saving opportunities by applying the water-cooled technology in condenser heat rejection.

The possibility of a wider application of water-cooled air-conditioning systems had been discussed. The feasibility of modifying an existing air-cooled air-conditioning system to an evaporative-cooled air-conditioning system has been investigated. In the present study, it is found that the modification is both technically and economically viable. Issues including prevention of legionnaire disease, interruption to building operation during modification of air-conditioning plant, space required, etc. should be further investigated.

Also introduced is the methodology that can be used in the feasibility study of district cooling system. The process involves a sequence of building design load computation, building dynamic simulation, and plant energy consumption analyses. Identifying the optimum DCS plant configuration actually involves the determination of the optimum locations of the seawater intake and discharge, the locations of the central plant and main distribution pipes, etc. This should be further explored

(Babus'Haq *et al* 1987, Nagaiwa *et al* 1995). The task can be extended to study the various options which will optimise the cost effectiveness of the DCS scheme such as co-generation or tri-generation, thermal storage, low temperature chilled water distribution, the possible use of phase change materials, ice-water slurries, etc. Various optimisation techniques such as dynamic programming and genetic algorithm (Sakamoto *et al* 1998) can be used in the above studies.

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