Sponge-Ball Automatic Tube Cleaning Device for Saving Energy in a Chiller

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ABSTRACT

The first sponge-ball automatic internal tube cleaning system, normally used for large heat exchangers in power plant applications, has been installed and tested in a seawater-cooled chiller in Hong Kong. The tests were thoroughly conducted under various weather conditions, cooling loads, and fouling conditions, in comparison with an identical chiller operating without a cleaning device. The low fouling factor maintained by the sponge-ball system is reflected by the small temperature difference between the condensing refrigerant and the condensing water outlet, ranging from 2°C and 4°C depending on the cooling load. Without a sponge-ball system, the temperature difference is typically between 5°C and 11°C. The sponge-ball system improves the overall coefficient of performance (COP) by 12%. An economic analysis shows that the payback period is within 3 years.

1. INTRODUCTION

Deposition of unwanted materials on heat exchanger surfaces, known as fouling, may be caused by precipitation (scaling), microbiological growth, accumulation of suspended particles, chemical reactions, corrosion, or solidification of heat transfer fluids. Fouling will increase both the overall thermal resistance and pressure drop, resulting in poor heat transfer efficiency and higher pumping power, respectively. Consequently, both energy consumption and operating costs proportionally increase. Fouling costs for the U.S. industries, including the costs of energy losses, increased maintenance, and lost production, were estimated to be US$ 3.8 to 7 billion per year [1]. It was estimated that fouling related expenses for the refinery heat transfer equipment in the U.S. totalled about US$ 1.4 billion annually [2].

The build-up of foulants can be reduced by chemical treatment. Chlorination is commonly used in steam power plants to inhibit the growth of organisms in the condenser cooling water systems [3, 4]. However, it is less effective on hard water, which contains inorganic substances. In addition, due to potential dangers to the marine life, environmental agencies have had restrictions on the use of chlorine in power plant cooling water.

Alternatively, heat exchanger tubes can be cleaned by off-line mechanical cleaning methods while the plant is shut down. However, several problems make the off-line methods undesirable. First, there is a loss of production caused by the plant shut down, which may occur as often as once a month for a chiller plant during the peak summer [5]. Second, as soon as the plant is brought back to operation after cleaning, the foulants will gradually build up and cause the plant operating at a low efficiency for a prolonged period until the next scheduled maintenance. Lastly, scale and corrosion products attach strongly to the surface over a long period of deposition. Abrasive cleaners, required to remove such deposits, may damage the surface or coating and thus promote pitting corrosion.

The problems mentioned can be resolved by using online mechanical systems which enable the cleaning process to take place while the plant is in operation [6]. The cleaning frequency is much higher, as many as 12 times per hour, so that the tubes are maintained clean at all times. Two such kinds of systems available in the market are the brush-and-basket type and the sponge-ball type. In general, the sponge-ball systems are more appropriate for large heat exchangers, such as those in power plant applications. The brush-and-basket systems, on the other hand, are more suitable for smaller heat exchangers, such as those used in water-cooled chillers. However, since a brush-and-basket system requires extra space for a flow diverter to reverse the water flow regularly, a sponge-ball system seems to be the only option to retrofit a chiller under the limitation of space. Hong Kong is a typical example as building spaces are often fully utilized. In this investigation, the performance of the first sponge-ball system installed for a seawater-cooled chiller has been tested thoroughly in Hong Kong. The energy and economic analyses are presented in this paper.

2. OVERVIEW OF FOULING

The types of fouling commonly found in heat exchangers are precipitation, biofouling, particulate, corrosion, and chemical reaction. Precipitation fouling, also known as scaling, involves crystallization and deposition of dissolved inorganic salts from a saturated solution onto a surface [7]. Since solubility generally depends on temperature, a change in the temperature of an unsaturated solution passing through a heat exchanger may make it saturated, resulting in precipitation. In practice, fouling problems often occur with inverse solubility salts, whose solubility decreases with increasing temperature. In this case, deposition of salts occurs at a higher temperature. One example is seawater used as coolant for condensers in chiller plants and power plants. Seawater contains inverse solubility salts, such as $CaSO_4$, $CaCO_3$, $Mg(OH)_2$, among others [1]. The precipitate firmly attaching to the surface can be removed by dissolving the salt back in the solution. The limit of precipitation build-up is at the state of equilibrium in which the rate of deposition of new salts equals the rate of deposit removal.

When water with high concentration of organisms is used, biofouling of heat transfer surfaces becomes an important issue. The two mechanisms involved in biofouling are the deposition of microorganisms, such as slime and algae, and the growth of macroorganisms, such as mussels and clams [8]. The growth of a biofouling film strongly depends on temperature. A temperature range between 30°C and 40°C (86°F and 104°F) yields the highest growth rate [9]. The velocity of water flow also affects the growth significantly. An increase in velocity usually reduces the fouling thickness as the higher shear stress at the wall increases the removal rate. However, it is not always true. The reason is that, despite the high removal rate, increase in velocity may bring more nutrients to the microorganism film, thereby increasing the growth rate. More details can be found in an experimental study by Harty and Bott on combined effects of temperature and flow rate [10]. Chemical treatment by chlorine is an effective means to control biofouling. However, due to the hazards to the marine life, chlorination is strictly regulated [11]. Bromine chloride and ozone are alternative chemicals that are less harmful to nature [12, 13].

Particulate fouling is caused by the deposition and accumulation of suspended particles from the fluid streams on the heat transfer surfaces [14]. Suspended particles include the ambient pollutants (e.g., mud, sand, and iron minerals) and corrosion products. Most of the studies on particulate fouling have been done in the power generation industry. In general, higher temperature and particle concentration tend to increase the foulant accumulation rate.

Corrosion fouling occurs when the material of a heat transfer surface reacts with the fluid and the corrosion products accumulate on the surface [15]. Corrosion fouling often occurs in power generating plants, operating at temperature as high as 600°C. The fouling layer found in iron and carbon steel consists of FeO, Fe_2O_3, Fe_3O_4, among others. The degree of corrosion can be reduced by adding chromium in alloy steel to resist oxidation.

Chemical reaction fouling is caused by the deposits formed as a result of chemical reactions within the fluid at the heat transfer surfaces. The surface material may not react with the chemicals at all, though it may serve as a catalyst. Control of chemical reaction fouling requires special attention in petroleum refining [16], food processing [17], and polymerization.

3. THERMAL ANALYSIS OF FOULING

The heat transfer, Q, between two fluids through the tube wall of a heat exchanger can be expressed by:

$$Q = UA_i(T_o - T_i) = \frac{1}{R}A_i(T_o - T_i) \tag{1}$$

where: U = overall heat transfer coefficient based on A_i,
A_i = inside surface area of tube,
T_i, T_o = temperatures of inner and outer fluids, respectively, and
R = thermal resistance based on A_i

For a fouling layer of thickness t_f as illustrated in Fig. 1, the overall heat transfer coefficient, U, can be related to the fouling factor, R_f, by the following expression:

$$\frac{1}{UA_i} = \frac{R}{A_i} = \left(\frac{1}{h_i\ A_i} + \frac{t_t}{k_t A_t} + \frac{1}{h_o A_o}\right) + \frac{t_f}{k_f\ A_i} = \frac{1}{A_i}\left(R_c + R_f\right) \tag{2}$$

where: h = convective heat transfer coefficient,
k = thermal conductivity,
A = tube surface area, and
t = thickness

subscripts:
c = clean
f = fouling layer
i = inside
o = outside
t = mean tube wall

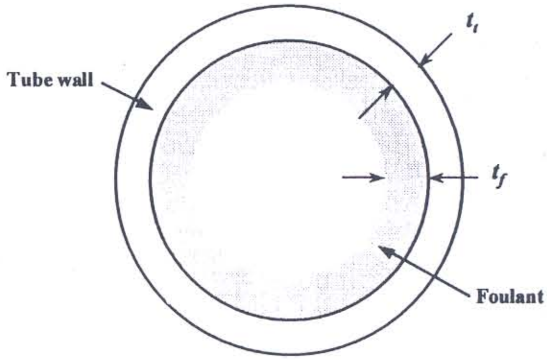

Fig. 1 Fouling of tube inner surface

4. SPONGE-BALL AUTOMATIC TUBE CLEANING SYSTEM

A sponge-ball system is an online mechanical cleaning device, in which rubber balls serve as tube cleaners. A schematic of this system is shown in Fig. 2. The cleaning balls are sized slightly larger than the tubes so that the scrubbing and wiping actions clean the tubes effectively. The major components include a debris filter, ball strainer, recirculating unit, ball collector, and control system.

During normal operation, cooling water is first directed through a debris filter to remove coarse solids. The cleaning balls are then injected into the main inlet to the heat exchanger tubes. The balls are evenly distributed among the tubes as the specific gravity of the balls is designed to be nearly equal to that of the cooling water. At the tube outlet the balls are collected by the strainer and further directed by the recirculating pump to the ball collector. The system can be operated continuously or intermittently. For continuous circulation, each tube is commonly cleaned every 5 minutes [18, 1]. Backwashing starts automatically when the differential pressures across the debris filter and the strainer screens increase to

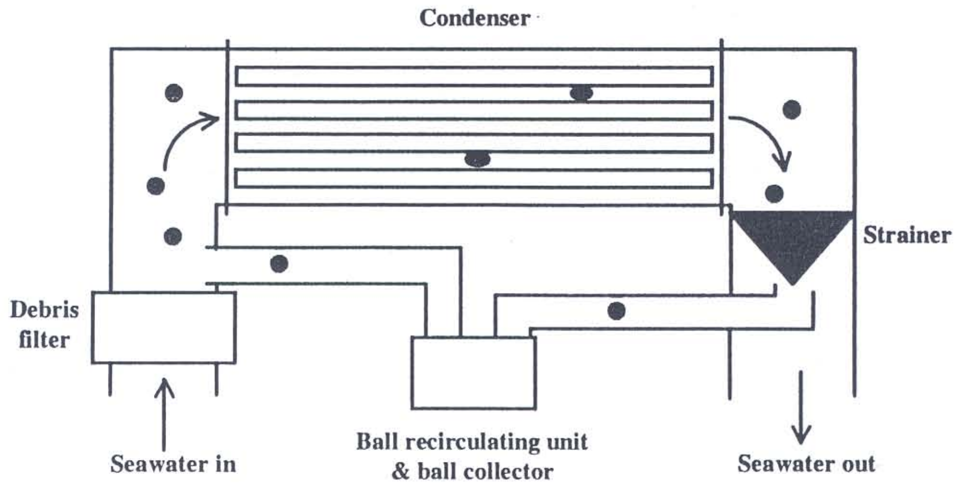

Fig. 2. Sponge-ball automatic tube cleaning system

the preset limit. The backwashing process begins with storing all the rubber balls in the collector. Then, the strainer screens are opened and the backwash rotor rotates underneath the filter segments causing an evacuation force that pushes the debris off the filter screens. The loose debris is further flushed away through the opened debris discharge valve.

There are various kinds of cleaning balls available in the market: standard, extended life, and abrasive [19]. The standard balls are designed for general applications. They are available in a variety of sizes and hardnesses and can withstand temperature as high as 140°C. The extended life balls are made by coating the standard balls with thin smooth skin. The skin wears out slowly resulting in an extended life. However, the smoothness reduces the cleaning efficiency. Thus, the extended life balls are only recommended for mild fouling problems. For harsh conditions, abrasive balls are suggested. They can be manufactured by either coating or blending the standard balls with abrasive materials.

5. TEST SITE AND EQUIPMENT

The first sponge-ball system designed for a seawater-cooled chiller in Hong Kong has been tested. The tested chiller plant serves adjoining twin towers, consisting of the 39-storey Dorset House and the 42-storey PCCW Tower. The two towers, sitting on top of four-basements, provide 126,000 m^2 of office space. The basement levels with a total area of 19,500 m^2 are mainly for car park.

The chiller plant consists of five chillers, seven primary chilled water pumps (two of which for standby), eleven seawater cooling towers, seven condensing water pumps (two of which for standby), and a seawater make-up system. The schematic diagram of the chilled water system is shown in Fig. 3. Chillers 1, 2, and 3 are 1540-ton seawater-cooled centrifugal chillers. Chillers 4 and 5 are 500-ton seawater-cooled screw chillers of identical model. Figure 4 illustrates that 11 two-speed seawater cooling towers are located on the roof to reject heat from the condensing water to the ambient.

A sponge-ball system was installed for Chiller 5 while Chiller 4 served as a control in this investigation. Fifty standard sponge balls of 17 mm diameter were introduced to the system and driven by a 0.55 kW recirculating pump. During normal operation, the balls were injected to the condensing water circuit to perform online cleaning at 3-minute intervals. The installation cost was HK$ 340,000 (US$ 43,600). The operation and maintenance, including ball replacement and pump energy, cost about HK$ 5,000 (US$ 641) per year.

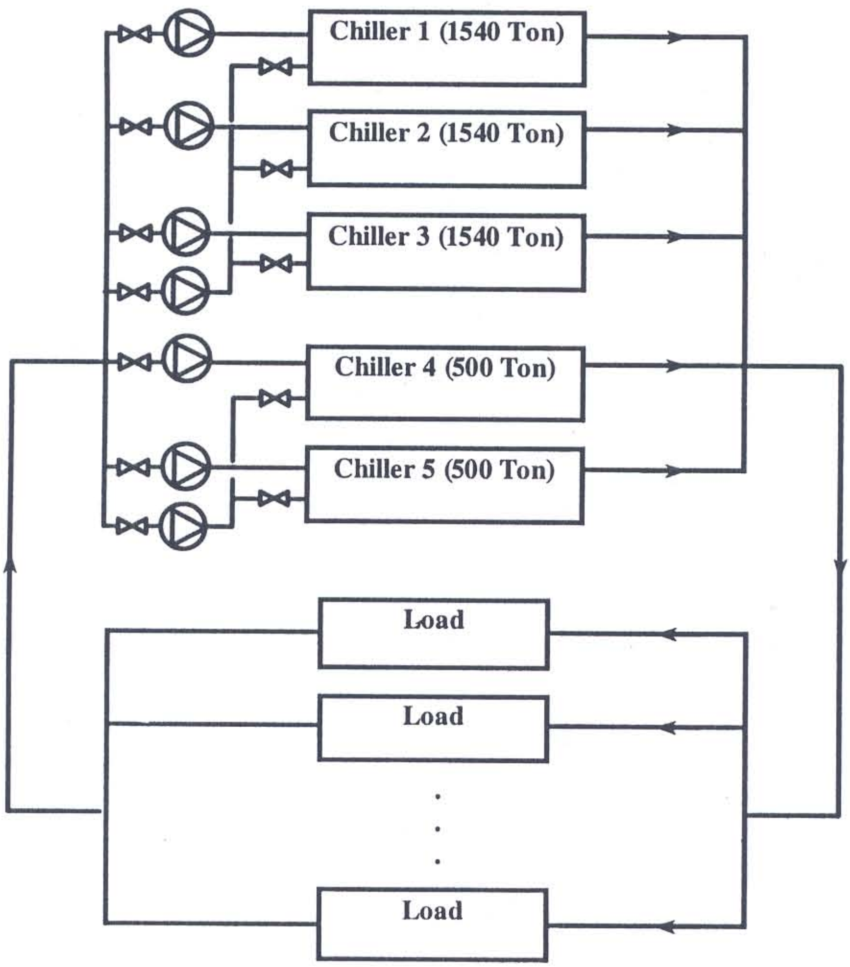

Fig. 3. Schematic diagram of chilled water circuit

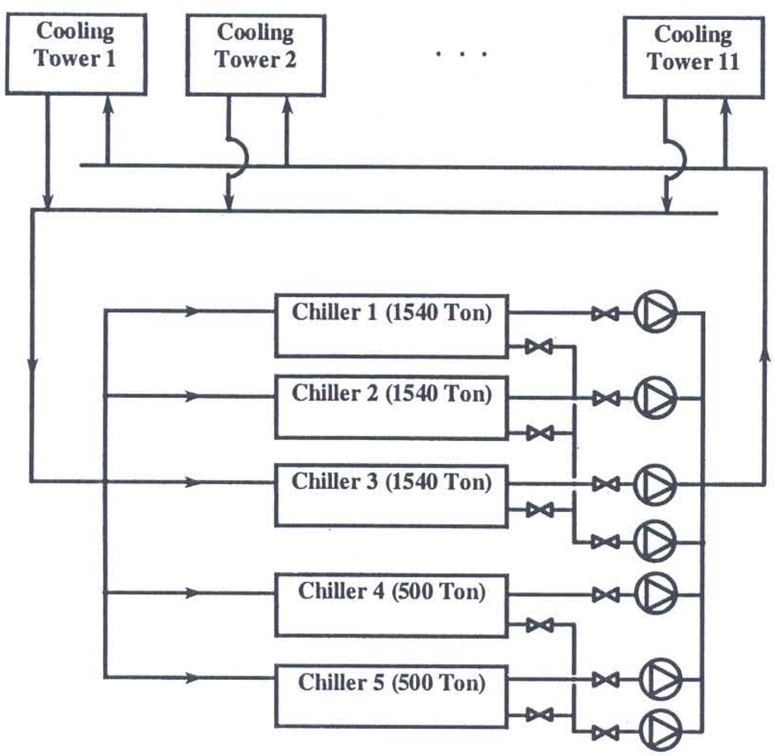

Fig. 4. Schematic diagram of condensing water circuit

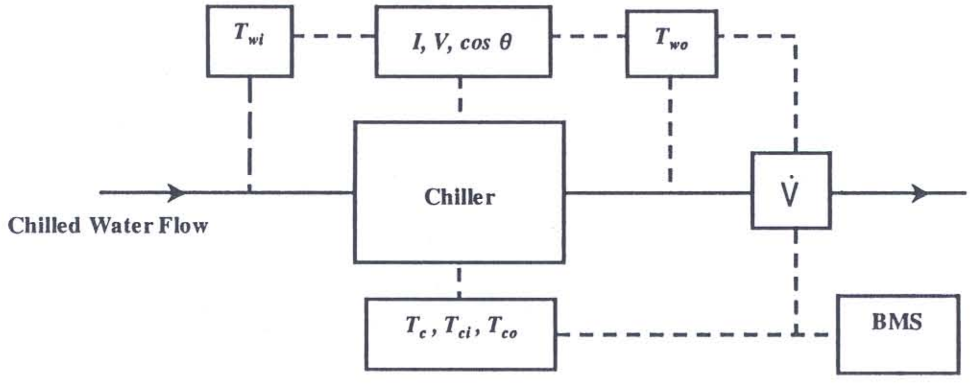

Fig. 5. Instrumental set-up of chillers 4 and 5

6. TEST PROCEDURES

The instrumental set-up for Chillers 4 and 5 is illustrated in Fig. 5. Two thermistors and one electromagnetic water flow meter were used to measure the inlet temperature (T_{wi}), outlet temperature (T_{wo}), and volumetric flow rate ($\dot{V}$), respectively, of the chilled water. A power analyzer was used to measure the three-phase electrical current (I), line-to-line voltage (V), and power factor ($\cos\theta$) for the electrical power input. Moreover, the condensing refrigerant temperature (T_c) and condensing water inlet and outlet temperatures (T_{ci} and T_{co}) were monitored. All the data were recorded by a computerized building management system (BMS).

Before the tests, the condensers of Chillers 4 and 5 were manually cleaned by off-line mechanical method. Both chillers were then operated at the same on/off schedule without the use of the sponge-ball system to verify that the chillers were of identical condition and performance. The measurements were recorded on an hourly basis. After one month, the sponge-ball system was turned on to test its performance on Chiller 5. Both chillers were monitored continuously for five more months.

7. ANALYSIS AND RESULTS

Since the condenser inlet water is common to all chillers as shown in Fig. 4, the fouling factor of a condenser, R_f, is proportional to the temperature difference between the condensing refrigerant and the condensing water outlet:

$$\Delta T = T_c - T_{co} \tag{3}$$

Figure 6 presents the temperature differences of Chillers 4 and 5 operating in the first month after the manual cleaning. The majority of the data fall between 2°C and 4°C increasing with the cooling load. The two linear regression lines indicate the similar overall heat transfer coefficients of the two condensers. After six months of continuous operation, the temperature difference of Chiller 4 increased considerably to a range of 5°C to 11°C, as shown in Fig. 7, because the fouling of the condenser severely reduced the overall heat transfer coefficient. For Chiller 5, the use of the sponge-ball system since the second month maintained low fouling factor and, therefore, the temperature difference changed slightly.

The effectiveness of the sponge-ball system on energy conservation can be evaluated by comparing the coefficient of performance (COP):

$$COP = \frac{Q}{P} \tag{4}$$

Variable P is the electrical power input:

$$P=\sqrt{3}VI\cos\theta \tag{5}$$

and Q is the cooling effect:

$$Q=\dot{V}\rho C_p(T_{wi}-T_{wo}) \tag{6}$$

where: ρ = density of chilled water (1,000 kg/m^3), and
C_p = specific heat of water (4.2 kJ/kg°C)

Figure 8 presents the *COP* versus cooling load in the first month after the manual cleaning of the two chillers. Without the use of the sponge-ball system for Chiller 5, both chillers operated at similar *COP*. According to the linear regression lines, the *COP* increased from 3 to 5 as the cooling load increased from 500 kW to 1800 kW. Based on Figs. 6 and 8, the two chillers were of similar initial condition and performance. Therefore, after the retrofit of Chiller 5 by the sponge-ball system, any difference in system performance should mainly result from the on-line cleaning effect.

The performance of the sponge-ball system is shown in Figs. 9 and 10. The trend of the data for Chiller 4 indicates the continuous drop in *COP*. On the other hand, the *COP* of Chiller 5 is relatively

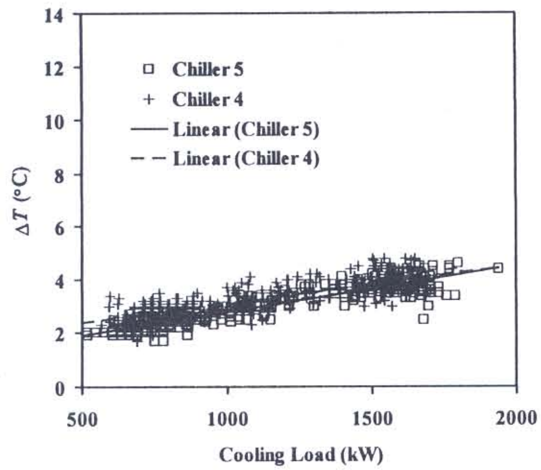

Fig. 6. Temperature difference (T_c - T_{co}) for clean condensers

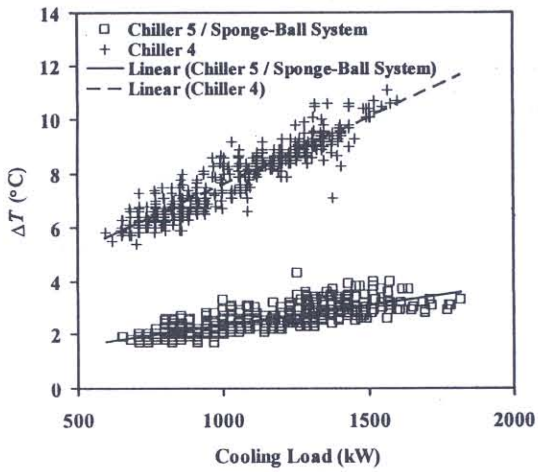

Fig. 7. Temperature difference (T_c - T_{co}) after 6 months of operation

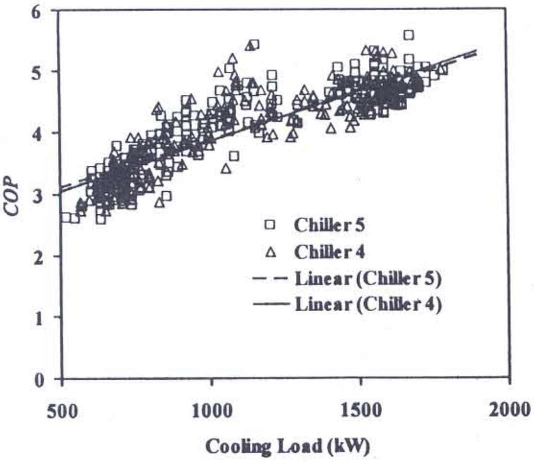

Fig. 8. *COP* obtained in the first month (before use of sponge-ball system)

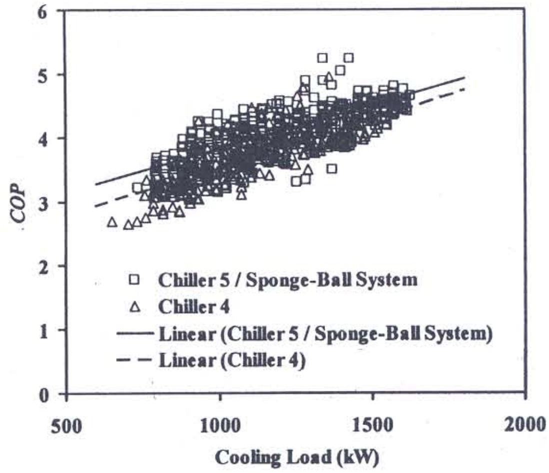

Fig. 9. *COP* obtained in the third month

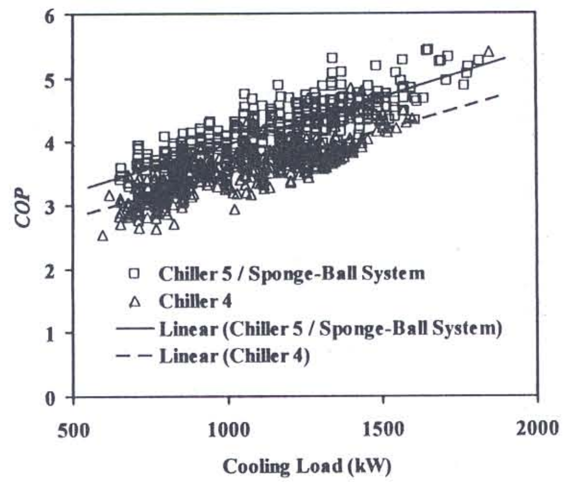

Fig. 10. *COP* obtained in the sixth month

stable. Over the 6-month test period, the sponge-ball system yields an average 12% increase in *COP*. It is noted that the scattering of the *COP* data (Figs. 8, 9, and 10) and temperature difference, $T_c - T_{co}$, data (Figs. 6 and 7) is mainly the result of the measurements taken under both daily and seasonal variations of the outdoor air temperature and seawater temperature.

Compared with a chiller cleaned manually twice a year, the projected annual energy savings due to a sponge-ball system is 152,000 kWh. At the current rate of HK$ 0.94 per kWh, the annual energy cost savings is HK$ 142,880 (US$ 18,318). Taking the operation and maintenance costs into account, the simple payback period is 2.5 years. Based on an equipment life of 10 years, the internal rate of return is 39%.

8. CONCLUSIONS

A sponge-ball automatic internal tube cleaning device, conventionally used for power plant, can effectively maintain low fouling factor in a seawater-cooled chiller condenser resulting in enhanced *COP*. For the first sponge-ball system in Hong Kong, the overall coefficient of performance (*COP*) is improved by 12% with a payback period of less than 3 years. Besides, the sponge-ball system totally eliminates the loss of production due to chiller shut down for periodic manual tube cleaning. The findings of this investigation are useful for designing and operating an automatic tube cleaning device when the limited space in a plant room does not allow to house a sizeable flow diverter.

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