Enhancing Sustainable Environment through mitigating Air-conditioning

CHAN K, Hong Kong

Key words : Magnetic water treatment, HVAC descaling mechanism, non-chemical approach, diamagnetism, energy saving.

SUMMARY

This paper is concentrated on investigating the feasibility, efficiency and payback of applying new energy saving technology of descaling treatment system (DTS) in the central heating, ventilation and airconditioning system (HVAC) for commercial buildings, with Hong Kong case study. The theories and practices of diamagnetism, non-chemical approach, magnetic water treatment and descaling mechanism for central HVAC system will be revamped with action research processes. The study is executed through structured interview and questionnaire conveyed to potential clients regarding the performance of their HVAC system, and a trial run with DTS via a performance contract. Site performance data and laboratory testing findings are adopted for conducting a cost benefit analysis on basis of U-value increases, non-chemical water treatment technologies, enhanced chiller performance, energy savings and financial returns. As a result, periodic descaling of the heat exchange equipment is virtually eliminated. Heat exchanger tube replacement, hardness control chemicals, water in recirculation systems, minerals/chemical concentrations, storage of chemicals, operation costs, and energy consumption are all mitigated to enhance better sustainability and environmental protection in a global perspective.

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1. BACKGROUND

According to the HKSAR Environmental Protection Department (EPD, 2009), Hong Kong has been facing two air pollution issues (1) local street-level pollution, and (2) regional smog problem. Diesel vehicles are the main source of street-level pollution. Smog, however, is caused by a combination of pollutants from motor vehicles, industry and power plants both in Hong Kong and the Pearl River Delta region. The HKSAR Air Pollution Control Ordinance provides the control of emissions from power plants, industrial and commercial sources, construction activities, open burning, asbestos, petrol filling stations and dry-cleaning machines. It also limits the sulphur content of industrial fuel, thus reduces the sulphur dioxide pollution to low levels. Emissions from power plants have been substantially reduced over the years even though demand for power has increased. However, about one-third of the total electricity consumption in Hong Kong goes to airconditioning systems. Majority of the airconditioning systems in local non-domestic premises is electric motor-driven centralized air-cooled type of fair energy efficiency. They account for about one-fourth of the total electricity consumption. Energy savings are associated with the prevention or removal of scale build-up on a heat exchange surface where even a thin film (0.8 mm) can increase energy consumption by nearly 10% (ASHRAE, 2001). A secondary energy savings can be attributed to reducing the pump load, or system pressure required to move the water through a scale-free, unrestricted piping system.

The magnetic technology has been investigated since the 19th century, when lodestones and naturally occurring magnetic mineral formations were used to decrease the formation of scale in cooking and laundry applications (Baker and Judd, 1996). Magnetic or electrostatic scale control technologies can be used as a replacement for most water-softening equipment (Reimers, DeKernion and Leftwich, 1979). Specifically, chemical softening (lime or lime-soda softening), ion exchange, and reverse osmosis, when used for the control of hardness, could potentially be replaced by non-chemical water conditioning technology (Quinn, Molden and Sanderson, 1996). This would include applications both to cooling water treatment and boiler water treatment in once-through and re-circulating systems. This savings is associated with the prevention or removal of scale build-up on a heat exchange surface, where even a thin film can increase energy consumption by nearly 10%. Secondary energy savings can be attributed to reducing the pump load, or system pressure, required to move the water through a scale-free, unrestricted piping system (Lienhard, 2001).

The technology involved uses a magnetic or electrostatic field to alter the reaction between scale-forming ions in hard water which contains high levels of calcium, magnesium, and other divalent cations (Marth, 1997). When subjected to heating, the divalent ions form insoluble compounds with anions such as carbonate. These insoluble compounds have a much lower heat transfer capability than heat transfer surfaces such as metal. They are insulators, where additional fuel consumption would be required to transfer its equivalent energy (Simpson, 1980). These technologies can be used as a replacement for most water-softening equipment. Specifically, chemical softening (lime or lime-soda softening), ion exchange, and reverse osmosis, when used for the control of hardness, can be replaced by the non-chemical water conditioning technology (Quinn, Molden and Sanderson, 1996). This would include applications both to cooling water treatment and boiler water treatment, in once-through and re-circulating systems. The magnetic technology is generally not applicable in situations where the hard water contains "appreciable" concentrations of iron (parts per million or mg/L). The action of magnetic field on the hardness-causing ions is very weak; and conversely, on the iron ions is very strong, which interferes with the water conditioning action (Fryer, 1995).

Generally, the preferred installation location for use with cooling towers or heat exchangers is upstream of the heat exchange location and upstream of the cooling tower. Downstream of the cooling tower but upstream of the heat source was also mentioned as a possible installation location, primarily for the use with chillers or other cooling equipment. The primary caveat on installation of the magnetic technology is that high voltage (230V, 3-phase or above) power lines interfere with operation by imposing a second magnetic field on the water. This second magnetic field most likely will not be aligned with the magnetic field of the device, thus introducing interference and reducing the effectiveness of the treatment (Busch, Parke, Darling and McAtee, 1986). Moreover, magnetic and electric fields interact with a resultant force generated in a direction perpendicular to the plane formed by the magnetic and electric field vectors. Positively charged particles will move in a direction per the Right-hand Rule, where the electric and magnetic fields are represented by the fingers and the force by the thumb. Negatively charged particles will move in the opposite direction. This force is in addition to any mixing in the fluid due to turbulence (Busch, Parke, Darling and McAtee, 1986).

Positive charged ions (calcium and magnesium, primarily) and negative charged ions (carbonate and sulfate, primarily) are directed toward each other with increased velocity. The increased velocity will result in increased collisions between the particles, forming insoluble particulate matter, and further growth of scale crystal (Marth, 1997). The treatment efficiency increases with increasing hardness; thus each ion will need to travel a shorter distance before encountering an ion of opposite charge. A similar reaction occurs at a heat exchange surface but the force on the ions results from the heat input to the water. Heat increases the motion of the ions, which then collide. The scale exhibits an inverse solubility relationship with temperature, meaning that the solubility of the material decreases as temperature increases. At the hottest point in a heat exchanger, the scale is least soluble. Due to thermally induced currents, the ions are most likely to collide nearest the surface. As above, the precipitate formed acts as a foundation for further crystal growth (Benson and Martin, 1994).

Calcite is an adherent mineral that causes the build-up of scale on the heat exchange surface. When the reaction between positively charged and negatively charged ions occurs at low temperature, the mineral form is usually aragonite. Aragonite is much less adherent to heat exchange surfaces, and tends to form smaller-grained or softer-scale deposits, as opposed to the monolithic sheets of scale common on heat exchange surfaces (Parsons, Wang, Judd and Stephenson, 1997). These smaller-grained or softer-scale deposits are stable upon heating and can be carried throughout a heating or cooling system while causing little or no apparent damage. This transport property allows the mineral to be moved through a system to a place where it is convenient to collect and remove the solid precipitate. This may include removal with the wastewater in a once-through system, with the blow down in a re-circulating system, or from a device such as a filter, water/solids separator, sump or other device specifically introduced into the system to capture the precipitate (Parsons, Wang, Judd and Stephenson, 1997).

Water savings are also possible in re-circulating systems through the reduction in blow down necessary. If the chemical consumption for scale control is reduced, it may be possible to reduce blow down also. However, the management of corrosion inhibitor and/or biocide build-up, and/or residual products or degradation by-products, may become the controlling factor in determining blow down frequency and volume (Fryer, 1995). In addition, water suppliers contain, magnesium and other divalent cations which usually precipitates and dorms scale when subjected to heat exchange. The scale will clog up inside the heat exchange equipment (such as the condenser and evaporator of chiller, air-handling equipment). This not only reduces the heat exchange capability but also eventually increases the operating cost for the scale has a much lower heat transfer capability than heat transfer surfaces such as metal.

The coefficient of the heat exchangers in airconditioning system must be increased if the scale in the tubes is removed. Descaling Treatment System can effectively remove scale in water carrying equipment without the use of any chemicals, which reduce the maintenance cost consumed under the conventional cleaning method. Without scale in the airconditioning system, smaller difference between the condensing temperature and evaporating temperature of the chiller is possible, so that the chiller energy performance can be improved with the electric energy consumption reduced. Besides, with higher heat transfer coefficient of the heat exchangers, smaller size of air-handling equipment and chillers can be designed for new air-conditioning systems so that initial investment can thus be reduced. DTS, using modern microprocessors and signal processing techniques, produces a complex, modulating frequency waveform to achieve in both scale removal and prevention. Under the attack of complex waveform, the scale molecules are restructured for recombination and the scale will gradually break and turn into aragonite. Aragonite is a stable crystallized particle in suspension which is highly soluble to water. To avoid further corroded by flowing water, the scale which has been transformed into aragonite will be detached form the pipe and flush away by the flowing normal water. Unlike any other system, the DTS not only prevents the formation of scale, but also removes any scale in the water system. The energy savings and market potentials of each candidate technology could be evaluated using a modified version of the Facility Energy Decisions Screening (FEDS) software tool (Dirks and Wrench, 1993).

2. RESEARCH METHODOLOGY

2.1 Structured interview with potential clients

Structured interviews with client and in-situ checking of the existing plant conditions are carried out. After collecting these information, by comparing the electricity tariff with the efficiency of the cooling system, possible energy reduction/saving and payback by adopting the descaling treatment system will be analysed for clients' consideration. Due to the continuous operation of cooling system; the condenser, chiller piping, fan coil units, cooling tower and evaporator will definitely accumulate certain scale especially for plants operating for more than 5-6 years old, resulting in low efficiency and high energy wastage.

It will be in the form of "Performance Contract" i.e. the rent payment will be according to the performance which meets the target electricity saving over a period of time. It is a smart, affordable and increasingly common method to achieve building improvements that save energy and money. It creates a win-win situation for the client and supplier, and there is no direct cost for equipment at initial stage. The potential benefits to client include (1) free to up-grade the condition of existing air-conditioning plants, (2) the energy saved will be used to offset the initial labor cost, maintenance cost during the contractual period, (3) the energy saving system will advance the maintenance system, and (4) less responsibility during the contract period. Benefits to the service provider encopmpass (1) simple contract terms to follow, (2) raise the business turnover rate from rent payment scheduled by client, and (3) less technical labor demanded for installation and maintenance. There will be a trial run for testing the initial performance. Recording the data by sensor before and after installing the equipment serves as a comparison for electricity savings. After evaluation of the performance, the bulk contractual works will be officially commenced.

2.2 Case Study and Monitoring

The subject building ACP is a commercial complex consisting of two 11-storey office towers, a 4 star hotel over a retail podium in central business district of Hong Kong. After checking with the existing HVAC system, the mock up trial will be held in the Tower 1 Ground floor AHU room. The test is carried out on one of the primary air units (PAU). The air-handling equipment (AHU, PAU and FCU) and chiller (condenser and evaporator) are all heat exchangers. To determine the thickness of scale and the performance of DTS, a test is designed to compare the heat transfer changes before and after DTS is installed. Then the energy saving and other benefits of adopting DTS on airconditioning system are analyzed. Moreover, an automatic data acquisition system will be installed in the plant room, and the following parameters have been measured:

- DB temperature, and relative humidity at inlet and outlet of air stream
- Air velocity, or air flow rate, on air side
- Water temperature at water inlet and outlet pipelines
- Water flow rate
- Water pressure drop across the heat exchanger

All the sensors are connected into the data loggers directly for mV output sensors and indirectly through transformers and/or transmitters for higher voltage output and current output sensors. The performance tests lasted for four months, with all the data recorded by a computer in 4-minutes intervals, and the DTS was installed near the end. The chiller water flow rate measurement was difficult job as there was no water flow rate sensor in the existing pipeline. In order not to damage the pipeline and stop the operation of the air-conditioning system, an ultrasonic flow meter was used. By removing approximately 200mm(L)x600mm (Perimeter) insulation layer from the surface of the supply chilled water pipe running to the primary air unit, one set of ultrasonic flow sensor was mounted on the upper surface of the pipe. Proper calibration of the flow meter was made in an accredited HK laboratory before test. All other sensors were calibrated from time to time, especially the humidity sensors. A more accurate humidity measurement kit was used to check the accuracy of the two humidity sensors regularly to maintain a high accuracy of the measurements.

2.3 Theoretical Analysis of U-value

A heat exchanger is to transfer heat between two fluid masses at different temperature. To account for the resistance offered by a clean and a non-clean cooling coil, the overall heat transfer coefficient U and outer area of respective tube surfaces are adopted. Yet it is difficult to predict the thermal conductivity of the scale. The exact values have to be referred to specific heat exchanger configurations; to particular fluids, to fluid velocities, to operating temperatures, and to the age of the heat exchanger. The thermal resistance generally drops with increased velocity and increases with temperature and age. To illustrate the impact of the scale on the heat transfer performance, different assumptions of the thermal conductivity and some other parameters are given for different applications.

a) Air-handling equipment

Some air-handling equipment including Air Handling Unit (AHU), Primary Air Unit (PAU) and Fan Coil Unit (FCU) are used in the project. They are all air to water heat exchangers with the chilled water flow inside the tubes to cool the air outside the tubes in the units. The thermal conductivities, the heat transfer coefficients and dimensions will follow the equation Eq. (1).

$$U = \frac{1}{\frac{1}{h_i}\frac{R_o}{R_i - W_s} + \frac{R_o}{k_{scale}}\ln\frac{R_i}{R_i - W_s} + \frac{R_o}{k_{pipe}}\ln\frac{R_o}{R_i} + \frac{1}{h_o}} \qquad (1)$$

Equation 1

b) Condenser

The condensers used in the project are shell-and-tube heat exchangers. Chilled water is circulated in the shell-and-tube condensers through one ore more continuous or assembled coils contained within the shell and the refrigerant vapour condenses outside the tubes.

c) Evaporator

The energy is transferred from the chiller water to the evaporator surfaces, and then conducted through the surfaces to the refrigerant. The refrigerant absorbs heat mainly as latent energy in the evaporator and the fluid from the compressor is usually superheated vapour. The other parameters remain unchanged. Based on Eq. (1) and the parameter assumptions of the air-handling equipments, condenser and evaporator; the increasing percentage of the U-value resulting from the removal of scales are shown in Fig. 1.

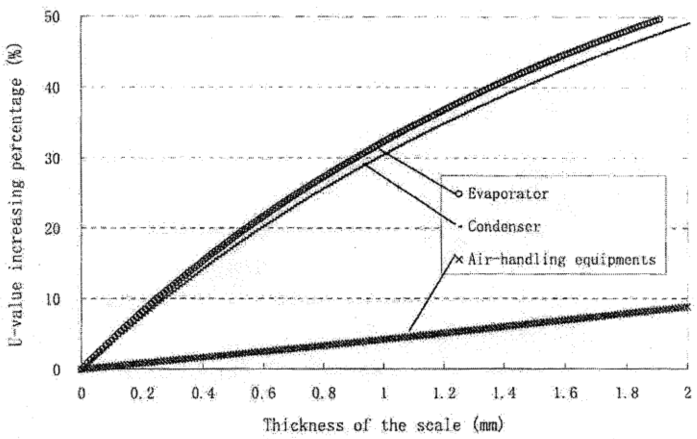

Fig. 1. U-value vs. scale thickness

The increasing percentage of the three applications is approximately linear with the thickness of the scale, but the slopes are different. The increasing percentage of the air-handling equipments looks small in contrast to that of the condenser and evaporator, mainly because the scale in the air-handling equipments has introduced smaller resistances than the scale in condenser and evaporator. Moreover, the increasing percentage of evaporator is a slightly larger than the percentage of condenser owing to the refrigerant heat transfer coefficient difference between these two heat exchangers.

3. RESULT AND ANALYSIS

The experimental data of the PAU during the four months are used to analyze the U-value variation before and after the installation of DTS. The heat transferred at any time between the chilled water in the tubes and the air outside the tubes can be expressed by:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$$

Equation 2

$$U = \frac{Q}{A \Delta T_{lm}} = \frac{\dot{m}_w c (T_{wo} - T_{wi})}{A \Delta T_{lm}}$$

Equation 3

The performance of heat transfer is affected by the inlet conditions of both fluid streams. Since the inlet air conditions vary during the data acquisition period, the energy saving performance of the DTS changes with the inlet conditions such as temperature and relative humidity. The change of the U-value according to the inlet air temperature under different relative humidity before and after DTS installation is displayed in Fig. 2.

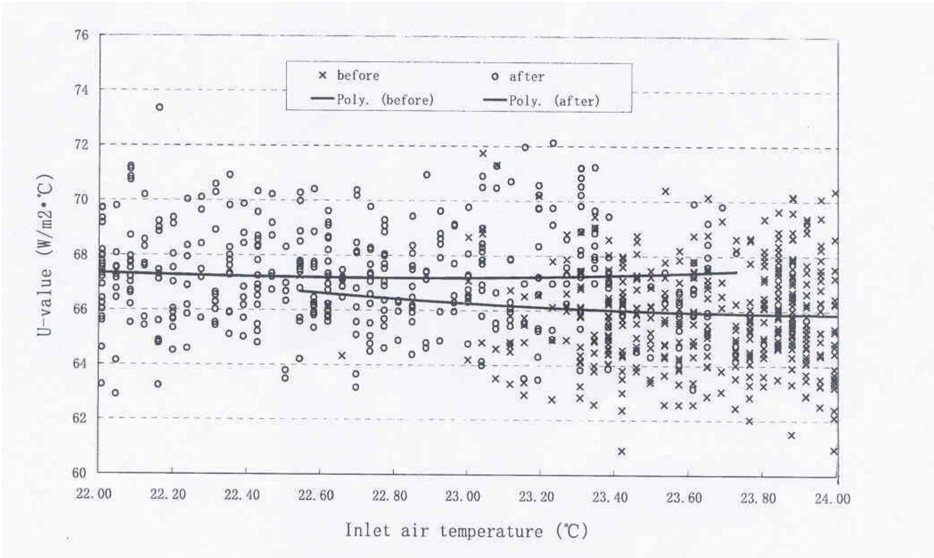

Fig. 2. Inlet air temperature

From the analysis, the mean increasing percentage of the U-value is about 1.15% after DTS installation. However, removing the prior build-up scales on heat exchanger surfaces may take 30 days to over a year. Depending upon the thickness and composition of the scale, the increasing percentage of U-value is estimated to about 1.5% after installing the PAU. According to the theoretical increasing percentage of the air-handling equipments shown in Fig. 1, the thickness of scale is about 0.36 mm with 1.5% U-value increasing percentage. This is also consistent with the actual situation. For the PAU, only a thin lamina of scale is formed after DTS installation. The mean thickness of scale for other heat exchangers (condenser and evaporator) would be also 0.36 mm.

4. ENERGY SAVING ANALYSIS

DTS could achieve energy saving for the chillers (due to higher chilled water supply temperature) and pumps (due to less flow resistance). When DTS is installed on the condenser side of chiller, the heat transfer performance of condenser will be improved, which will result in a smaller temperature difference between the cooling water and refrigerant. The same cooling water temperature, and the refrigerant temperature in condenser can be decreased. When the evaporator side of the chiller is installed with DTS, the refrigerant temperature in the evaporator can be increased. As to the air-handling equipments, after installing DTS, a higher chilled water temperature is possible which will produce a higher evaporating temperature. With a lower condensing temperature or a higher evaporating temperature or both, the heat transfer temperature difference of the refrigerant cycle will be reduced, thus a higher coefficient of performance (COP) and energy saving can be achieved for the chillers.

a) Variation of the condensing and evaporating temperature

With the increased U-value, to maintain the same heat transfer capability, the temperature difference between the two streams of the heat exchangers can be reduced correspondingly.

b) Variation of COP

The basic vapour refrigeration cycle is used to analyze the real chiller performance of the central airconditioning system. The cycle is a theoretical cycle because several assumptions are made and differerent from the responses in a real refrigeration cycle. It does not experience superheating of the refrigerant in the evaporator or subcooling of the refrigerant in the condenser. Even considering these differences between theoretical and real refrigeration processes, the analysis of a basic saturated cycle is worthwhile because the fundamental processes can be easily identified. Furthermore, the basic saturated cycle sets the standard against all actual vapour-compression cycles for comparison in determining their relative efficiency at various operating conditions.

c) Energy saving percentage

With the increased COP, to maintain the same cooling capability, the energy consumed by the chillers may be reduced. The annual net benefit for using the DTS is mainly achieved by savings in electric energy and chemical usage as demonstrated in Table 1.

Year	Reduction in Electricity	% shared by SK Mgt.	Less Service Payment	Maintenance Cost after Contract Period	Total Savings
0.5	26,403	20%	-21,122	-	5,281
1.0	26,403	20%	-21,122	-	8,281
1.5	26,403	23%	-20,330	-	6,073
2.0	26,403	23%	-20,330	-	6,073
2.5	26,403	26%	-19,538	-	6,865
3.0	26,403	26%	-19,538	-	6,865
3.5	26,403	32%	-17,954	-	8,449
4.0	26,403	32%	-17,954	-	8,449
4.5	26,403	40%	-15,833	-	10,570
5.0	26,403	40%	-15,833	-	10,570
6.0	52,805			-4,800	48,005
7.0	52,805			-4,800	48,005
8.0	52,805			-4,800	48,005
9.0	52,805			-4,800	48,005
10.0	52,805			-4,800	48,005
Total	**528,050**		**-189,553**	**-24,000**	**314,500**

Mode of payment based on reducing share of savings; electricity charge @$0.9/kWh

Table 1. Potential Savings of Applying Water DTS

If the A/C energy consumption per square meter is HK$130 and the local electric energy cost for commercial buildings is HK$0.90 per kWh, total saving of whole building will be:

$$N_{electric} = \eta \times A \times 130 \text{ kWh}/m^2 \times \text{HK\$ } 0.9 \text{ per kWh}$$

Equation 4

In systems that are descaled frequently or have low scale formation (due to low hardness and/or an effective chemical scale control program), the savings in energy consumption is lower. In systems where descaling is infrequent or absent, or where the chemical scale control program is not as effective as in controlling scale formation, the energy saving can be much higher. In each case, the energy saving percentage must be proportional to the thickness of the scale layer removed.

5. CONCLUSION

Minimizing electricity consumption helps in energy saving and decreasing carbon dioxide emission from power station. With the foregoing case study, it demonstrates an all-win situation for clients, service providers and global mankind. Through the rent to own contract, the rent payment is flexible and prorata with the energy to be saved. The warranty period can be commenced after the expiration of the lease period. Ownership of the equipment will be transferred by the service provider to client at the end of lease period at no extra cost.

Other potential energy savings would exist. The first is the elimination or reduction in the need for scale and hardness control chemicals. The handling and storage of chemicals (soda ash, salt, acid etc.) will be eliminated. In a typical plant, these materials and operational savings could mean a lot. Water saving is also possible in recirculation systems through reduction in blow down (to reduce/balance out the minerals and chemical concentrations). If the chemical consumption for scale control is reduced, blow down water is reduced too. Non-chemical water treatment technologies would also enhance better life cycle cost.

Secondly, there is a significant positive impact in maintenance. Periodic descaling of the heat exchange equipment is virtually eliminated. Thus process downtime, chemical usage, and labor requirements are eliminated. Field applications have shown that the technology is capable of controlling scale for extended periods of time.

The third potential savings is from reduction in heat exchanger tube replacement. Failure of tubes due to scale build-up and the resultant temperature rising across the heat exchange surface, will be eliminated or greatly reduced in proportion to reduction in scale formation. There are positive effects on the airconditioning system such as increased U-value of heat exchangers and increased COP of chillers.

The opportunity cost of potential environmental benefits have not been taken into account fully yet. Reduction in burning fossil fuels would cause lesser environmental problems e.g. particle emission, global warming gas generation.

REFERENCES

1. Armstrong Monitoring http://www.armstrongmonitoring.com/liquid/liq-cond/Federal%20Report%20-%20LKC21.htm, accessed in 1/2012.
2. ASHRAE (2001), Fundamentals, ASHRAE Handbook, *American Society of Heating, Refrigerating and Air-conditioning Engineers*, Atlanta, 2001.
3. Baker J.S. and Judd S.J. (1996), Magnetic Amelioration of Scale Formation, *Water Research*, 30(2):247-260.
4. Benson R.F., Martin B.B. and Martin D.F. (1994), Management of Scale Deposits by Diamagnetism, A Working Hypothesis, *Journal Environmental Science and Health*, A29(8):1553-1564.
5. Busch K. W., Busch M. A., Parke D. H., Darling R. E. and McAtee J. L. (1986), Studies of a Water Treatment Device That Uses Magnetic Fields in *Proceedings of Corrosion 85*, Boston MA.
6. Dirks J.A., and Wrench L.E. (1993), Facility Energy Decision Screening (FEDS) Software System, PNL-SA-22780 in *Proceedings of the Energy and Environmental Congress*, Minneapolis, Minnesota, August 4-5, 1993.
7. Fryer L. (1995), Magnetic Water Treatment A Coming Attraction? E-Source, TU-95-7
8. HKSAR Environmental Protection Department http://www.epd.gov.hk/epd/eindex.html, http://www.epd.gov.hk/epd/english/resources_pub/publications/files/PRD2010_1-6e.pdf, accessed in 2/2012.
9. Lienhard J.H. (2001), A Heat Transfer Textbook, *Phlogiston Press* USA, 2001.
10. Marth, R.A. (1997), *A Scientific Definition of the Magnetic Treatment of Water: Its Subsequent Use in Preventing Scale Formation and Removing Scale*, Research Conducted for Descal-A-Matic Corporation.
11. Parsons S.A., Wang B.L., Judd S.J. and Stephenson T. (1997), Magnetic Treatment of Calcium Carbonate Scale - Effect of pH Control, *Water Research*, 31(2): 339-342.
12. Quinn C.J., Molden T.C. and Sanderson C.W. (1996), Nonchemical Approach to Hard Water Scale, Corrosion and White Rust Control, in *Proceedings of Iron and Steel Engineer*, Chicago IL, September 30, 1996.
13. Reimers, R.S., DeKernion P. S. and Leftwich D. B. (1979), Sonics and Electrostatics - An Innovative Approach to Water and Waste Treatment, in *Proceedings of Water Reuse Symposium*, Volume 2. American Water Works Research Association and Research Evaluation, Denver, CO.
14. Simpson. L. G. (1980), Control Scale and Save Energy, *The Coast Guard Engineer's Digest*, Volume 20, Number 205, pp. 32-35.
15. STR Global http://www.strglobal.com/Default.aspx, accessed in 3/2012.