ENERGY SAVINGS FROM AN AUTOMATIC TUBE CLEANING SYSTEM (ATCS)

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ABSTRACT

The successful operation of a water-cooled HVAC chiller requires controlling the growth of biofilm and deposition of scale on the internal tubes of the condenser heat exchange surface. The formation of fouling reduces heat transfer efficiency and subsequently increases chiller work load and energy consumption. Commercially available ATCS specify replacement times for the sponge projectiles at every 1000 hours of chiller run time of operation based on application of 30-minute injections intervals. This paper presents research undertaken in conjunction with The University of Adelaide and focused on endeavours to understand what the impact of physical aging (number of cycles) has on the contact area, stiffness (shear force) and the diameter of the projectiles. The experimental results show that the projectile diameter and contact area increased with the number of cycles, while the shear force can drop in magnitude by approximately half. Separately, analysis of the mean fouling factor from on/off trials of a commercial chiller fitted with ATCS is presented. The mean fouling factor was in the order 15% lower when the ATCS is in operation. Furthermore, results from two case studies for the side by side comparison of ATCS installed on one of two identical 200-ton and 300-ton chillers operating in parallel yielded energy savings in the range of 13% to 19%.

INTRODUCTION

The fouling of heat exchangers is estimated to cost industrialized countries 0.25% of Gross Domestic Product (GDP) and it is responsible for 2.5% of the total equivalent anthropogenic emissions of carbon dioxide (Steinhagen et al., 2011). In Australia, this equates to approximately \$3.5 billion dollars annually, and it is evident that effective mechanisms of defouling heat exchangers would result in considerable expenditure savings as well as reductions in greenhouse gas emissions (Thulukkanam, 2013).

The physical properties of projectiles such as their size, shape and surface roughness as well as their cleaning performance properties such as shear force and contact area are important attributes to their effectiveness in cleaning. While the ATCS is in operation, the contact area provides a point of constant physical contact between the cleaning projectiles and the tube inner wall. These physical areas of contact determine the extent of the cleaning performance, as projectiles brush and sweep the walls of the tube while moving, and therefore a larger area of contact would indicate a greater removal of foulant material. The stiffness of cleaning projectiles produces radial stress towards the tube inner wall, and these stresses act as a normal force, thus forming a shear force between projectiles and the tube inner wall while the projectiles are moving in the tubes. In theory, a larger stiffness would produce a greater shear force and thus provide a better cleaning performance.

Projectiles are usually larger in diameter than the tubes, and this is important as it allows projectiles to have larger physical contact with tube inner walls. The performance of various projectiles has been extensively reviewed by Jalalirad et al., 2013a; Jalalirad et al., 2013b; Malayeri et al., 2014. It was found that flexible and rough projectiles are undoubtedly better in cleaning than stiff and smooth projectiles.

These authors developed a contact stability criterion, i.e. the Z factor, which relates the cleaning ability of the projectile to its stiffness in a qualitative manner. The Z factor is low for hard projectiles and vice versa. However, while a hard projectile can exert a shear force many times larger than a soft projectile, its cleaning ability is not appreciably better. The reason was attributed to poor contact stability with the tube surface. Instead, they showed that the size of projectiles plays an important role to provide a continuous cleaning. More recently, Abd-Elhadya et al, (2015) investigated the impact of hardness and surface texture on cleaning action of four different projectiles (1) rubber, (2) sponge, (3) notched and (4) ribbed. Their performance to clean a tubular heat exchanger was investigated as a function of the injection rate. A $CaSO_4$ solution was used as the foulant. The cleaning ability of the different types of projectiles was also observed to vary with the injection rate.

One factor that was not evident in the open literature reviewed to date is the anticipated changing physical performance due to ageing/degradation of the projectiles over time. In commercial chiller applications of the ATCS, sponge ball projectiles operate at a minimum of 1000 hours of chiller runtime before the manufacturer's requested point of replacement. Based on 30-minute injection cycles, the projectiles will undertake at the minimum for a single pass shell and tube heat exchange some 2000 injection cycles. It is standard operating procedure for the projectiles used in such applications to be 1 mm larger than the tube internal diameter.

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The study also reports the results from the analysis undertaken for several water-cooled condenser shell and tube heat exchangers operating with the ATCS. Two distinct types of tests were performed on different systems. Firstly, a sequence of ATCS on/off trials and its impact on the fouling factor analysed during the operating period. Secondly, a side by side comparison of two identical chillers, one fitted with ATCS and one without are presented for a medical centre and casino-hotel.

EXPERIMENTAL

The properties of cleaning projectiles are crucial to the ability to perform their cleaning action. This study investigated commercially available sponge ball cleaning projectiles obtained from Ningbo Everfly Industry Co. Ltd. (China). The manufacturer specifications in terms of the exact chemical composition and the overall physical properties of the sponge balls were not subscribed. As no detailed manufacturer specifications were enclosed, various physical properties of the sponge balls were investigated to enable distinction between each respective ball size.

Physical properties refer to the: diameter, width of the ball at its reference line; shape, the observed measure of the ball's overall spherical symmetry; surface roughness, the observed measure of the ball's roughness. The performance properties include the contact area, which refers to the surface area of the sponge ball with which it is in contact with the inner surface of the condenser tube and the shear force.

The full account of the experimental procedures for the contact area and shear force have been documented elsewhere (Malayeri et al., 2014). In brief, the reported contact areas were measured in a transparent tube with similar inner diameter to that of the tube (15mm) used in ageing experiments. Thus, the measured contact area would be similarly defined as the dynamic contact area (Malayeri et al., 2014). The hydrodynamic force and shear are determined from a test rig equipped with a pressure transducer, a flow meter and the facility for injecting projectiles. The projectile pass through the tube by the flow while the pressure in the back of the projectile and respective flow velocity were recorded. Considering the cross-section of the pipe, the measured pressure represents the required force for pushing the projectile by the force of the flow. When the hydrodynamic force is divided by the contact area between the projectile and tube, then the respective shear can be determined. However, the contact area between the projectile and the tube while under the force of the flow cannot easily be measured. To obtain reliable and consistent results Malayeri et al., (2014) required the soft projectiles to operate at the minimum flow velocity of 0.4 m/s. As this is considerably lower than the typical 1 m/s specified for the operation in commercial applications of the ATCS, undertaking analysis at this minimum would not yield the required representation of normal operation. While this represents a limitation of the present study, in the context of the findings it is believed this shortcoming is minimal in comparison to the implied assumption of consistent projectile properties when discussing fouling. Especially the potential extrapolation of short run experimental results conducted over several to tens of hours compared with 1000 plus hours in commercial operations.

The projectiles pass repeatedly through a tube testing system designed to quantify the degradation of the physical and performance properties. Wieland Werke AG provided the testing tubing and the test length of the tube was 1.6 m with a 15 mm inner diameter. Three projectile sizes (15 mm, 16 mm and 17 mm) are subject to 2000 cycles. The physical and performance properties of the sponge balls are obtained in intervals of 50 cycles. This means that a total of 40 measurements are taken on each sponge ball for each property investigated.

The second component of this study involved the investigation of an ATCS on/off trial as part of the Westmead Hospital's Chiller system located in Parramatta, Sydney. The unit fitted with the ATCS is a 19XR High Efficiency Hermetic Centrifugal Liquid Chiller manufactured by Carrier (model 19XR 70 71475 DJ S 854.). The characteristics of the condenser tubes are summarized in Table 1.

Table 1. Tube parameter for Carrier chiller at Westmead.

Number of tubes	870
Tube length	2.8 m
Tube diameter	15.875 mm

It was agreed with the Westmead Hospital's technical operators that the chiller would remain as the lead chiller and operational for 24 hours per day for the full 6-week trial, commencing on the 14th of August 2015. Prior to this period, the hospital's chiller had been idle for 4 months (low season load as southern hemisphere winter) and the chiller had not been cleaned since the beginning of its last operation. This reflects that the ATCS did not start from a clean state. However, based on fouling theory, as the surface temperature of the condenser tubes is less than the minimum sintered temperature, any new foulant formation occurs in the induction phase. A data acquisition system operated by ClimaCheck was used to obtain instantaneous measurements of various parameters, including temperatures, pressures, flow rates and power inputs at various positions on the chiller system. The logged data was used to obtain the overall heat transfer coefficient and therefore the fouling factor in the condenser tubes.

The rate of heat transfer, Q, absorbed by the condenser water from the refrigerant is found by the following equation,

$$Q = m_c C_p (T_{c,o} - T_{c,i}) \qquad (1)$$

The overall heat transfer coefficient, U for the condenser is then calculated at fouling and reference conditions, respectively. The reference overall heat transfer coefficient (condition prior to 14th) was obtained at 10 am on the 14th of August, as this is the point at which the condenser commenced operation and taken as the initial reference condition. The fouling factor is thus obtained as:

$$Rf = 1/U_f - 1/U_{ref} \qquad (2)$$

It is important to note that this analysis was on an active system, thus the analysis of the in-situ heat exchanger was not controlled. This is caused by the fact that the operating conditions of the chiller system vary as the demand for cooling in the Westmead Hospital changes (real world conditions).

This change in operating conditions affects the analysis of the ATCS as it influences the mass flow rate of the condenser water. It is desired that the analysis is carried out at a constant operating condition throughout the operating period, as this would result in the most feasible result. However, as the chiller adjusts its capacity based on the existent situation, it is implied that this variation in the operating condition is negligible over the short 6-week trial and the only variable in the analysis of the heat exchanger is the changing between "on/off" operations of the ATCS. In summary, for the six-week operational period of the analysis the ATCS was turned on for a total of 19 days, with the cumulative total of 912 injection cycles.

Finally, two case studies on the impact of the ATCS on identical chillers operated side by side, one with ATCS and one without, as the control, are presented. The chiller energy efficiency was analysed according to ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings.

RESULTS

Table 2 contains photographs of typical results found, with the 17 mm projectile degradation versus number of cycles presented here. Table 3 shows compares the 15, 16 and 17 mm projectiles at the beginning and at the end of the test, respectively. The 17 mm sponge ball loses its symmetry and shape during the course of 2000 testing cycles, moving from a spherical shape into an irregular one. The surface roughness of the sponge ball has also notably changed. A new ball's surface is smooth, with a low number of small surface pores. However, after 2000 cycles the surface roughness has increased significantly, with the number and size of pores both increasing.

The sponge ball also contains several areas which for the lack of better definition appear as though some surface delamination occurs, further increasing the irregularity in the shape of the ball. The 16 mm sponge ball's shape underwent the most significant changes during the testing period, changing from a sphere to a prolate spheroid. The 15 mm sponge ball was the most spherical at the end of the testing procedure out of three ball sizes. Overall with regard to surface roughness, the 17 mm ball retains the smoothest surface out of the three balls, with the 16 mm ball the roughest of the sponge balls. That is, projectiles that start with more pores, transition and finish with more pores.

Therefore, the balls initial roughness is likely to be more closely linked to its quality of manufacture and/or differences in chemical composition (unknown). High speed camera visualisation experiments conducted by Abd-Elhadya et al, (2015) upon the surface texture of sponge projectiles has shown pores undergo repeated cycles of compression and expansion with the movement of the projectile through the tube. While these visualisation tests were for only short run passes, it is surmised that this evidence when extended to longer duration tests as reported here, is the principle mechanism for the loss of elasticity of the projectile with time.

Table 2. Observations of shape and surface roughness for 17 mm projectile versus number of cycles.

Cycle	Photograph	Shape	Surface Roughness
New		The shape of the sponge ball is spherical.	The sponge ball's surface contains several very small pores, however, in general the ball is smooth.
100		The ball's shape has remained spherical as at the beginning of testing.	Obvious increasing in the number of pores and their size. The surface roughness has increased
200		Slight decrease in the ball's spherical shape.	Further increase in the number of pores and their size.
400		Further decrease in the spherical shape of the ball from 200 cycles.	Noticeable increase in the roughness of the ball in all areas except for the centerline line.
800		Noticeable loss in the ball's spherical shape	The surface roughness of the ball has increased significantly from 400 cycles
1600		The spherical shape of the ball has further decreased	The surface roughness of the ball has increased further from 800 cycles.
2000		The shape of the ball has not significantly changed since 1600 cycles.	No noticeable increase in the surface roughness since 1600 cycles.

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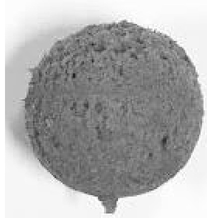
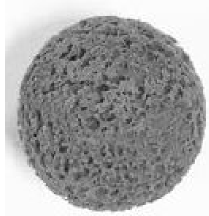
Table 3. Comparison of initial and final states of projectiles

Ball Size	Initial	Final
15 mm		
16 mm		
17 mm		

The change in the mean diameter of the 15, 16 and 17 mm sponge balls over the 2000 cycle testing period is shown in Figure 1. It was found that all three sponge balls experience expansion, with the 16 mm sponge ball experiencing the largest increase in its diameter while the 15 mm sponge ball experiences the least.

The 17mm sponge ball immediately expands 0.5 mm once submersed in water at the beginning of the testing operation. The diameter of the sponge ball increases steadily over the first 1000 cycles from 17.5 mm approximately 18.2 mm. A total increase of approximately 1.2 mm is observed from the beginning to the end of the test. The 16 mm ball expands approximately 0.1 mm initially, with a total increase of approximately 1.5 mm thereafter observed. The 15 mm ball initially expands 0.8 mm, the highest increase of the three balls evaluated. Thereafter, a total increase of approximately 0.4 mm was observed.

The contact area of all three sponge balls also increased during the tests, with the net contact area of the 17 mm sponge ball increasing the most and the 15 mm sponge ball increasing the least as shown in Figure 2. The degradation of the sponge balls during the testing period has indicated a positive relation with the contact area, which is attributable to the balls loss of elasticity. In terms of the contact area, as a property of the cleaning projectiles likely effectiveness, the 17 mm sponge ball delivers the highest contact area and therefore potentially the most effective in removing foulants.

At the end of the testing period, the 17 mm projectile final contact area was 475 mm^2, approximately 85 mm^2 larger than at the beginning of the test. It is concluded that the gradual increase in the diameter and contact area is a result of the steady loss in the elasticity of the ball, as the ball is unable to return to its original shape. It is effectively stretched out of shape. The change in the shear force of the 15, 16 and 17 mm sponge balls over the 2000 cycle testing period is shown in Figure 3.

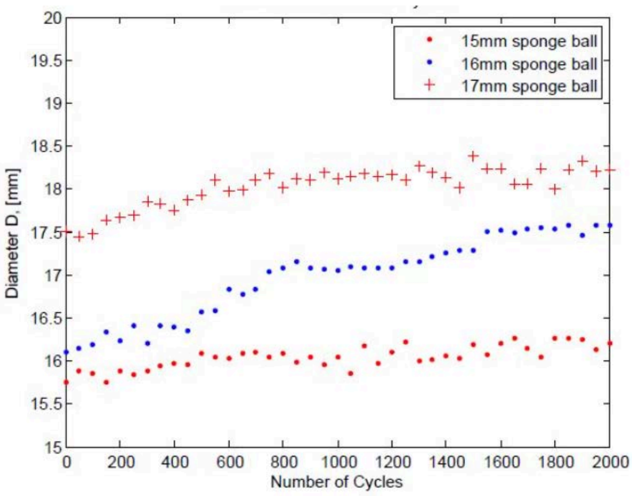


Fig. 1 Impact of the number of cycles passes through the tube on the diameter of the sponge balls

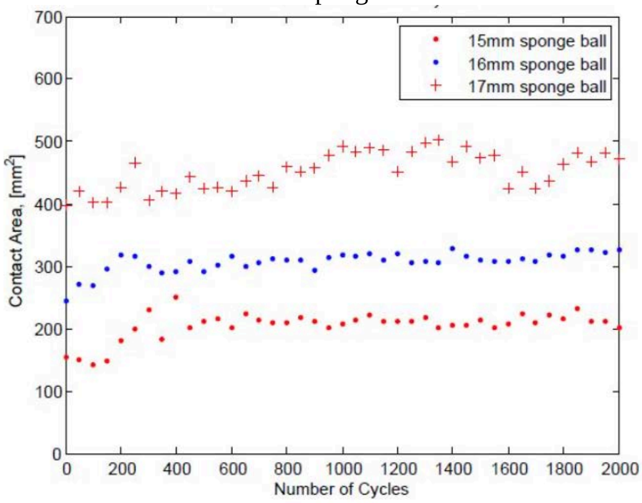


Fig. 2 Impact of the number of cycles passes through the tube on the contact area of the sponge balls.

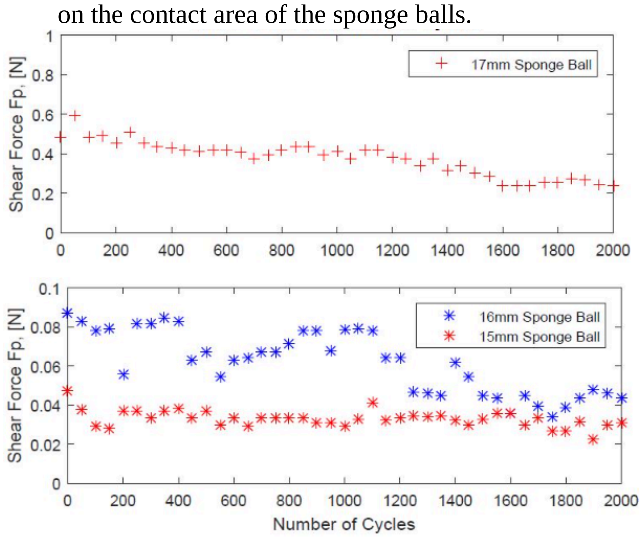


Fig. 3 Impact of the number of cycles passes through the tube on the shear force of the sponge balls.

It was observed that the shear force of both the 16 and 17 mm sponge balls drops in magnitude by approximately half, whereas the 15 mm sponge ball attains a much smaller drop. The degradation of the sponge balls during the testing period has indicated a negative relation with shear force, simply as the number of cycles increases the shear force decreases. As shear force is a desirable property for projectile cleaning of foulants, this decrease is unfavourable. Furthermore, the larger two projectiles exhibit the greatest reduction in shear force versus the smallest 15 mm projectile. Intuitively, as these projectiles deliver the highest shear forces against the inner tube wall (a desirable property), for every action there is an opposing reaction. Thus, because of repeated cycles of compression and expansion observed by Abd-Elhadya et al, (2015) more rapidly lose their elasticity. Consequently, deform and lose shape, exhibit in some instances delamination, increase in roughness and ultimately the projectile ages more rapidly.

Fouling factor

The fouling factor represents the theoretical resistance to heat flow due to the formation of undesired deposits on heat transfer surfaces (Bott, 1995). The formation of foulants in operational heat exchangers occurs in three distinct phases; induction, growth and the final asymptotic phase. To account for the various types of fouling and the resultant fouling factor, heat exchangers are designed with the consideration that fouling will occur. This design criterion is commonly known as oversizing, where additional surface area is added to heat exchanger tubes to lessen the negative effects of fouling. However, in most applications fouling will occur despite good design, effective operation and maintenance, and therefore heat exchangers must be effectively cleaned and sustained for their operation to run adequately.

In HVAC applications, fouling of the chiller condenser tubes has substantial impact on the power consumption of the compressor. Even with good water treatment programs, it's not uncommon to find chillers that appear to be in good working order operating at a fouling factor of 0.0025 hr-ft^2-F/Btu (0.014 m^{2}K/kW) or higher — causing compressor power consumption to increase by 25% or more (Piper 1999)

The results for the comparison of chiller operation with and without ATCS in operation is demonstrated in Figure 4 This figure presents the fouling factor (Rf) versus time at intervals of 5 minutes based on data collected by the ClimaCheck system. The oscillations in the data represent the variable refrigerant flow as the chiller responds to the daily thermal cooling cycle of the building with outside air temperatures and solar irradiance heat gains. It was initially conveyed this was fixed flow (as assumed in the calculations) but later confirmed by the plant manager as variable flow and was unable to be directly recorded by ClimaCheck. This represents a limitation on the present work. The average fouling factor on a daily basis was calculated and is displayed in Figure 5. The mean fouling factor (Rf) is displayed with and without ATCS turned on. Table 4 indicates that the fouling factor (Rf) at the beginning of the operational period is at its lowest value, as anticipated. It is important to note that this system was not commenced from a cleaned tube state. The chiller had been idle for four months commensurate with the winter low period of demand and had not been cleaned since the beginning of its last operation. The mean fouling factor (Rf) was found to increase when the ATCS is turned off and decreases when the ATCS turns on again. This result is anticipated, and shows that the impact the ATCS is having upon improving the heat exchanger's performance. The observed successive increase in the mean fouling factor at each respective switch over infers the system is in the growth phase and not the initial induction phase nor final asymptotic phase of fouling in accordance with fouling literature. This is the case when the surface temperature of the tube is greater than the minimum sintered temperature, foulant become partially sintered, and only a fraction of the total foulant can be removed.

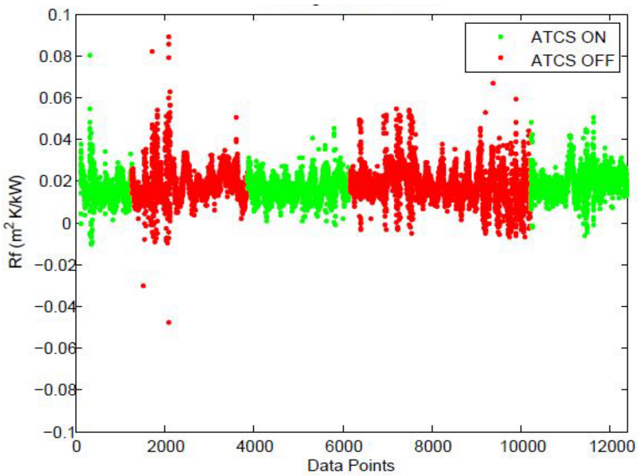


Fig.4 Fouling factor with and without ATCS in operation.

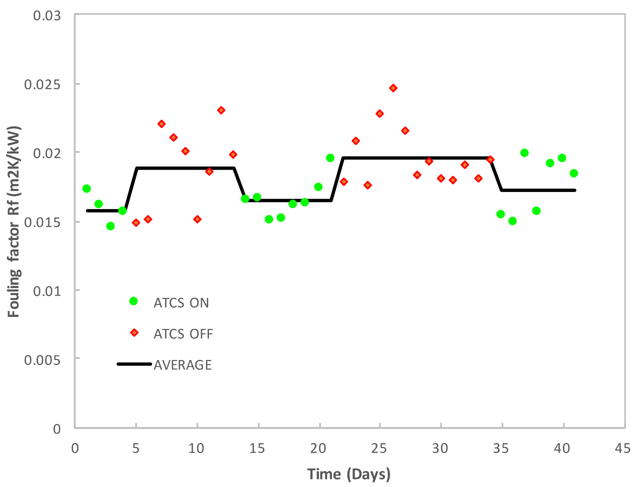


Fig.5 Average fouling factor with and without ATCS in operation.

Table 4. Mean Fouling factor (Rf)

Operation	Rf (m^2.K/kW)	% change
ATCS ON 1	0.0158	Reference
ATCS OFF	0.0188	+19.0 %
ATCS ON 2	0.0165	+4.4 %
ATCS OFF	0.0196	+24.1 %
ATCS ON 3	0.0172	+8.9 %

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As similarly presented in Ross et al. 2015, the calculation of energy related savings for a chiller with and without ATCS has adopted the International Performance Measurement & Verification Protocol (IPMVP) framework.

The dominant independent variable on cooling load is the outside weather. Weather has many dimensions, but for whole-facility analysis, the outside air temperature is sufficient. The standard practice of using a referenced base temperature cooling degree day (CDD) was once again used in the present study. Cooling degree days are based on the average daily temperature.

The average daily temperature is calculated as follows: [maximum daily temperature + minimum daily temperature]/2. A simple linear model was used to correlate daily chiller energy consumption without any adjustments, to a single independent variable, CDD. This is shown in Figure 6. The overall difference in energy consumption with and without ATCS in operation was 6%. This reduction in energy consumption is consistent with known literature when ATCS systems are in operation (ASHRAE 2000).

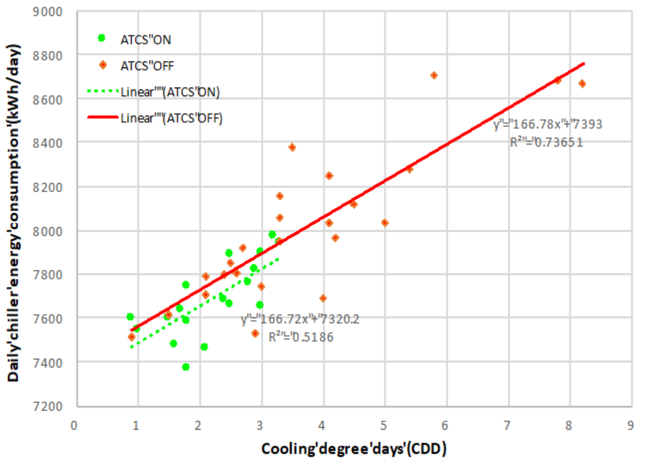

Fig 6. Daily chiller consumption versus CDD with ATCS on or off

Case studies

One common misunderstanding made by building owners and operators to the authenticity of the energy savings claims is that these savings simply reflect the improvements resulting from the initial tube cleaning conducted at the time of installation of the ATCS. Despite the extensive literature on the subject, the only acceptable proof is a side by side evaluation. The results presented here compare the operation of identical chillers to further eliminate any bias. That is, one chiller acts as the control, the other identical chiller is fitted with an ATCS.

In August of 2012, a sponge-ball type tube cleaning system was installed in one of two identical 300-ton chillers at The Plaza Hotel and Casino in Las Vegas, Nevada. The tube cleaning equipment was installed on Chiller 1, while Chiller 2 served as the control. These two chillers shared a common cooling tower circuit, thus eliminating potential differences of environmental variation on the chillers. The 3-month study on the impact of the tube cleaning system on chiller energy efficiency demonstrated the chiller with ATCS installed yielded energy efficiency gains of approximately 12%. The resulting comparison is shown in Figure 7 of the normalised power per ton of refrigeration (TR).

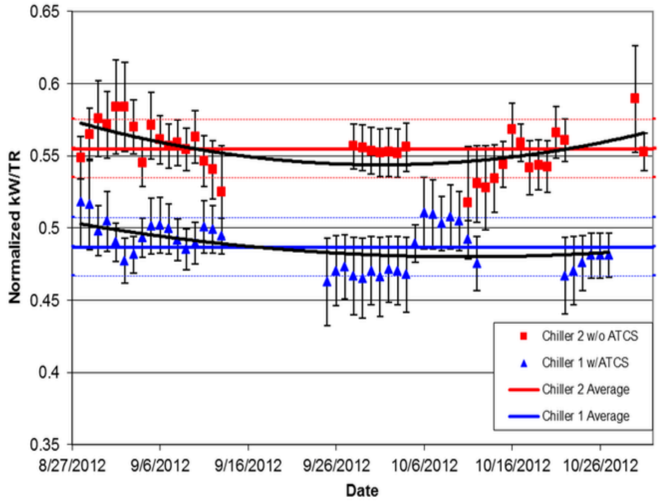

Fig. 7. Comparison of normalised chiller power

Data collection from the Plaza was continued beyond the initial performance review. This comparison in chiller efficiency is shown in Figure 8 below. After more than 3500 hours of operation, the chiller with the tube cleaning system continued to demonstrate significant energy efficiency improvement, and the average energy efficiency advantage rose to more than 13%.

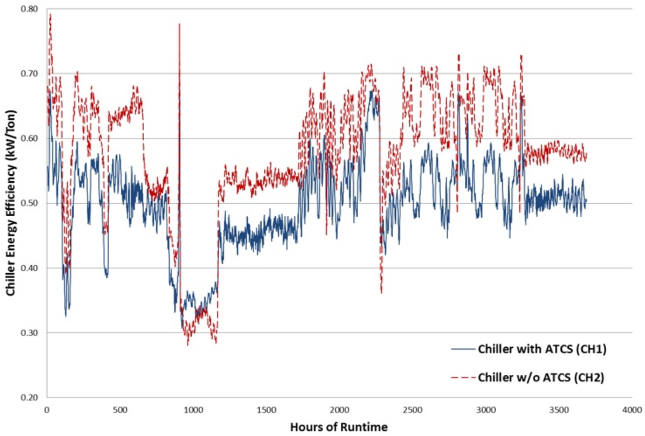

Fig 8. Analysis of side by side chillers with and without ATCS

At a separate facility, a sponge-ball type ATCS was installed to one of two identical 200-ton chillers at Winneshiek Medical Center in Decorah, Iowa. Both chillers were cleaned at the time of ATCS installation. A short term single point evaluation was performed after six weeks of operation to verify energy consumption in the chillers.

For the test, both chillers were operated at 100% capacity until the temperatures, pressures, and power consumption stabilised. The summarised results are presented in Table 5. The reduction in chiller power consumption was over 19% for the chiller fitted with an ATCS.

Table 5 Comparison of chiller performance after 6 weeks of operation

Parameter	With ATCS	No ATCS	change
Load	100%	100%	-
Average Amps	196.1	233.6	+37.5
Average Voltage	491.3	491.3	-
Tc,i (ºC)	32.7	33.3	-
Tc,o (ºC)	36.1	36.7	-
Condenser Approach (ºC)	1.3	1.6	+0.3
Chiller Power (kW)	150	178.7	+28.7
Normalised chiller efficiency (kW/Ton -TR)	0.75	0.89	+0.14

CONCLUSIONS

The physical and performance degradation of the sponge balls provides further understanding of the effectiveness of the Automatic Tube Cleaning System (ATCS) in removing fouling deposits. The ball degradation analysis has shown degrading effects during operation on the sponge ball's shape, surface roughness and diameter. It is not necessarily apparent how and which of these physical attributes necessarily impact the effects of degradation on the cleaning performance of the sponge balls over time.

The shear force is clearly the most important performance property encompassing both the ball's contact area and its shear stress. It was found to drop approximately by half for both the 17 and 16 mm sponge balls over the recommended 1000 cycle period. The drop is not as significant for the 15 mm ball, however this projectile delivers the least amount of shear force on fouling deposits. The understanding of the shear force degradation effects hopefully enables recommendations for the optimal use of the cleaning projectiles, thus further increasing the effectiveness and adoption of ATCS on chiller based system to improve energy efficiency.

The overall impact of projectile degradation upon the propensity of tube fouling and thus to the overall heat transfer in the chiller condenser is currently subject to further evaluation. The key question to be evaluated now, does a potential 50% reduction in the shear force of the projectile after 2000 cycles impact upon the performance improvement of the ATCS? Does it even matter, as fouling would be in the final asymptotic stage. If it does, what then is the optimal replacement frequency for the projectiles?

Comparisons of real world commercial applications of ATCS on chiller performance via on/off trails and side by side comparisons with and without ATCS fitted to identical chillers clearly demonstrate the effectiveness of tube cleaning. The reduction in tube fouling leads to improvements of chiller operating efficiency and lower fouling factors. ATCS installed on one of two identical 200-ton and 300-ton chillers operating in parallel yielded energy savings in the range of 13% to 19%.

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NOMENCLATURE

Tc,i	Inlet Temperature of Condenser Water, °C
Tc,o	Outlet Temperate of Condenser Water, °C
m_c	Mass Flow Rate of Condenser Water, kg/s
Cp	kJ/kg.K specific heat capacity of the condenser water.
U	Overall heat transfer coefficient, W/m^2 K
Rf	Fouling resistance of the fouling layer, m^2.K/kW

Subscript

i	inlet
o	outlet
f	fouled
ref	reference

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