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Performance Evaluation of Oil-free Chillers for Building Energy Performance Improvement

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Abstract

This paper investigates how to improve the energy performance of central air-conditioning systems by using oil-free chillers. Three conventional water-cooled centrifugal chillers of equal capacity were replaced by three oil-free chillers of the same capacity in an existing system. Operating data for performance evaluation were logged at 1-hr intervals for over one year before and after the replacement. The superior coefficient of performance (COP) of oil-free chillers with variable speed control brought an energy saving of 9.6% in the total electricity consumption of a shopping arcade when they operated for a wide range of system cooling demands. Results of data envelopment analysis gave an average technical efficiency of 0.6 which ascertains an opportunity for performance enhancement. The system COP can be further improved by tightening the control in the temperature of supply chilled water and implementing even load sharing among chillers to meet the overall system capacity.

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Keywords: Coefficient of performance; Data envelopment analysis; Oil-free chillers

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1. Introduction

Chillers are commonly used in central air-conditioning systems to produce cooling energy in the form of chilled water and their operation consumes the major proportion of electricity used in commercial buildings [1]. Variable speed control is increasingly applied to system components to enhance energy savings [2], considering that the building cooling demand varies with weather conditions and that the maximum demand occurs only in a very short period of time. Al-Bassam and Alasseri [3] identified energy savings of 5.8% when dual speed control was replaced by variable speed drives for evaporative cooling tower fans in a chiller system operating for summer seasons in Kuwait. Hartman [4] proposed an equal marginal performance principle to optimize the energy performance of chiller systems with variable speed control for chillers, condenser water pumps and cooling tower fans. Bahnfleth and Peyer [5] analyzed how variable speed control for chilled water pumps helped save pumping energy while maintaining proper temperature difference across the supply and return headers of a chilled water circuit.

Most current chiller systems are seldom designed with a full set of variable speed chillers because of their high initial cost—almost double of that of conventional chillers without variable speed drives. A few studies showed the potential benefits of using variable speed chillers. Aprea et al. [6] performed an experiment on varying the rotating speed of a scroll compressor in a small-scale chiller. A fuzzy logic algorithm was developed to regulate the speed for capacity modulation. This gave a significant energy saving of about 20% in relation to cycling on and off a conventional scroll chiller with the classical thermostatic control. In experimental tests on a scroll chiller by Cecchinato [7], varying the rotating speed of the compressors was preferable to the step capacity regulation by cycling the compressors in order to improve the part load efficiency of chillers. Romero et al. [8] developed a black-box model to control the speed of a chiller compressor based the dynamic response of chilled water temperatures. A steady state physical model was developed by Navarro-Esbrí et al. [9] to investigate the energy performance of a variable speed chiller under different operating conditions and, in turn, to optimize controlled variables for maximum performance. All the above studies focused on a small-scale chiller running alone in a system. Regarding multiple variable speed chillers in large scale systems for commercial buildings, Yu and Chan [1] identified load-based speed control in which the chiller rotating speed was adjusted by a function of capacity output for system optimization. Their simulation analysis showed that such control for a chiller system with all variable speed components decreased the annual total electricity use by 19.7% and annual water use by 15.9% relative to the corresponding system with constant speed control and step capacity regulation. If the load-based speed control was applied only to the condenser water pumps and cooling tower fans, a 5.3% decrease in the annual electricity use was estimated.

No previous study has illustrated the actual operating performance of oil-free chillers with variable speed control. Oil-free magnetic bearings are used in the chiller compressors to give friction-free rotation which brings improved compressor efficiency at speed regulation. Heat transfer effectiveness at the evaporators can be maximized as no lubricating oil is brought in the refrigerant. This paper examines the energy improvement of using oil-free chillers in a system retrofit. Technical, scale and overall efficiencies in data envelopment analysis were examined for each set of operating conditions. The significance of this study is to show the actual operating characteristics of oil-free chillers and how the data envelopment analysis can help identify optimal settings for controlled variables to achieve the highest performance.

2. Description of the chiller system and data envelopment analysis

The existing chiller system operates for a shopping arcade and consists of three identical water-cooled chillers running in pairs with evaporative cooling towers, as shown in Fig. 1. Before the replacement, chillers housed conventional centrifugal compressors at which inlet guide vanes were used to modulate capacity. Each of the chillers used the refrigerant R134a and had a nominal capacity of 1760 kW (500 tons of refrigeration) and a coefficient of performance (COP) of 5.2 at full capacity with a condenser water supply temperature of 29.4ºC. The COP is defined as the cooling capacity output in kW divided by the electric power input in kW. The integrated part load value (IPLV) of the chillers was 8.7. The IPLV represents a weighted average of COP at 25%, 50%, 75% and 100% of full capacity with weightings of 0.12, 0.45, 0.42 and 0.01, respectively [10]. In June of 2012, each of the chillers was replaced by a chiller of the same capacity but using a centrifugal compressor with oil-free magnetic bearings. Using oil-free magnetic bearings helps maximize heat transfer effectiveness at the evaporator as the refrigerant can be free from lubricating oil. The magnetic bearings provide a friction-free rotating shaft which facilitates an ultra-high rotating speed with improved compressor efficiency. The infinite speed modulation by a variable speed drive helps minimize the surge region at the low chiller load, enabling the chillers to operate down to 5% of full capacity. All these features result in a full load COP of 6.4 and a very high IPLV of 10.7.

The temperature of supply chilled water was controlled at 7°C at all capacities before the replacement. It was reset manually at above 7°C when the cooling capacity dropped from the full capacity after the replacement. The cooling towers operated in pairs with the chillers to maintain the temperature of water entering the condensers at around 30°C. Variable speed drives were installed with the chilled water and condenser water pumps to provide adjustable flow rates for the oil-free chillers.

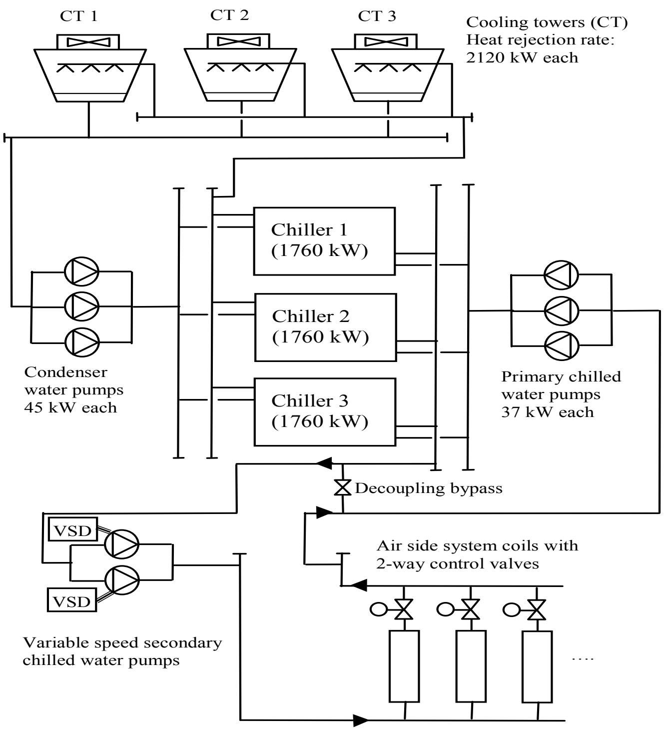

Fig. 1. Schematic diagram of the chiller system.

Regarding chiller sequencing control before replacement, all the operating chillers were fully loaded before operating one more chiller for the increasing system load. This is shown by the solid line in a plot of the percentage of full cooling capacity against the overall system capacity in Fig. 2. After the replacement, more oil-free chillers operated frequently at lower capacities with higher COPs to meet the increasing system loads. As data points in Fig. 2 illustrate, one, two or three oil-free chillers were operating when the system cooling capacity was below 1760 kW—the full capacity of one chiller.

Operating data monitored for each chiller included the temperatures of supply and return chilled water (T_{chws} and T_{chwr}) in °C, the electric power input (E_{cc}) in kW to the compressor and the mass flow rate (m_w) in kg/s of chilled water passing through the operating chiller. The cooling capacity (Q_c) in kW was calculated by $Q_c = m_w C_{pw}(T_{chwr} - T_{chws})$, where C_{pw} is the specific heat capacity of water and taken to be 4.19 kJ/kg°C. The COP was evaluated by Q_c divided by E_{cc}. All the variables were measured and logged at 1-hr intervals for over one year before and after the replacement. The measurement error of each variable and its actual range of measurement are shown in Table 1.

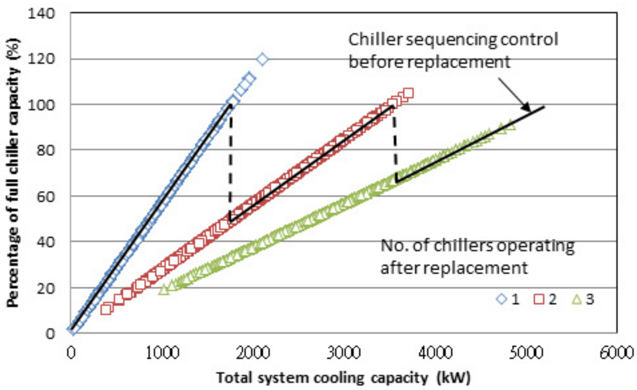

Fig. 2. Chiller sequencing control before and after replacements.

Table 1. Range and measurement errors of variables.

Variable	Measurement device	Measurement error	Range of measurement
Tchws	Resistance type sensor	±0.1oC	6.8 – 13.8ºC
Tchwr	Resistance type sensor	±0.1oC	8.4 – 16.6ºC
Ecc	Power analyser	±0.1 kW	9.8 – 474 kW
mw	Ultrasonic flow meter	±0.5% of measured value	78.0 – 98.3 kg/s

The measurement uncertainty of an output Y in response to the individual measurement error of inputs x_i can be calculated by Eq. (1) [11]. The relative uncertainty of the calculated COP was evaluated by Eq. (2) based on individual measurement errors of m_w, T_{chwr}, T_{chws} and E_{cc}. Given the range of each input and its measurement error in Table 1, the overall percentage error of COP calculated from Eq. (2) ranges from 1.07% to 2.21% which complies with an acceptable measurement uncertainty of below 5%.

$$\delta Y_{(\mathrm{rms})} = \sqrt{\sum_{i=1}^{n}\left[\delta x_i\left(\frac{\partial Y}{\partial x_i}\right)\right]^2} \qquad (1)$$

$$\frac{\Delta \mathrm{COP}}{\mathrm{COP}} = \sqrt{\left(\frac{\Delta m_w}{m_w}\right)^2 + \left(\frac{\Delta T_{chwr}}{T_{chwr}}\right)^2 + \left(\frac{\Delta T_{chws}}{T_{chws}}\right)^2 + \left(\frac{\Delta E_{cc}}{E_{cc}}\right)^2} \qquad (2)$$

Data envelopment analysis (DEA) is commonly considered in benchmarking business operations with outputs and inputs. It draws on a linear programming technique to evaluate relative efficiencies of an observation having a set of outputs and inputs [12,13]. Details of formulating a linear programming problem and the way to determine its coefficients are given in [14]. There are three measures of efficiency to compare outputs of observations having different inputs. Fig. 3 shows how to identify the efficiencies. Each of the 7 observations (P_1 to P_7) has one output and one input. The DEA searches for observations forming a piecewise envelope (or frontier) enclosing all the observations. The frontier is indicated by line segments joining P_1, P_2, P_3 and P_4. Any points on the frontier have a technical efficiency of one. Among four observations at the frontier, P_2 has the highest output-to-input ratio. Any point on the line joining the origin and P_2 (i.e. line ON) has an overall efficiency of one.

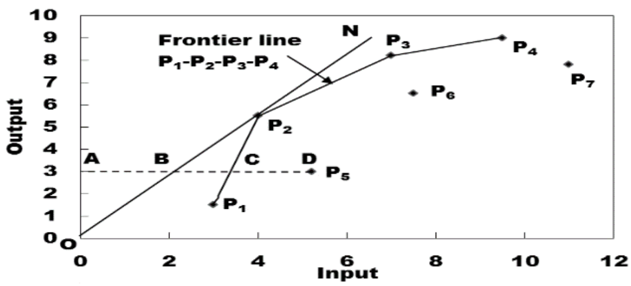

Fig. 3. Plot for explaining three measures of efficiency in DEA.

Considering the non-frontier observation at P_5, its overall efficiency is defined by the ratio of line segments AB to AD (i.e. AB/AD), technical efficiency by AC/AD and scale efficiency by AB/AC. The overall efficiency is given by technical efficiency multiplied by scale efficiency. All the efficiencies lie between 0 and 1. According to the definition of three measures of efficiency, an observation closer to the frontier has higher technical efficiency. Technical efficiency reflects the extent to which the output can increase to its highest value for a given set of inputs. Scale efficiency, on the other hand, indicates the extent of getting the highest achievable output when its inputs are adjusted to their optimal values.

In this analysis, the output was the system COP—total capacity output of operating chillers divided by their total electric power input. The inputs were the controlled variables of each operating chiller—the temperature of supply chilled water and the percentage of full capacity. An observation consisted of a set of hourly operating conditions logged at 1-hr intervals and there were 9380 observations for the oil-free chillers operating for more than one year. Coelli's DEA computer program [15] was used to compute the scale, technical and overall efficiencies for each observation. A data file listing the output followed by six inputs (two for each chiller) was compiled in rows for all the observations. Along with efficiencies calculated for each observation as the output results, the program computed the highest achievable system COP and the optimal inputs corresponding to the highest technical efficiency. The optimal inputs served to decide how the controlled variables should be set for the maximum system COP. Scale efficiency was used to investigate if the random weather-related variables placed limitations to achieve the highest system COP.

3. Results and discussion

3.1. Comparison of operating performance of oil-free chillers with conventional chillers

Fig. 4 shows how the COP varied with the percentage full capacity of the oil-free chillers and the conventional chillers. Both types of chiller gave a similar COP when running near the full capacity. Based on the solid trend line for the operating data of the oil-free chillers, the COP increased with a lower capacity extending to about 5% of full capacity. This agrees with their higher IPLV and superior part load COP under variable speed control. The COP of the oil-free chillers appeared to vary widely at lower capacities, suggesting its interaction with other random variables like the dry bulb and wet bulb temperatures of outdoor air. The COP of the conventional chiller dropped from the full load COP at lower capacities as reflected from the dotted trend line.

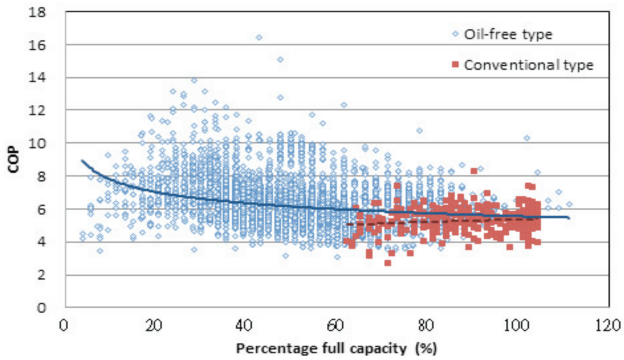

Fig. 4. COP against percentage full capacity for the oil-free and conventional chillers.

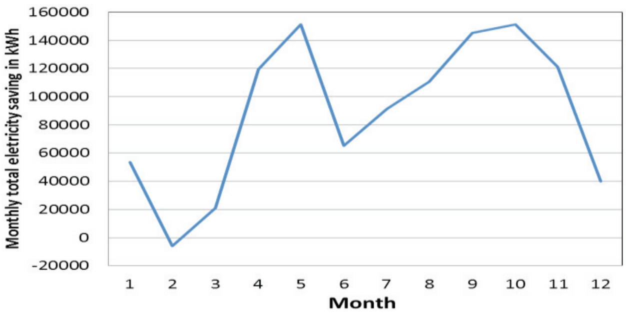

Fig. 5. Monthly total electricity consumption saving by using oil-free chillers.

The annual electricity saving by using oil-free chillers was estimated by comparing the monthly total electricity use in kWh before the replacement in Jun 2011 – May 2012 with that after the replacement in Jun 2012 – May 2013. An assumption for the comparison was that there was no significant difference on the electricity use by non-air-conditioning installations over the two periods. The annual total electricity reduction by using oil-free chillers was 1063930 kWh. This accounts for 9.6% of the annual total electricity consumption of the shopping arcade before the replacement. Figure 5 illustrates different degrees of monthly total electricity savings under the seasonal variation of system cooling demands. The highest electricity saving occurred in May and October during which all the oil-free chillers operated frequently at low partial loads with higher system COPs. The system cooling demand in June varied around the full capacity of two chillers, so the energy saving benefit of the oil-free chillers was tempered as the two conventional chillers operated with a high COP at near full load. In February, the total electricity consumption increased by 5974 kWh unexpectedly. This is due to the higher total cooling demand in 2012 compared with 2011, which resulted from the extra 29th day and the higher total cooling degree days in 2012. Both the conventional and oil-free chillers operated with a similar COP in the high load regions.

3.2. Findings of efficiencies with data envelopment analysis (DEA)

Using the DEA program by Coelli [15], technical, scale and overall efficiencies were computed for each set of operating conditions with three oil-free chillers running. Fig. 6 shows the relative frequency distribution of the three efficiencies. Over half of the technical efficiency data lie in a range of 0.5 – 0.6 and the mean of technical efficiency is 0.60. Regarding scale efficiency, the mean is 0.96 and 92.2% of the data fall between 0.9 – 1. Following this, the variation of overall efficiency is dominated by technical efficiency.

Fig. 7 illustrates the correlation of the system COP with technical and scale efficiencies. All the scale efficiency data are one when the system COP is above 10. The variation of scale efficiency has less impact on the change of system COP because most of the data are above 0.9. There is a positive correlation between the system COP and technical efficiency. The lower technical efficiency suggests an opportunity to improve the control of chilled water supply temperature and the load sharing among the operating chillers in order to enhance the system COP. Technical efficiency serves to identify the boundaries for the improved COP. At a technical efficiency of, say, 0.6, the system COP varies from 5.2 to 7.2. A higher technical efficiency will shift the boundaries of the system COP rightward. Technical efficiency helps determine the highest achievable COP under different operating conditions.

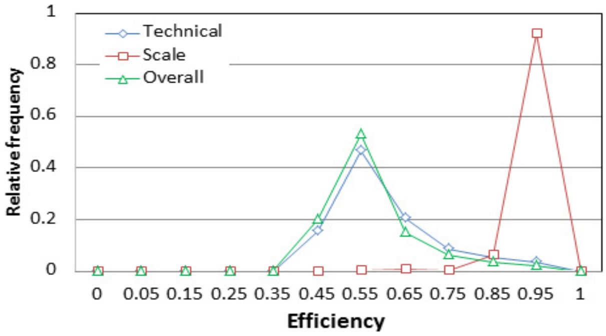

Fig. 6. Frequency distribution of technical, scale and overall efficiencies.

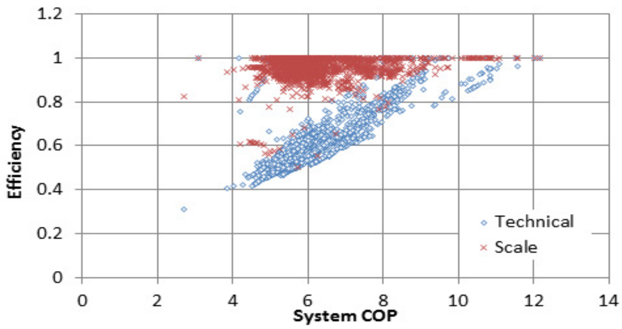

Fig. 7. Correlation of the system COP with technical and scale efficiencies.

Given most technical efficiency data of below 1, the potential increase of the existing system COP with optimal inputs is shown in Fig. 8. Based on an average technical efficiency of 0.60 and the positive correlation between the technical efficiency and system COP, the average existing system COP could be increased by 40% with a technical efficiency of one. If the existing system COP is below 6, the highest system COP will be even double of the existing value. Fig. 9 shows how the temperature of supply chilled water should vary with the percentage of full capacity to achieve the highest system COP. The existing reset caused a wider variation in the temperature of supply chilled water at different capacities. More precise control with a narrow dead band is required so that the temperature of supply chilled water hovers closely the existing lower boundary. The modulation of chilled water flow rate should complement this temperature reset control in order to meet the cooling demand.

The percentage load shared among the running chillers was slightly different when the chilled water flow rate was modulated by operating different numbers of chilled water pumps. Fig. 10 illustrates how the percentage of full capacity varied with the percentage of system capacity under the existing case and the optimal case for the highest COP. In the existing case, the oil-free chiller 1 tended to carry more system load with more diverse capacity outputs. The oil-free chillers 2 and 3 carried almost the same system load with the same percentage of full capacity. To achieve the highest COP, the diverse capacity outputs by chiller 1 should be limited to allow all the chillers to operate with the same capacity. Given that their energy performance is equally superior at low capacity, an equal load sharing strategy should be implemented to allow each chiller to operate with the lowest capacity. This calls for robust control for the temperature and flow rate of chilled water supplied in order to optimize the trade-off between the chiller power and pump power.

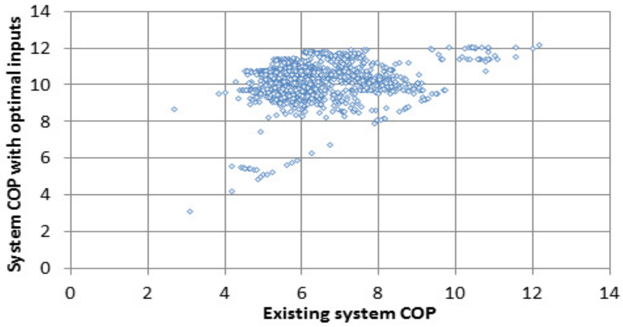

Fig. 8. System COP with optimal inputs against existing system COP.

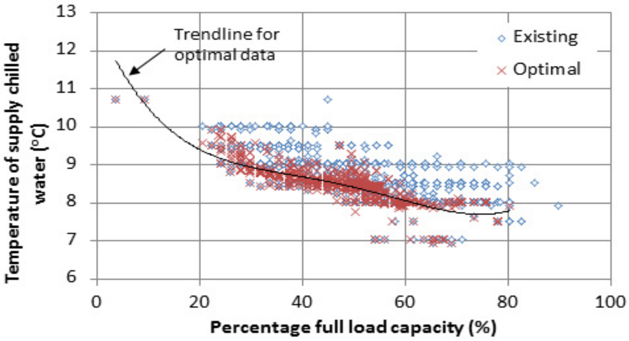

Fig. 9. Variation of the temperature of supply chilled water at different percentages of full load capacity.

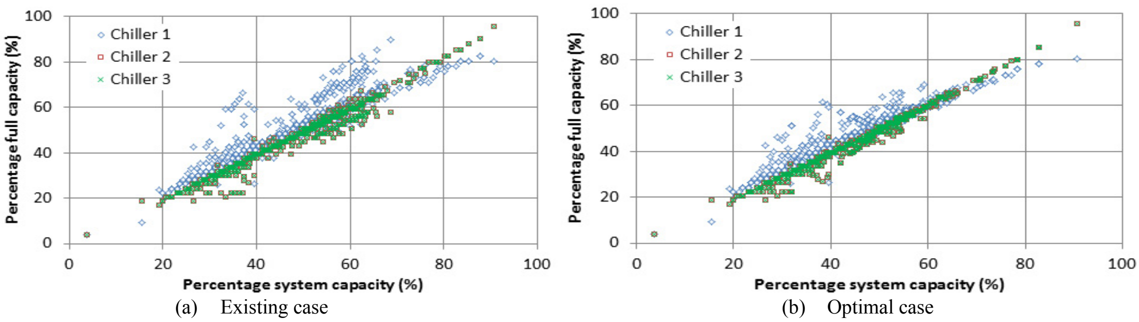

Fig. 10. Percentage full capacity of running chillers against the percentage system capacity.

4. Conclusions

This study investigates how oil-free chillers bring energy savings in central air-conditioning systems and ascertains further improvement of their energy performance with data envelopment analysis. Three conventional centrifugal chillers in an existing system were replaced by three oil-free centrifugal chillers of the same capacity. Operating data for performance evaluation were monitored at 1-hr intervals for over one year before and after the replacement. The uncertainty of the calculated COP was verified to be less than 3% based on the individual measurement errors of operating variables.

The oil-free chillers under variable speed control had a superior COP at low capacity. This brought an energy saving of 9.6% in the total electricity consumption of a shopping arcade when operating for a wide range of system cooling demands. Technical, scale and overall efficiencies in data envelopment analysis were examined for each set of operating conditions by the oil-free chillers. Technical efficiency had a mean of 0.6 and was identified to have a positive correlation with the COP. To achieve the highest possible COP—the output, the temperature of supply chilled water—the input—should be controlled with a narrower dead band so that it can hover closely the lower boundary of its reset under varying capacities. An even load sharing strategy should be implemented among the operating chillers, taking into account their dynamic interaction between the temperature and flow rate of chilled water supplied to meet a given system cooling demand.

The significance of this study is to illustrate the actual operating characteristics of oil-free chillers and the extent of COP improvement with data envelopment analysis. If the data acquisition facility is extended, it is possible to analyze the correlation between the COP and other operating variables like the refrigerant saturated temperatures and temperatures of condenser water, etc. A comprehensive multivariate regression formula can then be developed to mimic the scattering of COP data with a set of independent variables. Likewise, the data acquisition should cover the electricity consumption of other system components like pumps and cooling tower fans in each set of operating conditions in order to develop a holistic control strategy for optimizing the whole system.

Acknowledgements

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