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A Novel Control Strategy for Air-Cooled Twin-Circuit Screw Chillers

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Abstract

Air-cooled chillers are generally the major electricity consumers in air-conditioned buildings in the subtropical climate. To improve the energy efficiency of the air-cooled chillers at part load conditions, two or more refrigeration circuits are designed. This paper considers how the use of optimal circuit loading sequence (CLS) enables these chillers to operate more efficiently. A thermodynamic model for the air-cooled chillers with twin refrigeration circuits was developed using TRNSYS and validated using a wide range of operating data. Based on the sophisticated chiller model, an analysis was carried out on how the chiller COP varied with different CLS and variable condensing temperature control (CTC). A chiller plant designed for a representative office building in Hong Kong was investigated to assess the potential electricity savings by use of CLS. 4.2% of the annual electricity consumption by chillers could be achieved with optimal CLS compared with the base case. Under CTC, the coefficient of performance (COP) was improved further, and CTC coupling with optimal CLS would reduce the annual total electricity consumption for cooling by 9.6%.

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Keywords: Air-Cooled Chiller; Twin Refrigeration Circuits; Circuit Loading Sequence; Condensing Temperature Control

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1. Introduction

Air-cooled chiller systems are commonly used in commercial buildings due to their flexibility, especially for the cities that have water shortage problem [1]. Comparing to water-cooled chillers, air-cooled chillers are regarded as

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Energy inefficient. The chiller efficiency decreases significantly under part load conditions. To improve the chiller performance, many water chillers are designed with multiple refrigeration circuits connected by parallel, and each refrigeration circuit has one or more compressors. This design of multiple refrigerant circuits is to enhance the reliability and standby capacity, decrease in-rush current at system start-up. Such design also can reduce the power consumption at part load condition, and it gives an opportunity to improve the overall chiller performance. As one of the circuits or both circuits in a chiller may be operated at any given conditions, the chiller performance will be different under different operating schemes. This means that proper control strategy is critical, which is used to share the cooling load between the refrigeration circuits and sequence the compressors in each circuit. For this reason, it is desirable to identify operating strategies on proper refrigeration circuit loading sequence (CLS) that improve the efficiency of the chiller with multiple refrigeration circuits.

Yet there is limited research work relate to CLS strategies for chillers with multiple refrigeration circuits. The benefits of using two separate refrigeration cycles to meet demands was investigated for both the freezer and fresh food compartments in domestic refrigerators [2]. The load sharing strategies in a refrigeration system with two screw compressors were discussed [3]. Based on empirically models, a comparison was presented for a single-circuited centrifugal and a twin-circuited twin-screw chiller [4]. An air-cooled screw chiller model with four refrigeration circuits was developed to analyse the chiller performance, in which the tubes in the evaporator were treated as one-pass arrangement [5]. The performance of air-cooled twin-circuit screw chiller was investigated, based on the assumption that the two circuits shared the same cooling output [6]. However, there is a lack of developed strategy for realizing optimal CLS control and variable condensing temperature control (CTC), which is involved in the potential energy saving when the chillers operate in various outdoor temperatures and load conditions. The deficient performance of air-cooled chillers is mainly due to the traditional head pressure control (HPC) under which the condensing temperature floats around a high set point of 50˚C based on a design outdoor temperature of 35˚C, irrespective of different chiller loads and weather conditions [5]. CTC enables the condensing temperature to approach its lower boundary and minimize the sum of compressor power and condenser fan power for all operating conditions, hence improving the chiller COP [7].

The objective of this paper is to develop a novel method to improve chiller efficiency by optimizing the CLS in various operating conditions. First, a thermodynamic chiller model for an air-cooled twin-circuit chiller, with two screw compressors per circuit, is developed. With the sophisticated chiller model, the chiller performance is investigated with different control strategies of CLS and CTC. In what follows, the potential electricity savings resulting from the novel control strategy are assessed with regard to a chiller plant serving a representative office building. The results of this paper are useful in developing more efficiently chiller plants serving air-conditioned buildings.

2. Chiller model

2.1. Description of the chiller

In this study, a chiller plant installed in an institutional complex was investigated, which comprised of five identical screw chillers connected in parallel. Each chiller had two refrigeration circuits, namely circuit 1 and circuit 2, and each refrigeration circuit was equipped with two compressors, as shown in Fig.1. The nominal cooling capacity of the studied chiller was 1116 kW, and the rated power of the studied chiller was 398 kW. The air-cooled condensers contained 16 identical condenser fans to deliver a total airflow rate of 85.5 m^3/s by eight groups, and each refrigeration circuit had four fan groups. The fan speed was 15.8 r/s, and each fan consumed a power of 2.4 kW.

To investigate the performance of the air-cooled chiller, the operating data of the chiller plant were monitored year-round by a building management system, which were used to develop and verify the chiller model. Due to the accuracy of measured variables, the uncertainty associated with COP was determined by the single sample analysis [8], using the following equation:

$$\delta COP_{(rms)} = \sqrt{\sum_{i=1}^{n} \left[\delta x_i \cdot (\partial COP / \partial x_i) \right]^2} \tag{1}$$

In Eq. (1), x_i is the i_{th} independent variable, δx_i is the uncertainty of the variable x_i, and n is the number of measurements related to COP. The root sum square error of chiller COP ($\delta COP_{\text{(rms)}}$) due to all the uncertainties of the individual variables was evaluated to be 0.09 in a COP value of 2.8 at the design condition, and the uncertainty of COP was 3.2%.

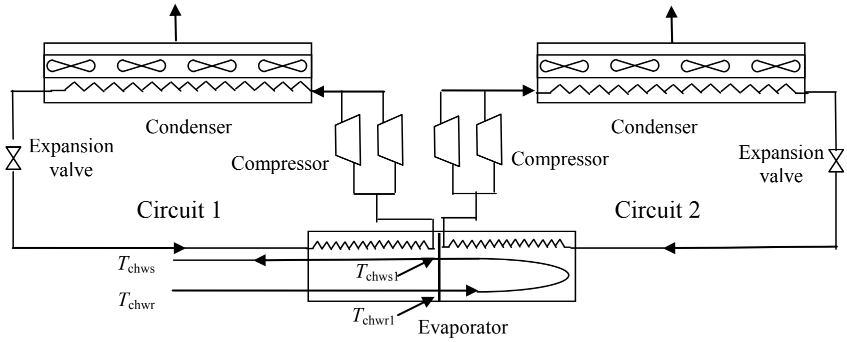


Fig. 1. Schematic of the air-cooled chiller.

2.2. Development of chiller model

The chiller model was developed using the simulation program TRNSYS based on mass and energy conservation laws. Classical heat exchanger efficiency method was used to model the evaporator and condenser. The whole model consisted of a set of equations. The general equations for energy balance and the assumptions made in the chiller model have been reported [5, 9]. The procedure to determine the operating variables of the chiller model referred to the flow chart reported [9]. The programme started with the model initialization using the input data. As the cooling load of the chiller could be shared within the refrigeration circuits randomly, the strategy for the CLS should be specified first. Then, the evaporating temperature and pressure of circuits 1 and 2 (T_{ev1}, T_{ev2}, P_{ev1} and P_{ev2}) and the cooling loads of the three sections of the heat exchangers (Q_{11}, Q_{12} and Q_2) were calculated through an iterative procedure by assuming an initial value of Q_{11}. Once the model had determined the evaporating temperature and pressure of circuits 1 and 2, the model evaluated the state variables of each refrigeration circuit. As the condensing temperature interacted between the compressor and condenser components, an iterative procedure was implemented to solve the operating variables of the two components simultaneously. To control the condensing temperature, there was another iterative loop for determining the number of staged condensing fans. The number of staged condenser fans and the corresponding airflow were computed according to the set point of condensing temperature.

The iterative procedures to estimate the heat rejection, the operating variables and the cooling load in both refrigerant circuits of the chiller were similar. The convergence criterion for computing condensing temperature and evaporating temperature in this model was 0.01 °C. When a converged solution was obtained, all the variables of the model would be computed with the required accuracy.

2.3. Validation of the chiller model

To verify the effectiveness of the developed modeling technique, the performance of the model was evaluated by comparing the modelled results with the operating data of the chiller. The measured data collected for validating the chiller model came from the chiller operating data under HPC, which covered a wide range of operating conditions (T_{db}: 18–35°C; PLR: 0.2–1.0). Fig. 2 shows that the modelled results of the chiller's COP agreed well with the corresponding COP calculated base on the measured data. Allowing for the experimental uncertainty of COP, being 3.2%, and the dead band for determining switching on one more or less condenser fan, which could result in COP depart from the measured ones, the deviations were within the allowable tolerance. With this good agreement, the simulation results, therefore, were considered to be satisfactory.

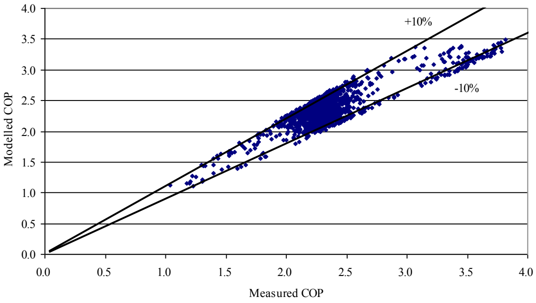


Fig. 2. Comparison between the modeled and measured chiller COP.

3. Cooling loads of the office building

In order to assess the energy efficiency by optimal CLS for air-cooled chillers with multiple refrigeration circuits in air-conditioned buildings, the cooling energy saving potential for a representative office building in Hong Kong was investigated when different control strategies of CLS were implemented to the air-cooled chiller plant. According to a survey of 64 commercial buildings in Hong Kong [10], the construction characteristics of high-rise office buildings were identified and a reference building was developed as the basis for simulation, which was a squared office building (36 m by 36 m) with 40 storeys. Hourly cooling loads for the representative office building were calculated using EnergyPlus and a typical weather year which represented the prevailing weather conditions in Hong Kong.

To meet the peak cooling load of 7338 kW of the representative office building, the chiller plant was designed with seven air-cooled screw chillers, each of which had a nominal cooling capacity of 1116 kW. The size of these chillers was comparable to that of the investigated chiller. The use of equally-sized chillers within a multiple chiller system facilitated implementation of a control strategy and provided more flexible operation and maintenance. The traditional chiller sequencing of a multiple-chiller system was considered in this study, which was to operate the minimum number of evenly loaded chillers to meet the required cooling load.

4. Results and discussion

4.1. Circuit loading sequence

For the chillers with multiple refrigeration circuits, there existed various modes of chiller circuit staging which yielded fluctuating efficiency under certain cooling load conditions. Chiller circuit sequencing was crucial to the improvement of chiller efficiency. As the studied chiller had two identical refrigeration circuits, the cooling load of the chiller could be shared by the two refrigeration circuits randomly, and there existed optimal load distribution between the two refrigeration circuits rather than split the load equally.

In this study, this simulation analysis considered the operating schemes of circuit loading sequence and variable condensing temperature control. Five operating schemes (CS1 to CS5) were investigated. Scheme CS1 was the operating scheme that loading with priority was given to the lead circuit when chiller load was less than half of the rated chiller capacity, and kept the capacity of circuits 1 and 2 be equal when the total chiller load was more than half of the rated chiller capacity, which was the traditional circuit sequence control and served as the baseline. The circuit authorized to start first was the lead circuit. Scheme CS2 was balanced circuit loading that the control system kept the capacity of circuits 1 and 2 be equal at any time when the chiller operated. Scheme CS3 was loading with priority given to the lead circuit until the lead circuit was fully loaded, and then the other circuit met the balance of the load when the total chiller load was more than half of the rated chiller capacity. Scheme CS4 was an optimal CLS, in which chiller load were optimally shared by two refrigeration circuits.

Operating schemes CS1 to CS4 were under HPC. As CTC could further improve the chiller performance, therefore, the chiller performance for the twin-circuit chiller under CTC was investigated. Scheme CS5 is the operating scheme CS1 under CTC. For all the operating schemes, the two compressors in one refrigeration circuit operated with even load when the cooling load of the circuit was more than 25% of the rated chiller capacity, or one compressor operated in this refrigeration circuit, which was the common control scheme.

4.2. COP improvements due to circuit loading sequence

As the use of different CLS brought about changes in the steady-state behavior of chiller COP, it was worth analyzing how this control strategy helped improve the chiller COP under various operating conditions. Fig. 3 shows COP curves of the studied chiller under various part load ratio (PLR) for scheme CS1, and the outdoor dry bulb temperature (DBT) was from 15 to 35 °C at an interval of 5 °C. The chiller COP varied following the operating sequence of the two refrigerant circuits and the sequence of compressors in one refrigeration circuit of the chiller. This clearly revealed that the chiller COP dropped substantially when an additional compressor or refrigerant circuit was staged to cope with a rising load, because compressor efficiency dramatically decreased at low part load conditions under HPC.

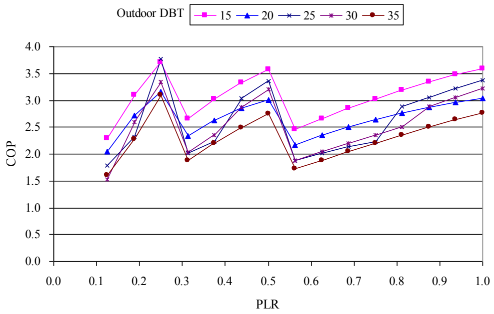
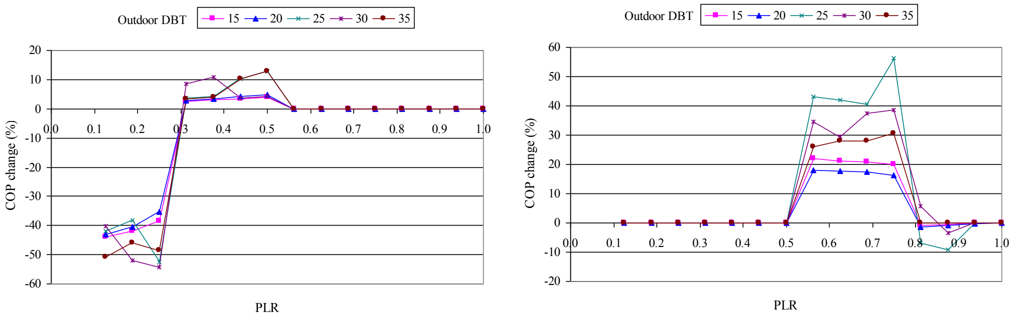


Fig. 3. Variation of COP with PLR of scheme CS1

Fig.4 shows the percentage change of chiller COP related to scheme CS1 under different circuit loading sequences. For the scheme CS2 as shown in Fig.4 (a), the chiller COP dropped significantly when the PLR was less than 0.25, and it could drop up to 54.3%. When PLR ranged from 0.25 to 0.5, COP could be improved up to 12.9%. When PLR was greater than 0.5, the operating schemes of CS1 and CS2 were identical, therefore, the chiller COP were the same.

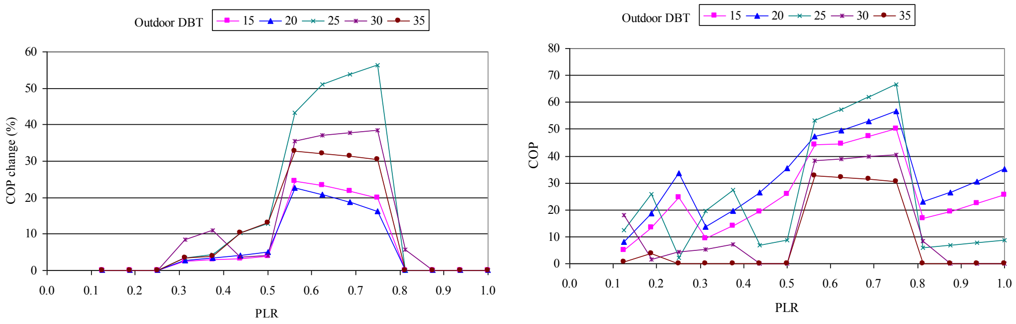
Fig.4 (b) shows that schemes CS1 and CS3 had same chiller performance when the chiller load was less than half of the rated cooling capacity. The COP could increase or reduce when the chiller load is more than 50% of the rated chiller capacity, depending on the working conditions. The chiller COP could be improved up to 56.3%, which was due to the fact that the circuit 1 was fully loaded with higher compressor efficiency, and the average COP of the two circuits was greater than that of scheme SC1. However, the COP of scheme CS3 was less than that of scheme CS1 when PLR was great than 0.8, because the two compressors worked with relative higher efficiency in CS1 compared with CS3 under such conditions.

For the scheme CS4, the optimal CLS was implemented, the chiller COP was improved by various degrees up to 56.4% when PLR was greater than 0.25. It revealed that the optimal CLS could obviously improve the chiller COP for the chillers with multiple refrigeration circuits. When the optimal CLS and variable condensing temperature control were applied together, the chiller COP could be further improved for all operating conditions up to 66.7% for scheme SC5. As shown in Fig. 4 (d), the extent of improvement of the chiller COP was much larger when the PLR ranged from 0.5 to 0.75, as under such conditions the optimal load sharing between the two refrigeration circuits could greatly improve the chiller efficiency. Schemes CS5 and CS1 had same chiller performance when the chiller load was less than 25% of the rated chiller capacity, as only one compressor for the two schemes operated under such conditions.



(a) Scheme CS2

(b) Scheme CS3



(c) Scheme CS4

(d) Scheme CS5

Fig. 4. Percentage change of chiller COP related to CS1 under different CLSs

4.3. Potential benefits from circuit loading sequence

From Fig.4, it was identified that the optimal CLS could obviously improve the chiller COP for the chillers with multiple refrigeration circuits. It was desirable to evaluate the cooling energy saving potential for a representative office building in Hong Kong when different operating scheme of circuit loading sequence were implemented to the air-cooled chiller plant.

The annual electricity consumption of the chillers under different operating schemes was evaluated, based on the building cooling load profile in Section 3. Table 1 shows the annual electricity consumption of the chillers serving the representative office building under different operating schemes. Average chiller COP was the annual cooling load over the annual chiller electricity consumption. Table 1 revealed that the chiller performance under scheme CS2 was inferior to that under scheme CS1 with annual electricity consumption increasing by 0.1%. For scheme CS4, optimal CLS enabled the total electricity consumption of the chillers to drop by 4.2%. Based on the local weather, chillers operated in part load conditions with an outdoor temperature of below 25°C for half of the time. Regarding this, there was a considerable scope to decrease the condensing temperature to improve chiller efficiency. It was expected that the COP improvements would be more considerable with CLS and CTC. When the advanced control CS5 was implemented, which was a combination of optimal CLS and CTC, it could enable the chiller plant to save the annual electricity consumption by 9.6% compared with scheme CS1.

Table 1. Energy performance of chillers under different control strategies

Case	Average COP	Annual electricity consumption (kWh)	Energy saving (%)	Notes
CS1	2.83	3.52×10^6	-	Base case
CS2	2.83	3.52×10^6	-0.1	
CS3	2.96	3.42×10^6	2.7	
CS4	3.01	3.37×10^6	4.2	
CS5	3.28	3.18×10^6	9.6	

5. Conclusions

When multiple refrigerate circuits of a chiller are sharing a cooling load, there exists an optimal operating scheme for CLS. The chiller performance and potential energy saving benefits due to CLS were investigated. The thermodynamic model of an air-cooled screw chiller was developed using TRNSYS, and it was validated using a wide range of operating data. With the sophisticated chiller model, an analysis was carried out on how the chiller COP varied with different CLS and CTC. For generality, a chiller plant serving a representative office building in Hong Kong was studied in order to assess the potential electricity savings by use of optimal CLS. With regard to the building cooling load profile, optimal CLS for CS4 enabled the annual electricity consumption of chillers to drop by 4.2% compared with the base case. The COP improvements due to CLS with CTC were more considerable for the air-cooled chillers, and the annual electricity consumption for the air-cooled chillers could be saved by 9.6% for the advanced control strategy CS5. This study demonstrates that a distinct improvement for the chiller COP is achieved with optimal CLS. Nowadays most chillers are designed with multiple refrigerant circuits, and the energy saving potential will be significant by implementing the novel control strategy of optimal CLS and CTC.

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References

[1] J. Yang, K.T. Chan, X. Wu, Performance enhancement of air-cooled chillers with water mist: Experimental and analytical investigation, Appl. Therm. Eng. 40 (2012) 114-120.

[2] A.I. Gan, S.A. Klein and D.T. Reindl, Analysis of refrigerator / freezer appliances having dual refrigeration cycles, ASHRAE T. 106 (2000) 185-191.

[3] K.A. Manske, S.A. Klein and D.T. Reindl, Load Sharing Strategies in Multiple Compressor Refrigeration Systems, ASHRAE T. 108 (2002) 327-333.

[4] D.J. Swider, A comparison of empirically based steady-state models for vapor-compression liquid chillers, Appl. Therm. Eng. 23 (2003) 539-556.

[5] F.W. Yu and K.T. Chan, Tune up of the set point of condensing temperature for more energy efficient air cooled chillers, Energ. Convers. Manage. 47 (2006) 2499-2514.

[6] S.H. Lee, F.W. H. Yik, J.H.K. Lai, Performance modelling of air-cooled twin-circuit screw chiller, Appl. Therm. Eng. 30 (2010) 1179-1187.

[7] F.W. Yu and K.T. Chan, Improved energy performance of air-cooled chiller system with mist pre-cooling, Appl. Therm. Eng. 31 (2011) 537-544.

[8] ASHRAE, ASHRAE Guideline 2, Engineering analysis of experimental data, USA: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 2010.

[9] J. Yang, K.T. Chan, X. Wu, et al., An analysis on the energy efficiency of air-cooled chillers with water mist system, Energ. Buildings. 55 (2012) 273-284.

[10] K.T. Chan and W.K. Chow, Energy impact of commercial-building envelopes in the sub-tropical climate, Appl. Energ. 60 (1998) 21-39.