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Investigation on year-round dispatch of multiple chillers in trigeneration system for high-rise building application

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Abstract

Trigeneration system is an energy-efficient solution to provide building cooling, heating and electricity. Owing to the waste heat recovery from the prime mover of trigeneration, it is natural to involve the thermally activated chiller. If the cooling demand is high, the electrically driven compression chiller would be supplemented. Since both absorption and compression chillers are adopted, multiple chiller staging would cover not only the quantity but also the type of chiller. In this study, a trigeneration system using two sets of diesel-engine prime movers was designed for a high-rise reference office building in a subtropical city. Two corresponding absorption chillers and one compression chiller were involved to share the peak cooling load. Year-round dynamic simulation was conducted to evaluate the interaction of these system components. It was found that the dispatch patterns of the two types of chillers were quite different in the hot and cold seasons.

Keywords: Trigeneration; energy efficiency; chiller dispatch; absorption chiller; compression chiller.

1. Introduction

Multiple chiller design is common in central chiller plant serving a high-rise building. Usually the chillers are identical to facilitate the chiller dispatch for different loading conditions. Cooling load is the primary control factor in this occasion. In trigeneration system, it is different. Thermally activated absorption chiller is generally adopted, since waste heat is available from the prime mover set during electricity generation. However, auxiliary electrical compression chiller is still needed in order to supplement the total cooling capacity. As such, both absorption and

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compression chillers would be involved, and multiple chiller staging would cover not only the quantity but also the type of chiller. Dispatch of these two types of chillers in trigeneration is then different from the approach adopted in a conventional chiller plant.

Wu and Wang [1] reviewed that electrical compression chiller is not a characteristic part of trigeneration, but it has a role to increase redundancy, diversity, reliability and economics of the trigeneration system. In fact, it is common to review the thermally activated cooling (TAC) technologies for trigeneration [2-4], but little mentions about the role of compression chiller and its operation coordinated with the TAC equipment. Underwood et. al. [5] studied scheduling of absorption chiller and compression chiller in trigeneration system, it suggests load sharing between the two types of chillers should be in a way that all waste heat is utilized by the absorption chiller.

Since trigeneration system is to provide cooling, heating and electricity simultaneously, the operation of prime mover set would dictate that of the system components including chillers. It is common to have the strategy of following electric load [3,6-7] for the control and operation of trigeneration system. As such, the primary control factor is the electrical load, which determines the staging of prime mover sets, it would lead to a complex interaction among the prime movers, the absorption chillers and the compression chiller in trigeneration system. Therefore it is worth investigating the chiller dispatch due to the characteristics of trigeneration system.

Nomenclature

COP	coefficient of performance
N_{pm}	number of operating prime movers
TAC	thermally activated cooling
T_{chwr}	chilled water return temperature
UA	overall heat transfer value
W_{ratio}	load ratio
τ_{ac}	air-conditioning hours scheduled
τ_{xAyC}	operating hours of a combination with x number of absorption chiller and y number of compression chiller

2. System Description

In this study, a trigeneration system was designed with the prime mover of diesel engine for a reference high-rise office building. Diesel engine, a type of internal combustion engine, is popular to be the prime mover of electricity generation due to its robustness in design and operation. The electrical efficiency of diesel engine can be maintained good when the part-load ratio is still above 50%. The design criteria and conditions of the office building are summarized as follows:

- Location: Hong Kong (22°16'N 114°11'E)
- Design indoor conditions: 24 °C and 60% RH
- Number of storey: 30
- Floor area: 1,664.64 m^2/floor
- Occupancy density: 8 m^2/person
- Sensible heat gain of occupant: 65 W/person (seated with light writing)
- Latent heat gain of occupant: 55 W/person (seated with light writing)
- Heat gains of lighting: 15 W/m^2
- Heat gains of office equipment: 10 W/m^2
- Outdoor air requirement: 8 L/s/person
- Number of lift: 4
- Lift power: 32 kW/lift
- Daily schedules of occupants, lighting, office equipment, lifts and air-conditioning system [8]
- Weather data: Typical meteorological year of Hong Kong [9]

Based on the design information, the peak electrical load, cooling load and heating load were determined to be 2,410 kW, 5,582 kW and 1,230 kW respectively. Two sets of 1,357-kW diesel-engine prime movers were therefore designed based on the electrical efficiency of 0.9. The peak cooling load was handled by two corresponding 1,339-kW absorption chillers and one 2,904-kW compression chiller. The cooling capacity of absorption chiller was determined by the waste heat recovered from one prime mover set. The schematic diagram of the diesel-engine-primed trigeneration system is shown in Fig. 1.

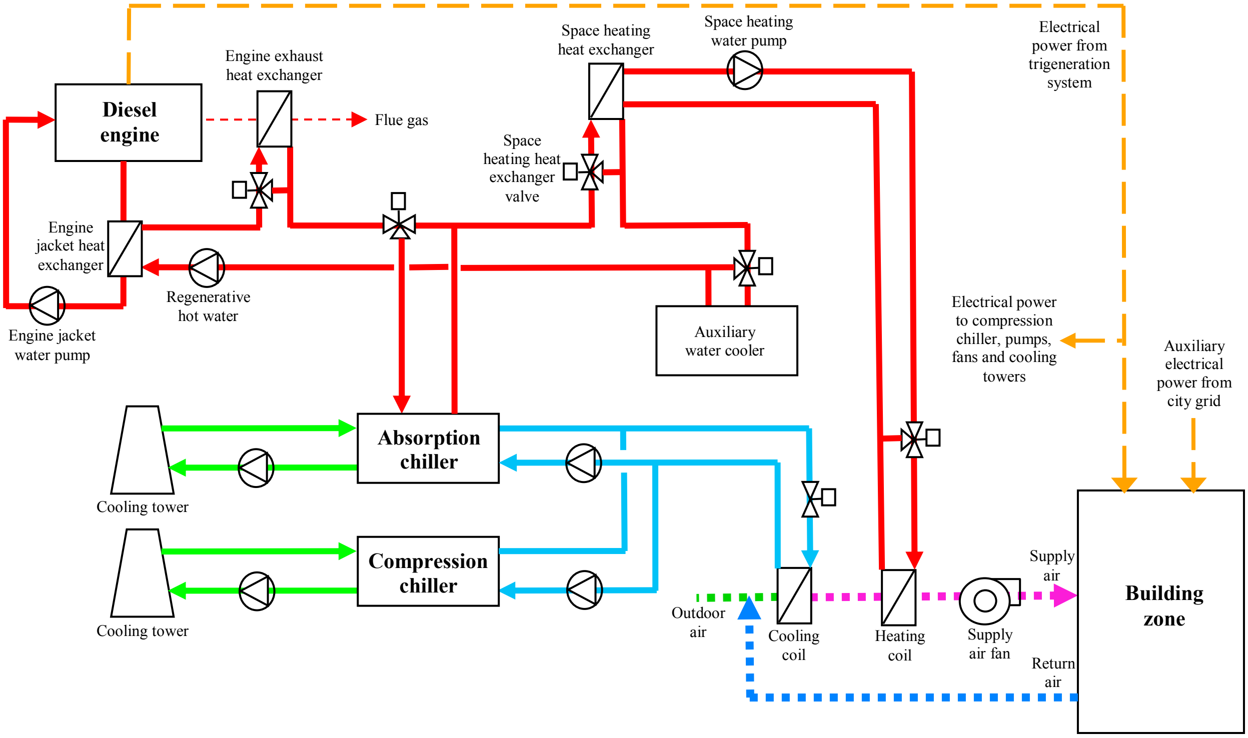

Fig. 1. Schematic diagram of diesel-engine-primed trigeneration system serving the reference office building.

3. System and control development

3.1. Dynamic system modeling

Dynamic model of the trigeneration system was built on the component-based simulation platform TRNSYS 17 [10] with its component library TESS [11]. The modeling details of the diesel engine (the prime mover), the absorption chiller and compression chiller are described in the previous work [12]. Other component models, like auxiliary water cooler, heat exchanger, pump, cooling tower, fan, coil, valve and building zone are available in the library of TRNSYS. The key design parameters of the prime mover of trigeneration are presented as follows:

- Rated electrical output: 1,357 kW
- Number of prime mover: 2
- Rated electrical efficiency: 35.1%
- Fuel type: Decane
- Heat recovered from engine jacket: 713 kW
- Heat recovered from flue gas: 1,099 kW
- Design fuel injection rate: 0.007 kg/cycle
- Total swept volume: 0.182 m^3
- Total clearance volume: 0.013 m^3
- Compression ratio: 15
- Overall heat transfer value *UA* of engine jacket: 1.75 kW/K
- *UA* of engine casing: 1.85 kW/K
- Casing area of generator: 15.9 m^2
- *UA* of engine jacket heat exchanger: 105.6 kW/K
- *UA* of engine exhaust heat exchanger: 6.56 kW/K
- Engine jacket water flow rate: 17 kg/s

The major design parameters of absorption chiller are consolidated below:

- Rated cooling capacity: 1,339 kW
- Number of chiller: 2
- Rated coefficient of performance (COP): 0.739
- *UA* of condenser: 345 kW/K
- *UA* of evaporator: 245 kW/K
- *UA* of generator: 245 kW/K

- *UA* of absorber: 225 kW/K
- *UA* of heat exchanger: 55 kW/K
- Solution flow rate at absorber outlet: 7.0 L/s
- Regenerative hot water flow rate: 28.8 kg/s
- Absorber cooling water flow rate: 82.2 kg/s
- Condenser water flow rate: 150.4 kg/s
- Chilled water flow rate: 58.1 kg/s

The essential design parameters of compression chiller are summarized as follows:

- Rated cooling capacity: 2,304 kW
- Number of chiller: 1
- Rated COP: 5.5
- Condenser water flow rate: 163.8 kg/s
- Chilled water flow rate: 126 kg/s

Year-round dynamic simulation was carried out to appraise the interaction of system components and the dispatch among the absorption and compression chillers. The simulation time step was 6 minutes. The operation situation of each chiller would be recorded in each time step.

3.2. Control schemes of prime mover and chillers

It is essential to have appropriate control schemes of the prime mover and the two types of chillers in response to the series of load variations. In this study, the switching of the prime mover depended on the total electricity demand in the previous time step. A load ratio W_{ratio} was employed which was defined as

$$W_{ratio} = \frac{\text{Total electricity demand}}{\text{Rated capacity of each prime mover}} \quad (1)$$

The corresponding control logic for the prime mover sequencing in the current time step was governed by W_{ratio} and the number of operating prime movers N_{pm} in the previous time step as summarized below:

- If $1.2 > W_{ratio} > 0.5$, then one prime mover would be in operation.
- If $0.5 > W_{ratio} > 0.4$ and $N_{pm} = 1$, then one prime mover would be in operation.
- If $W_{ratio} > 1.2$, then two prime movers would be in operation.
- If $1.2 > W_{ratio} > 1.1$ and $N_{pm} = 2$, then two prime movers would be in operation.
- If $W_{ratio} < 0.4$, then all prime movers would not be in operation, electricity was supplied by city grid.

The running of the absorption chiller and compression chiller was primarily governed by a thermostat set between 9.5 °C and 12.5 °C of chilled water return temperature T_{chwr} within the daily air-conditioning operating schedule. The control scheme of absorption chiller is described as follows:

- Only one absorption chiller would be stepped up or down during one time step.
- If $T_{chwr} > 12.5$ °C, one absorption chiller would be stepped up.
- If $T_{chwr} < 10.5$ °C and that the compression chiller was not in operation in the previous time step, one absorption chiller would be stepped down.
- In any circumstance, the total number of operating absorption chillers should not exceed the total prime movers energized.

On the other hand, the control scheme of compression chiller is shown as follows:

- If $T_{chwr} > 12.5$ °C and that there was no absorption chiller stepped up in the current time step, the compression chiller would be switched on.
- If $T_{chwr} < 10.5$ °C, the compression chiller would be switched off.

4. Results and discussion

Through the year-round dynamic simulation, the monthly performances of the trigeneration system were worked out. Fig. 2 presents the hour percentage of chiller in operation regarding to the total air-conditioning hours, which would be associated to the cooling demand around a year in the subtropical Hong Kong. The operating chiller included both the absorption and compression types. From Fig. 2, it was reasonable that the chillers operated over 90% during the summer period, i.e. from May to September. In the winter, air-conditioning was still necessary in office building, hence chillers would still be activated although they were likely in part-load operation.

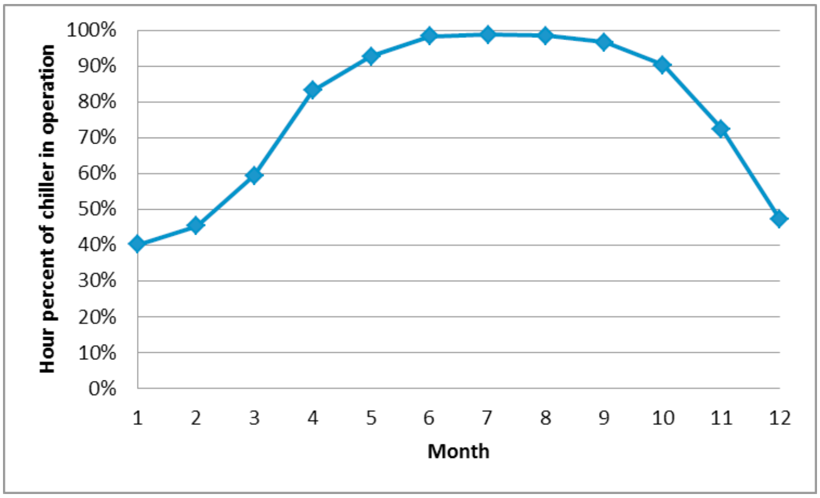

Fig. 2. Hour percentage of chiller in operation with respect to total air-conditioning hours.

Table 1 presents the operation of different combinations of absorption chiller and compression chiller along the year, where τ_{ac} is the air-conditioning hours scheduled in the respective month, while τ_{xAyC} is the operating hours of a combination with x number of absorption chiller and y number of compression chiller involved. τ_{ac} was determined by the period scheduled for calling air-conditioning operation in weekdays, Saturday and Sunday according to [8], so it was about the same in different months, no matter in the hot or cold season.

Table 1. Operating hours of different combinations of absorption chiller and compression chiller.

Month	τ_{ac}	τ_{0A0C}	τ_{1A0C}	τ_{2A0C}	τ_{0A1C}	τ_{1A1C}	τ_{2A1C}
1	362	216.7	98.9	0.8	24	20.8	0.8
2	320	175.1	92.6	3.2	22.1	24.8	2.2
3	358	145.2	114.2	14.2	31.7	36.4	16.3
4	334	56.2	74.6	37.6	32.3	55.6	77.7
5	362	26.5	32.8	57	14.6	65	166.1
6	344	6	6.7	26.7	2.6	61	241
7	348	4.4	6.6	26	2.6	60	248.4
8	362	5.7	6.4	27.4	2.7	60.4	259.4
9	330	11	14.4	41	3.5	58	202.1
10	362	35.1	58.7	40.7	24	90.8	112.7
11	348	96.1	107.4	22.1	31.2	59.7	31.5
12	344	181.6	107	2.9	26.4	23.7	2.4
Total	4174 (100%)	959.6 (23%)	720.3 (17%)	299.6 (7%)	217.7 (5%)	616.2 (15%)	1360.6 (33%)

It should be noted that τ_{ac} indicates whether the absorption/compression chiller was in operation only, but the associated chiller might be in part-load operation to satisfy the required cooling load in that time step. From Table 1, all six combinations of absorption/compression chiller occurred, including:

- 0A0C: No absorption chiller and no compression chiller in operation
- 1A0C: One absorption chiller and no compression chiller in operation
- 2A0C: Two absorption chillers and no compression chiller in operation
- 0A1C: No absorption chiller and one compression chiller in operation
- 1A1C: One absorption chiller and one compression chiller in operation

- 2A1C: Two absorption chillers and one compression chiller in operation

Based on τ_{ac}, 23% of operating hours did not need any call for absorption/compression chillers (i.e. combination of "0A0C"); 24% needed absorption chillers only (i.e. "1A0C" and "2A0C"); 5% required compression chiller only (i.e. "0A1C") and 48% called for both absorption and compression chillers (i.e. "1A1C" and "2A1C"). If considering the involvement of compression chiller, it accounted for 53% of the scheduled air-conditioning hours, or even 69% of the actual operating hours. This reflected the substantial contribution of compression chiller in the year-round operation of the trigeneration system. To understand the variation of each combination of chiller operation more clearly, Fig. 2 depicts the profiles of operating time ratio for different combinations in a year.

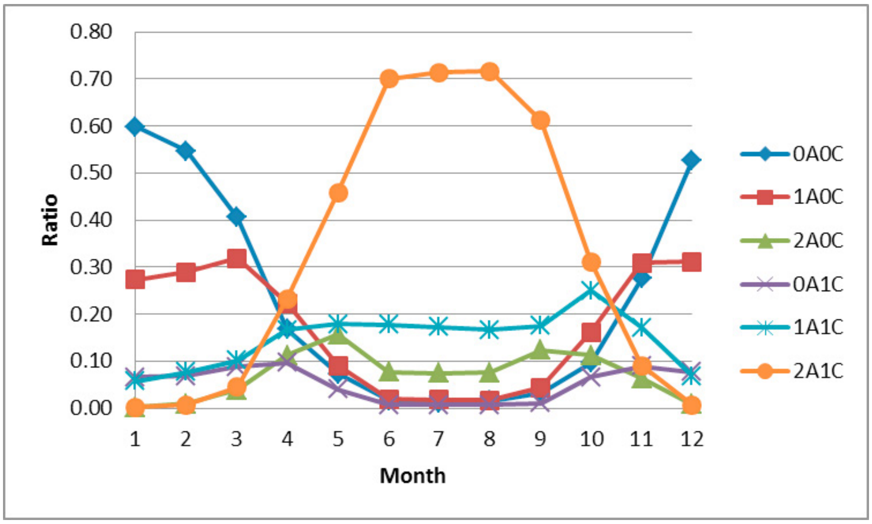

Fig. 3. Ratio of operating time of different combinations of absorption chiller and compression chiller.

From Fig. 3, it was found that there was a clear contrast in the dispatch patterns of the two types of chillers in the hot and cold seasons. In the winter time (December to February), the absorption chiller was chiefly in operation when there was cooling need, since the combination of "1A0C" prevailed. The compression chiller would be idle, instead of working in a low part-load condition. During the summer, the combination of "2A1C" dominated as illustrated in Fig. 3. Actually, the compression chiller was called in operation almost 90% of the cooling time from June to August by considering both combinations of "1A1C" and "2A1C". In such scenario, the compression chiller had priority in operation, and the deficit was supplemented by the absorption chillers. Although the two types of chillers used different forms of driving energy, the compression chiller was still far more energy-efficient than the absorption chiller under the inherent difference of COP.

Through the year-round evaluation, the annual primary energy consumption of the trigeneration system was 19,744 MWh while that of the conventional system was 23,362 MWh, resulting in 15.5% saving in primary energy. In addition, the annual carbon emissions of the trigeneration system and the conventional system were 4,936 tons and 5,887 tons respectively, leading to 16.2% carbon emissions cut. However, the installation cost of the proposed diesel-engine-primed trigeneration was 3 times of that of the conventional system. In economic analysis, it would be definitely unfavorable in the current situation. In order to promote the economic viability of trigeneration application, government subsidy or tax exemption should be applied on the installation cost, in particular that of the relevant equipment members like prime mover, absorption chillers, heat exchangers, auxiliary water cooler and the associated pipework. With respect to the running cost, carbon tax or even social cost should be covered. It is expected that trigeneration would gradually be one of the essential distributed generation sources for the sustainable future.

5. Conclusion

Through the year-round dynamic simulation, the dispatch of absorption chiller and compression chiller in trigeneration system has been identified. In the paradigm of trigeneration, it is natural to emphasize on the use of waste heat to drive the TAC equipment, like the absorption chiller in this case. In the regions with hot and humid climate, the cooling demand is generally not enough if solely offered by the TAC equipment. It is inevitable to involve the electrical compression chiller. Under the subtropical climate in this study, the cooling capacity of the compression chiller would be 52% of total cooling load, which becomes a characteristic part of the trigeneration system. Particularly in the summer time, the involvement of compression chiller would be so frequent that it is close to 90% of the operating time. As a result, the primary or secondary role of certain chiller type would be switched over in different seasons in trigeneration. Proper dispatch of the thermally activated absorption chiller and the electrically driven compression chiller is essential to maintain a self-sufficient cooling supply for building, as well as to minimize the energy need from power grid at the same time. The role of compression chiller is no more auxiliary, but active in operation in the hot and humid climate from a year-round perspective.

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