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Design and operation of a tri-generation system for a station in China

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ABSTRACT

Tri-generation usually refers to the simultaneous production of power, heating and cooling. Tri-generation can be regarded as a high-efficiency technology, provided that a large proportion of the energy rejected by the prime mover is used. In this paper, the design and operation of a tri-generation system for a railway station was investigated.

The system is composed of the internal combustion engine (ICE), absorption heat pump (AHP), heat exchanger (HE), and other facilities. The system was built and operated in 2011, and the energy efficiency level was analyzed. The results indicated that the calculated maximum comprehensive energy efficiency (CEE) was 94.94% in the winter and 84.33% in the summer; with the calculated maximum exergy efficiency is 38.01% in the winter and 36.01% in the summer. The primary energy saving (PES) of the system was 32.2% in the winter and 4.9% in the summer. The system could therefore be regarded as high efficiency tri-generation. The recovered year of the increased investment was 5.47 year compared with the reference system. These results could serve as a reference for designing or evaluating tri-generation systems.

1. Introduction

Developing efficient energy generation technologies has become a necessity due to increasing concern regarding the depletion of fossil fuel resources and environmental issues, especially global warming and climate change [1]. Tri-generation can be regarded as a high-efficiency technology, provided that a large proportion of the energy rejected by the prime mover is used. Tri-generation usually refers to the simultaneous production of power, heating and cooling, while cogeneration refers to heating and power only. The appropriate design of a tri-generation system for a specific site requires the consideration of several matters, such as the load profiles, the performance characteristics of the main devices, the process of the system, and the costs of the feasibility analysis. There are different methodologies for the analysis of cogeneration/tri-generation systems. A presentation regarding the status and development of the technologies was untaken by Wu and Wang [2]. A comparative analysis of potential prime movers and a comprehensive literature review was presented by Al-Sulaiman et al. [3]. Additionally, several studies have been conducted about the application of tri-generation systems in residential buildings [4], office buildings [5], supermarkets [6], tertiary buildings [7], etc. Several papers investigated the energy and economic analyses [8–11], exergy analysis [12–14], system optimisation [15–17], and pollution emission [18], etc.

In this paper, the design and operation of a tri-generation system for a station was investigated. The station, located in the north central region of the country, is classified as great size (building area 117,000 m^2). Natural gas supply is increasing in China, allowing for the growth of cogeneration capacity in the years to come. In this case study, the energy demand profiles of the station were simulated, the configuration of the tri-generation system was presented, and two different operation modes (winter mode and summer mode) of the system were analyzed. Two criteria were used to evaluate system performance: (i) comprehensive energy efficiency (CEE); (ii) exergy efficiency, and the primary energy savings (PES) was used to evaluate the energy saving of the system compared with the conventional system, and the recovered year of the increased investment Y was used to evaluate the economics of the system.

2. Energy demands of buildings

The space heating and cooling demands for the station were simulated by DeST (Designer's Simulation Toolkit), which is a tool developed for aiding HVAC engineers to realize 'design by analysis, design by simulation' [19]. The electricity demand was simulated based on the measured data. Fig. 1 shows the hourly space heating load profile and Fig. 2 shows the hourly cooling load profile. The maximum heating load was 12 MW, and the maximum cooling load ais 12.4 MW. Fig. 3 shows the hourly electricity load profile, and the maximum electricity load was 6.3 MW.

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Nomenclature

AHP	absorption heat pump
CEE	comprehensive energy efficiency (%)
CT	cooling tower
CWT	cooling water tank
COP	Coefficient of Performance
HE	heat exchanger
ICE	internal combustion engine
PC	primary circuit
PES	primary energy saving (%)
SC	secondary circuit
C_{cw}	cooling production of the tri-generation system (kW)
Ex	exergy flow rate (kW)
H_{hw}	heat production of the tri-generation system (kW)
h	specific enthalpy (kJ/kg)
LHV_{fuel}	lower heating value of natural gas (kJ/N m^3)
m_{fuel}	natural gas consumption of the tri-generation system (N m^3/s)
m	mass flow rate (kg/s)
$RefH_\eta$	reference heat efficiency (%)
$RefE_\eta$	reference electricity efficiency (%)
$RefC_\eta$	reference cooling efficiency (%)
s	specific entropy (kJ/kg K)
T_0	temperature of the environment (K)
W_{net}	electricity of the tri-generation system (kW)
Y	recovered year of the increased investment (year)
ε	exergy efficiency (%)
ΔC	initial investment increment
ΔR	operation and maintenance cost decrement

Subscripts

hw	hot water
cw	cooling water

3. Design of the tri-generation system

The sizing of the tri-generation system, its component efficiencies, and whether it operates at a partial load are all factors affecting system performance. However, a tri-generation system is often sized to provide a constant base load of electrical output where additional electricity needed can be purchased from the grid. For the station presented in this paper, the tri-generation system is sized such that it provides a constant base load and therefore often operates at full load. Two internal combustion engines are used as the prime mover, and the power generation of the two engines is sized 3.14 MW (Rated Power), which is equal to 50% maximum electricity load. When the heating, cooling and electric load changes above the base load, additional electricity can be purchased from the grid, and other peak shaving devices are used (boiler in winter and electric chiller in sumer) to satisfy the changed demands. The boiler and the electric chiller could be be quickly adjusted according to the change of load.

Fig. 4 shows the tri-generation system, and Table 1 shows the thermodynamic states of the tri-generation system with the engine at full load. The system is based on two 1570 kWe internal combustion engine (ICE) powered by natural gas. In Fig 4, we have presented only one series for ease of reference. One part of the fuel energy is converted into shaft power, and later into electricity in the electric generator. The remaining fuel energy not converted into shaft power is found in the exhaust gases, the engine jacket,

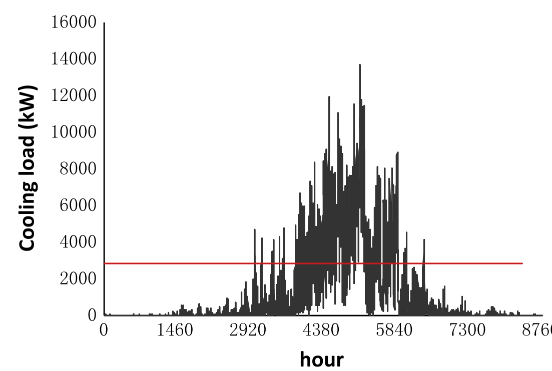

Fig. 2. Cooling load profile.

and the lubrication system. A fraction of the energy is lost by heat transfer from the engine block and components to the surroundings. In the winter (operation mode one), the waste heat of the engine is recovered in three parts. First, the primary circuit recovers energy from the engine jacket, and uses it by HE1 to produce hot water for space heating. Second, the secondary circuit recovers energy from the engine oil radiator, and uses it by HE2 to warm hot water for space heating or uses it by HE3 to warm the sanitary water. Third, exhaust gases with a high temperature are used to drive the absorption heat pump to recover the exhaust gases with

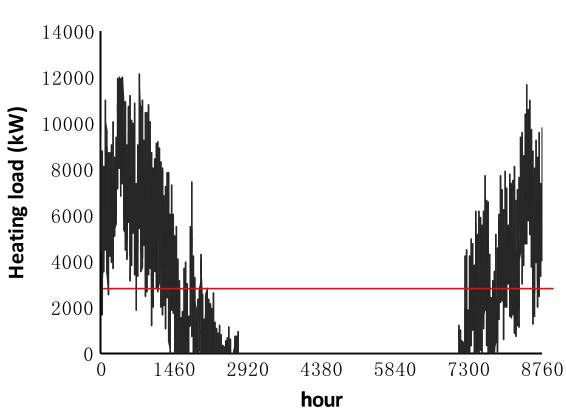

Fig. 1. Heating load profile.

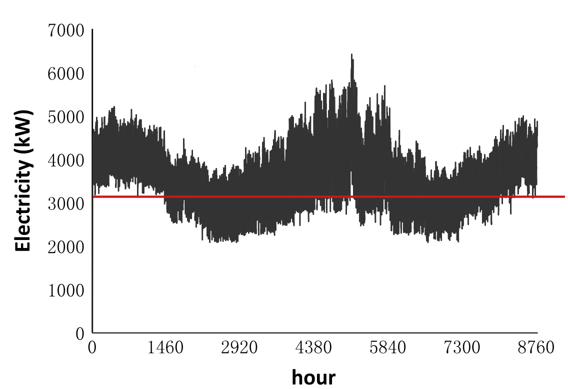

Fig. 3. Electricity load profile.