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Research Paper

Investigation of climatic effect on energy performance of trigeneration in building application

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HIGHLIGHTS

- Extent of energy merit of trigeneration depended on waste heat utilization.
- Associated to electrical efficiency of prime mover and building loads due to climatic effect.
- Trigeneration application was favorable in continental and tropical climates.
- Temperate climate might result in low energy merit for trigeneration.
- Energy saving potential of trigeneration was not guaranteed in certain occasions.

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ABSTRACT

Trigeneration is commonly considered as one of the energy-efficient solutions, since the heat recovered from electricity generation can be adopted to produce both heating and cooling for building use. It is generally accepted that the trigeneration system should outperform the conventional separate provisions of cooling, heating and power. However, energy efficiency of the prime mover of trigeneration would be diminished in part-load conditions, which are mainly determined by the changing climatic situations. In this regard, it is not sufficient to consider the energy performance of trigeneration based on the design point. Therefore, this study attempts to conduct year-round evaluation of trigeneration systems subject to climatic effect. Four cities with close longitude but different latitudes were involved, which had different heating-to-cooling ratios in building loads due to climatic conditions. A set of energy performance indicators were applied to thoroughly appraise the trigeneration systems against the conventional provisions. It was found that the extent of energy merit of trigeneration depended on the utilization degree of waste heat, which was associated to the electrical efficiency of prime mover and the building loads caused by climatic effect. While the year-round fuel energy utilization ranged from 61.9 to 83.8%, the respective primary energy reduction only varied from 0.4 to 7.5%. Energy saving potential of trigeneration might not be guaranteed in certain occasions in a year.

1. Introduction

Global warming due to CO_2 emissions has been the most controversial debate nowadays. There are possible environmental impacts on ambient air conditions [1–4] and fresh water supply [5–10]. The majority of worldwide CO_2 emissions come from the power plants. Hence, the quest for more effective power generation systems is one main direction of energy researches. Trigeneration system primarily produces electricity, meanwhile, it utilizes the waste heat captured from the prime mover to offer space cooling and heating. The recovered heat is used to energize a thermally-driven cooling equipment to provide air-conditioning. Due to utilization of waste heat, trigeneration is considered more energy-efficient than the classical power plants, and the system efficiency can be 60–80% [11,12]. Actually, the effectiveness of trigeneration would be affected by the loading ratio in building applications. Al-Sulaiman et al. [13] reviewed that it was common to use the electric-to-heating ratio to characterize different prime movers of trigeneration. Marques et al. [14] conducted thermodynamic analysis of trigeneration systems by taking into account both the electric-to-heating and electric-to-cooling ratios for buildings. Ebrahimi and Keshavarz [15] studied the prime mover sizing and operational mode for micro-trigeneration, it was found that they should be determined according to the climatic features. Hajabdollahi et al. [16] considered suitable operational strategy for

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Nomenclature

A	engine casing area (m^2)
COP	coefficient of performance of chiller
c_p	specific heat capacity at constant pressure (kJ/kg K)
EE	energy efficiency of trigeneration system
EUF	energy utilization factor of trigeneration system
$FESR$	fuel energy saving ratio
GEE	generator electrical efficiency
H	enthalpy (kJ)
h	specific enthalpy (kJ/kg)
LHV	lower heat value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
P_s	equilibrium vapor pressure of desiccant solution (kPa)
$PESR$	primary energy saving ratio
Q_{env}	heat energy lost from the engine casing to the ambient (kJ)
Q_{jac}	heat energy transferred from the engine cylinder to the engine jacket (kJ)
$\dot{Q}_{abs}$	thermal power removed from the absorber of the absorption chiller (kW)
$\dot{Q}_{cond}$	thermal power removed from the condenser of the absorption chiller (kW)
$\dot{Q}_{evap}$	cooling capacity of the absorption chiller (kW)
$\dot{Q}_{heat}$	thermal power transferred from the regenerative hot water to the space heating water (kW)
$\dot{Q}_{gen}$	thermal power absorbed by the generator of the absorption chiller (kW)
rps	rotation speed of engine (1/s)
T	temperature (K)
$\bar{T}$	average temperature (K)
T_m	log-mean-temperature difference (K)
UA_{env}	overall heat transfer value between engine cylinder and jacket (kW/K)
UA_{jac}	overall heat transfer value between engine casing and the ambient (kW/K)
V	volume (m^3)
W_{net}	net work output per cycle of the prime mover (kJ)
$\dot{W}_{building}$	total building power demand handled by conventional provisions (kW)
$\dot{W}_{grid}$	auxiliary electrical power supplied from city grid (kW)
$\dot{W}_{out}$	electrical power output of prime mover (kW)

Greek symbols

γ	ratio of specific heat capacity
ε	a coefficient determined according to Eq. (4)
η_{grid}	thermal efficiency of grid electricity
η_{ph}	thermal efficiency of primary heater
ξ	desiccant solution concentration (kg/kg)
σ	Stefan-Boltzmann constant (=5.669 × 10^{-11} kW/m^2 K^4)
ϕ	angular displacement of crankshaft during the constant-pressure combustion of the Diesel cycle (degree)

Subscripts

1, 2, 3, 4	state points in the *P-V* diagram of the engine cycles
ab	absorption chiller
abs	absorber of absorption chiller
abw	cooling water through the absorber
ai	absorber inlet
ao	absorber outlet
cas	engine casing
cond	condenser of absorption chiller
cw	cooling water
cyl	engine cylinder
dis	discharge
evap	evaporator of absorption chiller
ew	chilled water
fuel	fuel
gen	generator of absorption chiller
gi	generator inlet
go	generator outlet
hw	hot water
i	inlet
jac	engine jacket
jw	engine jacket water
o	outlet
r	refrigerant
s	desiccant solution
sshxr	solution-to-solution heat exchanger
suc	suction
vc	vapor-compression chiller
w	water

Abbreviations

AC	air-conditioning
BJ	Beijing
DE	diesel engine
EZ	exterior zone
GE	gas engine
HK	Hong Kong
IZ	interior zone
LL	lift lobby
SG	Singapore
SH	Shanghai

trigeneration, and appropriate deployment of cooling equipment should be applied in different climatic conditions. Hueffed and Mago [17] also studied design and operation strategies of trigeneration applied in places with various climates, but emphasizing on their effect on cost structure. Basrawi et al. [18] found that micro gas turbine trigeneration was better than the corresponding cogeneration in tropical climate, in terms of system configuration, economic payback and fuel energy saving. Eveloy et al. [19] and Stoyak et al. [20] had positive appraisals on trigeneration applications with extreme climatic conditions in Persian Gulf and Kazakhstan respectively. Wang et al. [21] analyzed the effect of building categories and climate zones on trigeneration performance, and it was found that trigeneration was favorable to the buildings requiring more heating. In fact, it is common to find that trigeneration application was effective with emphasis on heating demand [22]. In this connection, Fabrizio [23] and Kegel et al. [24] pointed out that cogeneration was more appropriate than trigeneration in Italian and Canadian climates respectively. Bianco et al. [25] investigated the performance of a cogeneration system for use in a food factory in Italy. Furthermore, Qian et al. [26] found that trigeneration might not be more fuel-efficient than the conventional system in certain scenario under different climates. Consequently, the energy merit of trigeneration is not fully guaranteed. However, there was no systematic study on the effect of loading and climatic conditions on trigeneration performance, nor the discussion of the different impacts of cooling and heating provisions on the overall performance of trigeneration.

As a result, this study aims at evaluating the energy performance of trigeneration through the heating and cooling load proportion, which is primarily subject to the climatic effect. Four Asian cities with close longitude, namely Singapore (SG), Hong Kong (HK), Shanghai (SH) and Beijing (BJ) were involved. Singapore