ARTICLE IN PRESS

Applied Energy xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance analysis of internal-combustion-engine primed trigeneration systems for use in high-rise office buildings in Hong Kong ☆

K.F. Fong, C.K. Lee *

Division of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Tat Chee Avenue, Hong Kong

HIGHLIGHTS

- Internal-combustion-engine-primed trigeneration (ICEPT) systems were analyzed.
- Three types of fuels, namely diesel oil, natural gas and petrol gas, were considered.
- Dynamic performances studied for use in high-rise office building in Hong Kong.
- Diesel-oil-fueled system yielded the largest primary energy saving.
- Natural-gas-fueled one offered the lowest carbon dioxide emission.

ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form 16 October 2014
Accepted 25 November 2014
Available online xxxx

Keywords:
Trigeneration
Absorption chiller
Vapor-compression chiller
Primary energy consumption
Carbon dioxide emission
Energy utilization factor

ABSTRACT

The energy and environmental merits of three types of internal-combustion-engine primed trigeneration (ICEPT) systems were investigated when compared with a conventional chilled water system powered by the grid electricity for use in a high-rise office building in Hong Kong. With the employment of the ICEPT systems, the year-round total electricity demand from the building was reduced by at most 10.4% for the natural-gas-fueled one. However, the saving in the total primary energy consumption (*PEC*) only ranged from 1.7% to 6.8% with the diesel-oil-fueled system being the best although for all the three types of ICEPT systems more than 70% of the energy from the fuel had been utilized. The huge difference in the coefficient of performance (*COP*) between the absorption chiller and the vapor-compression chiller was the main cause which impaired the benefit of recovering the waste heat to provide space cooling. The total carbon dioxide emission (*CDE*) varied widely with the types of fuels adopted with a maximum of 26.7% for the natural-gas-fueled system which was due to the lower carbon dioxide emission index of natural gas as compared to other fuel types. The overall ranking of the ICEPT systems depended on the weighing between energy and environmental merits.

1. Introduction

With the increasing awareness on climate change, the urge for the reduction in carbon dioxide emission has become a major mission of the government in the developed country. One possible direction is the employment of more renewable energy sources such as solar, wind, tidal and geothermal in place of the conventional power plants which run on fossil fuels. However, the high initial cost of the renewable energy systems is the main obstacle. Another feasible way is to optimize the use of energy delivered from the fossil fuels by designing more energy-efficient power systems. This can be achieved by utilizing the waste heat from the power systems for heating and/or spacing cooling of buildings through the use of heat-driven air-conditioning equipment, thus forming a trigeneration system. Fig. 1 shows the symbolic diagram of a trigeneration system. Fuel is supplied to a prime mover for generating electricity. Meanwhile, the waste heat delivered from the prime mover is recovered to provide space cooling and/or heating. With this design, usually more than 70% of the energy released from the fuels can be utilized.

Different kinds of prime movers may be used which include internal combustion engine, gas turbine, steam turbine, micro turbine and fuel cell. Studies have been made to investigate the thermodynamic performances of various designs of trigeneration systems [1–15] which mainly focus on the behavior of the trigeneration systems at different operating conditions. However, the

---

☆ This paper is included in the Special Issue of Energy innovations for a sustainable world edited by Prof. S.k Chou, Prof. Umberto Desideri, Prof. Duu-Jong Lee and Prof. Yan.

* Corresponding author.

E-mail address: a8304506@graduate.hku.hk (C.K. Lee).

http://dx.doi.org/10.1016/j.apenergy.2014.11.059
0306-2619/© 2014 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Fong KF, Lee CK. Performance analysis of internal-combustion-engine primed trigeneration systems for use in high-rise office buildings in Hong Kong. Appl Energy (2014), http://dx.doi.org/10.1016/j.apenergy.2014.11.059

Nomenclature

A	area (m^2)
CDE	carbon dioxide emission (ton)
COP	coefficient of performance
c_p	specific heat at constant pressure (kJ/kg K)
EUF	energy utilization factor
GEE	generator electrical efficiency
H	enthalpy (kJ)
LHV_f	lower heat value of fuel (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
PEC	primary energy consumption (MW h)
$\dot{Q}_{ab}$	heat power utilized by the absorption chiller (kW)
$\dot{Q}_{heat}$	heat power utilized for space heating (kW)
Q_{env}	heat energy loss from engine casing per cycle (kJ)
Q_{jac}	heat energy transferred to jacket water per cycle (kJ)
rps	engine speed (1/s)
T	temperature (K)
$\overline{T}$	average temperature (K)
UA_{env}	overall heat transfer value between engine casing and the environment (kW/K)
UA_{jac}	overall heat transfer value between cylinder and engine jacket (kW/K)
V	volume (m^3)
W_{net}	net work output per cycle (kJ)
$\dot{W}_{out}$	electricity output from the prime mover (kW)

Symbols

ϕ	angular displacement of crankshaft during the constant-pressure combustion of the Diesel cycle (degree)
γ	ratio of specific heat
σ	Stefan–Boltzmann constant (=5.669×10^{-11} kW/m^2 K^4)

Subscripts

1, 2, 3, 4	state points in the P–V diagram of the engine cycles
cas	engine casing
cyl	cylinder
env	environmental or ambient condition
f	fuel
i	inlet
jw	jacket water
o	outlet

Abbreviations

AbCV	absorption chiller control valve
AbCWP	absorption chiller cooling water pump
AbPChWP	absorption chiller primary chilled water pump
AbSChWP	absorption chiller secondary chilled water pump
AC	air-conditioning
AWCV	auxiliary water cooling valve
CCW	conventional chilled water
DEDO	diesel engine fueled by diesel oil
EEHX	engine exhaust heat exchanger
EEHXV	engine exhaust heat exchanger valve
EJHX	engine jacket heat exchanger
EJWP	engine jacket water pump
EZ	external zone
GENG	gas engine fueled by natural gas
GEPG	gas engine fueled by petrol gas
ICEPT	internal-combustion-engine primed trigeneration
IZ	internal zone
LL	lift lobby
RHWP	regenerative hot water pump
SAC	supply air cooling coil
SACV	supply air cooling coil valve
SAF	supply air fan
SAH	supply air heating coil
SAHV	supply air heating coil valve
SHHX	space heating heat exchanger
SHHXV	space heating heat exchanger valve
SHWP	space heating water pump
VCCWP	vapor-compression chiller cooling water pump
VCPChWP	vapor-compression chiller primary chilled water pump
VCSChWP	vapor-compression chiller secondary chilled water pump

building demand profiles for space cooling and heating can vary widely throughout the year. Hence, to evaluate more precisely the economic and/or energy merits of the trigeneration systems, year-round system performance analyzes are also conducted [16–20] (although comparatively fewer) which indicate that the benefit of applying trigeneration systems depends readily on the building type, the climate and the local cost levels of various types of energy. In particular, published works on the application of trigeneration systems to sub-tropical regions in which the air-conditioning load is cooling-dominated are rare. The main challenge is that the cooling demand can be low outside the peak-load season but at the same time the heating demand is still minimal which is not favorable for a trigeneration system.

Al-Sulaiman et al. [21] reviewed the characteristics of various kinds of trigeneration systems with different prime movers. They remarked that the internal-combustion-engine primed trigeneration (ICEPT) systems were among the most common and well-established types. Angrisani et al. [22] also highlighted the benefits of ICEPT systems for use in small- or medium-capacity applications. For the thermally-driven cooling devices, they may be absorption chiller, adsorption chiller, desiccant cooling system, etc. Fong et al. [23] commented that the absorption chiller performed the best in a solar cooling system when applied to a sub-tropical region like Hong Kong due to its higher coefficient of performance (COP) and the humid climate in summer. Hence, it can be expected that the combined use of the ICEPT system and the absorption chiller should offer satisfactory performance.

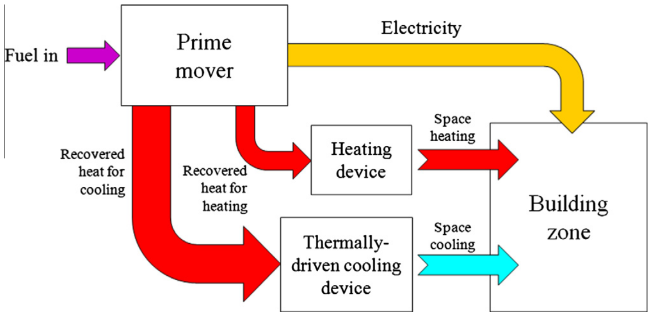

Fig. 1. Symbolic diagram of a trigeneration system.

Please cite this article in press as: Fong KF, Lee CK. Performance analysis of internal-combustion-engine primed trigeneration systems for use in high-rise office buildings in Hong Kong. Appl Energy (2014), http://dx.doi.org/10.1016/j.apenergy.2014.11.059