Energy 35 (2010) 3540–3550

Contents lists available at ScienceDirect

Energy

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

Thermoeconomic assessment of a multi-engine, multi-heat-pump CCHP (combined cooling, heating and power generation) system – A case study

P. Roque Díaz [a], Y.R. Benito [b], J.A.R. Parise [b,*]

[a] Center for Energy and Environmental Studies, Universidad Central Marta Abreu de Las Villas, C. Camajuani, km 5, Santa Clara, CP 54830, Cuba
[b] Department of Mechanical Engineering, Pontifícia Universidade Católica do Rio de Janeiro, 22453-900, Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Article history:
Received 7 November 2008
Received in revised form
17 March 2010
Accepted 5 April 2010
Available online 11 June 2010

Keywords:
Trigeneration
Exergy cost
Distributed energy
Structural optimization

ABSTRACT

Design and operation of complex systems for combined cooling, heating and power generation (CCHP) are always a matter of matching performance and demand characteristics of a thermal system set to supply electrical, cooling and heating loads, according to specific usage demands. Equipment selection and operation require the characterization of power, heating and cooling load demands, and their time variation during years, seasons, months and even hours or minutes. The paper aims at utilizing a general model for complex CCHP systems. The proposed model is based on the general theory of exergy cost and structural coefficients of internal links. A general model is presented, and a simple hypothetical cogeneration case is studied. The system operates with two heat engines, with waste heat recovery driving a chiller, in order to meet electrical power and refrigeration loads.

1. Introduction

In a world of continuously growing scarcity of primary energy as well as of an insurmountable irreversible environmental impact, due to human activity onto the biosphere, it is of utmost importance to look for alternatives to traditional energy sources. Obviously, the best energy source is the energy that has been saved by means of the increase in energy conversion efficiency. Recovered energy can be regarded, in fact, as an energy source which does not require additional primary energy consumption and also does not produce additional pollution. On the contrary, it mitigates the external impacts as a result of not using part of the energy resources that would have been utilized otherwise. How much of such virtual energy source can be utilized, for a given application? The answer to this key question is a matter of raising the energy efficiency and also of diminishing the not always rationally justified energy requirements of human society [1,2]. This paper deals with the first aspect of the answer.

The use of energy supply schemes which are based on combined heat and power (CHP or cogeneration) and combined cooling, heat and power (CCHP or trigeneration) has proven to be a rational approach which, in many cases, contributes to a noticeable decrease in primary energy consumption not only in industrial and other production activities, but also in the tertiary sector, namely hospitals and other healthcare facilities, hotels and resorts, commercial and residential buildings. Recent studies, from different countries [3–5], reveal that overall primary energy savings, ranging from 30 to 60%, can be expected, by the end of the next decade, with the use of CHP and CCHP technologies. The relative magnitude of savings will mainly depend on the dynamics of the load demands, on the available technology and on the characteristics of the process [6].

2. Trigeneration systems

2.1. CHP (cooling and power) and CCHP: equipment and technologies

Although the first cogeneration technology (late 19th century) was based on back pressure steam engines, nowadays, the majority of power generating heat engines (like internal combustion engines or gas turbines) is capable of producing waste heat, which can be applied to meet heating and, eventually, cooling demands. This fact provides a broad portfolio of alternatives from which the most suitable arrangement, for almost any application condition, can be chosen. CHP (heating and power) and CCHP have been made a reality, most of all, due to the available technology for waste-heat-driven refrigeration, namely, the absorption refrigeration cycle. For current technologies, see, for example [7].

* Corresponding author. Present address: Rua Marquês de São Vicente, 225 – Gávea. CEP 22453-900 Rio de Janeiro, RJ, Brazil. Fax: +5521 3527 1165.
E-mail address: parise@puc-rio.br (J.A.R. Parise).

0360-5442/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2010.04.002

Nomenclature

A	matrix of incidence
a_i	function coefficients of Eq. (38)
AMF	amortization factor
b_i	function coefficients of Eq. (39)
B	exergy flow rate [kW]
B^*	exergy cost flow rate [kW]
c	exergoeconomic unit cost [$/kWh, $/MJ]
c_i	function coefficients of Eq. (45)
COP	coefficient of performance
D	exergy destruction rate [kW]
D	vector of misbalance or exergy destruction
d_i	function coefficients of Eq. (44)
E_{in}	rate of energy input [kW]
EIC	equipment investment cost [$]
f	weighting coefficient of x [−]
FLT	total annual operating time of system at full load [h]
I	irreversibility rate [kW]
IRR	internal rate of return [−]
L	rate of exergy losses [kW]
n	economic life of plant [years]
N	generic variable
OMF	operation and maintenance factor
Q_C	cooling production rate [kW, MW]
Q_H	heat production rate [kW, MW]
Q_r	waste heat rate [kW]
R_C	cooling load demand to electric power demand ratio [−]
R_H	heating load demand to electric power demand ratio [−]
T_r	absorption chiller heat source temperature [K]
u	generic variable
W	power [kW, MW]
X	vector of conservative properties
x	generic variable
Y	vector of non-conservative properties
Y	generic variable
Z	non-energy related cost flow [$/s]

Greek symbols

α	waste energy recovery ratio from internal combustion engine-electrical generator [−]
β	distribution factor between vapour compression and absorption heat pumps [−]
γ	utilization ratio of electrical power load [−]
δ	uncertainty of variable
ΔQ_C	surplus cooling power [kW]
ΔQ_H	surplus heating power [kW]
ΔW	surplus power [kW]
η	thermal efficiency [−]
λ	load distribution ratio between the two heat engines
χ	heat engine partial load fraction [−]
ξ	structural coefficient of internal bonds [−]
ϕ	ratio between chemical exergy of fuel and its net calorific value [−]
σ	efficiency defect [−]
τ	time [s, h]
Π	exergoeconomic cost flow [$/s]
ψ	rational or exergy efficiency [−]

Subscripts

AC	absorption chiller
C	cooling
DE	energy demand
GB	global
GT	gas turbine
H	heating
IC	internal combustion engine
in	inlet
k	relative to a subsystem
max	maximum
min	minimum
P	product
Q_C	cooling power
Q_H	heating power
r	recovered waste
VC	vapour compression chiller
W	electrical power

Abbreviations

AC	absorption chiller
CCHP	combined cooling, heating and power
CHP	combined heating and power
GT	gas turbine
HP	heat pump
HRE	heat recovery equipment
IC	internal combustion engine
P	power distribution panel
PGM	power generating machine
TES	thermal storage device for cooling purposes
VC	vapour compression chiller

2.2. Multi-component trigeneration systems

A general case of a CCHP system, depicted in Fig. 1, can be represented by a set of power generating machines (PGMs) which deliver, besides mechanical work, waste heat to a set of heat recovery equipment (HRE), to heating utilities, or to a set of absorption refrigerators (AC), for cooling purposes. In order to even out misbalances in cooling, heating and power demands, the PGM set can also drive vapour compression cycle refrigerators (VC) or heat pumps (HP), the latter as a vapour compression cycle with the purpose of heating capacity. A number of thermal energy storage devices (TES), with cooling capacity, could also be provided for with the same objective.

It should be noticed that any of the generalized subsystems can be composed by a number of individual machines or components, which, in a general case, may perform in a different way to one another, providing an overall characteristic function, which results

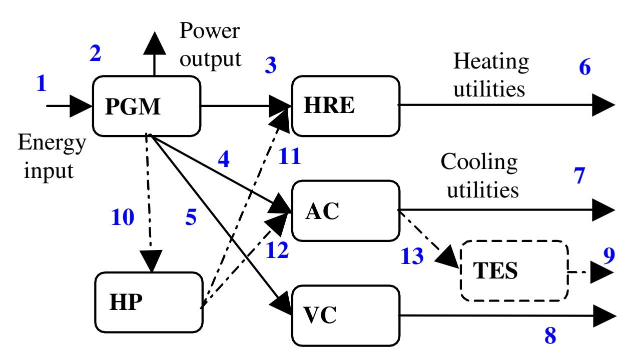

Fig. 1. General layout of a complex CCHP System.