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Thermodynamic analysis of tri-generation systems taking into account refrigeration, heating and electricity load demands

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ABSTRACT

Tri-generation is a novel application of energy technologies which simultaneously produces heat, refrigeration and electricity. An expression for the calculation of the thermodynamic performance of a generic tri-generation scheme is presented. A brief first-law analysis involving an energy conversion ratio and newly defined heating-to-cooling and electric-to-cooling load ratios to usual system component thermodynamic parameters (such as coefficient of performance or prime mover thermal efficiency) was carried out. To illustrate the usefulness of the criterion, a tri-generation pilot plant set up in an office building was studied.

1. Introduction

Tri-generation, the simultaneous production of electricity, heat and refrigeration from a primary source of energy, such as natural gas or bio-fuel, is a natural extension of co-generation. From a strictly thermodynamic viewpoint, a tri-generation system is simply a traditional combined heat and power (CHP) system plus an absorption and/or a vapor compression chiller (CCHP-combined cooling heating and power). However, the advantages of tri-generation, such as primary energy savings and greater overall efficiency have, in recent years, attracted authors, researchers and the construction community [1–11]. Tri-generation is clearly of importance in connection with pollution control. According to Meunier [12], who studied the impact of co- and tri-generation on the environment, CO_2 emissions could be reduced by at least 40% if sorption heat pump technology were to be developed. Moreover, tri-generation plants are economically viable in situations where electric energy is scarce and/or costly. Despite the attractiveness of tri-generation as an energy-integrated scheme, new energy demands arise, implying further operational constraints not present in co-generation.

In most tri-generation systems heat, refrigeration and electricity are produced by a combination of an absorption chiller and a Diesel or gas turbine generator. While the choice of a Diesel engine or gas turbine as a prime mover is dictated by a thermodynamic cost–benefit relation, the possibility of transforming low grade heat from CHP units into cold has made absorption chillers an almost indispensable component of most commercial applications. Absorption chillers offer good partial load performance, low maintenance and high availability and this may account for the fact that most research in the area has concentrated on tri-generation with absorption chillers. Some investigations [13,14] have focused on the food industry and supermarkets where items must be kept chilled or frozen in refrigerated cabinets throughout the year, subject to appreciable seasonal variations. These investigations highlighted the possible gains to be had from this new energy technology. However, less attention seems to be paid to the more important problem of the assessment of thermodynamic performance. Colonna and Gabrielli [15] studied tri-generation plants consisting of gas turbines and internal combustion engines driving ammonia-water absorption chillers. They defined an index of electric equivalent efficiency without, however, taking into account the various modes of energy encountered in tri-generation. Nevertheless, they confirmed the expected superiority of internal combustion engines over gas turbines by comparing the cold produced by tri-generation with that generated by a conventional compression chiller plant. In an interesting paper, Pépin Magloire and Bolle [16] linked the performance of tri-generation to that of co-generation, a century-old proven technology. Their "index d'économie d'énergie primaire" (index of primary energy economy) provides a useful measurement of performance. Later, Minciuc et al. [17] have shed some light on the calculation of the energy conversion efficiency of a tri-generation configuration by defining "energy

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Nomenclature

COP_c	cooling coefficient of performance
COP_h	heating coefficient of performance
ECR	energy conversion ratio
$\dot{E}_{load}$	electricity load [kW]
$\dot{H}$	energy rate equivalent of fuel consumption [kW]
$\dot{Q}$	heat transfer rate [kW]
$\dot{Q}^i_{cd}$	rate of heat transfer from condenser of chiller i [kW]
$\dot{Q}_{cooling}$	cooling load [kW]
$\dot{Q}_{heating}$	heating load [kW]
$\dot{Q}_{recovery}$	rate of total heat recovery [kW]
R_{CE}	cooling-to-electricity load ratio
R^*_{CE}	limit cooling-to-electricity load ratio
R_{FE}	energy rate equivalent of fuel consumption to electricity load ratio
R^*_{FE}	limit fuel consumption energy rate equivalent to electricity load ratio
R_{HE}	heating-to-electricity load ratio
R^*_{HE}	limit heating-to-electricity load ratio
$\dot{W}$	shaft power [kW]
$\dot{W}^i_{cp}$	shaft power to drive compressor of chiller i [kW]
x	fraction of the heat recovered from the exhaust and water cooling that goes to the building heat exchanger

Greek letters

α	fraction of heat engine energy-equivalent fuel consumption rate
Γ_{he}	overall heat recovery efficiency from heat engine
ε	heat recovery efficiency of heat exchanger
λ	cooling load distribution ratio
Σ_c	overall cooling efficiency factor
Σ_h	overall heat pump heating efficiency factor
η	efficiency

Subscripts

bo	boiler heat exchanger
bx	building heat exchanger
c	cooling
cd	condenser
co	heat engine coolant
cp	compressor
eg	electric generator
es	heat engine shaft
ev	evaporator
ex	heat engine exhaust
h	heating
he	heat engine
pb	peak boiler or pressurized auxiliary boiler
st	steam turbine
total	total

Superscripts

ac	absorption chiller
ec	electrically driven vapor compression chiller
sc	steam turbine driven vapor compression chiller

production” and “energy structure” indices to assess thermodynamic performance.

The aim of the present work is to derive an expression for the overall energy conversion efficiency of typical tri-generation systems in terms of two non-dimensional parameters, the heating-to-electric and the cooling-to-electric load ratios and in terms of the efficiencies of the system components. First, a generic tri-generation system is studied, followed by the application of the criterion to two practical cases.

2. Generic tri-generation system

2.1. System description

Fig. 1 shows, schematically, the system in question. A heat engine, which may be a gas turbine, a reciprocating internal combustion engine or even a Stirling engine, drives an electric generator. Electricity from the generator is used to power the vapor compression chiller which, apart from producing cold, rejects heat from the condenser. The electricity demand is met by the surplus of electricity production from the generator whereas the heat demand is met by recovering heat from the heat pump and from the heat engine exhaust gases and, in the case of reciprocating engines, from the coolant system as well. A heat recovery boiler extracts rejected heat from the engine exhaust gases, supplying steam to a steam turbine which, in turn, drives a vapor compressor chiller. Heat is recovered from the condensers of the three heat pumps. Such a generic system will hopefully be of use in the assessment of real systems.

The heat engine is characterized by the fuel energy distribution, to the shaft, exhaust and coolant, α_{es}, α_{ex} and α_{co}, respectively. The sum of α_{es}, α_{ex} and α_{co} is not necessarily equal to 1, as there are heat losses that are not recovered. In this generic case, it is assumed that the temperature at which heat is recovered from the engine coolant is high enough to drive the absorption chiller. In the case of a gas turbine, heat is extracted from the exhaust only, as there is no coolant fraction, and the two values of α take a different representation, corresponding to the fuel energy fractions that go to the heat recovery boiler and to the absorption chiller. The efficiency of the heat recovery boiler is ε_{ex}. The corresponding Rankine cycle, required for the conversion of steam from the heat recovery boiler to the steam turbine shaft work, is not represented in Fig. 1, its overall efficiency being characterized by η_{st}. Each heat pump, the electrically driven vapor compression, the steam turbine driven vapor compression and the absorption chillers, are each represented by a pair of COPs, for heating and cooling. Again, in contrast to the case of an ideal heat pump, the difference between the two COPs, heating and cooling, may not be equal to unity, due to the heat losses and gains.

The diagram of Fig. 1 shows that the tri-generation scheme runs entirely on a single energy source (denoted by “fuel”) and has three so-called energy products, namely heat, refrigeration and electricity.

2.2. Thermodynamic model

The following assumptions are made:

(a) The vapor compression and absorption chillers are sized to supply the entire cooling load;
(b) the heat engine/electric generator compound is designed to provide sufficient power to meet the electricity demand and to drive the heat pump compressor;
(c) the temperature at which rejected heat is recovered is sufficiently high to meet the heat load demand and to drive the absorption chiller.

These assumptions deserve some comments. A peak boiler is indispensable in meeting the heat demand as all (energy) demands are hardly ever met at the same time (e.g., Teopa Calva et al. [18]). Furthermore, only a high temperature heat rejection is