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Parametric investigation and optimization of an innovative trigeneration system

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ABSTRACT

The new technological trends are focused on the development of sustainable systems for covering the energy needs in buildings, using renewable energy sources and minimizing the carbon dioxide emissions. In this direction, the development of innovative trigeneration systems is an intelligent solution for creating energy efficient buildings which can satisfy their energy needs. In this paper, an innovative trigeneration system which uses low temperature level heat sources is analyzed and optimized. This system is consisted of an absorption heat pump and a steam turbine which consumes a part of the produced steam in the generator. This system is able to produce electricity, heating, cooling and hot water, covering the typical energy needs of buildings. Various scenarios are examined parametrically in order to present the system performance for various operation conditions. The final results proved that the exergetic efficiency is about 72% and the electrical output close to 9 kW, when a heat input of 100 kW is given. By selecting the proper parameters, the outputs of the system can be distributed according to the building energy demands, something very important for the sustainability of this system. The analysis is performed with the Engineering Equation Solver (EES).

1. Introduction

The role of energy consumption has a great importance in new societies because of the increasing living standards. Building sector is responsible for the 35% of the worldwide energy consumption [1]; a high value which influences on the energy markets and the energy policies, especially in the developed countries. In this direction, the EU members have been made agreements for reducing the energy consumption in all the domains and especially in the building sector [2]. Numerous directives have been implemented, with Directive 2010/31/EU [3] and Directive 2012/27/EU [4] on building energy performance and efficiency respectively, to be the most important. According to these directives, the buildings have to be more efficient, consuming fewer amounts of energy and using renewable energy sources in order to minimize the primary energy consumption. In the same direction, Kyoto's protocol indicates 20% renewable energy utilization, 20% reduction of CO_2 emissions and 20% more efficient buildings. Moreover, all the EU countries have adopted extra energy policies for enhancing the sustainability in the building sector. The most characteristic example among Europe countries is the Danish government which set as a goal to create a fossil fuel free energy system up to 2035 [5]. In order to achieve this challenging goal, the energy consumption in buildings has to be diminished up to 50% [6].

The utilization of renewable energy sources is an issue of high importance because it determines the sustainability of these policies. Wind energy, solar energy, geothermal energy and biomass are the main representatives of the green energy sources. Wind energy can only be transformed to electricity, while the other renewable energy sources are able to give electricity and heating; something that makes them ideal for the building sector which is characterized by high heating demand. Solar and geothermal energy are the most abundant energy sources, while biomass supply is more restricted. For this reasons, solar and geothermal energy sources [7] are the most appropriate renewable energies for direct utilization in buildings. The usual temperature levels that these sources can operate are up to 150 °C without concentrating technology; fact that shows the need of creating efficient systems operating in this temperature levels. On the other hand, in the case that concentrating collectors, as parabolic trough collectors, are selected, higher temperature levels (above 200 °C) can be succeeded and polygeneration/trigeneration systems of higher scale can be created.

Cogeneration, tri-generation and polygeneration systems for buildings are promising technologies for covering the building

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Nomenclature

E	exergy flow, kW
h	enthalpy, kJ/kg
L	mass ratio, –
m	mass flow rate, kg/s
P	pressure, kPa
Pel	electricity, kW
Q	heat rate, W
s	specific entropy, kJ/kg K
T	temperature, °C
X	LiBr mass concentration in mixture, –

Greek symbols

η	efficiency, –

Subscripts and superscripts

a	absorber
am	ambient
c	condenser
cool	cooling
e	evaporator
ex	exergetic
heat	heating
hex	heat exchanger
is	isentropic
g	thermal generator
G	electric generator
mg	mechanical-generator
opt	optimum
r	refrigerant
s	strong solution
sat	saturation
u	useful
w	weak solution

Abbreviations

EES	engineer equator solver
LiBr	lithium bromide

energy demands. Using these systems, electricity, space-heating, space-cooling and hot water can be produced in order the building energy needs to be covered totally or partially. In the literature, many researchers have investigated polygeneration and trigeneration systems in order to satisfy building demands by using solar energy. The design and the optimization of these systems is a difficult task because many parameters have been taken into account, as the load demand profiles, the environmental conditions and the varying prices of the electricity and of the fossil fuels [8]. Soutullo et al. [9] examined many study cases of using renewable energy sources in building for 3 cities in Spain. More specifically, they examined the use of solar energy and wind energy for covering the electrical needs and they tried to maximize their contribution to the total energy demand. Bingöl et al. [10] examined two innovative polygeneration systems energetically and exegetically and finally they proved that the total exergetic efficiency is greater than 60%; fact that proves proper energy utilization. Moreover, they concluded that the most suitable way for evaluation the polygeneration system is the use of exergy terms. Mohan et al. [11] analyzed a polygeneration system driven by solar collector energetically and financially. They finally concluded that the use of solar energy as heat source is able to lead to an accepted payback period of approximately 9 years. Wu et al. [12] examined a trigeneration system for cooling, heating and electricity production, operating with waste heat. They calculated the outputs in many study cases and they gave emphasis in the control and the management of the system. Baghernejad et al. [13] studied an innovative trigeneration system driven by parabolic trough collectors. This system uses an absorption heat pump coupled with a Rankine power cycle. More specifically, the power cycle rejects heat to the generator of the absorption heat pump and by this way the two subsystems are coupled. They conducted an exergoeconomic analysis and finally the managed to reduce the system cost close to the half. Hands et al. [14] investigated a solar trigeneration system with solar desiccant air conditioning in Australia and they proved high reduction in the natural gas consumption. Geothermal energy utilization is studied from Zare [15] in a recent publication. He coupled a simple Organic Rankine Cycle with an absorption heat pump in order to produce heating-cooling-electricity and a Kalina cycle with an absorption heat pump. He concluded that for heat source temperature of 120 °C, the Kalina cycle case is the most appropriate, based on exergetic criteria. Similar systems with ORC and absorption heat pumps were investigated by Al-Sulaiman et al. [16,17]. They examined the use of parabolic trough collectors, biomass boiler and solar oxide fuel cell in a trigeneration system and finally they concluded that the use of solar energy is the best choice. Zhao et al. [18] designed an interesting trigeneration system with an absorption heat pump, an internal heat engine and heat exchangers. The mean exergetic performance of this system is about 37% and the recovered time for this investment about 5.5 years; fact that proves the sustainability of this technology. Wang et al. [19] designed a trigeneration system with solar collectors, ejector, turbine and heat exchanger for heating, cooling and power production. This system was optimized with a multi-objective optimization procedure. They found a set of optimum solutions and they stated that every solution is suitable for a different case with its own demand profiles for heating, cooling and electricity.

On the other hand, there are also many studies where internal combustion engines or boilers are applied in trigeneration or polygeneration systems. Characteristic example is the work of Fong and Lee [20] where their design leads to high reduction of carbon dioxide emissions. Piacentino et al. [21] investigated the high efficiency criteria for combined heat and power systems and they concluded that storage tank capacity and load provision are very important parameters.

In this study, an innovative trigeneration system for producing electricity, cooling and heating is presented. This system is a new configuration which contains an absorption heat pump coupled with a steam turbine. The produced steam from the heat generator is separated and it is delivered partially to turbine and to condenser. By regulating these quantities, the system output can be adjusted to the building needs. An extra advantage of this system is the possibility of operating with renewable energy sources, because the heat source temperature levels have to be up to 150 °C, according to the results. More specifically, evacuated tube collectors seem to be an ideal solution for the presented system, because these collectors can efficiently operate in these temperature levels. The current approach is a thermodynamic analysis and optimization in order to predict the system performance in