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Design and evaluation of a micro combined cooling, heating, and power system based on polymer exchange membrane fuel cell and thermoelectric cooler

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ABSTRACT

The main purpose of the present study is to propose a combined cooling; heating and power cycle in microscale to be portable, maintenance free, undetectable, environmentally friendly and can provide the energy demand of a single-family when access to energy suppliers is limited. The prime mover of the cycle is a polymer exchange membrane fuel cell. Heat is recovered from a low-quality waste of 80 °C and water condensate is also recovered from the electrochemical products for domestic hot water. A thermoelectric cooler is used as the cooling system. The mathematical models of the fuel cell and the thermoelectric cooler are coded and the results of simulations are validated with the published data in the literature. The results show that the models are qualified and they can be trusted to be combined for proposing a new micro combined cooling, heating, and power system. The results show that the cycle is capable of producing 2.79 kW of electricity, 3.04 kW of heat and 26.8 W of cooling. The overall efficiency of the trigeneration cycle has reached 76.94% and a fuel saving of 43.25% is achieved. The exergy efficiency is 53.86%. In addition, the carbon dioxide production has reduced about 2.58 kg. hr^{-1}. The overall weight of the proposed cycle is estimated less than 100 kg. The exergy analysis introduces the fuel cell as the most exergy destructor.

1. Introduction

The world population has increased and human lifestyle has changed due to demanding high-quality comfort conditions that need consuming energy to be fulfilled. As a result, the footprint of electricity can be found in every corner of earth planet. In addition, heating and cooling are vital to reaching the requested standards of comfort conditions. As a result, the fuel consumption and air pollution have increased and new threats are emerging from the present human lifestyle. Limited energy resources, global warming, and air pollution are among the most dangerous threats that may vanish human civilization from the planet that used to be green.

Energy Information Administration (2016) reported that 14.77% of the world total electricity was provided by all renewable energy resources, 84.88% by different fossil fuels and the remaining 0.33% by other energy resources. International Energy Outlook has predicted that the share of renewable energy in the world total energy demand would increase to 16% until 2040 while the remaining 84% would be provided by the fossil fuels. These statistics and predictions reveal that the fossil fuels play the main role as the human energy resource up to 2040 [1]. Accordingly, improving the existing energy processes is vital to reduce air pollutants and increase the energy conversion efficiency in energy systems. Since most of the energy users need electricity, cooling and heating simultaneously, the combined production of cooling, heating, and power (CCHP) is an alternative to increase the overall efficiency while providing the energy demands locally. Local CCHP systems not only give the opportunity to use the waste heat of the power generator unit (PGU) but also omit the electricity grid losses.

Portable micro-CCHP systems that can provide the energy demands of a single family for inaccessible electricity grid situations are highly demanded and favorable especially if they could be highly efficient, silent, undetectable and environmentally friendly. This research is devoted to propose and design a micro-CCHP system with such characteristics.

To achieve such characteristics the PGU of the CCHP should be silent, has recoverable waste heat, and electrically efficient. In addition, the cooling system should be silent, light and compact as well.

Different PGUs such as micro-gas turbine, micro-steam turbines, Stirling engines, fuel cells and reciprocating internal combustion engines in microscale can be utilized in the micro-CCHP [2].

Micro-gas turbines are available in the capacity ranges from 15 kW to 250 kW for electricity production, the exhaust gas temperature

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Nomenclature

Abbreviations and symbols

A_{cell}(m^2)	cell area
A(m^2)	sectional area of the element
CCHP	combined cooling, heating and power
C(kJ. kg^{-1}. K^{-1})	specific heat capacity
COP	coefficient of performance
COP_e	coefficient of performance of the electrical chiller
conv	conventional systems
DHW	domestic hot water
E(W)	electricity
F(C.mol^{-1})	Faraday's constant
h(J. kg^{-1})	enthalpy
h_{cell}(W. m^{-2}. K^{-1})	air convection heat transfer coefficient
H_V(J.mol^{-1})	heat of evaporation of water
HHV_{H2}(J.mol^{-1})	higher heating value
i(A. cm^{-2})	current density
i_o(A. cm^{-2})	current density
I(A)	current
L (m)	element length
K (W. m^{-1})	thermal conductance of thermoelectric module
k(W. m^{-1}. K^{-1})	thermal conductivity of thermoelectric module
N_{cell}	number of cells
n_e	number of transmitted electrons
n	number of TEC modules
N	number of pairs of thermocouples in each TEC module
P (bar)	pressure
PEMFC	polymer exchange membrane fuel cell
PGU	power generation unit
PHE	plate heat exchanger
pp	power plant
P_{H_2O}(bar)	water saturation pressure
P_{H_2}(bar)	partial pressure of hydrogen
P_{O_2}(bar)	partial pressure of oxygen
P_{inc}(W)	input power
Q_c(W)	cooling capacity
R(J. mol^{-1}.K^{-1})	constant of gases
R(Ω)	electrical resistance of the thermoelectric module
T_{FC}(K)	temperature of the fuel cell
T_H(K)	hot side temperature
T_L(K)	cold side temperature
T_o(K)	ambient temperature
t_{FC}(°C)	temperature of the fuel cell
t_m(m)	membrane thickness
TEC	thermoelectric cooler
s(J. kg^{-1}. K^{-1})	entropy
V_{act}(V)	activation voltage loss
V_{conc}(V)	concentration voltage loss
V_{ohm}(V)	Ohmic voltage loss
$\dot{w}$(W)	power
X_{H_2O}	saturation molar fraction
$X_{N2,in}$	nitrogen mole fraction at the inlet
$X_{N2,out}$	nitrogen mole fraction in the outlet
α(μv. K^{-1})	seebeck factor for the thermoelectric thermocouple
β	exergy efficiency
α_T(μv. K^{-1})	total seebeck factor for a thermoelectric module
λ_{air}	air stoichiometric ratio
ε	emission coefficient
μ	membrane moisture content
σ(W. m^{-2}. K^{-4})	Boltzmann's constant
σ_m(m.Ω^{-1}.)	membrane conductance
η	efficiency
Φ(W)	exergy rate
ψ(J. kg^{-1})	specific exergy
Δ(W)	exergy destruction

Subscripts and superscripts

a	actual
b	boiler
act	activation
amb	ambient
comb	combustion
comp	compressor
c	cold
conc	concentration
cons	consumed
ele	electromotor
gen	generated
h	hot
ohm	Ohmic
inc	input cooling
FC	fuel cell
PEMFC	polymer exchange membrane fuel cell
l	liquid
m	membrane
s	isentropic
sat	saturated

ranges from 240 to 310 °C that is proper for heating and potential thermally activated cooling systems such as absorption and adsorption chillers [3]. However, the minimum capacity of the micro-gas turbine which is commercially available is 15 kW which is really big for a single family and portable demands. They are rather noisy (65 dB at 10 m distance at full load) and their electrical efficiency in this size is about 23%. The dimensions of a 15 kW micro gas turbine are $0.76 \times 1.5 \times 1.9$(m)and its weight is 578 kg. These characteristics cross the micro-gas turbine out as a candidate for the target micro-CCHP [4].

Micro-steam turbines which are mostly used in organic Rankine cycles are commercially available in electrical capacity of 275 kW and dimensions of $0.86 \times 1 \times 2$(m). They also need a micro steam generator, condenser and a feed pump [2]. According to the large size and capacity, the micro-steam turbine cannot be considered as the prime mover of a portable micro-CCHP.

Stirling engines, the reciprocating external combustion engines are available in three types of α, β, and γ. SOLO Stirling 161 uses helium as the operating gas. Helium is heated by an external burner to about 650 °C in the heater. The exhaust temperature is about 800 °C that is used for preheating of the combustion air to about 600 °C. The exhaust finally leaves the engine at 85 °C, the net weight is 460 kg and its dimensions are $0.98 \times 0.7 \times 1.28$(m). Its electrical output ranges from 2 to 9.5 kW with an electrical efficiency of 22–24.5%. The operating maximum pressure is 150 bar [5]. This engine is silent but its electrical efficiency is rather low. In addition, its weight and dimensions are rather big and the very high operating pressure of 150 bars is dangerous for portable applications.

Fuel cells are silent PGUs that have higher electrical efficiency with respect to rotary and reciprocating engines. No combustion exists inside a fuel cell, instead, some electrochemical reactions happen and the outputs include electricity, heat, and water. Fuel cells are available in different types of Alkaline (AFC), Proton Exchange Membrane (PEMFC), Direct Methanol (DMFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC), and Solid Oxide (SOFC). They have been compared