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Enhanced power generation through integrated renewable energy plants: Solar chimney and waste-to-energy

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ABSTRACT

In the present paper, a novel method is proposed to enhance the power production and resolve the inconsistent electricity generation of solar chimney power plants (SCPPs) during nighttime. For this purpose, an integrated renewable cycle is proposed by incorporating two technologies: solar chimney and waste-to-energy. The combination is performed by exploiting the warm air of the condensers outlet into the SCPP. The waste-to-energy (WTE) plant in Tehran is thermodynamically analyzed and the mass flow rate of the condensers cooling air is found. Results indicate that by decreasing the humidity of the municipal solid waste (MSW) from 40% to 30% or by increasing MSW feeding rate (0.934–1.146 kg/s), the mass flow rate of the condenser cooling air increases from 190.3 kg/s to 233.7 kg/s. In addition, by increasing the feeding rate or by decreasing the humidity of MSW in the mentioned range, net power output of the WTE plant increases from 1350 kW to 1650 kW. The best injection method is proposed for the warm air of the condensers outlet into the SCPP. Subsequently, the average power increase is examined in different months and parametric study is performed to assess the influence of the effective WTE parameters and meteorological variables on the power output of the SCPP. The final power of the SCPP reaches 20–70 kW (even at the hottest night of the year with 5% relative humidity) and increases 20–1200% and 65–94% (monthly average) compared to the case of without injection. Results demonstrate that in the integrated system, by a 22% increase in the MSW feeding rate (from 0.934 kg/s to 1.146 kg/s) or by decreasing the MSW moisture content (from 40% to 30%), power output of the WTE plant and SCPP increases by 22% and 7%, respectively. Additionally, relative humidity of the surrounding air can increase the SCPP power production by 25%. In addition, the results indicate that wind speeds higher than 12.5 m/s will not affect power production of the SCPP, while relative humidity of the surrounding air, ambient temperature, the MSW feeding rate, and humidity of the MSW have considerable effects on the SCPP power production. In average, total energy and useful exergy efficiency of the proposed system is increased by 0.15% and 0.12% compared to the standalone WTE plant during nighttime. The integration of SCPP with the WTE plant is an applicable method to enhance the power generation and overcome the inconsistent power production of SCPP during nighttime.

1. Introduction

Increased fossil fuel consumption and their environmental pollutants has been the major driving force for many researches on renewable energies. In 2016, total world renewable energy capacity was about 2 TW, counting for 3% of the total energy capacity; in which the share of bioenergy, renewable municipal solid waste, and solar energy was 110 GW, 16 GW, and 296 GW, respectively [1]. Electricity production using the renewable energies in Iran was reached 11 GW in the same year (32 MW, 3 MW, and 11 MW of solar, municipal solid waste, and bioenergy, respectively), showing a considerable increase of 41% from 2010 [1]. The most important advantages of using biomass resources in energy conversion systems are: continual availability, low gas emissions, and the ability to produce various biofuels [2].

1.1. Biomass gasification

Various methods are available for biomass conversion: thermochemical, physicochemical, and biochemical [3]. The only waste-to-energy plant in Tehran produces 3 MW electricity based on the gasification technology.

Recently, many researchers analyzed gasification methods, biomass-

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Nomenclature

A	area (m^2)
C_p	specific heat at constant pressure (J/K)
C_{Th}	thrust coefficient
$\dot{E}_x$	exergy rate
$\bar{e}$	exergy
G	solar radiation (W/m^2)
g	gravity (m/s^2)
h	enthalpy
h_r	irradiative heat loss coefficient (W/m^2 K)
$\bar{h}_f^{\circ}$	enthalpy of formation
h_w	free convective heat loss coefficient (W/m^2 K)
i	exergy destruction (irreversibility)
m_{steam}	mass of steam
$m_{dry,air}$	mass of dry air
$\dot{m}$	mass flow rate (kg/s)
$n_1, n_2, \ldots, n_{10}$	mole value
n'	mole of secondary air
P	pressure
$\dot{Q}$	heat rate (kW)
$\bar{R}$	gas constant (J/kg K)
s	entropy
T	temperature (K)
V	velocity (m/s)
w	amount of moisture per kmol of MSW
$\dot{W}$	power output (kW)
y_i	mole fraction
z	meters above sea level (m)
z_C	mass fraction of carbon
z_H	mass fraction of hydrogen
z_O	mass fraction of oxygen

Abbreviations

CETD	cold end temperature difference
HHV	higher heating value
LHV	lower heating value
MC	moisture content
MSW	municipal solid waste
SCPP	solar chimney power plant
WTE	waste-to-energy

Greek letters

ε	collector emissivity
η	efficiency
σ	Stefan–Boltzmann constant
η_f	friction loss coefficient
ψ	exergy-to-energy ratio for radiation
β	lapse rate, $\beta = 0.0065$ (K/m)
ϕ	relative humidity (%)
ρ	density (kg/m^3)

Subscripts

0	sea level condition
1,2,…,21	state point
CC	combustion chamber
CO	condenser
coll	collector surface
dyn	dynamic
ex	exergy
G	gasifier
I	thermal (first law of thermodynamic)
in	inlet
is	isentropic
out	outlet
P	pump
P.P	pinch point
S	solar
SG	steam generator
ST	steam turbine
sat	saturation
stat	static
sup	superheat
T	SCPP turbine
tot	total
v	vapor

Superscripts

sp	specific
ch	chemical

based systems, and integrated biomass systems to investigate their performance. Shijaz et al. [4] analyzed integrated gasification combined cycle power plant incorporating chemical looping combustion. Their main idea was introducing a chemical looping combustion, which enables the CO_2 capture without any efficiency reduction. The results showed that the efficiency of the integrated plant is 40.2% for a CO_2 capture efficacy of 99.97%. Prakash et al. [5] proposed a new method for gasification with heat and power generation. Syngas with different H_2/CO ratios has been extracted for utilizing in various applications. They investigated the effect of important parameters: biomass feeding rate, moisture content, type of biomass, and reactor temperature. Gholamian et al. [6] proposed a new biomass-based cogeneration system with wood and paper. They indicated that using wood and paper as feed material leads to 40.11% and 39.12% exergy efficiency, respectively. Also, a CO_2 emission of 4.99×10^{-2} t/MWh and 4.95×10^{-2} t/MWh was calculated for wood and paper, respectively.

1.2. Solar chimney power plant

Solar chimney power plants (SCPP) are among the renewable energy technologies with high potential all over the world. SCPP consists of three main parts: first, solar collector to absorb solar heat, second, tower that is generally placed at the center of the collector, and third, turbine which can be installed inside the tower or within the collector area [7]. Solar radiation heats up the air under the collector and thereafter air passes through the turbine and produces electricity. Unlike solar cells, SCPP can operate day and night, since the pressure difference always exists between the inlet and the outlet of SCPP [8]. Zanjan (Iran) and Manzanares (Spain) are examples of such SCPP models with the basic components.

Recently, many researchers studied the design, energy and exergy aspects and power enhancement methods of the SCPP [9–12]. Haaf et al. [13] are among the first researchers who tested the SCPP prototype in Manzanares in 1983. They reported that the SCPP power output would be 50 kW at 1000 W/m^2 solar irradiance.

Patel et al. [9] optimized the SCPP by varying the collector inlet and outlet diameters from 0.05 m to 2 m and 0.6 m to 1 m, respectively, at different chimney divergent angles (0° to 3°) and diameters (0.25 m to 0.3 m). Kasaeian *et al.* [10] simulated and optimized the geometric parameters of an SCPP in Tehran climate; indicating that the best values for the effective parameters of the SCPP would be 6 cm for the collector inlet, 3 m for the chimney height, and 10 cm for the chimney diameter.