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Designing a micro Stirling engine for cleaner production of combined cooling heating and power in residential sector of different climates

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ABSTRACT

In the present study the structure of an Alpha-type Stirling engine is designed which is capable of operating in reasonable operating condition ranges. The Alpha-type Stirling engine is simulated by GT-Suit program and the Solo V161 experimental data are used to validate the numerical model. The structure of the engine is kept constant and operating parameters such as, pressure, engine speed, temperature of the heater and working fluid are changed for using in a sample residential building in different climates. The engine is used for combined production of cooling, heating and power in micro scale (micro-CCHP). Three methods including following electrical load (FEL), following thermal load (FTL) and overall efficiency of the cycle are used for engine sizing. The maximum overall efficiency of the micro-CCHP ranges from 79% to 88% in different climates. The results show that both FEL and overall efficiency propose the same engine size and the highest overall efficiency for every climate. Furthermore, the reduction of environmental pollutants of CO_2, CO, and NO_x are calculated. The maximum CO_2 reduction for every climate is more than 40%. In addition, leaking that usually occurs in this type of engine is lowered by operating at considerably lower pressure.

1. Introduction

In conventional way of producing energy (SCHP: Separated producing of cooling, heating and power), electricity is generated in centralized power plants, transmitted and distributed through the national electricity grid. The required heating and cooling loads are provided either by using the grid electricity or utilizing other resources such as fossil fuels, and renewable energy sources. In this method, the overall efficiency of the power plant including the transmission and distribution processes, is estimated to be about 30%, in addition, producing heating and cooling loads have their own losses as well (Ebrahimi and Keshavarz, 2015).

In contrast, in the CCHP systems, a prime mover is used to generate the electricity in the vicinity of the consumer, so the transmission and distribution costs and losses are omitted. Furthermore, utilizing the waste heat of the prime mover to produce the heating and cooling loads increases the efficiency of the CCHP systems up to 80% (Fig. 1) (Ebrahimi and Keshavarz, 2015).

In comparison with the conventional systems, CCHP systems are more efficient in using primary fuel energy; environment friendly, and quick return on investment if well designed.

Up to 30% fuel can be saved in CCHP systems compare to the conventional methods. As a result, less pollutants and greenhouse gas are produced, and less money is invested on providing and distributing the fuel. For the same amount of cooling, heating, and electricity, CCHP systems produce 50% less CO_2 compare to SCHP systems (Ebrahimi and Keshavarz, 2015).

The fact that the fossil fuels will be the main energy source for human beings in many decades ahead, shows that the existing energy processes need to be optimized in order to reduce emissions and increase the overall efficiency of energy conversion (Ebrahimi, 2017). Recently, Ebrahimi (2017) proposed and thermodynamically simulated a CCHPP cycle to evaluate the feasibility of implementation of the installed existing units of gas turbines for CCHPP. By considering various factors, such as remaining lifetime of the gas

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Nomenclature

CCHP	Combined cooling, heating and power
FEL	Following electrical load
FTL	Following thermal load
FSS	Following seasonal strategy
HETS	Hybrid electric thermal system
Q_{hw}	Required heat for domestic hot water
LR	Load ratio
$\dot{m}$	Boundary mass flux into volume
A	Flow Area
COP	Coefficient of performance
E_{dem}	Electrical demand
V_r	Volume flow rate
C_f	Skin friction coefficient
T_f	Fluid temperature
D	Equivalent diameter
dp	Pressure differential acting across dx
h	Heat transfer coefficient
m	Mass of the column
SCHP	Separated producing of cooling, heating and power
F	Fuel
η_E	Electrical Efficiency
η_{0-CCHP}	Overall Efficiency of CCHP cycle
C	Cooling Load
Em	Emission production
H'	Heating produced by the auxiliary boiler
CCHPP	combined cooling, heating, power and process
u	Velocity at boundary
ρ	Density
P_H	Expansion space (hot cylinder) pressure
P_C	Compression space (cold cylinder) pressure
T_H	Temperature of hot cylinder
T_C	Temperature of cold cylinder
Q_{in}	Input heat to the engine (kW)
Q_{out}	Exhaust heat out of the engine (kW)
η	Efficiency (%)
ICE	Internal combustion engine
Q_{dem}	Heat demand
e	Total internal energy
C_p	Pressure loss coefficient
T_w	Wall temperature
dx	Discretization length
H	Total enthalpy
A_s	Heat transfer surface area
E_P	Electricity generated by engine
rec	Recoverable
j	0, 1 for SCHP and CCHP respectively, as superscript
η_{pp}	Power plant efficiency
H	Heating Load
D	Hot Water Demand Load
C'	Cooling produced due to the heat of auxiliary boiler
η_{grid}	Grid efficiency

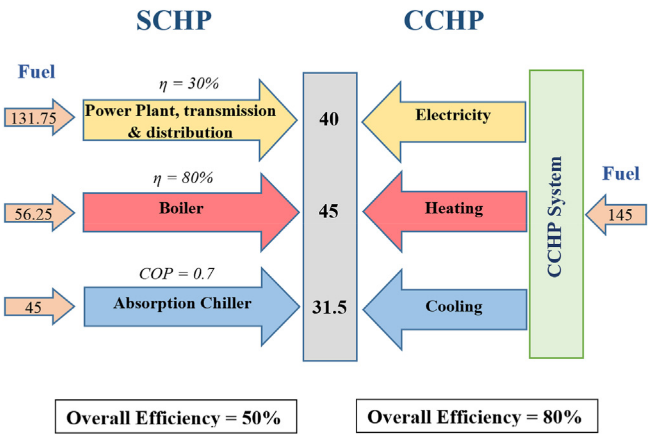

Fig. 1. Comparison between SCHP and CCHP systems.

turbine, climate, payback period, etc. It was estimated that CO_2, CO, and NO_X emissions reduce more than 52,000, 36 and 44 tons per year.

Yong et al. (2016) reviewed modeling, simulation, optimization and waste management that have been done for cleaner production. The main plans and technologies that recently were used for more efficient energy conversion, cleaner energy sources and biofuels, less emitting production, CO2 capture, optimization and waste energy management that can be used in the operating industry or become a cornerstone for the future development and investigations have been reviewed in this article. Schulze et al. (2016) studied energy management in industry to reduce energy consumption and related costs. They introduced some key parameters that are essential for energy management. They include strategy/planning, implementation/operation, controlling, organization and culture. Allouhi et al. (2015) analyzed the energy consumption and emission production of buildings around the world. They discussed policies, strategies, monitoring, etc implemented in different countries. Huisingh et al. (2015) evaluated carbon emission reduction potentials in different sectors of industrial, construction etc for different scales. They proposed that to reduce emission production, human need a drastic change from the present situation toward low/no fossil-carbon economies.

According to the report released by U.S. Energy Information Administration in 2014 (U.S. Energy Information Administrati, 2014), in 2012 the residential and commercial sectors allocated 39.68% of the total energy consumption to themselves. In addition, it is predicted that the energy consumption of these sectors to be 39.20% and 41.07% for the years 2025 and 2040, respectively (Ebrahimi and Keshavarz, 2015; U.S. Energy Information Administrati, 2014). Therefore, these sectors will be good targets to improve energy consumption characteristics.

All the mentioned advantages of the CCHP systems, along with many new and different job opportunities that could be created by this new technology, are beneficial for both governments and consumers. Although using CCHP systems increases the capital cost for the consumers, this cost is compensated within a reasonable time by lower fuel bills (due to the less fuel consumption), no payments for electricity bills, and selling electricity to the national grid (Ebrahimi and Keshavarz, 2015).

A common CCHP system is shown in Fig. 2. This system is comprised of a gas turbine, a generator, and an absorption chiller.

A CCHP system includes five main components; prime mover, electrical generator, heat recovery system, thermally activated cooling equipment and control system. Having studied the available technologies, the gas turbines, reciprocating internal