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Comparative assessment of the effectiveness of a free-piston Stirling engine-based micro-cogeneration unit and a heat pump

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ABSTRACT

In this article, a comparison of the thermodynamic and economic effectiveness of two heating systems dedicated to residential applications is presented: a natural gas-fueled micro-cogeneration unit based on a free-piston Stirling engine that generates additional electric energy, and a heat pump system. The measurements of the heat pump system as well as those of the energy (electricity and heat) demand profiles in the analyzed heating season were conducted in a single-family house. The measurements of the μCHP unit were made using a laboratory stand prepared for simulating a variable heat demand. The efficiency of electric energy generation in the μCHP unit was in the range of 7.2%–12.7%, and the overall efficiency was in the range of 88.6%–92.4%. The economic evaluation of the μCHP unit revealed a slight loss compared to the operation of the heat pump throughout the heating season. Sensitivity analysis of the unit price of natural gas and electric energy was performed, and revealed that a reduction in the gas price or an increase in the purchase price of electricity at 2% would have a beneficial financial effect when operating a μCHP system as compared to a heat pump.

1. Introduction

The main objectives of the European Union in terms of the energy policy are focused on reducing pollutant emissions, increasing the use of renewable energy sources and increasing energy security, most often understood as the diversification of fuel types used for energy production. An integral part of these objectives is the development of distributed generation, including prosumer energetics. With an appropriate transformation of the legal and economic environment with respect to low-emission sources, the beneficial economic indicators should be justified by increasing the micro-cogeneration (μCHP) thermodynamic potential. Improving equipment efficiency and developing novel operation strategies must be an integral part of the effort to implement new energy generation schemes. It is postulated that one of the priorities for the energy infrastructure is the need to invest in smart, efficient, and competitive power grid solutions based on decentralized sources including, primarily, renewable sources and μCHP sources. In particular, μCHP units are intended to be a remedy for reducing the load of centralized energy systems and enabling the active participation of final consumers (called prosumers) in energy management [1,2].

Prosumer μCHP systems are dedicated to residential applications. One of the ways to generate heat and power in a single family-house is a Stirling engine-based CHP system. Stirling engines, known since 1816, have an excellent operation culture and reliability. These engines were classified into three basic categories: alpha, beta, and gamma [3,4]. The basic classification changed in 1964, when William T. Beale (University of Ohio, USA) introduced a new beta engine-based design. Currently, two basic categories of Stirling engines are distinguished as follows [5]:

- Engines that use the reciprocating motion of the power piston for the rotating motion through the crankshaft and variable working mechanisms. The displacer is moved by a mechanical system.
- Free piston engines, characterized by no rotating parts. The displacer is moved by changing the pressure, and power is generated using a linear alternator located on the power piston [6].

A free-piston Stirling engine (FPSE) is characterized by a lack of mechanical linkage between the moving piston and the crankshaft, which minimizes the possibility of failure. The movement of the

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Nomenclature

c	unit price, PLN/kWh, PLN/m^3_n
CHP	combined heat and power
COP	coefficient of performance
E	energy, kWh, kWh/day
FPSE	free piston Stirling engine
K	costs, PLN
LHV	lower heating value, MJ/m^3_n
N	electric power, kW
n	number of days
OM	operating mode
P	amount of fuel, m^3
Q	heat, thermal power, kWh, kW
T, t	temperature, °C
V	volume, m^3
$\dot{V}$	volumetric stream, m^3/s
λ	coefficient of thermal conductivity, W/m^2K
μCHP	micro-cogeneration
η	efficiency
τ	time, h

Indices

amb	ambient
av	average
AUX	auxiliary
ch	chemical
cons	consumed
D	deliver
d	demand
el	electricity
gas	natural gas
global	total demand (including heating and hot tap water)
hs	heating season
hp	heat pump
OM	operating mode
OP	operating
p	purchased
prod	produced
q	thermal
Q	data from heatmeter
R	return
s	sold
W_i	data from water meter

displacer and the power piston is caused by the pressure difference associated with the heat delivery to the engine's hot section. The principle of the FPSE operation is shown in Fig. 1.

Stirling engines are widely discussed in the existing literature. Work on them has been going on for years and has significantly intensified over the last decade because of their potential use in distributed energy generation. Experimental studies have been conducted [7–9], aimed primarily at determining the potential of operation and efficiency for specific mechanical solutions. Research using computer-aided design and numerical analysis tools focus on modeling the Stirling cycle [10,11], and in the case of FPSE, also take into account the oscillations of its parts [12–15]. This approach allows to focus on and analyze the engine features and specifications.

However, if a Stirling engine integrated with a heating system is considered, then the entire μCHP device rather than its parts are analyzed. The estimation of the thermodynamic potential and the possible economic and environmental benefits in the case of a large-scale implementation of μCHP units for residential applications should be focused on. With respect to the analysis of micro-cogeneration units, few studies were experimental [16–20] or based on measurement data [21]. The dominant approach involves the modeling of such units in a simplified form, which facilitates the system analysis. The software for dynamic analysis is used [22–27].

The operation strategy is vital, from the viewpoint of economic and ecological effectiveness, for the optimal operation of the μCHP device. Typically, μCHP systems operate in the priority of the heat or electricity demand coverage. In most cases, to achieve a satisfying economic result, μCHP units operate as long as possible, which determines the need for the heat buffer to be a part of the installation. Various operation strategies are discussed in the literature [28,29]. Trigeneration systems equipped with cooling units have been analyzed [30,31], along with the use of interesting mathematical approaches such as fuzzy logic, although it concerns micro-cogenerators based on fuel cells [32] or micro-turbines [33]. However, theoretical analyses dominate, without taking into account the operation characteristics and limitations of the actual generation systems. It is postulated that experimental and modeling studies should be conducted, which will determine the operation characteristics of the μCHP systems and evaluate their thermodynamic and economic effectiveness.

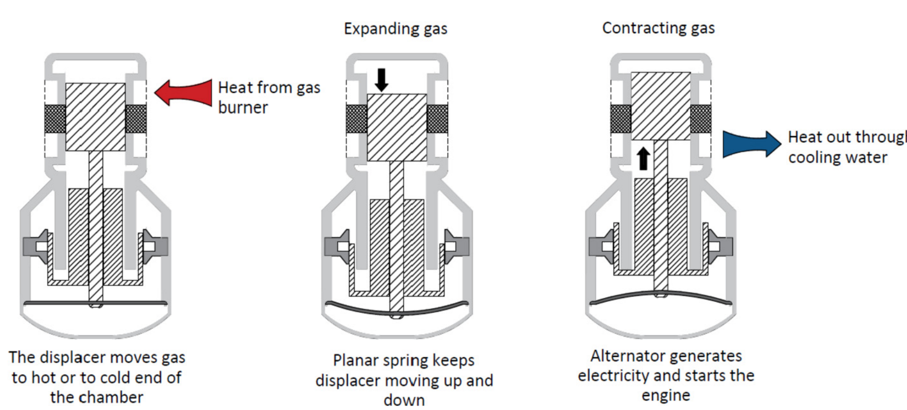

Fig. 1. Principle of free-piston Stirling engine operation.