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# Modeling and experimental investigation of a free-piston Stirling engine-based micro-combined heat and power system

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## HIGHLIGHTS

- An advanced model for a free-piston Stirling engine micro-CHP system is developed.
- The model considers acoustic impedance matching and nonlinear thermodynamics.
- The maximum deviation between experiments and simulations is within 10%.
- The micro-CHP system exhibits high efficiency over a large temperature lift.

## ARTICLE INFO

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## ABSTRACT

In recent years, combined heat and power (CHP) systems have attracted increasing attention worldwide. Owing to their advantages of high overall thermal efficiency, fuel flexibility, low noise and vibration, and low emissions, Stirling engines, especially dynamic Stirling engines (i.e., free-piston Stirling engines, FPSEs) are promising candidates for micro-CHP systems. In this paper, recent progress in Stirling engine-based micro-CHP systems and FPSE modeling and analysis is first briefly reviewed, and then a hybrid calculation model based on thermoacoustic theory is proposed and developed to simulate the entire micro-CHP system. Finally, the construction and testing of a pilot setup is described in detail. The obtained experimental results clearly validate the numerical model and scheme, with the primary deviation within approximately 10%. CHP performance tests revealed a maximum CHP efficiency of 87.5% and an output electrical power of 2.9 kW, corresponding to a 28% thermal-to-electric efficiency, when the delivering temperature was above 60 °C. Furthermore, acoustic impedance analysis indicated that the CHP efficiency remains high over a large temperature lift, which was also confirmed experimentally.

## 1. Introduction

In light of intense concerns about environmental issues and energy crises, shifting from the current methods of power production and use is one of the most urgent challenges for the sustainable development of human civilization. Developing combined heat and power (CHP) systems based on decentralized energy sources such as solar, biogas, and exhaust heat provides an alternative solution for reducing gross energy consumption and greenhouse gas emission and alleviating the increasing demand on central power grids [1,2].

The key component of CHP systems is the prime mover (i.e., the energy conversion unit). Currently, the main types of prime mover technology employed in CHP systems include gas turbines (micro-turbines) [3], internal combustion engines (ICEs) [4], Stirling engines [5], Rankine cycles [6–8], and fuel cells [9]. Some emerging technologies that are still in the early conceptual stage have also been proposed for CHP applications over the years, including thermofluidic oscillator (TFO) engines [10–12], free-piston engines [13–15], thermoacoustic engines [16,17], thermophotovoltaic (TPV) devices [18,19], and so on [20,21]. However, these emerging technologies are not expected to enter the CHP market in the short to medium term owing to their tremendous capital cost or technical immaturity.

It is known that constraints on power and efficiency restrict the choice of prime mover depending on the requirements of the specific field. In the area of micro-CHP systems for domestic applications, different technologies are compared in Table 1 concerning the thermal-to-electric and overall thermal efficiencies, the stage of the technology development, fuel versatility, investment cost and specific power. In

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $A$ | area, $m^2$ |
| $BL$ | force factor, N/A |
| $C_0$ | equivalent thermal conductivity, W/(m K) |
| $c$ | specific heat, J/(kg K) |
| $E$ | acoustic power, W |
| $f$ | spatially averaged diffusion function |
| $\dot{\boldsymbol{H}}$ | total energy power, W |
| $h$ | convective heat transfer coefficient, W/($m^2$ K) |
| $i$ | $\sqrt{-1}$, imaginary unit |
| $k$ | heat conductivity, W/(m K) |
| $l$ | length, m |
| $M$ | mass, kg |
| $\dot{\boldsymbol{m}}$ | mass flow rate of water, kg/s |
| $P$ | pressure, Pa |
| $p$ | pressure wave amplitude, Pa |
| $\dot{\boldsymbol{q}}$ | heat input per unit length, W/m |
| $Q$ | heat transferred, W |
| $R$ | gas constant, J/(kg K) |
| $R_e$ | load resistance, Ω |
| $R_m$ | mechanical damping coefficient, N·s/m |
| $r$ | radius, m |
| $t$ | time, s |
| $T$ | temperature, K |
| $U$ | volume flow rate, $m^3$/s |
| $V$ | volume, $m^3$ |
| $W$ | power, W |
| $Z$ | acoustic impedance, Pa·s/$m^3$ |
| Re() | real part of |
| Im() | imaginary part of |
| ~ | conjugation of a complex quantity |
| ǁ | amplitude of a complex quantity |

*Greek symbols*

| | |
|---|---|
| $\gamma$ | specific heat ratio |
| $\varepsilon$ | mean emissivity |
| $\zeta$ | correction factor for finite solid heat capacity |
| $\eta$ | efficiency |
| $\varkappa$ | spring constant |
| $\lambda$ | equivalent thermal conductivity, W/(m K) |
| ρ | gas density, kg/$m^3$ |
| $\sigma$ | Prandtl number |
| ω | angular frequency, $s^{-1}$ |
| Δ | relative error |

*Subscripts and superscripts*

| | |
|---|---|
| 0 | ambient |
| 1 | first order |
| 2 | second order |
| $a$ | ambient heat exchanger |
| alt | alternator |
| $b$ | bounce space |
| $c$ | compression space |
| $d$ | displacer |
| $e$ | expansion space or electric |
| $eng$ | engine |
| $eff$ | efficiency |
| $h$ | heating block |
| $in$ | inside or inlet |
| $m$ | mean |
| $out$ | outside or outlet |
| $p$ | isobaric or power piston |
| $r$ | regenerator |
| $rod$ | flex rod |
| $s$ | solid |
| $seal$ | seal space |
| $w$ | wall |
| $v$ | viscous |
| $\kappa$ | thermal |

**Table 1**
Comparison of different micro-CHP technologies [5,24].

| Technology | $\eta_{el}$(%) | $\eta_{th}$(%) | Energy source | Stage of technology | Investment costs (€/kWe) | Specific power |
|---|---|---|---|---|---|---|
| ICE | 20–30 | > 85 | Liquid fuel<br>Natural gas | Commercially available | 2100–4500 | 10–18 |
| Stirling engine | 11–35 | > 85 | Any type of fuel, solar radiation | Some models are already commercially available | 2800–10,000 | 7.3–9.1 |
| Fuel cells | 35–60 | 80–85 | Hydrogen hydrocarbon | In R&D and test prototype | > 30,000 | – |
| Micro Rankine engines | 6–19 | 70–85 | Any type of fuel | In R&D | – | – |

$\eta_{el}$, thermal-to-electric efficiency; $\eta_{th}$, overall thermal efficiency.

particular, fuel cells and micro Rankine engines are still under development with some pilot plants being currently tested. The major advantages of fuel cells and micro Rankine engine lie in the thermal-to-electric efficiency and low temperature waste heat applications, respectively. However, their capital costs are considerable. Currently, suitable commercially available technologies mainly include ICEs and Stirling engines. Of the two, ICEs are the more mature technology, which represents a great advantage with respect to their market diffusion [5]. ICEs have similar values of electrical efficiency to Stirling engines but theoretically require more frequent maintenance, which leads to increased cost. In addition, alongside issues with noise and pollutant emissions, conventional ICEs are designed for the direct consumption of fossil fuels and cannot directly utilize external heat sources. As a kind of external combustion engine, Stirling engines have for many years been considered as a promising technology for micro-CHP applications owing to their advantages of high cogeneration efficiency, fuel flexibility, extended service intervals, low noise and vibration, and low emissions [5,22,23].

The Stirling engine was invented in 1816 in Scotland by Robert Stirling [25]. Modern Stirling engines can generally be classified into two types, namely, kinematic and dynamic, from the perspective of the transmission mechanism [26,27]. In kinematic Stirling engines, the displacer and power pistons are rigidly connected via a mechanical contraption. In contrast, in dynamic Stirling engines (i.e., free-piston Stirling engines, FPSEs), the displacer and power piston are acoustically coupled from the viewpoint of thermoacoustics.