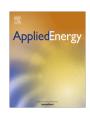


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## Numerical simulation for the design analysis of kinematic Stirling engines



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#### HIGHLIGHTS

- A thermodynamic analysis for kinematic Stirling engines was presented.
- The analysis integrated thermal, mechanical and thermodynamic interactions.
- The analyses considered geometrical and operational parameters.
- The results allowed to map the performance of the engine.
- The analysis allow the design assessment of Stirling engines.

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### ABSTRACT

The Stirling engine is a closed-cycle regenerative system that presents good theoretical properties. These include a high thermodynamic efficiency, low emissions levels thanks to a controlled external heat source, and multi-fuel capability among others. However, the performance of actual prototypes largely differs from the mentioned theoretical potential. Actual engine prototypes present low electrical power outputs and high energy losses. These are mainly attributed to the complex interaction between the different components of the engine, and the challenging heat transfer and fluid dynamics requirements. Furthermore, the integration of the engine into decentralized energy systems such as the Combined Heat and Power systems (CHP) entails additional complications. These has increased the need for engineering tools that could assess design improvements, considering a broader range of parameters that would influence the engine performance when integrated within overall systems. Following this trend, the current work aimed to implement an analysis that could integrate the thermodynamics, and the thermal and mechanical interactions that influence the performance of kinematic Stirling engines. In particular for their use in Combined Heat and Power systems.

The mentioned analysis was applied for the study of an engine prototype that presented very low experimental performance. The numerical methodology was selected for the identification of possible causes that limited the performance. This analysis is based on a second order Stirling engine model that was previously developed and validated. The simulation allowed to evaluate the effect that different design and operational parameters have on the engine performance, and consequently different performance curves were obtained. These curves allowed to identify ranges for the charged pressure, temperature ratio, heat exchangers dimensions, crank phase angle and crank mechanical effectiveness, where the engine performance was improved. In addition, the curves also permitted to recognise ranges were the design parameters could drastically reduce the brake power and efficiency. The results also showed that the design of the engine is affected by the conditions imposed by the CHP interactions, and that the engine could reach a brake power closer to 832 W with a corresponding brake efficiency of 26% when the adequate design parameters were considered. On the other hand, the performance could also be very low; as the reported in experimental tests, with brake power measurements ranging 52–120 W.

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	area (m²)	V	volume (m <sup>3</sup> )
	external wet area of the tube (m <sup>2</sup> )	$V_{de}$	total dead volume (m <sup>3</sup> )
	non-dimensional friction coefficient	W	work flow per cycle (J/cycle)
	form drag coefficient	$W_i$	engine indicated work (J/cycle)
	skin friction coefficient	$W_s$	engine shaft work (J/cycle)
	constant pressure specific heat (J/kg K)	$W_{ploss}$	energy loss due to pressure drop (J/cycle)
vater	constant pressure specific heat for inlet water (J/kg K)	W–	engine forced work (J/cycle)
vater	constant volume specific heat (J/kg K)	X	dead volume ratio
	diameter (m)		
,	hydraulic diameter (m)	Acronyms	
,	crank mechanism effectiveness	ACM	Aspen Custom Modeller
	friction factor coefficient	CHP	Combined Heat and Power
q	engine frequency (Hz)	SE	Stirling engine
۹	view factor	3E	Stiffing engine
	convective heat transfer coefficient (W/m <sup>2</sup> K)	C I	· to
	radiation heat transfer coefficient (W/m² K)	Subscrip	
vater	water film heat transfer coefficient ( $W/m^2 K$ )	b	buffer space
uter	thermal conductivity (W/m K)	C	compression space
	piston to displacer swept volume ratio	d	displacer
,	thermal conductivity (W/m K)	e	expansion space
/	length (m)	f	flame
	mass (kg)	h	heater space
	number of flow resistance layers	hous	regenerator housing space
water	mass flow of the inlet water (kg/s)	i	inside section
water	total mass of the working gas (kg)	k	cooler space
ΓU	number of transfer units	Μ	measured values
	pressure level (Pa)	0	outside section
h	engine charging pressure (bar)	r	regenerator space
r	engine brake power (W)	w ,	wall
1	heat transfer rate (W)	whe	heater wall
ıt	total heating requirement for the engine (W)	wk	cooler wall
t	total cooling requirement for the engine (W)		
k k	heat loss due to internal conduction (W)	Superscripts	
sh	heat loss due to shuttle conduction (W)	+	positive variation
ossr	heat loss due to regenerator inefficiency (W)	_	negative variation
0551	gas constant (J/kg K)		
i	conductive thermal resistance for tubes wall (K/W)	Greek symbols	
	fouling thermal resistance inside the tubes (K/W)	$\alpha_s$	surface absorptivity
)	fouling thermal resistance outside the tubes (K/W)	γ	adiabatic constant
i	convective thermal resistance inside the tubes (K/W)	$\eta_b$	brake efficiency
!	time (s)	$\eta_m$	mechanical efficiency
	temperature (K)	$\eta_t$	thermal efficiency
1	measured flame temperature (K)	σ	Stefan-Boltzmann constant (W/m <sup>2</sup> K <sup>4</sup> )
л itio	cold to heat temperature ratio	$\epsilon$	regenerator effectiveness
itio <sub>'</sub> i	temperature at the internal wall of the tubes (K)	ρ	fluid density (kg/m³)
vi vo	temperature at the outer wall of the tubes (K)	$\theta$	crank rotational angle (rad)
vo vater in	inlet temperature of the water (K)	μ	viscosity (kg/m s)
vater_ın	mean velocity (m/s)	•	3 ( 0) /

### 1. Introduction

The Stirling engine is a closed-cycle regenerative system that presents good theoretical capacities, which include a high thermodynamic efficiency, low emissions levels thanks to a controlled external heat source, and multi-fuel capability among others [1,2]. These could place the engine in a good position to address the efficiency and fuel flexible requirements for actual energy technologies [1,3,4]. However, the performance of actual prototypes largely differs from the mentioned theoretical potential as reported by Thomas [5] and Klemes [6]. Actual engine prototypes present low electrical power outputs and large energy losses. These are mainly attributed to the challenging mechanical interaction, the complicated heat transfer, and the complex fluid dynamics through

the different engine components [7]. These increased the need for engineering tools, such as numerical simulation, that could asses design improvements on the different components in order to increase the engine performance.

Simulation based analysis allows studying the influence of different parameters in the engine performance. The effect of operational variables like working gas temperatures, working fluid [8], engine frequency, compression ratio, and pressure levels have been presented by Strauss [9], Timouni [10,11], Tew [12], Garcia [13], Paul [14], Cheng [15] and others. In addition, the influence of design variables such as heat exchangers configurations [16–18], crank mechanism geometry [15,19,20], and regenerator materials [21,22] have been also reported. The studies have guided the development of Stirling engine prototypes. Some examples are

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