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Energy, exergy and cost analysis of a micro-cogeneration system based on an Ericsson engine

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Abstract

Hot air engines (Stirling and Ericsson engines) are well suited for micro-cogeneration applications because they are noiseless, and they require very low maintenance. Ericsson engines (i.e. Joule cycle reciprocating engines with external heat supply) are especially interesting because their design is less constrained than Stirling engines, leading to potentially cheaper and energetically better systems. We study the coupling of such an Ericsson engine with a system of natural gas combustion. In order to design this plant, we carry out classic energy, exergy and exergo-economic analyses. This study does not deal with a purely theoretical thermodynamic cycle. Instead, it is led with a special attempt to describe as accurately as possible what could be the design and the performance of a real engine. It allows us to balance energetic performance and heat exchanger sizes, to plot the exergy Grassmann diagram, and to evaluate the cost of the thermal and electric energy production. These simple analyses confirm the interest of such systems for micro-cogeneration purposes. The main result of this study is thus to draw the attention on Ericsson engines, unfortunately unfairly fallen into oblivion.

Keywords: Joule cycle; Ericsson engine; Micro-cogeneration; CHP; Exergy analysis

1. Introduction

In the low electrical power range (500 W ... 50 kW), combined heat and power (CHP), also called cogeneration, does not have the same development as for higher power. This lack of success, although the market for residential cogeneration could be strong, is mainly due to the absence of suitable systems for this power range: internal combustion engines generate noise and vibrations. The market seems more promising for systems based on external combustion. Especially a lot of developments are devoted to CHP systems with kinematic or free piston Stirling engines and some of these systems are already commercially available. We study a micro-cogeneration system based on an Ericsson engine coupled with a system of natural gas combustion. The objective of this plant is to produce sanitary and heating hot water and 11 kW of electric output. In order to design this system, we carry out energetic, exergetic and exergo-economic studies.

2. The ERICSSON engine: Principle and advantages

A tentative thermal machine classification has been proposed previously [1]. It allows to identify a special family of engines [2], with the following features: reciprocating engines, external heat supply, separate compression and expansion cylinders, regenerator or recuperator, monophasic gaseous working fluid. These engines are sometimes called hot air engines [3], even if the air used in the XIXth century engines has been replaced by high pressure hydrogen or helium in a lot of modern engines. Hot air engines have known commercial success during the XIXth century, but, since the beginning of the XXth century, they have been discarded and replaced by internal combustion engines or electric motors.

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Nomenclature

c	fluid velocity	$\text{m}\cdot\text{s}^{-1}$
c_i	exergy cost of stream i	$€\cdot\text{J}^{-1}$
D	diameter	m
$\dot{E}x_i$	rate of exergy transfer of stream i	W
L_t	tube length	m
$\dot{m}$	mass flow rate	$\text{kg}\cdot\text{s}^{-1}$
N_t	number of pipes	
P	cost	€
p	pressure	Pa
$\dot{Q}$	thermal power	W
R	net efficiency (Figs. 4, 5)	
$\overline{R}$	universal gas constant	$\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$
r	ideal gas constant	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
S	heat transfer area	m^2
T	temperature	K
$\dot{W}$	mechanical power	W
$\dot{Z}_i$	cost per unit time of component i	$€\cdot\text{s}^{-1}$

Greeks symbols

ε	heat exchanger effectiveness	
η	efficiency	
ξ	pressure loss coefficient	
ρ	density	$\text{kg}\cdot\text{m}^{-3}$
ψ	valve pressure loss factor	

Subscripts

amb	ambient combustion air
C	compression cylinder
CC	combustion chamber
chim	chimney
cr	working air between C and R
D	destroyed (exergy)
E	expansion cylinder
e	exhaust combustion gases, between CC and H
ep	exhaust combustion gases, between H and P
er	working air, between E and R
g	gaseous fuel
H	heater
h	working air, heater outlet
IC	inter-cooler
ind	indicated (work or efficiency)
in	in, inner
K	cooler
k	working air, inlet 1st stage of C
k1	working air, between $C1$ and IC
k2	working air, between IC and $C2$
mec	mechanical
net	net
out	out, outer
P	combustion air pre-heater
pa	pre-heated combustion air, between P and CC
R	regenerator or recuperator
rh	working air, between R and H
rk	working air, regenerator outlet
shell	shell
t	tube

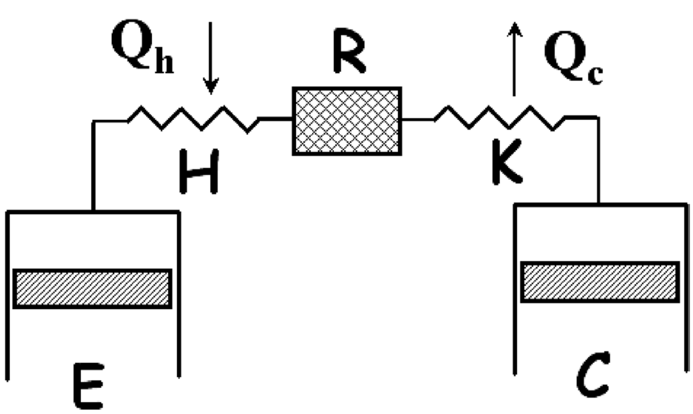

Fig. 1. Typical Stirling engine.

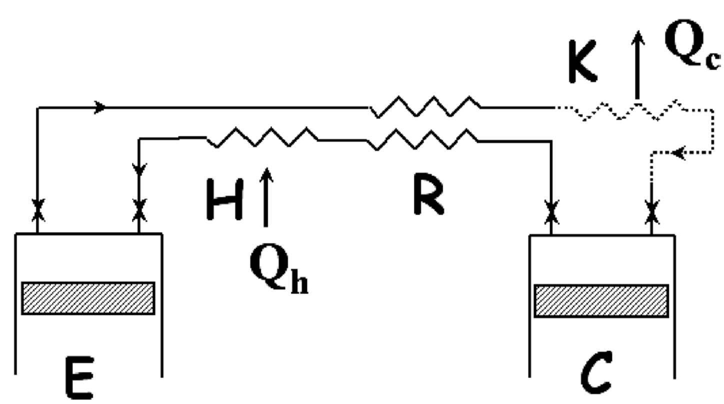

Fig. 2. Typical Ericsson engine.

The family of hot air engines is divided in two subgroups: the Stirling engines, invented in 1816, have no valves (Fig. 1) whereas Ericsson engines, invented in 1833 (Fig. 2) have valves in order to isolate the cylinders.

Since the work of the Philips company, around the second world war, the attention has been drawn on Stirling engines and lots of research and developments have been carried out. However, up to now, very little interest is dedicated to Ericsson engines.

On the opposite of internal combustion engine, the operation of hot air engine is not noisy and requires very low maintenance. The Ericsson configuration, with valves, shows several advantages compared to the Stirling configuration [4]. Amongst them, it is worth to note that the Ericsson engine heat exchangers are not dead volumes, whereas the Stirling engine heat exchangers designer has to face a difficult compromise between as large heat transfer areas as possible, but as small heat exchanger volumes as possible.