Energy Conversion and Management 135 (2017) 101–116

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Solar-driven Joule cycle reciprocating Ericsson engines for small scale applications. From improper operation to high performance

Dorin Stanciu [a,*], Viorel Bădescu [b]

[a] Department of Engineering Thermodynamics, University POLITEHNICA of Bucharest, Splaiul Independentei, 313, 060042 Bucharest, Romania
[b] Candida Oancea Institute, University POLITEHNICA of Bucharest, Splaiul Independentei, 313, 060042 Bucharest, Romania

ARTICLE INFO

Article history:
Received 14 September 2016
Received in revised form 21 November 2016
Accepted 24 December 2016

Keywords:
Parabolic trough collector
Ericsson engine
Proper design
Operation strategy

ABSTRACT

The paper focuses on a Joule cycle reciprocating Ericsson engine (JCREE) coupled with a solar parabolic trough collector (PTC). A small scale application located at mid Northern Hemisphere latitude (44°25″N) is considered. A new dynamic (time-dependent) model is developed and used to design the geometry and estimate the performance of the PTC-JCREE system under the most favorable weather conditions (i.e. summer day and clear sky). The paper brings two main contributions. First, specific constraints on the design parameters have been identified in order to avoid improper JCREE operation, such as gas under-compression in the compressor cylinder and gas over-compression and/or over-expansion in the expander cylinder. Second, increasing the work generated per day requires using a proper strategy to switch between different rotation speeds. Specific results are as follows. For the (reference) constant engine rotation speed 480 rpm, the output work per day is 39,270 kJ and the overall efficiency is 0.134. The output work decreases by increasing the rotation speed, since the operation interval during a day diminishes. A better operation strategy is to switch among three rotation speed values, namely 480, 540 and 600 rpm. In this case the output work is 40,322 kJ and the overall efficiency is 0.137. The performance improvement is quite small and the reference constant rotation speed 480 rpm may be a suitable choice, easier to use in practice. For both the constant and variable rotation speed strategies, the overall efficiency is almost constant along the effective operation time interval, which is from 8:46 to 15:15.

1. Introduction

Low cost engines with reasonably good thermal efficiency and compatible with many types of energy sources is expected to cover the entire output power range required by small scale domestic applications. Several solutions are presently available, including Organic Rankine Cycles (ORC) based engines, Stirling engines and Micro-gas turbine engines [1–4]. They have advantages and disadvantages, which depend not only on the operating cycle, but also on the targeting power range. When choosing among available solutions, acquisition and operating costs as well as thermal efficiency represent the main criteria. From this point of view, the Ericsson engine could be one of the best solutions in the power range up to 5 kW [3]. This engine belongs to the class of hot air engines and, beyond its name, it operates under the Joule cycle. Unlike the well-known gas turbine engines working on Joule cycle, the Ericsson engine is externally heated and performs the compression and expansion processes in reciprocating compressors and expanders, respectively. Several names are associated with this kind of engine, such as Reciprocating Joule-cycle engine [2], volumetric hot air Joule cycle engine [8], Joule cycle reciprocating Ericsson engine (JCREE) [7,8]. The last name is adopted here. Small power applications involve low mass flow rates; this make JCREEs a better option than micro-gas turbines, despite peculiar irreversibilities are associated with the operation of these engines, like those due to mechanical friction and flow through valves.

Several JCREE applications have been already reported. Some of them were treated using steady state models, based on the classical Joule cycle, further improved by taking into account the irreversible processes specific to piston engines operation. These models were used to estimate the JCREE performance in the low and middle power range (up to 5 kW and from 5 to 30 kW, respectively). For example, Moss et al. [2] developed a steady state design procedure for a JCREE used for domestic micro CHP (combined heat and power), producing 5 kW electrical power and 8 kW of heat. The goal was to achieve a higher efficiency than that of a gas-turbine plant of comparable size. The study predicted a thermal efficiency of 35% for

* Corresponding author.
E-mail addresses: sdorin_ro@yahoo.com, dorin.stanciu@upb.ro (D. Stanciu).

http://dx.doi.org/10.1016/j.enconman.2016.12.070
0196-8904/

Nomenclature

c_p	specific heat at constant pressure [J/(kg K)]
c_v	specific heat at constant volume [J/(kg K)]
C_D	discharge coefficient [–]
D	diameter [m]
E	energy [J]
e	rib height [m]
EVC	closing advance of expander exhaust valve [deg]
EVO	opening delay of compressor exhaust valve [deg]
f	friction factor
G_B	beam (direct) solar energy flux [W/m^2]
H	width [m]
IVC	closing advance of expander inlet valve [deg]
IVO	opening delay of compressor inlet valve [deg]
JCREE	Joule cycle reciprocating Ericsson engine
h	enthalpy [J/kg], convection heat transfer coefficient [W/(m^2 K)]
k	adiabatic exponent
K_θ	incident angle modifier [–]
L	length [m]
L_v	valve lift [m]
M	air mass [kg]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number [–]
N_r	engine rotation speed [rpm]
P	pressure [Pa]
p	pitch [m]
Pr	Prandtl number [–]
$\dot{Q}$	heat flux [W]
q_s	surface heat flux [W/m^2]
R	air specific constant [J/(kg K)]
Ra	Rayleigh number
Re	Reynolds number
T	temperature [K]
V	volume [m^3]
V_S	swept volume [m^3]
V_C	clearance volume [m^3]
w	velocity [m/s]
$\dot{W}$	power [W]

Greek symbols

α	absorptivity [–], helix angle [deg]
β	pressure ratio [–], tilt angle [deg], expansion coefficient [1/K]
ε	emissivity [–]
η	efficiency [–]
λ	ratio of connecting road to crank radius [–]
ν	kinematic viscosity [m^2/s]
τ	time [s], transmissivity [–]

Subscript

a	air in absorber tube
c	compressor, cycle
e	expander
eng	engine
env	environment, envelope
$high$	high side
gls	glass
m	spatial average
ptc	parabolic trough collector
sky	sky
usf	useful
in	inner, inflow
ex	outer
out	outflow
$(\bar{\ })$	time averaged per cycle

Superscript

(a)	absorption
(c)	convection
(r)	radiation
(rb)	ribbed surface
(sm)	smooth surface

the pressure ratio 7.5 and 1000 rpm. The authors concluded that this engine has considerable advantages compared with other prime movers in terms of efficiency, emissions and multi-fuel capability. Bonnet et al. [3] carried out energy, exergy and exergo-economic analyses for a JCREE driven by external natural gas combustion. Their study focused on the real engine by considering several irreversibilities due to low mechanical efficiency, valve pressure losses and heat rejected at the chimney. The authors concluded that the JCREE may be a suitable and profitable solution for thermal energy conversion in the low power range (1–5 kW). The same kind of global approach was performed by Creyx et al. [4] to explore the operation of an Ericsson engine working upon the Joule or Ericsson cycles and designed for micro CHP purposes. A sensitive analysis was carried out in order to find the optimal engine operation conditions. The authors found that the engine performances are maximum for an optimum pressure ranging between 5 and 8 bar, when the heat exchanger operates at the highest possible temperature that it can reach. Touré and Stouffs [5] analyzed a JCREE driven by recuperated heat and established relationships between the geometrical characteristics and operation parameters of the engine and its thermodynamic performances.

Other applications were analyzed by using dynamic models, which take into account the time-dependent movement of the piston and cylinder valves. Losses in valves, heat exchangers and pipes pressure were treated in details, while other mechanical losses were described by using empirical coefficients, in a way which is similar to steady state models. For instance, by using a dynamic model, Wojewoda and Kazimierski [6] investigated the performances of a closed JCREE designed to supply moderate levels of power (up to 30 kW). The engine-heat exchanger assembly was highly pressurized and greater values of engine rotation speed were considered. Additionally, two recirculation blowers were used to ensure the air circulation in the heat exchangers when the engine valves are closed. The output power and the efficiency of the engine were evaluated for a large range of rotation speeds (i.e. 500–3500 rpm) by taking into account the recirculation mass flow rate provided by the blowers. Results showed output powers up to 25 kW and thermal efficiency of about 25% for engine rotation speed of 3000 rpm and exhaust compressor pressure around 90 bar. Lontsi et al. [7,8] developed a dynamic model for predicting the performances of low-speed open JCREE. The air is compressed inside the compressor cylinder until a pressure of about 4 bar is obtained and the heat is supplied by a shell- and-tube heat exchanger in which the working fluid flows inside the tubes, which have a constant wall temperature of 873 K. Numerical simulations predicted rapid hot start of the engine (about 5 s) and stable engine operation with output power of 1716 W at efficiency around 23%, as well as good transient response to the perturbation induced by a sudden pressure drop occurring in the compressor intake manifold. A dynamic model for JCREE operation was proposed by