Applied Energy 97 (2012) 743–748

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Single-piston alternative to Stirling engines

Maxim Glushenkov [a], Martin Sprenkeler [a], Alexander Kronberg [a,*], Valeriy Kirillov [b]

[a] Encontech B.V., CTW/ThW, PO Box 217, 7500 AE Enschede, The Netherlands
[b] Boreskov Institute of Catalysis, Lavrentieva Street, 630090 Novosibirsk, Russian Federation

ARTICLE INFO

Article history:
Received 28 September 2011
Received in revised form 6 December 2011
Accepted 11 December 2011
Available online 12 January 2012

Keywords:
Energy
Stirling engine
Heat engine
Micro-CHP
Bio-oil

ABSTRACT

Thermodynamic analysis of an unconventional heat engine was performed. The engine studied has a number of advantages compared to state-of-the-art Stirling engines. The main advantage of the engine proposed is its simplicity. A power piston is integral with a displacer and a heat regenerator. It allows solving the problem of the high-temperature sealing of the piston and the displacer typical of all types of Stirling engines. In addition the design proposed provides ideal use of the displacer volume eliminating heat losses from outside gas circuit. Both strokes of the piston are working ones in contrary to any other types of piston engines. The engine can be considered as maintenance-free as it has no piston rings or any other rubbing components requiring lubrication. The only seal is contactless and wear free. It is located in the cold part of the cylinder. As a result the leakage rate in operation can be one-two orders of magnitude as small as that in Stirling engines. Balancing of the engine is much easy compared to Stirling engines with two reciprocating masses because of the only moving part inside the engine cylinder. The engine suits ideally to be fuelled with "difficult" fuels such as bio oil and can be used as a prime mover for micro-CHP systems.

The thermodynamic model developed incorporates non-ideal features of the cycle, such as specific regenerator efficiency, dead volumes and other geometrical parameters of the engine. The model shows that the energy efficiency is highly sensitive to regenerator performance. For realistic geometric and operating parameters and the regenerator efficiency of about 95% the ultimate energy conversion efficiency of the engine proposed can be as high as 40–50%.

A prototype of the engine was built and the feasibility of the engine concept was demonstrated.

1. Introduction

The strength of external combustion heat engines vis-à-vis internal combustion engines is compatibility with a wide variety of renewable energy and fuel sources. They may use a supply of heat from any sources such as biomass and biomass derived products, municipal waste, nuclear, solar, and geothermal energy. Other important advantages of external combustion engines are low emissions due to continuous combustion and low noise, due to elimination of exhaust of high-pressure combustion products.

Promising external combustion engine concepts are Stirling engines that convert thermal energy into mechanical energy of reciprocating piston(s). The pistons are moved due to a cyclic change of gas phase working fluid pressure caused by its temperature and volume change. High thermal efficiency of the Stirling cycle (Carnot efficiency), long maintenance interval and fewer moving parts are additional advantages of Stirling engines [1].

In the operation of practical Stirling engines a significant deviation from the ideal cycle due to frictional losses, working fluid leakage, dead volumes, etc. takes place. Technical problems, in particular balancing of pistons (or piston and displacer) reciprocating with a phase lag and a high-temperature sealing of the piston, currently prevent the wide application of Stirling engines.

Significant improvements of Stirling engines are expected by using engines in which the displacer is integrated with the power piston. In these engines the piston–displacer assembly is moved due to the cycling pressure change of the working fluid under the influence of change of its temperature and amount inside the working chamber.

The purpose of this study was to perform thermodynamic analysis of one of such engines.

2. External combustion single-piston engine

The engine studied in this article closely resembles the hot-air engine devised by Manson [2] and the machines patented by Bush [3] and Baumgardner et al. [4]. Fig. 1 illustrates the basic principle the engine cycle.

* Corresponding author. Tel.: +31 53 4891088; fax: +31 53 4893663.
E-mail address: a.e.kronberg@utwente.nl (A. Kronberg).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.12.050

Nomenclature

C_p	working fluid heat capacity at constant pressure (J/mol/K)
C_v	working fluid heat capacity at constant volume (J/mol/K)
f	frequency of piston reciprocation (s^{-1})
L	height of the displacer (m)
M	working fluid molecular mass (kg/kmol)
m	working fluid mass (kg)
N	number of moles [–]
N_0	$=\frac{P_0Sh}{RT_C}$ (–)
H	height of the cylinder (m)
h	piston/displacer stroke (m)
P	pressure (Pa)
R	gas constant (kJ/kmol/K)
r	regeneration efficiency (–)
T	temperature (K)
S	cross-sectional area of the cylinder/displacer (m^2)
S_p	cross-sectional area of the piston (m^2)
x	displacement (position) of the displacer (m)
x_1	distance between the displacer and the bottom at lower dead point (m)
x_2	distance between the displacer and the top at upper dead point (m)
x'_1	$=x_1/h$ (–)
x'_2	$=x_2/h$ (–)
α	$=T_C/T_H$ (–)
β	$=(S-S_p)/S$ (–)
γ	$=\frac{C_p}{C_v}$ (–)

$\Lambda = \beta/\alpha = \beta T_H/T_C$ $\quad \mathit{\Lambda} = \beta/\alpha = \beta T_H/T_C$

Subscripts

0	ambient conditions (in the chamber)
C	cold, upper chamber
H	hot, lower chamber
u	upward motion
d	downward motion

The engine consist of cylinder 1, divided by displacer 2 into hot (heated by combustion products) part 1a and cold (cooled by water jacket, for example) part 1b. The displacer is not sealed; the annular gap between the displacer and the cylinder provides a free gas flow between the hot and cold parts of the cylinder during reciprocation of the displacer. The displacer is connected directly to power piston 3 so that they move together as one piece. The annular gap between the power piston and upper part of the cylinder is sealed by means of a contactless seal 4. The power piston is connected to the crank mechanism 5 to transform the reciprocating motion of the piston to shaft power. The cylinder is also equipped with two valves 6 and 7 shown in the upper and lower parts of the cylinder.

The cylinder is filled with gaseous working fluid such as atmospheric air at ambient pressure. The engine starts when displacer 2 is in the middle position (Fig. 1A). Heating of the lower part leads to increasing of air pressure inside the cylinder. Under the pressure acting on the power piston it moves upward driving crank mechanism 5. During this motion the displacer displaces air from the cold part of the cylinder to the hot one and the pressure gradually rises, so driving the piston further. When the piston reaches the end of the stroke (upper position, Fig. 1B), valve 7 opens and hot pressurized air is released from the cylinder to atmosphere until the air pressures inside and outside the cylinder become equal. Then valve 7 closes and piston is pushed down (Fig. 1C) by virtue of inertia of the crank gear. During this motion residual air is cooled and its pressure drops down well below the ambient pressure. As a result the outside atmospheric pressure accelerates the piston downward performing the vacuum or suction power stroke. At the end of the stroke (Fig. 1D) upper valve 6 opens communicating the internal volume of the cylinder to atmosphere. Then valve 7 closes and the piston is pushed upward by the crank gear inertia displacing air in the cylinder from the cold chamber to hot one. Pressure in the cylinder rises driving the piston upward and the cycle repeats itself.

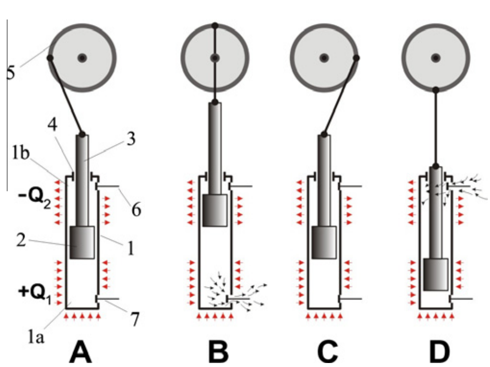

Fig. 1. Basic principle of the engine.

Instead of air any gas can be used as a working fluid. The engine can be modified to operate in a closed-cycle mode by using a container between the inlet and outlet valves. In such a closed cycle the pressure can be well above ambient pressure. This way the power generated can also significantly be increased.

To increase efficiency a heat regenerator can be used. For not very high power ranges (1–5 kW) a well developed side surface of the displacer can be used as the regenerator. In that case the valves must be located only in the cold area of the cylinder (valves 6 and 7).

3. Thermodynamic model and analysis of the heat process in the engine

Fig. 2 shows a sketch of the engine together with the notations used for the thermodynamic analysis.

3.1. Mass of the gas in the engine cylinder

The mass of the gas inside the cylinder depends on the stage of the cycle, or on the direction of the piston/displacer motion.

3.1.1. Upward motion

The amount of the gas (mass or number of moles) in the cylinder during the upward motion can be calculated at the lower dead

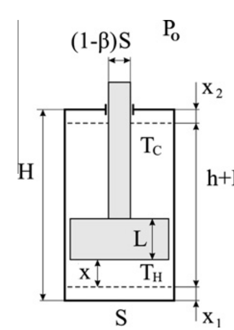

Fig. 2. View of the engine.