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ScienceDirect
Solar Energy 81 (2007) 884–895
SOLAR ENERGY
www.elsevier.com/locate/solener

Performance of a twin power piston low temperature differential Stirling engine powered by a solar simulator

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Received 7 July 2005; received in revised form 23 October 2006; accepted 27 November 2006
Available online 26 December 2006

Communicated by: Associate Editor Manuel Romero-Alvarez

Abstract

This paper provides an experimental investigation on the performance of a low-temperature differential Stirling engine. In this study, a twin power piston, gamma-configuration, low-temperature differential Stirling engine is tested with non-pressurized air by using a solar simulator as a heat source. The engine testing is performed with four different simulated solar intensities. Variations of engine torque, shaft power and brake thermal efficiency with engine speed and engine performance at various heat inputs are presented. The Beale number, obtained from the testing of the engine, is also investigated. The results indicate that at the maximum simulated solar intensity of 7145 W/m^2, or heat input of 261.9 J/s, with a heater temperature of 436 K, the engine produces a maximum torque of 0.352 N m at 23.8 rpm, a maximum shaft power of 1.69 W at 52.1 rpm, and a maximum brake thermal efficiency of 0.645% at 52.1 rpm, approximately.

Keywords: Stirling engine; Hot-air engine; Solar-powered heat engine; Solar simulator

1. Introduction

The low temperature differential (LTD) Stirling engine is a type of Stirling engine that can operate with a low temperature heat source. There are many low temperature heat sources available including solar energy. The LTD Stirling engine then provides the possibility of direct conversion of solar energy to mechanical work.

A LTD Stirling engine can be run with small temperature difference between the hot and cold ends of the displacer cylinder (Rizzo, 1997). LTD Stirling engines provide value as demonstration units, but they immediately become of interest when considering the possibility of power generation from many low-temperature waste heat sources in which the temperature is less than 100 °C (Van Arsdell, 2001). Some characteristics of the LTD Stirling engine are as follow (Rizzo, 1997):

(1) Displacer to power piston swept volumes ratio is large.
(2) Diameters of displacer cylinder and displacer are large.
(3) Displacer length is short.
(4) Effective heat transfer surfaces on both end plates of the displacer cylinder are large.
(5) Displacer stroke is small.
(6) Dwell period at the end of the displacer stroke is rather longer than the normal Stirling engine.
(7) Operating speed is low.

The LTD Stirling engine has been studied by many researchers. Many studies in the field of LTD Stirling

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doi:10.1016/j.solener.2006.11.004

Nomenclature

A	absorber area (m^2)	q_{in}	actual heat input to the engine (J/s)
C_P	specific heat of water at constant pressure (4186 J/kg K)	q_S	total heat input from heat source (J/s)
E_H	heat source efficiency	r	dynamometer brake drum radius (0.1465 m)
E_{BT}	Brake thermal efficiency	S	spring balance reading (N)
f	engine frequency (Hz)	T	engine torque (N m)
H	heating value of the gas used (J/kg)	T_C	cooler wall temperature (K)
I	average intensity on absorber plate (W/m^2)	T_H	heater wall temperature (K)
m_f	mass of gas burned (kg)	T_{w1}	initial water temperature (K)
m_w	mass of water to absorb heat (kg)	T_{w2}	maximum water temperature after the heat source has been turned off (K)
N	engine speed (rpm, rps)	t_1	initial time at water temperature of T_{w1} (s)
N_B	Beale number (W/bar cc Hz)	t_2	final time at water temperature of T_{w2} (s)
P	shaft power (W)	V_P	power-piston swept volume (cc)
p_m	engine mean pressure (bar)	W	loading weight (N)

engines have been investigated in the authors' former work (Kongtragool and Wongwises, 2003a). Some works related to the LTD Stirling engine are as follow (Kongtragool and Wongwises, 2003a).

Haneman (1975) studied the possibility of using air with low temperature sources. An unusual engine, in which the exhaust heat was still sufficiently hot to be useful for other purposes, was constructed. Spencer (1989) reported that, in practice, such an engine would produce only little useful work relative to the collector system size, and would give little gain compared to the additional maintenance required.

A simply constructed low-temperature heat engine modeled on the Stirling engine configurations was patented by White (1983). He suggested improving performance by pressurizing the displacer chamber. Efficiencies were claimed to be around 30%, but this can be regarded as quiet high for a low-temperature engine.

O'Hare (1984) patented a device passing cooled and heated streams of air through a heat exchanger for changing the pressure of air inside the bellows. The practical usefulness of this device was not shown in detail as in the case of Haneman's work.

Rizzo (1997) and Senft (1993) reported that Kolin experimented with 16 LTD Stirling engines, over a period of 12 years. Kolin presented a model that worked on a temperature difference between the hot and cold ends of the displacer cylinder as low as 15 °C.

After Kolin published his work, Senft (Van Arsdell, 2001) made an in-depth study of the Ringbom engine and its derivatives, including the LTD engine. Senft's research in LTD Stirling engines resulted in a most interesting engine, which had an ultra-low temperature difference of 0.5 °C. It has been very difficult to create any development better than this result. Senft's work (Senft, 1991), showed the motivation in the use of Stirling engine, their target was to develop an engine operating with a temperature difference of 2 °C or lower.

Senft (1993) described the design and testing of a small LTD Ringbom Stirling engine powered by a 60° conical reflector. He reported that the tested 60° conical reflector, producing a hot end temperature of 93 °C under running conditions, worked very well.

Iwamoto et al. (1997) compared the performance of a LTD Stirling engine powered by the hot spring heat with a high temperature differential Stirling engine powered by the combustion gas. Finally, they concluded that the LTD Stirling engine efficiency at its rated speed was approximately 50% of the Carnot efficiency. However, the swept volume ratio of their LTD Stirling engine was approximately equal to that of a conventional Stirling engine. Then its performance seemed to be the performance of a common Stirling engine operating at a low operating temperature.

Kongtragool and Wongwises (2003b) made a theoretical investigation on the Beale number for LTD Stirling engines. The existing Beale number data for various engine specifications from the literature were collected. They concluded that the Beale number for a LTD Stirling engine could be found from the mean-pressure power formula.

Kongtragool and Wongwises (2005a) investigated, theoretically, the power output of a gamma-configuration LTD Stirling engine. Former works on Stirling engine power output calculations were studied and discussed. They pointed out that the mean-pressure power formula was the most appropriate for LTD Stirling engine power output estimation. However, the hot-space and cold-space working fluid temperature was needed in the mean-pressure power formula.

Kongtragool and Wongwises (2005b) presented the optimum absorber temperature of a once-reflecting full-conical reflector for a LTD Stirling engine. A mathematical model for the overall efficiency of a solar-powered Stirling engine was developed. Limiting conditions of both