Applied Energy 229 (2018) 603–613

Contents lists available at ScienceDirect

Applied Energy

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

A novel solar-powered liquid piston Stirling refrigerator

Samuel Langdon-Arms[a], Michael Gschwendtner[a,*], Martin Neumaier[b]

[a] AUT University, 55 Wellesley St E, Auckland 1010, New Zealand
[b] Hochschule Rosenheim, Hochschulstraße 1, 83024 Rosenheim, Germany

HIGHLIGHTS

- Operational frequency deduced both analytically and computationally.
- Previously untested cooling configuration found to be the optimal.
- Development of validated computer model of physical system.
- Liquid piston instability linked to Rayleigh-Taylor phenomenon.
- Liquid piston maximum acceleration limit identified.

ARTICLE INFO

Keywords:
Stirling cycle
Refrigeration
Liquid pistons
Renewable energy
Solar heating and cooling
Free-pistons
Sage

ABSTRACT

The objective of this research project is to develop a solar-powered refrigerator in the lower capacity range of up to 5 kW of cooling power. With the use of liquid pistons and one of the most efficient thermodynamic cycles known, the Stirling cycle, this product has the potential to outperform rival solar cooling technologies while providing inexpensive, reliable, quiet, environmentally-friendly, and efficient solar cooling for residential use, due to its straightforward manufacturing, simple design and inert working gas. Presented in this paper are the newest results of the theoretical and experimental investigation into deducing the key design parameters and system configuration of the so-called Liquid Piston Stirling Cooler (LPSC), which will help lead to optimal performance. Computer models of the complex unconstrained system have been constructed and validated using the modelling software Sage and shown to replicate system behavior with reasonable accuracy in experiments. The models have been used to predict system improvements and identify limitations imposed by the use of liquid pistons. The results to date provide a unique insight into a relatively little studied area in Stirling cycle research.

1. Introduction

1.1. Background

Research into Solar Heating and Cooling (SHC) has attracted a great deal of interest over the last few decades. Cooling demand is rapidly increasing in many parts of the world, particularly in moderate climates. The potential for solar air-conditioning systems in Europe was highlighted by Balaras et al. [1]. The authors referred to the rapid growth of the air-conditioning industry as a leading cause in the dramatic increase in electricity demand. This is creating peak loads for electric utilities during hot summer days, which frequently leads to 'brown out' conditions when the grid is barely capable of meeting demand. The spread of solar cooling technologies would contribute to the reduction of this peak loading scenario and the unnecessary use of fossil and nuclear energy currently being relied upon. The International Institute for Refrigeration (IIR) estimated that 15% of total electricity production is used for refrigeration and air-conditioning—with these processes accounting for 45% of the total energy demand in domestic and commercial buildings. In many ways, solar energy is more suited to cooling applications than it is to heating. Solar cooling technologies benefit from the strong correlation between the intensity of the solar resource and the energy demand for cooling, especially for air-conditioning applications.

Thermo-mechanical cooling systems use the heat generated by solar collectors to drive a heat engine, producing mechanical work, which is used in a reversed heat engine, delivering the cooling effect. A schematic of this system is shown in Fig. 1.

The potential of the Stirling cycle for refrigeration has been known for just about as long as power generation applications. However, it was

* Corresponding author.
E-mail address: michael.gschwendtner@aut.ac.nz (M. Gschwendtner).

https://doi.org/10.1016/j.apenergy.2018.08.040
Received 23 December 2017; Received in revised form 2 August 2018; Accepted 6 August 2018

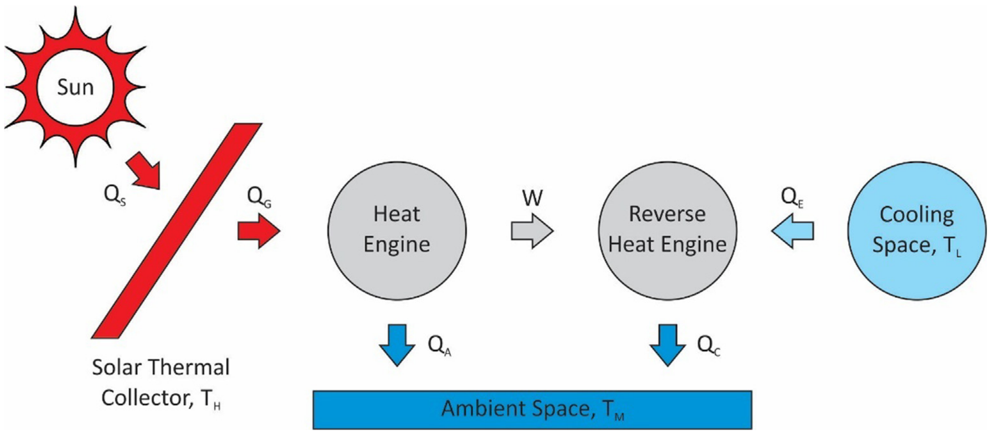

Fig. 1. Thermo-mechanical heat-powered cooling system.

not until the research by Philips that the foundational theory was laid for commercialization. Their first machine, with a cooling capacity of 1 kW at 80 K, went to market in 1956 and was virtually unchallenged. Presently, Stirling-based cooling systems feature in the cryocooler, air liquefaction and heat pump commercial markets [2]. These systems typically require a work input to function (this is usually in the form of an electrical supply). In the case where heat is to be used as the only external energy input, useful work would first need to be produced via a Stirling system operating as a heat engine (as depicted in Fig. 1).

Invented by Colin D. West in 1969, the liquid piston Stirling machine is a special type of the free-piston Stirling configuration, where the pistons are not physically connected to a work-coupling device [3]. Also known as a 'Fluidyne', a liquid piston Stirling engine employs liquid columns of water in place of conventional solid pistons. The pistons can be arranged in a 'U-tube' configuration or they can be housed in concentric tubes. Since West's work was first published in 1974, 'Fluidyne' systems have developed and have seen limited commercial success powering water pumping systems and have been proposed for low-capacity heat-driven power generation, typically operating at near-ambient pressure [4–7] (see Fig. 2).

In the late 1980s research was conducted on the physical basis of the excitation relationship between the tuning line (output piston) and the displacer piston, and how this varied with system pressure [8,9]. In 1994 Fauvel and Yu designed a Fluidyne as a low-cost irrigation pump using existing steel barrels [10]. Their design exhibited large liquid flow losses but they experimentally verified improvements to reduce these. Orda and Mahkamov published performance data of three different Fluidyne prototypes they had constructed for use as water pumps

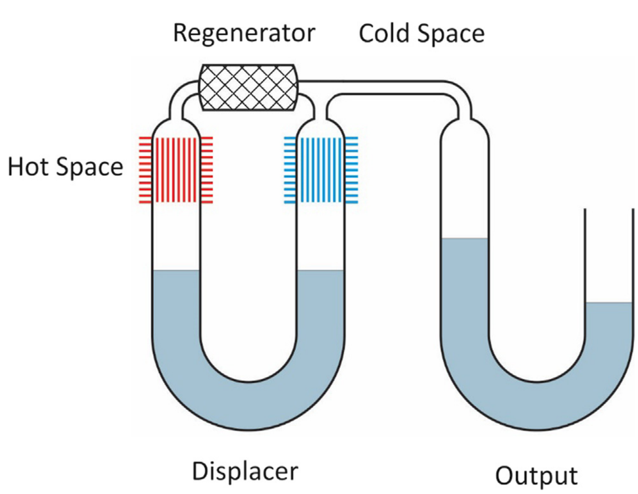

Fig. 2. Basic 'Fluidyne' configuration.

[4]. In 2009, Slavin et al. analyzed a novel 'Fluidyne' machine theoretically capable of producing 97 kW with a 37% thermal efficiency and a second law efficiency of 52%. It is stated that "Heat-resistant floats on the surface of water pistons ensure heat insulation between working gas and water and prevent intensive evaporation of water.", but no further details of the floats are provided [5]. An experimental investigation was performed on a solar-powered liquid piston Stirling engine using a Fresnel lens by Mason and Stevens [11]. The Fresnel lens provided sufficient heating to run the system, however, in their experiments the engine was not loaded. A solar-powered gamma-type Stirling engine with a solid controllable displacer but a liquid power piston for pumping water was investigated both numerically and experimentally by Jokar and Tavakolpour-Saleh [12]. A flat plate collector was used to heat the working gas inside the displacer cylinder. In the experimental setup no regenerator was used for simplicity, but water pumping could be achieved. Best performance was observed when the liquid piston oscillated at its natural frequency, since the system could be tuned by the controllable displacer. The authors suggest helium as a working gas for increased performance. A theoretical analysis of a system consisting of three Stirling cycles in series connected by U-tubes with liquid columns was carried out by Zhang and Luo [13]. In their analysis they used simulation modules that were developed for acoustic systems. They found that the natural frequency of the system increases with increased average gas pressure, and the pressure amplitude increases with higher Piston mass. However, in their idealised model they did not consider instability effects of the liquid piston surface.

Van de Ven explores the rationale behind liquid piston Stirling engines and identified many research challenges facing the technology. These include: modelling the liquid pistons' behavior; modelling system dynamics; optimizing for maximum power output and power density; assessing the stability of the liquid/gas interface; material selection for the liquid; material selection for the engine components; and energy storage for operating engines in reversed mode as heat pumps [6]. A comprehensive review of Stirling cycle engines for recovering low and moderate heat was recently published [14]. The review included a section specifically assessing liquid piston Stirling machine research projects, the majority of which were associated with water pumping applications. Compared with other types of Stirling machines, the Fluidynes assessed in the review achieved very low efficiencies (0.1–5%).

On the use of liquid pistons in general—more recent research has been done in conjunction with energy storage systems involving compressed air and other gas compressors taking advantage of the nature of liquid pistons. Liquid pistons not only offer perfect sealing capabilities but also the potential to adapt to different geometries. Zhang et al. studied the effect of a varying profile of the cross-sectional area of the compression chamber in a compressed air energy storage system using