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Development of a solar-powered liquid piston Stirling refrigerator

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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 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 behaviour 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 research.

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Keywords: Stirling Cycle, Refrigeration, Liquid Pistons, Renewable Energy, Solar Heating and Cooling, Free-Pistons, Sage

1. Introduction

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

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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 Figure 1. The potential of the Stirling cycle for refrigeration has been known for just about as long as power generation applications. However, it was not until the research by Philips that the foundational theory was laid for commercialisation. 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 in order 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 Figure 1).

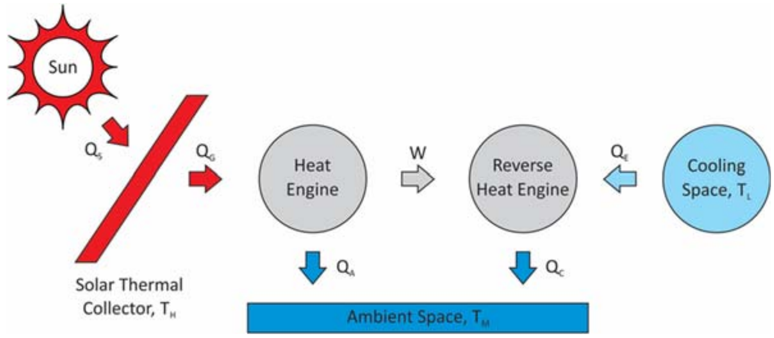

Fig. 1. Thermo-mechanical heat-powered cooling system

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' arrangement 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 [4-7].

This project aims to integrate both forward and reverse liquid piston engines into a single machine, capable of transferring work internally and thus eliminating the need for work coupling mechanisms. This is achieved by using four liquid pistons within a 4-cylinder double-acting alpha-type Stirling configuration as shown in Figure 2. The use of a system of liquid pistons renders piston seals and lubrication redundant, considerably simplifying design and manufacturing requirements. The system can also be hermetically sealed as no work transfer takes place across the system boundary. However, the use of liquid pistons adds considerable difficulty to the analysis of the system, as the interaction between liquid columns and adjacent gas spaces of varying gas pressures has not been researched in this context.

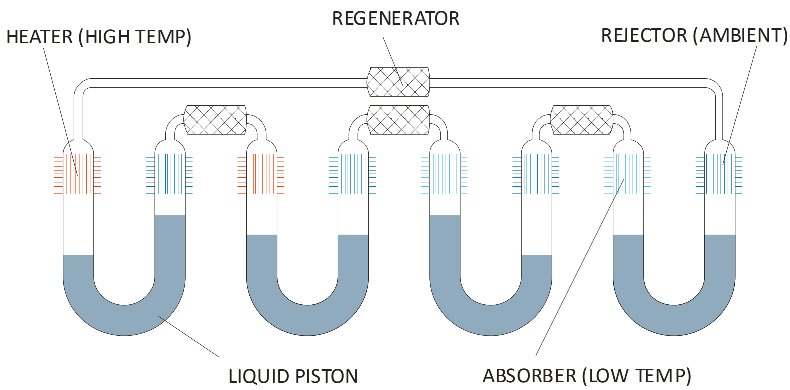

Fig. 2. Liquid Piston Stirling Refrigerator System (2 heaters 2 absorbers).