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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.

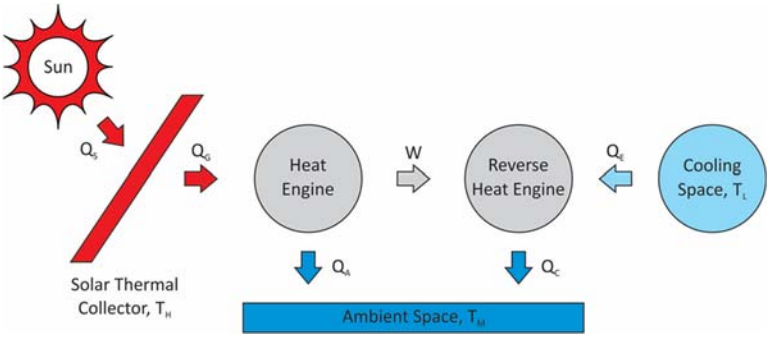

Fig. 1. Thermo-mechanical heat-powered cooling system

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).

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].

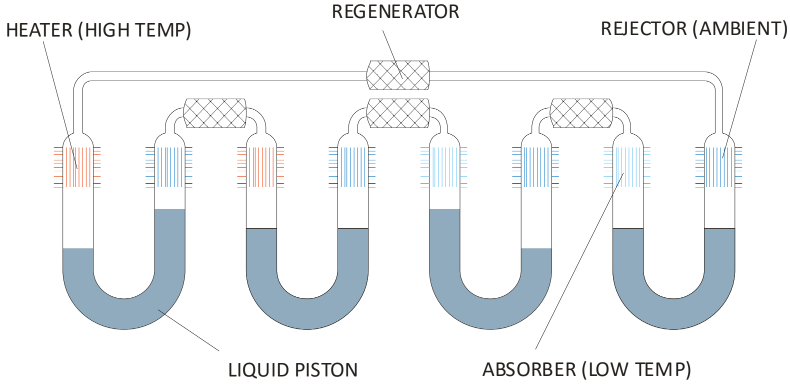

Fig. 2. Liquid Piston Stirling Refrigerator System (2 heaters 2 absorbers).

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.

In this configuration, two of the hot heat exchangers have been converted into absorbers. Gas expansion occurs in both components and heat still flows into the system through the absorbers. The difference is that the gas expansion in the heaters is induced by the high temperature heat input, which results in work being done on the liquid pistons. In the absorber, the gas is forced to expand due to the relative motion between adjacent pistons, moving away from each other. In this forced expansion the gas absorbs heat through the absorber walls, thus creating the cooling effect. Essentially, the work produced as a result of the heat input from the hot heat exchangers is used to force heat absorption by the working gas in the absorbers, resulting in their temperature drop below ambient. All of the heat energy input to the system through the heaters and absorbers is then rejected at ambient temperature through the rejectors (when the gas undergoes compression). The underlying principle of this concept is to use heat as the primary form of energy input to directly produce cold temperatures within a single system, as opposed to the inefficient sequence of generating electricity first and then using the electricity to drive a traditional refrigeration system.

2. Experimental apparatus

Figure 3 shows each of the four gas spaces, embodied by the 'H' shaped housings, resting above the wooden support structure, two in the foreground and two in the background. Each of these is connected in series to the adjacent housing sections via a steel U-tube, which completes the desired geometry of the system, as portrayed in Figure 2. The design of the test-rig allows changes in the geometry of the system so that its performance across a range of operating conditions can be analysed. For example, the liquid piston U-tubes can be exchanged with others of different diameters. Since the primary interest is in the behaviour of the liquid piston Stirling system, the heat input does not come from a solar source, but instead is supplied by electric heating cartridges used in conjunction with a heat exchanger. This enables more efficient, simplified experimentation with a constant and reliable heat source. An integrated solar collector system will potentially be considered for future research. In terms of data collection, eight thermocouples are installed in the gas spaces directly under each heat exchanger. These provide real-time temperatures of the gas in each of the compression and expansion spaces. Four pressure transducers are installed on the cold side of each gas space below the temperature sensor ports. All of these measurement devices are used in conjunction with LabVIEW to monitor, organise and collect the data for analysis.

Fig. 3. Liquid piston Stirling cooler (LPSC) set-up with U-tubes.

3. Modelling

The numerical modelling was carried out using the commercial Stirling simulation software Sage. Sage is a simulation software specifically designed for modelling Stirling engines and coolers, pulse-tube cryocoolers and other types of cryocoolers. It encapsulates gas flow effects and heat transfer between and through components to determine realistic performance characteristics. It is able to model heat transfer processes and fluid friction of oscillating flows – even through porous media such as the regenerator matrix. Each component of the system is analysed in a one-dimensional form subdivided into a user-defined number of spatial increments. While Sage primarily models the thermodynamic behaviour of the working gas, it also takes into account the interaction of the gas with the adjacent walls, as well as heat transfer by conduction in the canister walls in both axial and radial directions. In this respect, Sage is somewhere between a one- and two-dimensional modelling tool. Sage operates in a frequency domain and solves all fundamental conservation equations for each cell until it converges to a solution. Further features of this software package are a mapping tool, which allows a parameter study over a user-defined number of variables in a user-defined number of increments, and an optimisation tool. Components such as heat exchangers, pistons, cylinders, canisters, etc. can be selected from a menu and connected via characteristic variables. For instance, various gas volumes are connected via a mass flow variable; a piston face is connected to the adjacent gas space via a pressure variable. Figure 4 shows the graphical interface of the Sage model constructed for one of the four subsystems of the liquid piston Stirling cooler. The arrows indicate heat, flow and force connections between components. The liquid piston is modelled as a solid piston with a spring attachment for the restoring force of gravity, and a viscous damper with variable damping coefficient based on fluid friction approximations.

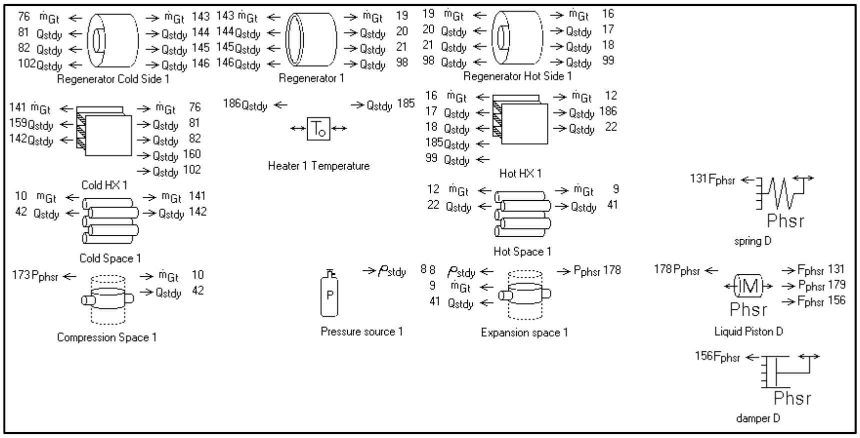

Fig. 4. Sage model of Liquid Piston Stirling Cooler (LPSC) sub-system.

4. Results

Prior to the experimental phase, it was unknown as to what extent the system would perform or whether it would function at all. Following an extensive experimental commissioning and modification phase, the test-rig was used to conduct a parametric performance study by varying several key operating parameters, these included heater temperature (up to 200°C) and gas charge pressure (up to 6 bar). The purpose of this was to obtain a range of experimental results to both understand system trends, and later validate the Sage model. It was found that above a certain initiation heater temperature, the LPSC test-rig would self-start and achieve self-sustained steady-state operation. The pressure amplitudes which developed in each of the four gas spaces varied in magnitude and were found to consistently achieve relative phase angles of 90° with adjacent sub-systems, while the piston displacement phasors developed relative phase angles in the region of 80°-100°. Figure 5 shows the pressure profiles for a one-second period of a typical experiment. Although the magnitudes of the pressure amplitudes developed in each of the four spaces varied by as much as 20%, the sum of the pressure amplitudes developed in the heated spaces was always equivalent to the sum of those induced in the absorber spaces. This indicated good energy conversion from the heat engines to the reverse heat engines, and although the temperature differences generated in the absorber spaces were relatively low (<5°C below ambient), the favourable dynamic behavior of the system suggested that the significant room for improvement and optimization of many system components (such as piston dimensions) might result in large performance gains.

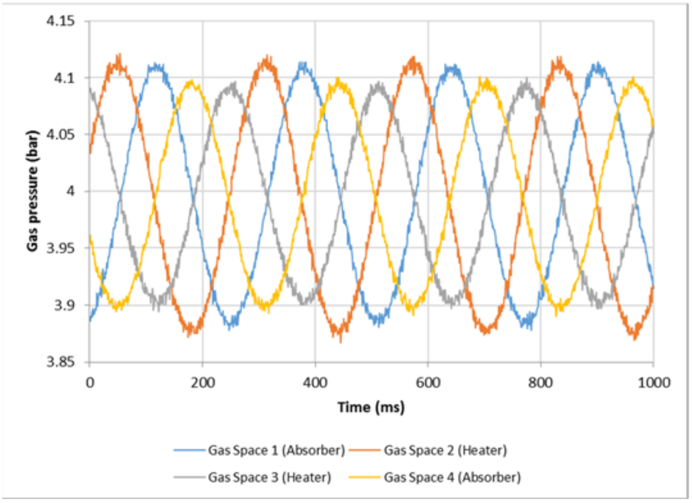

Fig. 5. Steady state gas pressure profiles measured across one-second period during typical experiment.

In the context of system analysis via Sage modelling software, the most important characteristic parameter needed for the LPSC machine is its operational frequency. After experimenting with the test-rig during the commissioning phase, it was noticed that the system frequency was very consistent and predictable, regardless of the configuration being tested or what heater temperature was used. This is plausible given that the LPSC system comprises a series of

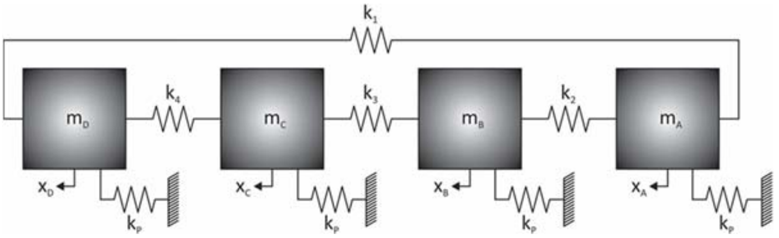

Fig. 6. Spring and mass representation of LPSC system

mass elements (pistons) and springs (gas spaces and piston gravity) connected end on end in a loop, like that shown in Figure 6. Once excited, such a system's natural vibrational behaviour has little dependence on factors other than geometry, mass and spring constant values. Unlike a machine exhibiting a work coupling mechanism, the frequency of the operation cannot be manipulated manually, and instead will settle at the natural frequency of the prevailing conditions and geometry. An analytical approximation for the system's natural frequency was derived using the system approximation in Figure 6, and solving the reulting series of equations of motion for each of the mass elements (assuming either adiabatic or isothermal gas behaviour).

Initially this was used as an input into the Sage model, however, it was discovered that the Sage model was too sensitive to use this approximate value as an input. Instead an alternative procedure was developed using the symetrical properties of the system with four heaters (and zero absorbers) to deduce the precise operational frequency required by the Sage model. It was then shown that this frequency has very little dependence on gas temperature, allowing it to be used as a better approximation for the 2 heater, 2 absorber configuration. Figure 7 shows a comparison between three methods of obtaining system frequency; experimental results, Sage prediction, and the analytical approximations (with adiabatic and isothermal gas behaviour).

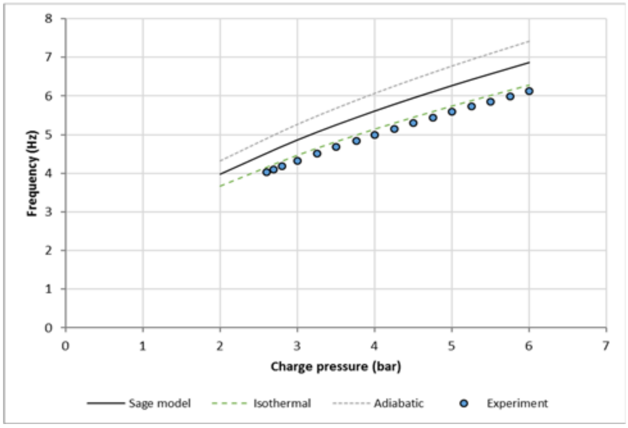

Fig. 7. Frequency comparison between Sage predictions, experiment and natural analytical estimates

Following the successful development of the procedure for using the Sage model independently, its predictions for system performance were able to be compared with the experimental results for the range of heater temperatures and gas charge pressures assessed experimentally. Figure 8 shows the comparison of the pressure amplitudes developed in one of the absorber gas spaces for experiments and simulations at two different heater temperatures (160°C and 165°C). The process was conducted for several different system configurations in order to validate the Sage model. The most important aspect of model validation is that the predicted performance trends aligned with the experimental results for different heater temperatures and gas charge pressures. This was confirmed with reasonably good accuracy, despite larger discrepancies occurring when maximum piston acceleration exceeded a certain threshold. These discrepancies are theorized to result from liquid piston surface instability, which is not accounted for in the Sage model.

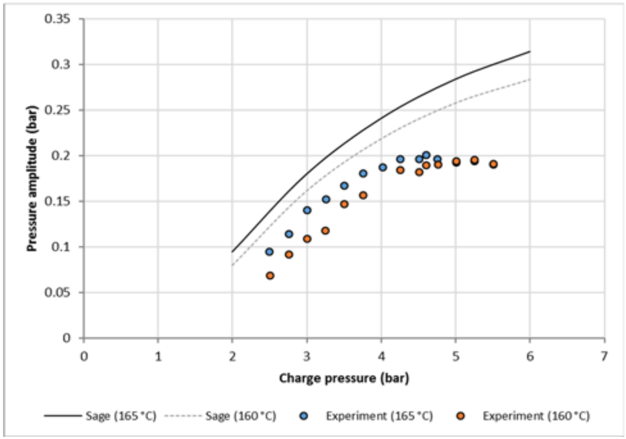

Fig. 8. Steady State gas pressure amplitude comparison between experimental results and Sage model

With the extra information available from the computer model, other important system behaviours and trends were now able to be evaluated. Figure 9 shows the overall coefficient of performance predicted for the LPSC test-rig used in experimentation. The maximum COP predicted occurs at 3.5 bar charge pressure and is approximately 0.53, meaning that for every 1 kW of heat supplied to the heaters, 0.53 kW of heat is absorbed through the absorbers. In this particular case, the absorber temperature was 5°C below ambient temperature; although, as previously mentioned, the experiments and simulations were conducted using an un-optimized test-rig with almost all associated component design having room for improvement. The working gas and liquid used for the liquid pistons can also be changed to better performing substances. For example, during modelling, the single change from using air as the working gas to using hydrogen resulted in the following performance improvements: The COP increased by 3%; the cooling capacity of the machine increased by 59%; the temperatures developed in the absorbers dropped by a further 6°C; and, the second law efficiency increased significantly from 5.3% to 9.9%.

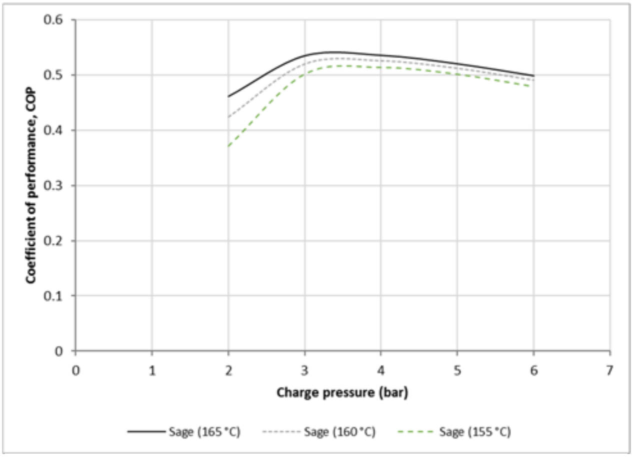

Fig. 9. Sage model predictions for the Coefficient of Performance (COP) of the system.

With a validated Sage model it is now possible to extrapolate system performance over a larger parametric range and investigate potential design improvements (such as liquid piston dimensions) in order to develop a prototype system capable of achieving the desired 5kW cooling capacity for commercial solar-powered cooling applications.

5. Conclusion

In its current un-optimised state, the Liquid Piston Stirling Cooler (LPSC) test-rig has proven to be functional over a wide range of relatively low mean gas pressures (< 6 bar), relatively low heat source temperatures (< 200°C), and with air as a working gas. The (previously untested) 2-heater, 2-absorber configuration proved to be the optimal configuration for cooling performance—with relative phase angles close to 90°, and a conversion ratio of heater gas pressure amplitude to absorber gas pressure amplitude of close to 1:1. A model of the LPSC was constructed in the computer modelling software Sage, and validated against experimental results. An approximation for the natural frequency of the system was derived analytically, and an independent procedure was developed to determine the operating frequency needed for the Sage model. When the working gas in the model is replaced with hydrogen, the performance of the LPSC increases significantly. The predicted COPs for the modified test-rig are close to current market-leading solar cooling options. With a gap in the market for low capacity machines (< 5 kW) a more thorough and targeted optimisation effort is recommended. Many aspects of the LPSC are capable of being improved, including manipulation of the gas space component dimensions such as heat exchangers and regenerators. Different working gases and piston liquids can be modelled—with higher charge pressures to advance plans for an optimised LPSC prototype. If successful, an integrated solar refrigeration system can be developed.

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