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γ-Stirling engine – The effect of different working gases and pressures

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Abstract. This paper presents an investigation into the effects of changing the charge pressure as well as the working gas in a gamma type Stirling engine. An algorithm is developed to predict the effects of engine pressure and the type of working gas on the performance of a gamma-type Stirling engine. Based on the equation of state and the principle of energy and mass conservation, a set of first order differential equations are established. The fourth order Runge-Kutta method is used to solve these equations. The heat losses due to imperfect regeneration and pumping losses in the heat exchangers are included in the solution. The results show that using a working gas of lower density will cause less power losses compared to a working gas of higher density. Above 7.5bar the increase in efficiency with increased pressure becomes less significant with less than 4% increase from 7.5bar to 15bar for air. There is a linear relation between the amount of actual work and the nominal pressure charge of the engine. The results obtained from this simulation show a satisfactory working condition of the engine. The model sections and subsections were verified step by step using detailed and laborious manual calculations.

Key words

Stirling engine, simulation, working gas, pressure variations, iteration, Runge-Kutta.

1. Introduction

In 1816, Dr Robert Stirling patented a new design for a hot air engine with an "economiser" as he called his regenerator. There are two main differences to standard hot air engines, namely the closed loop of the working gas and the regenerator. There was, however, a disadvantage to his new design as the working gas, being used continuously, needed to be cooled down at the end of each cycle. The regenerator is an addition to counteract these added losses due to cooling by acting as an intermediary storage for heat. This meant that the overall efficiency of this design could reach higher values than standard steam turbines. In 1827, both Stirling brothers submitted a new patent which described the use of different gases, other than air, as the working medium. Lowering the density of the gas will lower the work required to "push" the gas around the engine [1]. Numerous individuals contributed to the development of Stirling engines. Notably here are Dr Kammerich and D. Viebach who both managed to develop a working prototype of 1kW and 0.5kW respectively without any financial contributions from major companies. A modified version of the engine designed by D. Viebach (Fig. 1) is used as the basis for this paper. Several evaluations have been presented over the years in order to predict and facilitate the design of engines. The first analysis was carried out by Schmidt almost 50 years after the actual invention of the engine. Schmidt assumed that the compression and expansion spaces are kept constant and at the same temperature throughout the cycle. His major contribution was to link the pressure in the engine to the volume which he assumed to behave in a sinusoidal fashion. An analysis of non-isothermal assumptions was first carried out by Finkelstein in 1960 [2]. He was the first to introduce the concept of conditional temperatures depending on the direction of the working gas flow, by assuming that the heat transfer within the working space takes place due to forced convection. He divided the engine into different cells (compression, cooler regenerator, heater and expansion) and represented them by control volumes using the equation of state as well as energy and mass conservation laws. This principle is further developed by adding the losses due to pumping friction in the heat exchangers by Urieli and Berchowitz [3]. The approach developed by Urieli is also used by Scollo *et al.* to design and construct a Stirling engine prototype. They use the model to estimate results and improve their design and show the usefulness of this method to get preliminary indicative information of the engine behaviour. [4]. Martini presents a good collection of simulations as well as scaling parameters with worked examples [5]. In particular he describes the various approaches and limitations of first, second and third order methods to simulate Stirling engines. Whereas first order design methods [6] are usually used to give an initial idea at the beginning of the design stage, they are limited in the way