TEL AVIV UNIVERSITY
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Optimization of a Miniature Heat Engine

A thesis submitted toward the degree of
Master of Science in Mechanical Engineering

by

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Abstract

Micro power generator devices have been proposed as energy source for wide range of applications, from medical implants to a pump or fan for manportable cooling or heating. At the higher power ranges (of order 1-50 watts) those devices are envisioned to provide portable power for computers and personal electronics. At the lower power range (of order 1 milliwatt), they could power remote sensors or actuators. If produced at low cost they may even provide electricity for electricity networks.

One strategy is to downscale classical heat engines as gas turbines or steam engines to the sizes of the batteries while sustaining high power densities. This strategy faces significant difficulties because physical effects can be different in micro-scales. One example for those differences is sliding friction. In micro devices the surface forces between sliding or rotating parts can easily overwhelm driving forces, while in conventional engines, sliding friction while important is not overriding concern for the designers. A different approach is to design from the start a micro heat engine, which exploits microscale phenomena like improved conduction heat transfer, and which is built using well developed microscale manufacturing techniques, with materials amenable to micro-scale applications.

This work proposes a miniature heat engine SPICE (Saturation Phase-change Internal Carnot Engine), based on a cavity filled with a stationary working fluid and encapsulated by two membranes. Heat is transferred to and from the fluid by thermal conduction through one of the membranes. Deflection of the membranes generates mechanical power, which can be converted to electrical power using a piezoelectric layer or another electro-mechanical converter. We propose to use an external control force, which acts on the membranes and sustains constant internal pressure and temperatures, thus causing the internal efficiency to approach the Carnot efficiency.

An engine model was developed including coupled consideration of geometry, thermodynamics, mechanics, and heat transfer. The performance of this engine was analyzed and optimized, including the thermodynamic cycle, transient heating and cooling, and the elastic deformation of the membranes. A mechanical constraint on the yield stress of the membranes is considered in model design. Comparison to the Curzon-Ahlborn analysis shows that the irreversibility of finite rate heat transfer is not the only important factor that affects the performance of the engine. The heat capacity of the membrane is another factor that affects the performance, leading to the definition of an optimal frequency for the engine. Optimal design parameters, maximum power, and maximum efficiency of the engine are found by numerical optimization.

The engine model analysis leads to a conclusion that its performance can be characterized by three parameters, representing the geometry, frequency and internal temperature. Those parameters are then optimized to achieve maximum power density. The effect of geometric scaling to small dimensions is investigated. The result of the geometric scaling shows, that downsizing the engine by reducing the membranes thickness, but keeping the geometric ratios constant, will increase the power density. The specific power density and efficiency that are obtained for different sizes of the engine are compared to the performance of the proposed existing micro-scale and macro-scale heat engines. It was shown that the type of engine we have proposed in this work may have higher power density than conventional macro-scale heat engines, and its efficiency is better compared to other miniature engines.

The proposed model was based on the assumption of the thermodynamic equilibrium. This assumption does not hold for the obtained optimum working point and a way to keep this assumption as valid is discussed. Some important aspects were not handled at this work and should be analyzed in the future. The model did not handle the mechanisms of external control force, which assures realization of isothermal thermodynamic processes, the external mechanism of heat exchange and the electro-mechanical energy conversion mechanism. More work should also be done to analyze the impact of different working fluids and materials on the engine performance.