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Simulation-driven design of a passive liquid cooling system for a thermoelectric generator

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HIGHLIGHTS

- A passive liquid thermosyphon cooling system for a thermoelectric generator (TEG) was designed.
- The system has been computationally simulated and verified with experimental results.
- A parametric study was undertaken to optimize the heat sink fin height and fin spacing.
- The complete system was tested experimentally with a single TEG to evaluate power generation.
- The study demonstrates an effective cooling system and a method of design for such a system.

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ABSTRACT

Active cooling of thermoelectric generators (TEGs) is problematic since mechanical devices such as pumps and fans draw a high proportion of the limited power generated. Increasing the coolant fluid flow rate is typically a scenario of diminishing gains since the increased TEG power can be more than offset by the increase in power required for the fluid mover. Passive air cooling is an option, however the high air-side thermal resistance results in poor TEG power performance and low thermal efficiency. To address these issues, and others, a passive single phase liquid thermosyphon cooling system for use with TEGs has been designed, computationally simulated and experimentally tested. The novelty of the cooling system centres not only on the hot-side heat exchanger design, but also on the use of an open liquid reservoir as a dual-purposed heat store and air-side heat sink. This results in an effective source-to-sink heat exchange system that is entirely passive while providing effective cooling. This work describes the Simulation-Driven Design approach used to design the system for an example of a single TEG, experimental verification of the simulation results and TEG performance characteristics with the new cooling system.

1. Introduction

Thermoelectric generators (TEG) are solid state semi-conductor devices that convert heat directly into electricity via the thermoelectric effect. Despite their low efficiency of $< 7\%$, the absence of moving parts makes TEGs reliable power generators when operated under stable thermo-mechanical conditions [1]. As with any heat engine operating on a thermodynamic cycle, a TEG requires both a heat source and a heat sink, with associated heat exchangers to maintain the temperature differential as high as possible to maximize thermal efficiency. This study focusses on the cooling mechanisms for thermoelectric generators which can be categorised as active or passive and can use air or liquid as coolants.

Air cooled natural convection is a passive cooling technique whereby the heat is transferred directly to ambient air, with the coolant flow being driven by buoyancy forces. Generally, finned metallic heat sinks are required to dissipate the heat load in order to achieve a feasible air-side thermal resistance. Albeit a passive technique, the major drawback of air cooled natural convective heat sinks for TEG applications is their comparatively large size compared to the TEG, with associated heat spreading and convective thermal resistances which limits cooling effectiveness and thermal efficiency. In studies such as Refs. [2–4], the TEG systems have implemented natural air cooling, however the power output is low and well below the maximum rated power. However, the excellent reliability associated with the system having no moving parts makes this solution viable for space exploration [5], automotive heat recovery applications [6], remote power applications [7], domestic power generation [3,4], and solar power generation [8].

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Nomenclature

A_{ws}	wetted surface area, m^2
C_p	specific heat capacity, J/kg K
g	gravitational acceleration, m/s^2
Gr	Grashof number, –
h	fin height, m
h_{avg}	average heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
k_{Al}	thermal conductivity, W/m K
L	fin length, m
p	static pressure, Pa
P_{elec}	electrical power, W
Q	heat flow to heat sink, W
Q_{evap}	heat loss due to evaporation, W
$Q_{manifold}$	heat loss through manifold, W
Q_{pipe}	heat loss through pipe walls, W
$Q_{res,sides}$	heat loss through reservoir walls, W
q''	heat flux, W/m^2
Ra	Rayleigh number, –
R_L	electrical resistance of load, Ω
R_{TEG}	electrical resistance of TEG, Ω
R_{th}	thermal resistance, K/W
s	fin spacing, m
s_{opt}	optimal fin spacing, m
T_c	TEG cold side temperature, K
T_{feed}	feed water temperature, K
$T_{fin,avg}$	average fin temperature, K
T_h	TEG hot side temperature, K
T_{hs}	average heat sink base temperature, K
T_{retn}	return water temperature, K
T_{ws}	heat sink wetted surface temperature, K
ΔT_{lm}	log mean temp. difference, K
ΔT_{TEG}	TEG temperature difference, K
α	thermal diffusivity, m^2/s
α_{eff}	effective seebeck coefficient, V/K
β	thermal expansion coefficient, 1/K
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
υ	kinematic viscosity, m^2/s

It is worth noting that a hybrid passive solution to improve heat spreading over the air-side fins, and thus natural air cooling effectiveness, is to employ heat pipes [9,10].

Forced air cooled systems use mechanical means, such as fans and blowers, to substantially increase the air-side convective heat transfer coefficient compared with natural convection. This results in substantially lower thermal resistance and a more compact form factor of the cooling system. Although the TEG thermal efficiency may increase, the power requirement for the air mover must be taken into account when considering the Coefficient of Performance (COP) of the overall TEG system, since this energy must be supplied by the TEG [11,12]. TEG system start-up also becomes problematic since the electric motors on fans and blowers have a minimum cut-in voltage. The dilemma is that the TEG may require forced air flow in order to produce the minimum cut-in voltage to run the fan/blower. This then requires an electrical store, such as a battery, in order to run the air mover during start up or times of low power generation. Fans and blowers also suffer from reliability issues due to failure of mechanical components over long term use. Regardless, force air systems have been investigated for domestic and industrial applications [13–16], with acceptable power generation. Heat pipes have also been implemented in order to increase the area available for air-side cooling and thus improve the thermal resistance and TEG power output [17].

Liquid cooled forced convection is employed for higher power TEG applications. The high convective heat transfer coefficients achieved with liquids, in particular water, can also reduce the hot-side heat sink footprint to that of the TEG [18]. However, the end-to-end system can involve many components, including a pump, remote air-side heat sink and connecting tubing and fittings which increases the overall complexity and can adversely affect cost [1] and reliability. Positively, forced liquid cooled systems can achieve power generation comparable to the manufacturer's specifications. Once again, however, the COP of the integrated system must be considered since electrical power is required for circulating the liquid and air-side fan, when applicable. The former is particularly relevant for compact hot-side heat exchangers which require a high fin density to reach the target thermal resistance, which can adversely affect the required hydraulic pumping power due to increased pressure drop. Despite some shortcomings, forced liquid systems are commonly used in automotive [19,20], marine [21], industrial [22,23] and domestic cogeneration [24,25] applications.

An ideal cooling system for TEGs would incorporate the benefits associated with the cooling effectiveness of forced convective systems with the infinite COP and high reliability of fully passive systems. To this end, liquid cooled natural convection systems may provide an ideal engineering solution, though the published literature on this is limited. Champier et al. [26] used TEGs to cogenerate electricity and hot water from a domestic solid fuel stove with four TEGs attached directly to a reservoir of water. Initial demonstrators showed that the power generation was comparatively low per module, though this was improved by using finned heatsinks on the hot-side of the liquid cooling system. Juanicó et al. [27] developed a low cost TEG system using domestic hot water radiators in a single-phase thermosyphon configuration. The system thermal-hydraulics was modelled demonstrating that system optimization was realizable.

There exists few commercially available off-grid TEG power generators, typically marketed for use in camping and emergency power generation. Devices such as the PowerPot, FlameStower and Biolite KettleCharge use a small water reservoir directly attached to a TEG, with the heat being supplied by combustion of fuel. These systems are designed to take advantage of the very high heat transfer coefficients associated with nucleate boiling which can maintain hot-side TEG temperatures in the region of 100 °C. Though these devices provide a useful service and are completely passive, the performance of the TEG is greatly reduced by the high cold side temperature which reduces the thermal efficiency.

The above review illustrates that there are several methods available to provide cooling for TEG systems. The ideal system should provide effective cooling and operate passively. The latter is of utmost importance since it targets the lack of parasitic electricity draw from the limited power generated by TEGs, mitigates start-up issues and improves long term reliability. These issues are addressed in this work, where a single phase water thermosyphon concept is described. Designed using Simulation Driven Design (SDD), the passive system uses a compact finned heat exchanger and a remote reservoir. A novel aspect of the design is that, opposed to a conventional finned air-side natural convection heat sink, the reservoir acts in the capacity as a gravity-pump, a thermal store and a passive heat sink in order to provide effective cold-side heat sink temperatures of the TEG over long periods of time (> 10 h).

1.1. TEG theory and properties

Like any heat engine, to generate electrical energy a TEG requires heat transfer from a source of heat while simultaneously dissipating