HEAT STORAGE POWER SUPPLY FOR WIRELESS AIRCRAFT SENSORS

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Abstract: Aircraft energy harvesting technologies are very interesting as a power solution for wireless aircraft monitoring systems. Their feasibility is limited by the low availability of vibrations, avionic regulations and the requirement for specific location of sensors. These locations are rarely convenient for solar harvesting, and offer limited temperature gradients. Heat storage thermoelectric harvesters can address this restriction for aircraft exterior or skin monitoring applications, by using a heat storage unit to create a device-internal spatial ΔT from temperature variations in time. In this paper a new heat storage power supply is presented, including power management and storage. A generator energy output of 67 J is demonstrated from a typical ±20 ^{o}C flight temperature profile and 25 g of phase change material. The power management system delivers more than 40 J into a rechargeable battery, demonstrating an overall efficiency over 60%. This energy is enough for state-of-the-art duty-cycled avionic wireless sensors.

Keywords: energy harvesting, aircraft sensors, thermoelectric, heat storage

INTRODUCTION

Aircraft monitoring systems could benefit significantly from the use of self-powered wireless sensors, avoiding the weight and installation overhead of wired avionic networks. For this reason, the development of energy harvesting devices for aircraft has attracted a lot of attention the last few years, creating an emerging energy harvesting application area.

A variety of energy sources and harvesting techniques have been proposed, but low aircraft vibration levels, low light availability and limited temperature gradients at the device location have restricted their use. Recently, a new thermoelectric energy harvesting device was proposed, which exploits the variation of ambient temperature with time [1-3]. Laboratory and flight tests have demonstrated that the energy output per flight is adequate for low power wireless sensors [4]. In a previous paper, an analysis of heat flow in such devices was presented, highlighting the TEG properties required for optimal operation [5]. In another work, a set of design rules for heat storage thermoelectric devices was defined, including an assessment of expected energy density per flight and results from a prototype device demonstrating output energy of 105 J using 23 g of PCM, during a typical flight temperature profile [6] .

In this paper, a power supply based on an improved heat storage harvester is presented, including a power management and storage system. After a summary of the device concept, the fabrication details of the power supply are given. The performance of the generator and the power management response are discussed, followed by an assessment of the outlook for further work on heat storage thermoelectric harvesters.

DEVICE CONCEPT

The operation of the device is illustrated in Fig. 1. A heat storage unit (HSU) is used to capture and release heat while the ambient temperature T_{out} varies. A thermoelectric generator (TEG) is placed between the HSU and the environment. The HSU is otherwise insulated from the environment, so that heat can flow in and out the HSU only through the TEG.

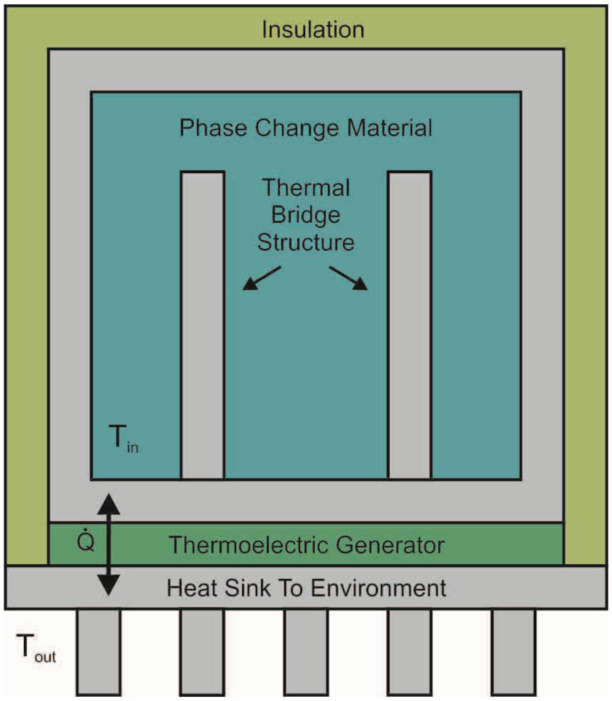

Fig. 1: Functional schematic of the heat storage thermoelectric harvesting device.

As T_{out} changes, a temperature difference ΔT occurs between the HSU and the environment, resulting in heat flow $\dot{Q}$ through the TEG, which is converted into electrical energy.

A phase change material (PCM) is used inside the HSU to increase the thermal capacity by its latent heat. This increases the available heat energy by an order of magnitude, which increases ΔT and TEG conversion efficiency, significantly increasing the total electrical energy output.

FABRICATION

The HSU used is a specially made 60×30×30 mm aluminium box with internal thermal bridges, waterproof lid and capacity of 30 cm^3. For thermal insulation, a 2 mm thick polyurethane box was designed and made-to-order by Custom Moulded Polyurethanes Ltd, to match the HSU dimensions. The TEGs used were two TG12-2-5 Marlow TEGs, with figure of merit $ZT = 0.72$, each having a thermal resistance of 3.6 K/W and an electrical resistance of 5 Ω. The two TEGs were installed side-by-side, i.e. in parallel for heat flow, but they were electrically connected in series to increase the total output voltage. Water was used as the PCM. For the experiments presented in this paper the HSU was filled with 25 cm^3 of distilled water.

A photograph of the device is shown in Fig. 2. The red cover is the polyurethane insulation, slightly lifted from its normal position to reveal the HSU for illustration purposes. On the bottom side of the HSU the two TEGs are visible. For temperature measurements, two T-type thermocouples were used, connected to a Fluke thermometer with an RS-232 interface. One thermocouple was located between the HSU and the insulation at the centre of an HSU face. The other was located on the top surface of a 100×50×10 mm Al plate which was attached to the bottom surface of the TEGs (not shown in Fig. 2). Thermal paste was used for all thermal connections. A custom cooling chamber was used to provide temperature variations between 20 ^oC and – 20 ^oC.

For electrical measurements, the combined voltage output of the two TEGs was monitored using a Velleman DVM 1200 digital multimeter with a USB interface. During measurements the combined TEG output was connected to a 10 Ω resistor, matching their series internal resistance, in order to achieve maximum power transfer.

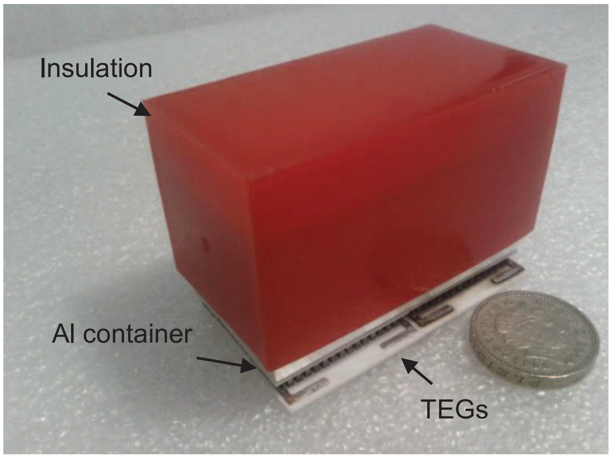

Fig. 2: Photograph of a device prototype.

GENERATOR PERFORMANCE

The device response to a temperature cycle between ±20 ^oC is shown in Fig. 3. As the outside temperature T_{out} (thick line in Fig. 3) is swept from +20 ^oC to -20 ^oC the HSU temperature T_{in} (thin line in Fig. 3) follows, with a delay determined by the thermal response time constant RC of the device, where R is the thermal resistance between inside and outside and C is the heat capacity of the HSU [6]. This effect occurs during the first 5 minutes of the cycle. Super cooling allows the water to cool down to -8 ^oC, but when freezing nucleation is initiated, its temperature jumps back to 0 ^oC and the phase change of water begins.

The duration of phase change is about 7 minutes. During this operation mode T_{in} drifts from 0 ^oC to -5 ^oC. This can be attributed to phase change non-uniformity and a thermal gradient inside the HSU. In addition, the phase change considerably affects the T_{out} profile. As the T_{in} sweep slows down, the outside temperature T_{out}, measured on the Al stage attached to the bottom TEG surface is also slowed down, staying almost constant at -16 ^oC throughout the phase change. This is due to the limited thermal capacity of the Al stage and the limited thermal conductance between the stage and the environment. This ΔT – limiting effect is expected to also occur in real flight conditions and its scale may be determined by device packaging and installation. An average ΔT of around 13 ^oC is observed.

After phase change, T_{in} continues sweeping towards T_{out} with a rate again determined by the thermal time constant. The opposite effects occur during warm-up, though with the phase change occurring as soon as the water reaches 0 ^oC. During the warm-up phase change, a T_{in} drift and T_{out} sweep slowing down similar to the cool-down phase change occurs. The warm up phase change duration is around 8 minutes, with an average ΔT of 18 °C.

Though the super-cooling, T_{in} drift and T_{out} sweep slowing down effects do not affect the total available heat energy from a flight cycle, they reduce significantly the average ΔT that is achieved and hence the efficiency of the TEGs. For this reason, significant improvement of performance is expected by their restriction.

The voltage output (dashed line in Fig. 3) is around -0.6 V during freezing and around 0.8 V during melting. The corresponding output power delivered on the 10 Ω load resistor can easily be calculated and is presented in Fig. 4, along with the total energy. The output energy is 29 J and 38 J during the cool-down and warm-up stages respectively. The total electrical energy output of 67 J, or 2.6 J per gram of PCM, corresponds to approximately 25% of the theoretical maximum for a ±20 °C temperature profile [6].

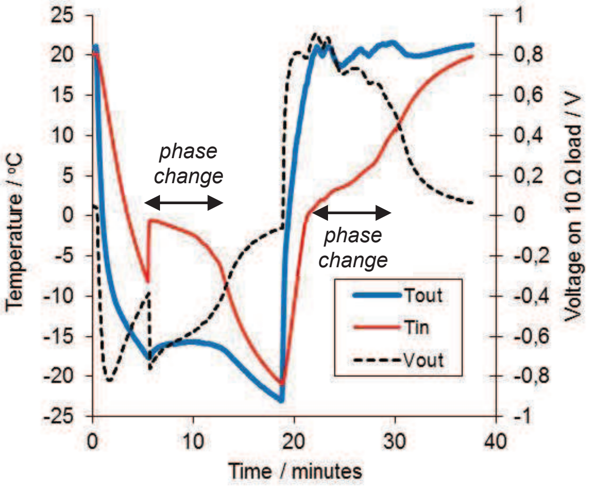

Fig. 3: Device response to a temperature cycle corresponding to a typical short-haul flight.

POWER MANAGEMENT

A power management system was developed in order to convert the generated voltage of the TEGs into a regulated output voltage and to store excess energy into a battery.

From the voltage profile shown in Fig. 3, it can be seen that a bipolar voltage is generated because ΔT changes sign midway through the complete cycle. Therefore it is necessary to incorporate a rectification stage into the power management system. However, due to the low voltages generated by the TEGs, simple bridge rectifiers are not suitable due to the diode voltage drops being comparable to the generated voltage of ±0.8 V.

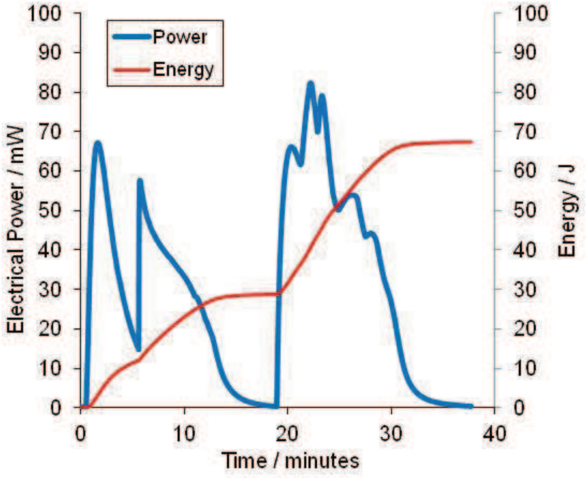

Fig. 4: Measured power and energy output corresponding to the data of Fig. 3.

In addition, it is desirable for the rectifier to cold-start which precludes the use of conventional active rectification requiring gate drivers. A new rectifier topology was developed using a combination of off the shelf enhancement- and depletion-mode MOSFETs. These were configured such that the required rectification path is available at the beginning of the temperature cycle without gate drivers. A full description and analysis of the power management system used in this power supply is currently in preparation.

The complete system includes a Texas Instruments BQ25504 impedance-matching boost converter and battery charger, a 4.1 V, 120 mAh rechargeable battery and an LDO regulator for output voltage regulation. A block diagram of the system is presented in Fig. 5

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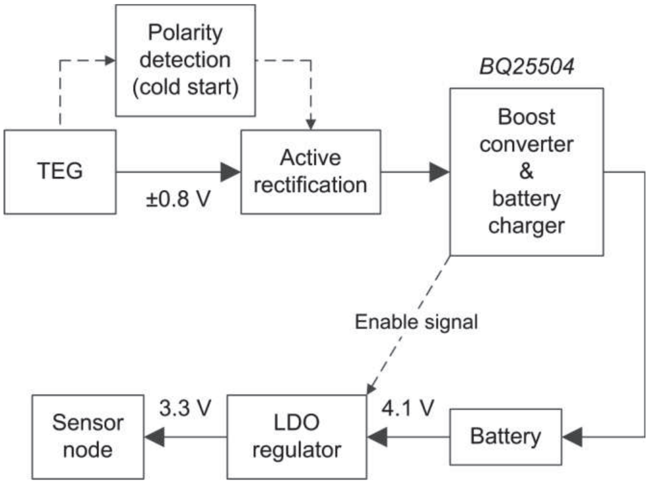

Figure 5. Block diagram of the power management system.

The harvester produced 68 J of electrical energy during the temperature cycle of which more than 40 J was stored in the battery. This corresponds to an efficiency of the power management system of approximately 60%.

CONCLUSION

Heat storage thermoelectric harvesters offer a promising solution to the challenges of powering aircraft sensors. An energy density of 2.6 J per gram of PCM has been demonstrated in this paper, for temperature profiles of typical flights. A power supply delivering 40 J of energy per flight into a battery was also demonstrated.

Higher performance is possible by addressing super-cooling and using TEGs with higher efficiency and thermal resistance. Power management of higher efficiency is also possible by design optimization of the novel circuit blocks and integration.

This technology is expected to enable energy autonomous wireless sensor networks for specific aircraft monitoring cases in the near future.

ACKNOWLEDGEMENT

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