A Novel Pyroelectric Generator Utilising Naturally Driven Temperature Fluctuations from Oscillating Heat Pipes (OHPs) for Waste Heat Recovery and Thermal Energy Harvesting

*D. Zabek [1], *J. Taylor* [1], *V. Ayel* [2], *Y. Bertin* [2], *C. Romestant* [2], *and C. R. Bowen* [1]

[1] University of Bath, Calverton Down, BA2 7AY, (UK).
[2] Pprime Institut CNRS – ENSMA – Université de Poitiers, UPR 3346, Futuroscope-Chasseneuil, (FR).

*e: D.Zabek@bath.ac.uk

Keywords: OHP, PHP, pyroelectric, waste heat recovery, thermal energy harvesting, heat engine.

Abstract: Low temperature thermal to electrical energy converters have the potential to provide a route for recovering waste energy. In this paper we propose a new configuration of a thermal harvester that uses a naturally driven thermal oscillator free of mechanical motion and operates between a hot heat source and a cold heat sink. The system exploits a heat induced liquid-vapour transition of a working fluid as a primary driver for a pyroelectric generator. The two-phase instability of a fluid in a closed looped capillary channel of an oscillating heat pipe (OHP) creates pressure differences which lead to local high frequency temperature oscillations in the range of 0.1 – 5 [K]. Such temperature changes are suitable for pyroelectric thermal to electrical energy conversion, where the pyroelectric generator is attached to the adiabatic wall of the OHP, thereby absorbing thermal energy from the passing fluid. This new pyroelectric-oscillating heat pipe (POHP) assembly of a low temperature generator continuously operates across a spatial heat source temperature of 55 °C and a heat sink temperature of 25 °C, and enables waste heat recovery and thermal energy harvesting from small temperature gradients at low temperatures. Our electrical measurements with lead zirconate titanate (PZT) show an open circuit voltage of 0.4 V (AC) and with lead magnesium niobate – lead titanate (PMN-PT) an open circuit voltage of 0.8 V (AC) at a frequency of 0.45 Hz, with an energy density of 95 [pJ cm^{-3}] for PMN-PT. Our novel POHP device therefore has the capability to convert small quantities of thermal energy into more desirable electricity in the nW to mW range and provides an alternative to currently used batteries or centralised energy generation.

1. Introduction

The volatile nature of thermal and electrical energy requires a continuous supply with the ability to generate and distribute large scale electric power, since our infrastructure, safety, health and comfort relies on the availability of electricity. Today, over 80 % of the world's electricity is generated from heat [1] and conventional generators such as internal combustion engines (>900 [°C]) or external combustion cycles (>450 [°C]) operate extremely efficiently at such high temperatures. However, the fossil fuel resources, such as coal and gas, which are required to generate high temperatures are limited in availability and the technologies are greatly optimised. At a lower temperature scale, Organic Rankine Cycles (ORCs) are capable of effectively utilising low temperature heat (>150 [°C]), but much of this low grade heat is often not exploited and is simply wasted and released into the atmosphere [2]. This untapped waste heat ranges from thermal management of microprocessors, industrial curing processes, and geothermal sources to more unconventional heat sources such as the human body and contact friction. When exploiting waste heat for energy generation, the generated electricity improves the conversion efficiency of the primary thermal driver and reduces thermal pollution, and is therefore an opportunity for harvesting otherwise unused thermal energy. However, temperatures below 100 [°C] are difficult to recover and to harvest, since the available thermal gradient is low. The use of thermoelectric generators (TEGs) when assembled into a device can be limited, since an effective use of such an approach requires large spatial temperature gradients [3].

There is an increasing number of industrial and consumer electronics devices with a need to achieve miniaturisation and circuit integration and this leads to thermally highly concentrated areas which require structurally small heat transfer devices to transport heat. This includes microprocessors, voltage transformers and current rectifiers, since much of the modern electronics requires a direct current (DC), and a wide range of mobile computing devices or electric motors; the use of water-cooling pumps or blower fans is undesirable here due to safety or noise concerns. As a result, the need for more effective heat transfer devices is rapidly growing [4]. The application area of heat pipes and oscillating heat pipes (OHPs), also termed pulsating heat pipes (PHPs), is attracting interest for thermal management or low gradient heat transfer, since they have a high effective thermal conductivity and can be fabricated in almost any shape and size [5]. When an OHP moves thermal energy from one place to another, the naturally driven fluid flow leads to temperature oscillations along the device surface and provides an opportunity for pyroelectric based energy harvesting. Pyroelectric materials produce an electrical current from temperature changes (dT/dt), and can therefore transform the temperature oscillation of an OHPs into electricity while it effectively provides cooling for heat concentrated areas. For such a system, the combination of compact cooling, waste heat recovery and thermal energy harvesting with pyroelectrics is of significant interest since naturally occurring temperature oscillations are often at much lower frequency

(<<1Hz). Efforts to employ pyroelectric materials for thermal energy harvesting at high frequencies have led the development of self-induced pyroelectric engines that make use of a bistable membrane for mechanical switching, generating an open circuit voltage of up to 13 [V] (primarily utilising the piezoelectric effect since all pyroelectrics are also pyroelectric) [6]. Other theoretical approaches employ the difference in thermal conductivity between a liquid and a vapour fluid to provide mechanical motion for a pyroelectric engine [7] or a cantilever structure which mechanically switches the heat flow [8]. However, due to the complexity of these systems the energy trade-off is typically small with pyroelectrics.

In this paper, we propose a novel type of waste heat recovery and thermal energy harvesting device capable of transforming low temperature fluctuations in oscillating heat pipes into electricity utilising the pyroelectric effect. The combination of pyroelectrics (P) with oscillating (O) heat (H) pipes (P) – POHP, enables highly effective heat transfer at low temperatures for transforming heat into electricity where needed. The proposed POHP system is free of mechanical motion where the pyroelectric element is powered by the heat that is exchanged within an OHP. This type of generator assembly has the potential for applications in compact cooling, operation in harsh environments due to the sealed design, solid-state operation, and utilising a wide range of temperatures by tailoring the working fluid. There is also potential for miniaturisation of the system with weight reductions and downscaling benefits with micro fluid systems. In addition, the cooling performance enhancement is expected to be 100 times greater than conventional cooling systems due to the variable surface tension with fluid mixtures and the possibility of a supercritical evaporation [9]. The POHP generator can therefore be considered as an efficient low temperature electric power generator and cooling device.

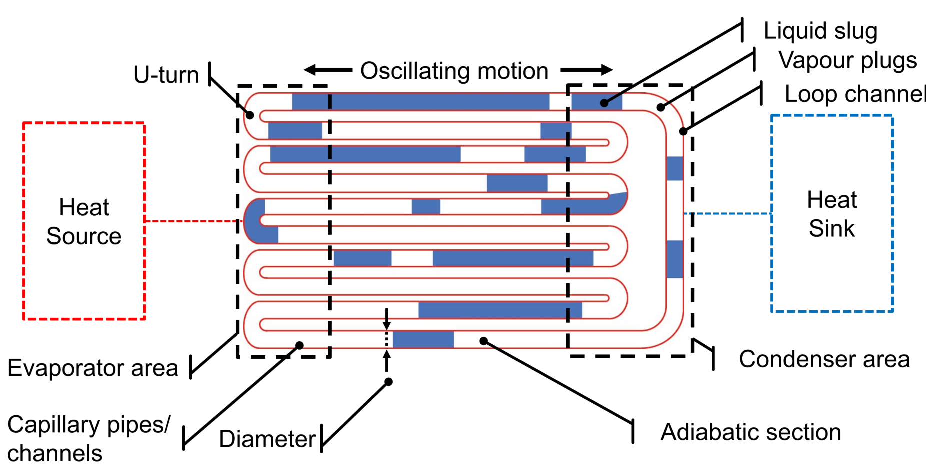


Figure 1: Schematic diagram of closed-loop oscillating heat pipe (OHP).

2. Pyroelectric - Oscillating Heat Pipe (POHP)

The complex interaction between the different heat transfer principles of conduction, evaporation and condensation is the driving force of a self-sustaining pulsating fluid flow in an OHP system. The OHP device is initially filled with a working fluid in the liquid-vapour saturation state, and is then placed between a hot reservoir (heat source) and a cold reservoir (heat sink). **Figure 1** shows a schematic of a closed-loop OHP device. In the OHP, a single capillary channel that separates the liquid 'slugs' by vapour 'plugs' moves the working fluid successively through the hot evaporator area (left side in **Figure 1**) and through the cold condenser area (right side in **Figure 1**) [5]. As a result, the working fluid evaporates at the evaporator zone at the left side of **Figure 1** and condenses at the condenser zone at the right side of **Figure 2** to create local pressure difference. The induced liquid-vapour phase transitions creates a self-driven, rapidly pulsating and circulating fluid flow in the looped capillary channel of the OHP [10]. This sudden change in thermodynamic state of the fluid is determined by the fluid temperature, pressure, gravity and fluid surface tension, where the self-arranged fluid continuously absorbs heat at the hot evaporator zone and ejects it at the cold condenser zone after passing through the central adiabatic section (centre of **Figure 1**) [11]. When considering the energy balance, and considering no heat losses to the surroundings, the amount of absorbed heat at the hot side corresponds to the amount of ejected heat at the cold side. A key variable to design a viable OHP device is the hydraulic capillary channel diameter (maximum diameter of channel) that separates the liquid-vapour plugs and slugs by the surface tension of the fluid. By consider the Bond number *Bo,* which is the ratio between gravitational and capillary forces acting on an isolated bubble in a vertical capillary tube, the first design approach for an OHP is to determine the critical channel diameter [5]:

$$Bo = \frac{1}{2}\frac{d_h^2 \cdot g(\rho_l - \rho_v)}{\sigma} \qquad (1)$$

where $\rho_l - \rho_v$ [kg m^{-3}] is the density difference between the two phases (ρ_l = fluid and ρ_v= vapour), and σ [n m^{-1}] is the surface tension of the fluid. The maximum diameter $d_{h,max}$ of the OHP tube is given by:

$$\frac{d_{h,max}}{2} \leq \sqrt{\frac{\sigma . Bo}{g(\rho_l - \rho_v)}} \qquad (2)$$

Equation 2 provides a geometrical upper limit of the OHP channel width for maintaining a separation of the slugs and plugs in the tubes. In addition to the channel diameter, other design parameters include the viscous pressure that increases along the channel length and limits fluid motion and is therefore a secondary geometrical limitation. In addition to the channel design, the selection of the working fluid influences the operation of an OHP with surface tension, latent heat, liquid viscosity and the pressure gradients, determining the characteristic liquid-vapour plug and slug separation in **Figure 1**. At the evaporator area, the emergence of evaporation and nucleated bubbles is the driving force of the natural and self-sustaining bubble train flow.

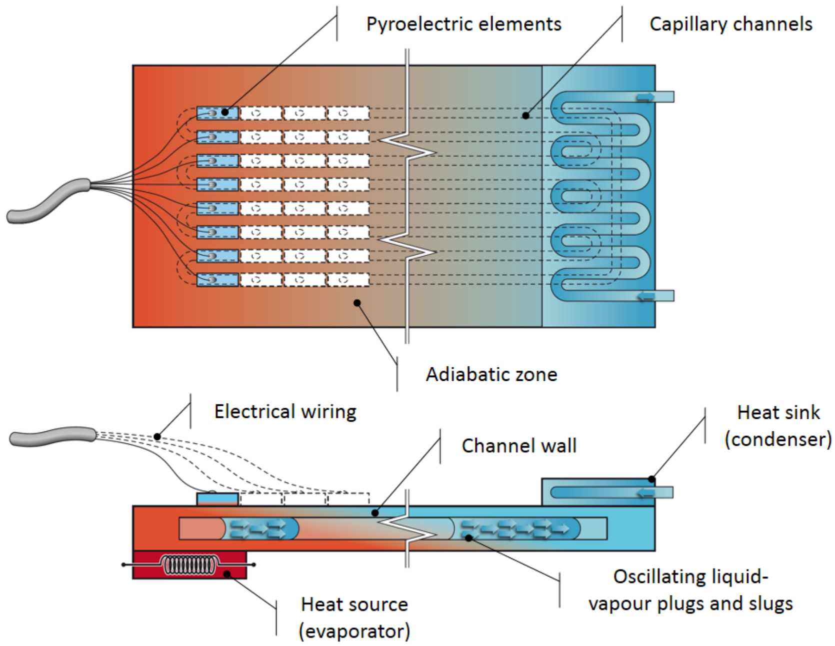


Figure 2: Working principle of a POHP generator with the hot evaporator on the left and the cold condenser on the right side.

Figure 2 shows a top- and a cross-sectional view of the capillary channels embedded in an OHP device. As a result of the change in heat transfer properties of the liquid slugs and gaseous plugs phases, they also exchange heat along the adiabatic channel wall of the OHP with local fluctuations in temperature. If we consider a pyroelectric element attached to the channel wall, as shown in the left side of **Figure 2**, the passing slugs and plugs sequentially heat and cool the pyroelectric element respectively. Since a pyroelectric directly converts a change in temperature into an electrical potential difference, the temperature variations induced by the passing liquid slug - vapour plug flow can create an alternating current (AC) proportional to the heat exchange between the fluid and the pyroelectric through the channel wall. While thermoelectric modules based on the Seebeck effect (TEGs) recover heat from spatial temperature gradients, the available transient change in temperature (dT) with OHPs changes the polarisation P [C m^{-2}] of a pyroelectric material [12].

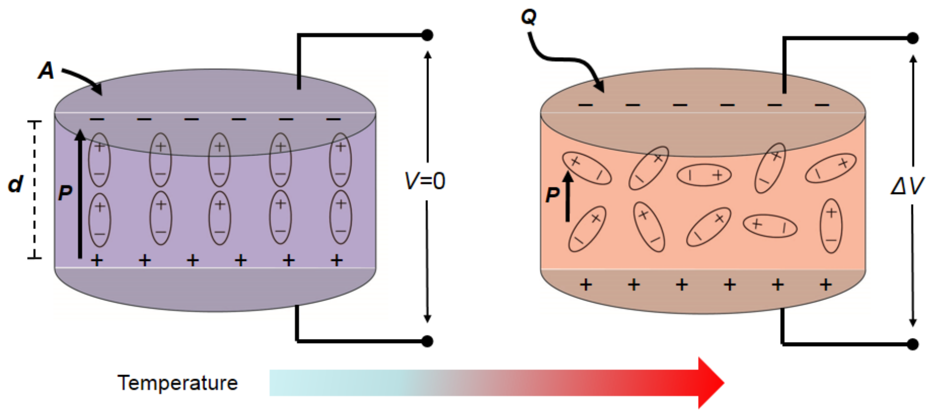


Figure 3: Simplified image of pyroelectric energy harvesting.

For the pyroelectric elements attached to the OHP channel wall, as in **Figure 2**, **Figure 3** shows the working principle of pyroelectric material to generate electrical energy from a temperature change. When the polar crystalline pyroelectric materials is heated due to a flux (Q), the increase in temperature (ΔT) leads to a reduction in the level of polarisation, P, repelling or attracting surface bound charge. When electrodes are attached perpendicular to the polarisation direction, P, free charge creates a potential difference ΔV [V] proportional ΔT [K]. For consecutive heating and cooling cycles at the OHP adiabatic wall, the passing liquid-vapour slugs and plugs inside the OHP channel continuously thermally excite the pyroelectric generator which then drives an alternating closed circuit current I [A]. Under short circuit conditions the current is defined by [13]:

$$I_{closed\ circuit} = A\,\frac{dP}{dT}\frac{dT}{dt} = A.p\,\frac{dT}{dt} \qquad (3)$$

and under open circuit conditions the voltage V [V] is given by [14]:

$$V_{open\ circuit} = \frac{p}{\varepsilon}d.\Delta T \qquad (4)$$

across the pyroelectric terminals in **Figure 3** and is therefore determined by the materials surface area A [m^2], pyroelectric coefficient p [C m^{-2} K^{-1}], rate of change in temperature dT/dt [K s^{-1}], effective permittivity ε [F m^{-1}], and generator thickness d [m]. When a pyroelectric material (P) is combined with an oscillating (O) heat (H) pipe (P), POHP, and the assembly operates under a constant heat source and sink conditions, the POHP moves heat from the hot side to the cold side while continuously thermally exciting the pyroelectric element divining a AC across the generator terminals. By carefully choosing the organic working fluids used in the POHP, the phase transition temperature of the evaporation of the system can be adjusted to the available temperature level to tailoring the cooling performance under different thermal conditions for compact cooling applications while simultaneously generating electricity from small temperature differences.

3. Methodology

For low temperature gradients, Akacshi [15] introduced a tubular shaped looped OHP partially filled with a working fluid which acted as a powerful heat transfer and cooling device. Compared to a tubular OHP design, flat plate heat pipes combine a high heat flow and a compact design, which is considered a more efficient approach [16]. Tubes fabricated from copper lead to high heat transport rates with minimal temperature gradients due to the high thermal conductivity of the material [17]. In this work we therefore employed a 20 channel flat plate OHP design (1.6 x 2.0) [mm^2] (**equation 1)** and **(equation 2**) with 12 U-turns machined into a 2 [mm] thick copper base plate (30 x 12) [cm^2] (**Figure 4**).

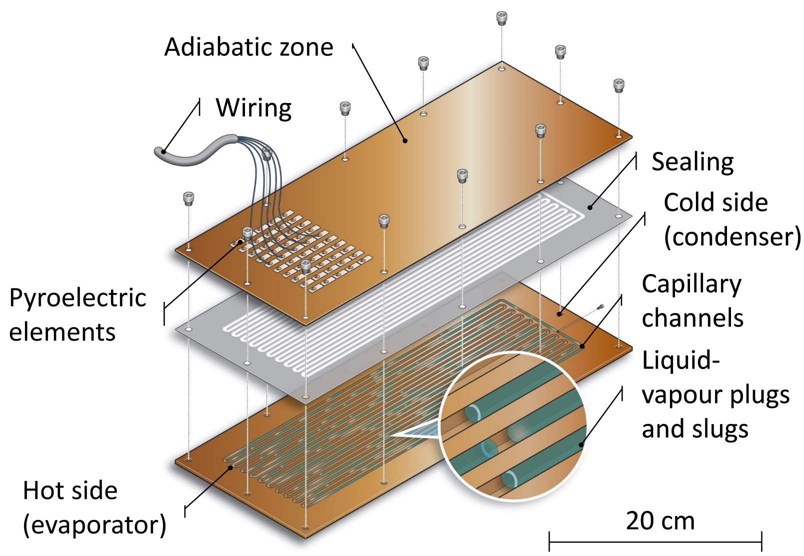


Figure 4: OHP with a pyroelectric generator attached to the wall showing a common ground and connected to an electrometer using the attached wires for pyroelectric voltage and current measurements

This plate was covered with a second plate with the same dimensions and 1 [mm] of thickness, where the adjacent channels were sealed off relative to one another. The evaporator zone of the flat plate pulsating heat pipe in **Figure 2** and **Figure 4** was heated by a wire electrical heater (Thermocoax Type ZEZAc10) that was embedded in a copper plate with dimensions of (10 x 120) [mm^2] and 2 [mm] thick by means of a serpentine groove machined on one side of the plate. The heater was connected to electrical power supply (EA ELEKTRO-AUTOMATIK model PS8360-10T). On the opposite side, the condenser zone (80 [mm] long and 120 [mm] wide) was cooled by an ethylene-glycol/water mixture flow that crossed an aluminium block whose temperature was controlled by means of a cryostat (HUBER CC240wl). Good contact between both surfaces (OHP and aluminium condenser) was provided by screws through OHP holes that uniformly distributed the pressure contact. A pressure sensor (GE PTX5076-TA-A3-CA-H0-PS) allowed recording of the pressure levels and fluctuations in the surrounding loop channel. The OHP was filled with ethanol as working fluid with a filling ratio (liquid volume on total channels volume ratio) of 50 %, where the horizontally orientated channels guide the circulating fluid through the system.

Figure 4 shows the design of our flat plate closed loop Pyroelectric - Oscillating Heat Pipes (POHP) harvesting and cooling set-up, where the pyroelectric elements are placed directly above the capillary channels of the OHP, where the pyroelectric is placed to generate electricity. For the liquid-vapour plugs and slugs, the orientation of the OHP wall is of particular interest since the gravitational force acting on the bubbles leads to a continuous aggregation of liquid at the evaporator zone, particularly in vertical orientation (bottom heated mode). Therefore, we examine two positions, one with the gravity acting planar to the OHP wall (vertical position), and the other with the gravity acting in a 45° angle perpendicular to the wall. In both positions the boundary conditions are maintained constant with the resistive electric heating power fixed at 120 [W] and the chiller, maintaining the cold condenser temperature at 20 [°C]. The experiments were conducted over several hours in order to establish constant average temperatures. If the device to be cooled acts as a heat source (left side **Figure 2** and **Figure 4),** the spatial temperature gradient across the system introduces liquid plugs and vapour slugs which exchange heat along the channel wall of the OHP leading to fluctuations in temperature at a relatively high frequency; we will see later in the paper that typical frequencies and temperature changes are 0.45 Hz and 5 [K] respectively.

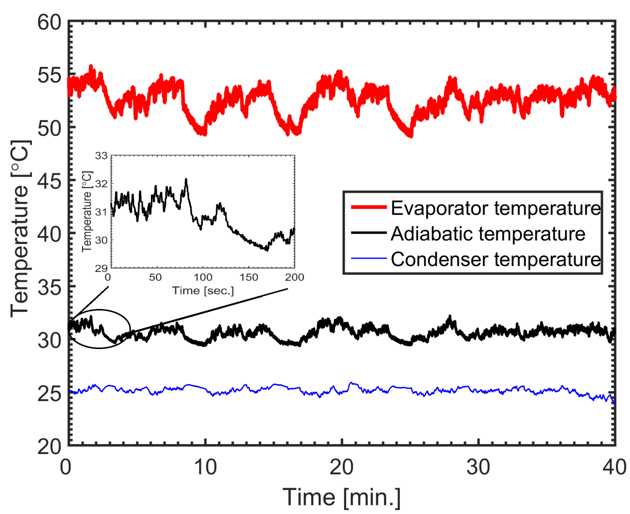


Figure 5: OHP temperature map for 45° operation at an arbitrary chosen time window.

Figure 5 shows the local temperature profile measured at the evaporator (highest temperature), the adiabatic zone and the condenser (lowest temperature) for the 45° tilted wall of the OHP. The temperatures were measured using K-type thermocouples located across the OHP wall. Although the system was synchronised between the evaporator and the condenser, thereby showing an identical temperature envelope, the fluid flow is chaotic and leads to random changes in temperature (*dT)*, starting from 0.1 [K] at the condenser to 5 [K] at the evaporator with no particular temperature oscillation frequency. A Fast Fourier Transformation (FFT) analysis did not reveal any characteristic or natural frequency providing a constant line across the frequency spectrum. Therefore, there is no evidence for distinctive temperature oscillation frequencies. This leads to the conclusion that the transient temperature profile is highly unsteady due to the two-phase instability of the working fluid under certain thermal and geometrical boundary conditions [18].

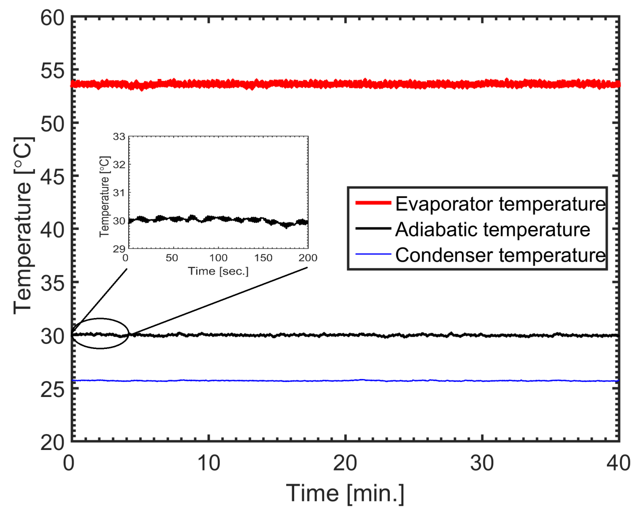


Figure 6: OHP temperature map for 0° operation at an arbitrary chosen time window.

With horizontally orientated channels (planar gravity), **Figure 6** shows the temperatures across all three OHP zones (evaporator, adiabatic and condenser). With an average evaporator temperature of 54 [°C], a chiller temperature of 26 [°C], and a temperature gradient of 28 [°C], the OHP operates at a steady state oscillation frequency of 0.45 [Hz]. Continuous and symmetric temperature oscillations are observed along the adiabatic zone with a temperature oscillation magnitude of 0.3 [K]; e.g. see the inset in **Figure 6**. The temperature oscillations at the OHP wall that are shown in **Figure 5** and **Figure 6** stem from the heat, exchanged with the surrounding environment, which can be utilised to successively heat and cool a pyroelectric generator attached to the wall surface. In order to achieve rapid (**Equation 3**) and large (**Equation 4**) temperature oscillations to maximise the pyroelectric signal we found from thermocouple measurements that the highest oscillation magnitude takes place at the lower region of the adiabatic zone, which is closer to the hot evaporator. At steady state operation conditions, as in **Figure 6**, the temperature constantly fluctuates between 38.4 [°C] and 39.7 [°C] leading to an available change in temperature of 0.3 [K] at 0.45 [Hz]. Ccompared to already existing pyroelectric thermal harvesters operating in the lower mHz oscillation range [19], the temperature oscillations frequencies in a POHP system are therefore much larger and faster.

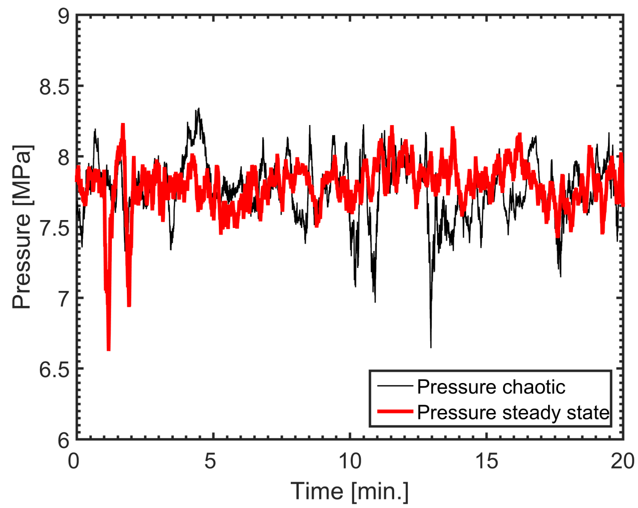


Figure 7: Condenser pressure for chaotic and steady state operation of the OHP at the loop channel.

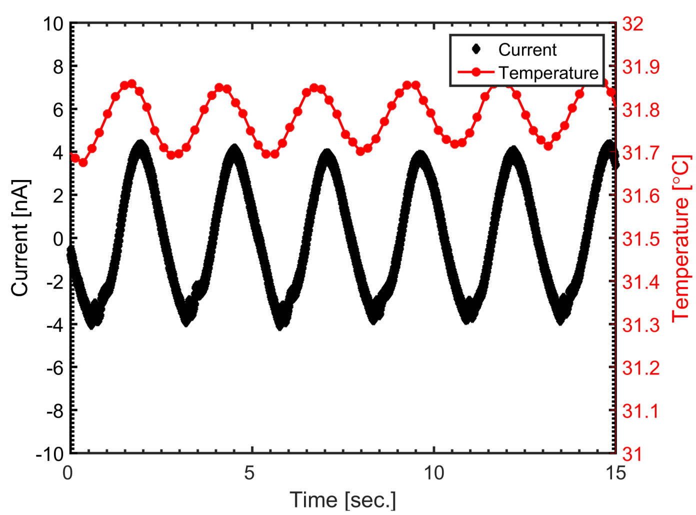
Since the available thermal gradients are low at the condenser section, the corresponding liquid-vapour pressure difference is also low. When a pressure sensor was placed at the surrounding looped channel of the cold condenser zone to measure the transient pressure, **Figure 7** shows the pressure fluctuations for both chaotic and steady state OHP operation. Since the fluid flow at low temperature and pressured gradients is perpendicular to the rest of the channel, pressure for chaotic operation and steady state operation are indistinguishable. However, as shown in **Figure 5** and **Figure 6,** the OHPs provide large and rapid naturally driven temperature oscillations without mechanical switching which are ideally suited to power a pyroelectric generator attached to the wall surface.

4. Results and discussion

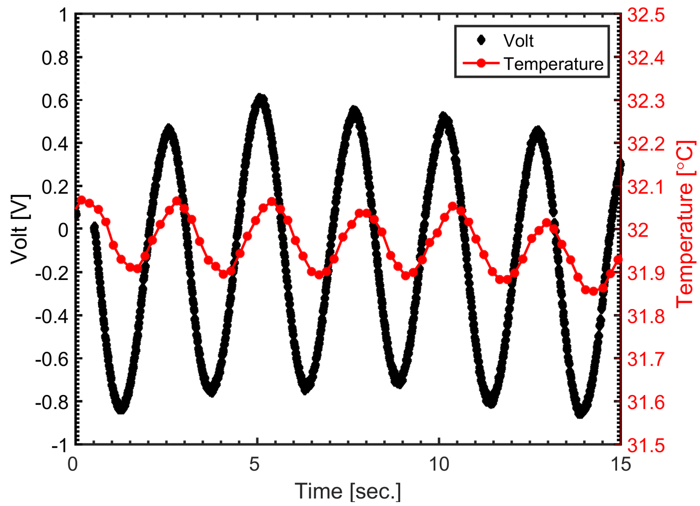
Compared to flexible polivinylidene difluoride (PVDF) pyroelectric active polymers [20], bulk ceramics pyroelectric materials are typically high stiffness and brittle (low fracture toughness) but exhibit significantly higher pyroelectric coefficients. Since pyroelectrics are typically electrically and thermally insulating, the heat exchanged between the OHP and the pyroelectric generator is assumed to be via conduction only, where the contact area between the pyroelectric element and the OHP wall determines the heat flow. In this work we have placed both, a (11 x 3) [mm^2] and 500 [μm] thick lead magnesium niobate – lead titanate (PMN-PT) single crystal and a polycrystalline lead zirconate titanate (PZT) (11 x 3) [mm^2] and 500 [μm], on the OHP wall directly above the adiabatic channel. Details of the two materials are provided in **Table 1**. **Figure 4** shows the geometrical position and the electrical setup where the pyroelectric was placed 35 [mm] from the heater (evaporator) and 9 [mm] from the edge. The open circuit voltage and the closed circuit current per element was measured using a Keithley 6517b electrometer (input impedance 200 TΩ) at a sampling rate of 100 [Hz] together with the temperature measurements using a Picotech TC-08 at a sampling rate of 10 [Hz]. A good interface contact between the pyroelectric element and the OHP wall was ensured using a copper paste (Electrolube-UK) providing a good thermal and electrical contact with the common ground. A ‘doctor blade’ deposition technique of the copper paste ensured good homogeneity and repeatability of this process, which is also used in ISO8301 for measuring conductivity of thermal insulators (e.g. ceramics and polymers). Temperature measurements were conducted using a leaf K-type thermocouple (OMEGA-US) directly below the pyroelectric element and encapsulated in the copper paste.

Table 1: Material properties for PMN-PT and PZT.

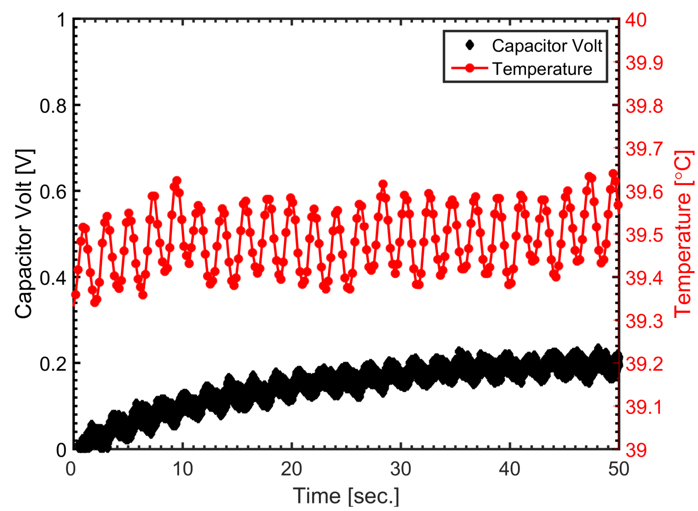
	PMN-PT	PZT	Reference
p [μC m^{-2} K^{-1}]	-746	-380	[15]
A [mm^2]	(11 x 3)	(11 x 3)	[-]
d [μm]	500	500	[-]
ε [-]	2100	2900	[15]
C [nF]	1.22	0.17	[-]
k [W m^{-1} K^{-1}]	2	0.8	[15]
T_{Curie} [°C]	121	200	[15]
$-p/\varepsilon$ [μC m^{-2} K^{-1}]	0.35	0.13	



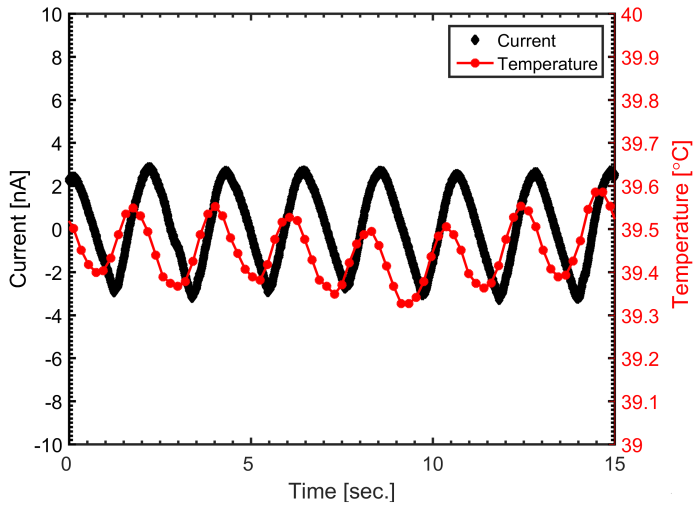
(a)


Volt
Temperature
Volt [V]
Temperature [°C]
Time [sec.]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
32.5
32.4
32.3
32.2
32.1
32
31.9
31.8
31.7
31.6
31.5
0
5
10
15

(b)


Capacitor Volt
Temperature
Capacitor Volt [V]
Temperature [°C]
Time [sec.]
1
0.8
0.6
0.4
0.2
0
40
39.9
39.8
39.7
39.6
39.5
39.4
39.3
39.2
39.1
39
0
10
20
30
40
50

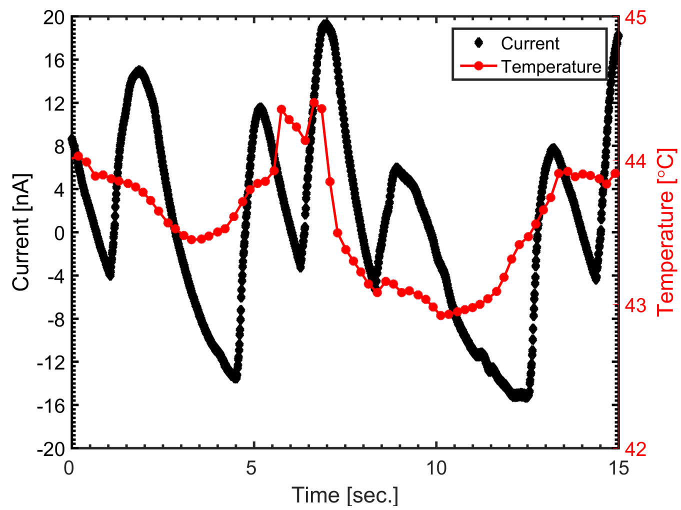
(c)



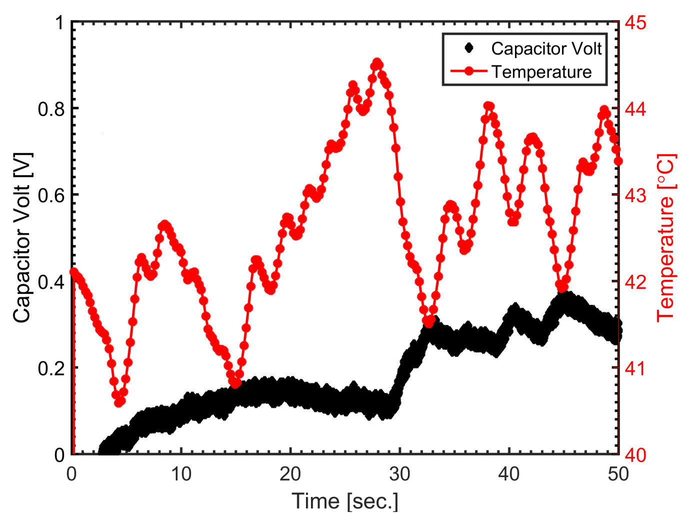
(d)

Figure 8: Closed circuit pyroelectric current with PMN-PT (a), open circuit pyroelectric voltage with PMN-PT (b), capacitor voltage with PMN-PT (c) and closed circuit pyroelectric current with PZT (d) for steady-state OHP operation.

For the steady state operating OHP (**Figure 6**), **Figure 8a** compares the recorded symmetric temperature oscillations with a measured pyroelectric closed circuit current of 4.2 [nA], generated by the PMN-PT pyroelectric element. The measured open circuit voltage with PMN-PT was 0.8 [VAC] (**Figure 8b)**. With an available electrical capacitance of 1.22 [nF] for the pyroelectric generator, the transformed electrical energy per thermal evolution stored in the capacitive element ($^1/_2CV^2$) was 1.56 [nJ cycle^{-1}], which corresponds to a specific energy density of 95 [pJ cm^{-3}]. When the generated alternating current (AC) was continuously discharged across a full wave bridge rectifier into a 50 [pF] external capacitor, the available temperature oscillations can charge the external capacitor within 40 sec. to 0.2 [V] (**Figure 8c**). This rectification stage is required, since the voltage supplied by the generator is an AC, and most of the modern electronics require a direct current (DC). Since electrical energy stored in a capacitive element suffers increasing leakage with increasing voltage, the voltage at the capacitor saturates because the supplied charge from pyroelectric equals the leakage at the external capacitor; suitable selection of low leakage capacitors can improve this response. The single crystal PMN-PT used in this study has been selected as it has an outstanding pyroelectric properties but does exhibit a relatively low Curie temperature (121 [°C]), limiting the potentially usable temperature range. Therefore, measurements have been taken with a polycrystalline PZT material, which can operate at higher temperatures due to the higher Curie temperature of 200 [°C] and consequently can operate at higher temperature levels. However, the pyroelectric coefficient of PZT is lower than PMN-PT (see **Table 1**) which results in lower closed circuit current measurements under identical operation conditions compared to PMN-PT; the PZT has a pyroelectric current of 3 [nA] (**Figure 8d)**. The corresponding open circuit voltage with PZT was also lower, 0.4 [V] compared to 0.8 [V] for PMN-PT and relates to the lower p/ε ratio of PZT; see Equation 4 and Table 1. The measured current for PMN-PT and PZT is in reasonable agreement with the calculated values for current from **Equation 3** (PMN-PT = 3.3 [nA] and PZT = 1.7 [nA]). The continuous pyroelectric signals together with the harmonic temperature oscillations at the OHP wall lead to the conclusion that the system operates at steady state with the fluid-vapour bubbles oscillating symmetrically across the adiabatic zone.



(a)



(b)

Figure 9: Closed circuit pyroelectric current with PMN-PT (a), and capacitor voltage with PMN-PT (b) for unsteady OHP operation.

To achieve chaotic changes in temperature, as in **Figure 5**, the OHP was tilted by 45° with respect to gravity, and the pyroelectric generator was placed in the same position as in steady state operation. **Figure 9a** shows the generated closed circuit current for a PMN-PT single crystal along with the temperature oscillations at the OHP wall. With a peak current of 20 [nA] the closed circuit current and the change in temperature are significantly higher than in the steady state operation of the OHP (typically 4 [nA], **Figure 8a**). However, no continuous pyroelectric signal can be generated since the temperature fluctuations are unsteady and do not follow a particular pattern. Therefore, a direct discharge of the generated electrical energy across the full wave bridge rectifier into the external 100 [nF] capacitor leads to a capacitor voltage of 0.4 [V] at the capacitor terminals. **Figure 9b** shows the charging profile of the capacitor powered by the pyroelectric PMN-PT with a four times higher rectified and stored energy for unsteady operation of 8 [nJ], compared to 2 [nJ] for steady operation. The temperature fluctuations performed, in both steady and unsteady modes of operation, are highly suitable for pyroelectric thermal to electrical energy conversion, due to the high oscillation frequency of up to 0.45 Hz, providing a new type of thermal to electrical generator operating at low temperatures. Performance enhancements can be achieved by using micro heat pipes of a similar size employed in this work and filled with water-heptanol mixtures that exhibit higher temperature oscillations and larger heat flows [21]. The system conversion efficiency in this work with the POHP and rectification circuit and only one pyroelectric element attached is η = 3.3 x 10^{-13} for the unsteady operation and η = 1.33 x 10^{-12} for the steady operation over 50 sec., determined by the generated energy (8 [nJ] and 2 [nJ]) over the heater power input (120 [W]). This is lower than the theoretical Carnot efficiency of η_{Carnot} = 0.09 % (55 ºC and 25 ºC), which leads to the conclusion that there is substantial space for optimisation of the OHP-pyroelectric generator system. Compared to conventional thermo-electric generators (TEGs) operating at an efficiency below 10 %, the here proposed POHP design convers only 0.04 % of the available surface of the OHP with a pyroelectric material providing additional space for improvement by improving the contact area. In addition, two distinctive modes of operation are presented, based on a constant heat input – available electrical output comparison, showing a four times higher energy generation in chaotic mode than in steady state mode. Limitations in transformed energy mainly stem from the poor contact conduction when using structurally thick copper walls which leads to a decrease and a delay in heat flow. It is worth noting that temperature oscillations of a greater amplitude have been observed in the OHP literature [18], suggesting that much larger energy recovery is expected from such systems. For constant temperature oscillations, one approach to improve performance is to introduce grooves into the OHP wall directly above the channel of the working fluid. The generator will ideally to be of equivalent dimensions to the vapour plug displacement inside the channel the fully exploit the temperature fluctuations. For chaotic temperature oscillations, the frequency and magnitude of the oscillations should be enhanced and a more thermally conductive generator geometry with a larger area and patterned electrodes will improve the interface contact conduction.

On an industrial scale, integrated cooling and heat recovery units have the potential to utilise the abundantly available heat through an OHP in order to drive a pyroelectric generator and effectively cool heat-concentrated areas without mechanical motion, while also generating electricity locally from the otherwise wasted heat. In the longer term, POHP type of systems can act as solid-state generators and thermal harvesters operating low-carbon micro-grids where the risk of mechanical wear and failure is eliminated. Therefore, POHP systems combine highly desirable solid-state electricity generation with a powerful closed packed cooling device absorbing otherwise unused heat. The thermal performance conversion of the system has the potential to cover range from Watts to kWatts of heat flow, capable of eg. replacing conventional blower fans and large sized heat sinks and providing μWatts to mW of electrical power, e.g. for wireless sensor nodes, internet of things (IoT) devices or battery-less technologies [22].

5. Conclusions

This paper presents the recovery of heat using pulsating heat pipes (OHPs) in conjunction with pyroelectric elements provides as a new approach for transforming thermal energy at low temperatures directly into electrical energy, available for discharge. In this paper we are the first to demonstrate that it is possible to exploit the rapid temperature oscillations of an OHP operating in both, steady state and unsteady modes, using a pyroelectric generator to effectively charge a storage capacitor and generate electrical energy while providing cooling. Since no external power supply is required to move the fluid in this solid state assembly, the self-sustaining system and the generated energy provides an additional and alternative power supply for the constantly growing number of electric and electronic devices. This new type of thermal generator uses lead magnesium niobate – lead titanate (PMN-PT) with a flat plate OHP and continuously generates an energy of 95 [pJ cm^{-3}] at 0.45 [Hz] without mechanical motion. In the chaotic mode of operation, the system effectively provides four times more electrical energy than in the steady state mode. With potential to further optimise the transformation performance, pyroelectric-oscillating heat pipe (POHP) generators provide a route to cool thermally concentrated areas while also provide electricity that is needed for monitoring and communication tasks or where wireless communication and self-sustaining applications operate remotely. Other potential applications beyond compact cooling are standalone small-scale generators where the unexplored properties of liquid-vapour hysteresis will lead to a more efficient thermal cycling fluid. Due to the nature of the fluid flow, this is a solid-state, 'fit and forget' design with no moving mechanical parts and no need of maintenance while transforming abundantly available waste heat into electrical power.

6. References

[1] Federal Energy Administration (2015) Available: www.energy.gov [Accessed: 30. April 2016].

[2] Zabek, D., Penton, J. and Reay, D., 2013. Optimization of waste heat utilization in oil field development employing a transcritical Organic Rankine Cycle (ORC) for electricity generation. *Applied Thermal Engineering*, *59*(1), pp.363-369.

[3] Dresselhaus, M.S., Chen, G., Tang, M.Y., Yang, R.G., Lee, H., Wang, D.Z., Ren, Z.F., Fleurial, J.P. and Gogna, P., 2007. New Directions for Low-Dimensional Thermoelectric Materials. *Advanced Materials*, *19*(8), pp.1043-1053.

[4] Fujitsu (2015) Fujitsu Develops Thin Cooling Devices for Compact Electronics. Available: www.fujitsu.com [Accessed: 30. April 2016].

[5] Ma, H., 2015. *Oscillating heat pipes*. Springer.

[6] Ravindran, S.K.T., Huesgen, T., Kroener, M. and Woias, P., 2011. A self-sustaining micro thermomechanic-pyroelectric generator. *Applied Physics Letters*, *99*(10), p.104102.

[7] Cha, G. and Ju, Y.S., 2013. Pyroelectric energy harvesting using liquid-based switchable thermal interfaces. *Sensors and Actuators A: Physical*, *189*, pp.100-107.

[8] Mostafa, S., Lavrik, N., Bannuru, T., Rajic, S., Islam, S.K., Datskos, P.G. and Hunter, S.R., 2011. A Finite Element Model of Self-Resonating Bimorph Microcantilever for Fast Temperature Cycling in A Pyroelectric Energy Harvester. In *MRS Proceedings* (Vol. 1325, pp. mrss11-1325). Cambridge University Press.

[9] Mochizuki, M., Saito, Y., Kiyooka, F., Nguyen, T., Nguyen, T. and Wuttijumnong, V., 2007, January. Advanced micro-channel vapor chamber for cooling high power processors. In *ASME 2007 InterPACK Conference collocated with the ASME/JSME 2007 Thermal Engineering Heat Transfer Summer Conference* (pp. 695-702). American Society of Mechanical Engineers.

[10] Lips, S., Bensalem, A., Bertin, Y., Ayel, V., Romestant, C. and Bonjour, J., 2010. Experimental evidences of distinct heat transfer regimes in pulsating heat pipes (PHP). *Applied Thermal Engineering*, *30*(8), pp.900-907.

[11] Tong, B.Y., Wong, T.N. and Ooi, K.T., 2001. Closed-loop pulsating heat pipe. *Applied thermal engineering*, *21*(18), pp.1845-1862.

[12] Sebald, G., Guyomar, D. and Agbossou, A., 2009. On thermoelectric and pyroelectric energy harvesting. *Smart Materials and Structures*, *18*(12), p.125006.

[13] Lang, S.B., 2005. Pyroelectricity: from ancient curiosity to modern imaging tool. *Physics Today*, *58*(8), pp.31-36.

[14] Bowen, C.R., Taylor, J., LeBoulbar, E., Zabek, D., Chauhan, A. and Vaish, R., 2014. Pyroelectric materials and devices for energy harvesting applications. *Energy & Environmental Science*, *7*(12), pp.3836-3856.

[15] Akachi, H., Actronics Kabushiki Kaisha, 1990. *Structure of a heat pipe*. U.S. Patent 4,921,041.

[16] Reay, D., McGlen, R. and Kew, P., 2013. *Heat pipes: theory, design and applications*. Butterworth-Heinemann.

[17] Ayel, V., Araneo, L., Scalambra, A., Mameli, M., Romestant, C., Piteau, A., Marengo, M., Filippeschi, S. and Bertin, Y., 2015. Experimental study of a closed loop flat plate pulsating heat pipe under a varying gravity force. *International Journal of Thermal Sciences*, *96*, pp.23-34.

[18] Górski, G., Litak, G., Mosdorf, R. and Rysak, A., 2015. Two phase flow bifurcation due to turbulence: transition from slugs to bubbles. *The European Physical Journal B*, *88*(9), pp.1-6.

[19] Zhang, Q., Agbossou, A., Feng, Z. and Cosnier, M., 2011. Solar micro-energy harvesting with pyroelectric effect and wind flow. *Sensors and Actuators A: Physical*, *168*(2), pp.335-342.

[20] Zabek, D., Taylor, J., Le Boulbar, E., and Bowen, CR.; "Micropatterning of Flexible and Free Standing Polyvinylidene Difluoride (PVDF) Films for Enhanced Pyroelectric Energy Transformation." *Advanced Energy Materials* 5, no. 8 (2015).

[21] Hu, Y., Liu, T., Li, X. and Wang, S., 2014. Heat transfer enhancement of micro oscillating heat pipes with self-rewetting fluid. *International Journal of Heat and Mass Transfer*, *70*, pp.496-503.

[22] Somov and Giaffreda (2015) Powering IoT Devices. Technologies and Opportunities. Available: iot.ieee.org [Accessed: 30. April 2016].

7. Acknowledgements

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement no. 320963 on Novel Energy Materials, Engineering Science and Integrated Systems.