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Urine transduction to usable energy: A modular MFC approach for smartphone and remote system charging

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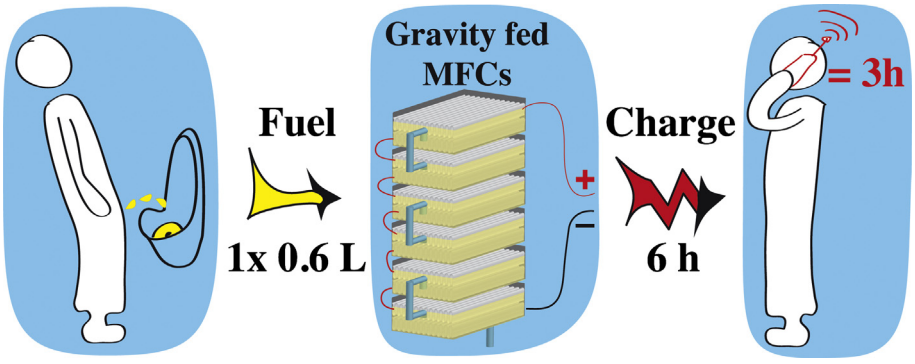
HIGHLIGHTS

- 1st application of a MFC design that can be scaled-up without power-density losses.
- 1st full charge of a basic phone within 42 and 68 h employing neat urine as MFC-fuel.
- 1st full charge of smartphone within 68 and 82 h employing neat urine as MFC-fuel.
- 1st charging system allowing 1 h 45 min phone call per 3 h of charge.

GRAPHICAL ABSTRACT



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ABSTRACT

This study reports for the first time the full charging of a state-of-the-art mobile smartphone, using Microbial Fuel Cells fed with urine. This was possible by employing a new design of MFC that allowed scaling-up without power density losses. Although it was demonstrated in the past that a basic mobile phone could be charged by MFCs, the present study goes beyond this to show how, simply using urine, an MFC system successfully charges a modern-day smartphone. Several energy-harvesting systems have been tested and results have demonstrated that the charging circuitry of commercially available phones may consume up to 38% of energy on top of the battery capacity. The study concludes by developing a mobile phone charger based on urine, which results in 3 h of phone operation (outgoing call) for every 6 h of charge time, with as little as 600 mL (per charge) of real neat urine.

1. Introduction

Microbial Fuel Cells (MFCs) are a bio-electrochemical technology converting organic waste into electricity [1]. An MFC comprises two electrodes, a cathode and an anode, and relies on the capacity of certain microorganisms to use the anode as their end-terminal electron acceptor in their anaerobic respiration. The technology's intrinsic characteristics are, low power – compared to established technologies, wide range of organic matter (otherwise considered as waste) can be used as fuel, low fiscal and maintenance costs, stacking of MFC collectives required for exploitable power levels and durability with robustness. Over the last three decades, research in the field has focused on (i) improving the power density of individual units [2,3], (ii) reducing the cost of each unit [4–6], (iii) assembling units into stacks to reach

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exploitable power [7,8], (iv) widening the range of potential fuels [9–11], and (v) demonstrating the implementation of this biotechnology into practical applications [12–18]. The results we present here focus on the latter aspect.

Previous research demonstrated the possibility of charging a basic mobile phone with urine as the fuel for MFCs (battery partially charged up to 3.7 V in 24 h) [17]. This previous study opened up the possibility of employing urine in remote locations for telecommunication purposes as well as demonstrated that the simplicity of the MFC design – i.e. ceramic membranes – was conducive to mass production. In the present study, the focus is also on the implementation of the MFC technology as a power supply for telecommunication purposes, however with significant advances, bringing the application closer to potential deployment. The aims of the study were therefore: (i) to fully charge the battery of both a basic and a smart phone, up to 4.2 V (full charge), (ii) to have a system independent of any external electrically powered peripherals (i.e. pump), (iii) to fuel the MFC system with the amount of urine of a single individual and (iv) to have minimal footprint and maintenance requirements.

To reach useful levels of power, pluralities of small MFCs need to be assembled into stacks or cascades. By assembling fluidically isolated small MFCs and electrically connecting them into parallel/series configurations, both the voltage and current can be increased [8]. The size of individual MFCs plays an important role in the performance of the collective, and although units can be enlarged, this is often at the detriment of power density [8,19]. This is primarily due to diffusion limitations and sub-optimal volume-to-surface-area (SAV) ratios, which can be improved by decreasing the size of the MFC reactor and thus maximally exploiting the (inter)active surfaces, where the microbial biofilms transfer electrons [8,19,20]. Provided that these parameters are respected in the re-design of a MFC architecture, then it should be possible to achieve equal power densities with both unit enlargement (to a certain extent) and miniaturisation [21]. This could be achieved by employing a medium size chassis, housing anode and cathode electrodes without a membrane, exposed to the same electrolyte [21]; in this setup, the anode is fully submerged to the fuel, whereas the cathode is only partially exposed to the bulk urine. Such MFC "module" can be considered as a collective of 20 MFCs connected in parallel, and in the present study, 6 such modules were used and connected in series. Such scaling up refers to the individual MFC elements within each box, which have been put together in a collective manner as a modular stack, indicating how they can be multiplied to produce higher power and treat higher feedstock volumes. The results demonstrate for the first time that this design can be employed to power practical applications by charging various types of cell phones. This system was recently shown to be robust and stable over 6 months, in a series electrical configuration – without any cell reversal [21].

An anaerobic ammonium abstraction, measured in the anaerobic part of the cathode, gave rise to the hypothesis that in such a setup, part of the cathode operation is ultimately in the nitrogen redox cycle [21]. It seems that the anaerobic part of the cathode was functioning as a denitrifying biocathode [22,23]. A similar mechanism has recently been reported by Li et al. (2016) who identified an electroactive ammonium oxidation process [24] and the use of an anaerobic nitrite-reducing cathode that was added to a classical MFC set-up. To achieve our aims, 6 modules were assembled, connected in series and employed to charge a basic mobile phone, a smartphone and in addition be implemented as a bespoke mobile phone charger, which provided ~1 h 45 min of call-time for every ~3 h of charging, only consuming 600 mL of urine as fuel every 6 h. It has to be noted that depending on the type of phone, electronic circuitry was built to manage the charge cycles.

2. Materials and methods

The whole system comprised 3 parts: the feeding mechanism representing the 'urination' of a single individual (Fig. 1a), a cascade of MFCs as the energy transducer and power source (Fig. 1b), and electronic circuitry managing the power produced by the MFCs to charge the cell phones (Fig. 1c).

2.1. Feeding mechanism

For any system and especially for a live biofilm system, the fuel supply rate is a critical factor [21]. As the ultimate aim of this study is the deployment of MFCs in real environments, the feeding mechanism needed to operate without any energy requirement. Hence, the pump was only present to (i) simulate an individual urinating and (ii) to provide a regular feeding pattern. Fuel was pumped into a tube that tilted, when the volume of urine reached 200 mL, into a bigger container, which included a syphon. This combined feeding mechanism was set to distribute 600 mL bursts (≈2.5 L min^{-1}) every 6 h (2.4 L d^{-1}). In field deployment conditions, such gravity feeding mechanism implies that a height of 80 cm below the urinal's floor is required.

Fresh urine was anonymously collected daily from healthy individuals and pooled together (pH ≈ 6.4–7.4). The reservoir tank was filled daily with 2.5 L of urine during weekdays, and with 9 L during weekends. Hence the urine pumped in the feeding mechanism aged consistently between 1 and 3 days (pH ≈ 8.4–9.3).

2.2. Microbial fuel cell cascade

The MFC cascade consisted of 6 modules whereby the outflow of upstream module was the inflow to the module downstream (Fig. 1). The height of the whole setup was 77 cm, including the

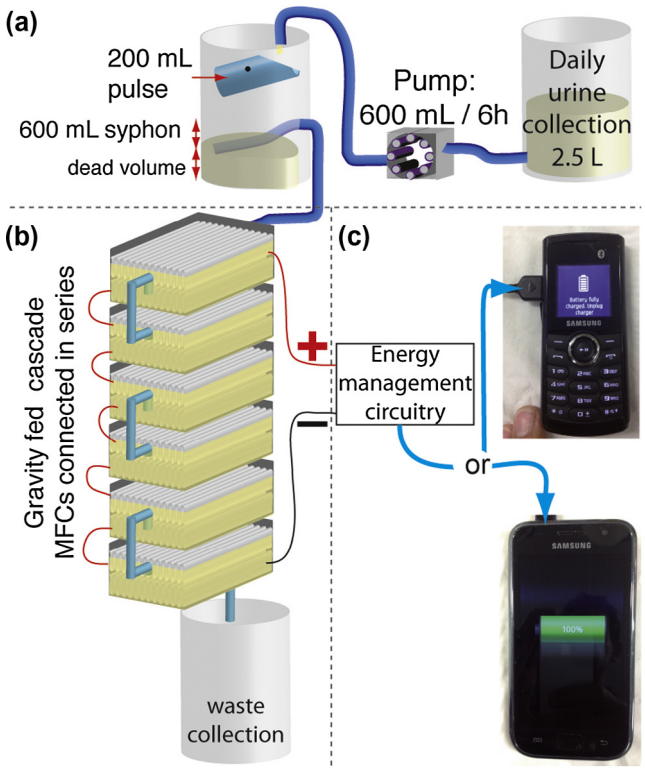

Fig. 1. Illustration of the different sub-systems of the setup employed to charge mobile phones. (a) Feeding mechanism, (b) cascade of MFCs, and (c) various energy harvesting circuitry allowing optimum mobile phone charging.

10 mm spacers between each box. Containers of 5 L in volume (H × W × L: 12 × 17 × 27 cm; "EuroStacking containers"; Plastor Limited, Berkshire, UK) were used that had 20 MFCs with the cathodes separated from the anodes by a 5 mm spacer. The cathodes and anodes were kept in place by vertical terracotta plates. The modules were initially inoculated with the anolyte effluent from established MFCs that had been running under long-term continuous flow conditions with urine. The displacement volume of each module was of 1.75 L, which is the parameter used for normalising power densities; the total displacement volume of the whole stack was 10.5 L. Thus the hydraulic retention time of the whole system was 105 h, based on a feeding rate of 2.4 L a day. The MFCs were operating in ambient temperature conditions (22.0 ± 0.5 °C).

As described in [21], cathodes were made from a carbon based micro-porous layer [5,25], and the anodes from carbon veil fibres (20 g m^{-2}; PRF Composite Materials Poole, Dorset, UK). The total surface area of the anode and cathode, for each module, was 30,000 cm^2 and 3612 cm^2 respectively [21].

2.3. Energy management and phone charging

During this study, various phones, battery capacities and charging modes were tested (Table 1). In the case of the basic phone, for comparison purposes, the same model was used as in our previous study [17] (Samsung GT-E2121B). This model of cell phone has a lithium ion battery, 3.7 V and 1000 mA h (BMP). A smart phone (SP) (Samsung Galaxy S I9000), equipped with a lithium ion battery (3.7 V, 1600 mA h), was also charged. Both the BMP and the SP were modified to allow a direct charge of the battery (mBMP and mSP, respectively).

Table 1
Different phones employed with corresponding battery capacity and charging mode.

Denomination	Phone	Battery (mA h)	Charge mode
Modified Basic Mobile Phone (mBMP)	Samsung E2121	1000	Direct to battery
Basic Mobile Phone (BMP)		1000	Normal
Plug-in mobile SIM Phone (PMSP)		150	Direct to battery
Modified Smart Phone (mSP)	Samsung Galaxy S	1650	Direct to battery
Smart Phone (SP)		1650	Normal

The phone modification was carried out by creating direct ground and positive connections to the handset battery, thus bypassing the proprietary phone charging circuitry, although some parasitic effects may have still occurred since the circuitry was not physically removed.

The electronics used for the direct charging experiments included a Texas Instruments bq25504EVM-674 – Ultra Low Power Boost Converter and an LM385Z-2.5 voltage reference. The bq25504EVM-674 was configured to the recommended settings for lithium ion charging and to the use of an external reference source (LM385Z-2.5) to control the input voltage of the MFCs at 2.5 V (Fig. 2a). A 6800 µF capacitor was connected to the "VSTOR input" of the TI board to help with signal smoothing and harvester regulation. The efficiency of the harvesting system was measured using a power supply and resistive loads. The average efficiency of the harvesting system was calculated at 85% (2.5 V/40 mA Input, 3.2–4.2 V Output).

The electronics used for charging the smartphone (SP) included two Maxwell BCAP3000 P270 super capacitors and a custom made Charge Control Board (CCB: Fig. 2b). The bq25504EVM-674 was modified to give a higher output voltage of 5 V to increase the energy stored in the super capacitors and therefore more energy transfer per charge to the phone battery. The method of adjustment for the upper output voltage limit (VBAT_OV) of the BQ25504EVM was to replace resistors R4 (Rov1) and R3 (Rov2) using the following equation:

$$VBAT\_OV = \frac{3}{2} VBIAS\left(1 + \frac{R_{OV2}}{R_{OV1}}\right)$$

VBIAS is a regulated output from the device of 1.25 V (±0.04 V). The sum of the resistors is recommended to be no higher than 10 MΩ. Based on these calculations R4 was set to 6.2 MΩ and R3 = 3.6 MΩ. Both of these resistors were of 1% tolerance. This would result in an upper output limit of 5.104 V, which was sufficient for our purposes.

The CCB consisted of a MAX917 comparator configured with additional hysteresis (Output goes high at 5 V and low at 4.5 V). The output of the MAX917 was connected to a PSMN0R9-30YLD N-channel MOSFET switch chosen for its very low ON-resistance (RDSon) of less than 1 mΩ @ > 4.5 V Vgs. When the MAX917

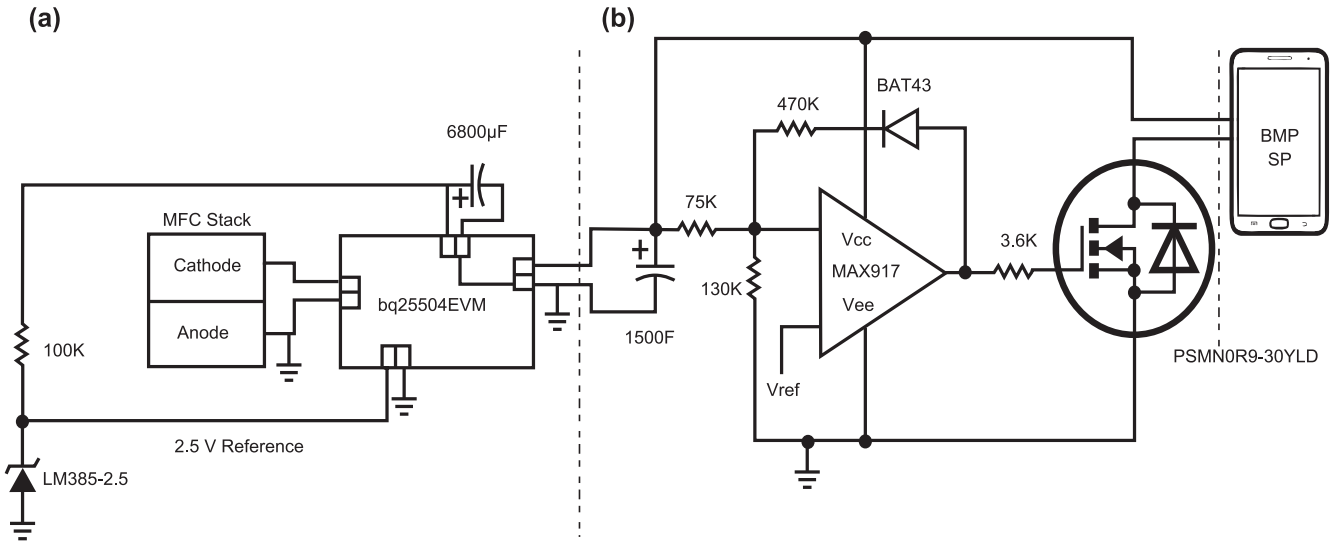

Fig. 2. Schematic of the energy management circuitry. (a) Circuitry employed for directly charging of the phone (BMP, mBMP, PMSP, mSP) and consisting of a TI energy harvesting board. (b) Added circuitry comprising two Maxwell super capacitors and one hysteresis board to charge the SP.

output goes high, the load is switched ON. When it goes low, the load is switched OFF. The two 3000 F Maxwell super capacitors were connected together in series and bottom balanced before any initial charging.

As already mentioned, the objectives were to fully charge a mobile phone (up to 4.2 V) and find the most appropriate energy management system for such a full charge, as well as develop a system capable of powering telecommunication apparatus in a remote area. To achieve the latter, a "plug-in mobile SIM phone" (PMSP, Table 1) was employed: a Samsung GT-E2121B modified with a 150 mA h lithium battery (Overlander, UK) that was directly charged from the energy harvesting circuitry (i.e. bypassing the phone built-in energy management circuitry).

2.4. Data capture and polarisation experiments

Voltage output was monitored against time using an Agilent LXI 34972A data acquisition/switch unit (Farnell, UK). Measurements were recorded every minute. Recorded raw data were processed and analysed using Sigma Plot v11 software (Systat Software Inc, London, UK). The polarisation scans were performed, using an automated resistorstat [26], and the resistive load values ranged from 38,000 Ω to 4 Ω. Each resistor was connected for a period of 10 min.

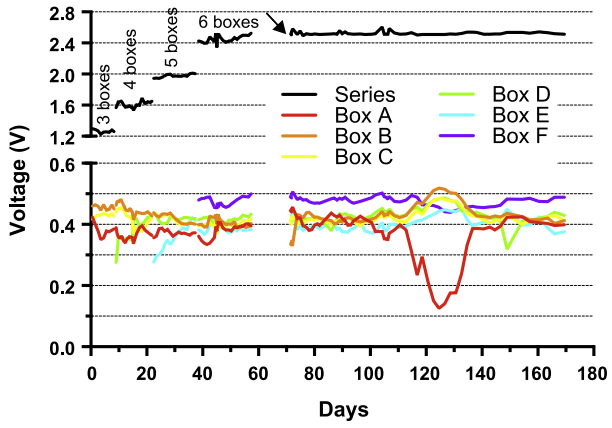

Fig. 3. Voltage monitoring of the different modules (A–F) when connected in series (black curves). At the beginning only 3 modules were connected in series. From day 38 to day 57 the stack was under a 57 Ω load (average of 2.47 V, 43.3 mA, 107 mW). The arrow indicates when the energy management circuitry (Fig. 2a) was connected to the stack and maintained its output voltage at 2.5 V. All data points from open-circuit conditions (i.e. when the charge cycle would finish) were removed.

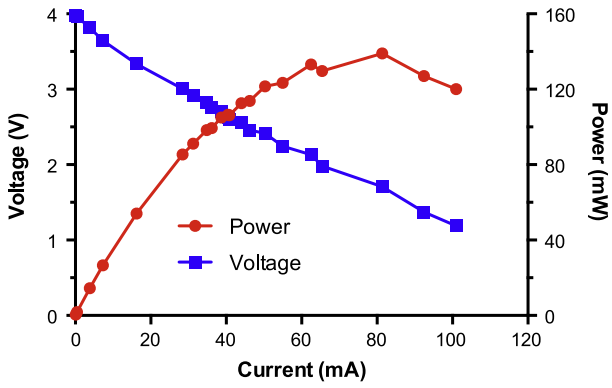

Fig. 4. Polarisation and power curves from the cascade of 6 modules. Each resistor was connected for a period of 10 min.

3. Results and discussion

3.1. Urine as a power source

The 6 MFCs modules, which were assembled into the single cascade stack, were identical to the large ones described in [21]. At first, 3 modules were connected in series, with 3 additional modules progressively added. Over the period of 6 months, during which these modules were electrically connected in series, no cell reversal was observed (Fig. 3), although the output of module A decreased to 125 mV during the period between days 118 and 132. Despite this and without any manual attempt to recover, the output from this module returned to the normal level of ca. 330 mV, at day 132. As the stack output was always kept at 2.5 V by the reference point of the microchip and bq25504-EVM, the voltage of the other modules (B–F) compensated for the voltage reduction of module A.

The polarisation experiment showed that the cascade of 6 modules was able to supply a maximum of 139 mW at 1.7 V under a load of 21 Ω (Fig. 4). However, to limit the harvesting loading, the system output voltage was fixed at 2.5 V by the reference chip and bq25504-EVM. Referring to the polarisation experiment, this set voltage corresponds to a power of 114 mW under a 53 Ω load. This power rating was further confirmed by the power output levels measured during the various charging cycles (from 95 to 120 mW, at 2.5 V).

3.2. Direct battery charging

Under the same conditions as previously reported [17] (i.e. Samsung GT-E2121B; 1000 mA h battery, direct battery charging), the full charge of the battery was achieved in 42 h (Fig. 5) whilst treating 4.2 L of urine. This result illustrates a clear efficiency improvement compared to the 24 h needed to reach 3.7 V

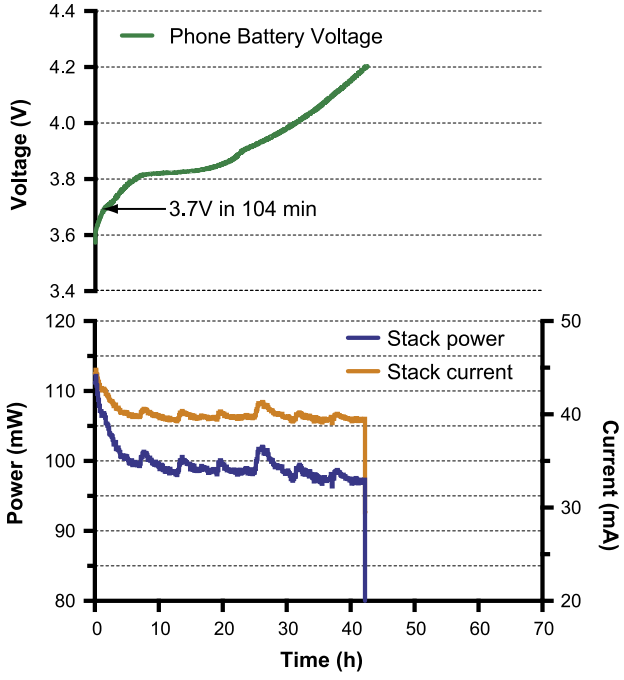

Fig. 5. Battery charge of the mBMP phone turned OFF. Voltage, power and current of the Stack during charge (mBMP). The battery was directly charged by the energy harvesting board that was set at 4.2 V (i.e. stop charging battery).

in the previous study: here this charge level was reached within 104 min.

The performance and cost (£360) of the present system, results in an equivalent cost analysis of £8.64/milliwatt/litre of urine, which is lower compared to previous reports (£13.38) [17]. Hence the present study pushes boundaries further by demonstrating that the set system is an economic, reliable and relatively compact power source for telecommunication apparatus.

The same apparatus was employed to charge the battery of a smart phone (Samsung Galaxy S I9000; battery of 1650 mA h). As with the conventional mobile phone, the output of the energy harvesting board was directly connected to the battery. Results indicate that the MFC cascade could fully charge the smart phone in 68 h when the phone was OFF (Fig. 6a). As expected, when the phone was turned ON, it took longer to fully charge the battery (82 h; Fig. 6b). Nonetheless, results demonstrate that the stack of MFC was sufficient to provide energy for smart phones to function as well as to charge their battery.

Since the stack was continuously providing the same amount of energy (≈105 mW; Fig. 6a and b), the charge time differences reflect the amount of energy consumed by the phone when turned ON. Calculations indicate that 25.7 kJ – over 68 h – was required to charge the battery, when the phone was OFF. Conversely, when the phone was ON, 30.9 kJ was needed to fully charge the battery – over 82 h. Hence, it can be assumed that the stand-by consumption was 5.2 kJ. Interestingly, after being in open circuit for 17 min the power output of the stack increased from 105 mW to 120 mW. This 14.3% power increase resulted in a 13.7% faster charge. This illustrates and supports the previous report that intermittent loading increases the efficiency of the membrane-less ceramic-based MFCs (capacitive-properties) [27].

3.3. Conventional battery charging

To examine further the implementation of MFCs as a power source for telecommunication purposes, we investigated charging the mobile phone through their built-in energy management circuitry (i.e. “normally”).

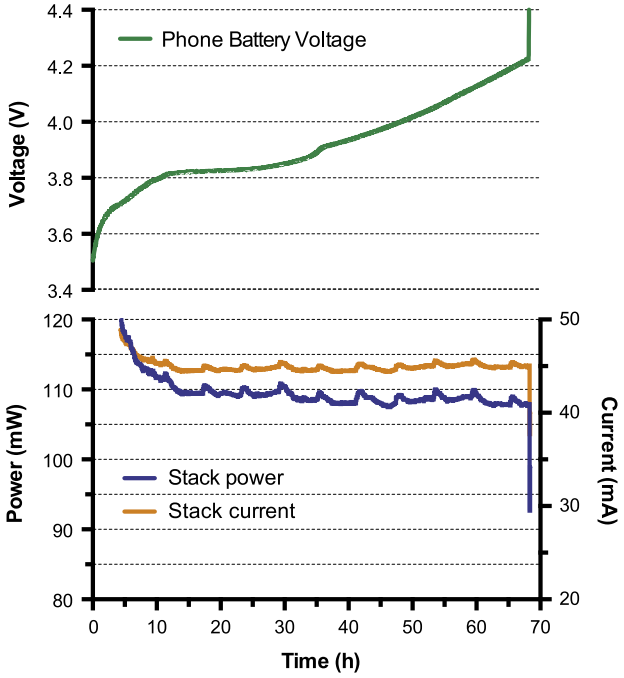

Fig. 7. Battery charge of the BMP phone turned OFF (conventional phone). The figure shows the battery voltage and the stack power and current. The phone was charged through its micro-USB port, i.e. by the phone built-in proprietary energy management circuitry.

The conventional mobile phone (BMP; 1000 mA h battery) was turned OFF and fully charged in 68 h (Fig. 7). Compared to a direct connection of the battery, using the BMP built-in charging circuitry increased the charging time by 26 h (Figs. 7 and 5). This charge cycle of 68 h at 110 mW corresponds to a total energy of 26.9 kJ. That is 11.8 kJ more than the direct charge from the battery (Fig. 5). This result implies that the BMP built-in circuitry required 11.8 kJ to charge 15.1 kJ in the battery.

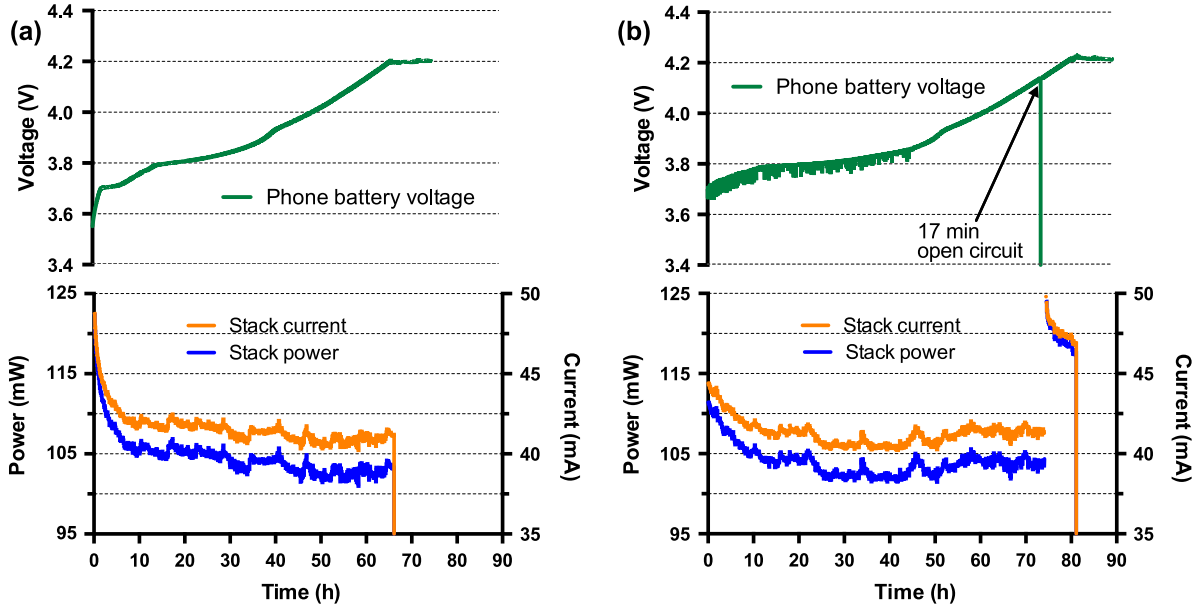

Fig. 6. Monitoring of the battery charge of the mSP phone (modified Samsung Galaxy S I9000). Data shown are the voltage of the phone’s battery and the stack’s power and current during charging (mSP; stack being maintained at 2.5 V output). (a) Direct charge of the 1650 mA h battery of the turned OFF mSP. (b) Direct charge of the battery with the mSP turned ON. The difference of charging time is due to the power consumption of the running phone, thus illustrating that the cascade produced more energy than what was required for the phone to function.

Following the same approach, the cascade was used to charge the smart phone that was switched OFF (SP; 1650 mA h battery). However, although the built-in charging circuitry recognised the power source as sufficient to charge the phone (charge symbol visible), measurements of the battery voltage indicated that no charge was occurring. Hence, a bespoke circuit was built to charge the phone through its built-in proprietary circuitry. The system that was implemented comprised 2 super-capacitors and an external hysteresis board (EHB) inserted between the harvesting board and the SP. The hysteresis mechanism of the harvesting board was set to stop harvesting energy when the output voltage (one of the super-capacitors) was above 5.0 V. The EHB was set to discharge the energy from super-capacitors to the phone between the voltage levels of 5.0 V and 4.5 V.

The full charge of the SP took 110 h (Fig. 8a), during which the MFC cascade produced an average power of 98 mW at 2.5 V. At the beginning of the experiment, the hysteresis board was unstable and was triggered before the super-capacitors reached 5.0 V (Fig. 8a). Despite this and even if irregular, the current flowing towards the phone (425 mA; Fig. 8b) was sufficient to charge the SP. As illustrated (Fig. 8b), towards the end of the charge, the current flow gradually decreased as the battery was getting full.

This intermittent-charge required a total energy of 38.8 kJ (98 mW over 110 h). In comparison, charging directly the battery required 25.7 kJ (Fig. 6a). This means that the stand-by energy was 13.2 kJ. Without questioning the efficiency of the phone's built-in charging circuitry, results indicate that either more MFCs are needed to reach the required power, or the phones to be charged have to be adapted to this specific charging system.

As illustrated by the time needed to fully charge either the conventional phone (BMP) or the smart-phone (SP), the size of the system has to be increased to practically charge modern phones that have higher power capacity than the one employed here. Such a larger charging system reaching USB-1 output implies (i) double the number of modules to reach 5 V, and (ii) 10 times larger compartmentalized modules to produce 500 mA, thus removing the need for any energy management circuitry. In the present study, it is the lack of fuel (urine) that prevented the scale-up of the MFC charging system. Nonetheless, the presented stack (i) was able to fully charge a smart-phone for the first time, and (ii) was sufficient to power an adapted off-grid plug-in SIM phone.

3.4. Adapted plug-in mobile SIM phone

The aim for the implementation of such a charging mechanism is to provide power in remote areas, which also means appropriately customizing the telecommunication device. Hence, to adapt the phone, the charging/discharging duty cycle needs shortening – i.e. to charge reasonably quickly to a practical level that would allow for daily autonomy. Because the MFC cascade was tailored to a single individual use, its size increase was not desired. Moreover, the energy harvesting board – needed for the cascade homeostasis and optimum operation – was redundant considering the phones' proprietary built-in charging circuitry. Hence, as a proof-of-concept, the mBMP (i.e. bypassing built-in energy management circuitry) was employed in combination with a smaller battery (150 mA h). This phone was designated as a "plug-in mobile SIM phone" (PMSP).

Results showed that the battery was fully charged in approximately 6 h (Fig. 9a), which interestingly corresponds to the refuelling time (600 mL every 6 h). However, because it would not be practical to empty the battery and wait another 6 h before using the phone again (i.e. emergency call), the device was left plugged-into its urine-fuelled MFC power supply. In addition, it

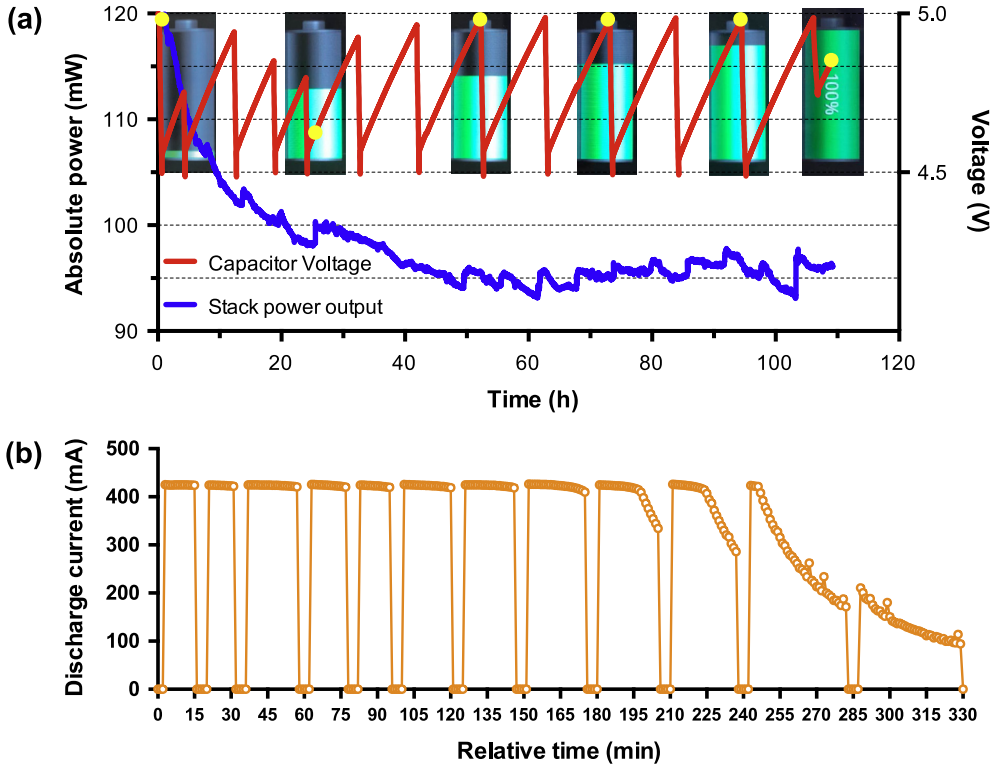

Fig. 8. Charging of the Samsung Galaxy S I9000 through its USB port (SP). (a) Power produced by the stack and voltage illustrating the charge/discharge cycles of the supercapacitor. The pictures indicate the charge state of the phone (yellow dots indicate when pictures were taken). (b) Current delivered by the supercapacitors during the discharge cycles. The time between each discharge cycle (approx. 10 h of using the phone) is not represented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

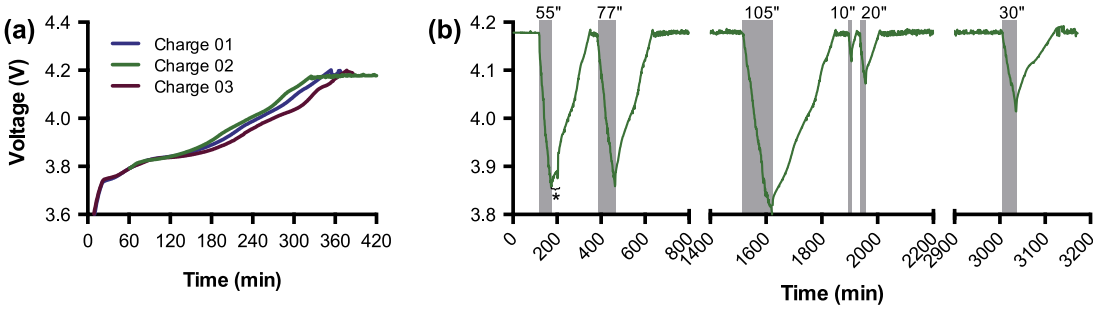

Fig. 9. Charge and discharge curves of the Plug-in mobile SIM Phone (PMSP; turned ON). (a) Voltage of the 150 mA h battery illustrating the consistency in the charge cycles. (b) Temporal voltage measurements showing the relationship between the discharge time (outgoing phone calls; coloured in grey) and the charging time.

was considered that on regular use, the battery should not be allowed to drop below 3.8 V (charge half-time). With these considerations in mind, increasingly longer phone calls were made, ensuring to stop communications as soon as the battery voltage reached 3.8 V, which corresponded to half the charging time of the PMSP's battery.

Results show that the longest call lasted 105 min before the battery voltage reached the 3.8 V (Fig. 9b). Plotting the call time with the corresponding charge time indicated that the charge/use duty cycle was 2 to 1: $Y = 2.295 \cdot X \pm 5.5$ min ($R^2 = 0.962$). Y stands for the charging time and X for the call length. In this experiment, the cascade of 6 modules delivers sufficient energy to run the phone. However, this energy was insufficient to power the communication itself, hence the need for the smaller battery, which in this case was acting as an energy storage/buffer for communication. Practically, these results show that a single individual urinating 600 mL every 6 h would have 1 h 45 min of phone conversation every 3 h, and another 1 h 45 min of communication in a case of emergency.

4. Conclusions

Results demonstrated that the MFC technology is sufficiently mature for implementation in out-of-the-lab applications. The system developed here – consisting of the feeding mechanisms, the MFC cascade and the energy harvesting circuitry – demonstrated for the first time the full charge of mobile phones, including smart phones, with neat urine as fuel. Moreover, it was shown that this system could be tailored to specific needs, in the present case to the need of a single individual. At the moment this system has a charge/discharge duty cycle of 2 to 1. Nevertheless, the results presented here are the first demonstration, in real conditions, of a complete MFC-based system able to power telecommunication devices in remote areas.

Acknowledgements

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