The Journal of The Textile Institute

ISSN: 0040-5000 (Print) 1754-2340 (Online) Journal homepage: https://www.tandfonline.com/loi/tjti20

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To cite this article: Aleksandrs Vališevskis, Uģis Briedis, Žaneta Juchnevičienė, Milda Jucienė & Miguel Carvalho (2020) Design improvement of flexible textile aluminium-air battery, The Journal of The Textile Institute, 111:7, 985-990, DOI: 10.1080/00405000.2019.1676521

To link to this article: https://doi.org/10.1080/00405000.2019.1676521

THE JOURNAL OF THE TEXTILE INSTITUTE
2020, VOL. 111, NO. 7, 985–990
https://doi.org/10.1080/00405000.2019.1676521

ARTICLE

Design improvement of flexible textile aluminium-air battery

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ABSTRACT
Lately there have been a growing demand for energy sources that are suitable for powering smart textiles. A number of promising prototypes have been developed, many of which address important issues, but only to face new challenges. In this paper we propose a new approach to the development of energy source for smart textiles in order to overcome these challenges. The main feature of the new design is that the electrolyte is separated from the electrodes and is applied only when the cell needs to be activated. This makes shelf-life virtually infinite. We stress that this solution is suitable for specific applications only, outlined in the paper. The main aim of this study is to test viability of such an approach, using only textile materials. The presented electrical characteristics of the new battery should be assessed in this context. The main components of the battery include aluminium anode, air cathode and the shell made from cotton fabric. The paper focuses on the choice of textile-based materials for the anode and the cathode, since non-textile materials were used in these components in the original design. Besides that, the pure metal wire meshes have shown to be prone to oxidation. The new materials should address that issue as well. Electrical characteristics of the new design of the battery are measured, which confirm that there is no loss in battery performance. Next steps for further development of a multicell flexible textile battery, based on the results presented in this study, are outlined at the end of the paper.

ARTICLE HISTORY
Received 9 May 2019
Accepted 2 October 2019

KEYWORDS
aluminium-air battery; flexible battery; smart textiles; embroidery

1. Introduction

Smart textile field has been booming during the last decades and one of the main challenges that has been acknowledged was related to finding an energy source that is suitable for integration into wearables and particularly into smart textiles. Lately a number of important studies have been published, which address just this problem. Being constrained by the strict limitations, dictated by the application conditions, many of the developed prototypes face new challenges. These studies mostly focus on electrode material selection, electrolyte selection and integration techniques. The proposed solutions usually fall into one of three main categories: double layer capacitors, pseudocapacitors, and batteries (Jost, Dion, & Gogotsi, 2014). For example, in (Jost et al., 2011) supercapacitors made from YP17 and CXV carbon coated textile are proposed, which are tested with a number of non-toxic electrolytes. Authors of (Avoundjian, Galvan, & Gomez, 2017) take another approach and propose a paper-based flexible aluminium-air battery, which uses commercially available inexpensive materials, as well as 1.5 M KOH electrolyte. Three such cells, connected in series configuration allow to power simple electronic devices and LEDs, although the chosen electrolyte make them unsuitable for use in smart textiles. Woven battery based on copper and nickel (Normann, Kyosev, Ehrmann, & Schwarz-Pfeiffer, 2016) uses gel electrolyte, but shows modest electrical characteristics and should be improved in order to be used for powering electronic devices. Besides that, nickel should be avoided due to possible allergic reactions. Measurements of textile batteries, prepared from different conductive woven fabrics with a nanofiber mat as an interlayer filled with iodine-triiodide solution show rapid destruction of metal electrodes and degradation of electrolyte (Resuli, Turhan, Ehrmann, & Blachowicz, 2018), which limits shelf-life of these batteries just to a few days, making such batteries only useful for instant use.

In this paper we propose a new approach to the development of energy source for smart textiles. The main feature of the new design is that the electrolyte is separated from the electrodes and is applied only when the active part of the smart textile product needs to be energised. It is important to stress that this solution is suitable for very specific applications only and is not a universal solution, however it enables to solve one of the biggest challenges, which is faced by flexible textile energy sources today – their storage time. Since during inactive phase the electrodes are separated from electrolyte, there is no medium for the redox reaction to occur, so the storage time is virtually infinite. The battery activates only when liquid is applied from outer environment, which acts as an electrolyte and activates the battery.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/tjti.

Thus, it is a single-use battery, which is intended for one-time activation, so that it can energise the electronic device attached and be discarded afterwards or re-activated by drying and eventually after replacing the aluminium electrode, if it has degraded. This puts pressure on the costs of the cells, which must be sufficiently low in order for this solution to be practically applicable. The described battery can be thought of as of an active moisture sensor, as well as of an energy source.

The described battery was specifically designed for medical applications, which often require a reaction to the appearance of bodily liquids, for example in enuresis alarm systems, in disposable bed mats, in diapers, especially in those intended for children or unconscious adults, who have no means to communicate that the diaper is full. Other applications include use in storage facilities, where thaw water can activate the sensor with an e-ink display to indicate that there the freezing equipment has failed at some point in time.

The measured electrical characteristics prove practical usability of such a design. Although lack of control of various components of this open system makes it doubtful that the proposed battery will outperform other self-contained textile batteries, this can be considered as a specific design for special purposes, which addresses particular challenges.

Aluminium-air batteries are becoming more and more popular lately due to various factors, the major two being the abundance of aluminium in Earth crust, hence its low price, and its relatively high theoretical voltage and energy density (Li & Bjerrum, 2002; Yang & Knickle, 2002). However, their large-scale implementation is impeded by a number of technical and scientific problems, which are mostly related to self-corrosion of aluminium electrode and improvement of electrochemical reactions, by employing different alloys, inhibitors, electrolytes and catalysts (Liu et al., 2017).

Another major advantage of aluminium-air batteries is that they can be made, using safe and non-toxic materials. A basic design consists of aluminium anode and a cathode, which needs to draw oxygen for operation. This can be accomplished by using porous material, which ensures oxygen diffusion, such as carbon. Besides that, it is possible to use aqueous electrolytes, such as NaCl solution, which makes the battery completely safe. When this electrolyte is applied to pure aluminium electrodes, potential values in the range 0.65-1.1 V can be obtained (Liu et al., 2017), but these values are expected to be somewhat lower, when used with textile-based materials.

This paper addresses a number of issues that we came across after an extensive experience with the flexible aluminium-air battery that was proposed in (Briedis, Vališevskis, & Zelča, 2017). The main concerns that are dealt with in this paper are rigidity and proneness to oxidation of the materials originally used. A more thorough description of the original design can be found in the next section. This paper focuses on the choice of materials for aluminium anode and air cathode, which constitute the main components of the battery. The battery itself is a flexible energy source, which is specifically intended for use in smart textile applications. This poses limitations and requirements on the potential materials that can be used. Some of these limitations are as follows:

- the materials should not be hazardous or harmful,
- they must have appropriate electrochemical properties, and
- they should have textile-like structure and properties, so that the overall structure and tactile feel of the battery is similar to the product where it is intended to be used,
- materials, up to the underlying layer, should be highly permeable, in order to ensure proper soaking with electrolytic liquid and timely activation of the battery.

The critical parts of the battery are (1) *aluminium anode*, where the oxidation takes place, it should have enough metal to support the reaction; and (2) *air cathode*, where the reduction takes place, it can be broken down into two parts: (a) porous carbon layer, which ensures gas diffusion and (b) conductive current collector (Li & Bjerrum, 2002; Yang & Knickle, 2002). The proposed improvements are described in Section 2.

The main objective of this study is to determine materials, that will be used in the next stage of the battery development, namely creating a multicell battery, which further improves the electrical characteristics of a single-cell battery. At the end of the paper we present results of the first studies, which indicate the general layout of the multicell battery.

Original design

In (Briedis et al., 2017) the original design of a flexible aluminium-air battery is presented. The original battery consists of a cathode (copper mesh with carbon granules encapsulated in cotton jacket), which is surrounded by aluminium mesh anode.

For the sake of comparability, size of the elements is fixed at 50x50 mm. Highly concentrated 2,85 M NaCl aqueous electrolyte was used for the sake of first experiments. *PicoScope 3204B* digital oscilloscope was used for voltage measurements and *Extech EX320* multimeter was used for current measurements. These conditions remain the same for further experiments, unless stated otherwise. After a series of experiments, the following elements have been chosen for the original design:

- *embroidered cathode pack*, which encapsulates a layer of carbon 1-2 mm granules, a layer of #100 copper mesh and additional layer of carbon 1-2 mm granules in a cotton jacket;
- 0.28 mm diameter aluminium wire woven mesh (#18 x #16 Mesh) was used as an *aluminium anode*, the mesh was folded in half in order to increase current output of the battery.

The original designed has shown promising electrochemical properties with open-circuit voltage $V_{OC} = 800\,mV$ and short-circuit current $I_{SC} = 50\,mA$. Although after this cell was left at rest for four weeks period, the second measurement has shown a drop to $V_{OC} = 640\,mV$ and $I_{SC} = 35\,mA$. During this period the battery was dried and was staying in inactive state.

The drop in performance can be explained by the heavy oxidation of the copper mesh used in the embroidered cathode pack. In order to solve this problem, it is necessary to consider other materials, i.e. metals, which have higher resistance to oxidation, for use in the cathode section.

Another drawback is the increase in the rigidity of the battery due to rather stiff 0.28 mm diameter aluminium wire mesh, as well as copper mesh, which is substantially less flexible than textile materials.

The proposed solutions to these issues are described in the next section.

Proposed improvements

In order to solve the issue of increased rigidity it was decided to use textile-based materials. It ensures that the flexibility and feel of the battery will be as close as possible to the textile materials, where it is intended to be integrated.

A number of options has been considered for the substitution of copper mesh in the cathode:

1. The first option is *Shieldex® Nora-PW* conductive fabric (Shieldex® Nora-PW Technical Data Sheet, 2018), which is highly conductive (Surface Resistivity: < 0.03 Ohms/□), although its high density makes it relatively heavy at 83 g/m^2. Technically it is a Ni/Cu/Ag plated nylon, so it should have better oxidation resistance.
2. The second option is *Shieldex® Budapest* conductive fabric (Shieldex® Budapest Technical Data Sheet, 2013), which is less conductive (Surface Resistivity: < 1.00 Ohms/□), but is much lighter at 28 g/m^2 and thus has better permeability, which is crucial for this design. Besides that, it is 99% pure silver plated polyamide fabric, so has good oxidation resistance. Another possible advantage is related to the unoccupied *d*-orbital of silver (Ag), which is in a vacant state, allowing it to act as a catalytic centre (Liu et al., 2017).
3. Fine (#500) stainless steel wire mesh is used as another option, which should eliminate the oxidation issue. It should be noted that although this mesh is made from pure metal, it is the only metal mesh in this experimental set with flexibility and tactile properties very similar to that of textile fabric.

Regarding aluminium mesh anode, used in the original battery, there are a few substitution options as well:

1. Textile fabric coated with aluminium by magnetron sputtering. As is shown in (Briedis et al., 2017), this method is not suitable, since due to insufficient amount of aluminium, this type of anode is highly inefficient.
2. Mtex® aluminium-textile composite made by Frenzelit GmbH is another option. It is a metal-textile composite material based on an innovative, thermal, binder-free coating process. The textile substrate is directly coated with aluminium. Mtex® also boasts high electrical conductivity and can be processed with all common textile industry techniques (Frenzelit, 2017).

Regarding gas diffusion layer, 3 mm carbon-impregnated nonwoven fabric is chosen as a possible alternative to carbon granules and is included in the experiments.

In order to avoid discrepancies introduced by slight changes in the newly prepared samples, all the materials used in the original battery will be once again directly compared to the newly proposed materials.

Thus, the materials included in the experiments can be summarized as follows. Different combinations of these materials are tested and the electrical characteristics of the new designs are compared:

1. gas diffusion layer (cathode):
   a. embroidered cathode pack with carbon granules,
   b. 3 mm carbon-impregnated nonwoven fabric;
2. aluminium anode:
   a. 0.28 mm diameter aluminium wire woven mesh (#18 x #16 Mesh),
   b. Mtex® aluminium-textile composite;
3. conductive cathode current collector:
   a. 0.03 mm diameter copper wire mesh (#100 Mesh),
   b. 0.025 mm diameter stainless steel wire mesh (#500 Mesh),
   c. Shieldex® Budapest conductive textile,
   d. Shieldex® Nora PW conductive textile.

In the next section these materials are combined together, samples are prepared, experiments are carried out, and measurements and results are presented.

Experiments and results

The battery can be divided into three functional components: (1) (1)gas diffusion layer, (2) cathode current collector, (3) aluminium anode, thus the experiments are organized in three groups for each functional component. In each experimental batch only one component is changed, while all the other parts remain the same.

Gas diffusion layer

Cathode gas diffusion layer is necessary is necessary to support electrochemical reaction. Two types of gas diffusion layer are tested, in both cases copper wire mesh is used as current collector. The embroidered cathode pack, used in the original design was compared to 3 mm thick carbon-impregnated nonwoven fabric, which is permeable and similar to material used in air filters.

Results are presented in Table 1. Voltage-current characteristic is shown in Figure 1.

Table 1. Experiments with materials for gas diffusion layer.

Material	Open-circuit voltage	Short-circuit current
Embroidered cathode pack with carbon granules	680 mV	35 mA
3 mm thick carbon-impregnated nonwoven fabric	500 mV	13 mA

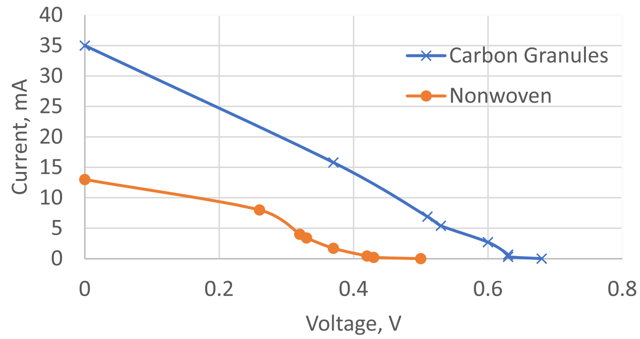

Figure 1. Voltage-current characteristic for gas diffusion layer materials.

Table 2. Experiments with aluminium anode materials.

Material	Open-circuit voltage	Short-circuit current
0.28 mm diameter aluminium wire woven mesh (#18x#16 Mesh)	700 mV	11.7 mA
Mtex® aluminium-textile composite	700 mV	22.9 mA

Embroidered cathode pack with carbon granules is chosen for further experiments.

Aluminium anode

Rigid aluminium wire mesh (0.28 mm diameter wire) is compared to Mtex® aluminium-textile composite material. Mtex® fabric has textile base and textile-like tactile feel, but is not permeable, thus it is used only in the underlaying layer. Please note that for this experiment batch 20x20 mm size cells were prepared with 6.25 times smaller surface area than for other experiment batches. Cells of this size are intended for use in multicell batteries, which are currently in the development phase. The results are presented in Table 2. Voltage-current characteristic is shown in Figure 2.

Mtex® aluminium-textile composite material is chosen for further experiments.

Cathode current collector

Cathode current collector is made of conductive material and is used to pass current from the cathode. Copper wire mesh used in the original design, which was prone to fast oxidation, was compared experimentally to three other materials and the results are summarized in Table 3. For this experiment several embroidered cathode packs were prepared with different integrated current collectors. Voltage-current characteristic is shown in Figure 3.

Shieldex® Budapest and Shieldex® Nora PW have shown very similar results. Although in a practical sense Shieldex® Nora PW seemed less suitable, because due to its impermeability it has caused activation of the battery to be unstable

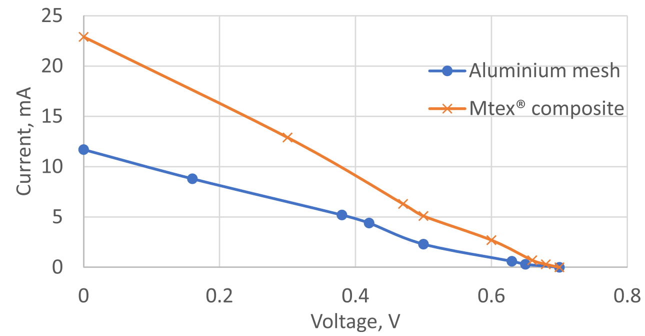

Figure 2. Voltage-current characteristic for aluminium anode materials.

Table 3. Experiments with cathode current collector materials.

Material	Open-circuit voltage	Short-circuit current
0.03 mm diameter copper wire mesh (#100 Mesh)	670 mV	22.2 mA
0.025 mm diameter stainless steel wire mesh (#500 Mesh)	740 mV	31.2 mA
Shieldex® Budapest conductive textile	750 mV	40.3 mA
Shieldex® Nora PW conductive textile	740 mV	43.2 mA

and it took more time for measurements to stabilize. In order to differentiate between these two materials additional experiments had been carried out, using smaller 20x20 mm elements. The results are shown in Table 4. Voltage-current characteristic is shown in Figure 4.

Results and discussion

Based on the experiment results, the following materials have been chosen for further development of the battery:

- *Gas diffusion layer*: carbon granules. Carbon granules are inserted into embroidered cathode pack.
- *Aluminium anode*: Mtex® aluminium-textile composite material. Since this material is not permeable, it is placed only in the underlaying layer.
- *Cathode current collector*: Shieldex® Budapest conductive textile. Cathode current collector is integrated into embroidered cathode pack, which includes carbon granules mentioned above.

The new design of the flexible textile aluminium-air battery is shown and explicated in Figure 5.

The actual components that constitute a 20x20 mm battery, as well as the embroidered cathode is shown in Figure 6.

Another important result is that during the experiments the cells have shown a non-linear response to changes in their size, as can be seen from data in in Tables 3 and 4. As can be seen, reduction in size is not proportional to the reduction of electrical characteristics of the cells. This behaviour might indicate a bottleneck in the design, which limits the performance of the battery, or lack of uniformity of the samples. Since the topic of further study is the development of a multicell battery, size is an important factor. On the other hand, further reduction in size does not seem practical, taking into account other constituent materials of

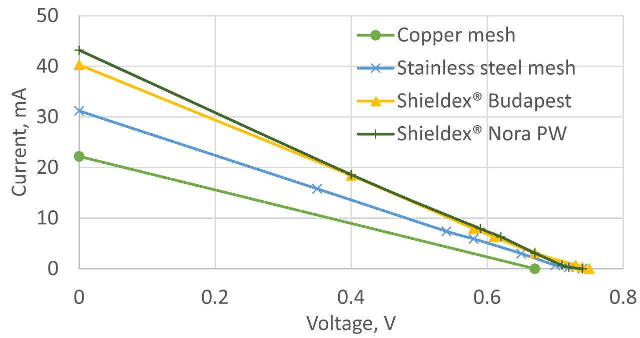

Figure 3. Voltage-current characteristic for cathode current collector materials.

Table 4. Experiments with Shieldex® materials using 20x20 mm elements.

Material	Open-circuit voltage	Short-circuit current
Shieldex® Budapest conductive textile	690 mV	41.5 mA
Shieldex® Nora PW conductive textile	560 mV	33.2 mA

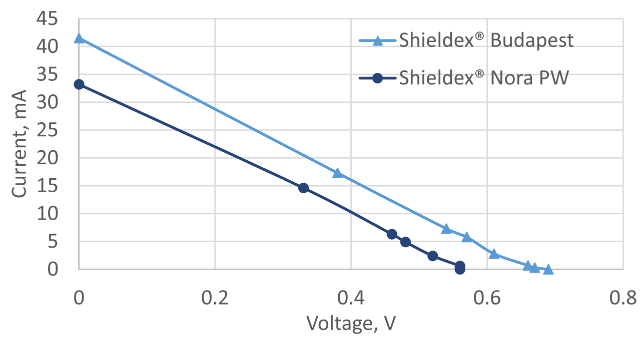

Figure 4. Voltage-current characteristic for cathode current collector materials, additional experiments with 20 × 20 mm elements Shieldex® Budapest conductive textile is chosen for further experiments.

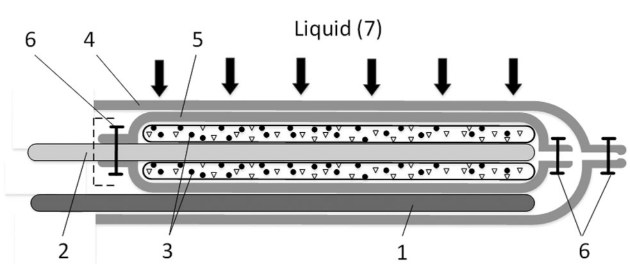

Figure 5. New design of flexible textile Al-Air battery.

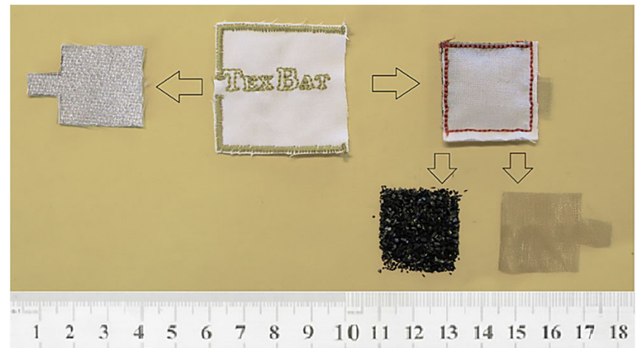

Figure 6. Actual components of the new battery design in 20 × 20 mm size.

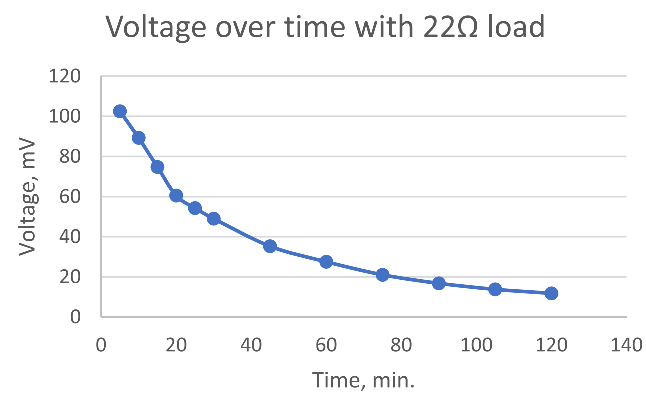

Figure 7. Voltage change over time of a single cell with 22 Ω load applied.

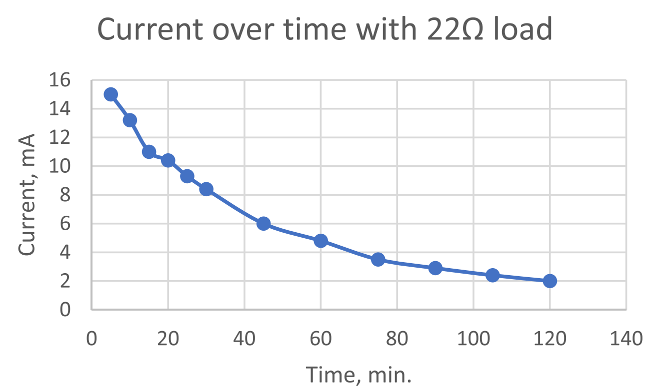

Figure 8. Current change over time of a single cell with 22 Ω load applied.

the battery (more importantly carbon granules, which contributes to the overall width of the element). Thus, 20x20mm size will be used in further studies.

In order to test th capacity of the battery, it was discharged under a constant load of 22 Ω, which puts battery under stress comparable to that of real applications. It should be noted that the design of the battery implies that it is not intended for storage in the activated state (i.e. with the electrolyte applied) – it is intended to accomplish its function right after activation. Thus, it is not practical to test the degradation of the battery without load. In this experiment load has been applied to the cell and voltage/current change over time can be seen in Figures 7 and 8.

This completes an important step on the path to developing a functional multicell energy source that can be used in wide variety of applications. Next section shows the results of the first experiments, which also indicate the direction of our further work.

As expected for this open design of a battery, the specific energy of the cell is estimated to be quite low, around a few *Wh/kg*, which is consistent with cell's intended areas of application and in this case it is a necessary trade-off for the prolonged storage time.

A glimpse at further development

As was already mentioned, next step is to make a multicell battery pack. It is possible either to stack cells or place them on a plane. The former solution may be problematic, because the conductive electrolyte may create detrimental short-circuits, which may decrease performance of the

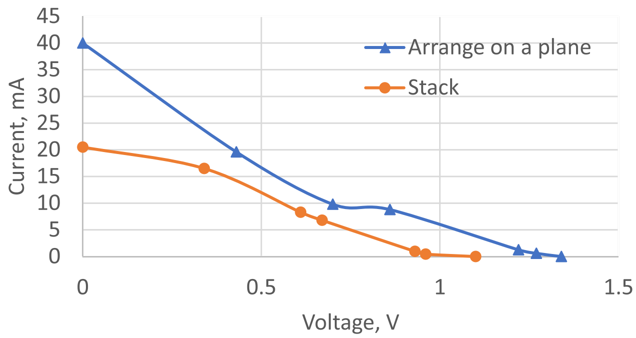

Figure 9. Combining two cells together.

battery. Figure 9 shows the results obtained by placing two cells in the aforementioned positions.

As can be seen, better results are obtained when the cells are arranged on a plane, with a separating barrier established between them, which makes it easier to ensure their electrical isolation. Thus, the biggest challenges in combining flexible textile cells on a textile substrate will be to ensure their isolation by directing the flow of electrolyte and making connections in an appropriate way. This can be achieved by proper isolation of the individual cells with appropriate sealants.

Conclusion

This paper presents a set of experiments that was devised to determine suitable materials for flexible textile aluminium-air battery. The new materials show promising results and performance that is equivalent to that of pure metal elements, which were used in the original design and caused various issues, described in detail in this paper. The new design includes only textile-based materials, which ensure greater flexibility and better fusion with textile materials, where the battery is intended to be integrated.

Besides that, results of first experiments with multiple cells are presented, which show that the arrangement of the cells in a multi-element pack should be horizontal rather than vertical. Compact multicell battery packs capable of generating a few volts is the main topic of our further research. These batteries can be integrated into smart textiles and can stay in inactive state for unlimited time, before liquid is introduced, which activates the battery. It expands their potential use to storage solutions and healthcare products. The battery can be reactivated by replacing the consumed aluminium anode. Now that the viability of such a design is established, further study will focus on lowering NaCl concentration in electrolyte.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work has been supported by the European Regional Development Fund within the project no. 1.1.1.1/16/A/020 "Synthesis of textile surface coating modified in nano-level and energetically independent measurement system integration in smart clothing with functions of medical monitoring".

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