Optimised flexible thermoelectric generators manufactured by metallic threads sewn on fabrics

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ION RAZVAN RADULESCU
DOINA TOMA
ELENA PERDUM
ADRIAN MARIN
LAURENTIU DINCA
RALUCA MARIA AILENI

ABSTRACT – REZUMAT

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Autonomous energy harvesting sources in wearables enable supply for sensors, antennas and transmission lines, with powers in the range of mW. Thermoelectric generators (TEGs) based on the Seebeck effect are noiseless and have a relatively good energy harvesting efficiency when compared to other sources. Flexible TEGs (F-TEGs) are made of metallic threads and coatings applied on textile substrates that can be integrated into wearable systems. This paper relies on previously manufactured prototypes of T-type and J-type F-TEGs by applying metallic threads onto textile substrates, with the new goal of optimising the harvested voltage, based on a mathematical relation from the scientific literature. This relation yields an optimal ratio of the cross-sectional areas of the n- and p-legs of the F-TEG with respect to their thermic and electric conductivities. The J-type F-TEG was selected for optimisation, and the ratio of the Constantan and Stainless Steel threads was modified from 2:2 to 1:3, according to the mathematical relation. The optimised prototype was designed, manufactured, and measured under the same physical conditions as the initial prototype, yielding better voltage-harvesting values: the slope between temperature difference and harvested voltage increased from 0.0646 to 0.0832.

Keywords: *thermocouples, textiles, energy harvesting, wearables*

Optimizarea generatoarelor termoelectrice flexibile realizate din fire metalice cusute pe materiale textile plane

Sursele autonome de generare a energiei în articole purtabile permit alimentarea senzorilor, antenelor și liniilor de transmisie cu puteri în domeniul mW. Generatoarele termoelectrice (TEGs) care funcționează în baza efectului Seebeck sunt silențioase și au o eficiență energetică relativ mare comparativ cu alte surse autonome de energie. Generatoarele termoelectrice flexibile (F-TEGs) sunt realizate din fire sau acoperiri metalice pe substraturi textile, care se pot integra în sisteme purtabile. Această lucrare continuă studiul prototipurilor F-TEG de tip T și de tip J, prin aplicarea de fire metalice pe substraturi textile, cu obiectivul nou de a optimiza tensiunea electrică generată, în baza unei relații din literatura de specialitate. Din relație rezultă un raport optim între aria secțiunii elementelor de tip n și a elementelor de tip p, în funcție de conductivitatea termică și electrică a acestora. F-TEG de tip J a fost selectat pentru optimizare, iar raportul între firele de constantan și inox a fost modificat de la 2:2 la 1:3, în conformitate cu relația analitică. Prototipul optimizat a fost proiectat, fabricat și măsurat în aceleași condiții ca prototipul inițial, cu valori mai bune pentru tensiunea electrică generată: coeficientul curbei între diferența de temperatură și tensiunea generată a crescut de la 0,0646 la 0,0832.

Cuvinte-cheie: *termocupluri, textile, generare energie, articole purtabile*

INTRODUCTION

Wearable products encompass a strong trend in the field of textiles and clothing, with main applications in the monitoring of vital signs for sports and medicine [1, 2]. While many of the technical issues related to wearables have found proper solutions (transmission lines via metallic threads [3], embedded antennas [4], sensors via metallic coatings [5]), the energy supply of such textile-electronic systems (textronics) still encounters difficulties [6]. The main goal is to ensure an integrated and autonomous energy supply of textronics, having in view that the electric power needed for the sensors, antennas and transmission lines is relatively low, in the range of mW.

Considering these aspects, many research studies deal with the energy harvesting of autonomous sources for powering the textronic systems, based on various physical principles. These autonomous energy harvesting sources replace the heavy, bulky and un-washable batteries [7]. The following sources of autonomous energy harvesting and their related technological solutions were identified [8]: photovoltaic cells (solar light), electrodynamic transducers (motion, force), piezoelectric transducers (mechanical vibration) and thermoelectric generators (temperature gradient). Each of these sources has advantages and drawbacks to be considered when implementing into a textronic system [8].

Thermoelectric generators (TEGs) rely on the Seebeck effect and are used for electric energy harvesting from a temperature gradient. The physical principle describes pairs of two different metallic legs, with connections at the hot and cold junctions. One pair builds a thermocouple leg, while several thermocouples connected in series build a thermopile. The harvested energy of a thermopile is the sum of the energy of the series thermocouples. This is usually needed due to the relatively low electric power, in the range of mW, harvested by TEGs. The pairs have to include one p-material (generating positive holes) and one n-material (generating negative electrons). The heat at a junction disperses both holes of the p-material and electrons of the n-material, with the generation of a small electric current [9].

When considering TEGs, the main advantages are the high amount of power compared to other sources and their noiselessness [8]. TEGs require a temperature gradient; they require many legs connected in series; they are relatively expensive; and they generate low output voltage and high currents, requiring stabilisation via Boost converters [10].

Several technical solutions were proposed to apply flexible TEGs (F-TEG) in wearables and textronics [11–14].

Lund et al. [11] have a comprehensive paper on a F-TEG, manufactured on a felted wool fabric with pairs of silver threads as n-type material and PEDOT:PSS coated thread as p-type material. The horizontal geometry of the F-TEG describes the upper part of the fabric as the hot junction and the lower part as the cold junction, while the conductive threads are sewn through the fabric. Manufacturing, modelling and optimisation are tackled in the paper, with a description of all the required physical parameters. The generated voltage was 2.3 mV at 30 K.

Allison et al. [12] bring valuable results with an F-TEG achieved by deposition of PEDOT:CL as p-type material and Carbon threads as n-type material on a cotton substrate. The vertical geometry of the fabric is meant for bending, so that one side of the fabric is the outdoor cold junction and the other side is the inner hot junction. The harvested voltage of 1.1 mV at a temperature difference of 30 K represents a promising result.

Hardianto and the team of UGent [13] studied in depth the supply of e-textiles via F-TEGs. Various pairs of legs were achieved, mainly Nickel and Carbon Fibers on the same thread, with the Nickel on one side of the fabric and the Carbon Fibers on the other side. The geometry consists of a hot junction at the upper part of the fabric and the cold junction at the lower part, which enables measurement by an experimental setup composed of a hotplate, thermometer and nano-voltmeter. Results encompass voltages of 700 μV at a temperature gradient of 30 K.

Another contribution of the UGent and the UWB teams [14] describes pairs of n-type and p-type legs of different metallic threads, embroidered on a fabric with left-right geometry: the cold junction is on the left part of the fabric, while the hot junction is at the right part. The harvested electric power had good results, with values of 1.2 mV at 60°K temperature gradient.

More recent research contributions focused on advanced geometries for integrating TEGs into smart garments [15–21]. Vertical thermoelectric elements were integrated into a smart glove with n-type material of SWCNT doped with Polyethylene-imine and p-type material with SWCNT doped with PEDOT:PSS. Performance outlined values of 23.2 mV generated voltage and 2.6 μW generated power were outlined at a 48°C temperature difference [15]. COMSOL simulations were performed to assess the F-TEG's optimal dimensions in relation to the generated voltage. For the thermocouple legs, silver was applied as n-type material, while PEDOT:PSS was used as p-type material, according to the simulation [16]. A silicone rubber sheet with horizontal geometry and elements of Ni-doped Bi_2Te_3 as n-type material and $Bi_{0.3}Sb_{1.7}Te_3$ as p-type material had outstanding energy harvesting performance with a voltage of 1 V and a power of 77.41 mW at a 60°C temperature difference [17]. An F-TEG built with graphene and copper legs reached a power of 11 μW at a temperature difference of 75°C [18]. One bracelet for monitoring vital signs of the human body was autonomously powered by miniaturised TEGs [19]. Another F-TEG used PANI/graphite and bismuth telluride composites for the thermocouple legs [20], while Single-Wall Carbon Nanotubes were used in another similar application [21–23].

Our paper proposes an F-TEG designed on a textile substrate with metallic threads, by applying the T- and J-Type thermocouple pairs, with a geometry of the fabric similar to contribution [14]. By considering the initial prototypes of T- and J-type thermocouples presented in our paper [22], an optimisation of the prototypes based on the relation of the legs' cross-section area and their electric/thermic conductivity is tackled within the current paper [11]:

$$\frac{A_n}{A_p} = \sqrt{\frac{\sigma_p \lambda_p}{\sigma_n \lambda_n}} \qquad (1)$$

where $A_{n/p}$ is the cross-section area and $\sigma_{n/p}$ and $\lambda_{n/p}$ are the electric/thermic conductivity of the thermocouple legs.

DESIGN OF THE F-TEGS

Concept

Two main design concepts were identified from the scientific literature regarding F-TEGs:

– the horizontal geometry with the hot and cold junction on the upper and lower part of the fabric [11];
– the vertical geometry with the hot and cold junction on the left and right part of the fabric [12].

Figures 1 and 2 showcase the identified geometries. The F-TEGs presented in this paper were designed and manufactured according to the vertical geometry, by adapting the concept from contribution [14]. The distance between the parallel legs was 20 mm, while the length of a leg was 100 mm, considering the need for dielectric isolation between the legs as well as a

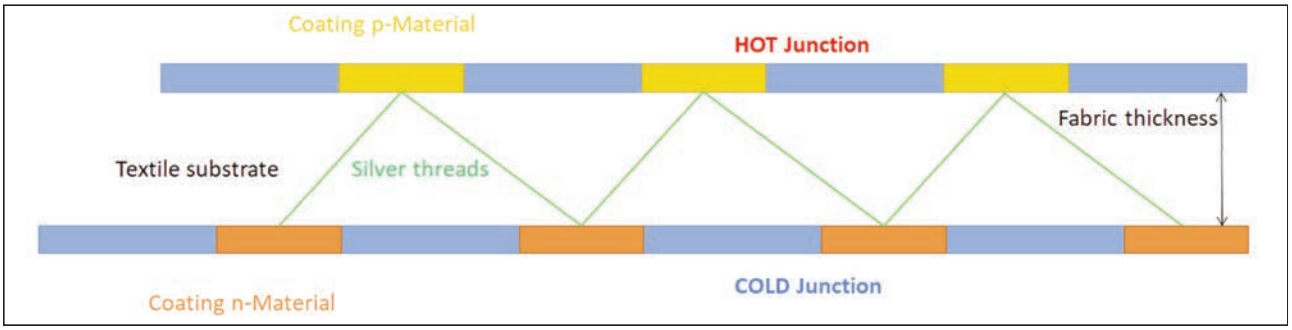

Fig. 1. The horizontal geometry of the F-TEG

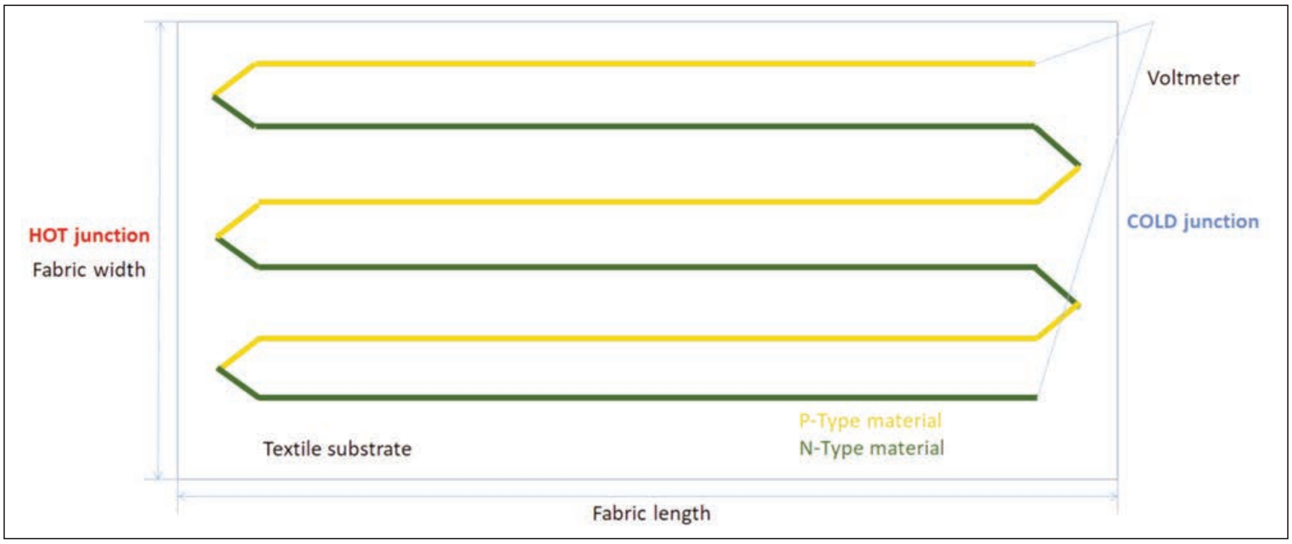

Fig. 2. The vertical geometry of the F-TEG

feasible distance between the hot and the cold junction. Multi-filamentary threads with metallic and PES filaments were sewn onto the 100% PES textile substrate.

Materials

Our previous attempts to achieve F-TEGs based on metallic threads yielded results in the range of 7.2 mV for T-type thermocouples and 4 mV for J-type thermocouples, at a temperature difference of 60 K [24]. Figures 3 and 4 present the initial manufactured F-TEGs [24].

Table 1 includes the design and the physical-mechanical properties of the textile substrate for the F-TEG. The copper, constantan and stainless steel threads have a multifilament structure of 100% PES with

Fig. 3. F-TEG type T
Pairs of legs of Constantan and Copper threads
Junctions consolidated by Silver threads
Electric circuit Ohmic resistance: 55 Ω

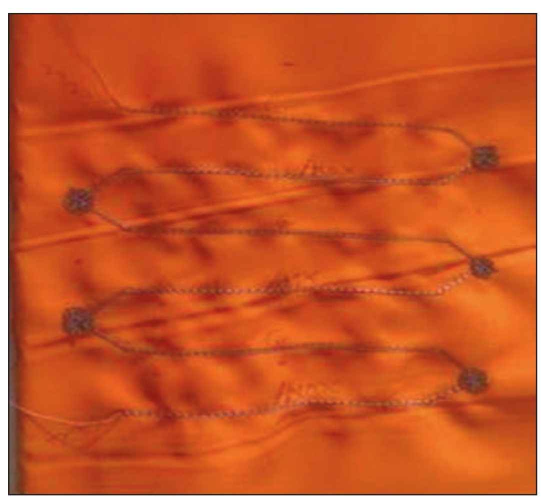

Fig. 4. F-TEG type J
Pairs of legs of Constantan and Steel threads
Junctions consolidated by Silver threads
Electric circuit Ohmic resistance: 375 Ω

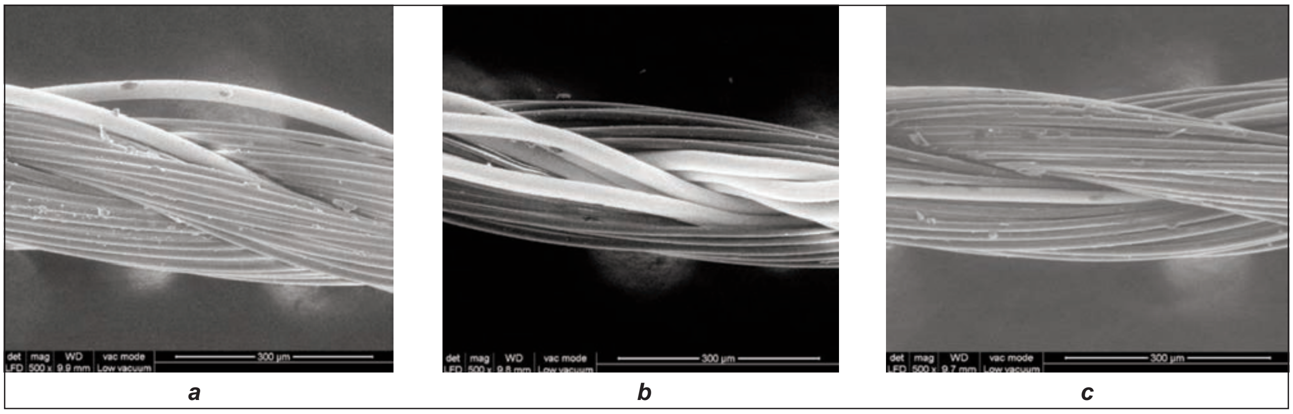

Fig. 5. SEM image of the multifilament metallic thread, mag 500x:
a – Constantan; *b* – Copper–Silver; *c* – Stainless steel

Table 1

DESIGN AND PHYSICAL-MECHANICAL PROPERTIES OF THE TEXTILE SUBSTRATE		
No.	**Design structure/ Physical-mechanical property**	**Value**
1	Fibrous composition (%)	100% PES
2	Weave	Plain weave
3	Specific mass (g/m^2)	258
4	Tensile strength Warp/Weft (N)	2400/1070
5	Elongation at break Warp/Weft (%)	48.4/25.8
6	Tear strength Warp/Weft (N)	60/26
7	Air permeability (l/m^{2}s)	27.5

metallic insertions and were purchased from Clevertex, Czech Republic. Figure 5, *a–c* presents the SEM images of the multifilament thread with metallic insertions of Constantan, Copper-Silver, and Stainless steel. Every two threads were sewn in parallel for the conductive F-TEGs legs.

Methods

The main aim of this paper is to optimise the performance of the F-TEGs based on relation 1, namely to tailor the cross-section area of the threads in relation to their electric/thermic conductivity. The electric conductivity was computed according to relation 2 from the specification of the threads regarding linear resistance and optical diameter [25], in table 2:

$$\sigma = \frac{1}{R_L}\frac{L}{A} = \frac{1}{R_L}\frac{4L}{\pi D^2} \qquad (2)$$

with A – the cross-sectional area, L – the length of the thread and R_L – the linear electric resistance [Ω].

The next step was to compute the thermic conductivities of the metallic threads based on analytical relations 3:

$$\lambda_{eff} = \sum \lambda_i v_i \qquad (3)$$

with v_i – volume fraction of each component and λ_i – thermic conductivity of each component. The volume fraction of metallic multifilament/PES multifilament was determined from the SEM images of the yarns

Table 2

ELECTRIC CONDUCTIVITY OF THE METALLIC THREADS			
Type of metallic thread	**Linear electric resistance R_L (Ω/m)**	**Optical diameter D (μm)**	**Electric conductivity σ (S/m)**
Copper/Silver	3	160	17580000
Constantan	210	220	125000
Stainless steel	1150	250	17730

Table 3

THERMIC CONDUCTIVITY OF THE METALLIC THREADS			
Type of metallic thread	**Thermic conductivity PES, v_{PES} = 5:6 (W/mK)**	**Thermic conductivity metals, v_{metal} = 1:6 (W/mK)**	**Thermic conductivity (W/mK)**
Copper/Silver	0.19	415	70
Constantan		22	3.83
Stainless steel		20	3.49

Table 4

OPTIMAL RATIO CROSS SECTION AREA COMPUTED FOR THE TWO TYPES OF F-TEGs – RELATION 1			
F-TEG Type	**Electric conductivity (S/m)**	**Thermic conductivity (W/mK)**	**Optimal ratio cross section**
T-type Constantan Copper/Silver	 125000 17580000	 3.83 70	$A_{Constantan} = 50 \times A_{CopperSilver}$
J-type Constantan Stainless steel	 125000 17730	 3.83 3.49	$A_{StainlessSteel} = 2.8 \times A_{Constantan}$

and from the EDS elemental composition, as to 1:6 of metallic content to PES.

RESULTS

The optimal ratio between the cross-section areas of the thermocouple legs was computed according to optimisation relation 1 and presented in table 4.

Since the T-type F-TEG requires a very high ratio between the cross-sectional area of the two legs (1:50), with no practical feasibility, we have drawn our attention towards the J-type F-TEG with a ratio of (2.8:1).

In order to technically meet the demand of the optimisation ratio (2.8:1) between the Stainless Steel and the Constantan F-TEG legs, a new prototype was manufactured with 3 Stainless steel threads in parallel and a single one Constantan thread, keeping the same design pattern and the same electric/thermic conductivities of the legs. The optimisation relation makes sense when the sum of the cross-sectional area is kept constant: $A_n + A_p = const.$ The new J-type F-TEG is displayed in figure 6.

Fig. 6. Optimised J-type F-TEG with Stainless steel: Constantan threads ratio 3:1
Electric circuit Ohmic resistance: 300 Ω

The optimised J-type F-TEG prototype has an internal electric resistance of 300 Ω, when compared to the initial prototype with 375 Ω. The two J-type F-TEG prototypes were once again measured via the experimental setup, consisting of a hotplate with variable temperature (hot junction), an ice bath (cold junction), an IR thermometer and a voltmeter.

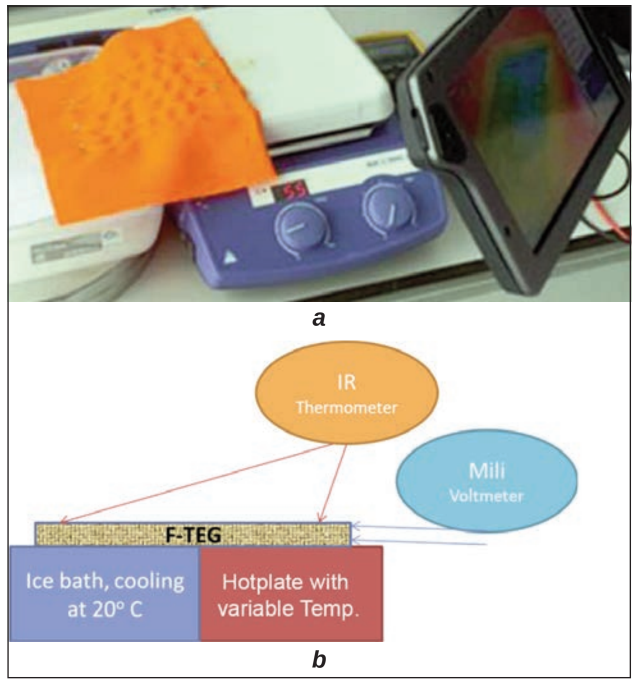

Fig. 7. Graphical representation of: *a* – image of the experimental setup; *b* – scheme of the experimental setup

Figure 7 presents the experimental setup, and figure 8 presents the achieved results.

The linear increase of the generated voltage with the temperature difference is the first good result of the J-type F-TEGs.

DISCUSSION

Two linear trend lines were added to the voltage as a function of temperature difference, with the slope increasing from 0.0646 for the initial prototype to 0.0832 for the optimised prototype. A maximum of 6.6 mV was harvested at a 70°C temperature difference by the optimised F-TEG. Once again, the optimisation relation makes sense, single if $A_n + A_p = const.$ One statistical indicator was computed to evidence the fulfilment of the optimisation condition (1), considering the constant thermic and electric conductivities of the applied threads (table 5).

A smaller statistical indicator shows a better fulfilment of the analytic condition. Whereas in the case of the initial F-TEG the indicator is 1.14, in the case of the optimised F-TEG this indicator is 0.27, showing a better fulfilment of the optimisation condition. The

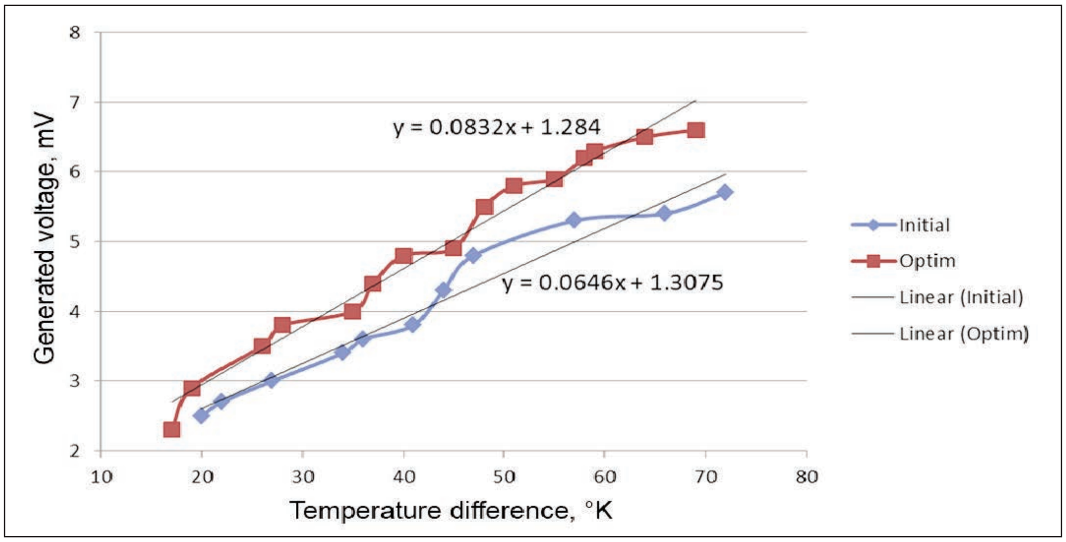

Fig. 8. Graph of the achieved voltages with the initial and the optimised J-type F-TEG

Table 5

STATISTICAL INDICATOR COMPUTED FOR THE INITIAL AND OPTIMIZED F-TEG

Optimization relation		Optimized F-TEG	Initial F-TEG
Electric and thermic conductivities	$\sqrt{\frac{\sigma_p\lambda_p}{\sigma_n\lambda_n}}(= X_{norm})$	0.36	0.36
Cross-section area	$\frac{A_n}{A_p}(= X)$	0.26	0.77
Statistical indicator	$\frac{\lvert X - X_{norm}\rvert}{X_{norm}}$	0.27	1.14

optimised prototype harvested better voltages than the initial prototype by designing the cross-section area of the legs according to relation 1.

CONCLUSIONS

The paper tackled the design optimisation of a flexible thermoelectric generator type J, based on an analytic relation. Both the initial and the optimised prototypes were manufactured and measured, with an increase of the slope between temperature and voltage from 0.0646 to 0.0832, proving the better voltage harvesting values for the optimised prototype. Stainless steel and Constantan threads were used for the J-type F-TEG, while considering the cross-sectional area within the optimisation process. Future optimisation work will follow the integration of boost converters for balancing the ratio between current and voltage, as well as applying larger dimensions of legs onto the wearable system, to achieve a voltage of 1.8 V, typically needed to supply most sensors and microcontrollers used for wearable systems.

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Authors:

ION RAZVAN RADULESCU, DOINA TOMA, ELENA PERDUM, ADRIAN MARIN, LAURENTIU DINCA, RALUCA MARIA AILENI

National Research and Development Institute for Textiles and Leather,
16 Lucretiu Patrascanu Street, 030508, Bucharest, Romania
e-mail: office@incdtp.ro

Corresponding author:

ION RAZVAN RADULESCU
e-mail: razvan.radulescu@incdtp.ro