NUKLEONIKA 2020;65(1):31–35
doi: 10.2478/nuka-2020-0004

ORIGINAL PAPER

Efficiency calculation and comparison of fluidic and solid-body power sources using corpuscular radiation

Tomasz A. Miś

Abstract. Research done on a set of simple fluidic (with the fluid used as the ionized medium being air under atmospheric pressure) alphavoltaic cells – small ionizing reactors or "nuclear batteries", designed in the Faculty of Power and Aerospace Engineering of Warsaw University of Technology, Poland – has shown the possibility of accumulation of usable amount of electric charge. Two simple methods are proposed to describe the fluidic alphavoltaic cells in terms of their efficiency. The results of these methods are presented and compared with the efficiencies of other contemporary types of solid-body (semiconductor junction-based) alpha- and betavoltaic cells. The comparison showed that despite the far-reaching simplicity in design, the designed fluidic cells are still more efficient than some of the solid-body devices that use the alpha type of decay.

Keywords: Alphavoltaic • Nuclear battery • Radioactivity • Ionizing reactor • Plutonium-239 • Americium-241

Introduction

The effect of differentiation of the electric charge/electric potential on the equipment exposed to corpuscular radiation has been reported in the very early developmental stages of the science of radioactivity of materials [1]. This effect mostly served as a simple way of indication of a material's radioactivity; later, multiple experiments, conducted in the 21st century, showed that usable electric potential difference (voltage) and power could be obtained with non-fission nuclear devices, namely, the corpuscular radiation power sources, or simply "nuclear batteries", among which two main types could be distinguished – alphavoltaics and betavoltaics, using, respectively, alpha and beta radiations. In 2017, a series of experiments carried out in the Faculty of Power and Aerospace Engineering of the Warsaw University of Technology, Poland, showed that a possibly usable amount of electric energy could be obtained using a very simple cell composed of a radiation source, a two-dimensional electrode, and air under atmospheric pressure as an ionized medium [2]. To be effectively compared with other nuclear batteries, using different ionizing mediums (various solid substances and semiconductors instead of a fluid) [3], two methods for describing the efficiency of such fluidic alphavoltaic cells are presented, and the final efficiency is compared with that of some other types of nuclear batteries.

T. A. Miś
Division of Radiocommunication
Faculty of Electronics and Information Technology
Institute of Radioelectronics and Multimedia Technology
Warsaw University of Technology
Nowowiejska 15/19, 00-665 Warsaw, Poland
E-mail: t.mis@ire.pw.edu.pl

Received: 28 August 2018
Accepted: 16 January 2020

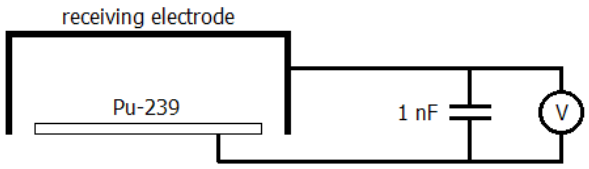

Fig. 1. Principal schematic representation of the alphavoltaic cell experiment conducted in 2017 with Pu-239.

Experiments on fluidic alphavoltaic cells

As described by Miś in 2017 [2], a simple fluidic alphavoltaic cell could be set up as a radiation source, acting as the primary electrode (in this case, two circular Pu-239 samples, 50 mm and 25 mm in diameter, producing 34 050 Bq and 20 961 Bq, respectively), covered with a cylindrical receiving (secondary) electrode (see Fig. 1); these are all put in an enclosed glass compartment for separation from the external ions, which could affect the ionization of the electrodes. The device charged a 1 nF ceramic capacitor via copper cables.

The theoretical formula describing the electric charge accumulation (the augmentation of electric potential difference) can be expressed as the following simple linear function [2]:

$$U_T(t) = \frac{A}{C}\left(Q_\alpha + \frac{R_{15}}{R_\alpha} k Q_j\right) \cdot t \tag{1}$$

where U_T is the voltage in volts, A is the activity in becquerels, C is the charged capacitance in Faradays, Q_α is the electric charge of an alpha particle in coulombs, Q_j is the electric charge of a pair of ions created by the passage of the particle in the ionizing medium in coulombs, R_{15} is the maximum radius of the particle in the experiment (15 mm), determined by the design of the ionization chamber, R_α is the maximum range of an alpha particle (38.2 mm) for Pu-239, k is the number of ions created on the particle's path (for Pu-239 and maximum particle range: 159 824 [2]) and t is the time measured in seconds. This formula describes the perfect phenomena – with 100% efficiency.

The real functions of the augmentation of electric potential difference – according to the experiments [2] – can be described by the following logarithmic formula:

$$U_R(t) = \frac{1}{b}\ln(1 + abt) \tag{2}$$

where a and b are real, experimentally obtained and non-zero numbers and U_R is the voltage in millivolts. Formulas (1) and (2) are plotted in Figs. 2 and 3 – the huge difference between the theoretical and real (measured) models is mainly due to poor particle recuperation on the surfaces of the electrodes and the high degree of in-medium recuperation of the freshly created ions [2].

Differential method for calculation of fluidic alphavoltaic cell's efficiency

As can be noticed in Figs. 2 and 3, the huge difference between the described functions clearly denotes a very low efficiency of the experimental fluidic alphavoltaic cell – as the theoretical model states that all created particles are recuperated, therefore rendering its efficiency 100%. The theoretical and perfect model of its functioning uses a simple linear function, the derivative of which is a numerical value, which includes the activity of the radiating material, the number of ions created in a single particle passage and the charged capacitance. This value, containing the parameters vital for a certain alphavoltaic cell, could be compared with the respective derivatives of the real functions describing the working of a fluidic alphavoltaic cell.

The first derivative of the logarithmic formula (2) is simply described as follows:

$$\frac{\partial U(t)}{\partial t} \quad \overline{abt +} \tag{3}$$

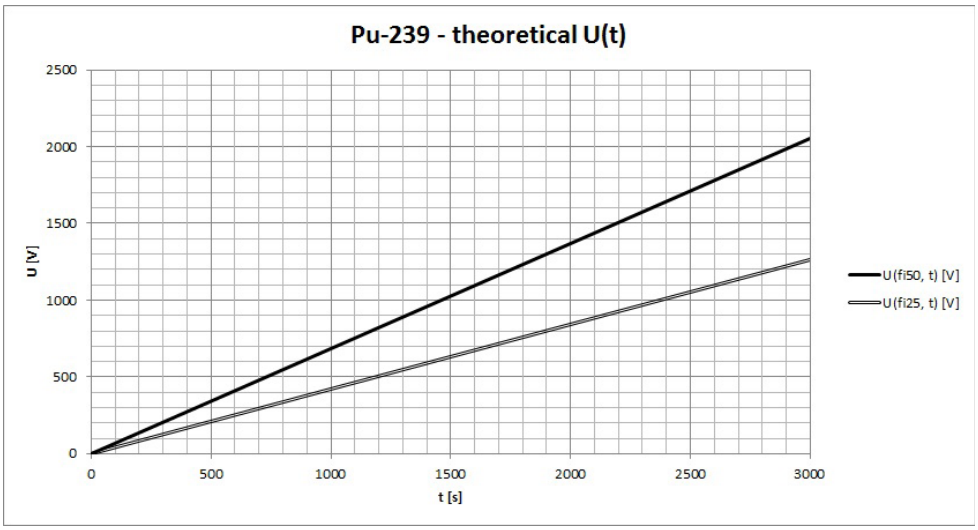

Fig. 2. Theoretical electric potential difference against time for a fluidic air alphavoltaic cell [2]. Two different materials – aluminium and copper – were used for the secondary electrode. Notations 'fi25' and 'fi50' indicate the diameters of the Pu-239 samples for which the curves were created.

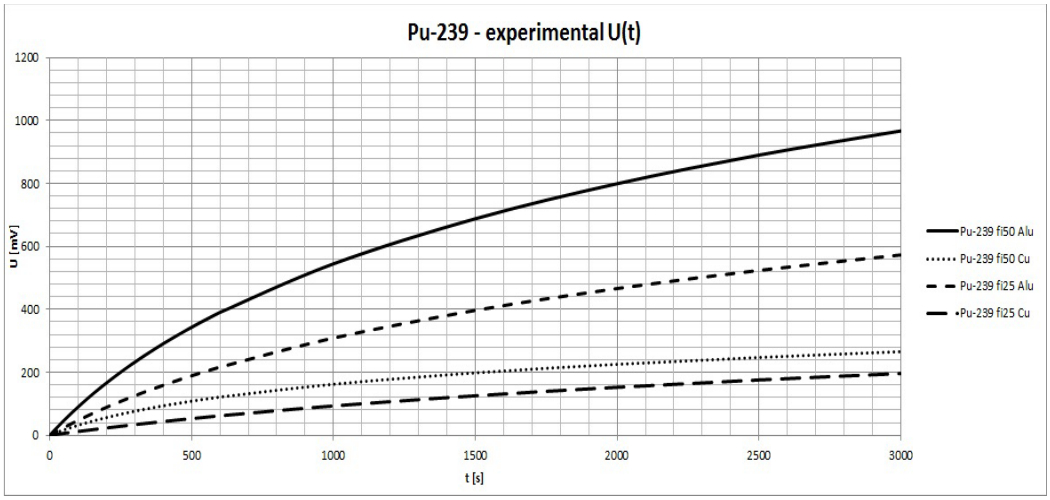

Fig. 3. Experimental functions of the electric potential difference against time for a fluidic air alphavoltaic cell [2].

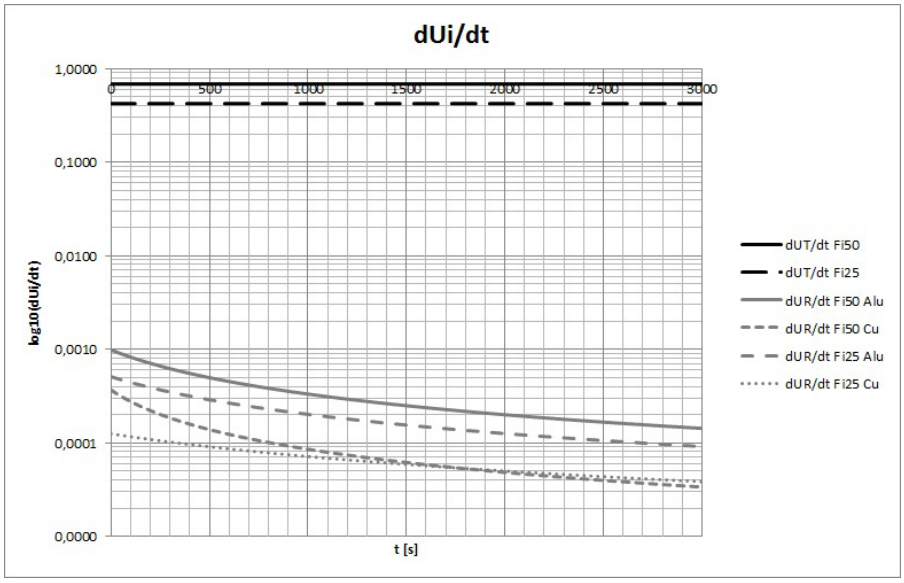

Fig. 4. The derivatives of the $U_R(t)$ and $U_T(t)$ functions for different sizes of Pu-239 samples and different cathode materials.

The derivatives (time-dependent) for the respective real functions (Fig. 3) are shown in Fig. 4. The two uppermost lines are constants representing the derivatives of the theoretical functions (Fig. 2). Using a simple proportional transformation between the real and theoretical functions, assuming that the theoretical function bears 100% efficiency, weget the following expression:

$$\eta_{\text{diff}} = \frac{\frac{\partial U_R(t)}{\partial t}}{\frac{\partial U_T(t)}{\partial t}} \cdot 100\% \tag{4}$$

Formula (4) is plotted in Fig. 5; it represents the efficiencies for the experimental cells described by Miś [2]. Their time-dependency can be explained by the fact that the cells (their ionized mediums) actually saturate with electric charge in time; the growth in the cells' electric potential difference slowly decelerates in time – less pairs of ions are being transformed into useful electric energy. As the circuit has no load in it (no receiving resistance, a capacitance only), the created electric charge is not dissipated; therefore, the cell saturates and its efficiency decreases.

Direct method of calculating a fluidic alphavoltaic cell's efficiency

A simpler, direct method of checking the fluidic alphavoltaic cell's efficiency is simply omitting the derivatives in formula (4) and substituting them with the values of the functions $U_T(t)$ and $U_R(t)$. This enables comparison of the theoretical functions with the real results from the experiments; the theoretical functions are no longer represented as numerical variables. Figure 6 shows the efficiencies calculated using this method. Comparison with the previous method clearly shows that the maximum values of the efficiencies (for a non-saturated cell – close to the beginning of its work) are nearly identical, which makes both methods useful for determining the initial efficiency of a specific cell for further analysis; yet, the intersections of the functions change.

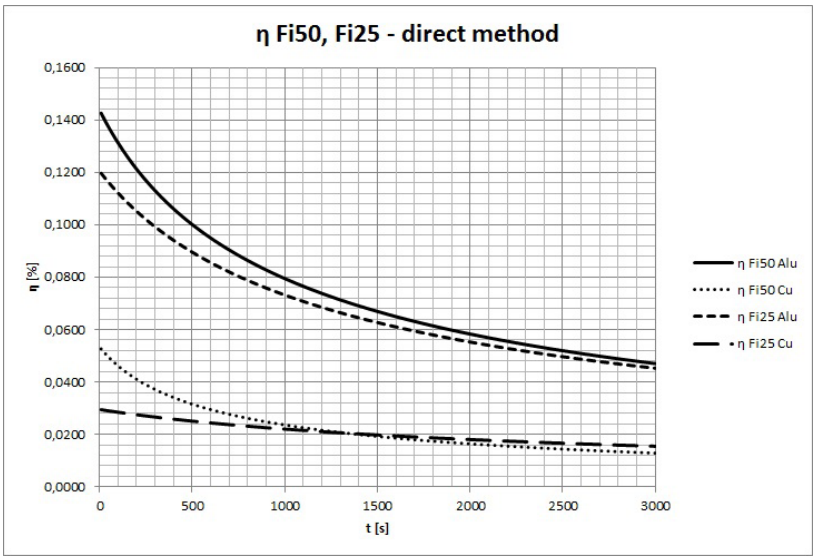

Fig. 5. Efficiency of the experimental fluidic alphavoltaic cells, obtained using the differential method.

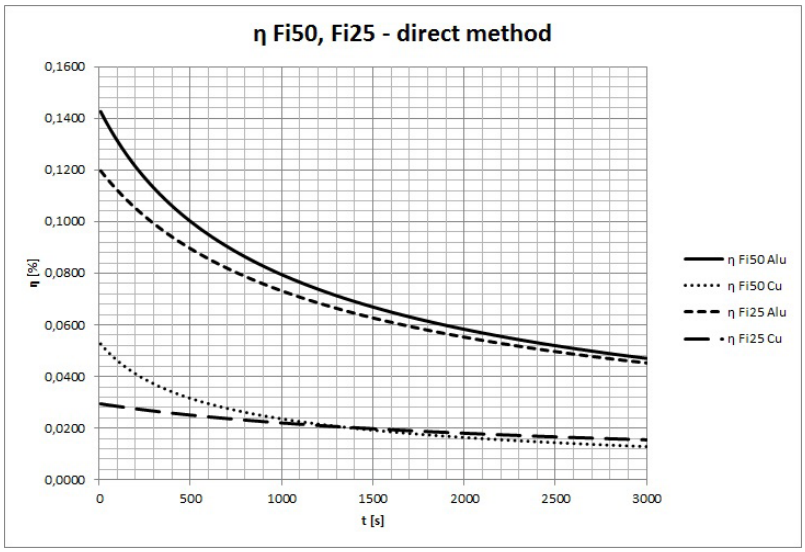

Fig. 6. Experimental determination of efficiency of fluidic alphavoltaic cells using the direct method.

Very early-occurring intersections in the differential method show that smaller cells (shorter distances between the electrodes) may reach higher efficiencies than their bigger versions for certain metals used for the secondary electrodes (clearly visible for the sets of functions for copper, less visible – but still occurring – for the sets of functions for aluminium); yet, this would need proving in further research and experiments. As the differential method of efficiency calculation uses the first-degree derivatives of the functions, its results may be used for the indication of rapid efficiency loss/saturation of a specific alphavoltaic cell: in this case, the quickest saturation process is observed in the case of the 50-mm-diameter sample with copper cathode (the alphavoltaic cell is initially efficient, but the efficiency rapidly drops – more rapidly than for the aluminium cathodes). The same process for the smaller sample with copper cathode is less detectable, as the cell had been less efficient already.

Comparison with other power sources using corpuscular radiation

As a single passage of an alpha particle in an easily-ionized medium (gaseous medium – i.e., the air) creates – for the discussed Pu-239 case – up to ~160 000 ion-electron pairs [1], a simple fluidic alphavoltaic cell is nearly as efficient in terms of ionization as solid-state betavoltaic cells, which – for a cell using e.g. Sr-90 – reach up to 200 000 slow electrons in a single high-energy electron passage in a solid state medium such as germanium or silicon [4]. This efficiency can be increased by the modification of the ionized fluid and/or the device's electrodes, yet it is still of high level for a very simple, atmospheric cell, not using any complicated semiconductor junctions or other rare/precisely manufactured materials. As many new experiments and models of solid-body alpha- and betavoltaic cells have been described, built and tested since 1962 [3, 5], a comparison of the fluidic alphavoltaic

Table 1. Research and experiments with nuclear batteries showing efficiency <1% [2, 3]

Authors	Isotope	Decay type	*E* [MeV]	*A* [Bq]	*h*	Annotations
Min Lu, Guo-guang Zhang	Ni-63	beta	2.137	1 295 000	0.32	*A* [Bq/mm^2]
Flicker, Loferski, Elleman	Pm-147	beta	0.225	2.331E+11	0.40	–
Flicker, Loferski, Elleman	Pm-147	beta	0.225	2.516E+11	0.77	–
Cress, Landi *et al*. (2006)	Am-241	alpha	5.638	41 440	0.04	–
Sychov, Kavetsky, Yakubova	Pu-238	alpha	5.593	1.11E+10	0.11	–
Qiao, Chen, Ren, Yuan (2011)	Am-241	alpha	5.638	666 000	0.10	*A* [Bq/cm^2]
Miś (2017)	Pu-239	alpha	5.245	34 050	0.14	*h* max.
Miś (2017)	Pu-239	alpha	5.245	20 961	0.12	*h* max.

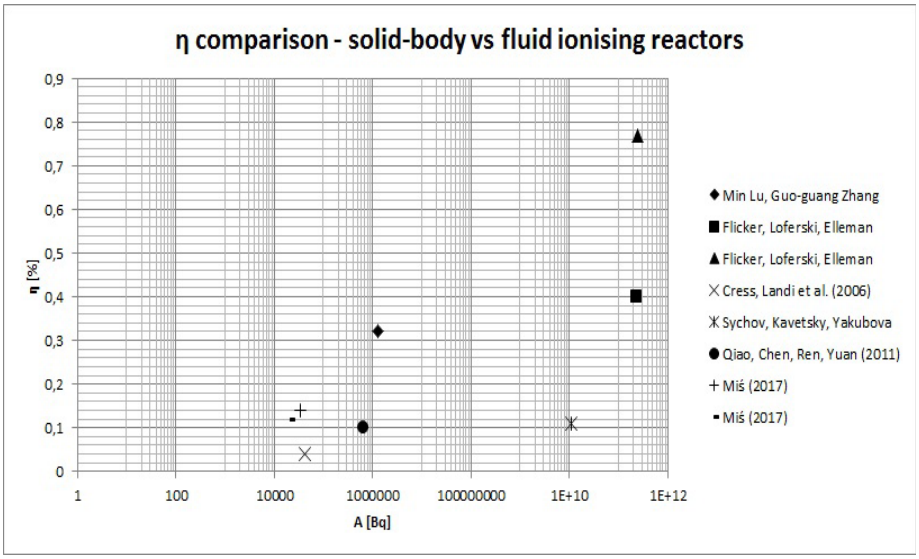

Fig. 7. Efficiency comparison of results obtained from the research and experiments on nuclear batteries showing <1% efficiency [2, 3].

experiments with this research is to be presented. The efficiencies of the solid-body cells vary due to their different designs and the activities of the chosen isotopes [3]; to make the comparison clear, the experiments presenting efficiencies <1% were chosen. Table 1 presents the experiments and their basic data (isotopes, type of decay, particle energies and efficiencies); Fig. 7 compares these experiments according to their efficiency in percentage vs. activity in becquerels.

Conclusions

Relatively low efficiencies <1% are reached by certain alphavoltaics and betavoltaics. The betavoltaics, herein using mainly Pm-147, have nearly 25 times lower particle energy, which results in the need for using high activities of the radiation sources, resulting in the shorter half-life of the isotope and many difficulties in its procurement. More convenient alphavoltaics, using for example easily trade-obtainable Am-241, vary in efficiency; however, all of them (all the solid-body special junction versions) have efficiencies less than that of the fluidic versions – despite the fact that the fluidic versions were very primitive in design and operation. This opens up more opportunities for the fluidic alphavoltaics, as future improvements in their electrode designs, materials used and fluids utilized as ionization mediums may greatly increase their efficiency without a very significant increase in manufacturing costs, making them more obtainable by dedicated (research/industry), or even individual, consumers.

ORCID

Tomasz A. Miś http://orcid.org/0000-0002-3921-6875

References

1. Dorabialska, A. (1952). *Natural radioactivity of chemical components*. Warsaw: PZWS. (in Polish).
2. Miś, T. A. (2017). *The design and analysis of an alphavoltaic reactor for the use in astronautics*. Warsaw: Faculty of Power and Aerospace Engineering, Warsaw University of Technology.
3. Prelas, M. A., Weaver, C. J., Watterman, M., Lukosi, E., Schott, R., & Wisniewski, D. (2014). A review of nuclear batteries. *Prog. Nucl. Energy*, *75*, 117–148. DOI: 10.1016/j.pnucene.2014.04.007.
4. Łapiński, M. (1962). *Teleelectrical measurements. Auxiliary measuring equipment*. Warsaw: Wydawnictwa Komunikacji i Łączności. (in Polish).
5. US Army Research Laboratory. (2017). *Design of alpha-voltaic power source using americium-241 and diamond with a power density of 10 mW/cm^3*. Adelphi: US Army Research Laboratory.