BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 62 (66), Numărul 3, 2016
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

EXPERIMENTAL ANALYSIS AND FEM SIMULATION OF A ELECTRICALLY CONTROLLABLE THERMAL STATE ACTUATOR

BY

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Received: June 1, 2016
Accepted for publication: June 30, 2016

Abstract. The paper presents the study and operating control of a thermal state actuator (TSA). The paper proposes a practical approach for TSA displacement control using a PLC technology. Proposed thermal state actuator has two essential features: low linear displacement and high strength. The thermal state actuator is a dynamic system that can be investigated through transfer functions. Also, the step response of the TSA was analyzed, the transfer functions and time constants values were identified for different quantities of volatile liquid. The results of the evaluation through finite element method are presented.

Key words: volatile liquid; transfer function; response time; linear displacement; thermoelectric element.

1. Introduction

There are many applications that use a wide variety of linear actuators offering reduced displacements and developing high forces. In general, these

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actuators use as active element a flexible chamber, into which are inserted certain amounts of liquids or gases to obtain mechanical work. These types of actuators have been implemented in various applications such as robotics, domotics etc. Thus, have been identified studies in connection with these types of actuators that use hydrogen, with applications in regenerative medicine (Shuichi *et al*., 2008). Others are successfully used in vascular surgery (Gagarina *et al*., 2001), robotics (Kawamura & Hayakawa, 1994), ophthalmology (Li *et al*., 2010), pneumatic micro-drives (Yang *et al*., 1997; Gorisson *et al*., 2013).

The experimental study based on transfer functions has imposed the realization of appropriate experimental stands, able to reflect the characteristics and dynamic performance of the test object and concretized in: delay, transient regime speed and the coefficient of amplification. The TSA can be used in applications requiring small displacements and high forces.

2. Operating Principle and Mathematical Model of the TSA

The thermal state actuator (Fig. 1) is made from a bellows-type flexible chamber, partially filled with a volatile liquid and thermally excited with a battery of thermoelectric elements. The flexible chamber is under the action of the heat provided by the thermoelectric element, supplied with a positive or negative electrical polarity from a DC power source. Thus, the TSA will have an elongation or contraction, knowing that the dynamic behavior of the actuator is linked to the vaporization and condensation phenomenon.

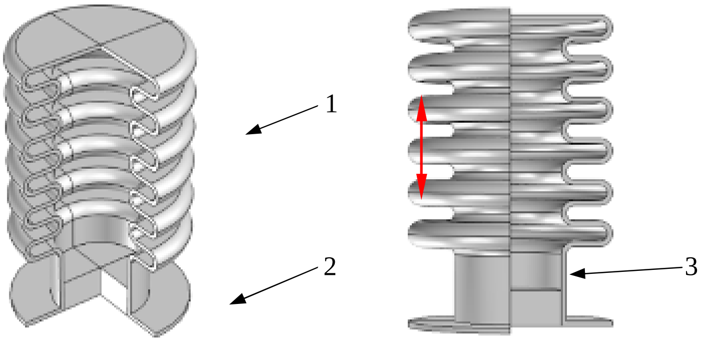


Fig. 1 – TSA 3D view: 1 – flexible chamber; 2 – heat source contact surface; 3 – volatile liquid chamber.

To understand the operation of the TSA, the two phenomena are presented. Vaporization is achieved by leaving the liquid by some of its molecules. To leave the liquid mass, a molecule must go beyond by superficial layer of the liquid where must defeat the existing attraction of the remaining liquid. This is possible only if the kinetic energy of the molecule is large enough. If the number of molecules leaving the liquid exceeds those entering into liquid, vaporization occurs.

The TSA operation is based on the following laws of vaporization, in a gaseous atmosphere: the vaporization in a gaseous atmosphere is slow and not instantaneous and the maximum vapor pressure in the gaseous atmosphere is the same as if the vapor would occupy the same volume. The TSA operation is dependent by the nature of the used volatile liquid, the ambient temperature, the variation law of the applied step signal and the geometry of the flexible chamber.

To highlight the evolution of the factors and physical processes mentioned above, were designed some test stands with a private character. The most representative experimental test bench (Ungureanu *et al.*, 2015) is shown in Fig. 2. The experimental stand is close to the real shape of the designed TSA, consisting of a chamber, partially flexible, carried out by means of a bellows mounted in the extension of a glass transparent cylinder, which includes a quantity of volatile liquid which is thermally excited from the exterior by means of a thermoelectric element.

The evolution of the temperature within the cylindrical chamber was monitored using a EasIR$^{\text{TM}}$-4 infrared camera thermal imager (Olariu *et al.*, 2016; Irimia & Bobric, 2015). After a detailed analysis of the experimental results obtained with the infrared camera (Fig. 2), it was concluded that the amount of saturated vapor pressure depends only on the nature of the considered volatile liquid and temperature. As a result, the saturated vapor pressure value does not depend on the liquid mass and vapor mass ratio which is in equilibrium with the liquid.

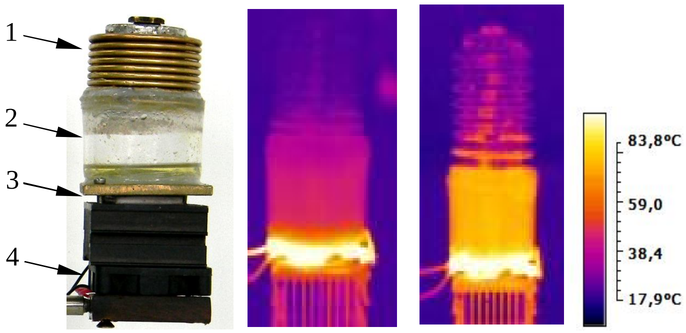


Fig. 2 – The evolution of the temperature within the TSA cylindrical chamber. Thermal maps at the beginning and at the end of the vaporization process: 1 – bellows-type flexible chamber; 2 – glass cylinder; 3 – thermoelectric element; 4 – cooling system.

Thus, if we try to reduce the available volume to the saturated vapors is found that, some of the vapors condense until the remaining vapor pressure is equal to the saturated vapor pressure at operating temperature. So, saturated vapor pressure is the maximum pressure that can exert a given volatile liquid vapors in contact with the liquid from which they formed. The saturated vapor pressure increases with temperature.

Any technical dynamic system is characterized by an input value $x_i(t)$

and an output value $x_e(t)$. The situation where $x_e(t)$ is constant is called stationary regime of the process. The period between the two stationary regimes represents transient regime of the process characterized by duration, time constant and dead time. In order to identify the processes also for the study of the transient regime, one method is to determine the transfer functions that represent the time variation of the output value of transient process that occurs due to a step signal applied to the input. In determining the transfer functions, the signal value has to be about 5,...,15% of the maximum possible input value for given regime. The end of the transient regime is marked by the achievement of steady state output value of the process.

The TSA mathematical model identification involves the following parameters: delay (τ), time constant, (T) and the coefficient of amplification (k). The transfer functions identification was made on the basis of process equations, PT_1 and PT_1T_m respectively, as follows:

$$T\frac{\mathrm{d}x(t)}{\mathrm{d}t}+x_e(t)=kx_i(t), \tag{1}$$

$$T\frac{\mathrm{d}x(t)}{\mathrm{d}t}+x_e(t)=kx_i(t-T_m), \tag{2}$$

where: T_m represent the dead-time of the process and t – transient time.

The eqs. (1) and (2) indicate processes having the following step responses:

$$x_e(t)=k(1-\mathrm{e}^{-\mathrm{t/T}}), \tag{3}$$

$$x_e(t)=k(1-\mathrm{e}^{-\mathrm{t/T}})(T-T_m). \tag{4}$$

The coefficient of amplification represents the output value variation in the transition from initial permanent state in the final permanent state, relative to the signal unit input:

$$k=\frac{x_e(0)-x_e(\infty)}{\Delta x_m}, \tag{5}$$

where: $x_e(0)$ and $x_e(\infty)$ are output values in initial and final permanent regime and Δx_m is input signal value, in % of execution element displacement.

3. TSA Displacement Control

The solution adopted by the authors for TSA controls is with a XC101 PLC. The TSA experimental test bench is illustrated in Fig. 3 and the circuit block diagram is presented in Fig. 4. The TSA displacement is measured with linear potentiometer whose voltage is read by PLC with an analog input

(%IW2). The PLC controls two relays which allow powering a thermoelectric element with DC voltage in both polarities. This experimental test bench was designed to measure dynamic response for the TSA. The relay block is used to ensure the reversal of the DC current through the thermoelectric element in order to obtain the two situations in TSA operation, drive and return respectively.

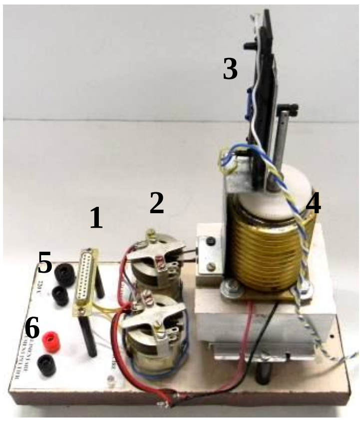


Fig. 3 – Experimental test bench for the TSA: 1 – XC101 PLC interface connections; 2 – relays for thermoelectric element powering; 3 – linear potentiometer; 4 – flexible chamber bellows-type; 5 – cooling/heating set up; 6 – thermoelectric element supply terminals.

To study TSA dynamic response we need to measure the displacement and for that we choose a resistive sensor. The software application for PLC is made using XSoft CoDeSys program. The CoDeSys allows to make a software application in different programming languages as follow: *Instruction list*, *Structured text*, *Ladder diagram* and *Function block diagram*. A software application can be developed in more subroutines.

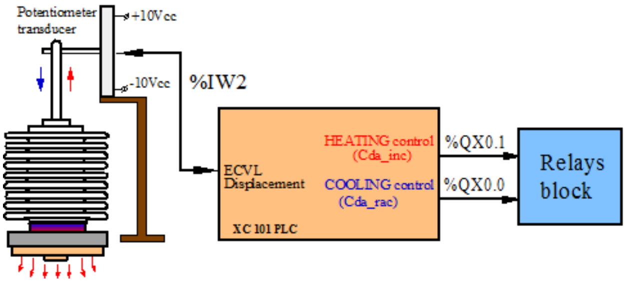


Fig. 4 – Block diagram for TSA control.

The software application is made in two subroutines: the main program in *Ladder diagram* (Fig. 5) and a subroutine in *Structured text*, illustrated in

Fig. 6, used to control the block relays for powering the thermoelectric element with proper polarities, according with TSA position.

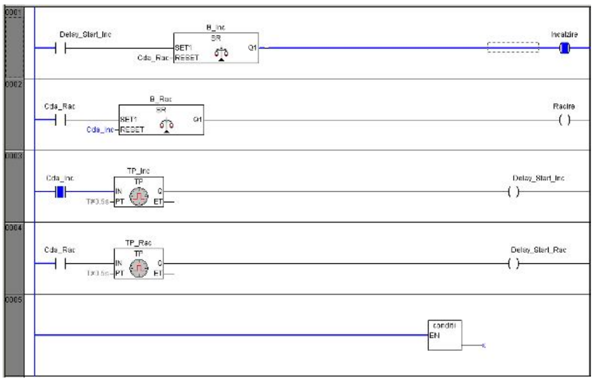
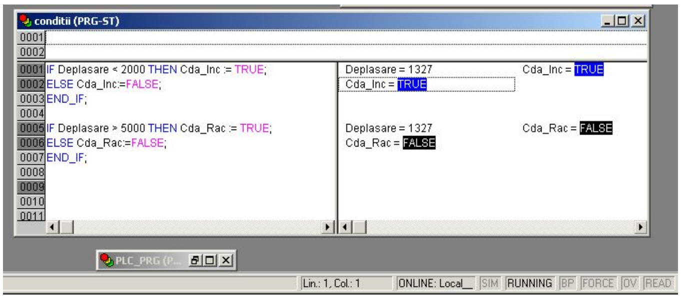


Fig. 5 – The main program used for TSA operation control.



```
IF Deplasare < 2000 THEN Cda_Inc := TRUE;
ELSE Cda_Inc:=FALSE;
END_IF;

IF Deplasare > 5000 THEN Cda_Rac := TRUE;
ELSE Cda_Rac:=FALSE;
END_IF;
```

```
Deplasare = 1327          Cda_Inc = TRUE
Cda_Inc = TRUE


Deplasare = 1327          Cda_Rac = FALSE
Cda_Rac = FALSE
```

Fig. 6 – The program subroutine used for TSA displacement control.

4. TSA Experimental Results

Based on experimental data were drawn the TSA characteristics at no-load. For the interpretation of the results was performed a comparative analysis of experimental and theoretical characteristics after the identification of the transfer functions with the previous eqs. 1,...,5. It was considered for TSA a step signal by 15% of the rated value of the thermoelectric element (I_n = 3 A). To study the dynamic regime an experimental test bench was conducted (Fig. 7). To highlight the influence the liquid volatility used to fill the bellows were used two different volatile liquid: petroleum ether and ethyl ether. For each of the two volatile liquid were set two different amounts into the flexible chamber: 2 ml and 10 ml.

Thus, the experimental and theoretical transfer functions were obtained, for each quantity of each type of volatile liquid. In Fig. 8 are presented the $\Delta x = f(t)$ characteristics in the case of using petroleum ether. The $\Delta x = f(i)$ characteristics for diethyl ether are presented in Fig. 9.

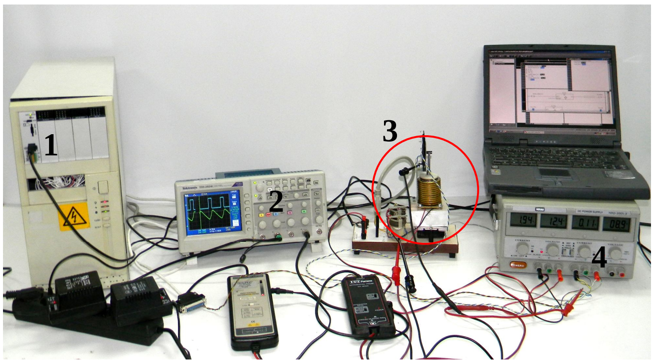
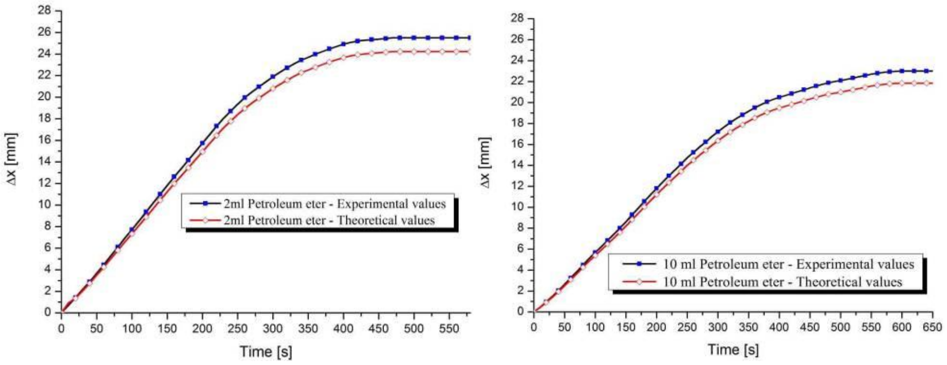


Fig. 7 – Experimental test bench for TSA transient regime analysis:
1 – XC101 PLC; 2 – Tektronix TDS 2024C oscilloscope;
3 – TSA control block; 4 – DC power source.

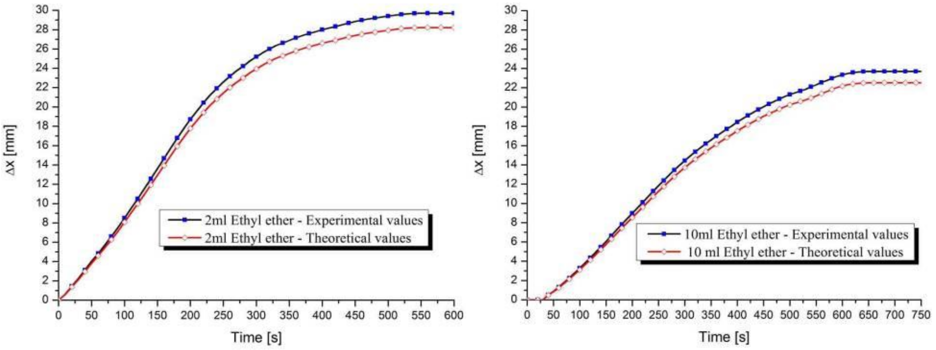
Thus, the mathematical model of the TSA, thermally excited with a thermoelectric element is represented by an element of PT_1 type, according to general systems theory. The equations processes, transfer functions and the time constants values for the applied input step signal are presented in Table 1.

In the experiment was highlighted the actuator operation and its displacement by connecting an oscilloscope to the resistive sensor and DC power source of the thermoelectric element. The image that illustrates the thermoelectric element activation and the displacement made by TSA actuator, is presented in Fig. 10. This experiment was initiated for an amount of 2 ml petroleum ether and successively for 1 A and 2.2 A thermoelectric element input values.



a *b*

Fig. 8 – Time variation of the TSA displacement: 2 ml (*a*)
and 10 ml (*b*) – petroleum ether.



a *b*

Fig. 9 – Time variation of the TSA displacement: 2 ml (a) and 10 ml (b) - ethyl ether.

Table 1

TSA Process Equations

Process equation	**Transfer function expression**
2 ml Ethyl ether, Time constants: T = 211.26 s; t = 633.78 s ***Process type: PT$_1$***	
$211.26\frac{\mathrm{d}x_e(t)}{\mathrm{d}t}+x_e(t)=29.8x_i(t)$	$x_e(t)=29.8(1-\mathrm{e}^{-t/211.26})$
10 ml Ethyl ether, Time constants: T = 289.29 s; t = 856.1 s ***Process type: PT$_1$***	
$282.29\frac{\mathrm{d}x_e(t)}{\mathrm{d}t}+x_e(t)=23.7x_i(t)$	$x_e(t)=23.7(1-\mathrm{e}^{-t/289.29})$
2 ml Petroleum ether, Time constants: T = 205.02 s; t = 615.06 s ***Process type: PT$_1$***	
$205.02\frac{\mathrm{d}x_e(t)}{\mathrm{d}t}+x_e(t)=25.5x_i(t)$	$x_e(t)=25.5(1-\mathrm{e}^{-t/205.02})$
10 ml Petroleum ether, Time constants: T = 245 s; t = 735 s ***Process type: PT$_1$***	
$245\frac{\mathrm{d}x_e(t)}{\mathrm{d}t}+x_e(t)=23x_i(t)$	$x_e(t)=23(1-\mathrm{e}^{-t/245})$

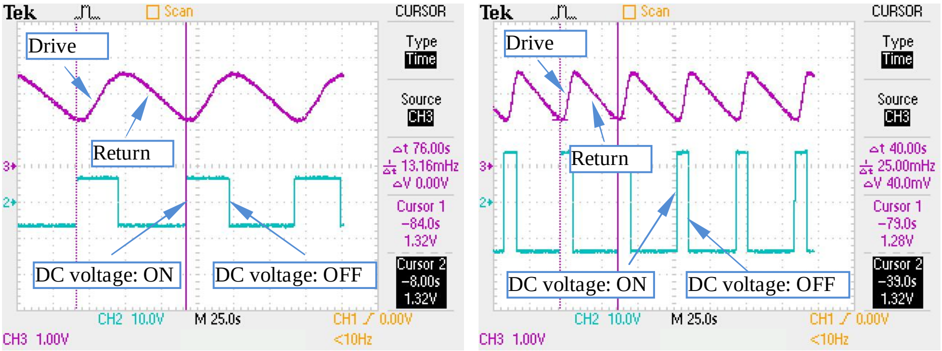


Fig. 10 – The TSA displacement for 2 ml of petroleum ether for $I_n = 1$ A and $I_n = 2.2$ A. Heating - Cooling cycle period: $\Delta t = 76$ s and $\Delta t = 40$ s respectively.

Also, through the use of the resistive transducer can be determined the transitory regime and the transfer functions respectively of the thermal state actuator. A good example is the transfer function obtained for 2 ml petroleum ether (Fig. 11).

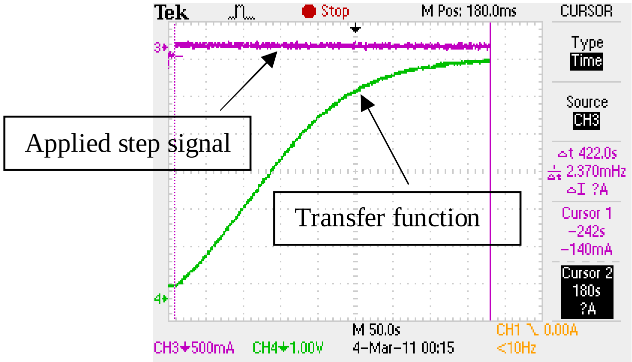


Fig. 11 – The transfer function for 2 ml petroleum ether, obtained with resistive transducer.

4. TSA FEM Simulation

For modeling the TSA behavior, the element finite method was used (Tanta *et al*., 2016). The application made in Comsol was defined as a problem of thermal stress that combines mechanics of solids with heat transfer and includes thermal effects due to temperature change. Parameters were defined and presented in Table 2. Have been defined the materials for the bellows and his cap (beryllium copper), to the liquid (petroleum ether) and to the vapors.

Table 2
TSA Parameters

Quantity	Value	Description
Sylphon wall thickness	1.3×10^{-4}	t_w, [m]
Sylphon bottom mounting-end height	0.007	h_b, [m]
Sylphon to mounting-end height	0.003	h_t, [m]
Sylphon curvature radius	8.75×10^{-4}	r_c, [m]
Sylphon inner radius	0.0173	R_i, [m]
Sylphon outer radius	0.025	R_o, [m]
Sylphon number of curls	12	n
Inner width of a sylphon curl	0.00175	a, [m]
Sylphon length	0.05	L, [m]
Reference temperature	273.15	T_0, [K]
Volatile liquid quantity	10	petroleum ether, [ml]

The coupling between the two basic problems occurs in areas where the temperature of *Heat transfer* interface acts as a thermal load for *Solid mechanics* interface, causing the thermal expansion.

The *Thermal stress* interface provides the equations and characteristics of solids mechanics and answers in movements establishment. Also, the free borders, the borders without heat loss, the borders through that exist heat exchange have been defined. It was considered that the bellows basis is a border without heat loss.

The initial temperature, the same in all areas was considered as ambient temperature, 293.15 K. The bellows base was defined as the border with the displacement constraints. The mesh was carried out with triangular elements, the network being finer to the outside of the bellows, particularly in the corrugations (Fig. 12).

The maps of the temperature and elongation of the TSA are presented in Figs. 13 and 14. Hereafter, the simulation results will be presented when the TSA is heated by a thermoelectric element.

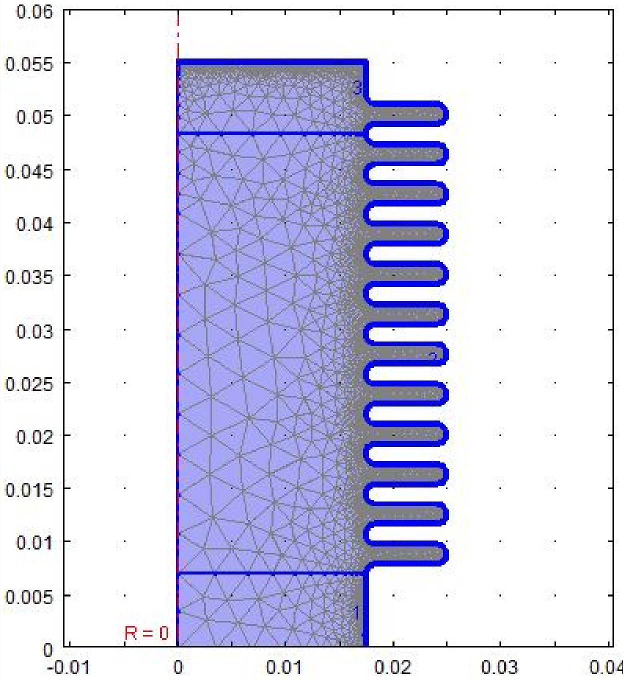
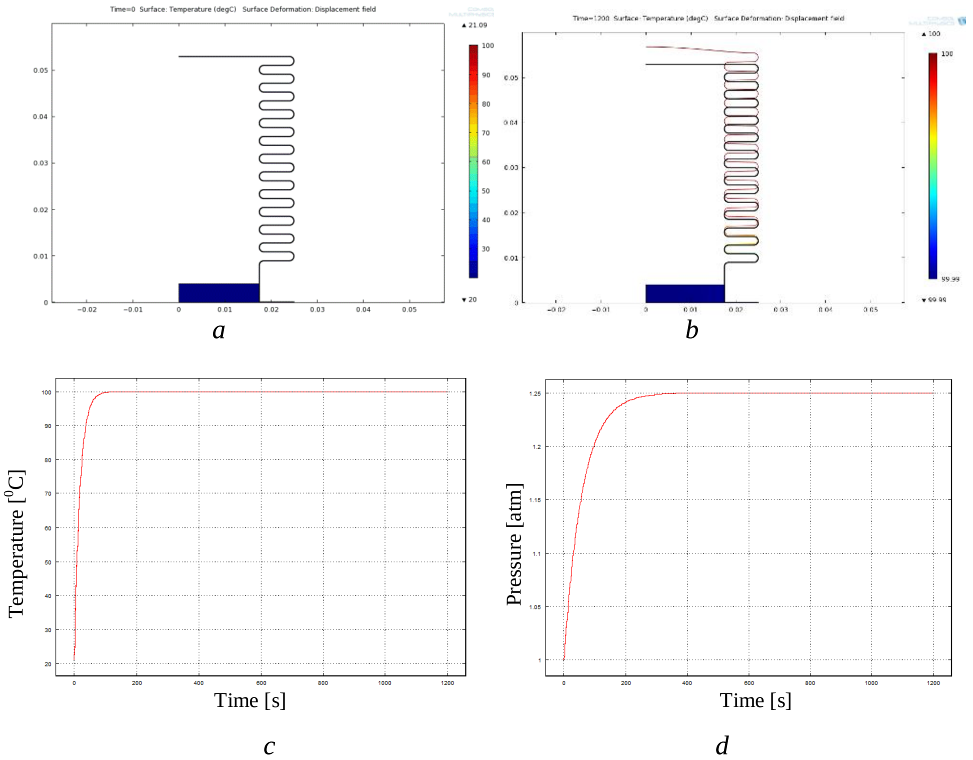


Fig. 12 – The mesh of the TSA.

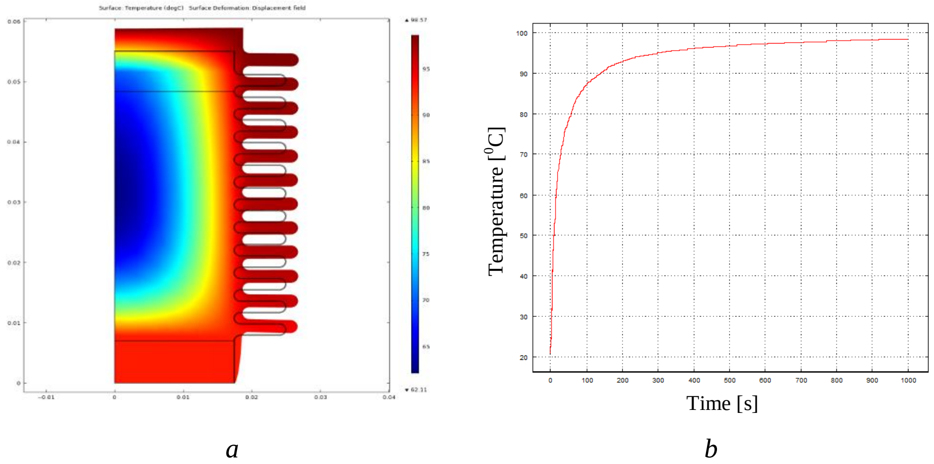
The displacement of the bellows free end is achieved after an exponential law, its speed being higher at the beginning of the process (Fig. 15). It can be noted that the free end of the TSA is moving exponentially in relation to time and linear in relation to the pressure (Fig. 16).



a *b*

c *d*

Fig. 13 – The cumulative influence of temperature and pressure on the flexible chamber elongation: *a* – beginning of simulation; *b* – end of simulation; *c* –time variation of the temperature; *d* – time variation of the pressure.



a *b*

Fig. 14 – The cumulative influence of temperature and displacement exerted by the volatile liquid: *a* – temperature-displacement map; *b* – time variation of free end bellows temperature.

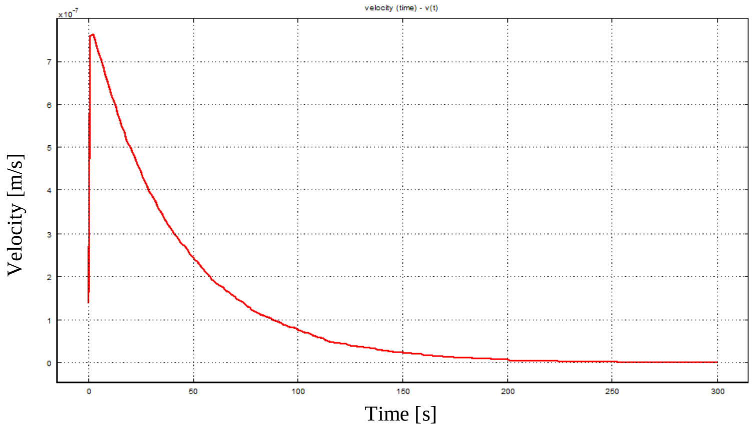


Fig. 15 – Time variation of the free end bellows velocity.

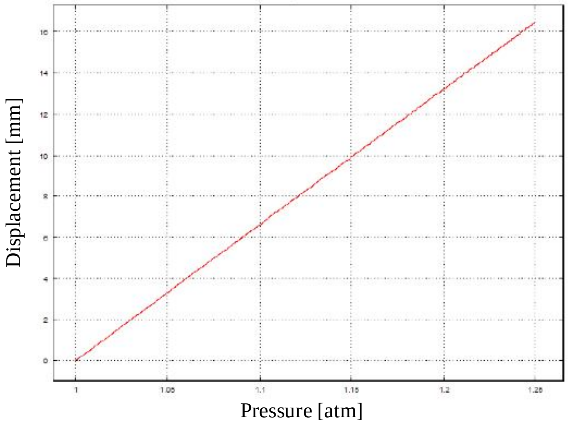


Fig. 16 – The bellows displacement as a function of the inside pressure.

5. Conclusions

The thermal state actuator represents a dynamic system which, according to general systems theory, can be studied using the mathematical model through transfer functions.

The experimental tests highlight the fact that the associated mathematical model to TSA is, generally, a first-order differential equation. The transient regime speed is dependent on volatile nature of the liquid.

Analyzing the experimental results obtained for petroleum ether we can say that increasing the amount of volatile liquid lead to a decrease of the actuator displacement. This conclusion is valid also for the ethyl ether.

By using petroleum ether, the TSA displacement is slightly higher than when using ethyl ether due to the low boiling point of the petroleum ether (~30ºC) compared to the ethyl ether (~34.2ºC).

The simulation results show that the variation of the temperature of the free end of the bellows follows exponential laws. Also, the displacement of the free end is linear with respect to time in relation to the pressure.

The results obtained by experiment and simulation are slightly different by the fact that, in experiment appears the thermal inertia.

Future research will analyze the behavior of the thermal state actuator arranged in different positions of operation. Different values for the TSA displacement due to change of the contact surface value between the volatile liquid and bellows are anticipated.

Acknowledgements. Infrastructure was partly supported by project Integrated Center for Research, Development and Innovation in Advanced Materials, Nanotechnologies, and Distributed Systems for Fabrication and Control, Contract No. 671/09.04.2015, Sectoral Operational Program for Increase of the Economic Competitiveness co-funded from the European Regional Development Fund.

Part of research from this article was presented at the 2016 International Conference and Exposition on Electrical and Power Engineering, EPE2016, event organized by the Faculty of Electrical Engineering, "Gheorghe Asachi" Technical University of Iaşi.

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ANALIZA EXPERIMENTALĂ ŞI MODELAREA CU ELEMENTE FINITE A UNUI ACTUATOR CU SCHIMBARE DE FAZĂ CONTROLAT ELECTRIC

(Rezumat)

Sunt prezintate studiul şi controlul funcționării unui actuator cu schimbare de fază (TSA). Lucrarea propune o abordare practică pentru controlul deplasării actuatorului utilizând tehnologia PLC. Actuatorul propus prezintă două caracteristici esențiale: deplasare liniară redusă şi forță relativ mare. Actuatorul este un sistem dinamic care poate fi analizat prin intermediul funcțiilor indiciale. În acest sens, pentru diferite cantități de lichid volatil au fost analizate următoarele aspecte: răspunsul indicial, funcțiile de transfer şi constantele de timp. Sunt prezentate rezultatele evaluării prin metoda elementului finit.