Modeling and study the Physical properties of a Thermal Actuator for Micro-Electromechanical systems (MEMS) Applications

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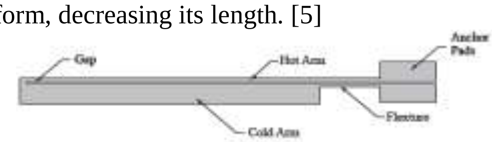
Abstract
The paper introduces a study of one of the most components coupled in the Micro-electromechanical system (MEMS) devices, the thermal actuator. In this study a type of micro thermal actuators modeled by commercial finite element analysis (FEA) package ANSYS.
The study includes design of polysilicon micro thermal actuator and study of thermal and mechanical actuating by an electrical load. A potential difference applied across the electrical connection pads induces a current to flow through the arm and blade. The current flow and the resistivity of the polysilicon produce Joule heating (I^2R) in the arm blade. The Joule heating causes the arm and the blade to heat up. Temperatures in the range of 700 -~1000 ^oK generated. These temperatures produce thermal strain and thermally induced deflections. All the results of nodal temperatures and mechanical deflections listed and the maximum and minimum values illustrated for each reaction using the nodal solution contour plots and graphs. The Electric potential- Nodal temperature, and Nodal Temperature-Deflection curves graphed to illustrate the behavior of electro-thermal mechanical inducing.

Keywords*: micro electro-mechanical systems MEMS, finite element analysis FEA, coupled field modeling.*

Introduction
Micro-electromechanical systems (MEMS), or (Micro-Electro-Mechanical) is the technology of the very small (between 1 to 100 micrometer in size), and merges at the nano-scale into Nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micro-machines (in Japan), or Micro Systems Technology MST (in Europe). They usually consist of a central unit that processes data, the microprocessor and several components that interact with the outside such as micro-sensors. [1][2]
Thermal actuator is one of the most important component in MEMS devices, which is able to deliver a large force with large displacement, thus they have found various applications in electro-optical-communication, micro-assembly and micro-tools. Currently Si-based materials have been predominantly used to fabricate thermal actuators due to its mature process and stress-free materials see fig(1)[3][4]. Most of micro cells implement the standard form of that Guckel electro-thermal actuator. It is a 'U' shaped structure that uses differential thermal expansion to achieve motion along the wafer surface.

Fig(1) Thermal actuator (U-Shape) ≈200 µm

When a voltage is applied on the terminals, the current flows through the device. However, because of the different widths, the current density is unequal in the two arms. This leads to a different rate of Joule heating in the two arms, and thus to a different amounts of thermal expansion. The thin arm is often referred to as the hot arm, and the wide arm is often referred to as the cold arm or the blade see fig(2). Backward deflection of the device is possible by temporarily delivering too much power to the device. Although too much power can easily destroy the device, at the right level the hot arm will plastically deform, decreasing its length. [5]



Fig(2) Thermal actuator Parts

The precise motion of these thermal actuators can be used to operate a wide variety of devices, limited only by the imagination of the designer. Temperature actuated valves [6], switches, latches, clamps and control devices are typical applications. The high heats of fusion and heat capacities of the Thermoloid material make it an excellent candidate for heat sink applications. See fig(3a-b)[7][8][9]

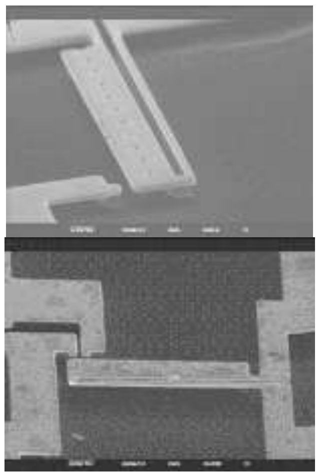


Fig.3-(a) Micromechanical switches with single and double contacts

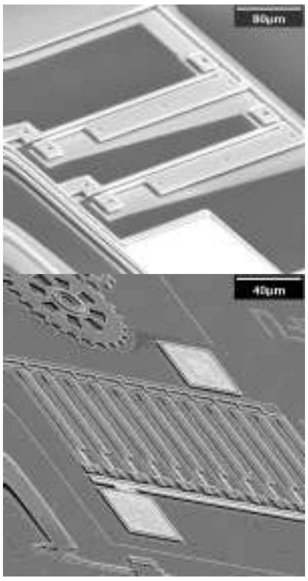


Fig.3-(b) SEM of coupled and array of electro-thermal actuators.

The simulation of micro electro-mechanical systems (MEMS) involves numerical analyses in diverging areas of physics, such as solid mechanics, electromagnetics, heat transfer, fluid dynamics and acoustics. The interaction between these individual phenomena can be simulated by a coupled field analysis.[10]

ANSYS is a general purpose software package based on the finite element analysis (FEA). This package allows full 3- dimensional simulation without compromising the geometrical details. The analysis can be static, harmonic, modal and transient; linear or nonlinear. Electrical and mechanical lumped elements facilitate discrete circuit simulation. ANSYS parameter design language (APDL) provides a convenient way to realize a weak coupling.[11]

Current study Objectives

The general goal of this study is to enrich our country especially the field of higher education and scientific research with studies within the up-to-date techniques from the Computer Aided Design CAD systems, to the using of modeling and simulation packages, in which reduces of time, costs, and the human efforts. However the main objectives for this study are:

- Determine the nature of the actuated mechanical motion of the device.
- Determine the tip deflection through progressive voltage along period of time.
- Determine maximum temperature and the transient thermal energy (Heat flux) for those voltages.

Theory

1- Electrical

The resistance of the actuator can be determined by the following equation:

$$R = \rho(L / w_h t + L\text{-}F / w_c t + F / w_f t) \quad \text{…….(1)}$$

Where, R is the total resistance, L is the total length of the actuator, *F* is the length of the flexure, t is the actuators thickness, ω_h is the width of the hot arm, ω_c is the width of the cold arm (the blade), ω_f is the width of the flexure, and ρ is the resistivity of the thermal actuator's material. The thickness *t* of the actuator will be either 2μm or 3.5μm.[12]

2- Thermal

2-1 Thermal Expansion of Micro-Devices:[13]

Nearly all materials undergo a change in volume or dimensions as their temperature changes. For solids such as semiconductors, metals and dielectric materials, their volume increases as the temperature increases, as follows:

$$\alpha = \frac{\left(\frac{\Delta V}{V}\right)}{\Delta T}$$

α = *volumetric thermal expansion coefficient*

ΔV = *change in volume*

V = *total volume*

ΔT = *change in temperature*

Alternatively, we can define:

$$\beta = \frac{\left(\frac{\Delta L}{L}\right)}{\Delta T}$$

β = linear thermal expansion coefficient

ΔL= change in length along one dimension

L= total length of that same dimension

Note the relation that exists between the two coefficients:

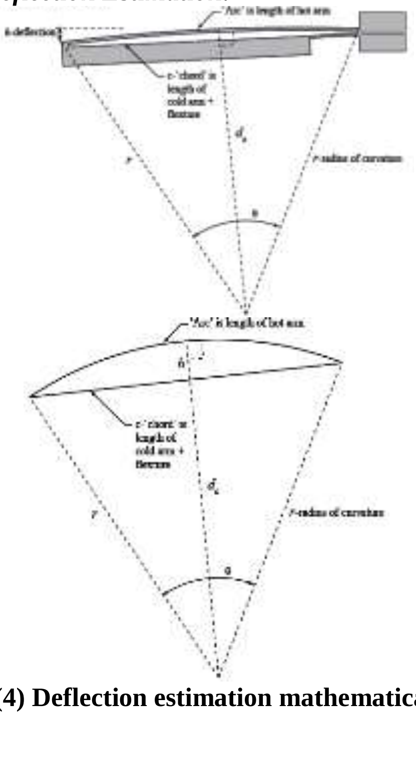
$$\alpha = 3\beta$$

2-2 Thermal Actuators

Based on Ohmic heating of different cross-sectional areas, we will attempt to estimate the deflection of this device, based on the following assumptions:

- Cold arm remains straight
- Connection of cold arm and hot arm considered as a point.

2-2-1 Deflection Estimation:



Fig(4) Deflection estimation mathematically

Some useful circle formulas:

$$\theta = \frac{arc\ length}{r}$$

$$r = h + d_o$$

$$c = 2r\sin\left(\frac{1}{2}\theta\right) \quad d_o = r\cos\left(\frac{1}{2}\theta\right)$$

$$c = 2\sqrt{r^2 - d_o^2} \quad d_o = \frac{1}{2}\sqrt{4r^2 - c^2}$$

For thermal actuators, we usually know:

$$L_h(hot\ arm\ length) = arc\ length = L(1 + \alpha\Delta T)$$

$$L_c + L_f = (cold\ arm + flexture\ length) = chord\ length\ c$$

Therefore, based on this information, we can determine both, r and θ Then, we can use r and θ to determine the tip deflection using:

$$\delta = r - r\cos\theta = \frac{1}{2}r\theta^2$$

3-Mechanical

A thermal actuator can be considered to be a cantilever. The cantilever has a no load deflection based on some input parameter (such as voltage or current). The following formula can be used:

$d = do(a) + C_f$ ...(2)

Where, *d* is the deflection (length), d_o is the no-load deflection (length) and is a function of some input parameter *a, C* are the compliance (length per force), and *f* is the applied force. Typically, d_o (0) =0.

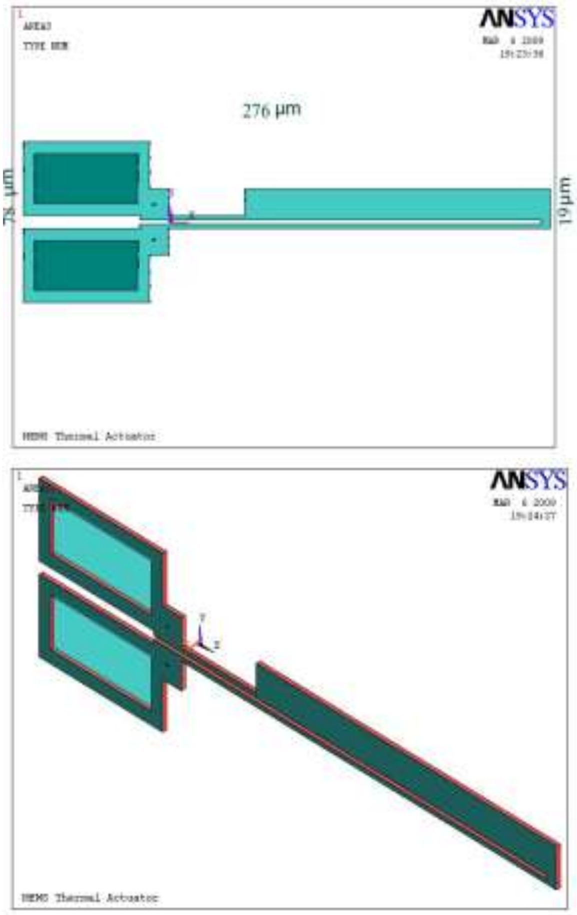
A reasonable expression for the current density throughout the actuator could be found, the resistivity is a function of temperature. As the temperature will vary throughout the device from room temperature to well over 1000°K, this cannot be ignored. Also, the coefficient of thermal expansion is also a function of temperature. Determining the value of d_0 requires an electro-thermal-mechanical simulation. [12]

It should be possible to determine the compliance *C* of an actuator with a closed form equation. However, the actuator cannot be considered as a simple cantilever, and so a more advanced approach is required. However, the compliance can also be determined using numerical methods. A mechanical simulation, easily and quickly performed using ANSYS, can be used to determine the compliance.

ANSYS MODELING

A new model of thermal actuator has been created and solved by ANSYS package. The modeling and analyzing steps were as follows:

1- Actuator design: A Three dimensional design of the actuator was created with 276µm ultimate Length, 2µm thickness, minimum width (from the lower Tip of the hot arm to the upper tip of the blade) 19µm, and maximum width (from the lower to the upper pad) 78µm. See fig(5).



Fig(5) ANSYS model of the thermal actuator

2- Material properties: The material properties were defined using the Polysilicon as the actuator material because of its advantages for such type of devices. The properties defined in units of µMKS Table (1) below shows the Polysilicon properties.

Table(1) Material Properties for the actuator

Material Properties for Polysilicon (µMKSV units)	
Young's modulus	169e3 MPa
Poisson's ratio	0.22
Resistivity	2.3e-11 ohm-µm
Coefficient of thermal expansion	2.9e-6/°K
Thermal conductivity	150e6 pW/µm°K

3- The FE mesh: For the (FEA) within current solid model the suitable element was found the SOLID98, which is one of the Coupled-Field state elements (Tetrahedral Coupled-Field Solid). This element typically used in multiphysics analysis problems. It has a quadratic displacement behavior and is well suited to model irregular meshes (such as produced from various CAD/CAM systems). When used in structural and piezoelectric analyses. SOLID98 has large deflection and stress stiffening capabilities. The element is defined by ten nodes with up to six degrees of freedom (DOF) at each node, Electrical, magnetic, thermal, Piezoelectric, mechanical, Fluid and more other DOF. See fig (6). Then the Finite Element mesh applied the volume using automesh function on the volume. See fig(7)

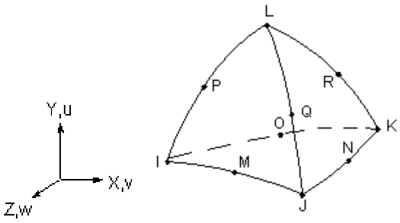
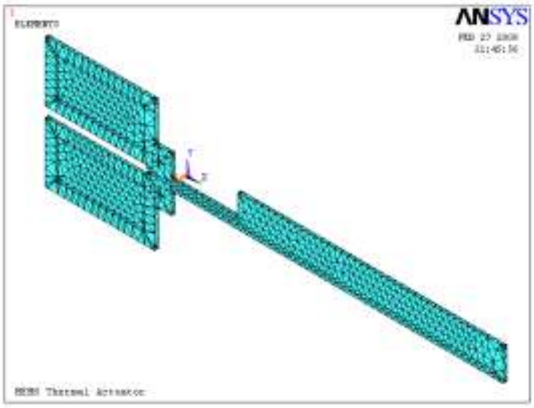


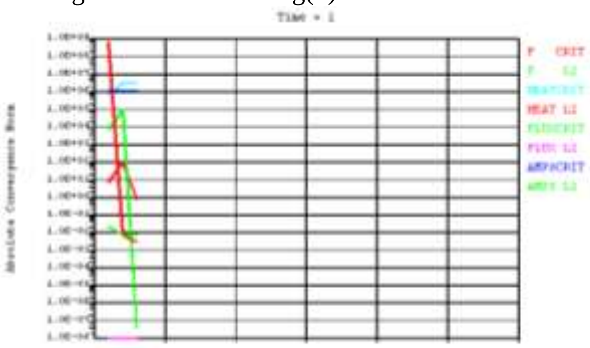
Fig (6) SOLID98 Element with its DOF



Fig(7) the FE Mesh on the model

4- Boundary Conditions: The main load was an electric potential difference between the two pads, an electric load of (5Volt) applied on the upper pad and (0Volt) applied on the lower pad (in order to extract a potential difference between the two pads). Thermal load and mechanical 0 displacements acts as a constraint boundaries.

5- Solving the model: To obtained an accurate non linear solution the solution control function was used to chose the suitable number of iterations and the progress of load through the time (the load divided into five steps, with 1increment for each step) the most accurate iterations number to obtain the convergence was 100.see fig(8).



Fig(8) The iterations of convergence Solution

Results and discussion:

All interactions between the three coupled fields were summarized as the following:

(1) Electrical→ Thermal interaction: The electrical current passing through the blade into the other pad (through the hot arm) causing a temperature rising. Temperature rise due to (I^2R) heating. Fig (9) shows the nodal temperature results due to the electrical current.

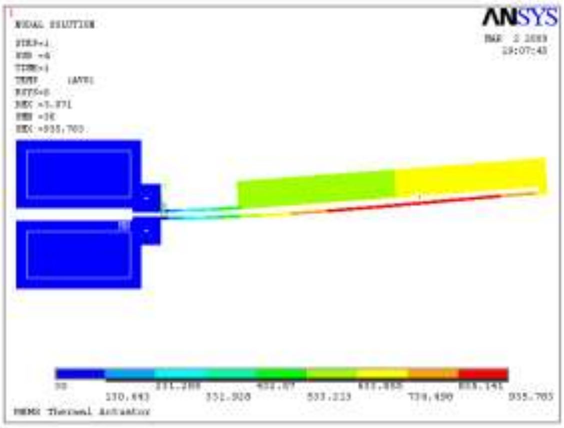


Fig (9) the nodal temperature rsults

Fig (9) Shows that the maximum temperatures are on the hot arm the reason is that the resistance in the thin arm is greater than the resistance in the blade. Therefore, the thin arm heats up more than the blade, the maximum temperature in this region was about 892.501K^o, the graph in fig (10) below shows the relationship between the electric potential and the nodal temperatures as it's function.

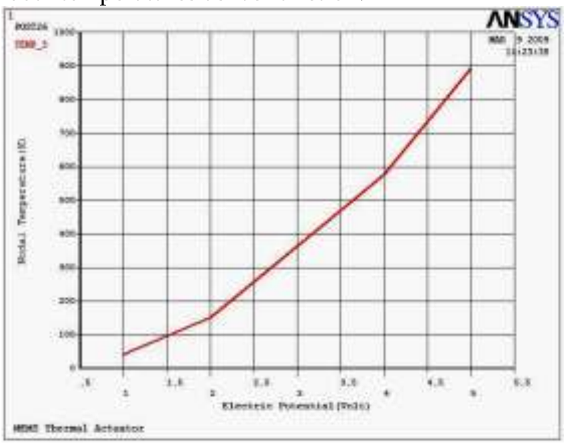
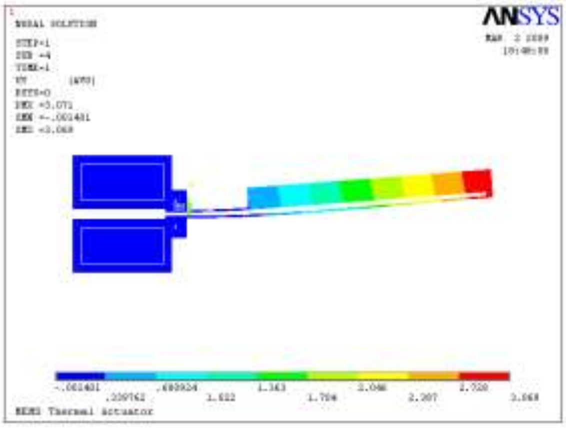


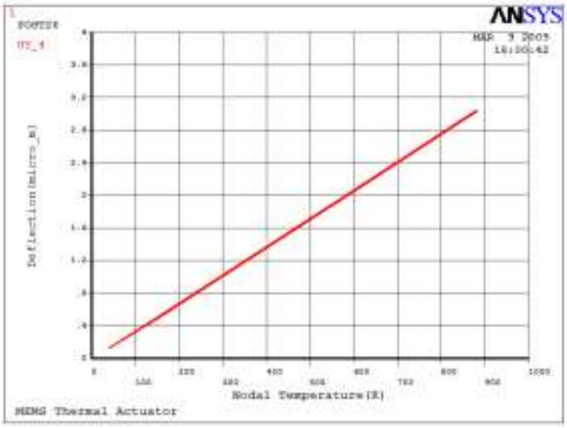
Fig (10) Electric Potential vs. Nodal Temperature

Although, the linear increasing of the electric load with the time, the results of nodal temperatures seems to have a bit nonlinearity behavior in some regions. In the first part of the graph (1<E< 2 Volt), the temperature increases linearly in a little amounts with the Electrical load, then at E>2Volt, the curve shifts into the left until E >4Volt there is more shifting toward the left. These two shifts may be found due to the differential resistance. The resistance of the materials increases with the time; here we have a linear electric load with the time. then we can suppose that the continuity of increasing of the load with the time make resistance increases with the load as (I^2R) and with the time as (dR/dt) that means that the resistance has another factor for increasing, that makes the curve shifts to the left with that factor.

(2) Thermal → mechanical interaction: As the hot arm and blade heated up because of the electrical-thermal interaction, as mentioned above the hot arm heated up greater than the blade; also there is a different expansion in each one Because the difference in thermal coefficient between the blade and the hot arm (that's due to the different volume). Therefore the hot arm expands more than the blade, which causes the actuator to bend toward the blade. The maximum deformation occurs at the actuator tip was 3.05µm. Fig (11-a) below shows the deflection results on the entire model, and fig (11-b) shows the curve of relationship between the nodal temperatures and the deflection at all the time of analysis.



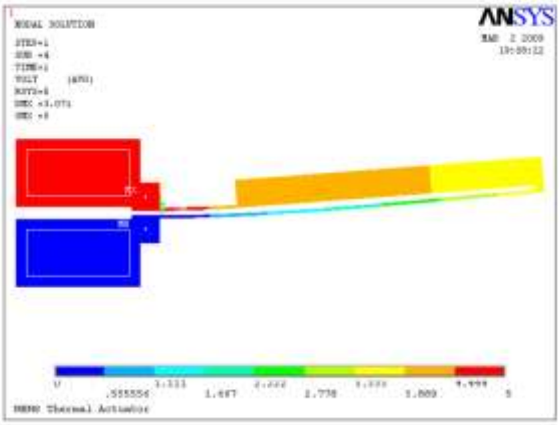
Fig(11-a) The deflection results



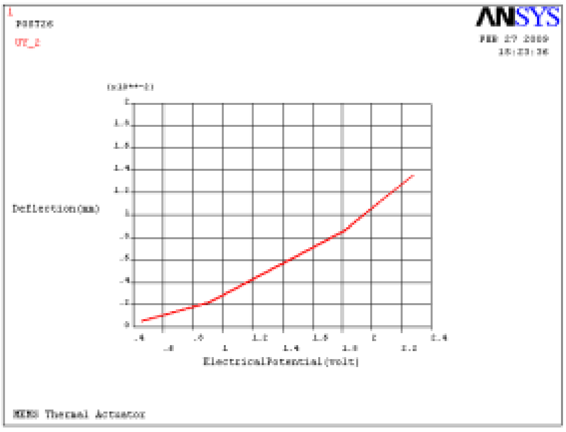
Fig(11-b) Nodal temperature Vs. Deflection

From fig (11-a) we saw that a few values of deflection are negative (≈ -0.0014 µm) this value is tiny, but it must interpreted, the negative value generally occurs due to the bit deflection in the lower direction (the negative coordinate[1]) this negative value found almost in the flexure region. As the blade deflects toward the positive side, the flexure shifts a bit toward the negative side as a reaction for the major deflection. The curve in figure (11-b) is a linear, so that the deflection increases linearly with increasing of temperature, then the mechanical deflection proportional directly to the temperature.

(3) Electrical - Mechanical interaction: The amount of tip deflection (or force applied if the tip is restrained) is also a direct function of the applied potential difference. Therefore, the amount of tip deflection (or applied force) can be accurately calibrated as a function of applied voltage. See fig (12-a, b)



Fig(12-a) Electrical Potential defference for the entire model



Fig(12-b) the tip deflection as a function of the applied voltage

In addition of the above results, the results of thermal flux through the model was obtained and the relationship between the flux and the distance a cross the model was graphed. Fig (13) shows the thermal flux results and the histogram of the distance upon it.

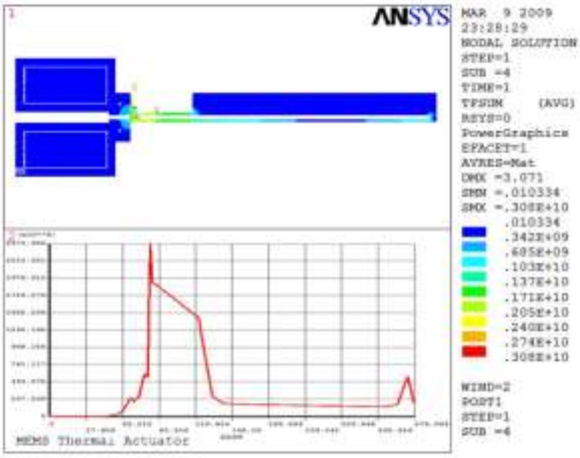


Fig (13) the thermal flux along the model.

Fig(13) shows that there is a sharp peak on the graph shows that there is a maximum flow in a closed area in the first part of the flexure region (about 3E11 J/m.s2 at the joint of the flexure with the pads) that is may be due to the high voltage which causes a high energy in the cross area at the first moments of time

1 ANSYS uses the vectors system in solving of the designed models

in this region, after this peak the flux decreases gradually along the flexure region, at the second edge of the flexure the flow has a clear value (about 0.14E+10), the flow then become almost stable around the value (0.16E+09J/m^2) through all the region of the blade, the reason for that decreasing is the increasing in the cross sectional area that face the flow on the edge of the blade and then the recognized area of the blade make the flow stability.

Conclusions:

1- The current study will establish the basis to find out solution for the future problems as to as find out the right amount of electric potential to make a thermal actuator working in safe mode, the improper calculations of electric potential to producing a desired deflection to make a perfect micro switches

2- Although the linear increasing of the potential deference, the relationship between the nodal temperature and electric potential found nonlinear a bit because of the factor of deferential resistance (dR/dt) . the graph in fig(10) shows that the relation between the two is close to the exponential function, thus we may illustrate the temperature as an approximately exponential function for the electric potential in the time range problems in thermal actuators.

3- The relation between the tip deflection and nodal temperature is linear [see fig (11-b)]. Thus we may assume that the deflection proportional directly with the temperature, this leads us to assume the same exponential relation between the deflection and electric potential in which insures in the graph of fig(12-b).

4- For the thermal flux, the graph in fig(13) shows that there is a sharp peak then there is a stable state in the range of the blade region, that's may indicates that there is an instant transient of a great amount of thermal energy and quickly exchanging through the blade, this is a positive point, because if the thermal energy spent a long time through the actuator it may produces a thermal hysteresis in the device and make the switch work inaccurate, in addition the high amounts of thermal hysteresis in such device may destroy it and make it malfunction.

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تصميم ودراسة الخصائص الفيزياوية للمشغل الحراري المستخدم في التطبيقات الكهروميكانيكية الدقيقة

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الملخص:

يتناول البحث الحالي دراسة أحد اكثر العناصر المهمة في الأنظمة الكهروميكانيكية الدقيقة، وهو المشغل الحراري المستخدم في اجهزة السيطرة والعمليات الدقيقة (كالتطبيقات الالكترونية الدقيقة).

استخدمت برمجية الأنسس في تصميم نوع من المشغلات الحرارية المكونة من مادة البولي سيليكون، وتمت دراسة التأثير الحراري والميكانيكي الناتج على مادة المشغل عند تسليط حمل كهربائي. حيث تم تسليط فرق جهد متزايد بصورة تدريجية مع الزمن (١-٥ فولت لكل ثانية) على طرفي المشغل، وخلال مرور التيار عبر المشغل تولدت طاقة حرارية بسبب مقاومة المادة للتيار (I^2R) مما سبب تسخين ذراع المشغل بحدود (٧٠٠-١٠٠٠ K^o) تقريباً. درجة الحرارة المتزايدة سببت تمدد غير متكافئ في اذرع المشغل مما ادى إلى انحراف شفرة المشغل (الذراع العريضة) نحو جهتها. وقد تم حساب قيم الحرارة الناتجة عبر المشغل وحسبت أعلى درجات الحرارة والانحراف عند طرف الشفرة. كذلك تم رسم منحني فرق الجهد الكهربائي مع درجات الحرارة العقدية المتولدة، ومنه رُسم منحني درجات الحرارة العقدية مع الانحراف الميكانيكي الناتج، كذلك رسمت نتائج التدفق الحراري عبر النموذج بأكمله بالإضافة إلى الرسوم الكنتورية لكل من فرق الجهد، درجات الحرارة العقدية، والإنحراف الميكانيكي.