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A New Model for an Electrostatically Actuated Miniature-Scale Diaphragm Compressor for Electronics Cooling

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ABSTRACT

This paper presents a new approach for quasi-static modeling of an electrostatically actuated diaphragm compressor for miniature-scale refrigeration systems that can be used in electronics cooling. The compressor consists of a flexible circular diaphragm that is clamped at its circumference. A dome-shaped cavity encloses the diaphragm completely. Two valves control the inlet and discharge flows. Metallic electrode layers are deposited on the membrane and on the cavity surfaces. A potential difference is applied between the diaphragm and the cavity to pull in the diaphragm towards the cavity surface progressively from the outer circumference towards the center of the diaphragm. This zipping action reduces the volume available to the refrigerant gas, thereby increasing its pressure. The model developed in this paper uses a segmentation technique where the diaphragm is divided into a series of parallel-plate capacitors with movable plates that simulate the diaphragm deflection during actuation. For a sustained zipping actuation, the electrostatic force between the parallel plates must be higher than the elastic force induced by the stretching of the diaphragm and the pressure force of the fluid being compressed. A diaphragm pull-in voltage is calculated for a given geometry, material properties and pressure ratio. The model is compared with the literature and the results show a reasonable correlation.

1. Introduction

Thermal management of electronic components is of increasing concern in the development of reliable electronic devices of increasing performance. The need to reduce package weight and volume while increasing the functionality has received much attention in recent years. Moore (1965) predicted that the number of transistors on an electronic chip would double approximately every 18-24 months. It has been predicted that the heat generated by a desktop computer microprocessor will reach 200 W by year 2010. Of the emerging cooling techniques, a vapor compression refrigeration system appears to be one of the most promising methods to replace conventional air-cooled heat sinks. One of the most challenging aspects of implementing refrigeration systems for electronic cooling is the design of an efficient and compact compressor. An electrostatically actuated miniature-scale diaphragm compressor offers promising geometric and performance features for use in electronics cooling. It is very compact in size, does not require an electric motor, and has the potential for achieving high thermodynamic efficiency. This paper investigates the operation of a diaphragm compressor, reviews different modeling approaches in the literature, and proposes a new analytical modeling scheme.

2. Operating Principle

A diaphragm compressor consists mainly of a dome-shaped compression chamber and a circular thin diaphragm (Figure 1). The diaphragm is clamped at its circumference. Two metallic electrodes are deposited on both sides of the diaphragm and on the inner surfaces of the chamber and a dielectric layer is deposited on top of the electrodes to prevent electric shorting when the diaphragm touches cavity surface.

When a voltage differential is applied between one surface of the chamber and the diaphragm, an electrostatic field is developed in the chamber. If this field is stronger than the elastic restoring force in the diaphragm and the pressure acting on the membrane, then the diaphragm is pulled in towards the cavity surface thereby compressing

the trapped gas in that pocket volume. The diaphragm pull-in starts at the circumference and continues progressively toward the center as illustrated in Figure 2. This is also known as "zipping" actuation of the diaphragm. When the fluid pressure reaches the discharge pressure, the discharge valve opens and the fluid is pushed from the chamber by the moving diaphragm. At the end of the compression stroke, the voltage difference is switched to the other cavity surface and the diaphragm zipping actuation starts in the opposite direction.

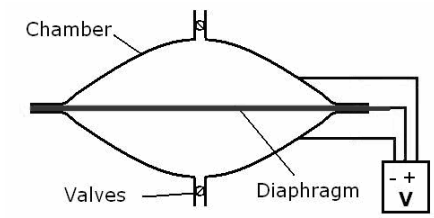

Figure 1 Schematic of a diaphragm compressor

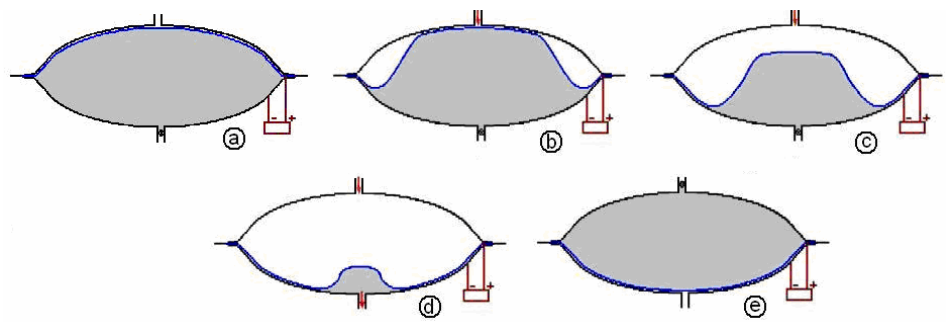

Figure 2 Progressive zipping actuation of diaphragm

3. Literature Review

A number of studies in the literature have considered movable plate capacitor systems involving electrostatic force actuation. In particular, the electrostatic pull-in of a circular clamped diaphragm has been investigated by Nathanson et al. (1967). They presented one of the first approaches to model a resonant gate transistor and postulated a parallel plate capacitor model to estimate the electrostatic field between two movable parallel plates. They assumed that one plate was fixed while the other was connected to a wall by an elastic spring. The spring is allowed to move in a direction perpendicular to the surface. If the plates, initially at a distance d, are excited by a voltage, the movable plate moves toward the fixed one under the influence of the electrostatic force. The deflection of the movable plate continues until an equilibrium position is reached, at which the elastic restoring force equals the electrostatic force. If the voltage is increased, a new equilibrium position is achieved. However, they showed that the system can achieve a stable equilibrium until the gap between the plates is higher than or equal to two-thirds of the initial distance. It was demonstrated that if the gap between the two plates was less than this limit, the system becomes intrinsically unstable and the plates collapse towards each other. This was due to the fact that the electrostatic force becomes self-sustained and increases significantly as the distance between the plates is reduced. This is an instability phenomenon intrinsic to the movable plate capacitor system and is known as a pull-in phenomenon. Senturia (2001) developed a spring-parallel plate capacitor model to corroborate the pull-in theory developed by Nathanson et al. (1967) and he computed the pull-in voltage for a parallel movable plate capacitor. The pull-in voltage is defined as the voltage required to reach the equilibrium position at two-thirds of the initial gap between the plates. Once the plates reach this equilibrium position, any appreciable increase in the voltage causes the plates to collapse toward each other. Thus, the pull-in voltage is considered as the minimum voltage that should be applied to the capacitor plates to achieve complete contact between the two surfaces.

The concept of using an electrostatic field to move a plate to pump a fluid has been investigated in recent years. A donut-shaped diaphragm compressor using refrigerant R134a for use in a miniature cooler circuit has been modeled, fabricated and tested by Shannon et al. (1999). The compressor was modeled using a lumped method where a force balance was made on the diaphragm to estimate the required actuation voltage. A donut-shaped cavity profile was used and it was estimated that the required pull-in voltage was approximately 40 V. Saif et al. (1999)

modeled both a dome-shaped and a donut-shaped electrostatically actuated diaphragm for a small pump. A lumped energy balance approach was used and the electrostatic field was modeled using a single flat plate capacitor. At equilibrium, the capacitive electrical energy between the electrodes on the cavity and on the membrane was set to be equal to the sum of the strain energy of the membrane and the pressure energy of the fluid. From this energy balance the pull-in voltage was obtained.

A few micropump prototypes have also been developed for pumping incompressible fluids (Cabuz et al., 2001, Chan, 1998), and numerical CFD models were used to predict the flow rate achieved (Athavale et al., 1999). However, CFD models were found to be computationally expensive, and simpler approaches continue to be sought.

In general, analytical models in the literature were developed to estimate the equilibrium position of the plates and to study the control strategy of the actuation mechanism. The simplest methods do not consider capacitors that have non-flat plates and in which the curvature of the electrodes is important. The gas compression using an elctrostatically actuated flexible diaphragm also needs further investigation.

In this paper, a new model is presented to describe the compression process of a gas by using an electrostatically actuated flexible diaphragm. The operating voltage of the compressor is computed by using a series of movable plate capacitors, which are able to simulate the behavior of the compressor during the compression stroke, that is, the zipping actuation of the diaphragm.

4. Diaphragm Pull-In Theory

The electrostatic force on the diaphragm can be calculated by using a parallel-plate capacitor theory that considers two electrostatically charged parallel plates separated by a small gap (Senturia, 2001). As the diaphragm deflects under the influence of the electrostatic force, it develops an elastic force (Di Giovanni, 1982) that acts in a direction opposite to that of the electrostatic force. Since there is a pressurized fluid trapped in the chamber, a fluid pressure force acts on the diaphragm as well. For a sustained zipping actuation of the diaphragm, the electrostatic force must overcome the sum of the elastic force and the pressure force.

The dome-shaped cavity profile represented by a 6th-order polynomial is divided into multiple radial segments (Figure 3) and each segment acts as a parallel-plate capacitor with different initial gaps (Figure 4). The profile of the compression chamber cavity was chosen to ensure a smooth variation of the deflection during the zipping actuation; the cavity resembles a dome shape, which is elevated in the center and smooth near the circumference. The profile is represented by the following equation:

$$\frac{y}{y_{\max}} = 1 - \left(\frac{r}{R}\right)^2 - 0.1\cdot\left(\frac{r}{R}\right)^3 + 0.1\cdot\left(\frac{r}{R}\right)^4 - 0.1\cdot\left(\frac{r}{R}\right)^5 + 0.1\cdot\left(\frac{r}{R}\right)^6 \tag{1}$$

where y is the depth of the cavity at any radial coordinate r, R is the radius of the compressor chamber, and y_{max} represents the maximum depth of the cavity at the center as shown in Figure 3.

The diaphragm zipping actuation is assumed to be quasi-static, i.e., the dynamic effects because of diaphragm motion are neglected. The diaphragm elastic modulus is also assumed to be uniform (elastic moduli of metal and dielectric layer are neglected) and the diaphragm strain is assumed to be in confined to the radial direction. Also, the compression process is assumed to be isentropic.

The force balance calculations are initiated with the segment near the circumference and are continued toward the center. The voltage required to deflect the segment through a pre-defined gap is calculated, and is denoted here as segment pull-in voltage. The overall pull-in voltage for the compressor or the "operating voltage" is the maximum segment pull-in voltage.

The simulations are run for a cavity radius of 40 mm and maximum cavity depth of 200 µm. The diaphragm is made of metallized polyimide and has a thickness of 25 µm. The cavity surface has a dielectric layer coating of 0.8 µm. The working fluid is refrigerant R-134a and the vibration frequency of the diaphragm is 90 Hz. The flow rate achieved by the diaphragm is ≈3000 ml/min. If the pressure rise in the compressor is ≈750 kPa, then the estimated cooling capacity is ≈200W.

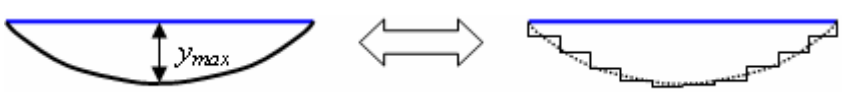

Figure 3 Segmentation of cavity shape into multiple segments

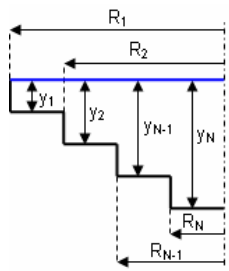

Figure 4 Segmentation with N equal-width radial segments

For each segment, the force balance on the diaphragm is given by:

$$F_{es,i} = F_{el,i} + F_{gas,i} \tag{2}$$

where $F_{el,i}$ is the elastic force in each segment of the diaphragm, $F_{gas,i}$ is the force of the pressurized fluid in each segment, and $F_{es,i}$ is the electrostatic force in each segment of the diaphragm. For each segment, the elastic force is calculated using a lumped elastic spring constant K_i and the axial gap y_i of each segment. K_i is a function of the elastic properties of the diaphragm:

$$F_{el,i} = F_{el,i-1} + K_i \cdot (y_i - y_{i-1}) \tag{3}$$

Because the zipping action reduces the volume available to the refrigerant gas, the rise in the pressure of the fluid essentially results from the decrease in the volume available for the fluid. If an isentropic compression process is assumed, then the pressure rise of the fluid for each segment can be computed as follows:

$$P_1 \cdot V_1^n = P_2 \cdot V_2^n \tag{4}$$

where P_1 and P_2 are the pressures in the chamber before and after the deflection of each segment, respectively. V_1 and V_2 are the compression chamber volumes before and after the deflection of each segment and N is the isentropic exponent of compression for R134a vapor.

For each segment, the electrostatic force is computed by using a parallel-plate capacitor approach (Senturia, 2001) which can be summarized by the following equation:

$$F_{es,i} = \sum_{j=1}^{N} \frac{\varepsilon_0}{2} \frac{V_i^2 \cdot A_j}{\left(\frac{t_d}{k_d} + y_j - y_{i-1} \right)^2} \tag{5}$$

where ε_0 is the permittivity of the vacuum, and V_i is the voltage applied, t_d is the thickness of the dielectric material, and k_d is its dielectric constant (defined as the permittivity of the material to the permittivity of the vacuum). The force balance can be solved for each segment and the voltage to compress the refrigerant vapor can be computed. In conclusion, the maximum voltage among the segments is taken as the operating voltage of the compressor to achieve the final pressure ratio.

5. Results and Discussion

The model discussed in the previous section was implemented in MATLAB[1]. And the refrigerant properties were calculated by using REFPROP[2] The segmentation-based modeling approach yields the pull-in voltage for each segment. Figure 5 shows the variation of the pull-in voltage for the segments starting from the circumference (value of 1 on x-axis) and traversing to the center (value of 0 on x-axis). The segment pull-in voltage increases as long as the fluid is being compressed and then reduces once the fluid pressure reaches the discharge pressure and the discharge valve opens. It is observed that the elastic force developed in the diaphragm is negligible compared to the fluid pressure force. The overall strain developed in the diaphragm is well below the plastic yield limit for the diaphragm material.

Figure 6 shows the pull-in voltage of the compressor for different numbers of segments. As the number of segments increases, the operating voltage decreases because the series of parallel plate capacitors approximates more accurately the cavity profile of the chamber. At approximately 10,000 segments, the curve flattens out and a further increase in the number of segments does not alter the operating voltage predicted. Thus, as a trade-off between computational cost and accuracy of the solution, the number of segment was set to 10,000. A pressure head of 750 kPa was achieved at an operating voltage of the diaphragm compressor of 1243 V.

The model results are compared with the literature (Saif et al., 1999) for different dielectric layer thicknesses (td, microns) on the cavity surface as shown in Figure 7. Saif et al. modeled the deflection of an electrostatically actuated membrane by using an energy balance approach on the diaphragm to calculate the required pull-in voltage. Both results from Saif et al and the current work show similar trend, that is, the required pull-in voltage for achieving a certain discharge pressure increases as the thickness of the dielectric layer increases. However, the current model predicts a lower pull-in voltage compared to the simulation results discussed in Saif et al. work because it uses a large number of parallel-plate capacitors to represent the curved geometry of the cavity as opposed to the single flat-plate capacitor used in Saif et al investigation. It can be argued that the segmentation-based approach developed here predicts the electrostatic field and the zipping actuation more accurately.

The current model neglects the bulging of the diaphragm because of the gas pressure. Inclusion of the diaphragm bulging effect, dynamic effects of the diaphragm motion and the viscous damping force exerted by the fluid on the diaphragm are being undertaken in ongoing work. The simulation model will also be validated against experimental results obtained with a prototype to be fabricated.

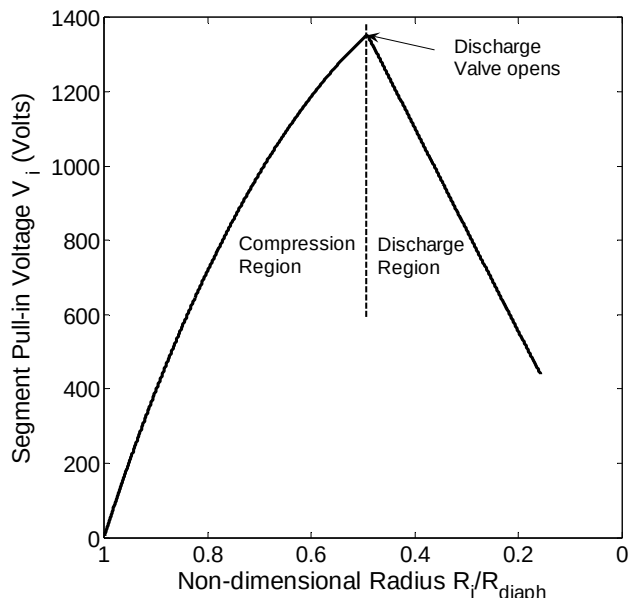

Figure 5 Segment pull-in voltage for diaphragm compressor.

[1] MATLAB is a registered trademark of The MathWorks, Inc.
[2] NIST Reference Fluid Thermodynamic and Transport Properties – REFPROP Version 7.0

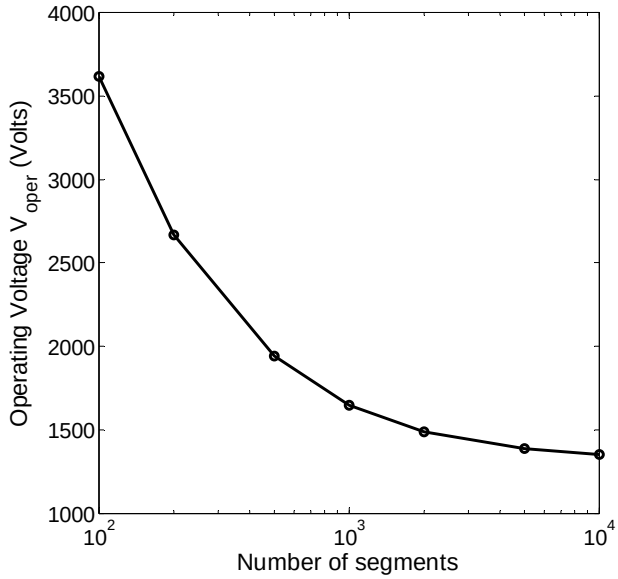

Figure 6 Diaphragm operating voltages for different number of segments showing that a mesh-independent pull-in voltage is obtained at approximately 10^4 segments

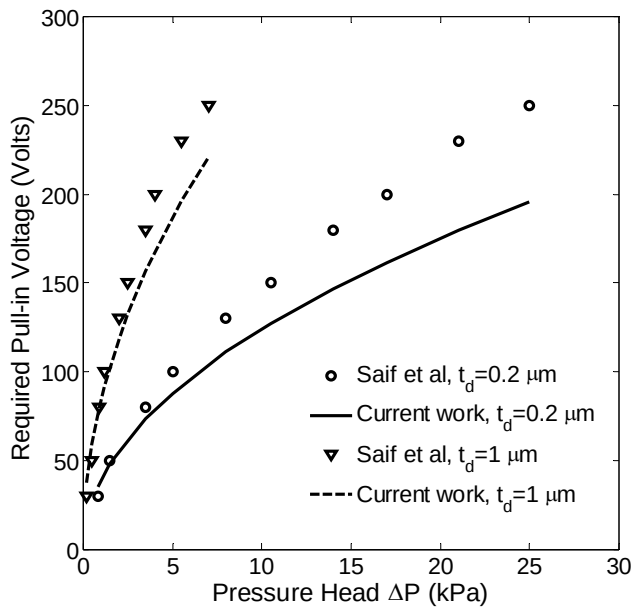

Figure 7 Comparison of current work with results from the literature (Saif et al., 1999) different dielectric layer thicknesses

6. Conclusion

A segment-wise simulation model has been developed for an electrostatically actuated diaphragm compressor. The segmentation technique involves dividing the cavity compression chamber into a finite number of movable parallel plate capacitors. A force balance on the diaphragm was performed during the electrostatic zipping actuation, which represents the compression stroke. The model, which was verified with analytical approaches in literature, predicts the operating voltage of the compressor and the vibration frequency of the diaphragm. In comparison to the

results from previous work, a slightly lower voltage was estimated because the cavity profile was approximated more accurately by the series of the capacitors. The simulation results from the current work show that to generate a pressure head of 5 to 25 kPa, the model predicts an operating voltage of 250 V, while for a pressure head of 750 kPa the diaphragm compressor needs an operating voltage of 1243 V. Finally, if the vibration frequency of the diaphragm is 90 Hz, which results in a refrigerant flow rate of about 3000 ml/min, the diaphragm compressor can be used in small-scale refrigeration systems for electronics devices.

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