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# Analysis of a nano-scale thermo-acoustic refrigerator

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ABSTRACT

Purpose of this study is to analyze a nano scale thermo-acoustic refrigeration cycle in terms of its thermodynamic performance. A nano scale thermo-acoustic refrigerator operating with Maxwell–Boltzmann gas and $He^4$ is chosen as the working fluid is considered. Thermo-size effects that are dominant at the nano scale are taken into account too. In addition, a new thermo environmental method identified as modified ecological function for the refrigeration cycles is proposed. Considered system are analyzed with this new proposed method as well as basic thermodynamic criteria including COP, cooling load, work input and entropy generation. Results are obtained numerically and presented.



# Analyse d'un réfrigérateur nanométrique thermo-acoustique

*Mots clés :* Échelle nanométrique ; Thermo-acoustique ; Froid ; Fonction écologique modifiée

## 1. Introduction

Currently, there is increasing trend toward the use and the design of more effective heat engines and refrigerators. Therefore, improving the performance and efficiency of refrigerators has become an obligation. The use of alternative energy sources or the development of new technologies can be investigated as two possible solutions. In this paper, thermo-acoustic refrigerators that make possible to cool any place by means of sound wave are the subject of investigation.

One way to obtain more efficient thermal cycles is to apply finite-time thermodynamic (FTT) proposed by Curzon-Ahlborn and Novikov. They presented an endoreversible heat engine called as Curzon–Ahlborn–Novikov (CAN) engine (Curzon and Ahlborn, 1975; Novikov, 1958). Following the development of

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**Nomenclature**

| | |
|---|---|
| $A$ | area [m$^2$] |
| $ec$ | classical ecological function [J] |
| $E$ | modified ecological function [J] |
| $F$ | free energy [J] |
| $H$ | enthalpy [J] |
| $m$ | mass [kg] |
| $N$ | number of particles |
| $S$ | entropy [JK$^{-1}$] |
| $Q$ | heat [J] |
| $T$ | temperature [K] |
| $V$ | volume [m$^3$] |
| $P$ | pressure [kPa] |
| $U$ | internal energy [J] |
| $W$ | work input [J] |
| $x$ | pressure ratio |

*Subscripts*

| | |
|---|---|
| $A$ | amplitude |
| $H$ | high |
| $gen$ | generation |
| $L$ | low |
| $m$ | mean |
| $o$ | environment |
| $R$ | refrigerator |

*Greek letters*

| | |
|---|---|
| $\varphi$ | coefficient of performance |
| $\lambda$ | coefficient of performance of reversible refrigeration cycle |

FTT, new criteria were submitted by several authors to evaluate the thermal cycles. The most widespread criterion was submitted by Angulo-Brown (1991) and improved by Yan (1993). Some examples of the refrigeration cycles with FTT and ecological as well as thermo-acoustic cycles can be found in references Acikkalp (2013), Chen et al. (2005, 2007a, 2007b, 2007c, 2009, 2012), Huang et al. (2008), Kan et al. (2011), Li et al. (2009, 2011), Sisman and Muller (2004), Tyagi et al. (2002), Wu et al. (2003, 2009, 2010), Yan and Lin (2000), and Zhu et al. (2005a, 2005b, 2006a, 2006b). In references Acikkalp (2013), Chen et al. (2005, 2007a, 2007b, 2009, 2012), Huang et al. (2008), Li et al. (2009, 2011), Tyagi et al. (2002), Wu et al. (2009), Yan and Lin (2000), and Zhu et al. (2005a, 2005b, 2006a, 2006b), conventional refrigeration cycles were investigated with ecological function. Huang et al. (2008) evaluated the performance of irreversible four-temperature-level heat pump. They found that the ecological optimization makes the entropy generation rate decrease 76.8%, the coefficient of performance increase 33.6% and the heating load decrease 53.7%. An irreversible three-temperature-heat source refrigerator was researched by Yan and Lin (Yan and Lin, 2000). They reported that using the ecological optimization criterion to investigate the optimal performance of an irreversible three-heat-source refrigerator is effective and advantageous. In Chen et al. (2005, 2007a), an irreversible Carnot refrigeration cycle and an irreversible Carnot heat pump were optimized with exergy-based ecological function and these results are obtained for refrigeration cycle and heat pump respectively; exergy output rate decreased about 17%, the cooling load decreased about 16%, the COP increased about 8% and the entropy generation rate decreased about 30% and the exergy-output rate decreased about 16.6%, the COP increased about 16%, and the entropy-generation rate decreased about 40%. In Chen et al. (2007b, 2009, 2012), Li et al. (2009, 2011), and Zhu et al. (2005a, 2005b, 2006a, 2006b), exergy-based ecological function is used for investigation of the irreversible and endoreversible refrigeration cycles with different heat transfer laws. They asserted that ecological function had advantageous thermodynamical criterion. Tyagi et al. (2002) researched Stirling and Ericsson heat pump with ecological function. Considered heat pumps are assumed as operating with finite heat reservoir. Acikkalp (2013) investigated four-temperature-level absorption refrigerator and suggested a novel criterion. Wu et al. (2009, 2010) studied micro thermoacoustic micro refrigeration and heat engine cycles operating with ideal Bose gas. Wu et al. (2003) analyzed and made optimization of an irreversible thermocoustic engine, which is used generalized heat transfer laws, with FTT. Chen et al. (2007c) evaluated an irreversible thermoacoustic cooler by using exergetic efficiency. In Chen et al. (2012) and Kan et al. (2011), irreversible thermoacoustic cooler and heat engines were analyzed with finite-time exergoeconomic criterion.

Nano thermal cycles may be an alternative for more efficient thermal cycles. Interests of researchers about the nano scale thermal cycles have risen for last decades, because of the fast development in the nano science and technology. However, thermo-size effects should be considered, because of important influences on the thermal properties. In Babac and Sisman (2011a), Firat et al. (2010), Ozturk et al. (2011), Sisman (2004), Sisman and Babac (2012), Sisman and Muller (2004), and Sisman et al. (2007), thermal properties of quantum gases are investigated deeply regarding thermo-size effects. As a result of this, some papers can be found about assessment of nano scale thermal cycles in Açıkkalp and Caner (2015a, 2015b, 2015c, 2015d), Babac and Sisman (2011a, 2011b), Guo et al. (2012), Nie and He (2008, 2009), Nie et al. (2008), and Şişman and Saygin (2001). Nano/micro thermal cycles operating with Maxwell–Boltzmann gases are studied in Açıkkalp and Caner (2015a, 2015b), Nie and He (2008, 2009), and Nie et al. (2008). Some cycles investigated are Brayton, Carnot, refrigeration and dual cycles. They are aimed to obtain maximum performance conditions. Similarly, thermal cycles operating with Bose and Fermi gas under different degeneracy conditions are investigated to obtain their performance characteristics (Açıkkalp and Caner, 2015c, 2015d; Guo et al., 2012; Şişman and Saygin, 2001). Babac and Sisman (2011b) analyzed for heat engine and refrigeration cycles considering thermosize effects. Their work output, efficiency and coefficient of performances are studied to obtain the most efficient performance.

In this paper, we analyze a nano scale thermo-acoustic refrigerator as an alternative thermal device. Working fluid of the nano scale refrigeration cycle operating with Maxwell–Boltzmann gas ($He^4$) and thermo-size effects that affect thermal behavior of the gas in the nano scale are considered too. In addition, we propose a modified ecological function to assess refrigeration cycles and use it first time at the thermo-acoustic refrigerator. Classical ecological function considers work output and exergy destruction for heat engines and cooling load and lost cooling potential for refrigeration cycles. We aim to consider all losses in a refrigeration cycle with modified ecological function. Detailed information about the modified ecological function is provided in section 2. We apply this method to thermoacoustic refrigerators because thermoacoustic refrigerators might be an alternative technology for sustainability.

Nano thermoacoustic refrigerator operating Maxwell–Boltzmann gas considering thermosize effects is studied first time. In addition, it is evaluated with modified ecological function. Modified ecological function and basic performance parameters involving COP, work input, entropy generation and cooling load are investigated and results are obtained numerically.

## 2. System analysis

We consider nano scale thermo-acoustic refrigeration cycle and its thermodynamic analysis is made; P-V diagram of the cycle is showed in Fig.1. It is assumed that refrigeration cycle operates with Maxwell–Boltzmann gas and $He^4$ as working fluid. In the nano scale, thermodynamic laws must be adapted by using statistical mechanics. In addition, thermo-size effects are considered in the analysis. Free energy (F) must be defined and it is written as follows (Sisman, 2004; Sisman and Muller, 2004):

$$F = -NkT\left(\ln\left(\frac{V\pi^{3/2}}{8L_c^{3}N}\right)+1\right)+NkT\frac{L_cA}{2\sqrt{\pi}V} \tag{1}$$

where $N$ is number of particles, $L_c$ is half of the most probable Broglie's wave length $\left(L_c(T)=\frac{h}{\sqrt{8mkT}}\right)$, $h$ is the Planck constant, $k$ is the Boltzmann constant, $A$ is the area, $V$ is the volume and $T$ is the temperature. Using the free energy (F), entropy (S) of the Maxwell–Boltzmann gas is obtained as:

$$S = -\left(\frac{\partial F}{\partial T}\right) \tag{2}$$

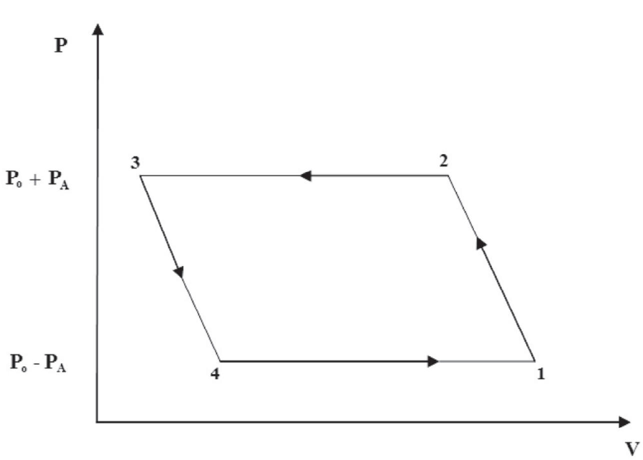


**Fig. 1 – P-V diagram of the nano scale thermo-acoustic refrigerator.**

$$S = -\frac{kN}{16}\left(\frac{Ah\sqrt{2/h}}{\sqrt{kmTV}}-16\ln\left(\frac{2\sqrt{2}\pi^{3/2}(kmT)^{3/2}V}{h^3N}\right)-40\right) \tag{3}$$

where $m$ is the atomic mass of the gas. Similarly, pressure (P) of the gas is given as follows:

$$P = -\left(\frac{\partial F}{\partial V}\right) \tag{4}$$

$$P = \frac{AhkNT}{4\sqrt{2\pi}\sqrt{kmT}V^2}+\frac{kNT}{V} \tag{5}$$

The internal energy of the gas (U) can be defined as:

$$U = F + TS \tag{6}$$

$$U = \frac{k_BNT}{16}\left(24+\frac{Ah\sqrt{2/\pi}}{\sqrt{kmT}V}\right) \tag{7}$$

The enthalpy of the gas (H) is

$$H = U + PV \tag{8}$$

$$H = \frac{5k_BNT}{2}+\frac{3AhkNT}{8\sqrt{2\pi}\sqrt{kmT}V} \tag{9}$$

Heat input ($Q_H$), removal heat ($Q_L$) and work input ($W$) are defined respectively by eqs. (10)–(12):

$$Q_H = H_2 - H_3 \tag{10}$$

$$Q_L = H_4 - H_1 \tag{11}$$

$$W = Q_H - Q_L \tag{12}$$

Using the second law of the thermodynamics, entropy generation ($S_{gen}$) of the system is given as follows:

$$S_{gen} = \left(\frac{Q_H}{T_H}-\frac{Q_L}{T_L}\right) \tag{13}$$

The coefficient of performance (COP) of the refrigerator can be obtained as follows:

$$\varphi = \frac{Q_L}{W} \tag{14}$$

Original ecological function for heat engines and refrigeration cycles is shown in eqs. (15) and (16) respectively:

$$ec = W - T_oS_{gen} \tag{15}$$

$$ec_R = Q_L - \lambda T_oS_{gen} \tag{16}$$

In this paper, ecological function (E) is modified for the refrigeration cycle and this modified ecological function is described in eq. (15).

$$E = Q_L - (W + T_oS_{gen}) \tag{17}$$

**Table 1 – Fixed parameters used in the calculations.**

| Data | Unit | Value |
|---|---|---|
| $m$ | $kg$ | $6.6474 \times 10^{-27}$ |
| $h$ | $Js$ | $6.6262 \times 10^{-34}$ |
| $k$ | $J$ | $1.0381 \times 10^{-23}$ |
| $T_o$ | K | 298.15 |
| $A$ | $m^2$ | $6 \times 10^{-18}$ |
| V | $m^3$ | $1 \times 10^{-27}$ |

The purpose of this modification is to obtain maximum cooling load, while sum of the work input and exergy destruction ($T_oS_{gen}$) is minimum. The sum of the work input and the exergy destruction can be considered as the losses in the cycle, therefore minimized for a refrigeration cycle. Decreasing at work input cause increasing at the COP, this can be seen in eq. (14). Similarly decreasing exergy destruction or lost potential work that is originated from the entropy generation is an undesired result for all thermal cycles and it is tried to decrease. Hence, reduction at the exergy destruction is resulted in increasing at the COP. Operating pressures of the thermoacoustic refrigeration cycle are $P_o + P_m$ and $P_o - P_m$, where $P_o$ is the initial pressure and $P_m$ is the mean pressure. Similarly, operating temperatures are $T_m + T_A$ and $T_m - T_A$, where $T_A$ is the temperature amplitude and $T_m$ is the mean temperature. Temperature and pressure relations are shown in eqs. (18)–(22) (Wu et al., 2009, 2010):

$$T_2 = T_m + T_A \tag{18}$$

$$T_4 = T_m - T_A \tag{19}$$

$$T_3 = T_4 x^{0.4} \tag{20}$$

$$T_1 = \frac{T_4}{x^{0.4}} \tag{21}$$

$$x = \left(\frac{P_2}{P_4}\right) = \left(\frac{P_m + P_A}{P_m - P_A}\right) \tag{22}$$

where $x$ is the pressure ratio of the system. In this paper considered parameters are investigated as dimensionless because of avoiding very small values and facilitating calculations. They are expressed in eq. (23):

$$w = \left(\frac{W}{Nk_BT_m}\right), \quad q_L = \left(\frac{Q_L}{Nk_BT_m}\right), \quad e = \left(\frac{E}{Nk_BT_m}\right), \quad s_{gen} = \left(\frac{S_{gen}}{Nk_B}\right) \tag{23}$$

## 3. Results and discussion

In this section, results are presented. Our purpose is to determine which parameter including temperatures ($T_A$, $T_m$) and pressures ($P_A$, $P_o$) affects the system mostly. That is why we hold other parameters constant except for investigating one. Fixed parameters used in the calculations are listed in Table 1.

Figs. 2–5 show the effects of pressures on the system. Effect of $P_A$ can be seen in Figs. 2 and 3. Considered parameters are obtained by changing $P_A$ and holding constant other variables, and then these parameters are combined and Figs. 2 and 3 are made. Range of the $P_A$ is assumed from 100 kPa to 390 kPa to determine the effect of the $P_A$. Fig. 2 shows changes of $w$, $e$, $s_{gen}$ and $q_L$ in terms of $\varphi$. As it is seen, change of the parameters is logarithmic. Work input has a maximum, while others have not an extremum point. $w$ Reaches its maximum at $\varphi = 5.54$; changes of $q_L$, $e$ and $s_{gen}$ are fast until the point

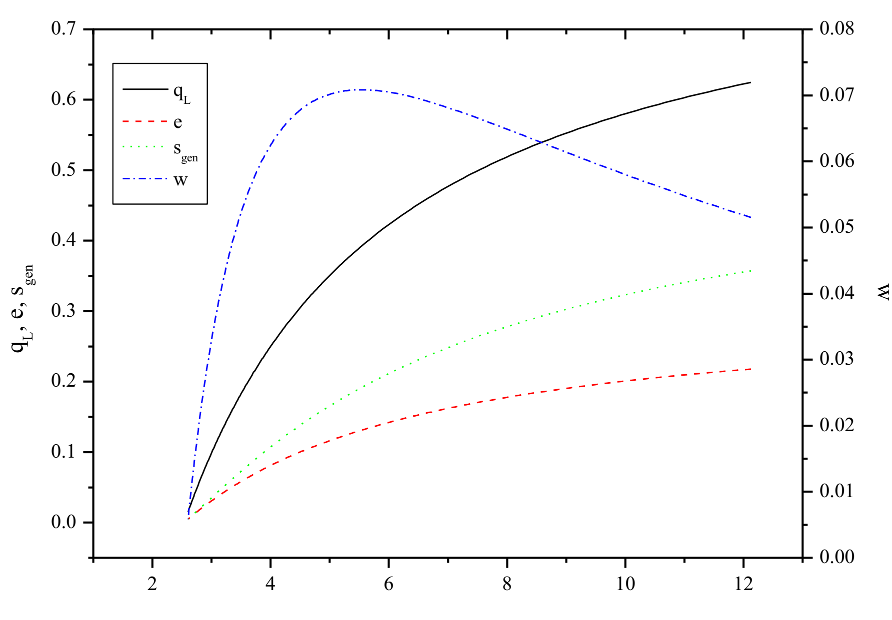


**Fig. 2 – Change of parameters according to φ with effect of $P_A$ ($P_A$ changes from 100 kPa to 390 kPa, $T_m$ = 300K, $T_A$ =50 K, $P_o$ = 1000 kPa).**

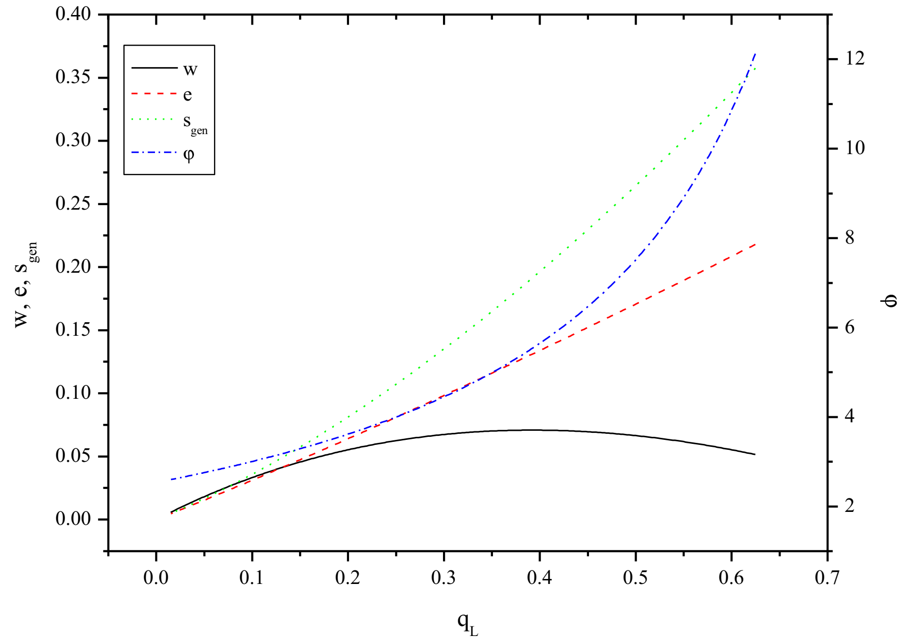


**Fig. 3 – Change of parameters according to $q_L$ with effect of $P_A$ ($P_A$ changes from 100 kPa to 390 kPa, $T_m$ = 300K, $T_A$ =50 K, $P_o$ = 1000 kPa).**

where $w$ is the maximum. Changes of $w$, $e$, $s_{gen}$ and $\varphi$ according to $q_L$ are indicated in Fig. 3. $w$ Reaches its maximum when $q_L$ is equal to 0.393; other parameters increase with $q_L$. These increases are linear for $e$ and $s_{gen}$ but logarithmic for the COP.

According to Figs. 4 and 5, investigated parameters are affected by the $P_o$, in which variation range is chosen between 1000 kPa and 2000 kPa. Figs. 4 and 5 are made in similar way with Figs. 2 and 3. Investigated parameters are calculated by changing $P_o$ and holding all other variables constant and then they are combined. Results shows that effects of $P_o$ is less than effect of the $P_A$. All changes are nearly linear for $\varphi$ and $q_L$ and all parameters except for $w$ decrease with $\varphi$ and vice versa is true for the change with $q_L$.

Figs. 6–9 reveal the variation of investigated parameters according to $T_A$ and $T_m$. They are made in same way with other graphics. As it is seen in them, $\varphi$ is affected so little by $T_A$ and $T_m$. On the contrary, other parameters are highly affected by

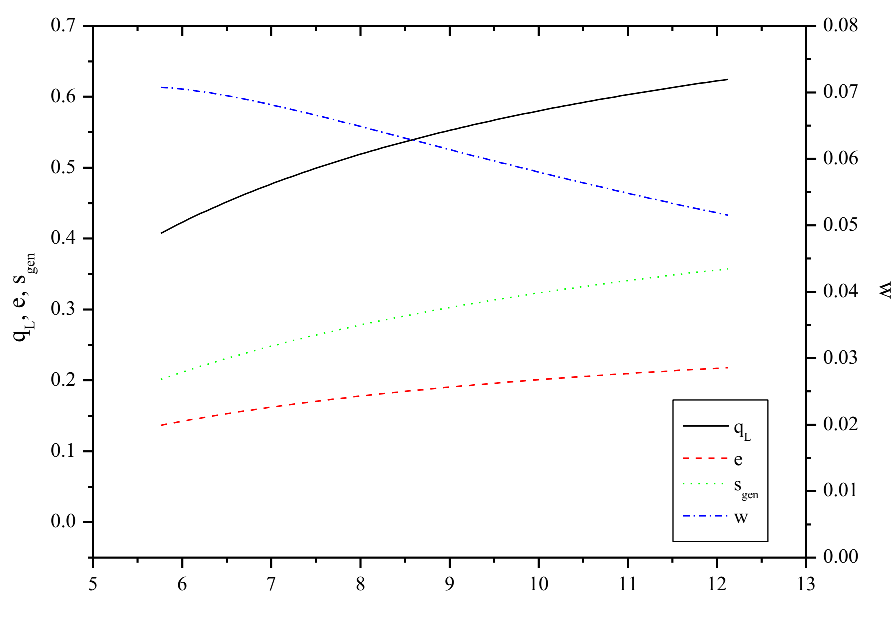


**Fig. 4 – Change of parameters according to φ with effect of $P_o$ ($P_o$ changes from 1000 kPa to 2000 kPa, $T_m$ = 300K, $T_A$ =50 K, $P_A$ = 200 kPa).**

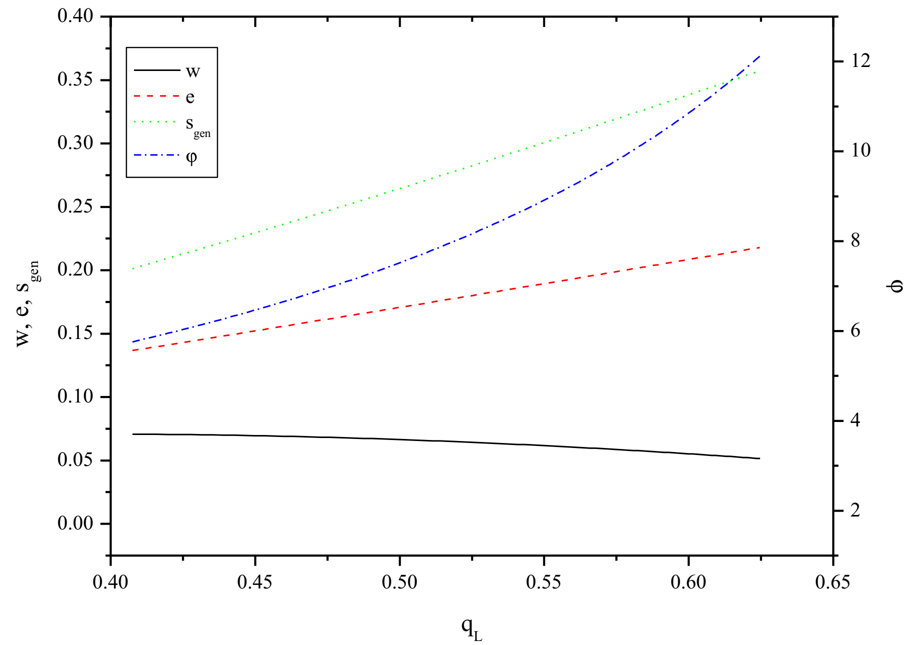


**Fig. 5 – Change of parameters according to $q_L$ with effect of $P_o$ ($P_o$ changes from 1000 kPa to 2000 kPa, $T_m = 300K$, $T_A = 50$ K, $P_A = 200$ kPa).**

the $T_A$. They change logarithmically and all of them increase with φ. Change of $T_A$ is from 25 K to 100 K. Similar results are valid for change with $q_L$; however, variation of the $w$ is linear. Variations of the parameters with $T_m$ can be seen in Figs. 8 and 9. Mean temperature range in Figs. 8 and 9 is from 250 K to 340 K. It can be seen in Fig. 8 that all parameters change linearly and their changes are low except for $w$. In addition, all parameters tend to increase according to $\varphi$. Same results are true for Fig. 9. Variations of $w$, $e$ and $s_{gen}$ increase so slow according to $q_L$, in contrast to $\varphi$ that rises up fast.

These results show that $P_A$ is the most effective parameter on the nano scale thermo-acoustic refrigerator. It causes a maximum for work input that is an undesired result for any refrigeration cycle. Because, the higher work input means the lower COP value. In addition, $P_A$ leads to great increases for the investigated parameters that vary logarithmically. Similarly, $T_A$

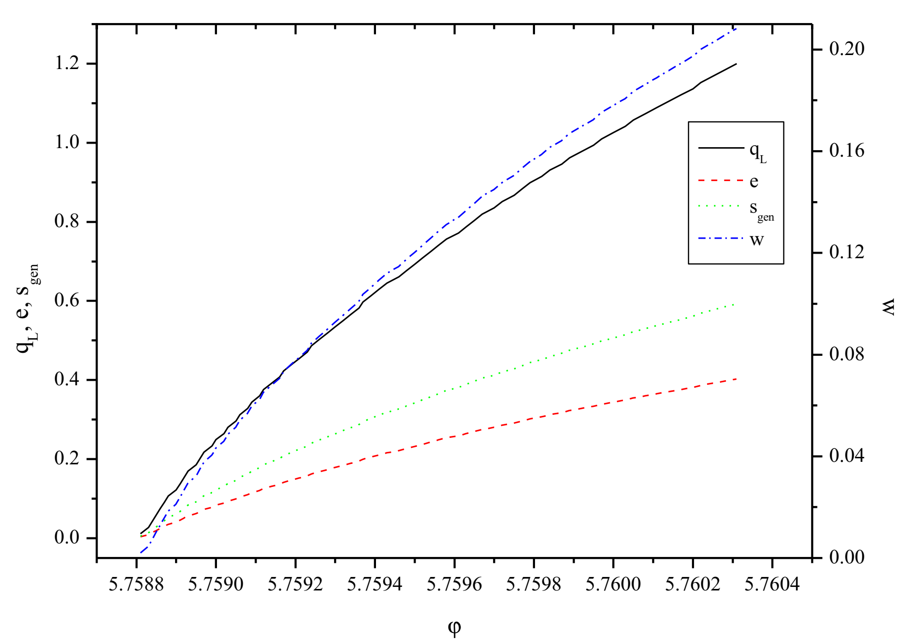


**Fig. 6 – Change of parameters according to $\varphi$ with effect of $T_A$ ($T_A$ changes from 25 K to 100 K, $T_m = 300K$, $P_o = 1000$ kPa, $P_A = 200$ kPa).**

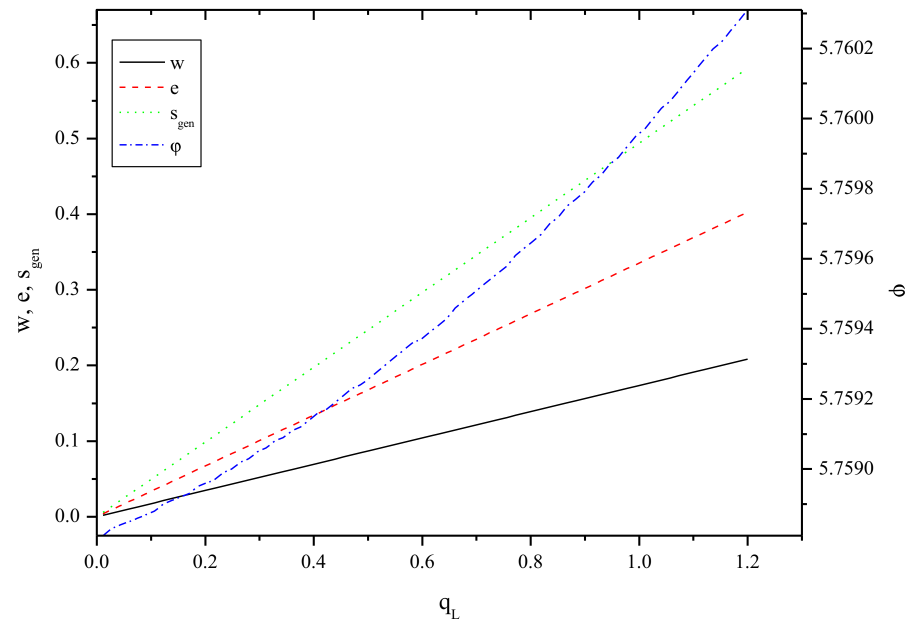


**Fig. 7 – Change of parameters according to $q_L$ with effect of $T_A$ ($T_A$ changes from 25 K to 100 K, $T_m$ = 300K, $P_o$ =1000 kPa, $P_A$ = 200 kPa).**

affects the investigated parameters significantly except for the COP.

## 4. Conclusions

In this paper, a nano scale thermo-acoustic refrigerator operating with Maxwell–Boltzmann gas is studied. Effects of some parameters including $P_A$, $P_o$, $T_A$ and $T_m$ are investigated. According to results mentioned above, $P_A$ and $T_A$ are the most effective parameters for the system. In addition, $P_A$ causes the maximum work input. It should be avoided from the maximum work input value that reduce COP of the system.

Finally, it is recommended that more research should be conducted about the analysis of nano scale thermal system since developments at the nano technology have been increasing fast for the last decade and it is a promising discipline for the energy research.

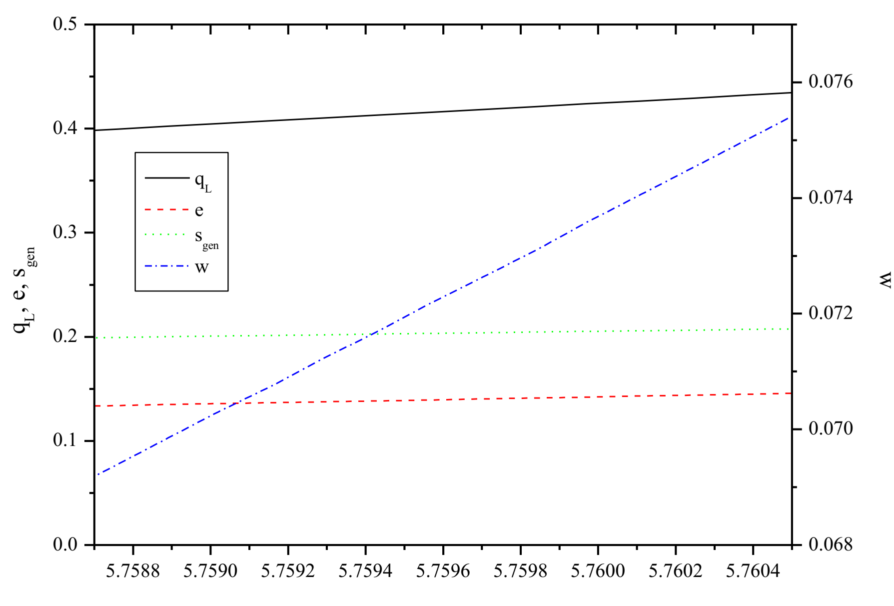


**Fig. 8 – Change of parameters according to φ with effect of $T_m$ ($T_m$ changes from 250 K to 40K, $T_A$ = 50K, $P_o$ =1000 kPa, $P_A$ = 200 kPa).**

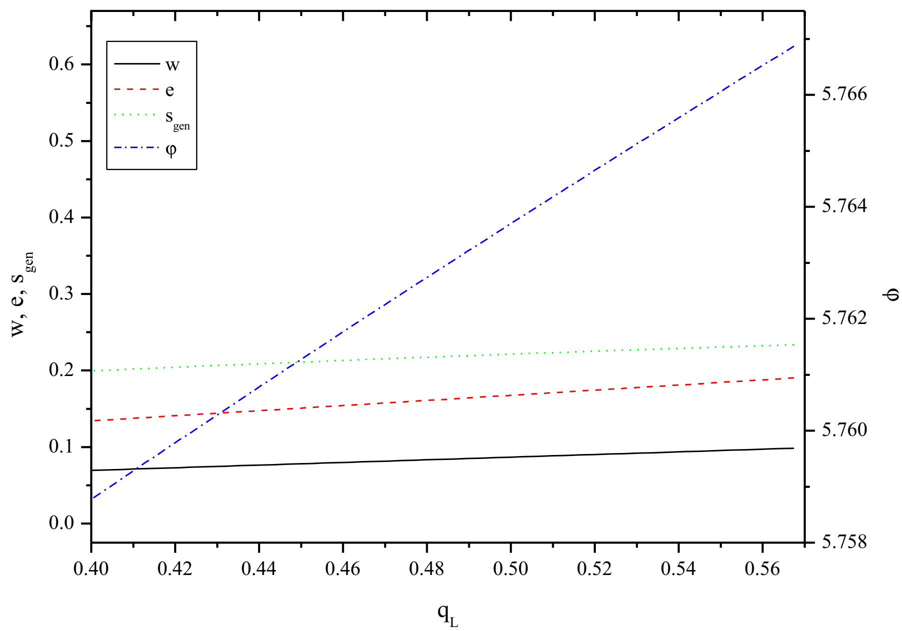


**Fig. 9 – Change of parameters according to $q_L$ with effect of $T_m$ ($T_m$ changes from 250 K to 40K, $T_A$ = 50K, $P_o$ =1000 kPa, $P_A$ = 200 kPa).**

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