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Review Article

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A Review Study of the Feasibility of Piezoelectric Fan Techniques for Cooling Electronic Components

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Abstract

The electronic equipment industry has developed rapidly in recent years. The amount of heat emitted from such equipment is seriously increased. Increasing the temperature of the electronic devices degrades their performance and as a final result their failure. Therefore, the requirements for an effective cooling system have become more important than ever. One of the most important methods of heat dissipation that the researchers focused on is the use of piezoelectric fans (PE). The current study reviews most of the developments that have taken place since its discovery nearly 40 years ago and focused on reducing power consumption. Most of the improvements and developments have been focused on obtaining optimal designs for these piezoelectric fans, which are used in different applications. This review clarifies the foundations and concepts of designing piezoelectric fans by comparing the data presented in previous studies. Furthermore, in the last ten years, numerical simulation has entered as an effective tool in predicting the optimal design of piezoelectric fans. The design of piezoelectric fans is in two forms, either single or multiple. The single fan system is used within a limited range of applications, as large cooling systems cannot be replaced by it. Therefore, the cooling system consisting of multiple piezoelectric fans is promising as a unique solution to effectively dissipate heat in electronic devices. The percentage of experimental studies is about 32 % while the studies of CFD is about 21 %, and the combined one is about 47 %.

Keywords: Piezoelectric fans, Heat sink, Heat dissipation, Power consumption, Frequency.

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1. Introduction

Microelectronic devices such as mobile phones, laptop computers, etc. have become small and thin, while the functions they perform have increased, and this leads to an increase in the heat emitted from them. To keep it from failing, the cooling requirements also increased, and it became the most important goal for engineers and researchers to obtain an efficient cooling system with low energy consumption. Unlike traditional cooling methods, which use rotating fans and consume relatively large energy and produce annoying sounds and vibrations, piezoelectric fans have several advantages, the most important of which is their low energy consumption and the absence of rotating parts that cause unwanted sounds, in addition to that they require a small size for installation. Where the fan consists of a vibrating fin stirred by an alternating current that causes it to vibrate in the desired direction. According to its position, vertically or horizontally. Because of the movement of the blade back and forth near the hot surface, it breaks the thermal boundary layer and changes the properties of the surrounding air. Therefore, investigation and research within this field aims to reach piezoelectric fan designs that cause the largest possible disturbance near the hot surface of the air layer and obtain sufficient air velocities to increase heat exchange. The end of the seventies and the beginning of the eighties is the date when piezoelectric fans were used for the first time [1] It was presented in academic forums for the first time in 1985 [2] . Analysis into this field aims to obtain small-sized cooling systems with low energy consumption.

This review will focus on studying the effect of changing the parameters including applied frequency, blade amplitude, geometrical parameters of the piezofan, fan blade orientation, and the piezofan blade tip-hot surface gap of the different piezoelectric fans on the performance of the cooling system.

During the next few decades, piezoelectric fans can be considered a promising research area for the development of cooling systems that are suitable and cheap in terms of design and energy consumption, other than systems that rely on liquids or phase-changing materials to cool electronics [3-10]. The use of air-cooling techniques is cheap and efficient, and currently more than 90% of cooling solutions in electronics depend on air [11-16]. Some air-cooling techniques, especially those that use rotating fans, indicate some defects, including their need for great energy [17-23]. Currently, piezoelectric fans, due to the focus of many researchers, have been considered alternative solutions to traditional air-cooling technologies due to their high efficiency and ease of components [24-30]. The greatest challenge facing is to increase their applications in different fields, thus reducing energy consumption rates in many technical applications.

Because of the great need to find alternative solutions and techniques for air moving mechanics, the last decade witnessed a huge boom in the study of piezoelectric fans, as well as the availability of advanced numerical simulation programs that made understanding its principles easier, so many studies were published in the field of piezoelectric fans recently. The piezoelectric fan with a single blade is a rectangular bar of fixed width and thickness (w, t) and is driven by a voltage source to sway back and forth periodically. The piezoelectric fan is made of different types, but the most famous one is PZT. These fans consume less energy and operate at the resonant frequency to obtain maximum displacement and therefore greater agitation of the air surrounding the hot surface.

This review was divided into six sections as follows: section 1 introduces general introduction about the piezoelectric fan technology. Section 2 summarizes the most important principles of piezoelectric fans. Section 3 states the geometric and operational features of the blade. Utilization of numerical methods as an effective tool for a greater understanding of piezoelectric fans is discussed in Section 4. Section 5 mentions some applications of piezoelectric fans and their usefulness in reducing energy consumption, and the last section is the conclusions.

1. Piezofan fluctuation

It is important to know the basics and principles of manufacturing piezoelectric fans. As well as knowing the different parameters and their impact on the performance of the piezoelectric fan, including how the blade moves and other important properties. These are essential in understanding and researching this field. Figure 1 shows the most important parameters of the piezoelectric fan.

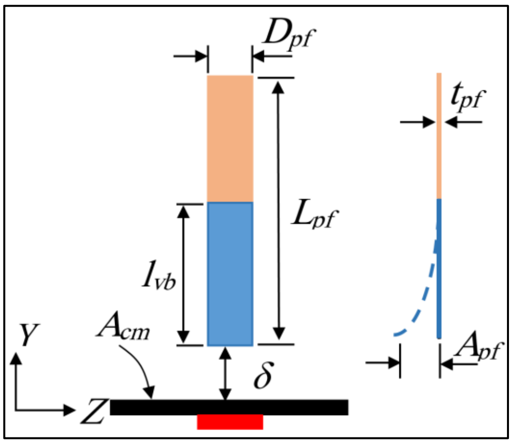

Fig. 1 Geometrical parameters of piezoelectric fan [31].

Where, l_{pf}, D_{pf}, t_{pf}, A_{pf}, are length, width, thickness, and amplitude of the piezoelectric fan, respectively. l_{vb} is the vibrating blade length, A_{cm} is the hot surface area, and δ is the distance from hot surface to blade tip. The shape of the piezoelectric fan is affected by the piezoelectric (PZT) material installed on it and it can be defined mathematically as in eq. (1) [32], where y(x) represents the displacement of the flexible blade, A_{xc} is the cross-section area of the flexible blade, coefficient β is represented by eq. (2) [32]. Where, m is the mass, I is the moment of inertia, f operating resonant frequency of the piezoelectric fan, L is blade length and E is Young's modulus of the blade.

$$Y(x) = A_{xc}\,[(sin(\beta.L) - sinh(\beta.L)).sin(\beta.x) - sinh(\beta.x)) + (cos(\beta.L) - cosh(\beta.L)).(cos(\beta.x) - cosh(\beta.L)) \quad (1)$$

$$\beta = \sqrt[4]{\frac{2\pi.f.m}{L.I.E}} \quad (2)$$

The piezoelectric fan blade is stimulated by the piezoelectric patch when a sinusoidal voltage is applied to both sides of the patch, which causes the blade to vibrate in a periodic alternating manner, as in eq. (3) [33] which represent the instantaneous displacement of the blade along any t. Where f is the resonant frequency of the first mod shape (gives the maximum displacement and oscillation of the blade) which is supplied by a DC voltage source, y is the displacement of the blade at any time t. A is the peak amplitude of the flexible blade. The instantaneous applied voltage V across the piezoelectric patch is represented by eq. (4) [34]. Where V_0 represent the maximum supplied voltage.

$$y(t) = A.sin(2\pi.f.t) \quad (3)$$

$$V(t) = V_0.sin(2\pi.f.t) \quad (4)$$

When the blade moves back and forth periodically, a pair of vortices is formed for each cycle of vibration. The direction of rotation of these vortices is opposite one to the other and is seen on both sides of the tip blade through each single cycle. Most of the previous literature in this field adopted the two-dimensional case, so that taken a section at the midpoint of its blade. The motion of the vortices is such that the air near the trailing edge of the blade is of positive value [2].

When vortices are formed due to the vibration of the piezoelectric fan blades, as shown in Fig. 2, it passes through four distinct stages: initiation, development, separation, and diffusion. The first stage begins with the formation of vortices at the maximum displacement (90) degrees, (2b, 2a), when the velocity is low and the pressure difference between the front and the back of the blade is close to zero [35, 36]. The development of vortices continues in the second stage when the blade returns to the center position 0 (2c) until reaching -45 (2d) [37], After that, the stage of separation of the vortices forming comma shape (Fig. 2) and start spread in the space surrounding the blade, moving in the opposite direction (-90) so that it has a maximum displacement (2e) when the tip of the blade is displaced to the point where the pressure returns to zero between the two ends of the blade [35]. The numerical study showed that the pressure difference plays an essential role in the formation of vortices when the piezoelectric fan blade is vibrating [35] .

Agarwal et al. [38] showed that vortices form near and around the tip of the fan blade and are horseshoe-shaped at the beginning when it accelerated from zero velocity at the maximum displacement of the blade. When the flexible fan blade moves to τ = -π/5 (τ: phase) as in Fig. 3, the horseshoe vortices start separate from the fan blade tip and another hair-pin vortices forms. At the end, the eddies of edge and tip are met to form the airflow downstream.

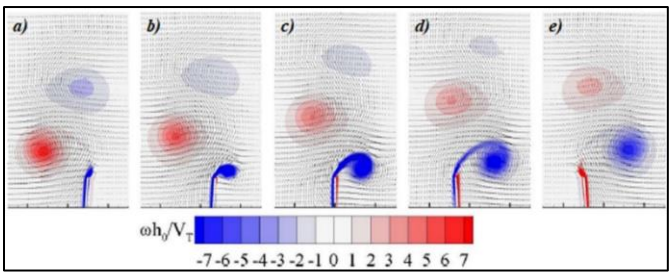

Fig. 2 Vortices generation stages [35].

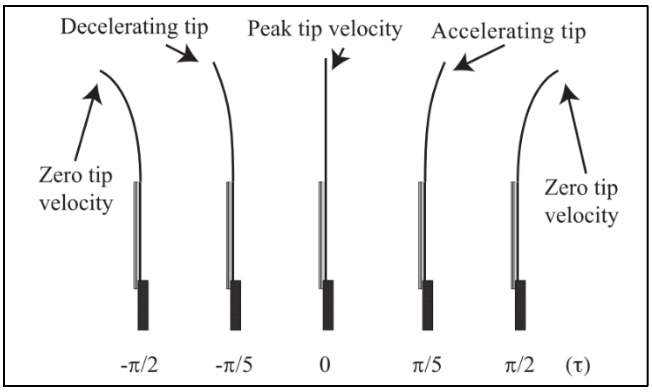

Fig. 3 Fan oscillation phase (τ) [38].

2. Influence of piezoelectric fan operational parameters

To understand the piezoelectric fan accurately, many important parameters that affect the work of the piezoelectric fan must be examined. These parameters and geometric properties, in addition to the blade materials, must be considered as key points because it controls the operating properties of the piezoelectric fan, including the blade vibration amplitude and operating resonance frequency. These important relationships will be clarified in this section. Obtaining the maximum resonant frequency and maximum displacement of the piezoelectric fan blade is very important in piezoelectric fan applications. Achieving this is difficult, but satisfactory solutions must be reached.

2.1. Effect of operation frequency

Yoo et al. [39] studied several types of flexible plates used in piezoelectric fan design and carried out a structural dynamic analysis to find the optimal resonance frequency for the best material. He found a non-linear relationship between the frequency and the blade length of the piezoelectric fan with constant piezoelectric patch length as shown in eq. (5). He concluded that the shorter the length of the fan blade, the higher the frequency, and thus the higher air flow velocity, which reaches a maximum of 3.1 m / s at 60 Hz, 220 volts.

$$f_r = G * \frac{t}{L^2} * \sqrt{\frac{E}{12 * \rho * (1 - \sigma^2)}} \quad (5)$$

Where, f_r resonance frequency, E material modulus of elasticity, G coefficient equal 0.125π, L blade length, t blade thickness, ρ density, and σ is poisson's ratio.

Kimber and Garimella [40] showed that the resonance frequency has the most prominent role in reaching the best performance of the piezoelectric fan among other operating parameters such as blade displacement, length, or width, etc. Because operating under the resonant frequency yields the maximum displacement for the piezofan, it results in increased circulation and greater air mixing. This, in turn, enhances the heat exchange process and improves the cooling operation.

Lin et al. [41] designed five different types of piezoelectric fans with blades of rectangular or trapezoidal shapes, as in the as in Fig. 4. They studied the geometric parameters of the blade shape, as shown in Fig. 5. They showed that the E fan (Fig. 4) has the highest resonant frequency while the F fan has the lowest frequency. When the ratio of blade width to piezoelectric patch width (w_2/w_1) is less than one (fan E), the blade mass generates an inconsistent load distribution towards the clamping point. Thus, the resonance frequency increases [38, 42]. While when the ratio is greater than one, the opposite happens (fan D).

$$I = \frac{t_{blade}^3 * W}{12} \quad (6)$$

Where, I is blade moment of inertia, t_{blade} and W are blade thickness and width, respectively.

It was concluded that the operating frequency of the piezoelectric fan blades has a significant effect on the air flow rate, as it found an increase in the flow rate by 22.4%, 49.3%, and 97% as the frequency increased by 17.3%, 36. 7% and 47.7%, respectively,[41].

Lei et al. [43] found that the rate of heat transfer from the hot surface is 13% lower when working with the second mode of frequency compared to the first mode, This is because the second frequency results in a smaller oscillation displacement for the piezoelectric fan compared to the first frequency, thus weakening the air mixing process. Consequently, this leads to a reduced heat transfer due to stagnant air, resulting in less efficient heat transfer compared to the first frequency.

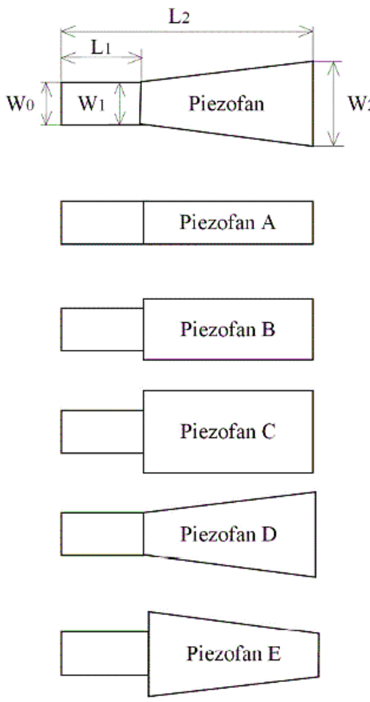

Fig. 4 various shapes of piezoelectric fans [41].

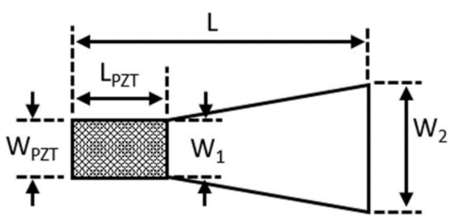

Fig. 5 Geometry of piezoelectric fan blade [41].

Wait et al. [44] studied the higher vibration modes of the piezoelectric fan blade. They found an inverse relationship between flow velocity and the increase of oscillation mode number, while the proportional relationship between power consumption and the increase of the oscillation mode number.

Fairuz et al. [45] also, concluded that the higher oscillation modes are ineffective for cooling microelectronics because the pair of vortices that were observed in the fundamental resonance frequency disappear with increasing the number of vibration modes, and this reduces the mixing efficiency and excitation of the air surrounding the heated surface. The heat transfer rate decreases by 4% and 5% for the second and third resonance frequencies, respectively.

2.2. Effect of fan blade amplitude

Equations (1) and (2) show that the vibration amplitude depends on the design and material of the piezoelectric fan blades, but it can change by adjusting the operating voltage [40]. It is noted that there is a direct relationship between the vibration amplitude of the blade and the operating voltage theoretically [46, 47] But practically, air motion induced by vibration of the blade when the voltage is increased, the damping rate increases significantly [43, 46]. Therefore, the dimensions of the piezoelectric fan blade and the required frequency must be determined first, and then the vibration amplitude is calculated gradually, but without negatively affecting the rest of the properties. Focusing on Fig. 4, the design *E* needs more power to reach the same amplitude of oscillation, and this is considered an additional load due to the distribution of the blade mass [32, 42].

Lin [28] proved that the rate of heat transfer increases with the increase in the vibration amplitude of the piezoelectric fan blade as shown in Fig. 6, which is attributed to the air jet velocity generated by the vibration of the blade. The same result was reached by Liu et al. [49], where verified the hypothesis that heat transfer and the increase in the oscillation amplitude of the blade are directly related.

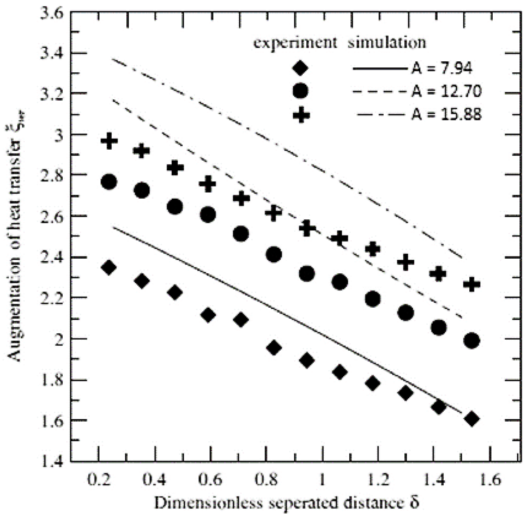

Fig. 6 Dimensionless gap δ against heat transfer increase ξ for various vibration displacements [48].

Yoo et al. [39] concluded that there is a direct relationship between the amplitude of fluctuation of the blade tip and the emerging non-directional air velocity, this causes an increase in fluid flow and disturbance of the surroundings, which causes an increase in the rate of heat transfer. The nondirectional velocity requires a deeper investigation to understand this hypothesis, because at higher vibration amplitudes, the piezoelectric fan blade may generate flow in several directions.

2.3. Effect of piezoelectric fan geometrical parameters

As previously mentioned, the geometrical parameters largely determine the operating characteristics of the piezoelectric fan. It also affects the air dynamics around the surroundings generated by the movement of the piezoelectric fan blade. Understanding the influence of these parameters provides a solid foundation for obtaining piezoelectric fan systems of high quality and efficiency.

Laboratory work done by Yoo et al. [39] deduced the strong relationship between operating frequency and blade length $1/L_2$. Therefore, the use of piezoelectric fans with short blade lengths has become widespread, as high resonant frequencies are obtained. Acicalin et al. [50] reached the same findings by experimenting with two blades of different lengths, 76.2 mm and 68.6 mm, with frequencies of 62 Hz and 103 Hz. It was found that the flow rate is higher by (10-20) % for the shorter blade compared to the larger blade.

However, due to the different applications that use piezoelectric fans, there is no optimal blade length as it differs from one application to another. In this case, the thickness of the blade can be used, which has a direct relationship with the increase in the resonance frequency, to reduce the reverse effect. To prove this theory, [49] conducted a laboratory experiment on two blades of different lengths by a ratio of 3.17%, The theory shows that the difference in the length of the two blades by 3.17 [49], will reduce the operating frequency by 6.25%, but by increasing the thickness of the blade by 33%, the resonant frequency will increase by 12.8%. This proves the feasibility of changing the thickness of the blade to control the resonant frequency instead of its length. The drawback of increasing the thickness of the blade is the increase in the power demand as shown by eq. (6), where the increase is in a cubic rate with increasing thickness while keeping the blade amplitude constant.

Blade thickness is a very important and most used parameter in the literature for controlling the resonance frequency, in contrast to the length, which also allows for frequency adjustment, the blade thickness does not affect the airflow field [41].

We talked about the length and thickness of the blade, and the third dimension remained, which is the width. The width of the blade is one of the easiest dimensions of the geometric shape of the blade because it is not related to the operating frequency at all. Equation (6) Shows that blade width influences and increases power consumption when blade displacement is unchanged [41] proved by recent experiments that the width of the blade has a strong and direct effect on the air flow field when the blade vibrates of the piezoelectric fan, which was imposed by [1] before him, which states that there is a proportional relationship between the disturbance of the flow field and the width of the blade.

Lin [41] investigated the effect of piezoelectric fan blade width on airflow and vortex formation while operational parameters such as resonance frequency and oscillation amplitude are determined by blade thickness. The effect of the irregular blade width of the piezoelectric fan can be illustrated as in Fig. 7, where a clear difference appears between the generation of vortices from the blade E when compared to the rest. When the fans (A-D) vibrate, the flow lines (streamlines) return and are drawn back to the trailing face, thus, creating vortices, and this does not happen in the same way for blade *E*.

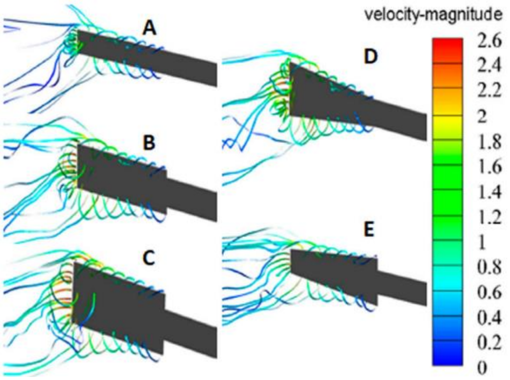

Fig. 7 Streamlines for various piezoelectric fan blade design [41].

The shape of the piezoelectric fan blade affects the air velocity and flow field. Therefore, this effect can be analyzed through experiments shown in Fig. 8, [41]. If we compare the red curves in Fig. 8 as well as the black curves, we will find that the tip of the narrow blade generates small air velocities. On the other hand, the blue curves, which belong to the blades with wide edges, gave high velocities, causing great disturbances near the tip of the blade.

The material of the blade has an important and clear effect on the performance of the piezoelectric fan, and the material parameters such as the modulus of elasticity and the Poisons ratio are among the most important properties, as in eq. (4) [39]. Shyu [51] studied different types of blade material including (Mylar, aluminum, and stainless steel) to show their effect on vibration amplitude and heat transfer. He concluded that the performance of the piezoelectric fan is greatly affected by the type of blade material. Furthermore, it was found that when using Mylar material, it gives high vibration amplitudes but operates at a low frequency (E = 2.28 GPa, 38.5 Hz, 10.4 mm) compared to aluminum (E = 70 GPa, 75.5 Hz, 4.5 mm) or stainless steel (E = 200 GPa, 52.5 Hz, 3 mm). Also, when using Mylar, the improvement in heat transfer is 225%, while for aluminum it is 110% and only 60% for stainless steel.

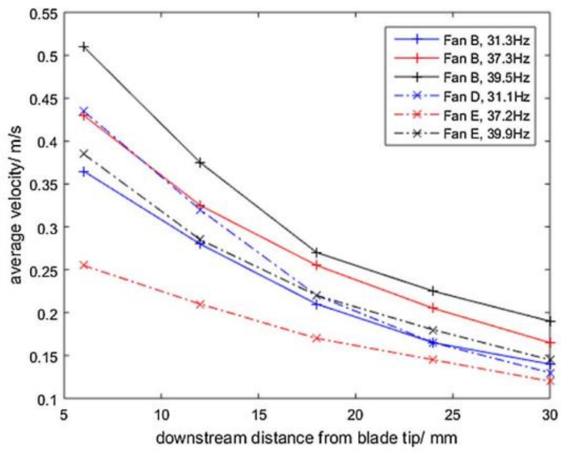

Fig. 8 Air velocity as a function of distance from blade tip with different frequancies [41].

2.4. *Effect of fan blade orientation*

Piezoelectric fan orientation with heated surface can be in several situations, is the piezoelectric fan in a horizontal orientation with respect to the hot surface or vertical? Is the hot surface in a horizontal or vertical orientation relative to the fan? Through these questions, the orientations of the piezoelectric fan and the heated surface can be analyzed to each other.

From the literature, the orientation of the piezoelectric fan with respect to the hot surface or the orientation of the hot surface with respect to the fan influences the performance of the piezoelectric fan.

Açikalin et al. [24] tested four piezoelectric fans in horizontal and vertical orientations with a heat sink and heater assembly. Three positions in the vertical orientation while one position in the horizontal orientation were investigated. It was concluded that the vertical orientation has a significant effect on the improvement of heat transfer and may reach 100%, while in the horizontal; the improvement rate reaches merely 52% as depicted in Fig. 9.

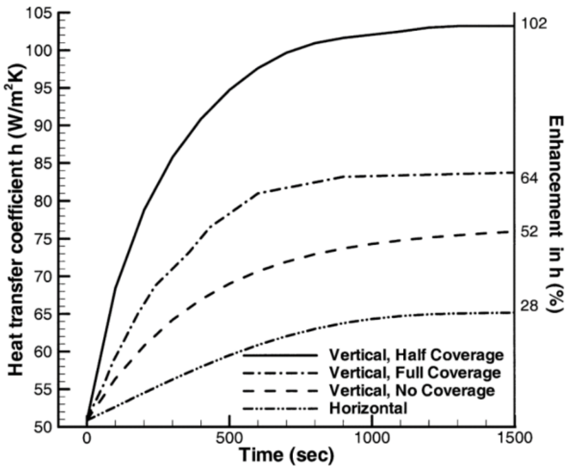

Fig. 9 Heat transfer enhancement at four different orientations of piezoelectric fan [24].

Liu et al. [49] investigated the effect of geometric parameters, including the horizontal and vertical orientations on the rate of improvement of heat transfer Fig. 10. It is found when the piezoelectric fan blade is positioned vertically to the heated surface, the heat transfer deteriorates clearly compared to the horizontal arrangement as in Fig. 11.

Lin [48] studied two piezoelectric fan arrangements in the vertical and horizontal orientation with a hot surface. The results of the study showed that the difference between the two orientations is not significant.

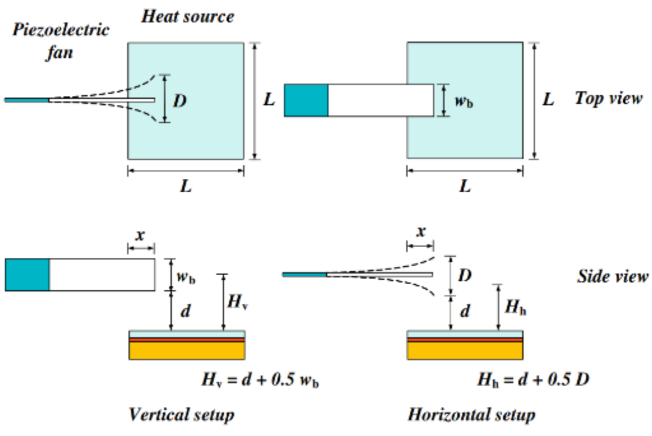

Fig. 10 Setup of piezoelectric fan at horizontal and vertical orientations [49].

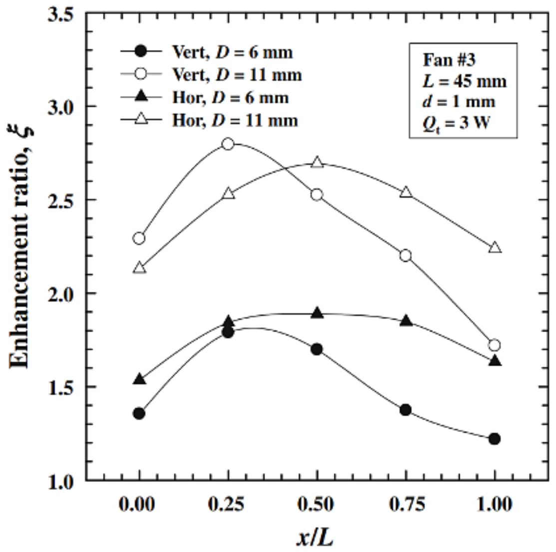

Fig. 11 Heat transfer enhancement ratio versus dimensionless blade tip at various orientations and distances [49].

2.5. Effect of fan blade-hot surface gap

There is an inverse proportional relationship between the increase in heat transfer from the heated surface and the distance of the piezoelectric fan from it as in Fig. 6, where the less the distance to certain limits, the greater the heat transfer, which was proven by many researchers and reached the same results with the presence of this relationship [52-54]. The heat dissipation increases by 8.4%, 18.6% and 31.3% when the gap distance between the fan and the heated surface decreases by 30%, 60% and 90% respectively. This relationship can be explained by analyzing and understanding the principles of air flow as it is a well-established relationship.

Kimber et al. [55] show that reducing the gap between the heated surface and the piezoelectric fan significantly (0.08mm), the above-mentioned relationship is not achieved as the effect is opposite and heat transfer decreases. Therefore, the optimal distance is not subject to a fixed rule, but it should not be too big or too small, but rather a medium between the two. The reason for the drop in performance when the separation distance is too small is that the air rushes away from the heated surface and thus does not lead to a high removal of the emitted heat. The width of the blade and the amplitude of vibration can be controlled and considered as key parameters to overcome this problem.

Eastman and Kimber [43] concluded that the vortices, their strength, and the excitation of the air space surrounding the heated surface decrease significantly when the distance between the piezoelectric fan and that surface increases, resulting in a decrease in heat transfer.

Kimber and Garimella [40] studied the importance of the effect of blade width on the gap between the piezoelectric fan and the hot surface. They tested several values for the width (w) and non-dimensional distance (G/A) as in Fig. 11, which explains the heat distribution of a heated surface cooled by three piezoelectric fans with different blade widths. They uniquely find the optimal distance that shows a similar heat distribution contour. Also noticed an increase in heat transfer by 4% when the gap increases from 6.11 mm to 10.8 mm.

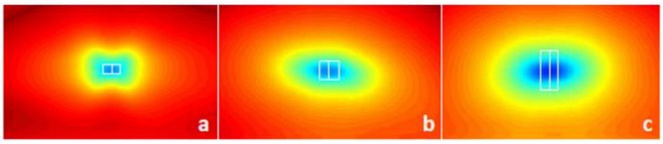

Fig. 12 Convection heat transfer coefficient contour for three fans (a) $G/_A$ = 0.75, w = 6.35 mm. (b) $G/_A$ = 2.75, w = 12.7 mm. (c) $G/_A$ = 4.75, w = 25.4 mm [40].

3. Numerical simulation in piezoelectric field

Due to the development of numerical simulation programs in recent years, the use of CFD in research fields has become widely popular. One of the important areas in which it was used recently is the field of microelectronics cooling, where many researchers tended to use numerical simulations with experimental [56]. Whereas, conducting experimental work is necessary for the credibility of the numerical results, which apply to specific applications.

Electronics cooling research using piezoelectric fans has recently used numerical simulation where a single blade or several blades can be used in the design of the numerical model. Moreover, most of the researchers used a combination of heat sinks and a heat source included with the flow model. The use of the vibrating blade (the piezoelectric fan blade) to generate a high air flow causes changes within the domain and this causes the flow disturbance, so the transit model was used to deal with such a scenario using Navier-Stock equations with appropriate boundary conditions and assumptions.

In most applications in the engineering field, the CFD method is used to deal with high fluid velocities and steady state with the RANS scheme. In the case of piezoelectric fans, the flow is turbulent and unstable due to the movement of the fan blade, and here the numerical simulation of such a scenario is a challenge. Such a model can be dealt with using several methods, including large eddy simulation (LES) or direct simulation methods (DSM), which are methods with great accuracy and are considered effective tools for such a type of flow, but their use is limited due to the limited computational resources [57].

3.1. Simulation setup

For each application, a numerical simulation model must take into account some necessary and important steps appropriate to the intended application. This point will be discussed by reviewing the research papers below, many research papers use the method of finite volumes to solve the models, and it is the most appropriate method because the Navier-Stoke equations are more stable in it, although other researchers use the finite element method [58], which is less stable [59] .

The Navier Stock equations, which govern fluid motion, are complex differential equations that can only be solved by making some appropriate assumptions for each model. For example, neglecting buoyancy forces in some two dimensional models because the gravitational force is perpendicular to the plane of the model [55, 60, 61]. Also, the fluid is incompressible because the pressure drops, or gradient is not noticeable. Radiation in some models is also neglected, although some studies have shown that neglecting it increases the final cumulative error between experimental verification and the model itself [54, 62].

The majority of research papers in the field of piezoelectric fans assume that the flow is turbulent, especially near the tip of the blade, and analysis of this turbulence is important. From the literature, four types of models have been observed that describe the turbulent behavior of the fluid near the tip of the blade, namely, SST k-ω [33, 45, 54, 62], k-ε [35], Large eddy Simulation (LES) [63], and RNG k-ε [64].

Below is a simplified explanation of the models. SST k-ω is used for the near and far regions of the piezoelectric fan blade end [65, 66]. k-ε is preferred when the flow is highly turbulent [67]. RNG k-ε is an update of the basic k-ε model that considers the eddy effect on turbulence as well as another parameter to improve flow accuracy [68]. The LES model has been used by a few researchers, including Bidakhvidi et al. [63] which showed that the intensity of turbulence when vortices overlap cannot be obtained using another turbulence model. The limited computational resources made this model less used in the literature [59], but with the development of these sources, this model will become more used than the rest of the models in the coming years.

The poor computational capabilities led to the assumption that the laminar flow in some research papers, and this is what Florio and Harnoy [58] considered as the source of the error and gives a poor evaluation of the performance of the piezoelectric fan in cooling electronics, but with the progress of computational techniques, the laminar flow hypothesis will become unworthy of attention.

Two-dimensional models require little time and computational capabilities compared to three-dimensional models, but at the expense of the accuracy of the solution, as the latter is more accurate, but requires much more time for the solution.

More than one research paper verified the accuracy of the two dimensional models experimentally, including Abdullah et al. [69] found a difference between the numerical and experimental solution by 11%, due to the presence of simplification hypotheses in the numerical model. Acicalin et al. [70] concluded that the effects of the three-dimensional model cannot be neglected, which is consistent with the conclusions of Bidakhvidi et al. [63] who studied both 2D and 3D models of piezoelectric fans. A lot of evidence has shown that the use of the 3D model is desirable, and studies that use this model have become more common since 2014. The advances in computer technologies and numerical analysis programs have made the use of the three-dimensional model possible and more applicable than before.

3.2. Grid generation

The balance between the time of implementation the numerical simulation and the accuracy of the results determines the type and size of the mesh used for each case under study.

The 3D model uses at least 450,000 elements as in the literature and up to 15,000,000 [44]. Acikalin and Garimella [60] dealt with both 2D and 3D models, where they used 14,500 nodes in 2D, and 450,000 nodes in 3D, which took a long time to solve reached six weeks.

In two-dimensional domains, most research papers use the triangular mesh type [43, 61, 64, 69] and others use the quadrilateral [58]. In three-dimensional domains, the matter is different, as the domain mesh consists of several types of mesh (hybrid mesh) containing quadrilateral and hexagonal surfaces [71]. The mesh type of the blade in the 3D model is often quadrilateral because it is considered as a surface [71].

3.3. Experimental methods of validation

Simulation can be used to reach an initial conception and under experimental conditions by means of numerical modeling to understand the experimental aspect more accurately before conducting it to reduce time and costs. The use of some high-accuracy algorithms such as LES in the simulation gives more reliable results than the experimental aspect of many of the cases under study. Moreover, numerical modeling can be used to obtain an optimal system for cooling electronics using piezoelectric fans with minimal time and space costs. On the other hand, all numerical simulations contain hypotheses and simplifications to reduce the complexity of the case under study and simplify the system of governing coefficients. Therefore, verifying the numerical results by experimental means is extremely important and inevitable because the hypotheses and simplifications in the numerical section led to predictions with errors. There are two main methods available to the researchers to verify the results of the numerical simulations by means of experimental measurements, which are described below:

3.3.1. Quantitative validation

It can be applied by comparing heat transfer coefficient data derived from numerical simulations with experimental ones for the same model. This method has been used by many authors for more than twenty years. Lei et al. [64] studied an experimental two-dimensional model that includes a single piezoelectric fan for the purpose of cooling a heated surface and used quantitative validation. Convective heat transfer coefficient data is collected for several points on the heated surface. It found the largest error in the data was 15%. In addition, many 3D models have been validated in the same process. Errors were different for many research papers such as 10% and 8% [48], 15.1 and 17% [71] and 11.3% and 15% [54]. Huang and Fan [72] Used the same method to validate the simulation, a maximum error of 15% was shown, while Abdullah et al. [62] got an error of about 1% with the same process.

3.3.2. Thermal analysis method

Heat transfer analysis leads to quantitative error results but reduces the scope of validation. Therefore, this method requires conducting experiments when there are obvious changes in the numerical model parameters. This is achieved by analyzing the behavior of the fluid flow which causes heat transfer phenomena.

Other researchers, such as Choi et al. [35] Using a different process, they investigated the airflow generated from the blade tip of the piezoelectric fan. The air flow velocity curves were compared with the numerical model for several distances, as shown in Fig. 13, they showed a good agreement between the experimental work and the numerical simulation. In addition, they compared the different properties of the generated vortices, their size, and the direction of their movement with the numerical results, they found significant empirical correlations between them. All airflow domain was analyzed in this way, producing a clear quantitative validation that can be used to analyze the heat transfer and geometry characteristics of different systems.

This method is limited by the requirements of the experimental work and the devices used to measure the air flow generated by the piezoelectric fan, including the air velocity measurement device such as PIV (particle image velocimetry) as well as it's limited for the two-dimensional model. Therefore, the validation of the model is limited to 2D. For both validation methods, there are significant limitations. For the first, it cannot be used for a wide number of heat transfer and geometrical parameters. For the second, researchers should overlook the errors that appear and validate with a three-dimensional model, although some research papers have identified some errors that must be considered in the three-dimensional model and not neglected. Agarwal et al. [38] Use the large technical and computational developments using PIV to give results for 3D model that may be a strong basis for validation using the 3D model.

In general, an error of at least 10% has been noted in the model validation methods for most of the literature. Researchers summarized the major sources of primitive errors and showed that the effect of radiation was neglected in their study, and this was evident when they compared the error values with the values taken from the experimental work. Temperature ambient measurements and inconsistent fan blade resonance frequencies were classified as contributors to the errors.

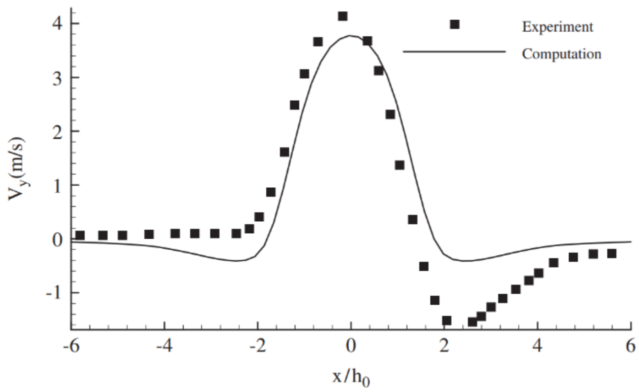

Fig. 13 Blade tip velocity curves for simulation and experimental over one complete cycle of the piezoelectric fan [38].

4. Applications of piezoelectric fan system

Piezoelectric fans are used as an alternative to traditional cooling technologies because it could reduce energy consumption in many applications and taking advantage of the air generated by the piezoelectric fan to remove heat from the systems and keep it within the permissible limit. Cooling or heat dissipation technologies using liquids and phase change materials are considered complex systems in design and are not cheap [3, 4]. The ultimate goal of the thermal management systems design engineers is to produce an effective and cheap cooling systems, this is achieved by using air as a working fluid, it's the reason that 95% of cooling methods in computers use air, so the piezoelectric fan system is a promising field for this purpose [73].

4.1. piezoelectric fan competition with traditional axial fan

Piezoelectric fan cooling techniques are often compared to high-speed axial fans, where they are found to perform well at around 50% of the energy requirements [25, 26, 60]. It depends on the volume air flow rate generated as a result of the input energy, so this technology is useful for some specific applications such as heated surfaces. The use of piezoelectric fans is limited to confined spaces, which is appropriate for axial fans, which generate a large amount of airflow towards the hot spot. Recorded data prove that using a typical axial fan can generate ten times more air compared to a piezo fan. Therefore, from an economic point of view, we need ten fans to generate the same amount of air flow rate compared to axial fan, this is not feasible, therefore, insert of piezoelectric fans in its current state in some electronic applications is not useful. The improvement and development in the field of piezoelectric fans and the production of optimal cooling systems to reduce the number of flexible blades is very necessary to expand the range of their applications [72, 74].

Axial fans require a larger amount of energy, as they have other disadvantages as they contain moving parts that get damaged over time and emit annoying sounds and noises that are not desirable in some applications, for example personal electronic devices [75] . By contrast, piezoelectric fans are free of moving parts [76] and operate smoothly and without noise. Determining the optimal engineering and operating parameters for piezoelectric fans is the key to reducing energy consumption in the future, for example using multiple blades or making the blade vibration transverse to the direction of air flow.

4.2. Power consuming

Reducing the use of energy to a minimum is an urgent matter, as there are many difficulties and challenges in some technical fields. For example, there is a big gap between the requirements of communication technologies and energy control systems. Communication systems are responsible for an energy consumption of at least 8% in 2013 of global energy consumption [77]. The demand for energy has increased in the world every year by 11.7% [78, 79] since the year 2000 until it reached (416.2) tons watt/hour. However, 40% of this energy is used to cool electrical devices parts [17]. High speed axial fans are used in such systems to control heat emission [34]. Use of piezoelectric fans is an acceptable and reliable solution in many electronics industries and an effective cooling method for parts that radiate heat less than 10,000 W/m^2 [80].

4.3. Energy reducing

All the data recorded in the data collection centers show that the use of piezoelectric fans has a significant impact on energy savings in many industrial applications. About 33% of global energy comes from fossil fuels [81]. This gives an amount of energy equivalent to 2.9 million barrels of oil [81, 82]. Burning this amount of fuel to provide power for axial fans in applications causes carbon dioxide emissions of up to 1.25 metric tons to the atmosphere [83]. This gas is one of the main contributors to global warming. Therefore, replacing piezoelectric fans in place of axial fans reduces greenhouse gas emissions and thus reduces environmental pollution in many applications.

5. Summary of the study

To conduct more efficient methods for dissipating heat from electronic devices than conventional approaches, researchers have engaged in an exploration of the realm of piezoelectric materials, particularly focusing on piezoelectric fans. The investigation commenced with practical experiments designed to demonstrate the viability of integrating piezoelectric fans as a dependable solution for electronics cooling.

Subsequently, with the rapid advancement of computer software, numerical simulation emerged as a potent tool to streamline the cost and time required for obtaining results. In the present research, and based on information available in publicly accessible sources from prior studies in this field, we observed that numerical studies constituted 21% of the research, while experimental studies accounted for 32%, and the combined studies comprised 47%, as depicted in Fig. 14.

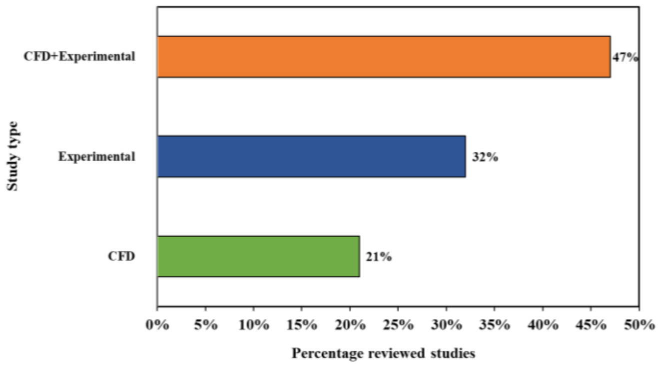

Fig. 14 The percentage of the reviewed studies.

6. Conclusions

Most of the statistics and evidence related to piezoelectric fans indicate that their use significantly reduces the energy consumption necessary to operate thermal control systems. In addition, the rapid development in the electronics industry is not commensurate with the available heat treatment techniques, which is confirmed by most recent articles. Therefore, air cooling systems must be improved to catch up with the development of the electronics industry. Piezoelectric fans are an ideal short-term solution for some applications and increasing the performance of these systems expands the horizons of their applications. When reliance on piezoelectric fan systems increases in the field of cooling, it has environmental benefits in terms of reducing fossil fuel burning and greenhouse gas emissions.

The performance of piezoelectric fans can be improved by controlling many engineering and material parameters that determine their operating properties such as frequency and oscillation amplitude in applications. The effect of changing these parameters is governed by mathematical equations and is well understood. Most of the literature showed that changing the frequency or capacity of the piezoelectric fan blade generates more airflow and causes turbulence around the blade, especially near the tip of the blade. Also, reducing the separation distance from the edge of the blade leads to an increase in heat transfer.

In recent years and since 2014, numerical simulation has become an integral part of most research papers, as software is advancing rapidly. Inserting of numerical modeling in the field of piezoelectric fans allows reaching an optimal design in a shorter time and at a rate of development higher than the pure experimental for specific applications.

In general, at the present time, the numerical methods are greatly limited by the validation method of the numerical model. Where the model is often verified by taking one case from the experimental data, which is either the convective heat transfer coefficient from a heated surface or a hot point. This method is not very accurate as the model variables need other states to validate. For example, air flow and vortex generation were compared, and the model was verified by the abovementioned method, although it is only two-dimensional [35]. Therefore, the development of experimental and numerical methods is very important to achieve verification in the three-dimensional model and its impact on different research fields. In the current work, from the literature reviewed papers, about 21% was CFD studies while the experimental was 32%, and the combined one about 47% as explained in Fig. 14.

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