PERFORMANCE ANALYSIS OF THE AIR-MOVING CAPABILITIES OF PIEZOELECTRIC FAN ARRAYS

BY

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THESIS

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ABSTRACT

This study focuses on the air-moving performance of geometrical arrays of piezoelectric fans, specifically relating to the fan curve. In the past, many studies have been conducted on the performance of single piezoelectric fans. The heat transfer benefits over natural convection have been well studied and most applications are focused on electronics cooling. However, for applications requiring higher pressures and flow rates piezoelectric fans have not been considered. This study is aimed at improving the performance by implementing an array of piezoelectric fans. A performance analysis for two array geometries is shown and efficiencies and correlations are discussed. Although previous work has been performed investigating the fan curve performance of a single piezoelectric fan, this work represents the first investigation of the air-moving capabilities of an array of piezoelectric fans.

ACKNOWLEDGMENTS

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1. Introduction and Literature Review

With increasing heat rejection from electronics, innovative design concepts must be realized to cool such devices efficiently. Piezoelectric fans may be well suited for such applications. Piezoelectric fans consist of a cantilever beam with a piezoelectric actuator bonded to one side (asymmetric) or both sides (symmetric) that extend from the clamped end to a certain length down the cantilever. By driving the piezoelectric actuator with an alternating voltage, motion can be created at the free end. The amplitude of the motion is enhanced when the driving frequency matches the resonance frequency of the cantilever. It is at this operating point that the surrounding fluid is agitated the most. Fans of this nature have applications in cooling electronics due to their small power consumption, low noise, which is achieved by keeping their resonance frequency below 100 Hz, and ability to spot cool efficiently.

1.1 Flow Field

The flow around vibrating cantilevers was first investigated by Toda [1], [2] who proposed models for the flow and the vibration of multilayered piezoelectric polymers. Ihara and Watanabe [3] also studied the flow using the smoke-wire method of flow visualization and developed numerical techniques to predict the velocity at three positions downstream of the fans. They observed that the time-averaged flow at a distance 3mm away from the free end was approximately the same as the speed of the tip of the fan. Yoo, *et al.* [4] studied the dependence of the resonance frequency and the velocity 1 mm away from the tip of the fan on the overall length and material of the non-piezoelectric section of the fan. They observed that the resonance frequency increased with decreasing free length, and they achieved tip displacements of 35.5 mm and a wind velocity of 3.1 m/s with a 64.8 mm long phosphor-bronze fan resonating at 60 Hz and driven by 220V. Kim, *et al.* [5] continued the investigation of the flow field around a vibrating cantilever and observed counter rotating vortices being shed from the tip of the fan with a high velocity region between these two vortices. Acikalin, *et al.* [6] developed computational methods to map the two-dimensional streamlines caused by a baffled piezoelectric fan. These methods were validated with flow visualization experiments and are relevant for fan design and installation. Further investigation into the flow field was undertaken by Wait, *et al.* [7]. They conducted flow visualization tests to determine the two-dimensional performance of piezoelectric fans operating at higher resonance modes. They found that the fans showed the best performance when actuated at the fundamental resonance mode and the power consumption dramatically increased for each subsequent resonance mode while the air-moving performance decreased.

1.2 Shape Optimization of Piezoelectric Fans

Studies have been conducted to optimize the shape of piezoelectric fans. For instance, Burmann, *et al.* [8] developed models for the deflection of a symmetric piezoelectric fan and presented design guidelines using these models. An electrical to mechanical conversion factor was developed and the analytical model was used to optimize this factor as well as others. The dynamic response of the first mode of a symmetric fan was investigated with the goal of amplifying the tip deflection by Lobontiu, *et al.* [9]. An analytical model based on a lumped-parameter approach was developed and used to create geometrical parameters that could be exploited to optimize the tip deflection of a fan. Shen, *et al.* [10] developed a model that involved solving a transcendental equation to find the resonance frequencies and profile of an asymmetric piezoelectric fan. A method utilizing composite beam theory and Hamilton’s principle was devised by Basak, *et al.* [11] to calculate the dynamic profile of both symmetric and asymmetric configurations of piezoelectric fans. This method agreed well with finite element method simulations. The response of piezoelectric fans to an alternating voltage has been characterized and analytical methods have been developed in prior work.

1.3 Heat Transfer

The heat transfer effects of these devices have been studied by Acikalin, *et al.* [12] who found an increase of up to 375% in the heat transfer coefficient over natural convection. Also investigated by Acikalin, *et al.* [13] was spot cooling in a laptop enclosure, which showed better performance than a radial fan. Kimber, *et al.* [14] conducted tests to measure the local convective heat transfer coefficients for flow from a piezoelectric fan impinging on a heat source. They conducted these tests with various fan amplitudes and various distances from the fan tip to the heat source. Using their data, they correlated the Nusselt number to the Reynolds number for an isoflux surface in air. Furthermore, Liu, *et al.* [15] quantified the effects of geometrical arrangement relative to the heat source. They found that the heat transfer performance for a horizontal arrangement, for which the motion at the tip of the fan is perpendicular to the heat transfer surface, was on the same order of magnitude as that of a vertical arrangement, for which the motion at the tip of the fan is parallel to the heat transfer surface, relative to the heat source.

1.4 Integration of Piezoelectric Fan into Heat Sink

The effect of integrating a piezoelectric fan and an extruded aluminum heat sink was investigated by Petroski, *et al.* [16]. They mounted a fan on the fin side of the base of a heat sink and conducted flow visualization tests to validate flow models developed using commercially available computational fluid dynamics software. Heat transfer measurements were also conducted to measure the increase in cooling performance. They then adjusted the shape of the heat sink and obtained a coefficient of performance of 5 over a non-enhanced heat sink and a peak velocity of 1.5 m/s. This represents the first known attempt to integrate a fan of this structure into a heat rejection device.

1.5 Single Piezoelectric-Fan Fan Curves

For engineers to implement and design piezoelectric fans optimally, a study of the pressure and flow rate curve, i.e. the fan curve, must be conducted. Kimber, *et al.* [17] investigated the fan curve of a single piezoelectric fan. The amplitude of two fans was varied and the effect of this variation on pressure and flow rate was measured. The fan curves of the piezoelectric fans were presented and compared to radial fans commonly used in electronics cooling. It was found that the piezoelectric fans in the specific setup tested were more efficient in converting the electrical energy into mechanical energy compared to the radial fans. Also, they noted the flow rate depended on the tip velocity, whereas the pressure depended on the resonance frequency. Although Kimber and coworkers presented a complete study of the fan curve of a single piezoelectric fan, there has been no investigation of the fan curve for an array of piezoelectric fans reported in the open literature.

1.6 Objective

An array of piezoelectric fans may be useful in a diverse range of applications. These applications might include cooling a server or other large electronic enclosures as a prime mover, integration into a heat exchanger to construct an integrated-fan-heat-exchanger combination, or implementation into a printed circuit board to not only spot cool electronics but also bulk air movement.

The aforementioned study by Kimber, *et al.*[17] to determine the fan curve of a single piezoelectric fan also needed measurements to determine the fan curve of a radial fan. The radial fan achieved pressures double that of the highest pressure induced by the piezoelectric fans and the flow rates were also higher for the radial fan. For an engineer to replace a radial fan with a piezoelectric fan the performance must be higher. Therefore, in the present study the use of multiple piezoelectric fans in a geometrical array to boost the overall performance is considered with the goal of implementation into a system as the prime mover.

2. Experimental Setup and Methods

2.1 Construction

2.1.1 Individual Fan Construction

Each piezoelectric fan was comprised of a standard quick-mount piezoelectric actuator from Piezo Systems, Inc. The fans were made by bonding 0.15” thick polyester with cyanoacrylate to the piezoelectric ceramic. A piezoelectric fan is shown in Figure 1. The attachment length was 20 mm. Each fan had a width of 12.7 mm and a free length, which was measured from the end of the piezoelectric actuator to the end of the non-piezoelectric blade, of approximately 26-27 mm. The free length varied due to a target natural frequency being established as 107 Hz. Determination of these parameters was based on a series of tests that are discussed further in Appendix A.

Figure 1. General piezoelectric fan assembly.

2.1.2 Array Construction

Two types of arrays were tested in this investigation. The *staggered array*, which consisted of eight piezoelectric fans, had the geometry shown in Figure 2. The other array that was tested was the *inline array*, which consisted of nine fans, and is shown in Figure 3. Due to the manufacturing procedures used to construct the fans, most of the piezoelectric fans have differing initial resonance frequencies. In order to have an array of fans of which all have the same resonance frequency the following method was devised. The fans were constructed, mounted and connected to the driving circuit. A target frequency was selected and the length of each fan was trimmed until its largest displacement amplitude was manifested at the target frequency. The operating frequency of the array may be different from the target frequency due to a distribution of resonances around the target. Therefore the operating frequency was chosen as the frequency which corresponded to the highest no-flow pressure with the array installed in the fan-curve apparatus described later. The difference between the target and the operating frequencies was consistently less than 5 Hz. The operating frequency for each test can be seen in Table 1.

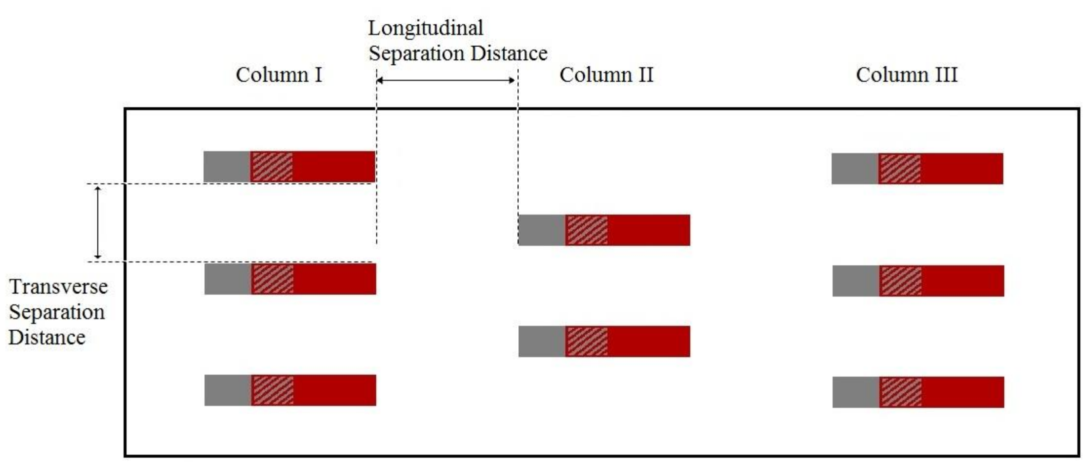

Figure 2. Staggered array defining the column designations and the separation distances in the transverse and longitudinal directions.

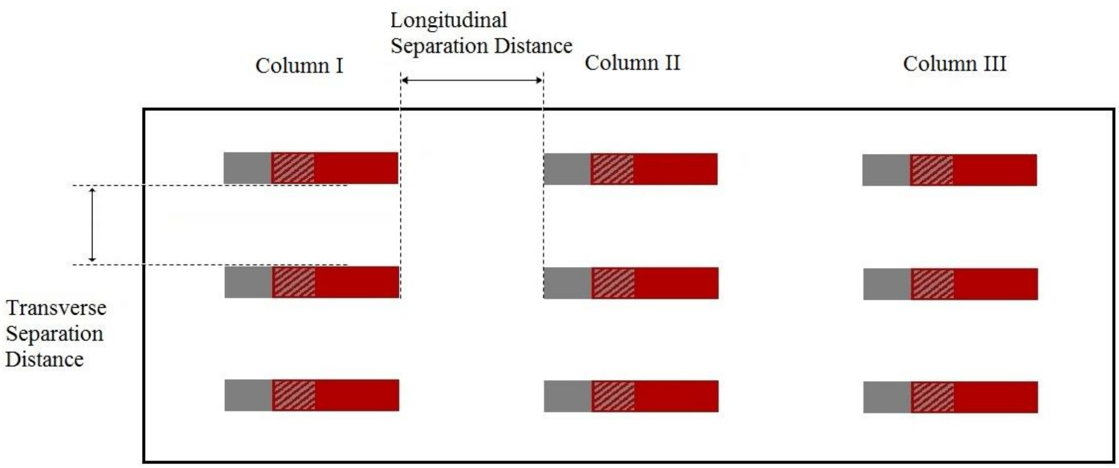

Figure 3. Inline array schematic defining the separation distances in both the longitudinal and transverse directions.

The flow caused by a piezoelectric fan is inherently three dimensional. As outlined earlier, the two-dimensional flow field has been investigated by others [3], [5], [6], [7], [16]. However, the unsteady, three-dimensional flow induced by arrays of piezoelectric fans has not been characterized. Rather than undertake a computational study of the flow-a very time consuming, expensive, and unlikely-to-succeed approach-a heuristic, experimental approach was adopted to explore the effects of the transverse distance as well as the longitudinal distance between neighboring fans on the performance of the array.

In conventional blowers the distance between the edge of the fan blade and the housing is minimized. As this distance is increased the attainable pressure difference across the blower decreases. Using that information to guide the design of the piezoelectric fan array, the difference between the channel height and the tip-to-tip displacement of the fan was minimized. Thusly, when determining the height of the channel the amplitude was chosen to be the driving dimension. Determination of the width of the channel was based on this same idea. However, as discussed earlier, this three-dimensional flow is not very well understood, and therefore the distance between the edge fans and the channel walls was somewhat arbitrarily chosen to be a constant of 5 mm. This distance was chosen through limited trial and error, and there is no reason to expect it is optimal.

2.1.3 Mounting System

Ideally, the mechanical energy supplied by the piezoelectric actuators would all be transmitted vibrations in the non-piezoelectric material, i.e. the fan blade. However, during experiments it was clear that there were small vibrations transmitted to the mounting system. These vibrations were problematic during early experiments, and in order to minimize these vibrations two approaches were taken. The first approach, was to simply maximize the clamping force. However, it was found that small vibrations were still transmitted to the mounting system and this approach led to a long set up time. Although it would have been preferred to solve this problem with using a mechanically dissipative element, eventually two rubber o-rings were used above and below the piezoelectric fan mount on the bolt. Figure 4 shows a diagram view of this approach. The implementation of the rubber o-rings led to a much smaller amount of vibrations being transmitted through the mounting structure and a notable increase in amplitude at the free end of the piezoelectric fans.

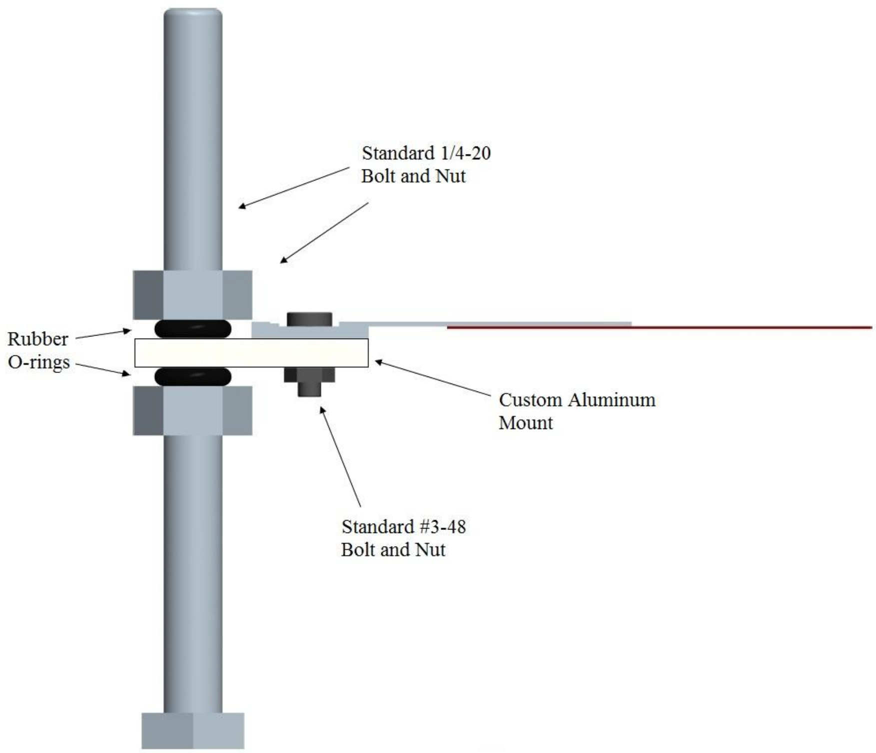

Figure 4. Detail of the individual piezoelectric fan mounting system.

For minimizing the setup time for each array of fans, a mounting system had to be created. The final mounting system, which was used for all fan curve measurements, consisted of two 305 mm x 610 mm plates of plastic with 6.35 mm holes placed 25.4 mm apart in a grid pattern. These plates were used for the top and bottom of the channel. Each piezoelectric fan was mounted to a standard ¼-20 bolt which was then fixed to the bottom and top of the channel plates. The piezoelectric fan was placed so that it was in the vertical center of the channel. Layers of plastic of the same width and having a length of 610 mm, of varying thicknesses, were used to create the side walls of the channel. The varying thicknesses allowed a multitude of channel heights to be implemented without new construction, minimizing the setup time.

2.2 Experimental Methods

2.2.1 Fan Curve Methods

To accomplish the task of measuring the data required to construct the fan curves for piezoelectric fan arrays, the following experimental apparatus was employed. Using AMCA/ANSI 210/99, which is the standard for measuring the air moving performance of fans and blowers, as a general guideline an apparatus was designed. A schematic of the apparatus is shown in Figure 5.

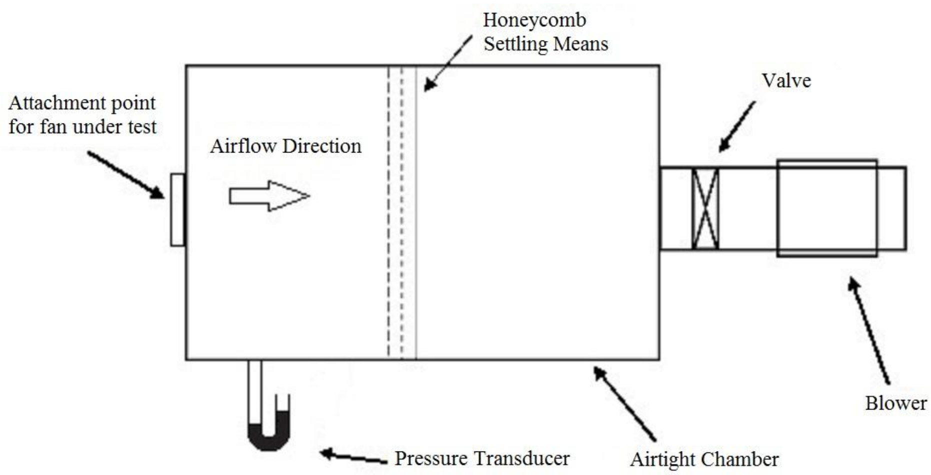

Figure 5. Schematic of the test apparatus for obtaining the data needed to develop fan curves of piezoelectric fan arrays.

In accordance with AMCA 210, the pressure was measured at a distance of 94 mm from the entrance plane of the airtight chamber. An Omega PX653 pressure transducer having an experimental uncertainty of ±0.62 Pa was used. The output signal from the PX653 was measured with a National Instruments USB-6009 and logged with a custom program in the Labview environment. The velocity was measured with a hot-film anemometer, a TSI Velocicalc 8355, with a manufacturer-quoted uncertainty of ±0.01 m/s. The plane for the velocity measurements was located at the entrance to the channel as shown in Figure 6. Velocity measurements were recorded at equi-spaced positions in the measurement plane, with a minimum distance of 5 mm and a maximum distance of 10 mm between neighboring measurement positions. Each measurement of the velocity was recorded over at least a ten second period and consisted of a moving average of measurements at one-second intervals. The sampling frequency was 5 Hz; thus each of the ten measurements obtained over ten seconds represented an average of fifty measurements. Furthermore, each velocity measurement was recorded after the reading reached a steady-state value over a ten second period, which was determined by a value that did not change by more than 0.01 m/s over a fifteen second period.

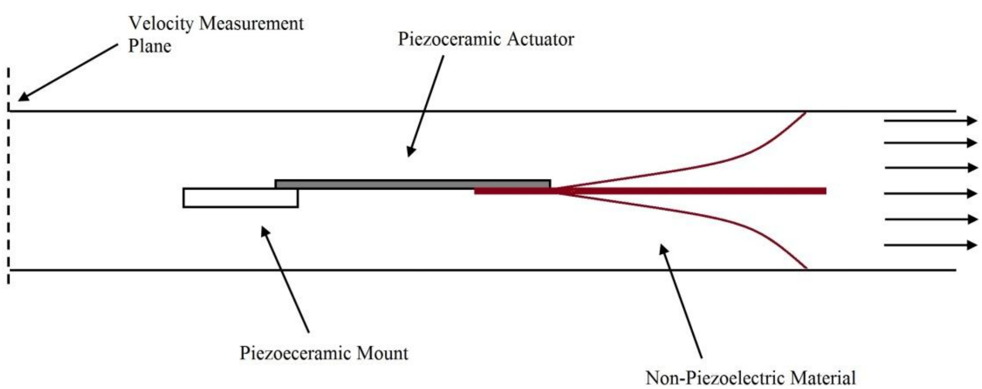

Figure 6. Schematic of the channel where the piezoelectric fan was mounted, and of the driving circuit.

The gage pressure measurements were conducted with the following procedure. For the "shut-off" condition the valve was closed and the fans were driven at the desired operating point.

In order to minimize the uncertainty, the pressure measurement was conducted over a ten-minute period after a steady-state value had been reached. Steady state was assumed to prevail when 500 successive measurements taken over 10 seconds deviated by less than 1.5 Pa. The velocity measurements were conducted during this ten-minute period. In the case that the velocity measurements required more than ten minutes to obtain, the pressure measurement over the entire time of velocity measurement was used. For each consecutive measurement along the fan curve the valve was opened. In order to achieve the "free-delivery" condition a blower was implemented and the valve was incrementally opened until the gage pressure within the chamber was measured to within 0.5 Pa of zero. At this point, the free-delivery condition was achieved.

2.2.2 Single Fan Pressure Methods

The design of an array of piezoelectric fans depends heavily on the design of the individual fan. If a poorly designed fan is chosen to make up the array, then it is expected that the array will not perform well. Therefore, in order to develop a piezoelectric fan array with good performance some time was devoted to design the single piezoelectric fan. Two important design variables were the tip-to-tip displacement amplitude and the resonance frequency. The effects of both of these parameters on the pressure and flow rate were discussed by Kimber *et al.* [17]. In that work, the pressure was found to have an almost cubic dependence on the resonance frequency and an almost quadratic dependence on displacement amplitude. The flow rate was also found to have a quadratic dependence on both the frequency and the displacement amplitude. The shut-off pressure of the fan is an important factor, due to the low pressures attained by piezoelectric fans when compared to conventional fans. Therefore, a set up similar to that used in Kimber, *et al.* was implemented to measure the pressure. Figure 7 shows a diagram of the configuration of a single fan at the entrance to the fan-curve apparatus.

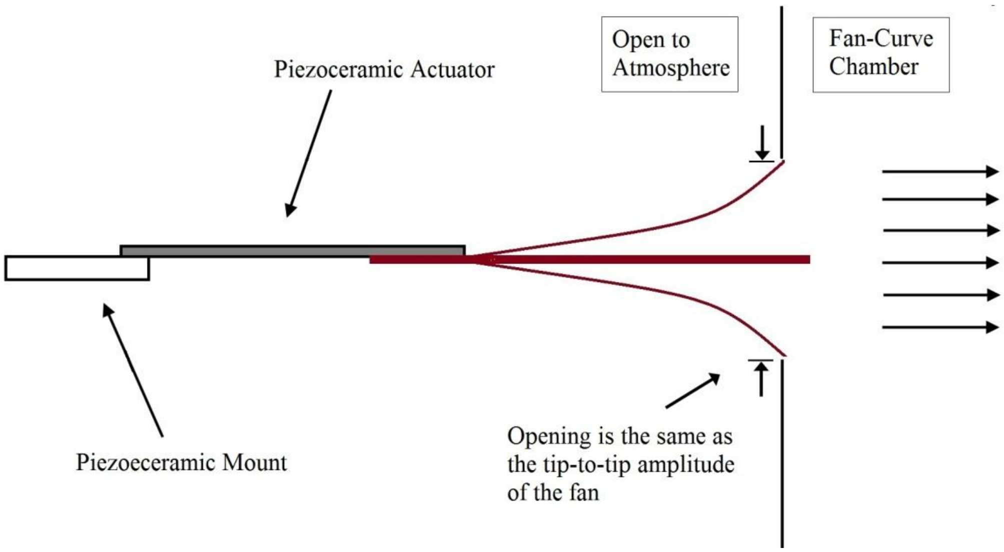

Figure 7. A diagram of the configuration of the piezoelectric fan for testing the pressure dependence on frequency.

At the entrance to the airtight pressure chamber, a small inlet was cut with the same width as the fan tip and the same height as the fan displacement amplitude. Since the resonance frequency, as discussed by Yoo, *et al.* [4] increases with decreasing length, the fan length was decreased by increments of 1 mm. The amplitude was measured by increasing or decreasing the height of the inlet to the chamber by adding or taking away material until the fan tip just struck the top and bottom of the inlet. The height was then measured with a scale.

2.2.3 Parallel Array Methods

When designing a system using conventional fans, it is sometimes useful to implement multiple fans in series or in parallel. When implemented in series, the maximum pressure will increase linearly with the number of fans, whereas when in parallel the maximum flow rate will increase [19]. This behavior is understood for conventional fans; however, how piezoelectric fan array operating in parallel or series has not been explored. Therefore, the behavior of an array of piezoelectric fans placed in series and parallel was investigated.

For testing the behavior in parallel operation, the following scheme was devised. Initially, the first test conducted examined the behavior of a single staggered array, i.e. one set of eight fans as depicted in Figure 2. After this was well characterized in the form of a fan curve, an additional layer was added above the initial staggered array. The additional layer was also a staggered array and each piezoelectric fan was mounted on the same bolt as a fan in the lower array. A sheet of aluminum shim stock 0.1778 mm thick was mounted on the bolts to separate each layer. The fan curve was then measured for the system of two layers of staggered arrays (16 total fans). Subsequently, a third layer (24 total fans) was mounted in the same fashion and the fan curve for the three layers operating at the same resonance frequency was characterized. Note that for each deployment of fans, the channel height was set according to the criteria put forward earlier.

2.2.4 Series Array Methods

The performance of the arrays of fans operating in series was evaluated using the following procedure. In order to add two or more full staggered or inline arrays in series would require an entrance channel whose length was not feasible. Therefore, each column of an inline array was tested. The fan curve of the first column (3 fans) of the inline array was measured initially, and then the second (6 fans total) and third (9 fans total) columns were added sequentially. This test procedure produced test results of a smaller array consisting of three fans operating in series with up to three arrays involved.

2.2.5 Power Consumption

The power consumption of a piezoelectric fan must be measured if it is to be compared to conventional radial fans, and piezoelectric fans must be driven by an alternating current. Therefore, the controlling circuit consisted of a frequency generator, which generated sine waves that were amplified by a Piezo Systems, Inc Model EPA-104, a linear amplifier. The voltage and the frequency were measured with a Hewlett Packard 54610B oscilloscope, which had an uncertainty of 0.72 V and a maximum horizontal uncertainty of 0.006 s. The current was measured with an Amprobe 15XP-A, which had an uncertainty of ±0.9 mA, connected in series to the piezoelectric fans.

3. Results and Discussion

The objective of this study was to characterize the performance of arrays of piezoelectric fans and attempt to optimize the arrays via a heuristic approach. The focus for optimizing the performance was on power consumption as related to pressure and flow rate. Also, to be comparable to standard radial fans the power consumption of the arrays should be lower than conventional fans. Finally, due to the low pressures attainable with piezoelectric fans attempts to increase the maximum pressure were undertaken. Therefore, this section is presented to represent these objectives.

3.1 Separation Distance

It would be beneficial to decrease the initial cost of implementing an array of actuators to make them competitive with conventionally designed fans. Therefore it is imperative to increase either the air-moving performance or decrease the number of piezoelectric fans while maintaining a certain degree of performance. For instance, if the area affected by the flow of the arrays can be increased with little penalty to the performance of the arrays then the cost of implementation into a real system may be decreased. Therefore investigation of the dependence of the air-moving performance on the transverse and longitudinal separation was undertaken.

3.1.1 Transverse Distance

The results of fan curve measurements for the inline arrays are shown in Figure 8. The first design tested was that of the inline array with a transverse separation distance of 1 mm and a longitudinal separation distance of 90 mm and therefore the subsequent designs were attempts to not only characterize how the separation distance affects performance but also to improve the performance based on this design.

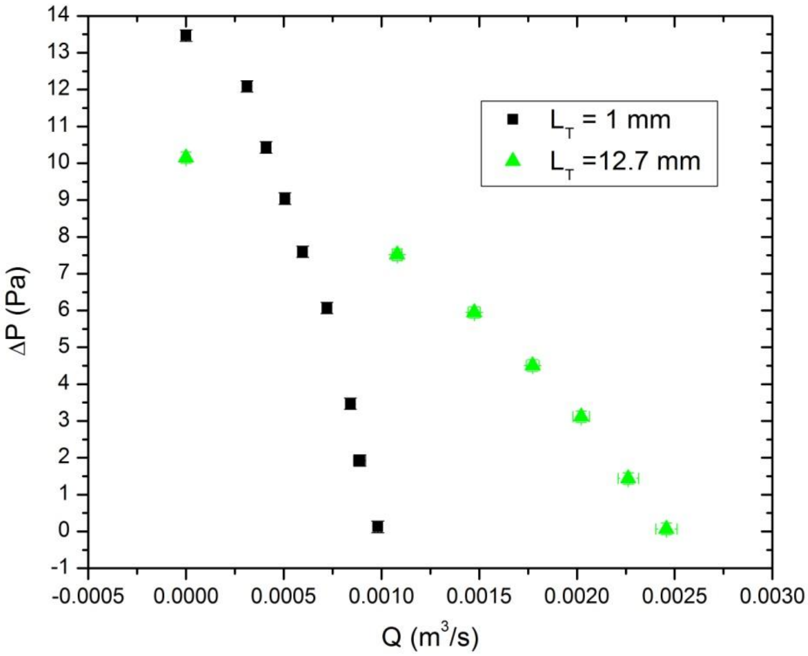

Figure 8. How varying the transverse separation distance affects the performance of the inline array.

By increasing the transverse separation distance between the piezoelectric fans in the inline array from 1 mm to 12.7 mm there was a significant increase in the average velocity, which increased the volumetric flow rate. The fan curve with the average velocity being used on the horizontal axis is shown in Figure 9. The average velocity at free delivery increased 40%, from 0.89 m/s to 1.25 m/s. Due to the mandatory increase in cross-sectional area the overall flow rate at free delivery increased from 0.00098 m³/s to 0.00246 m³/s, which is an increase of 151%. Unfortunately the pressure at the shut-off condition decreased from 13.5 Pa to 10.2 Pa.

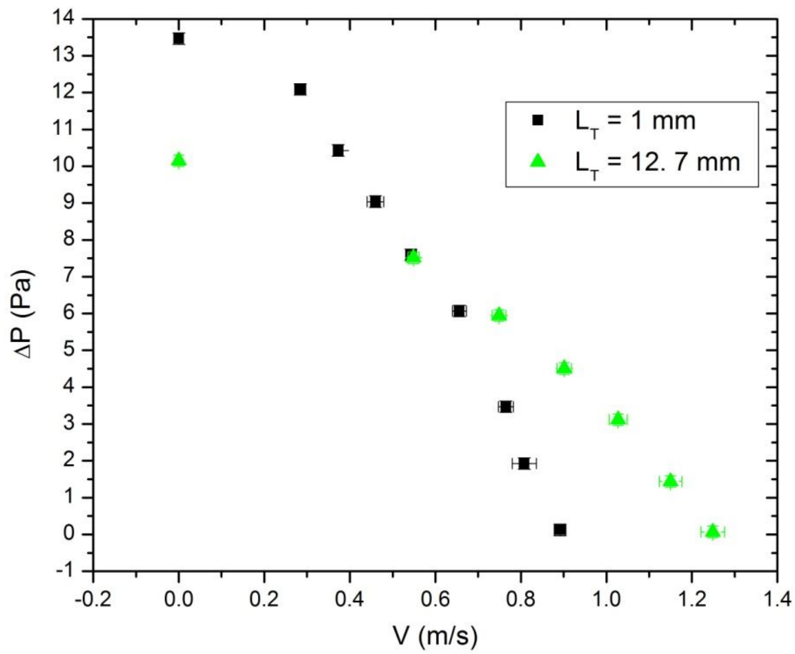

Figure 9. Transverse separation distance variation and its affect on the average velocity in an inline array.

The staggered array was the next design to be tested, and the results are shown in Figure 10 and Figure 11. It was expected that the behavior of the L_T = 1 mm design for the staggered array would be similar to that of the inline array, and therefore the transverse separation distances were 12.7 mm, 25.4 mm, and 38.1 mm. The L_T = 12.7 mm staggered array design showed a 33% decrease in the maximum attainable pressure, compared to the inline array with a transverse separation distance of 1 mm. The volumetric flow rate showed a 114% increase over the L_T = 1 mm inline array, and a 16% decrease compared to the L_T = 12.7 mm inline array.

Although the flow rate conditions at free delivery were comparable to the inline array, the average velocity was only 1.00 m/s compared to 1.25 m/s.

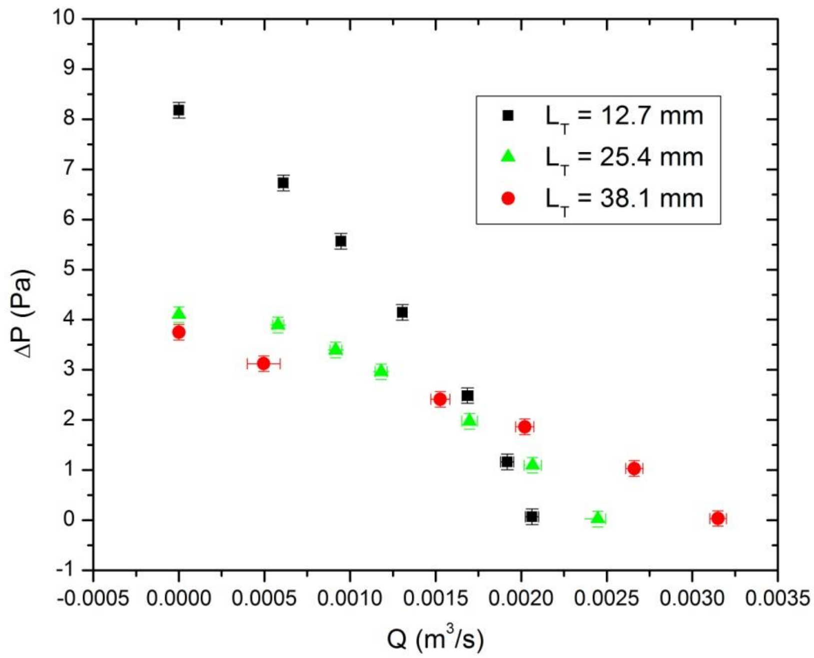

Figure 10. Results of testing the transverse separation dependence of the fan curve for staggered arrays.

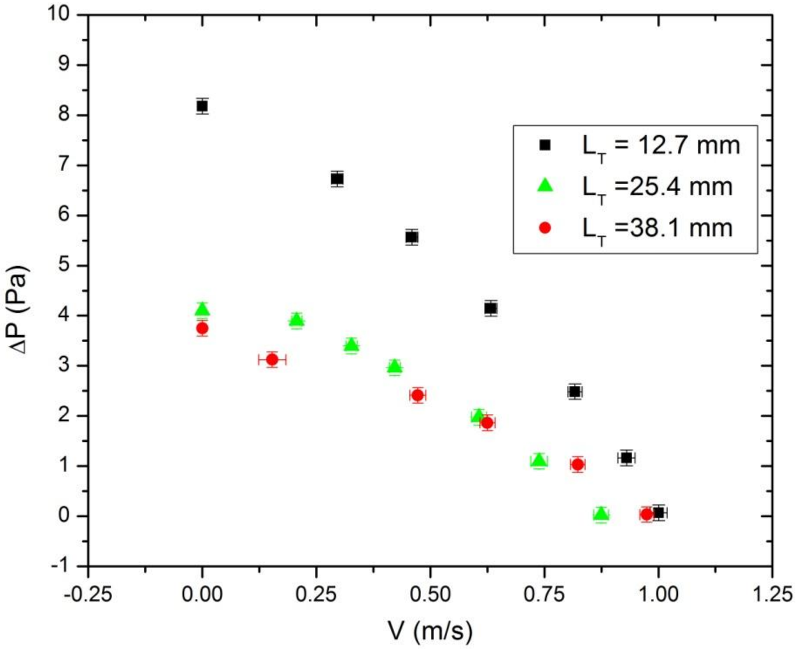

Figure 11. Dependence of the transverse separation distance on the pressure and the average velocity of the staggered array design.

Because of the very large design space and time limitations, further experiments to explore the effects of L_T and L_L on piezoelectric fan arrays were restricted to the staggered array. The results presented thus far suggest that the general trend obtained with this array extend to the inline array. The maximum pressures attained at the shut-off condition for the staggered arrays with L_T = 25.4 mm and L_T = 38.1mm were much lower than for the staggered array with L_T = 12.7 mm. In fact they were both approximately half that of the L_T = 12.7 mm case. This decrease in pressure was accompanied by an increase in the volumetric flow rate at free delivery in both situations. However, for the L_T = 25.4 mm design the average velocity at free delivery decreased while for the L_T = 38.1 mm case the average velocity was approximately the same as for the L_T = 12.7 mm design.

The decrease in average velocity for the staggered array with L_T = 25.4 mm can be attributed to an increase in friction in the channel. The mounting device for the center fans in both column 1 and column 3 had an increased cross-sectional area. This increase in cross-sectional area introduced more friction for the piezoelectric fans to overcome, which therefore decreased the average velocity at free delivery. It is possible that this increased friction also contributed to the decrease in the maximum pressure. However, since the maximum pressure would have been much lower than either inline array designs or the L_T = 12.7 mm staggered array, it was deemed unnecessary to design and implement a new mount.

3.1.2 Longitudinal Distance

After the dependence of the performance of the staggered and inline arrays on the transverse separation distance was characterized, the next item was to characterize how varying the longitudinal separation distance would affect the air-moving performance of the arrays. It was assumed that the behavior exhibited in one array would be similar to that of other arrays.

The transverse separation of the staggered array was fixed at L_T = 12.7 mm while the longitudinal separation distance was varied from L_L = 30 mm to L_L = 90 mm in three increments of 30 mm. The results of these tests are shown in Figure 12. The horizontal axis is shown as the velocity since the cross-sectional area was the same for each test.

The results show very little dependence of the fan curve performance on the longitudinal separation. However, there is a slight decrease in average velocity at free delivery from the L_L =

30 mm distance compared to that of the L_L = 60 mm and L_L = 90 mm cases. This is probably caused by frictional losses along the walls of the channel and points to one obvious conclusion. As the longitudinal distance between the columns of fans is increased the performance can be expected to decrease. The length of the channel limited the measurements of the longitudinal separation distance and therefore no more tests could be conducted to further corroborate this conclusion.

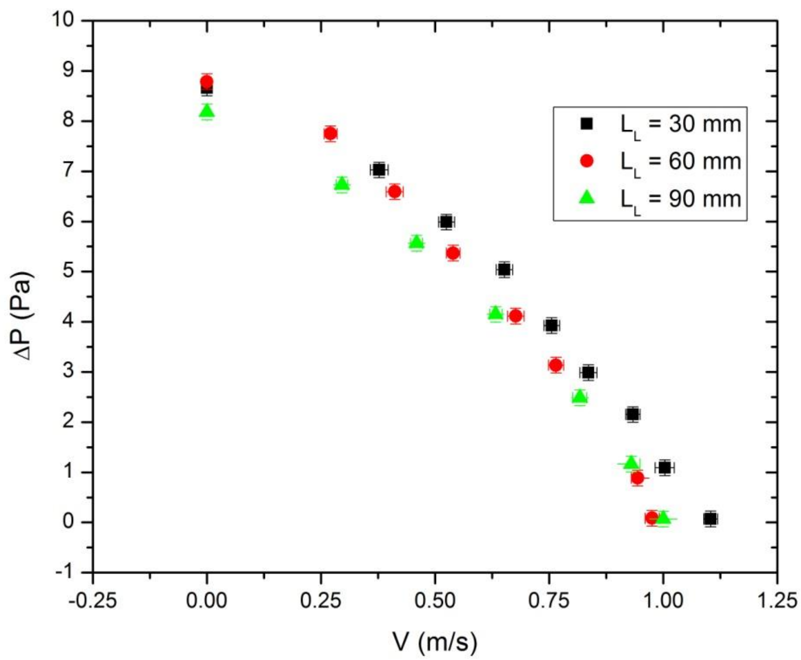

Figure 12. The results of varying the longitudinal separation distance in a staggered array with a transverse separation distance of 12.7 mm.

3.2 Results from Parallel Operation

Conventional fans are sometimes used in parallel in systems requiring more volumetric airflow than one fan can produce. When two or more fans are operated in parallel the flow rate is increased in direct proportion to the number of fans. Although the flow rate is increased the maximum pressure stays the same. Overall the fan curve is stretched along the volumetric flow rate, i.e. horizontal, axis by the number of fans operated in parallel [19]. Ideally the arrays of piezoelectric fans would behave in a similar fashion when placed in parallel operation. However, it was necessary to conduct experiments to test this hypothesis.

The results of the parallel testing using staggered arrays are shown in Figure 13. At the no-flow condition the pressures for each layer of testing were within 1 Pa of one another, which is similar to the behavior of conventional fans in parallel operation. The flow rates for each additional layer tended to add linearly. The flow rate for two layers at free delivery was off the calculated amount of double the flow rate for one layer. The value obtained was 18% lower than the expected flow rate. However, the flow rate for three layers of staggered arrays was only 3.3% lower than the expected flow rate of 0.00619 m^3/s.

Typically, with the addition of a fan running in parallel with another fan, the fan curve is stretched along the flow rate axis by a factor of two. This stretching represents the increase in cross-sectional area. Since the fans are operating in parallel the average velocity does not change. By observing the average velocities of the one, two, and three layer staggered array tests, the variation is seen to be approximately 4%. However, examining the cross-sectional areas reveals the cause of the deviation of the two layer flow rate. The cross-sectional area for the two-layer test was 15% lower than double the cross-sectional area of the one-layer test. Therefore, it is concluded that indeed the piezoelectric fan arrays operate similar to conventional fans when placed in parallel operation.

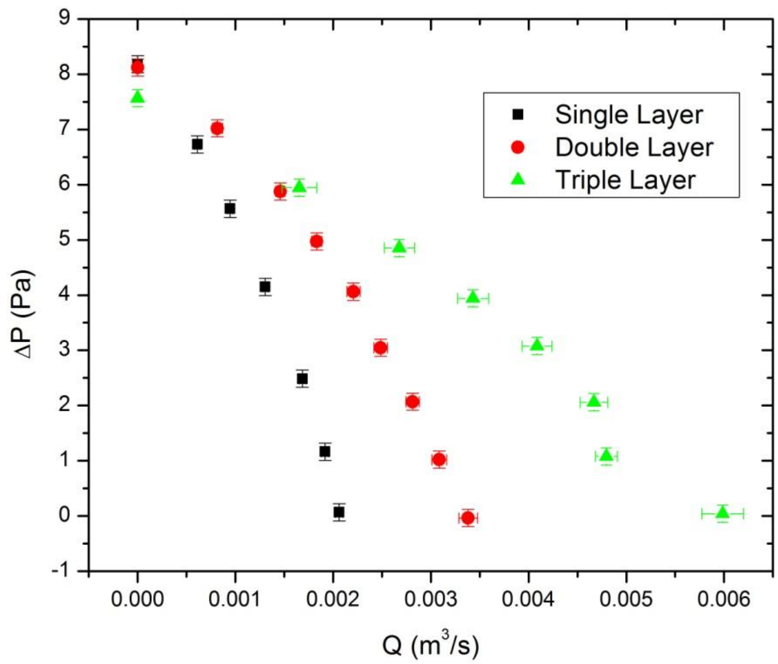

Figure 13. Results of testing multiple layers of staggered arrays in parallel.

3.3 Results from Series Operation

In order to understand how to increase the pressure induced by a single array the separate columns of an inline array were tested consecutively. The purpose for this group of tests was to investigate how additional columns may improve the air-moving performance of the array. The behavior of arrays of piezoelectric fans in series was determined from these tests.

The results of these tests are shown in Figure 14. The horizontal axis of the figure shows velocity due to the tests being conducted in a channel with the same cross-sectional area. As can be seen from the figure, there were two interesting differences from the 1 column test to the test of both the 1 and 2 columns. For instance, the free-delivery velocity increased by 27% between the two tests. This increase represents the additional acceleration imparted to the fluid for the additional column. This acceleration decreases when another column in added to form the full inline array design. In this case the increase in the free-delivery velocity was only 3%. It is concluded that adding more columns will not increase the free-delivery velocity of the piezoelectric fan array by a significant amount.

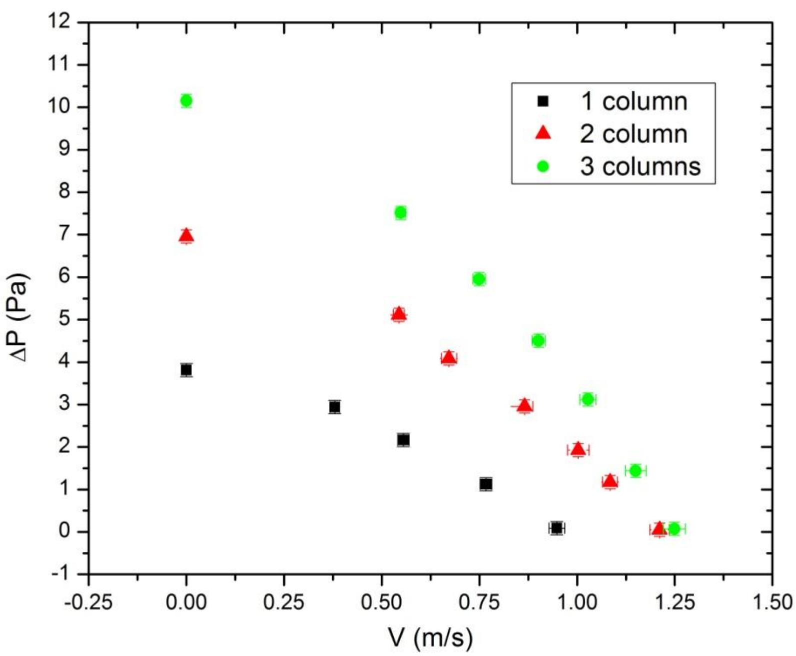

Figure 14. The results of testing one, two, and three columns of the inline array to determine how the addition of more columns would improve the performance are shown.

However, there is another advantage to append more columns to the inline array design. The results of these tests show that the pressure at the shut-off condition increases linearly with each additional column. The following relation has been developed by relating the number of columns in the inline array to the maximum pressure:

$$P = 3.17n + 0.63 \quad (1)$$

where P and n are the pressure and the number of columns respectively. Figure 15 shows this function compared to the three experimentally determined maximum pressures at the no-flow condition.

By adding additional columns to the inline array two conclusions can be made. With each additional column added to the full inline array the average velocity, and thus the volumetric flow rate, will stay essentially constant. However, the addition of another column to the inline array can be expected to increase the maximum attainable pressure by about 3 Pa. Therefore, if the application of the array requires a higher pressure, then the reasonable design step would be to design the array with the maximum number of columns possible.

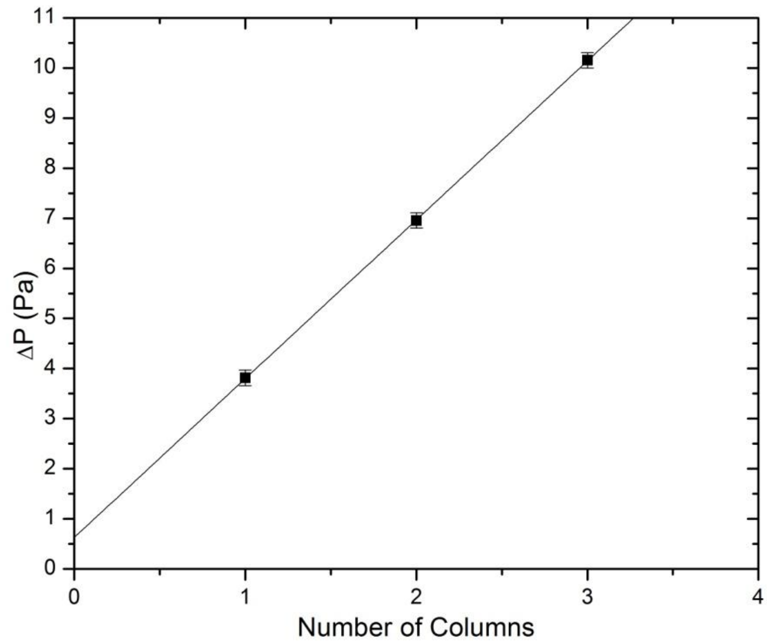

Figure 15. The best-fit line is shown for the maximum pressure dependency on the number of columns in an inline array.

3.4 Results from Single Fan Pressure Testing

The work presented here is for piezoelectric fans with specific resonance frequencies. Although the operating frequencies are similar for each test it, was deemed necessary to characterize how the performance of the piezoelectric fans is affected by a change in resonance frequency. Therefore the following test was devised.

In order to test how the performance is affected by a change in the resonance frequency, the maximum pressure induced by a single fan operating at different resonance frequencies was measured. The experimental set up was quite similar to that of the fan curve testing. The apparatus discussed in section 2.2.1 and shown in Figure 5 was used for these tests as well. However, the fan was inserted into an opening that had a width of 13.0 mm and a height that was equal to the displacement amplitude of the piezoelectric fan. The fan was inserted such that at the peak amplitude the fan tip was in line with the entrance plane.

For each individual test a single parameter was changed. The resonance frequency of the piezoelectric fan was increased by trimming the fan blade after each test. The frequencies tested ranged from 41 Hz to 130 Hz, which corresponded to free lengths of 44 mm and 23 mm. The driving voltage was held constant. Since the voltage was held constant, the displacement amplitude decreased as the frequency increased. Therefore the amplitude was measured with a scale to the nearest 0.5 mm. The amplitudes measured ranged from 30 mm to 20.5 mm. After the amplitude for the specified resonance frequency was determined the opening to the chamber was decreased to match the measured amplitude.

The results from these tests are shown in Figure 16. It is quite evident that as the natural frequency of the piezoelectric fan increases the pressure induced by the fan increases as well. The relationship appears to be linear, in fact, a linear curve fit (shown) results in an adjusted r-squared value of 0.98929. These results can be used to guide the design of piezoelectric fan arrays that are similar in structure to the arrays studied in this work, but with different operating frequencies. The engineer can also use these results in conjunction with the results of the fan curves for the arrays to determine an approximate fan curve for an array with an operating frequency that is higher or lower than that associated with the experimentally determined curves.

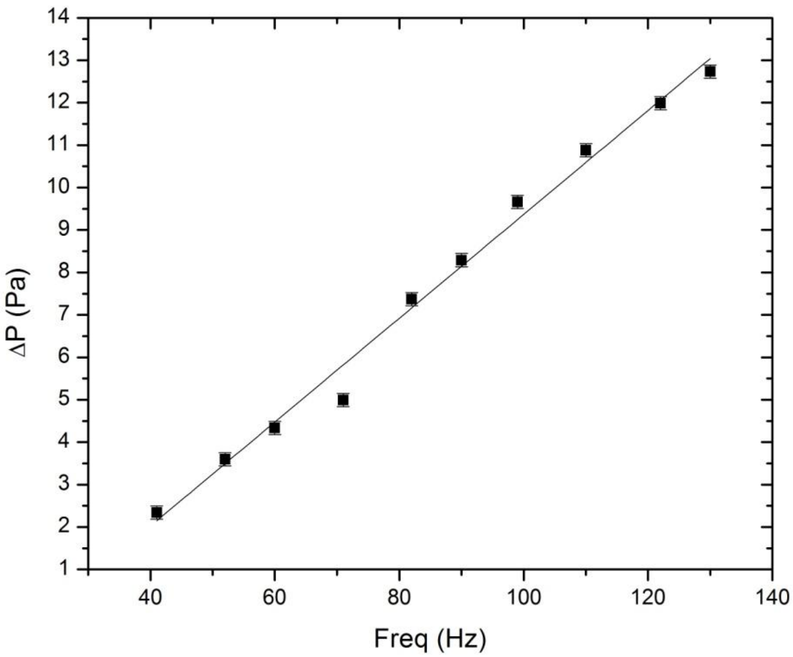

Figure 16. Pressure dependence of a single piezoelectric fan on the resonance frequency.

3.5 Comparison to Conventional Radial Fan Test

In order to assess the feasibility of using the piezoelectric fan arrays in applications such as those currently using radial fans it was necessary to compare their performance to that of conventional radial fans. The results shown in Figure 17 compare the best inline and staggered arrays to a radial fan traditionally used to cool electronics enclosures. The fan was a DC brushless fan with a model number BP1240M manufactured by ACT-RX Technology co., LTD. Not shown in this figure are the average velocities at free delivery, which were 1.0, 1.25, and 1.1 m/s for the staggered array, inline array, and radial fan respectively.

The radial fan outperforms both arrays when considering the pressure at the no-flow condition. However, the inline array outperforms both the radial fan and the staggered array with respect to the average velocity and the flow rate at free delivery. Furthermore, it is worth noting that the arrays of piezoelectric fans are able to be implemented anywhere along their fan curves whereas the radial fan should be implemented for system pressures below and volumetric flow rates above the inflection point, which occurs near 0.0012 m^3/s. When a fan has an inflection point along its fan curve, it is recommended that the fan be operated for volumetric flow rates away from where this point occurs. This recommendation is to avoid possible instabilities that may occur if implemented to the left of the inflection point [4719]. Although the piezoelectric fan arrays outperform the radial fan with respect to the range of pressures and flow rates for which they can be used, still a more relevant comparison can be achieved if the efficiencies of the different types of the arrays and the radial fan are compared.

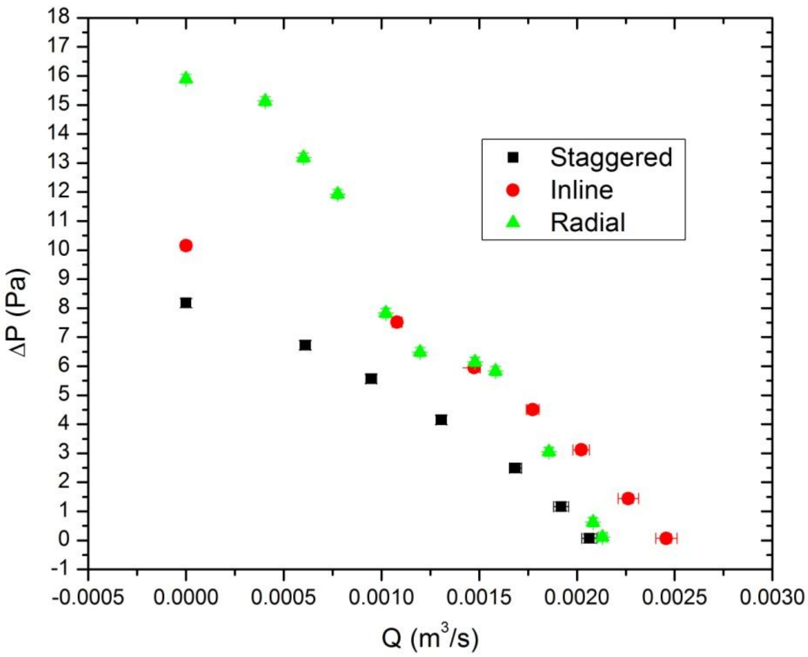

Figure 17. Fan curves comparing the performance of the radial fan to the best inline and staggered arrays.

3.6 Efficiency of Piezoelectric Fans

In order to compare the overall performances of the individual arrays to one another and to conventional fans the efficiency was calculated. The efficiency was calculated per the AMCA 210 standard [20]:

$$\eta = \frac{\Delta P \; Q}{power\ consumed} \tag{2}$$

where P and Q are the pressure increase and volumetric flow rate along the fan curve respectively. This method was applied to all experimentally measured fan curves for comparison.

3.6.1 Efficiency of Arrays in Series

Figure 18 shows the efficiency of the inline array for the numbers of columns in series, as discussed in section 3.3. Q_o is the highest volumetric flow rate achieved for each individual experiment, i.e. the volumetric flow rate at free delivery. An intuitive result is that as more columns are added to the inline array, the peak efficiency increases. This improvement is caused by the increase in pressure that is accompanied with a slight increase in power consumption. However, it should be noted that the increase in efficiency is almost certain to be small with the further addition of columns, because only the pressure will be increasing. The increase in efficiency from one column to two columns was due to the increase in pressure and volumetric flow rate; whereas, the increase in efficiency from two columns to three columns was mainly due to the increase in pressure, as the increase in flow rate was very small.

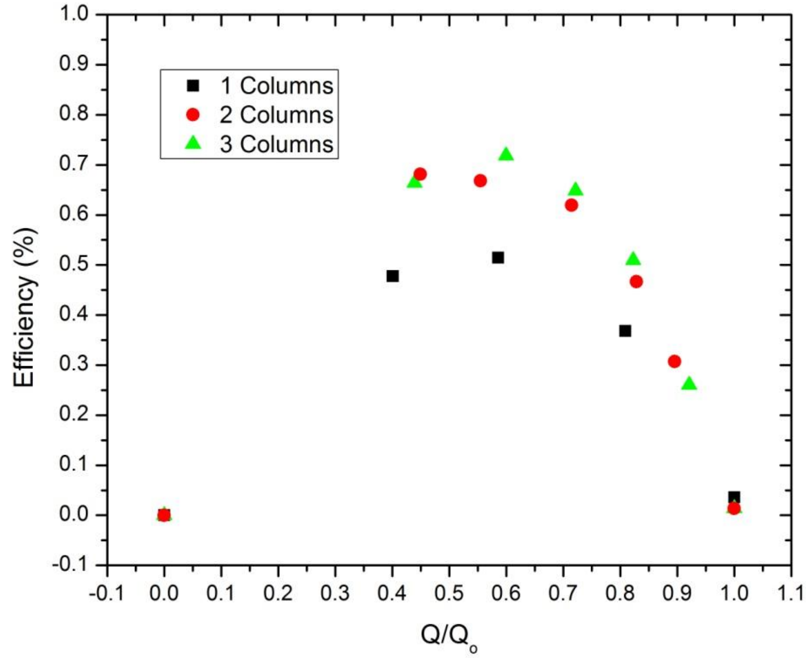

Figure 18. The efficiencies of the series tests for the inline array are shown.

3.6.2 Efficiency of Arrays in Parallel

The efficiencies of the parallel staggered arrays are shown in Figure 19. The efficiencies for the parallel configuration show the same trend with the same approximate values. As discussed earlier, since the flow rate and the power consumption increase at approximately the same rate while the pressure is relatively constant, the efficiencies of the staggered arrays operating in parallel were similar.

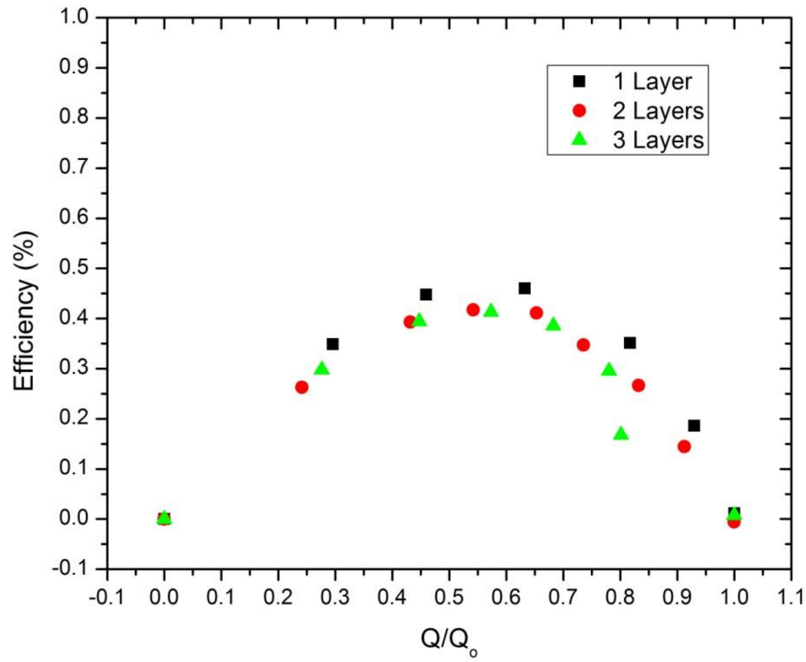

Figure 19. The efficiencies of testing parallel staggered arrays are shown. Notice that the general shape and approximate values are similar.

3.6.3 Comparison of Efficiencies

The efficiency of the best inline and staggered arrays are compared to the efficiency of the conventional radial fan in Figure 20. The inline array shows an improvement over the staggered array with peak efficiency that is 54% higher. However, the radial fan exhibits a peak efficiency that is 118% more than that of the inline array. Therefore the conventional fan exhibits efficiencies that are higher than the best design of piezoelectric arrays.

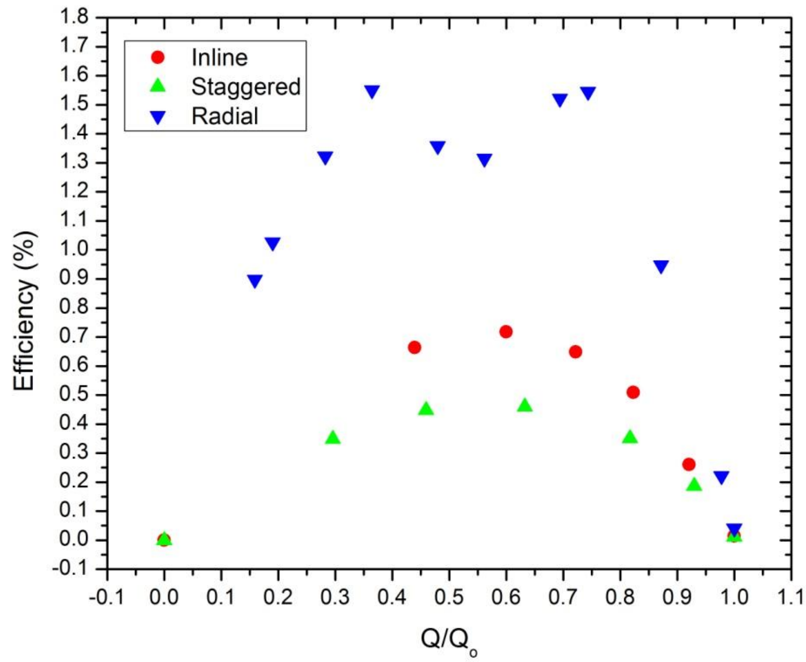

Figure 20. A comparison of the efficiencies of the radial fan to the best inline and staggered arrays.

This result is in stark contrast to the results reported by Kimber, *et al.* [17]. Their efficiencies obtained for a single piezoelectric fan were reported to be an order of magnitude larger than the conventional radial fan. The discrepancy is probably due to inherent losses in the geometrical arrays. For example, the channel height is designed to be less than 1mm larger than the amplitude of the piezoelectric fans, but this distance is certainly not optimized. Also, the vortices generated at the tip of the fan were not entering into a large chamber. In fact, they interact with the top and bottom of the channel, which results in a loss in performance. Finally, the individual fans were only able to draw fluid from upstream instead of in all directions. The overall efficiencies shown here represent a more realistic implementation of piezoelectric fans for heat exchanger applications, as opposed to spot-cooling applications.

Another possible factor for the decrease in efficiency is the ratio of swept area to the total cross-sectional area. The efficiencies reported by Kimber and co-workers [17] were for a piezoelectric fan in which the swept area was equal to the total cross-sectional area through which the air was flowing. For the current work, this ratio was 0.48 for the inline array with L_T = 12.7 mm.

As discussed earlier, the individual piezoelectric fans were manufactured in house. Although great effort was expended to make this process uniform and to select a good shape of the fans, manufacturing defects and a non-optimal fan shape could be another reason why the efficiency was lower. For instance, the fans used in this study had varying bonding layer thicknesses. This bonding layer decreases the amplitude which would therefore decrease the efficiency of the array [18].

3.7 Normalization of Fan Curves

A useful technique for comparing the performance of different types of fans is to normalize the fan curve. Kimber, *et al.* [17] performed this normalization for their experiments with a single piezoelectric fan. Their curve fit normalized each fan curve with respect to the highest pressure, which was obtained at the shut-off condition (P_o), and the highest flow rate, which was obtained at free delivery (Q_o). They proposed a curve fit of the following form:

$$\frac{P}{P_o} = 1 - \left(\frac{Q}{Q_o}\right)^x \qquad (3)$$

It is obvious that when the pressure is at the shut-off condition the left hand side becomes one and at free delivery the right hand side also becomes unity. In this correlation, the x represented an experimentally determined constant, which Kimber and co-workers [17] found to be 1.6.

The curve fit of Kimber, *et al.*[17] was applied to the fan curves obtained for the piezoelectric fan arrays. The fan curves all normalized to follow the curve fit presented above with the same value for x. These results are shown in Figure 21,

Figure 22, and Figure 23. This result is unexpected due to the piezoelectric fans being in arrays as well as different geometrical testing configurations. Therefore, the design engineer implementing these arrays or arrays with different geometrical arrangements may view equation (3) as a confirmed design rule. Thus, the fan curve for any array geometry can be found by experimentally determining two data points, which are the pressure at the no-flow condition and the flow rate at free delivery.

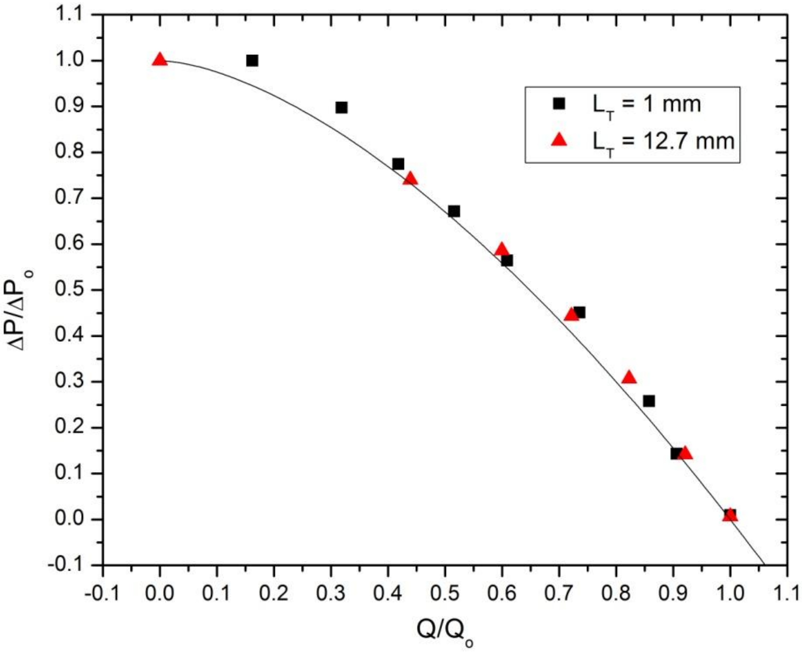

Figure 21. Shown is the comparison of the experimentally determined normalized fan curves for the inline array with transverse separation distances of 1 mm and 12.7 mm to the correlation.

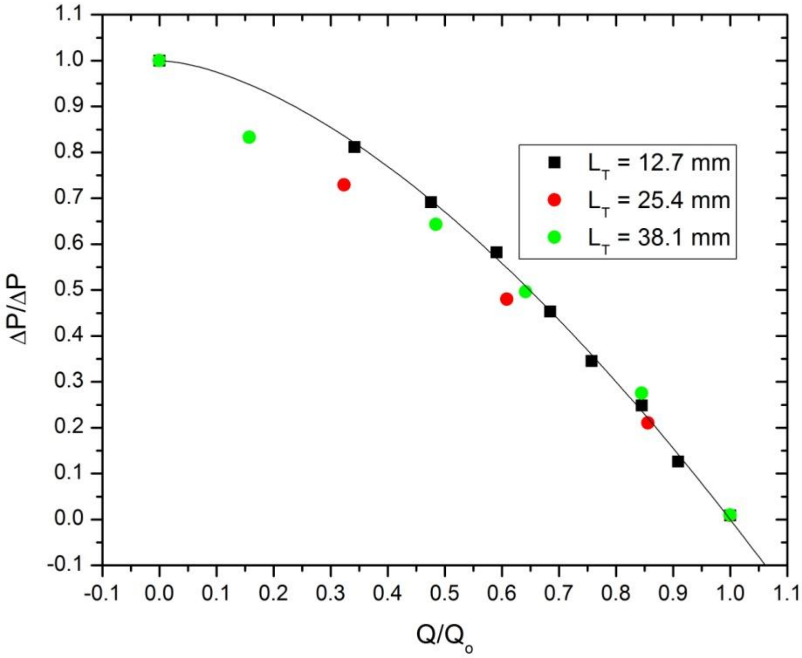

Figure 22. Shown is the comparison of the normalized fan curves for the staggered arrays with transverse separation distances of 12.7, 25.4, and 38.1 mm to the correlation.

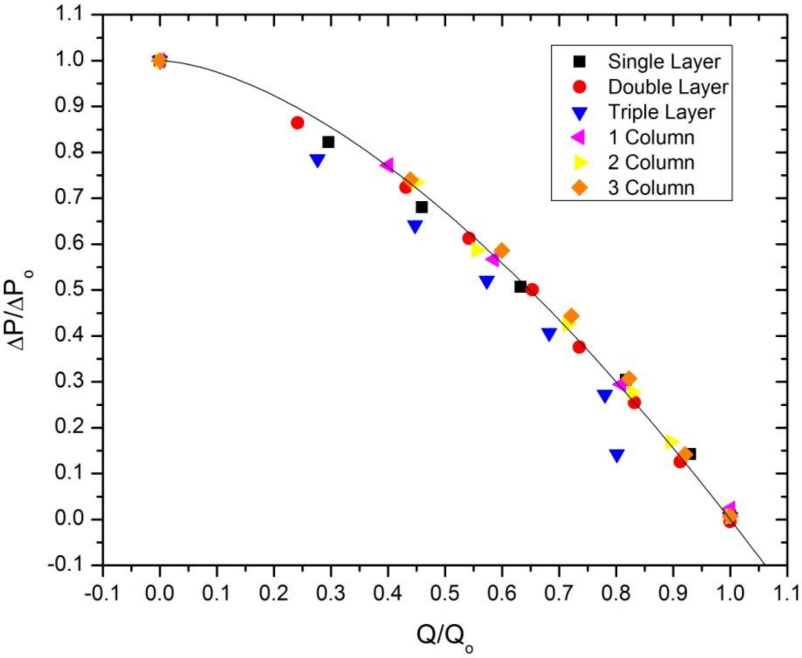

Figure 23. Comparison of the correlation for normalized fan curves for piezoelectric fans in arrays in series and parallel is shown.

4. Conclusions and Recommendations

The results from the experiments conducted in this work allow the following conclusions to be drawn. Firstly, increasing the transverse distance decreases the pressures attainable by a piezoelectric fan array. Although there is an increase in volumetric flow rate, the drop in pressure decreases the efficiency and results in poor performance. However, from the transverse distance testing with the inline array, the efficiency increases from the L_T = 1 mm to the L_T = 12.7 mm transverse distances by 71%. This result combined with the result that the efficiencies of the staggered arrays decreased as the transverse distance increased leads to the conclusion that there is a maximum efficiency related to the transverse separation distance, which may be close to L_T = 12.7 mm.

From studying the results of varying the longitudinal separation distance, L_L, of the staggered array, it can be concluded that this distance has only a small affect on the performance of the arrays. There was a 15% decrease in the average velocity at free delivery when the longitudinal distance increased from L_L = 30 mm to L_L = 60 mm. This increase was well within the repeatability study and therefore is not significant. However, implementation into a real system would most likely demand a small volume of space to be occupied by the array and therefore any improvements that a small longitudinal distance gives will be realized by a compact design.

How the piezoelectric fan arrays behave in parallel and series was a question that needed to be answered by this study. The tests of the parallel staggered arrays show that the arrays behave quite similar to conventional fans. For instance, the shut-off pressure stayed constant with each additional layer while the flow rate increased at the same rate as the cross-sectional area. The series tests showed a linear increase in the shut-off pressure with each additional column of piezoelectric fans. Meanwhile, the velocity at free delivery increased significantly when an additional column was added to a single column. Therefore, when implementing the inline array into a real system, it would be beneficial to require at least two columns of fans, and more columns could be added to obtain the pressures needed for the system.

The experimentally determined fan curves show that the piezoelectric fans when implemented into arrays show the same behavior as exhibited by a single piezoelectric fan. Furthermore, the fan curves can be reasonably approximated by only measuring two points along the curve, i.e. the flow rate at free delivery and the pressure at shut-off. Therefore, if new geometries of arrays were designed for a system the fan curve could be easily obtainable by measuring these two points.

An interesting result from this study comes from a comparison of the efficiencies of the arrays of piezoelectric fans and a radial fan. The efficiencies of the arrays were much lower than that of a conventional axial fan. As discussed earlier, this was unexpected since others [17] have reported efficiencies for a single fan an order of magnitude higher than axial fans. This finding leads to the following conclusion. The current design of arrays of piezoelectric fans should not be implemented into a real system unless efficiency is unimportant. However, as explained earlier it may be possible to increase the efficiency of these arrays and more investigation is recommended in this area.

The design space for implementing an array of piezoelectric fans as a prime mover is quite large. The current work attempted to cover a portion of this design space and to offer suggestions for further research and development. For example, it may be beneficial if directional vanes were added after the piezoelectric fans to guide the vortices generated at the tip of the fans and increase the efficiency of the arrays. The current work only thoroughly investigated two different geometrical arrays and only investigated parameters in two dimensions. Other array geometries may result in performance enhancements and further investigation may be beneficial.

Table 1. Summary of Parameters Tested

Array Type	Test	Transverse Distance (mm)	Longitudinal Distance (mm)	Channel Height (mm)	Channel Width (mm)	Operating Frequency (Hz)	Average Current (mA)	Operating V_{rms} (V)	Average Efficiency (%)
Inline	Separation	1	90	22	50	109	20.5	55	0.28
Inline	Separation	12.7	90	25	78	103	22.4	55	0.4
Inline	Series-1 column	12.7	90	25	78	103	8.6	55	0.28
Inline	Series-2 column	12.7	90	25	78	103	14.7	55	0.39
Staggered	Separation	12.7	30	27.5	75	108	22.6	55	0.3
Staggered	Separation	12.7	60	27.5	75	108	21.9	55	0.27
Staggered	Separation	12.7	90	27.5	75	108	21.6	55	0.26
Staggered	Parallel-2	12.7	90	45	78	107	39.7	55	0.25
Staggered	Parallel-3	12.7	90	80	78	106	58.9	55	0.25
Staggered	Separation	25.4	90	28	100	103	20.29	55	0.13
Staggered	Separation	38.1	90	26.5	122	107	19.85	55	0.18
Conventional	Radial Fan	--	--	40	50	--	49.7	12	1.07

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Appendices

A. Volumetric Channel Testing

Preliminary testing was conducted to find promising shapes of the individual piezoelectric fans and the geometry of the arrays before the complete test setup as discussed in Section 2.2.1 was constructed and used. This series of tests also served to help better understand the performance of single piezoelectric fans and arrays made up of them. This testing was also motivated by previous research and the attempt to replicate that research. The parameters that were tested were the attachment length of the piezoelectric material to the non-piezoelectric material, the unattached length, the flow rate dependence on frequency, and the thickness of the non-piezoelectric material.

A.1. Attachment Length

For testing how the above parameters affect performance, a series of volumetric tests that were easily set up and conducted were performed. For testing the attachment length, free length, and width parameters, the volumetric channel had a height of 30 mm, a width of 100 mm, and the velocity measurements were recorded a distance of 150 mm down the channel from the tip of the piezoelectric fan. The velocity measurements were recorded at the vertical center of the channel and were spaced 8 mm apart in the horizontal direction.

The velocity was averaged over three tests for each different attachment length. The velocity profile averaged over three rows in each measurement position separated by 5 mm is shown in Figure 24 and summarized in Table 2. By varying the attachment length the average velocity and the power consumption did not change. However, it was noted that with the smaller attachment length of 3 mm the bonding layer failed shortly after the tests had been completed. Therefore the combination of these observations led the authors to design the piezoelectric fans with an attachment length of 20 mm.

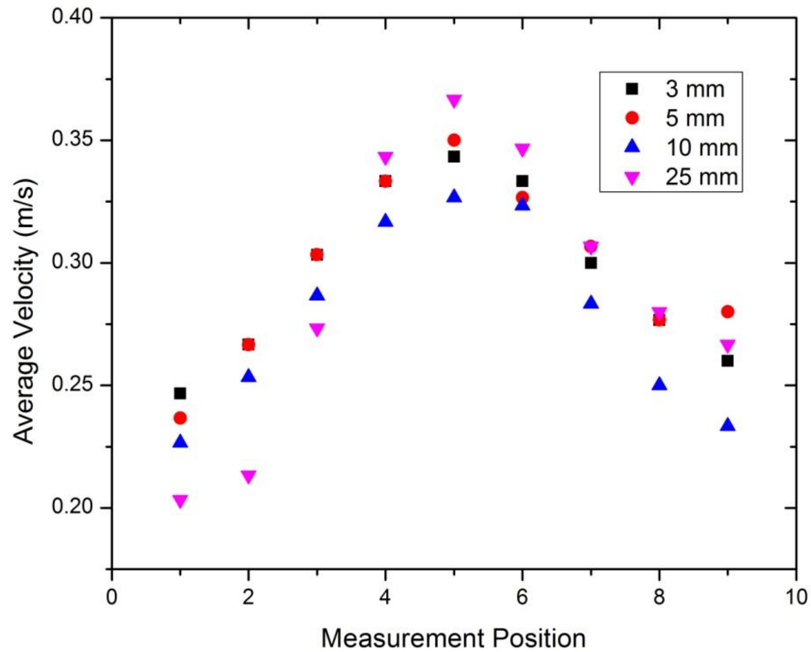

Figure 24. Profile of the average velocity for the tests varying the attachment length of the piezoelectric fans.

Table 2. Summary of Attachment Length Tests

Attachment Length (mm)	V_{avg} (m/s)	Power (mW)
3	0.3	26
5	0.3	26
10	0.28	26
25	0.29	27

A.2. Flow Rate Dependence on Frequency

As described by Yoo, *et al.* [454] the resonance frequency of piezoelectric fans is inversely proportional to the square of the free length. However, how the average velocity behaves by varying the frequency is poorly understood. The results of the tests determining this behavior are shown in Figure 25 and Figure 26. As the free length decreased the flow rate increased at the same rate as the frequency. However, the flow rate began to decrease as the free length decreased below 27 mm, which corresponds to approximately 105 Hz. These tests were conducted with .127 mm thick aluminum shim stock as the non-piezoelectric material and the failure that occurred for frequencies above 105 Hz is due the fatigue properties of aluminum. Although the piezoelectric fans used in this study consisted of mylar to avoid any failure, the target frequency for all subsequently constructed piezoelectric fans was 105 Hz.

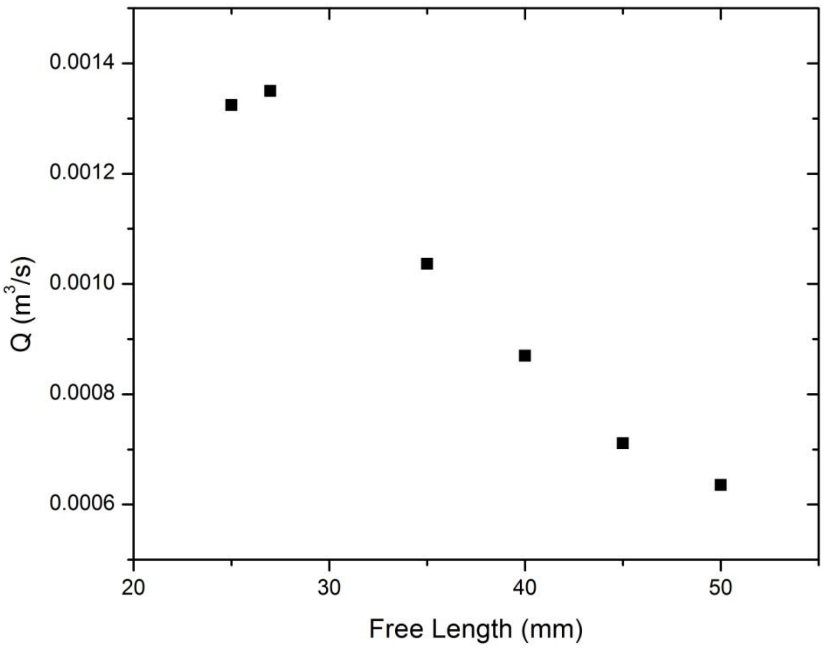

Figure 25. Flow rate dependence of a single piezoelectric fan on the free length.

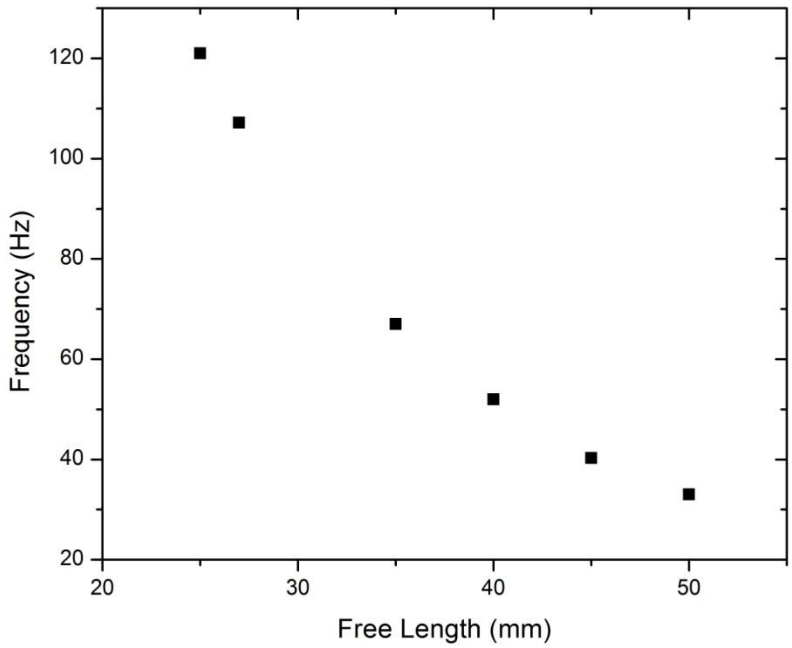

Figure 26. Frequency dependence of a single piezoelectric fan on the free length.

A.3. Thickness

The setup for the volumetric channel tests for thickness was slightly different. The channel had a height of 50 mm and a width of 266.7 mm. The velocity measurements were recorded at three positions in the vertical direction at distances of 15, 25, and 35 mm measured from the top of the channel. In the horizontal direction the velocity was measured at 25.4 mm intervals. Each piezoelectric fan had a free length of 30 mm, was constructed out of mylar, and was driven with a voltage of 70 V at its resonance frequency. Also, just as in the other volumetric channel tests, three different tests were performed for each variation in the thickness of material and the velocity measurements were also averaged over a ten second time period.

The results for testing how the thickness of the non-piezoelectric material affects the performance are shown in Figure 27. The frequency varied with the thickness linearly, just as beam theory predicts [4]. However, the flow rate drastically increased with the thickness of the non-piezoelectric material. Higher thicknesses, i.e. 0.3175 and 0.381 mm, were also tested, but mechanical failure was observed on the non-piezoelectric material at the end of the piezoelectric actuator. This failure indicates that the performance of the fan was limited to the fatigue limits of the material. Therefore, the thickness of 0.254 mm was used for all subsequently constructed piezoelectric fans and no failure was observed over the hours of testing conducted for this study.

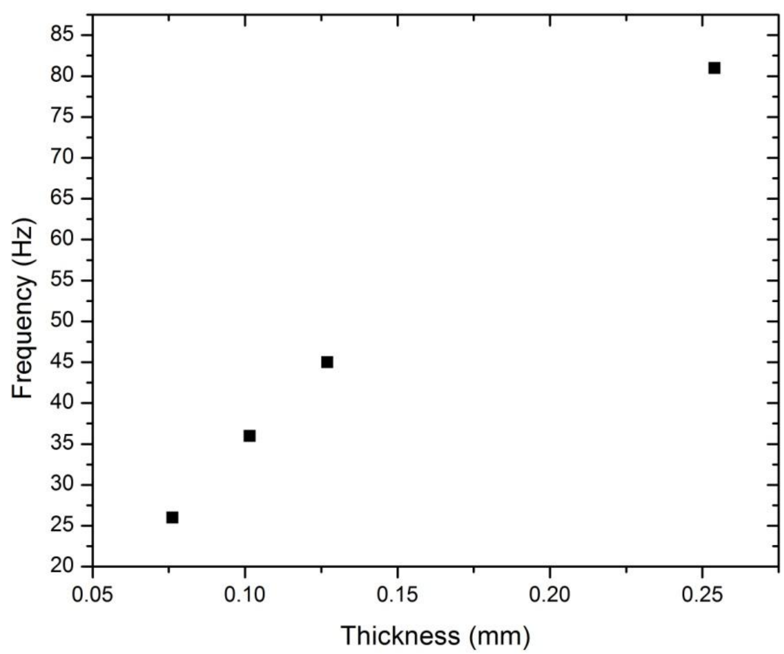

Figure 27. Frequency dependence on the thickness of the non-piezoelectric material.

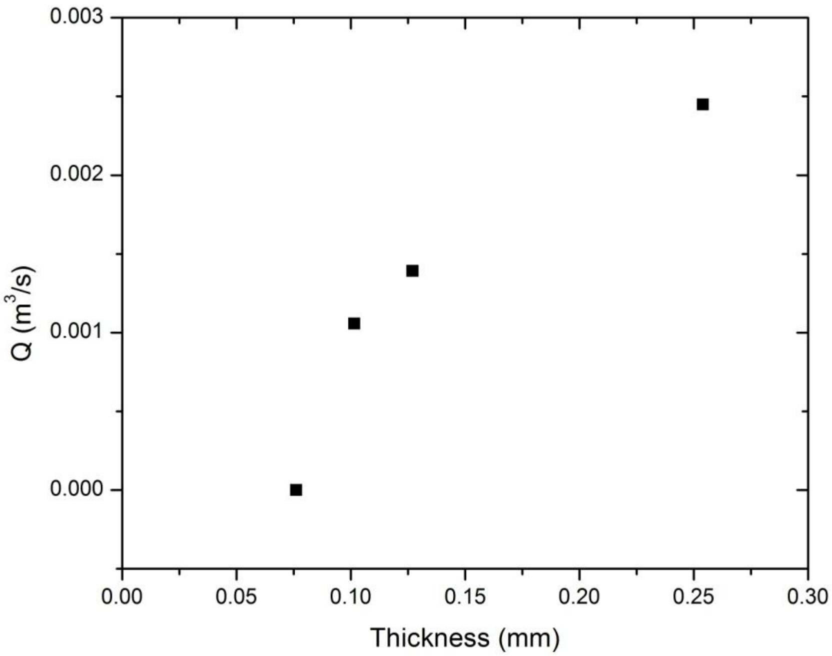

Figure 28. Flow rate dependence on the thickness of the blade of the piezoelectric fan.

A.4. Conclusions from Volumetric Tests

From the simple volumetric channel tests for the single piezoelectric fan, certain design parameters were determined. To maximize the flow rate, the thickness was determined to be .254 mm and the target fundamental resonance frequency was set at approximately 105 Hz. The tests to determine how the attachment length affected the performance of the individual piezoelectric fan showed no variation in flow rate or power consumption and therefore based on failure criteria and ease of implementation, the attachment length of 20 mm was chosen. These design parameters were fixed throughout the remaining part of the study and varying them was never conducted to determine how they would alter the performance of the arrays under a pressure load, i.e. measurement of the fan curve.

B. Repeatability Study

In order to accurately gauge the performance of the piezoelectric fan arrays, a detailed study on the repeatability of the results was required. Therefore, the following method was devised. An inline array with a transverse separation of L_T = 12.7 mm and longitudinal separation of L_L = 90 mm was tested with the same nine piezoelectric fans. The fans themselves were numbered and then randomly reconfigured into the different inline array locations. For instance, the piezoelectric fan numbered 8 was in the first position in the first column for the first run. For the second run the random number generator placed the piezoelectric fan numbered 8 in the first position of the third column. This allowed the repeatability of the same array consisting of the same fans in differing positions to be quantified.

The results of the repeatability study are shown in Figure 29. The results of the repeatability study showed a small variation of the pressure and a significant variation of the flow rate with the rearrangement of the piezoelectric fans. The variations in the performance are due to the variability of the individual fans. The manufacturing process for the fans is still quite crude, and the performance of the individual fans differs slightly. The piezoelectric fans differ mainly in resonance frequency by approximately ±2 Hz. This variation is less than 1% of the frequency, which depends on the free length of the piezoelectric fan, but obviously has a considerable impact on the performance of the arrays.

Run 1

8	9	4
1	5	6
2	3	7

Run 2

4	2	8
3	9	1
6	7	5

Run 3

6	1	3
2	5	9
4	8	7

Run 4

5	7	2
4	3	6
1	8	9

Run 5

1	9	7
6	2	5
8	4	3

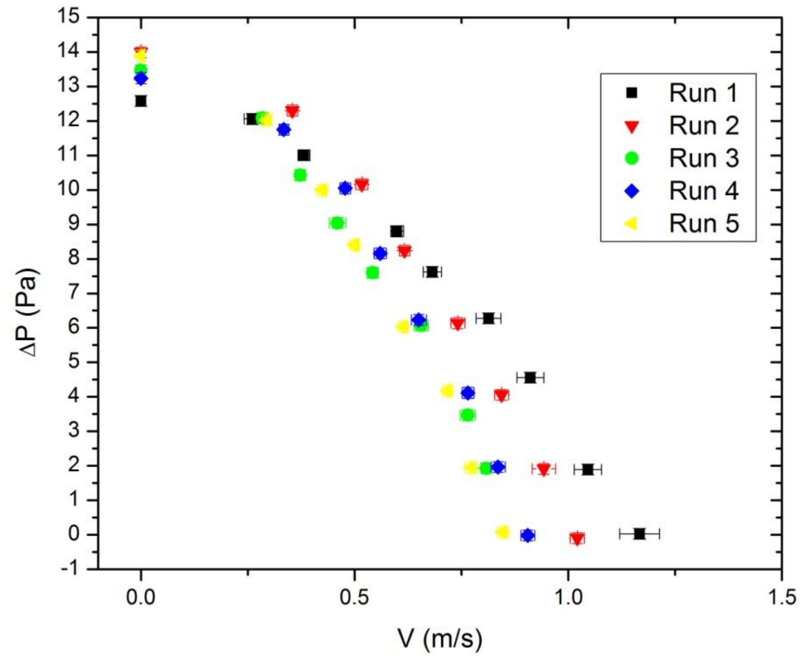

Figure 29. Results of the repeatability study are shown.

C. Sound Pressure Level Measurements

An important aspect of implementing an array of piezoelectric fans into a commercial application is the amount of sound that that is produced by the array. Therefore, to simulate a possible implementation, the sound pressure level produced by three layers of the staggered array was measured. The sound pressure level was measured with an Omega HHSL1 at three different locations around the arrays. The measuring positions were 1 meter away from the center of the three layers in the x, y, and z directions. The sound pressure level was measured to be 49.0 dBA along the x-axis, which was directly behind the opening of the channel housing the three layers of the staggered arrays, 48.3 dBA along the z-axis, which was directly above the center of the arrays, and 46.1 dBA along the y-axis, which was run transversely through the center of the layers. The background noise was measured to be below the range of the sound pressure level meter.