Energy Harvesting from Air Conditioning Condensers with the use of Piezoelectric Devices

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Abstract

Several on-campus air conditioning units were used to determine potential sources of waste energy found in an air conditioning condenser unit, and energy harvesting methods are devised. These methods of energy harvesting are called *vibration and airflow-driven* energy harvesting using piezoelectric devices. The objective is to generate power from the exhaust airflow (analogous to jet engine afterburners, but on a much smaller scale). For the piezoelectric device, the idea is to make the device vibrate to generate power. Students and faculty in an engineering technology program studied air conditioning units to determine potential sources of waste energy. Measurements were made to determine operational time based on seasons, vibration levels, and exhaust fan flow from a condenser. Measurements were taken and compared to calculated potential power to be harvested from the condenser. This undergraduate research project is one of several campus-wide efforts to promote energy conservation and to investigate the use of clean renewable energy resources.

Introduction

The term *piezoelectricity* is derived from the Greek word *piezein*, which means squeezing and pressing. *Direct* and *converse* effects are the two piezoelectric effects. In a direct effect, an electrical charge is generated from mechanical stresses. In a converse effect, there is a mechanical movement generated by the applications of an electrical field. Piezoelectric energy harvesting uses the direct effect and k_p, k_{33}, d_{33}, d_{31}, g_{33} are the characterizations of the piezoelectric material properties. The *k factor*, referred to as a piezoelectric coupling factor, is typical way to conveniently and directly measure the overall strength of the electromechanical effect [1-4].

Piezoelectric energy harvesting is a method that translates mechanical energy into electrical energy by straining a piezoelectric material [5]. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and resulting in a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, since it provides higher strain for a given input force [6]. The voltage produced varies with time and strain, effectively producing an irregular AC signal on the average. Piezoelectric energy conversion produces relatively higher voltage and power density levels than an electromagnetic system. Moreover, piezoelectricity has the ability to generate an electric potential of elements such as crystals and some types of ceramics from a mechanical stress [7]. If the piezoelectric material is not short circuited, the applied mechanical stress induces a voltage across the material. The most common type of device used to scavenge vibration energy is a cantilever piezoelectric device which generates electricity by bending, shaking, and deforming [8].

There are many applications based on piezoelectric materials, such as electric cigarette lighters. In this system, pushing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the high voltage produced jumps across a small spark gap, thus igniting the flammable gas. Following the same idea, portable sparkers are used to light gas grills and stoves, and a variety of gas burners ignition systems based on piezoelectric based ignition systems [9]. The best-known applications of piezoelectric crystals are: sensing elements, ultrasound imaging, sonar sensors, chemical and biological sensors, music instruments, automotive applications, piezo-resistive silicon devices, etc. [10-13].

In a study conducted by Marzencki [14] to test the feasibility and reliability of different ambient vibration energy sources, three different vibration energy sources including *electrostatic*, *electromagnetic*, and *piezoelectric* were investigated and compared according to their complexity, energy density, size, and the problems that were encountered (Table 1).

Table 1. Comparison of vibration energy harvesting techniques [14].

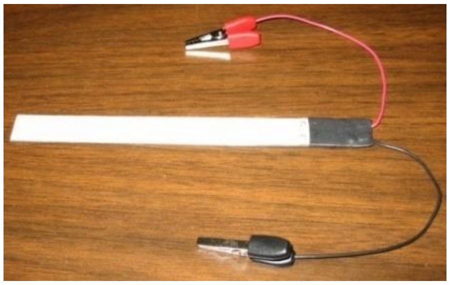
	Electrostatic	**Electromagnetic**	**Piezoelectric**
Complexity of process flow Energy density Current size	Low 4 mJ cm^{-3} Integrated	Very High 24.8 mJ cm^{-3} Macro	High 35.4 mJ cm^{-3} Macro
Problems	Very high voltage and need to add charge source	Very low output voltages	Low output voltages

The problem of how to get energy from a person's foot to other places on the body, for example, has not been suitably solved. For a radio frequency identification tag or other wireless device worn on the shoe, the piezoelectric shoe insert offers a good solution. However, the application for such devices is extremely limited and not very applicable to some low powered devices such as wireless sensor networks. Active human power that requires the user to perform a specific power generating motion is common and may be referred to separately as active human powered systems [15].

An example of energy harvesting using unimorph piezoelectric structures was conducted by Thomas, Clark, and Clark [16]. This research focused on a unimorph piezoelectricity circular plate which is a piezoelectric layer assembled to an aluminum substrate. The vibrations were driven from a variable ambient pressure source such as a scuba tank or blood pressure meter. The researchers showed that by creating the proper electrode pattern on the piezoelectric element (thermal "regrouping"), the electrode was able to produce an increase in available electrical energy. In the system, as the cantilever beam vibrated, it experienced variable stresses along its length. Regrouping the electrodes targeting specific vibration modes resulted in maximum charge collection. This type of design may add possibilities for miniaturization and practicality to piezoelectric energy harvesting technology.

Piezoelectric Devices

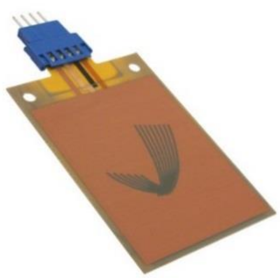
Two of the piezoelectric devices were used for this research. The first device was made of active piezoelectric fiber composite materials which are capable of generating electricity when exposed to an electric field. A piezoelectric fiber composite bimorph (PFCB) device based on this technology was implemented in this research. The composite is comprised of uni-directionally aligned piezoelectric fibers which provide the electric charge and stiffness of the composite. The fibers are surrounded by a resin matrix system which provides damage tolerance through load transfer mechanisms. Electrical inputs/outputs are delivered through a separate inter-digital electrode layer [17]. The PFCB was tested alone by flicking the tip of the piezoelectric device with a mechanical pencil without any mass attached on it; an oscilloscope and multi-meter were used to observe the power output signal characteristics. A photograph of the PFCB is shown in Figure 1 and displays the inter-digitized electrodes used to align the field (energy harvesting circuit) with the fibers.



Device size (mm): 130 x 10 x 1
Active elements: AFCB
Mode: d_{33}
Full scale voltage range (V): ±400
Full scale power range (mW): ±120

Figure 1. Basic specifications of the PFCB.

The second piezoelectric device for this research was purchased from the Mide Company. Mide products are manufactured based on wafers with a copper clad protective skin. This skin protects the normally brittle piezos and hermetically seals them against harsh environmental elements. The copper clad skin also provides a high degree of electrical insulation and enables pre-attached leads for easy connection [18]. The Mide *Volture* is a robust, reliable, and inexpensive means to harvest vibration energy for your application. The volture vibration energy harvester device harvests otherwise wasted energy from mechanical vibrations by using piezoelectric materials to convert mechanical strain into usable electrical energy [19]. A photo of the volture piezoelectric device and corresponding specifications are shown in Figure 2.



ELECTRICAL CHARACTERISTICS

Product	Single Wafer Series Capacitance (nF), measured at 100 Hz	Single Wafer Series Resistance (Ohm), measured at 100 Hz	Single Wafer Series Capacitance (nF), measured at 120 Hz	Single Wafer Series Resistance (Ohm), measured at 120 Hz
V20W	69	390	69	340
V25W	130	210	130	175

NOTE:
1. All dimensions are in inches
2. Connector thickness = 0.100"

Product	Typical Thickness (in)
V20W	0.034
V25W	0.024

Figure 2: MIDE Volture 25W photo and electrical characteristics [18-19]

Source of Waste Energy – AC Condenser

For the source of vibrations, a York 6 and ½ ton AC condenser unit was used (Figure 3). In figure 4, the source of waste energy from exhaust fans is depicted. Exhaust fans from an AC condenser unit located near industrial technology laboratory building at Sam Houston State University were the vibration source. The building used for this project is a combined laboratory and shop and classroom facility with two condenser units–one single fan and one twin fan. The initial study employs the twin fan unit. Initially, the AC condenser unit was studied, and potential paths of the study were generated.

Figure 3. R-410A XP series 6-1/2 ton 60Hz AC Condenser Unit

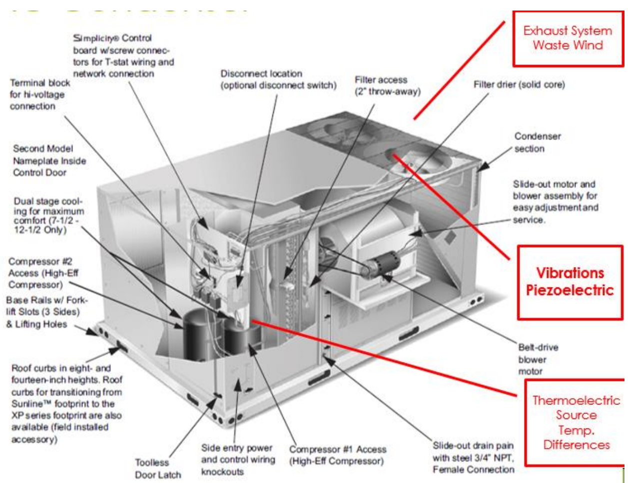


Figure 4. Pictorial of AC condenser unit showing waste energy sources for energy harvesting

Viewing the unit from above, the rotation of both fans is clockwise. The fan blade length is approximately 7 inches, each set at approximately 30° from horizontal, and the outside diameter of the blade arc is 24 inches. The metal housing for the fan exhaust has a 3.5 inch deep taper that tapers out at approximately 16° with a fillet radius at the top. Therefore, the metal housing fan exhaust opening has an inside diameter at the top of the fan of 24 inches and an outside diameter approximately 3.5 inches above the fan of 26 inches. The metal housing has a flat portion approximately 2 inches wide between the two 26 inch openings. Basic dimensions of the housing area of interest are shown in Figure 5.

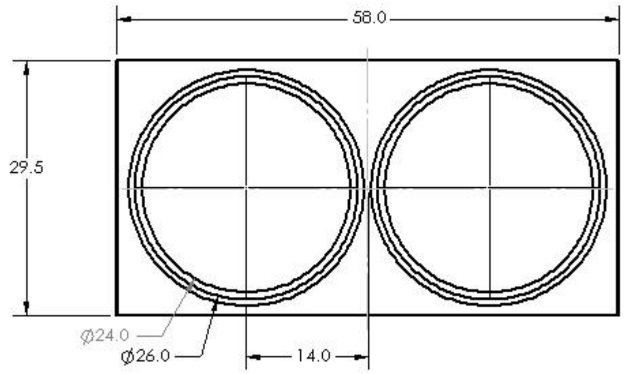


Figure 5. Fan housing dimensions (top view, inches)

The design of the housing and fan rotation generates noticeable air currents above the housing. The salient points are summarized below:

- Because of the aggressive pitch of the fan blades and the fact that there is so much area in the center of the fan that has no pitched blade, a vacuum is actually generated at the center of each fan (i.e. at X=±14inches in Figure 6). The rotation about the motor axis is clockwise when viewed from the top, yet still shows low pressure in the center. This is consistent with cyclostrophic flow, which is not an unreasonable analogy, given the boundary conditions (in cyclostrophic flow, the mathematics do not define counterclockwise versus clockwise rotation per se, unlike the case of geostrophic flow which applies to normal large scale weather patterns in the atmosphere and does define a flow rotation relative to the gradient). *Note*: Cyclostrophic flow describes a steady-state flow in a spatially varying pressure field when the frictional and Coriolis actions are neglected. In addition, the centripetal acceleration is entirely sustained by the pressure gradient.
- Because both fans rotate clockwise, there is a turbulent interaction zone where the flows from the fans collide. It is unclear at this point whether this turbulent zone results in localized counterclockwise flow as one might expect; however it is apparent that a low pressure zone is generated in this area (see Figure 6 at X=0) so at least some degree of rotational flow might be expected.
- Vertical air speed readings taken with a simple handheld vane type anemometer are shown in Figure 6. The *Kestrel* brand used is shown in Figure 7. These readings were taken on a coarse measurement grid. Additional readings were taken at higher elevations above the fans to determine the decrease in speed with vertical distance from the fans. Measurement on a finer grid using a hot wire anemometer probe may show slightly different slopes and peaks/valleys, but the basic shape should be retained. The three dimensional visualization of Figure 6 could be described as *Siamese twin funnel cakes*.

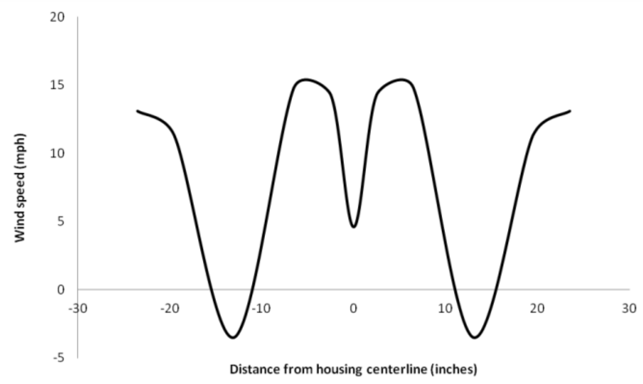


Figure 6. Wind speeds along centerline of fans at 2 inches above housing (approximately 5.5 inches above top plane of rotating fan blade).

Figure 7. Wind meter used to obtain data for Figure 6.

- The direction of the forced air movement above the fans is influenced by the ambient wind speed and direction (variable 1-10mph gusting in the Y direction). In an attempt to visualize the flow pattern, a smoke generator system was used to inject smoke into the flow (Figure 8). The smoke did not give as clear a picture as was desired so a probing wand in the outflow might be a better option (similar to wind tunnel devices) rather than a large smoke injection into the intake as was done here.

Figure 8. Smoke pattern

- Strips of surveying tape also confirmed the high and low pressure areas and rotation of the airstream (Figures 9 through 11).

Figure 9. Tape held the in area of maximum airspeed showing angle of flow (partially induced by slight ambient wind, but mostly due to rotational flow).

Figure 10. Tape held at center of fan showing vacuum.

Figure 11. Tape held close to X=0 location. Flow was small and almost horizontal or slight vacuum in this region.

An initial estimate of flow using SolidWorks Flow Simulation was performed using the following estimated parameters:

- Velocity 1m/s
- Fan swirl 2rad/s
- Turbulence intensity 5%
- Turbulence length 0.0254m.

These parameters and the physical model require refinement based on both measured data and boundary conditions. In SolidWorks, one boundary condition that is pre-programmed for the user is a fan. However, initial experience with this boundary condition indicates that there may not be a convenient way to simulate the rather large center hub area of the real condenser unit fan that has no blade surface and does have a vacuum. This might be simulated by working on the accuracy of the fan swirl estimate and by either putting a blocking plate in the center of the fan opening in the solid model or by formulating a true ring (i.e. annulus) shaped boundary condition with vector manipulation to induce the swirl. The initial model simulation using flow lines is illustrated in Figure 12. Once the model is perfected, mass flow predictions may be used to estimate power production from harvesting devices placed in the airflow.

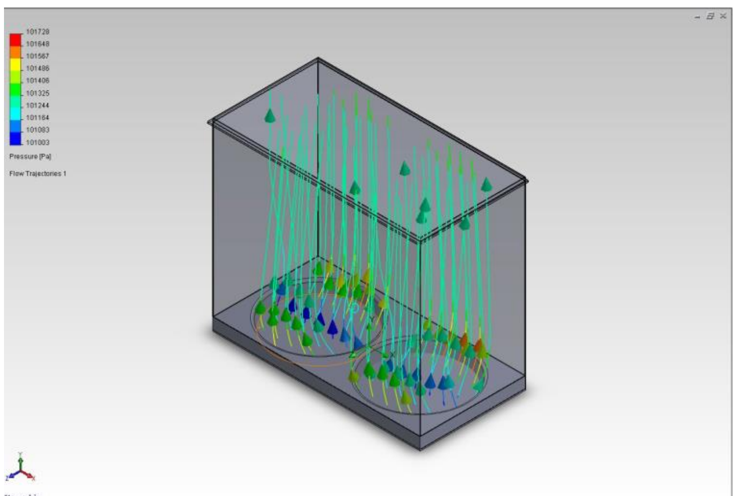


Figure 12. Initial flow simulation model (fan swirl 2rad/s).

Implementation and Testing

In this research, only a piezoelectric device was used for energy harvesting. The objective was to generate power from the exhaust airflow (analogous to jet engine afterburners but on a much smaller scale). Because of the scale of the project and the fact that the flow varies from pressure (reasonably large) to vacuum (fairly small) and includes a rotational component, the harvesting devices chosen for basic proof of concept are relatively small (i.e., smaller than the fan housing opening). In addition, the selection of devices must be considered–the airflow from the fans is not necessarily straight up from the unit (i.e. parallel to the fan rotational axis). The flow has a rotational component and is affected by ambient wind speed and direction which can make the whole flow pattern lean over. *Prior to considering harvesting devices in detail, the fan exhaust was completely blocked in the vertical direction in order to determine if a harvesting device* *would significantly affect the current draw of the entire unit. The change was considered insignificant (less than 0.2A)*. For the piezoelectric device, the idea is to make the device vibrate to generate power. Aircraft designs are usually optimized to reduce or eliminate flutter. In this project, we actually want to purposefully generate flutter, but avoid failure from uncontrolled excitation of a natural frequency. The approach is to attach a compliant or loosely attached airfoil to the end of the piezoelectric strip; the airfoil should generate cyclic displacement due to the airflow and the turbulence in the airflow.

The testing was conducted using the two previously described piezoelectric devices. Two small brackets attached to mount both piezoelectric devices on the grid of twin exhaust fans. Additionally, a *Mide volture* device was mounted on the wind turbine metal frame about 1ft height from the exhaust grid (Figure 13). A small weight was attached to the tip of the vulture piezoelectric device. *The PFCB piezoelectric device's cables were damaged during the first test. No frequency and power output information was recorded due to unexpected damage on the wires coming from the fibers of the device. The researchers are in the process buying more piezoelectric devices to make a comparison study and for back-up in the case that further damage occurs during the testing of the devices. The results of the comparison study will be shared with academia during the presentation at the ASEE conference*.

Figure 13. Mide volture piezoelectric device under testing – *mounted to wind turbine stand*

For this testing, no power output was obtained from the piezoelectric device. The only output was frequency (~25 - 55 Hz). Then the device was mounted on the grid with a different custom made bracket to measure the frequency, amplitude, and power outputs (Figure 14). The piezo device was mounted where two exhaust fans were closer to obtain higher amplitude from the device. The locations of the air output are defined in previous sections. Based on the findings, the piezo device was mounted between the twin fans on the grid.

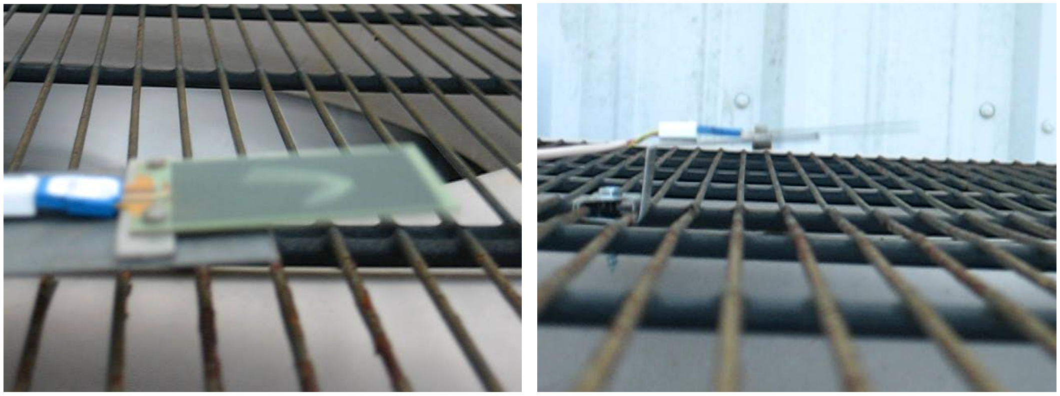


Figure 14. Mide volture piezoelectric device under testing – *mounted to exhaust grid*

For this test, the output power and frequency/amplitude were obtained and evaluated. The frequency was recorded as ~72Hz - 95Hz. Open circuit voltage was recorded as ~32V – 68V. A precision resistor was connected as a load to the piezo device through a rectifier circuit to determine power output of the device (no mass added). The power output was recorded as ~ 3.4W – 4.2W. Students are in the process of re-building the energy harvesting circuit to receive more accurate information including the frequency changes based on the various masses applied tip of the piezo device (Figure 15). The energy harvesting circuit will be capable of storing µA level of current levels from any piezoelectric devices to higher levels as compared to the current levels.

Assessment of Student Learning or Experiences

The Engineering Technology (former Industrial Technology) program offers a variety of renewable energy related projects to students who either volunteer or enroll for independent study courses. The projects are not part of the class/term projects; rather, they are mostly hands-on type activities for the undergraduate students. The projects may be accomplished either individually or as teams with 2-6 students under faculty supervision. Some of the recent energy related projects are:

- Implementation of an Electric Vehicle
- Building of Renewable Energy Lab Equipment
- Hybrid Electric Boat Design and Development
- Building a Hydrogen Fuel Cell, Solar, and Wind Powered Hybrid Electric Boat
- Self-Powered Athletic Field Striping Machine
- DC LED Lighting Analysis and Piezoelectric Powered Flash Light

All the projects are accomplished by the undergraduate students. No official surveys are offered to students to get feedback from the research; however, the verbal feedback is very positive in terms of learning, collaborations, team working, dealing with industry for help, purchasing, literature review, use of power tools, and software packages, etc. Most of the students had not been exposed to any type of individual or team work research in the past, according to verbal communications during the research. There were freshmen students who had not declared a specific major and minor under engineering technology before they were exposed to the research. After the research experiences they were involved in, students decided to seek a degree related to research in which they were involved. For example, a freshman student who worked on the self-powered athletic field stripping machine decided to on a design and development major with electronics minor instead of construction management. However, faculty who supervise the research may be required to spend more time with freshman and sophomore standing students than with the advanced classes depending on the students' knowledge levels.

In this specific project, there were two electronics students, one design and development student, and one electronics and computer engineering technology major student involved. The most common feedback from the students centered on skillsets gained for team work and their increased knowledge of waste energy, vibrations, energy harvesting, circuits, testing and measurement devices etc. Two of the students showed interest in extending the project to overcome some of the issues they faced during the study of the piezoelectric research. A new student will enroll in an independent study course to work on this project during the spring and summer 2015 semesters. For demonstration purposes, developed research will be used in two renewable-energy related classes offered in the engineering technology program. This type of project produces hands-on activities and demonstration modules for the students enrolled in energy classes. For example, the outcomes of this study created several lab activities for the students. The lab activities include an overview of how to take measurements (voltage, current, resistance, temperature, pressure), an overview of piezoelectric energy and energy harvesting, learning materials, simulation study (finite element analysis), soldering (copper), machining (used to machine the plates), design work (2D/3D design), theoretical analysis, implementation and evaluation of the technology, how to conduct a literature review for a project, and others. In this study, students were encouraged to see firsthand the relative merits and disadvantages of this type of technologies.

Instrumentation and energy knowledge and projects are important to prepare students to be competitive for careers in the growing fields of instrumentation, automation & control, energy-related engineering, science, and technology. Preliminary projections from the Bureau of Labor Statistics state that the number of expected energy related green jobs is expected to increase by 11% by 2016, and most of it in environmental or energy-related sectors [20-21] . Edgar Dale's cone of learning shows that participating in discussions or other active experiences may increase retention of material by up to 90% [22]. Richard Felder and Linda Silverman recommend several teaching techniques to address all learning styles, one of which is to provide demonstrations for students with sensing and visual learning styles and hands-on experiments for students with active learning styles [23]. According to Moore, there is a direct correlation between in-class performance, laboratory attendance, and performance [24]. In capstone related project, active learning can be achieved through a variety of activities that include lab and project experiments with hands-on projects and hands-on laboratory experiments [25-28].

Conclusion

The research was carried out to examine reliability of energy harvesting systems. Ambient energy harvesting systems represent a fruitful area of research and possibilities for further research are created with the convergence of miniaturization of the components used, low-power system designs, and developments in materials and mechanical systems. Special attention in this study was given to overall components and applications of the energy harvesting system to increase its overall efficiency and decrease power consumption of the application; this increases output capability of energy harvesting systems. A brand new class of piezoelectric materials were implemented in this research.

Building environments are rich places to capture the vibrations caused by human power, wind, sound, and other sources. These common places include floors, ceilings, windows, air ducts, home appliances, staircases, and HVAC, as well as from machinery running within the building. In this study, an air conditioner condenser was investigated to discover how to produce low power from potential vibrations. The study will continue during the spring and summer 2015 semesters for more detailed findings, as more students become involved in the research. There is constant low power output from a piezoelectric device due to vibrations from condenser exhaust fans. The next phase of the project will be to design and develop an energy harvesting circuit to scavenge usable energy in batteries and super capacitors and to divert stored energy for potential low power applications in the building.

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