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HARVESTING ENERGY FROM SOUND USING ELECTROMECHANICAL SYSTEM

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Abstract*-Development of portable equipment, wireless sensors networks and self-powered devices generate a strong request for micro-energy harvesting devices. The noise in the road and industries can be able to convert into electric energy and lights the street lightning, signals and various other electrical appliances. In this work, the harvested energy using piezoelectric material has been investigated and measured under the pressure oscillation wave of sound. The sound wave displaces back and forth between the potential energy of compression or lateral displacement of the matter and the kinetic energy of the oscillation which creates a force that is sufficient to deform the piezoelectric material and finally generates power. In this paper a system is proposed to convert sound into electrical energy for use in powering autonomous low power electronic systems as well as saving in battery.*

Keywords: Piezoelectric material, Sound, Harvesting energy, Mechanical, Electric energy.

1. INTRODUCTION

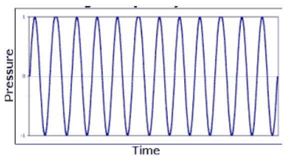
Energy harvesting is a burning issue for present decades. Due to limited conventional source of energy, it is now urgently necessary to save lost energy. Sound is one kind of energy which is lost everywhere in every time. From the law of thermodynamics it is stated that energy can’t be created but can be transferred from one from to another form. At this age of industrialization everyday huge noise and sound is produced in industry, highway road, workshop, station and so on. This paper investigates how to utilize this lost energy by converting into electric energy.Researchers have put much effort into energy conversion[1] and recent researchers have discovered that piezoelectric materialsare one the best option in energy conversion from mechanicalinto electrical or vice versa. These materials are also widely usedas sensors and actuators [2]. Piezoelectric material can be used as a mechanism to transform sound pressure into electrical energy. This energy can be stored and used to power up electrical and electronics devices. The process which is used is the combination of mechanical and electrical system. The output powercan be used for electronics devices, so entirely this process is called electromechanical system (EMS). With the recent advancement in micro scale devices, PZT power generation can provide a conventional alternative to traditional power sources used to operate certain types of sensors/actuators, telemetry, and MEMS devices. The aim of this paper is to develop the piezoelectric material as a power generator for these applications.

2. SOUND ENERGY

A waveis a disturbance that transfers energy through matter or space. Soundis a form of mechanical energy produced by vibrations. It travels in longitudinal (compression) waves and moves much slower than the speed of light. In longitudinal waves, matter vibrates in the same direction as the waves are traveling. Sound waves require a medium (solid, liquid, or gas) through which to travel. Longitudinal waves cause molecules of a medium to vibrate “back and forth” in the same direction that the wave is traveling. The speed of sound depends on the type of medium (how dense) it is passing through and the temperature of the medium. Pitch is the rate at which the vibrations are produced. The higher the frequency, the higher the pitch. When the vibrations are fast one can hear a highpitch & when they’re slow, hear a low pitch as shown in Fig.1.

2.1 Noise

Noise can be defined in different ways. People who study acoustics define noise as complex sound waves that are a periodic, in other words, sound waves with irregular vibrations and no definite pitch. In engineering, noise is defined as a signal that interferes with the detection of or quality of another signal [3]. Basically, noise is unwanted sound. It is a pollutant anda hazard to human health and hearing. Table 1 shows the different sound level which is usually used. We are discussed about noise or high decibel sound cause of



harvesting sufficient energy. That means about 90 to 170 and above sound is sufficient for this conversion.

Fig.1: High pitch of sound wave

Table 1: Loudness of sound in decibel

Sound	Loudness (dbs)	Hearing damage
Average Home	40-50	No
Loud Music	90-100	After long exposure
Rock concert	115-120	Progressive
Jet Engine	120-170	pain

2.2 Factors to Be Considered

There are several terms of measuring sound are considered as main factors of EMS like types of sound source, sound intensity, pressurepower, power level, velocity, types of wave, Frequency and pitch.

2.3 Measurement of Sound/Noise Parameters

Sound level, its frequency spectrum and its variation over time characterizes the nature of noise. Sound intensity (also called sound power density) is the average rate of sound energy transmitted through a unit area perpendicular to the direction of sound propagation, typically measured in PW/m^2.. Because of dealing with large range of numbers, a logarithmic measure called decibel (dB) is used to describe sound level. The sound level in decibel is defined as follows: Sound level,

$$L\,(db) = 10log\left(\frac{P}{P_0}\right)^2 = 20\log\frac{P}{P_0} \qquad (1)$$

Where, P is root mean square value of the sound pressure (N/m^2) and P_0 is the standard reference pressure (20 µN/m^2).

The parameter universally used in discussions of noise pollution of environment is Leq,Mathematical expression of Leq[4] is as follows

$$Leq = 10log\left[\frac{1}{T}\int_0^T \frac{f^2}{f_0^2}dt\right] = 10log\left[\frac{1}{N}\sum_i 10^{\frac{Li}{10}}\right] \quad (2)$$

Where, T is the period of measurement and Li is the average noise level during interval i.As the velocity of sound is proportional to the frequency so high velocity of sound is better forconversion.

2.4. Sources

As the industrial machinery has come into being by development of industrial technology, the productivity of the existing industrial machinery has improved. In industry or workshop there are several machines are available like Compressor, Forging machine, Metal cutter, Press, Blaster, Crusher, Riddle, Briquet pressing machine, Centrifuge, Sawing machine, Woodworking machine, Concrete pipe and pile making machine, etc. The forging machine is the noisiest of the industrial machinery as 117.6 dBA. The average sound power level for the industrial machinery is 100.1 dBA. The automatic packing machine, sewing machine, grinder, mixer, and the molding machine emit the sound power level lower than the average by more than 10 dB [5]. Besides industry above 100 db sound is also found in busy bus & train station, turning point of road,airport, concerts, power plant, rocket engine, overcrowded place as shown in Table 2.

2.5. Energy Equation of Sound

For a particle vibrating simple harmonically, the general equation of displacement is,

$$Y = a\sin(\omega t + \alpha) \quad (3)$$

Here y is the displacement and a is the amplitude and α is the epoch of the vibrating particle and ω is the angular velocity. The total (kinetic + potential) energy of a vibrating particle is

$$\text{Total energy,} E = 2\pi^2 m a^2 n^2 \qquad (4)$$

This energy is supplied by source that is,

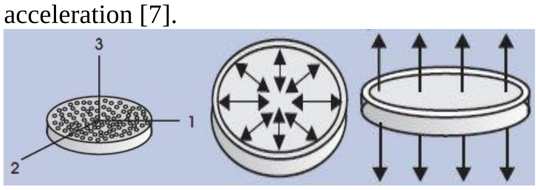
$$\text{Energy transfer per unit area per second} = 2\pi^2 \rho n^2 a^2 \upsilon \qquad (5)$$

Table 2: Sound sources with power [6].

Situation And Sound source	Sound power Pac watt	Sound power Level L_w db re 10^{-12} W
Rocket engine	1000000	180
Turbojet engine	10000	160
Siren	1000	150
Heavy truck engine or rock concert	100	140
Machinegun	10	130

3. PIEZOELECTRIC MATERIALS AND FUNCTIONS

Typically, lead zirconatetitanate (PZT) is used for piezoelectric energy harvesters becauseof its large piezoelectric coefficient and dielectric constant, allowing it to produce more powerfor a given input acceleration [7].



(a) (b) (c)

Fig. 2: (a)three axis of the material (b) radial oscillation (c) thickness oscillation.

In this project soft PIC 151 model piezoelectric material is used in this prototype for transducing because it is a modified lead zirconate – lead titanate material with high permittivity, high coupling factor and high piezoelectric charge constant. This material is the standard material for low power ultrasonic transducers and low frequency sound transducers and several deformation or oscillation as shown in Fig. 2. The force applied and change of internal molecule with polarization is shown in Fig. 3.

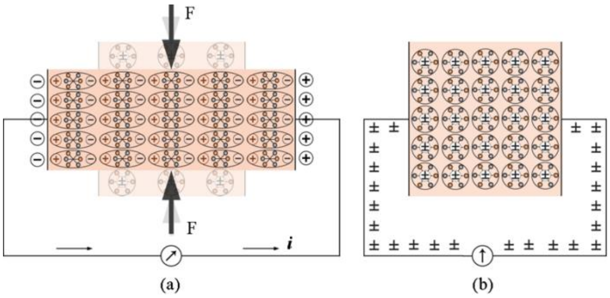


Fig. 3:Piezoelectric phenomenon: (**a**) The neutralizing current flow when two terminal of piezoelectric material, subjected to external force, are short circuited; (**b**) The absence of any current through the short-circuit when material is in an unperturbed state.

The generated voltage from a piezoelectric material can be calculated from the followingequation.

$$V = S_v \times P \times D \tag{6}$$

Where V = Piezoelectric generated voltage (Volts)
S_v = Voltage sensitivity of the material (Volt *meters /Newton)
P = Pressure (N/m2)
D = thickness of material (meters)

Following the linear theoryof piezoelectricity [8], the density of generated fixed charge in a piezoelectric materialis proportional to the external stress. In a first mathematical formulation, thisrelationship can be simply written as:

$$P_{pe} = d \times T \tag{7}$$

Where,$P_{pe}$is the piezoelectric polarization vector, whose magnitude is equal to thefixed charge density produced as a result of piezoelectric effect, *d* is the piezoelectricstrain coefficient and *T* is the stress. The reverse piezoelectric effectcan be formulated as:

$$S_{pe} = d \times E \tag{8}$$

Where $S_{pe}$is the mechanical strain produced by reverse piezoelectric effect and *E* isthe magnitude of the applied electric field.

3.1. Conservation of Energy

The principle is based on the fact that the total energy ofthe PZT bender stored is equal to the sum of the mechanicalenergy applied to the round plate and the electrical energy on thecharges being applied by the electric field [9,10,11]. When amechanical stress is applied, the energy stored in a PZT layer isthe sum of the mechanical energy and the electric-field-inducedenergy. Thus, the energy stored in a PZT layer is expressed asfollows:

$$U_u = \frac{1}{2}(s_{11}^E \sigma_1 - d_{31} E_3)\sigma_1 = \frac{1}{2} s_{11}^E \sigma_1^2 \tag{9}$$

where σ is the stress and *s* is the stiffness matrix.On the other hand, the energy in the metal layer can beexpressed by a simple equation because of the lack of theelectric field as follows:

$$U_m = \frac{1}{2} s_m \sigma_1^2 \tag{10}$$

The total energy is given as [9]:

$$U_{total} = \int_0^L \int_0^W \left(\int_{\frac{t_1}{2}}^{\frac{t_2}{2}+t_1} d\,D_u\,dz + \int_{-\frac{t_2}{2}}^{\frac{t_2}{2}} d\,D_{um}\,dz + \int_{-\frac{t_2}{2}-t_3}^{-\frac{t_2}{2}} d\,D_u\,dz \right) dy\,dx \tag{11}$$

Hence the capacitance*C*free can be found,where no load is applied[9]:

$$C_{free} = \frac{v_{33}^T WL}{2t_3}\left(1 + \frac{6S_m t_3 (t_2+t_3)^2 - X}{X} K_{31}^2\right) \tag{12}$$

Where *K*31 is the coupling coefficientThus, the voltage generated is found as a function of theapplied force:

$$V = \frac{Q}{C_{free}} = -\frac{6 d_{31} s_m t_3 (t_2+t_1) L}{v_{33}^T WX\left(1+\left(\frac{6S_m t_3 (t_2+t_3)^2}{X} - 1\right)K_{31}^2\right)} F_0 \tag{13}$$

The n-th natural frequency, xn, is given as in the followingequation:

$$\omega_n = (\beta_n L)^2 \sqrt{\frac{EI(x)}{\rho A(x) L^4}} \tag{14}$$

The analytical solution for the output voltage is [12]

$$\left|\frac{V_0}{\omega^2 W_{b0}}\right| = \frac{\tau_c \omega \varphi_{rn}(t) \int_0^L W_{rn}(x)\,dx}{\sqrt{[\omega_n^2 - \omega^2(1+2\zeta_n \tau_c \omega_n)]^2 + [2\zeta_n \omega_n \omega + \tau_c \omega]^2}} \tag{15}$$

3.2. AC-DC Conversion Technique

Due to stress and strain caused by vibration to the piezoelectric material, dual polarity of charge resultsin an alternating current (AC), which is then converted into direct current (DC) by a full bridge rectifier.The rectified current is then used to charge a capacitor or a battery, which can hold energy. Themaximum power transfer technique will be used to design the circuit for this energy conversion.AC-DC converter [14] is used to maximize the power transfer to the load. The reason to use AC-DC converter is to convert a variable input voltage into a constant output voltage.

4. AMPLIFICATION OF SOUND

As the high output energy is dependent on the high deflection of piezoelectric material so it can be said that if the source sound intensity and pressure can be raised then energy will high. There are several methods [15] of amplification of sound which are described below,

4.1 Reflection of Sound

Let XY be the plane reflecting surface and AMB they incident plane wave front. All the particles on AB will be vibrating in phase. Let I be the angle of incidence as shown in Fig.4.

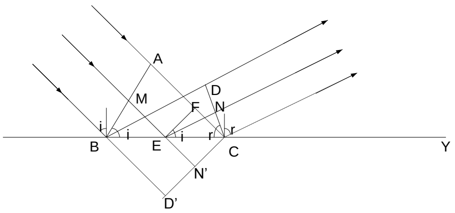
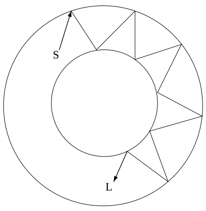


Fig. 4: Reflection of a plane wave at a plane surface.

In the time the disturbance at A reaches C, the secondary waves from the poit B must have travelled a distance BD equal to AC. Thus, all the secondary waves from the different points on AB reach the corresponding points on CD at the same time.

4.2 Whispering Galleries

S is the position of a speaker and L is the position of an observer as shown in Fig. 5.Even a very low intensity sound made by S can be heard by the observer at L when he keeps his ear close to the wall.This is due to the multiple reflection of the sound waves from the curved wall of the gallery.



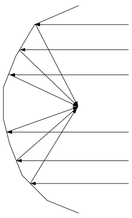


Fig. 5: Whispering galleries Fig. 6:Echo focusing

The principle of reflection of sound is used in an auditorium. A large plane sounding board (cylinder of parabolic) is placed behind the speaker as shown in Fig. 6. The speaker stands at the focus of the board.When the speaker speaks, the sound waves get reflected from the soundin board and the reflected sound travels towards the audience. The enables increase in the intensity of sound and also uniform distribution of sound.

4.3 Demonstration of Refraction of Sound

The principle of refraction of sound waves can be demonstrated with a simple experiment. A Rubber balloon L in the shape of a convex lens is taken and it is filled with carbon dioxide as shown in Fig. 7. A source of sound is kept at A. The spherical wavefront goes through the lens and converges to the point B.

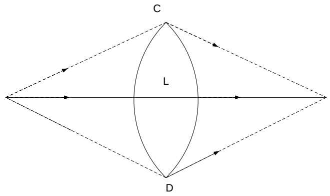


Fig. 7: Refraction of sound.

4.4 Intensity of Sound at A Point Due to A Plane Wavefront:

Figure 8 depicts that ABCD is a plane wavefront perpendicular to the plane of the paper and P is an external point at a distance b (OP=b) from the wavefront. λ is the wave length of sound. OP is perpendicular to ABCD. TO find the resultant intensity at P due to the wavefront ABCD, Fresnel's method consists in dividing the wave front into a number of half period element or zones called Fresnel's zones and to find the effect of all the zones at a point P.

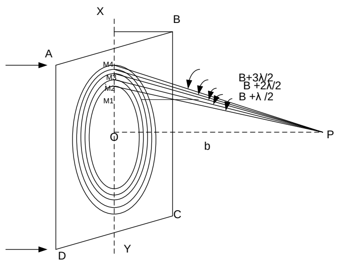


Fig. 8: Resultant effect of sound at external point.

The resultant amplitude due to the whole wavefront, A = $m_1 2$. The resultant intensity of sound at a point is proportional to the square of the amplitude, $I = m_1^2/4$. Thus, the intensity at P is only one-fourth of that due to the first half period zone alone.

5. COMPONENTS AND METHOD

The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field).This material is used because of piezoelectricity is found in useful applications such as the production and detection of sound, generation of high voltages, electronic frequency generation and etc.Electricity can be generated directly from sound energy by piezoelectric effect as shown in Fig. 9.

The way it works is that the mechanical energy of sound is applied directly to a crystal (or possibly a ceramic) with strong piezoelectric characteristics, and the crystal will generate a small amount of voltage in response tothe application of that mechanical energy (sound). What we are doing is "squeezing" the crystal. A squeeze willgenerate a small voltage for the duration of the squeeze. When the crystal is released, another small voltage will be generated in the opposite polarity.

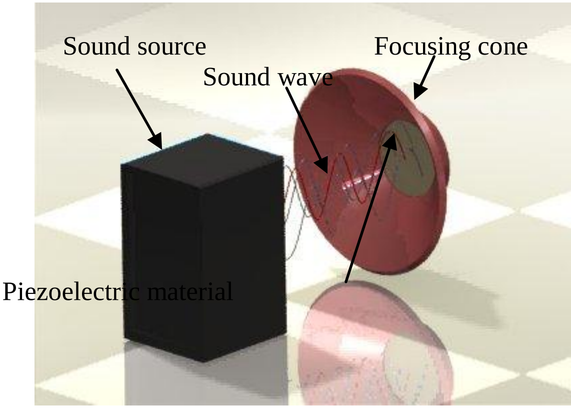


Fig. 9:3D view ofstriking the piezomaterial by sound pressure

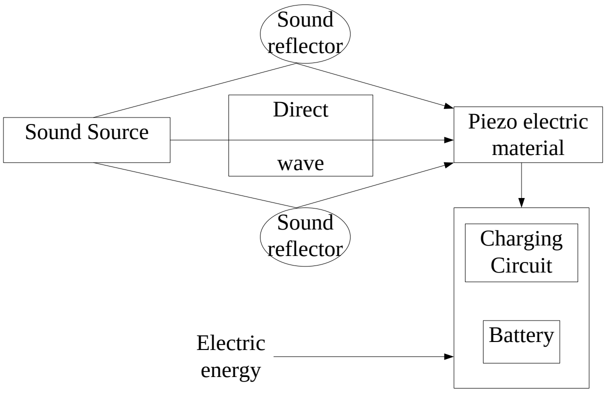


Fig.10: Block diagram of harvesting energy.

5.1 Experimental Setup

The wave emits from sound source has no any specific direction. It spreads into several directions around the source. That's why it is very tough to accumulate all sound pressure in a point. In this paper a devise has been designed which can focus several waves within its range in a point and increases the sound intensity at a focus point as shown in Fig.10. Its helps to better displacement of piezo material which is kept into focus point as well as better output voltage. Figure 11 shows the dimensions of the design of focusing cone. Sound wave from different direction can reflect by sound reflector face and the reflected wave is focused on the piezo material. Thus the intensity of sound has been increased by using this device and the amplification process is discussed before.

The voltage found from the sound is very poor for small arrangement and low intensity. From Fig. 12, it is clear that output voltage is fluctuating continuously with changing time and frequency that's why capacitor is used in the circuit. The experiment is done in a very short range. By calculating voltage with high frequency about 2V – 2.5V and voltage is considered to charge battery as shown in Fig. 13.

The amount of harvesting energy from sound is small. For this reason the device should be focused at several places around the sound source. The output voltage found from piezo material is not constant and fluctuating continuously i.e. 1.2V, 1.5V, 2.1V with varying time. Figure 14 depicts waveform of several output voltage at the time of displacement of piezoelectric material.

The voltage may have positive or negative polarity due to applied force and released force so Rectifier Bridge is used here. The capacitor provides constant charges for battery charging

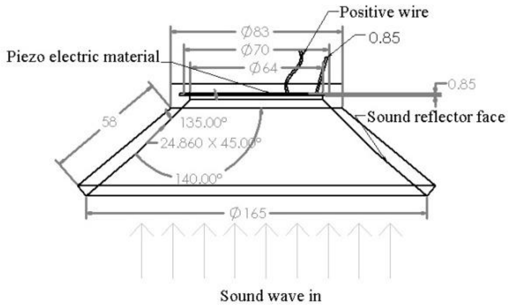


Fig. 11: Piezoelectric device (focusing cone) for converting sound to electric energy.

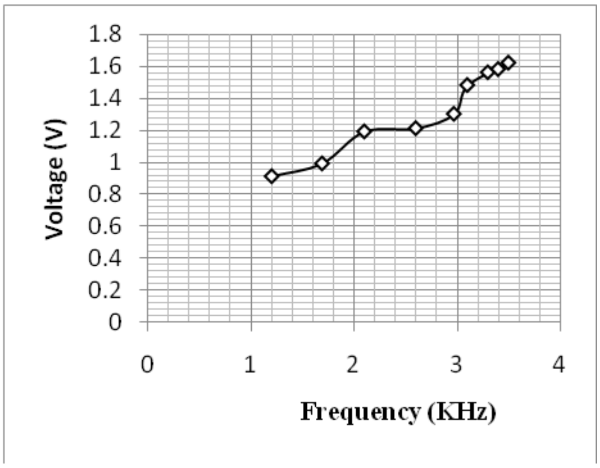


Fig. 12: Voltage output graph with respect to frequency.

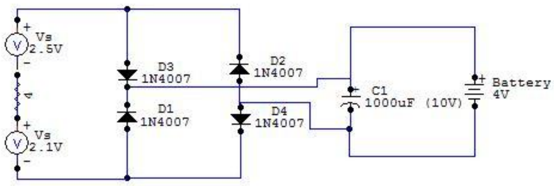


Fig. 13: Circuit diagram of charging battery.

6. RESULT AND DISCUSSION

Electromechanical system is used for micro power harvesting. In this prototype, the power may be found in micro scale.Depend upon the frequency and amplitude of sound sources, the voltage may vary from 900 mV to 1.8 V. It is not a constant output. It is fluctuating very rapidly. The amount of current is in mA that's why battery takes more time to charge. Thus final power is also in mW. High power can be transduced by this process in large arrangement. In industry, high range sound energy is available and that energy should be utilized by this EMS system.

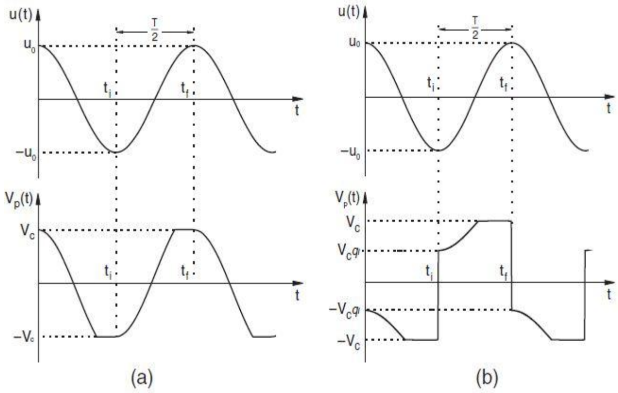


Fig. 14: Typical waveforms of displacement and piezoelectric voltage for (a) the standard and (b) the SSHI [13] electronic interfaces.

7. CONCLUSION

Simultaneous advances in low-power electronic design and fabrication havereduced power requirements for individual nodes, and therefore, allow the feasibilityof self-powering these autonomous electronic devices. This opens the possibility for completely self-powered sensornodes, and the notion of a small smart material generator-producing enough poweris not far-fetched. However, these smart material generators need to be optimallydesigned, which was the central topic discussed in this paper and further research is also needed for accomplish this project more efficiently.Basically, in this paper it is shown a system and prototype with 3D model that how can be utilized the lost vibrational energy for productive purposes. There are several methods of doing this task but here a simple and easy method is explained. The optimum design and setup of an energy harvesting system using piezoelectric generators depends on the kind of the surrounding kinetic energy to be exploited (amplitude and frequency) as well as on the electrical application tobe powered.Current challenges in the field of piezoelectric energy harvesting concern the robustnessto frequency mistuning and the improvement of the power harvested from broadbandsound

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10. NOMENCLATURE

Symbol	Meaning	Unit
E	Energy	(W)
υ	Velocity of wave	(m/s)
V	Piezoelectric generated voltage	(Volts)
Sv	Voltage sensitivity of the material	(Volt *meters / Newton)
P	Pressure	(N/m^2)
D	Thickness of material	(m)