Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 55
ISSUE 2
December
2012

Evaluation of piezoelectric smart materials subjected to impact test over range of temperatures

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Received 18.10.2012; published in revised form 01.12.2012

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ABSTRACT

As the demand for technological advances increase on daily basis, so does the dependency on existing fossil fuels, which is depleting at an alarming rate. The work presented in this paper addresses key solutions to energy management, and particularly energy harvesting for powering electronic devices and sectors in general, particularly applications where components are exposed to severe subzero temperatures. This research compares the energy output in terms of voltage for 3 piezoelectric smart materials, ceramic based PZT (Lead, Zirconate Titanate), polymer membrane PVDF (Polyvinylidine Fluoride) and foam based PP (Polypropylene). Impact analysis using concentrated mass of 1.02kg from a fixed height of 17mm was allowed to drop roughly in the centre of piezoelectric material samples as the temperature was increased from approximately -33°C to room temperature. Voltage output was recorded at various temperature increments using pico-scope software, which indicated that generally, voltage increased for all 3 materials as temperature decreased.

Keywords: Piezoelectric; Subzero; Temperature; Energy harvesting

Reference to this paper should be given in the following way:
I. Patel, E. Siores, Evaluation of piezoelectric smart materials subjected to impact test over range of temperatures, Journal of Achievements in Materials and Manufacturing Engineering 55/2 (2012) 355-362.

1. Introduction

Piezoelectric effect is the ability of certain material to generate voltage when pressure is applied and vice versa. However, piezoelectric phenomenon should not be confused with pyroelectricity, which is the ability of certain materials to generate voltage when heated or cooled. The change in temperature alters the positions of the atoms within the crystal structure, and as such the polarization of the material changes. This polarization change gives rise to a voltage across the crystal.

Strides have been made to incorporate computers and digital systems into our everyday lives and extensive work has been carried out to investigate the possibility, practicality and efficiency of imbedding them into our clothing, or in biological systems, such as the human body [1]. The use of power harvesting devices to capture the energy lost during everyday human functions seems exciting, and as a result, it has been one of the many topics facilitating the rapid growth of the energy harvesting sector. Possibly the first investigation of power scavenging systems incorporated into a biological system was performed in 1984 by Hausler et al. [2]. Their work proposed the use of an implantable physiological piezoelectric PVDF film power supply. Based on the concept that the energy expended for respiration could be converted into electric power, Hausler et al used the motion of the ribs during inhalation and exhalation to deform a converter. A miniaturized prototype was designed and experiments were conducted on a dog, where a converter was fixed to its ribs and spontaneous breathing led to a peak voltage of 18 V, which corresponded to a power of about 17 µW. However, the energy generated was insufficient to power the required micro electronic device. It was assumed that optimization of the PVDF film properties, as well as more suitable converter attachment at the ribs would make it possible to produce power in the region of 1 mW, yielding a mechanical power load of 20 mW.

Throughout our daily activity, a significant amount of energy is wasted in various forms, some of which could make for attractive energy harvesting applications. A paper published by Starner in 1996 [3], carried out an investigation into the amount of power delivered from range of human activities. The paper contained a survey of several power generation methods ranging from body heat and breath to finger and upper limb motion. An analysis of the power available from each of the different locations was presented. He calculated that approximately 67 W of power is lost during walking and that a piezoelectric smart material device mounted inside a shoe with a conversion efficiency of 12.5% could achieve 8.4 W of power. One idea he explained was to place piezoelectric film patches in the joints of clothing to harvest the energy lost during movement which he estimated to be about 0.33 W.

The work of Starner [3] brought the possibility of power harvesting locations around the human body to the attention of many researchers and the work in wearable power supplies began to grow. As a result Swallow and Patel investigated the feasibility of in cooperating piezoelectric material for energy reclamation in hand glove structure [4] with accepted patent for 'Detection and Suppression of Muscle Tremors' *Patent* GB0623905.7. Recent work of Patel and Siores compared the voltage output for ceramic based PZT, polymer membrane PVDF and polymer foam PP when subjected to vibratio frequency of between 0-120 Hz and impact test under room and elevated temperatures ranging from room to approximately 150°C [5]. Post and Orth [6] investigated the concept of "smart fabric" for wearable clothing. Their research described techniques used in building circuits from commercially obtainable fabrics, fasteners etc. Multiple different conductive fabrics were explored, including silk organza, constructed of silk thread wrapped in thin copper foil that is highly conductive and can be sewn using industrial machines. Several devices have been constructed of fabric including a type of fabric keyboard that could be crumpled up, thrown in the wash and even used as a potholder without losing its ability to function. These materials would be very effective for transmitting the energy generated around the body to the storage medium in a seamless way. The use of piezoelectric actuators located inside the sole of a shoe for power harvesting was studied by Kymissis et al [7]. The piezoelectric based power harvesting devices were a multiple layered PVDF patch and a piezoelectric ceramic Thunder actuator. The PVDF patch was placed in the sole of the shoe to harvest the bending energy and the Thunder actuator was located in the heel to harvest the impact energy. It was found that the PVDF patch and Thunder actuator produced an average power of approximately 1.1 mW and 1.8 mW of power respectively. The circuit used a capacitor to store the charge until a sufficient amount was captured. Then the circuitry allowed the power to be released to a transmitter that would send a 12-bit code. The system could transmit the code about 6-7 times every 3-6 steps.

Similar to the work of Kymissis et al. [5], Shenck's Master's thesis [8], demonstrated electrical energy generation from piezoelectric patches in a shoe. A rigid bimorph piezoelectric ceramic transducer was developed and integrated into a mass produced shoe insert. A design study was conducted by Ramsey and Clark [9], published in 2001, which investigated the feasibility of using a piezoelectric transducer as a power supply for a MEMS application.

Rather than developing a method of accumulating the energy developed by piezoelectric materials, Ottman et al [10] researched to develop a circuit that would maximize the power flow from the piezoelectric device. Hofmann et al. [11] extended the work of Ottman et al. [9] by implementing a similar circuit to maximize the power flow. Following the work of Sodano et al. [8], a second paper was published [12] to further investigate the ability of piezoelectric materials to recharge batteries. This study compared the macro-fiber composite (MFC) actuator with the monolithic piezoceramic material PZT for recharging batteries. The MFC is an actuator that uses piezoelectric fibers and interdigitated electrodes to capitalize on the higher g_{33} piezoelectric coupling coefficient, allowing it to reduce higher strain and force than typical monolithic PZT [13].

2. Materials investigated

There are three most common types of piezoelectric materials - ceramic based PZT, polymer based PVDF and polymer based foam PP. The polymer materials are soft and flexible; however, they possess lower dielectric and piezoelectric properties than ceramics. Conventional piezoelectric ceramic materials are rigid, heavy and can only be produced in block form.

The ceramic PZT which consisted of two ceramic materials, with active piezoelectric fibres of 250 µm and 120 µm diameters were embedded in a polymer matrix and encapsulated in copper-clad laminate, see Figure 1c. A ceramic Bimorph material consisting of two 250 µm fibre diameter materials adhered to either side of a rigid metal centre shim material and 4 layers of 250 µm material adhered together using standard epoxy resin. All the PZT specimens were obtained from Advanced Cerametrics Incorporated (ACI).

A laminated piezoelectric polymer material, PVDF, where two 125 µm polyester laminates were attached to the either side of a 28 µm thick piezoelectric film element and two un-laminated PVDF materials of 28 and 52 µm thickness was used, see Figure 1a. The PVDF specimens were supplied by Measurement Specialities Incorporated (MSI). Finally, a fully shielded, low mass, thin ribbon PP sample was used. The sample consisted of a sensing element constructed of elastic electret, 3 layers of polyester film. Aluminium electrodes with crimped connectors were used for connecting to electrodes and double-sided sticky tape for convenience, see Figure 1b as supplied by Emfit. The dimensions and classification of the piezoelectric polymer and ceramic materials are given in Table 1.

Table 1.
Tested piezoelectric PVDF, PP and PZT samples and their characteristics

Material	Width (mm)	Length (mm)	Thickness (μm)
LDT1-28 μm laminated PVDF	16	41	205
LDT4-28 μm laminated PVDF	22	171	205
DT4-28 μm un-laminated PVDF	22	171	40
DT4-52 μm un-laminated PVDF	22	171	70
65 μm laminated PP	20	100	320
Ø120 μm PZT	15	140	190
Ø250 μm PZT	15	140	320
Ø250 μm Bimorph PZT	15	140	720

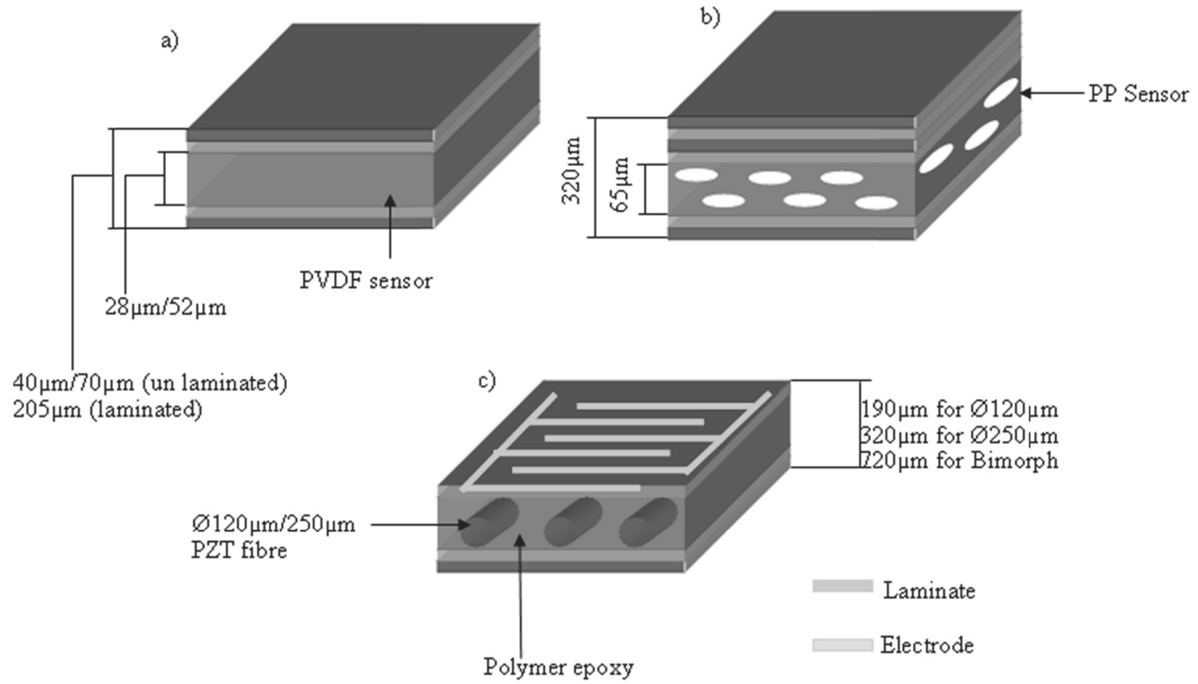

Fig. 1. Schematic representation of piezoelectric samples a) PVDF membrane film, b) porous PP with pores approx. 20 μm diameter and c) piezoelectric PZT fibre embedded in an epoxy with copper clad electrodes etched on to the inner surface of the laminate which acts as electrodes. (Refer to Table 1 relevant dimensions)

3. Experiment methodology, results and discussion

Pellets of dry ice of approximately 10 mm diameter and 20 mm in length were used to reduce the temperature of the samples. The dry ice pellets were sealed in a small standard metallic box size (L110 mm x W60 mm x D30 mm), see Figure 2a and b which displays the experimental rig construction. In order to minimize lateral movement and deflection of the specimen, the piezoelectric material was adequately secured using a masking tape onto the top surface of the metallic box. Potential voltage output across open circuit configuration was recorded under normal room temperature as the mass was released from the latch and struck the sample. After this, the metallic container was filled with pellets of dry ice and sealed, the cycle of striking the piezoelectric material with the mass at various temperature increment was repeated. The mass of 1.02 kg was released from a fixed height of 17 mm three times within a 5second time frame for any given temperature and results were averaged. A calibrated hand held infra red thermometer (model no. CHY 110) was used to ascertain the temperature of the sample surface. After evaluating each of the materials, the container was left under normal room temperature until the temperature stabilised prior to commencing further tests.

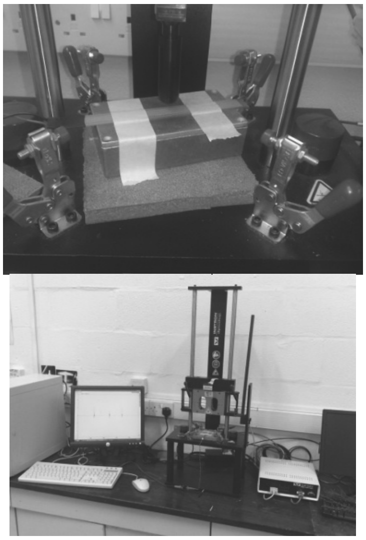

Fig. 2. Photograph left, shows placement of sample on top of the metal box which contains dry ice and right, shows actual experiment set-up using free standing Instron machine and

3.1. PVDF

The Figure 3 represent averaged voltage output for the PVDF piezoelectric materials, namely un-laminated with 52 µm thickness polymer membrane. After the initial experiment using the dry ice in the metallic container to reduce the temperature of the sample, the dry ice pellets were carefully removed from the metal box and safely disposed. Results indicated that generally, voltage recorded increased as the temperature was reduced. For this PVDF DT4-52 µm sample, the voltage output marginally dropped to 14.65V at -10°C point an increased to 22.61 and 22.91 V for -19°C and -26°C temperature, respectively.

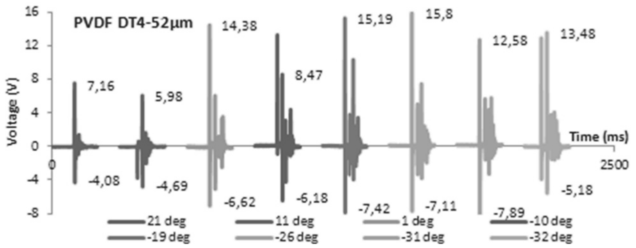

Fig. 3. Comparison of voltage output for PVDF (DT4-52 µm un laminated) material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the pico scope software

The Figure 4 shows that beyond -31°C, the voltage output dropped to 20.47 V and at -32°C it dropped to 18.66 V. It seems that beyond this point, the temperature of the dry ice began to normalise and would not reduce any further. Furthermore, it may have been futile to progress below -35°C since glass transition temperature (T_g) becomes apparent for the PVDF material. The increase in voltage resonance was also more apparent with this material compared to PP sample.

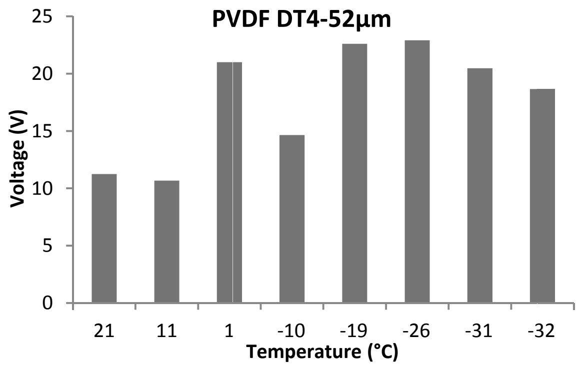

Fig. 4. Comparison of voltage output for PVDF (DT4-52 µm un laminated) piezoelectric material at various temperatures

The experiment was repeated using yet another PVDF un laminated piezoelectric material, this time with a 28 µm thick polymer membrane, see Figure 5 as opposed to 52 µm thick membrane. Evidently, the 28 µm thick membrane piezoelectric material exhibited much lower voltage output at any given temperature range due to 50% reduction in material volume.

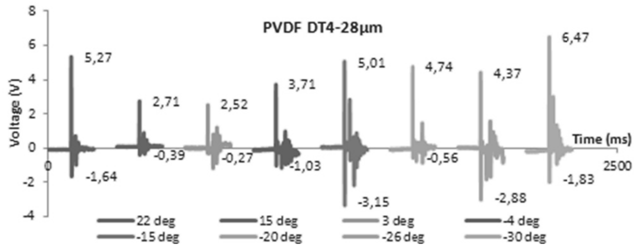

Fig. 5. Comparison of voltage output for PVDF (DT4-28 µm un laminated) material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

Again, as shown in Figure 6, the representation indicates steady increase in voltage output as temperature is decreased, with the exception of 8.16V at -15°C which shows a significant increase in voltage output. The overall trend points to an increase in energy output for this material as the temperature continues to fall.

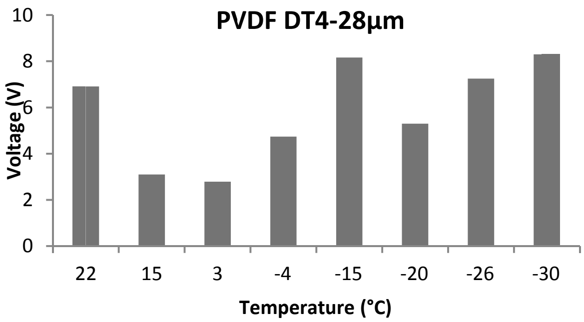

Fig. 6. Comparison of voltage output for PVDF (DT4-28 µm un laminated) piezoelectric material at various temperatures

As shown in Figure 7, an overall maximum voltage output increase as a result of temperature reduction for the piezoelectric material PVDF LDT4-28 µm (laminated). Here, the voltage resonance increase was more prominent and that repeatability and distribution is clearly visible. The distinct increase in the voltage resonance could be the result of lamination on either side of the host structure, since laminated piezoelectric material increases its energy output due to increase in material stiffness. Again Figure 8 shows a gradual increase in voltage output as the temperature is lowered.

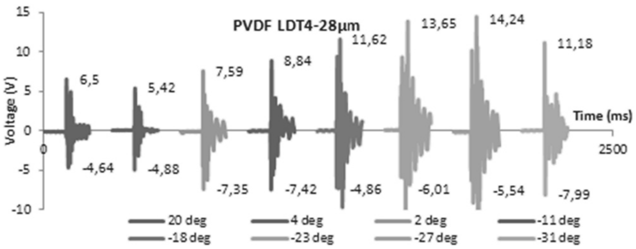

Fig. 7. Comparison of voltage output for PVDF (LDT4-28 µm laminated) material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

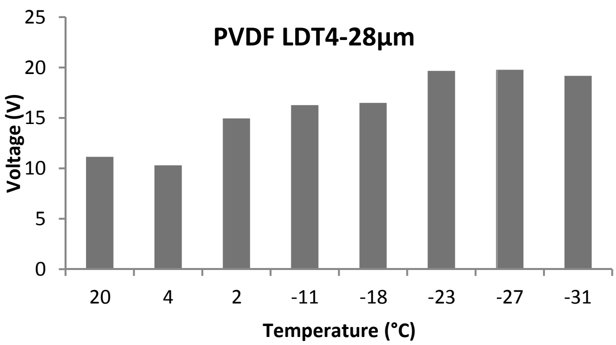

Fig. 8. Comparison of voltage output for PVDF (LDT4-28 µm laminated) piezoelectric material at various temperatures

The final experiment conducted using PVDF piezoelectric material was on the laminated (LDT1-28 µm) short sample from the PVDF batch. Figure 9 and Figure 10 indicates maximum voltage output and as can be translated, the voltage and resonance increases with the reduction of temperature, similar to results previously obtained.

However, the LDT1-28µm material seemed to produce the largest amount of voltage output in comparison to the rest of the PVDF material configuration. This may be due to the short materials ability to completely "charge" the membrane to its maximum capacity with no loss of energy, i.e. larger samples subjected to given stress is only able to charge certain percentage of the materials volume and the remainder of the material is termed "dead" region. Hence, the dead regions draw electrical charge from the active regions, which results in overall reduction in measured voltage output. For example, when considering dropping a known mass from a fixed height into the pond, the ripples generated in the smaller pond will reach the edges of the bank with relative ease, whereas ripples in the larger pond will tend to diminish before it reaches the banks.

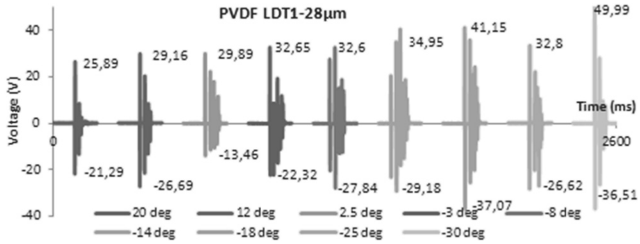

Fig. 9. Comparison of voltage output for PVDF (LDT1-28 µm laminated) material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

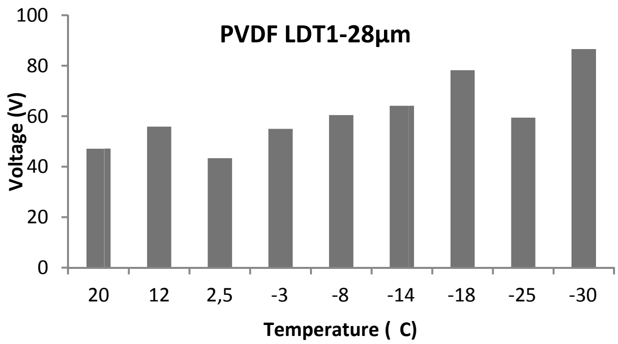

Fig. 10. Comparison of voltage output for PVDF (LDT1-28 µm laminated) piezoelectric material at various temperatures

3.2. PP

The output voltage discussed here are for the maximum voltage output. Figure 11 shows the voltage output using a PP piezoelectric material of 65 µm thickness at various temperatures ranging from room to -33°C. The figure indicates that as the temperature is reduced, overall maximum voltage is shown to increase, see Figure 12 for comparison. A gradual increase in the energy output resulted from 9.13V at 20°C (room temperature) to finally at 17.1V when the sample temperature dropped to -33°C. However, as reflected in Figure 12, the voltage output managed to drop marginally when the temperature fell to -3.5°C and as low as -30°C, although an increase in energy output increased once again. Furthermore, reduction in temperature has also resulted in increased voltage output frequency. The increase in frequency could be the result of the metallic container which was gradually transforming into a brittle structure, hence allowing the dropped mass to rebound and cause vibration in the metal, thus this being highlighted in the results.

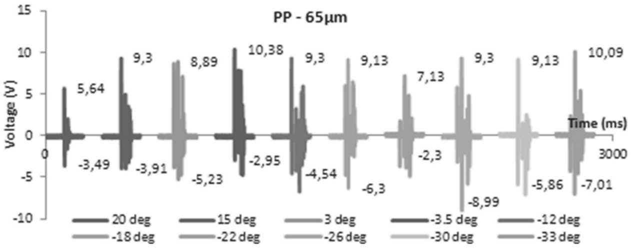

Fig. 11. Comparison of voltage output for Polypropylene (65 µm) material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

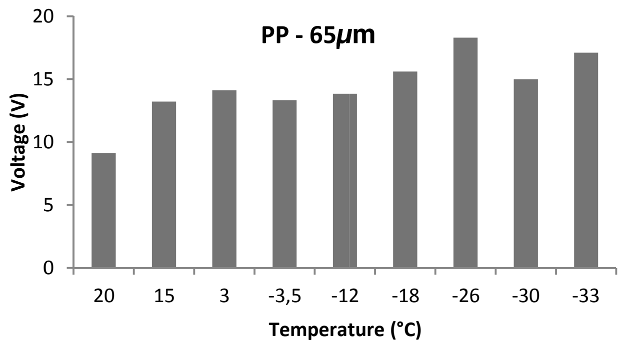

Fig. 12. Comparison of voltage output for polypropylene (65 µm) piezoelectric material at various temperatures

3.3. PZT

Figure 13 represents voltage output versus temperature which shows that PZT 250 µm diameter piezoelectric material embedded in a polymer matrix follows similar trend to that of PP and PVDF material, where a reduction in temperature results in increased voltage output. With the PZT 250 µm piezoelectric material, the voltage resonance also increases, however, there is a minimal negative cycle produced compared to the foam and polymer. This could be explained due to PZT being much more rigid material, and thus, minimising rebound.

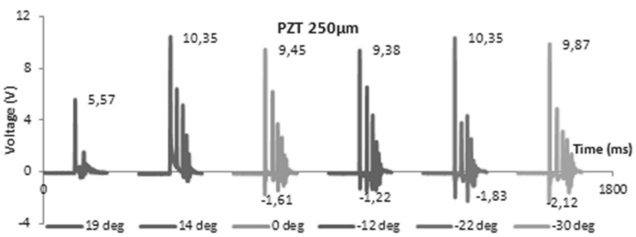

Fig. 13. Comparison of voltage output for PZT 250 µm material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

Furthermore, after the initial maximum voltage peak, the remainder of the peaks that followed gradually decreased (with the exception of point -22°C), indicating much more stable and repeatable conditions. This may also suggest the controlled transfer of vibration from the metal container as it froze and thus affecting the piezoelectric material. Once again, as can be seen from Figure 14, the actual trend for voltage output increases with the reduction of temperature, with the exception of -12°C which slightly drops to 10.60 V from 11.06 at 0°C.

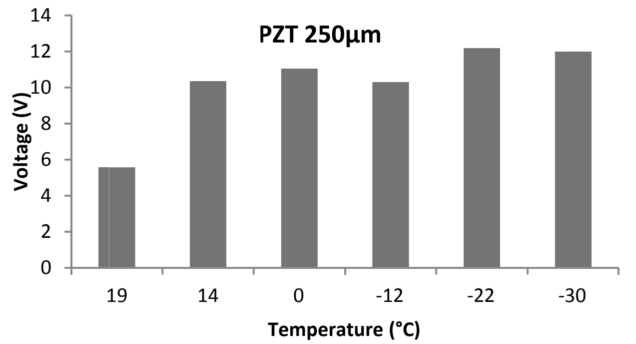

Fig. 14. Comparison of voltage output for PZT 250 µm piezoelectric material at various temperatures

As expected, PZT bimorph (two piezoelectric layers with a metallic shim in between) exhibited higher voltage output in comparison to 250 µm piezoelectric material due to addition of metal shim in between the duel layers which exaggerated vibrations, resulting in higher voltage output, see Figure 15. The metal shim may have also contributed to the larger negative amplitude effect and lack of repeatability since the metal shim was an additional parameter introduced into the host structure resulting in out of phase signal generation. Figure 16 represents gradual increase in energy output as a reduction of temperature, with marginal drop in voltage from 16.31 V to 12.63 V at -9°C and -15°C, respectively.

Final experiment was performed on the PZT 4 layer piezoelectric structure, see Figure 17. The piezoelectric sample consisted of 4 individual strips attached in stack configuration with the certain adhesive from the manufacturers. The 4 material acted independently in terms of data acquisition when the mass struck the material, whereas the bimorph material behaved as a single unit. Although the 4 layer piezoelectric material had 100% and 200% increase in the volume of piezoelectric active material in comparison to bimorph and single layer material, respectively, it failed to exhibit significant increase in the total overall voltage output. This was the result of the 4 independent piezoelectric materials acting independently and the collective voltage signals were forced to cancel each other to a certain extent, i.e. out of phase signal was generated. However, an overall increase in the voltage output was observed as the temperature was decreased below sub-zero, see Figure 18.

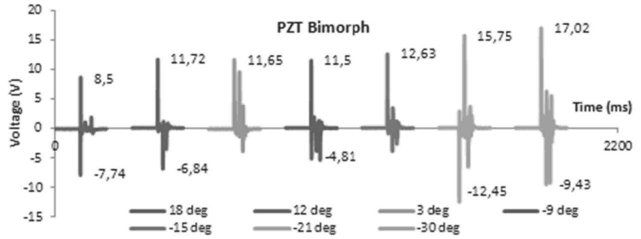

Fig. 15. Comparison of voltage output for PZT Bimorph material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

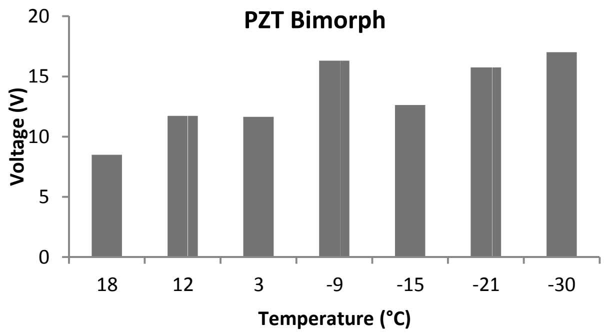

Fig. 16. Comparison of voltage output for PZT Bimorph piezoelectric material at various temperatures

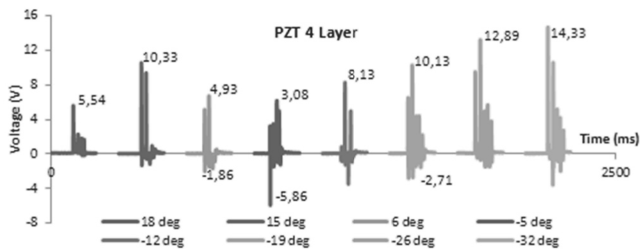

Fig. 17. Comparison of voltage output for PZT 4 layer material when subjected to impact force at various temperatures. Above represents actual voltage resonance as captured by the picoscope software

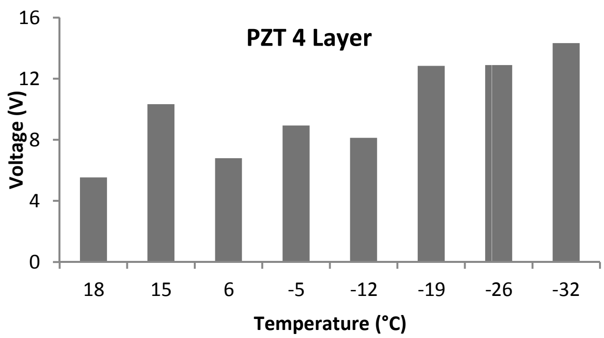

Fig. 18. Comparison of voltage output for PZT 4 layer piezoelectric material at various temperatures

4. Concluding remarks

Impact analysis at sub zero temperatures established that as the temperature of the material is allowed to decrease from normal room temperature to around -30°C, the voltage ascertained at various temperatures intervals generally increases for all 3 piezoelectric materials, PP, PVDF and PZT, regardless of single or multi layer and for any given material configuration. However, at certain subzero temperatures intervals, the voltage output marginally decreases but quickly regains escalating trend.

This was apparent with all PZT samples where a drop in voltage manifested between -12°C and -15°C. Moreover, PZT 250 μm piezoelectric material displayed by far the best repeatability due to the single layer, whereas the bimorph with metal shim and the 4 layer sample proved to be slightly inconsistence mainly in terms of positive and negative amplitude output. With regards to PVDF samples, LDT1-28 μm (shorter version) exhibited largest voltage output due to complete charge of the material, followed by DT4-52 μm (un-laminated) sample because of 100% increase in material volume. The laminated (LDT4-28 μm) was in the third place due to kapton laminate which increases the stiffness of the material and thus, raises the energy output. Finally, the DT4-28 μm (un-laminated) piezoelectric material showed lesser energy output. This also indicates that the kapton laminate increases the energy output from both impact and vibration analysis, but also protects the piezoelectric membrane.

The subzero experiments concluded that in order to fulfil commercial / domestic application needs, it is advantageous to use shorter (LDT4-28 μm) laminated PVDF material for maximum energy harvesting application. This will also ensure greater flexibility from engineering prospective, as well as reducing weight and cost. The increase in voltage output as a result of reduction in temperature could be explained due to the enhanced closed packing / stacking of atoms and molecules, and thus, increases the electron transfer mobility when internal charge is generated.

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