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Smart Woven Fabrics in Renewable Energy Generation

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1. Introduction

Initially, the first purpose of fabric making was only for covering the body and sheltering. However, with a growing population and ever improving advanced technologies, today's fabrics are mostly used for fashion and performance thus enhancing the standard of people's everyday life and enjoyment.

Most of the technologies which increase the standard of living also increase carbon emission and adversely affect human life indirectly. Warming buildings, using cars, provide hot water, cooking food etc. need energy generated by using coal, gas, fuel or electricity. Burning gas and fuel accelerate the threat of nature and eventually contribute to global warming. Even electricity generation causes carbon emission unless it is generated by using renewable energy sources. Interest in providing renewable usable electrical power from the environment has grown, particularly in the elimination of battery usage, because of their sizeable dimensions, weight and limited lifetime.

Since global warming is being considered as the biggest danger for the nature, many scientists and researchers have brought a new breath to their researches. As almost all areas of renewable science and technology, researchers are now working in the field of textile fabrics capable of generating green electricity.

Undoubtedly, weaving is the oldest fabric making method which has been a part of human life for protection from nature's elements and hazards. It is now possible to produce smart woven fabrics by combining the oldest fabric making method with smart fibre material technologies. The chapter named "Smart Woven Fabrics in Renewable Energy Generation" contains a brief introduction to smart materials, focusing on piezoelectricity and polymer based piezoelectric fibre production. The rest of the chapter explains how to produce smart woven structures by integrating smart fibres into the fabric during weaving process and examples for possible applications for energy regeneration from nature's elements are given.

2. Brief introduction to weaving and looms

2.1 Vertical and horizontal looms

The first loom consisted of only a branch of a tree that is parallel to the ground. In this simple design, warp threads were directly fastened to the branch of a tree and held parallel to each other under tension caused by tied stones at the other end of the warps. The weft threads work from right to left and left to right by passing through hanging warps until the
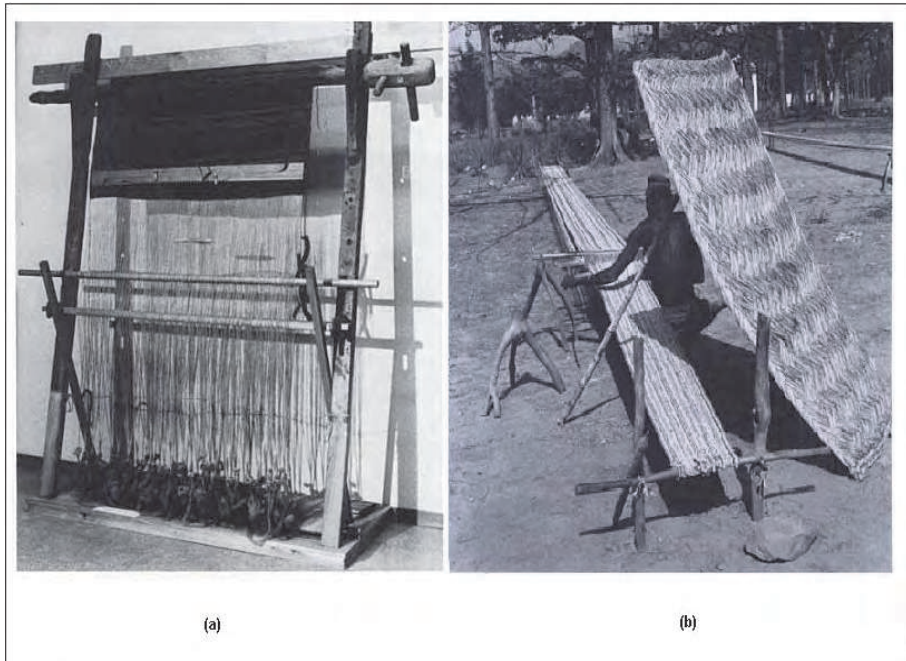
Fig. 1. (a) A vertical warp-weighted loom used in Iceland, reconstructed and set up before 1914, National Museum of Iceland-Photograph by Gilsli Gestsson (Broudy, 1979),
(b) a horizontal ground loom used in Northen Cameroon-Photograpgh by René Gardi (Broudy, 1979).
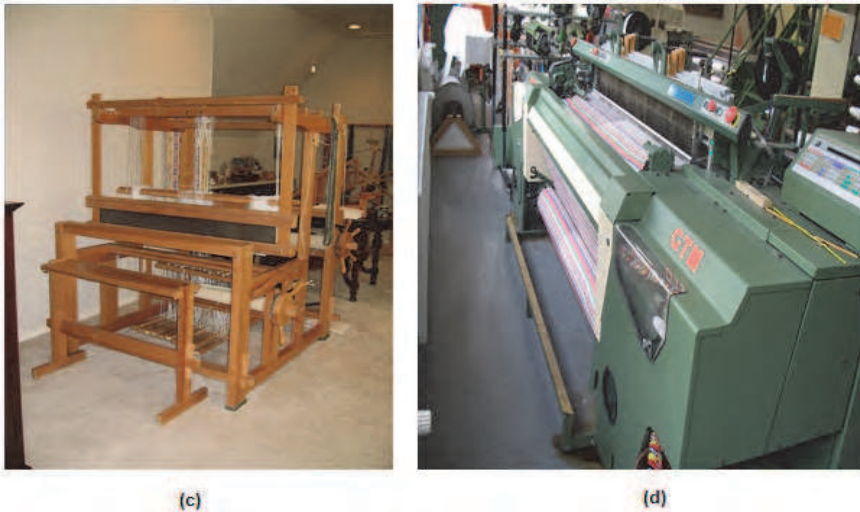

Fig. 1. (c) An example of laboratory scale hand looms and (d) an example of automated looms (wikipedia, 2011).

designed fabric is composed. Later, a simple framework was made of tree branches to form a vertical loom to use for indoor as well as outdoor.

Figure 1 (a and b) show examples for early vertical loom and horizontal looms and Figure 1 shows a laboratory scale hand loom (c) and automated loom (d). Warp threads are attached to heddles and held parallel to each other on the loom and weft thread is held by a shuttle. The heddles keep warp threads apart so that the shuttle could pass through easily and cary the thread from left to right and right to left so that the weft will work over and under warp threads to form a fabric. Movements of the heddles on hand looms are controlled by pedals beneath the loom.

Current generation looms (Fig. 1d) are fully automated. Movements of the heddles are automatically controlled according to the fabric design sent via a computing system. The important parameters, such as tension, speed, temperature etc., are measured and/or controlled by the controlling systems. Thus, any errors that occur during the fabric production are immediately detected.

2.2 Main weaving constructions

Weaving is one of the traditional fabric making methods. There are two sets of threads, warp threads and weft threads which form a fabric by being interlaced row by row. Weaving has three main construction techniques; plain weaving, twill weaving and satin weaving. Any other techniques developed are variations of these main techniques.

Plain weave is created by interlacing the weft across the warp threads and for this at least 2 heddles are needed. Weft thread goes under a warp thread and then over the next one so that the equal amount of weft and warp is seen on both surfaces of the woven fabric.

Twill weave is created by interlacing two or more weft threads over and under one or more warp threads so that at least three heedles are needed to make a twill woven fabric. In twill wovens, parallel diagonal ribs are formed from left to right or from right to left that depends on the formation, woven fabric is characterised and named as "S" or "Z" twill, respectively. If a twill woven has more warps than the wefts on the fabric face is known as warp faced twill and if it has more wefts on the fabric face, it is known as weft faced twill.

Satin weave is created by floating four or more yarns before a single interlacing occurs and at least 5 heddles are needed to make a satin woven fabric. The warp or weft threads pass across many threads in such a way, like 4/1, 5/1, 7/1 etc., that the face of the woven fabric is mostly covered with either warp or weft threads and known as warp satin or weft satin, respectively.

Depending on the construction of the weave and characteristics of the used warp and weft threads, fabric properties may vary. Count of the used fibres/yarns determines the fabric density which affects the weight, feel, appearance, thickness etc. Variable properties are many and can be found in the literature (Gioello, 1982). They include:

- Weight
- Hand and feel
- Drapeability
- Appearance
- Covering power
- Surface texture
- Body fit

- Thickness
- Lustre
- Strength
- Flexibility / pliability
- Resiliency
- Warmth
- Affinity to dyestuff

Fabrics created by using plain weave technique are tough compared to twill and satin weave. The fabrics made by twill weaving technique are more pliable and drapable than plain weave fabrics but not as pliable as satin weave. However, strength of plain woven fabrics is higher than both twill and satin woven fabrics.

3. Smart materials and piezoelectricity

A smart material is one that shows extraordinary response when subjected to a stimulus. Piezoelectric materials are considered as smart materials because of their ability to generate electricity against the stimulus which is mechanical strain or vibration (Fig.2a). This property of piezoelectric materials is known as direct piezoelectric effect. The reverse effect is also possible in that this material undergoes a slight deformation in shape when a small electrical field is applied (Fig.2b).
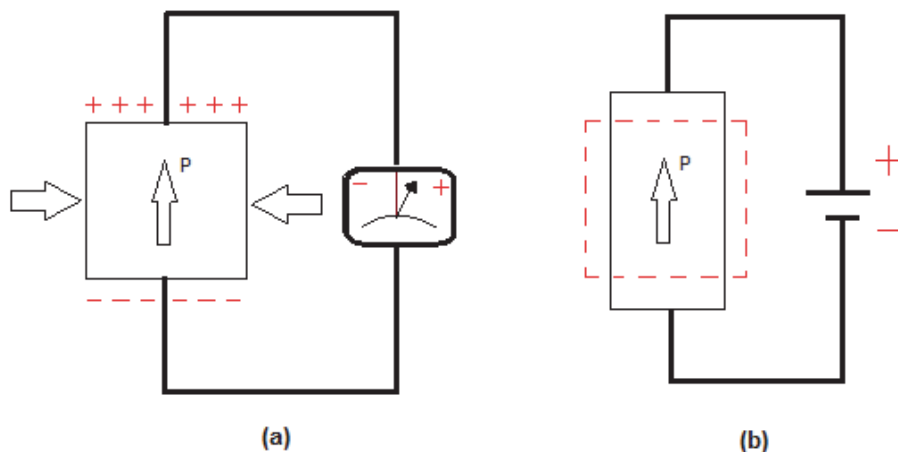

Fig. 2. (a) Direct piezoelectric effect; mechanical energy is converted to form electrical energy, (b) Converse piezoelectric effect; electrical energy causes deformation in the shape of piezoelectric material.

Direct piezoelectric effect of the materials is also known as "generator effect" or "sensor effect". The terms "motor effect" and "actuator effect" are also used to mean converse piezoelectric effect of the piezoelectric material. It should also be pointed out that the piezoelectric effect can be induced when heat or cooling is involved, in which case this phenomenon is termed thermoelectric or pyroelectric effect.

Direct piezoelectric effect is mainly used for energy harvesting. The term "Energy Harvesting" is used to describe the process of extracting energy from the environment and the extracted energy is converted and stored in the form of electrical energy.

Although energy harvesting technologies have been known for many years, increasing concern about global warming has led to intensive research for alternative energy sources including piezoelectrics. With an increasing concern about global warming, piezoelectricity has gained a significant importance and intensive research and development efforts are being made for extracting energy from the environment [Umeda et al., 1997; Sodano et al., 2004; Mateu & Moll, 2005].
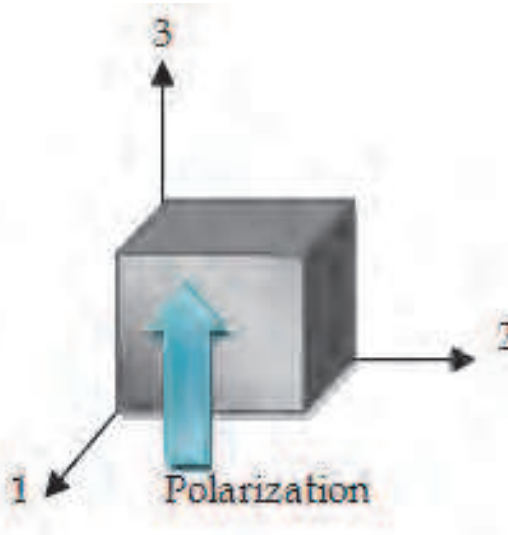

Fig. 3. Defining the modes of piezoelectric material

The generated electrical charge of a piezoelectric material under a mechanical stress can be formulated in terms of dielectric displacement, D (charge per unit area, C/m^2) [Schwartz, 2002; Granstrom et al., 2007; Swallow et al., 2008]

$$D_i = d_{ij}\sigma_j \tag{1}$$

where "d_{ij}" is the piezoelectric charge coefficient (C/N) and "σ_j" is the stress (N/m^2). "i" is the direction of polarization and takes terms 1–3 and "j" is the direction of applied stress having subscripts 1–6 (Fig. 3).

In Figure 3, numbers 1, 2 and 3 present x,y and z axes of piezoelectric material, respectively. Modes 31 and 33 are two coupling modes of piezoelectric materials that when a force is applied in the perpendicular direction to the poling direction, the piezoelectric voltage coefficient acts in the mode 31. When a force is applied in the parallel direction to the poling direction, the piezoelectric voltage coefficient acts in the mode 33 which generally yields a higher coupling coefficient (*k*) [Roundy et al., 2005; Baker et al., 2007; Anton & Sodano 2007; Patel et al., 2010] which is the ability of piezoelectric materials to convert mechanical energy into electrical energy and vice versa, and can be defined by,

$$k = \sqrt{\frac{Y}{\varepsilon}} d \qquad\qquad (2)$$

where "ε" is dielectric constant and "Y" the elastic modulus of the material.

Piezoelectric voltage coefficient (g) relating the electric field generated by an applied mechanical stress and relationship between the piezoelectric charge coefficient and piezoelectric voltage coefficient can be expressed as [Jordan & Ounaies, 2001],

$$gij = dij / \varepsilon_0 Kj \qquad\qquad (3)$$

where; "ε_0" is the permittivity of free space (8.85x10-12 F/m) and "Kj" is the relative dielectric constant of the material.

Since the discovery of piezoelectricity in ceramics [Shirane & Suzuki, 1952; Jaffe et al., 1971] and polymers [Kawai, 1969], various studies have been carried out on structural changes [Ramos et al., 2005; Sencadas 2006], poling [Seo et al., 1985; Holstein et al., 1999; Neagu et al., 1999; Parvanova & Nadoliisky 2005] and applications, such as sensors [Tzou & Tseng 1990; Sirohi & Chopra 2000], actuators [Baz & Poh 1988; Schmidt et al., 2006], energy harvesting [Sodano & Inman 2004; Shu & Lien 2006; Granstrom et al., 2007; Ramadass & Chandrakasan 2010] and so on. PZT has been pre-eminent due to its piezoelectricity among other piezoelectric materials, with a piezoelectric coefficient (d_{33}) of 220pC/N [Hellwege, 1996] while PVDF exhibits much lower piezoelectric coefficient of $d_{33} \approx 35$pC/N [Sencadas et al., 2006; De-Qing, 2008; Jain et al., 2010; Patel et al., 2010]. However, flexible nature of polymers adds extra versatility for applications against ceramic based piezoelectric materials.

With the invention of new polymers exhibiting piezoelectric and better mechanical properties, the scope of application has widened. Both ceramic and polymer based piezoelectric materials have found a wide range of application in many areas. Ceramic based piezoelectric materials, in general, have a higher piezoelectric constant compared to polymer based piezoelectric materials. However, polymer based piezoelectric materials have an advantage of being flexible which makes them preferable for many applications, particularly for wearable applications. This flexibility can also result in better conversion of energy in certain applications.

3.1 Flexible piezoelectric fibres

There are many naturally occurring piezoelectric structures, such as cane sugar, tendon, silk, bones etc., but polymers are not natural piezoelectric materials. However, polymers such as polyvinylidene fluoride (PVDF), polyproplylene (PP), polyethylene terephthalate (PET), odd numbered polyamides (PA11, PA9, PA7, PA5) etc. can be made piezoelectric (Kawai, 1969; Newman et al. 1980; Dunn & Carr, 1988; Harrison & Ounaies, 2001).

Siores et al (2010) were the first to develop and patent a continuous process for making piezoelectric fibres by extruding suitable polymers. To produce piezoelectric PVDF fibres via a continuous process on the melt extruder, granular PVDF was fed to extruder screw which was heated above melting point of the polymer. To gain the piezoelectricity, molecular chain of the PVDF fibre must be re-oriented and transformed from non-piezoelectric α-phase to piezoelectric β-phase by applying a high stretching ratio (Sencadas et al., 2006), heat (Neagu et al., 1999) at the stretching region and high voltage (Holstein et al., 1999 & Ramos et al., 2005), simultaneously.

3.1.1 Fibre extrusion and poling

High purity PVDF polymer granules are fed a melt extruder. The extrusion temperature is kept at 195°C which is 20°C higher than the melting point of PVDF inside the feeding screw. The temperature is slightly higher at the die, 205°C, where the fibre is extruded. The extruded fibre is then air cooled with a blower and water cooled on the initial stage rollers which help in further cooling of the extruded fibre.

Poling is a critical step for piezoelectric fibre generation. Temperature, drawing ratio and applied electric field play a crucial role in the amount of polarisation. Highest polarisation charge coefficient was given in the literature (Sessler, 1981; Wegener et al., 2002).

The drawing of fibres takes place at the rollers, which have heating coil inside to vary the temperature during stretching of fibres. The temperature of these rollers is maintained constant on PVDF fibre when it leaves the roller and an appropriate electric field applied on PVDF fibre while being drawn.

Fig. 4. Piezoelectric polyvinylidene fluoride (PVDF) filament production via a continuous process using a melt extruder

Figure 4 shows the continuous process of producing piezoelectric polymer in a customised melt extruder. This is a less expensive and less time consuming method for preparing piezoelectric polymer fibres in that all process variables are applied simultaneously. Detailed information on polymer based piezoelectric fibre production via a continuous process has been reported (Siores et al, 2010).

3.1.2 Testing of generated piezoelectric fibres

Generated polymer fibres, shown in Figure 5, are embedded in between two thin sheets of aluminium or copper which act as electrodes. The fibres are placed close to each other such that the top electrode would not contact the bottom one. The top and bottom electrodes act as positive and negative terminals for the energy generating polymer piezoelectric device.

Poled PVDF fibres generate about 5 V_{oc} when a moderate mechanical stimulus is applied on to the fibres. The obvious advantage of producing flexible piezoelectric fibres is to be able to produce large area active surfaces by incorporating piezoelectric fibres in wearable technologies. However, to generate enough electricity for wearable applications to power small electronic devices, produced flexible piezoelectric fibres need to be used in a fabric structure such as woven, knitted, nonwoven and 3D structures.

Fig. 5. Polymer based flexible piezoelectric fibre generated by a continuous process using the melt extruder.

4. Smart woven fabrics

Each fabric making method has its own special attributes which help us to find most applicable fabric structure and method for a specific application. By weaving polymer based piezoelectric fibres into woven fabrics, smart piezoelectric fabrics can be produced and used for many responsive applications.

Weaving is one of the best fabric making techniques that can be used for smart fabric production. Warp threads can be located at the heddles with different orders and wefts are travelled through warps by shuttle(s). The position of heddles designates where wefts will be going over or under the warps.

While a fabric is being designed, expectations from the final fabric are taken into consideration. For smart piezoelectric fabrics, depending on expected energy generation from the final product, weaving designs can be variable. In this case, intersection of piezoelectric (the charge generator) and conductive (the charge carrier) fibres is crucial. One piezoelectric fibre can interlace more than one conductive fibre. One conductive fibre can also interlace more than one piezoelectric fibre. However, one conductive fibre can only interlace the same pole of the each piezoelectric fibre.

A number of weaving designs are studied below for smart woven fabrics. Conductive fibres and conventional (non-conductive) fibres are needed alongside piezoelectric fibres. Because piezoelectric fibres carry negative charges on one side along its length and positive charge on the other side, a conductive material is needed to carry the charge produced by

movements of the piezoelectric fibres. Conductive wires would add extra rigidity to the fabric which is an undesirable outcome for most textile structures.

The best alternative to undesirable wires may be conductive fibres are produced and patented (Perera & Mauretti, 2009). It is claimed (Mauretti & Perera, 2010) that conductive filaments are flexible, non-toxic and conformable for wearable applications. Electrical conductivity of metallised synthetic (acrylic) conductive textile yarns is widely studied (Vassiliadis et al., 2004, 2009, 2010). Mechanical and electrical properties of metallised conductive yarn are controlled by blending conventional and conductive fibres in the yarn and changing the ratio of fibres in the blend. The way piezoelectric, conductive and conventional fibres are integrated into fabric structure by weaving technique, gives a good indication of the performance of resultant fabric. When more piezoelectric fibres are used in the fabric, this results in higher energy generation by movement and mechanical strain. However, to be able to carry as much charge as it is possible, the right number of conductive fibres need to interlace with piezoelectric fibres.

The possible woven fabric designs for energy generation for wearable textiles are shown in this chapter. Blue lines represent piezoelectric fibres while red lines represent conductive and grey lines show non-conductive conventional fibres. This is the simplest weaving pattern produced by plain weaving technique. However, by integrating piezoelectric and conductive fibres into this basic structure, the resultant woven fabric becomes a smart fabric which can harvest energy from the natural sources.
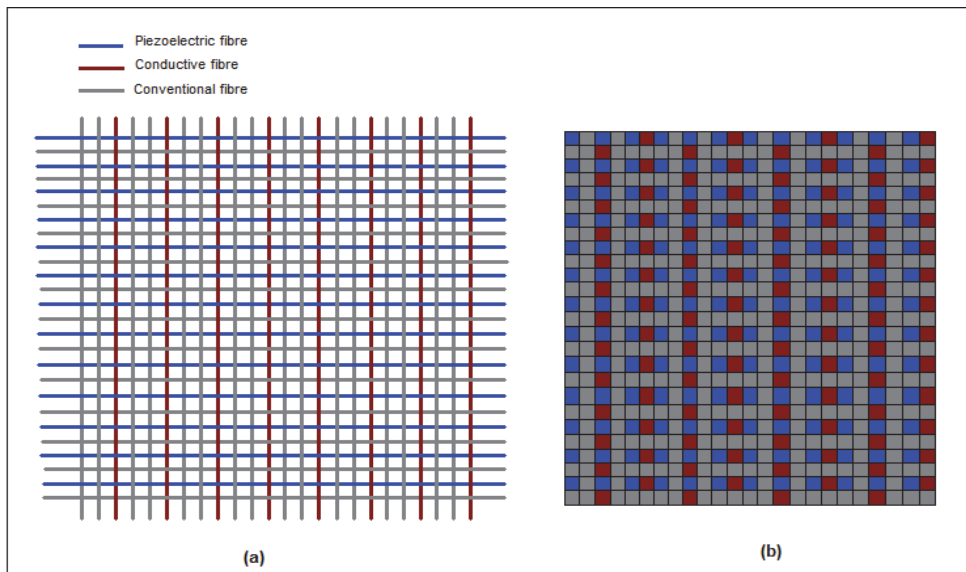

Fig. 6. (a) Smart woven fabric design 1 consisting of piezoelectric, conductive and non-conductive conventional fibres, (b) Face of the woven fabric consisting of piezoelectric, conductive and non-conductive fibres

Polymer based piezoelectric fibres can be used as either weft or warp into the woven structure and conductive fibres can be used as negative and positive electrodes for charge transfer so that the resultant fabric can produce energy for micro powered electronics.

The main advantage of the use of polymer based piezoelectric material in this application is its flexibility and the fact that it can easily be incorporated in the woven structures without causing any problem. It is impossible to integrate existing ceramic based piezoelectric fibres into similar structures because these fibres are rigid and brittle thus can cause major problems in the weaving process. For the first design shown in Figure 6(a), 2 heddles are needed to locate conductive and non-conductive fibres/yarns and 2 shuttles, the one with piezoelectric fibres/yarn and the other with non-conductive conventional fibres/yarn. In the warp direction, 2 conventional fibres are located between conductive fibres. Conductive fibres act as negative and positive electrodes.

If a number is given to each warp from left to right, odd numbered warps are located on the first heddle and even numbered warps are located on the second heddle. During the shuttles' travel along the loom's width, according to design, while the first conductive fibre only interlaces with negative pole of piezoelectric wefts, second conductive warp interlaces only positive pole of the piezoelectric filling fibres/yarns. Thus, any short circuit is avoided. Figure 6(b) shows interlace of warp and weft threads and possible appearance on face of the fabric. If the used fibres counts are the same and the warps and wefts are located with an exact sequence, the resultant fabric will contain 24% piezoelectric, 16% conductive and 60% non-conductive conventional fibres/yarns.
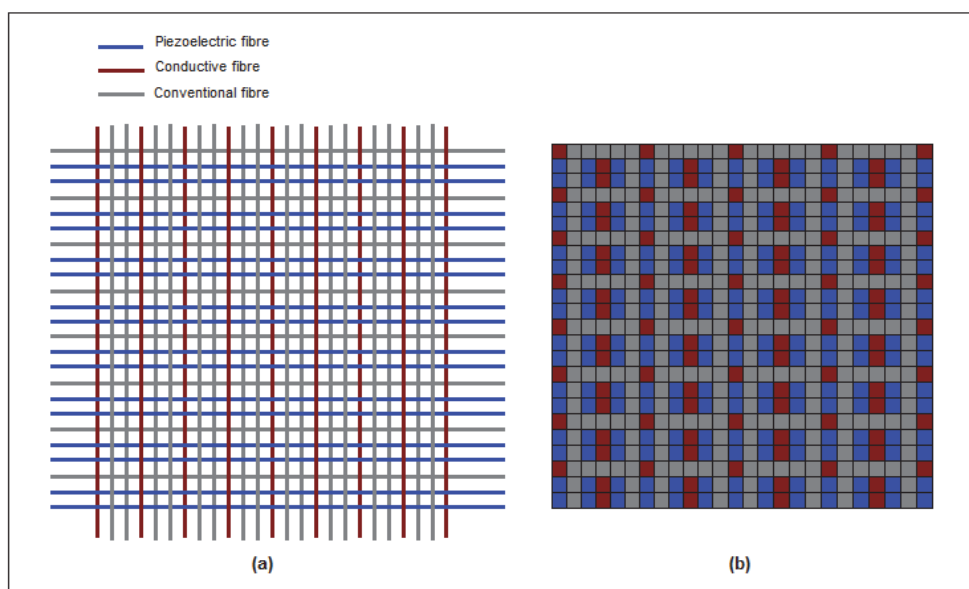

Fig. 7. (a) Smart woven fabric design 2 consisting of piezoelectric, conductive and non-conductive conventional fibres, (b) Face of the woven fabric consisting of piezoelectric, conductive and non-conductive fibres

The design shown in Figure 7(a) needs 2 heddles to locate conductive and non-conductive fibres/yarns and 2 shuttles, the one with piezoelectric fibres/yarn and the other with non-conductive conventional fibres/yarn. If a number is given to each warp from left to right, odd numbered warps are located on the first heddle and even numbered warps are located on the second heddle.

During the shuttles travel along the loom's width according to the design, the first heddle is kept in place, second heddle is uplifted so that warps are kept apart and shuttle travels through easily. Shuttle carrying piezoelectric fibre travels twice and then the other shuttle which carries non-conductive conventional fibres/yarn travels once. The whole process is repeated until the desired fabric structure is created. Thus, the first conductive warp only interlaces with negative charged sides of piezoelectric wefts, second conductive warp interlaces only with the positive charged sides of the piezoelectric filling fibres/yarns.

Figure 7(b) shows interlace of warp and weft threads and possible appearance on face of the fabric. If the used fibres counts are the same and the warps and wefts are located with an exact sequence, the resulted fabric will contain 34% piezoelectric, 18% conductive and 48% non-conductive conventional fibres/yarns.
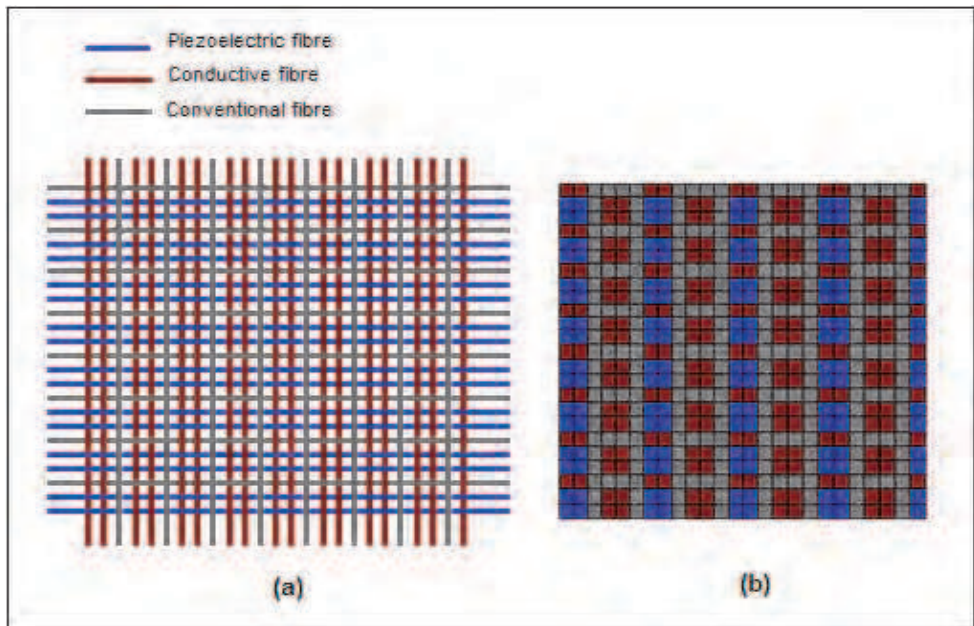

Fig. 8. (a) Smart woven fabric design 3 consisting of piezoelectric, conductive and non-conductive conventional fibres, (b) Face of the woven fabric consisting of piezoelectric, conductive and non-conductive fibres

The design shown in figure 8(a) needs 2 heddles to locate conductive and non-conductive fibres/yarns and 2 shuttles, the one with piezoelectric fibres/yarn and the other with non-conductive conventional fibres/yarn. If we give a number to each warp from left to right, 1st, 2nd, 7th, 8th, 13th, 14th, 19th, 20th and 25th warps are located on the first heddle and other warps are located on the second heddle.

According to design in figure 8(a), while first heddle is kept in place, second heddle is uplifted so that warps can be kept apart from the first heddle's warps and shuttle, which carries piezoelectric fibres/yarn, can easily travel through. The shuttle which carries piezoelectric fibre travels twice and then the first heddle is uplifted while the second heddle

is lowered so that the other shuttle which carries non-conductive conventional fibres/yarn travels once through the warps. The same movements are carried out with the same order again and again until a fabric structure is created. Thus, all the conductive warps on the first heddle only interlace with negative pole of piezoelectric wefts and all the conductive warps on the second heddle interlace only with positive pole of the piezoelectric wefts.

Figure 8(b) shows interlace of warp and weft threads and possible appearance on face of the fabric. If the used fibres' counts are the same and the warps and wefts are located with an exact sequence, the resultant fabric will contain 34% piezoelectric, 34% conductive and 32% non-conductive conventional fibres/yarns.
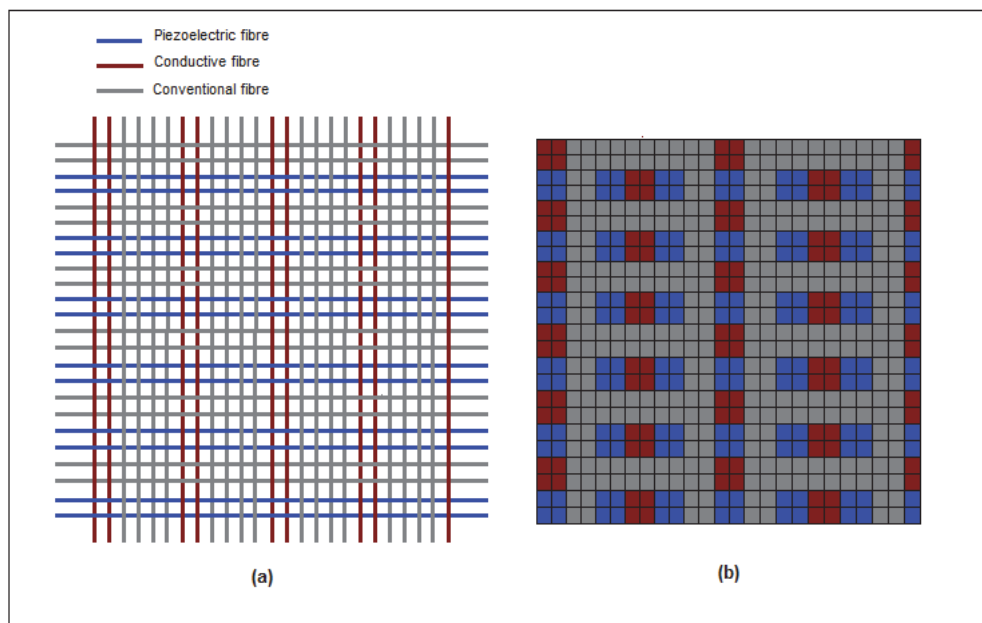

Fig. 9. (a) Smart woven fabric design 4 consisting of piezoelectric, conductive and non-conductive conventional fibres, (b) Face of the woven fabric consisting of piezoelectric, conductive and non-conductive fibres

The design shown in Figure 9(a) needs 2 heddles to locate conductive and non-conductive fibres/yarns and 2 shuttles, the one with piezoelectric fibres/yarn and the other with non-conductive conventional fibres/yarn. If we give a number to each warp, 1st, 2nd, 5th, 6th, 9th, 10th, 13th, 14th, 17th, 18th, 21st, 22nd and 25th warps are located on the first heddle and others are located on the second heddle.

During the first shuttle's travel along the loom width, the first heddle is kept in place and the second heddle is uplifted so that warps can be kept apart from the first heddle's warps and shuttle which carries piezoelectric fibres/yarn can easily travel through. The shuttle carrying piezoelectric fibre travels twice and then the first heddle is uplifted while the second heddle is lowered so that the other shuttle which carries non-conductive conventional fibres/yarn travels twice through the warps. The same movements are carried out in the same order again and again until a fabric structure is created. Thus, all the

conductive warps on the first heddle only interlace with negative pole of piezoelectric wefts and all the conductive warps on the second heddle interlace only with positive pole of the piezoelectric wefts.

Figure 9(b) shows interlace of warp and weft threads and possible appearance on face of the fabric. If the used fibres counts are the same and the warps and wefts are located with an exact sequence, the resultant fabric will contain 26% piezoelectric, 18% conductive and 56% non-conductive conventional fibres/yarns.

5. Conclusions

Polymer based piezoelectric fibres can be used as either weft or warp into the woven structure and conductive fibres can be used as negative and positive electrodes for charge transfer, therefore the resultant fabric can produce energy to power small electronic devices.

The advantage of polymer based piezoelectric fibre is their flexibility so that they can easily be used in woven structures. It is impossible to integrate existing ceramic based piezoelectric fibres into a similar structure since they are brittle.

For all four fabric designs studied in this chapter, interlace of piezoelectric and conductive fibre/yarn is significant. In a woven fabric structure, one piezoelectric fibre can interlace with more than one conductive fibre and one conductive fibre can also interlace with more than one piezoelectric fibre. However, to avoid any short circuit, one conductive fibre can only interlace with the same pole of the each piezoelectric fibre.

Since the fibres are considered having the same thickness, in the first design, piezoelectric and conductive fibres interlace 96 times in the fabric. The times of interlace of piezoelectric and conductive fibres are 153 for the second design whilst it is 289 and 117 times for the third and forth fabric designs, respectively. Therefore, the highest energy generation is expected from the third design when they all designs are subjected to the same amount of mechanical stimulus.

Smart piezoelectric woven fabrics can be used where they can be subjected to mechanical strain/stress or vibrations. Depending on the application and energy need, smart piezoelectric woven fabrics can be used to produce whole textile structure or only a part of it. For instance, tents, awnings and umbrellas can be wholly made of smart piezoelectric fabrics and produce electricity under rain as well as wind. However, waterproof finishing is needed if the fabric will be used for outdoor applications.

Energy generated by piezoelectric materials is always in the form of AC, therefore a small rectifier is needed for the conversion of the generated energy (AC) into usable energy (DC) for low power electronics.

The best weaving technique for smart piezoelectric fabric is plain weaving and its derivatives. Possible smart woven fabric designs are not limited. Depending on energy need, different fabric designs can be made with less or more interlacing. Other existing fabric making methods (other than weaving) such as embroidery can also be used to produce smart fabrics.

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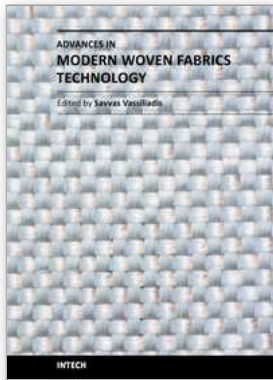
Advances in Modern Woven Fabrics Technology

Edited by Dr. Savvas Vassiliadis

The importance of woven fabrics increases constantly. Starting from traditional uses mainly in clothing applications, woven fabrics today are key materials for structural, electronic, telecommunications, medical, aerospace and other technical application fields. The new application fields of the woven fabrics is directly reflected in the contents of the book. A selected collection of papers in the technological state-of-the-art builds the book "Advances in Modern Woven Fabrics Technology". It is written by internationally recognized specialists and pioneers of the particular fields. The chapters embrace technological areas with major importance, while maintaining a high scientific level. This interdisciplinary book will be useful for the textile family member as well as for the experts of the related engineering fields. The open access character of the book will allow a worldwide and direct access to its contents, supporting the members of the academic and industrial community.

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