Preliminary theoretical study about a "Piezoelectric Shingle" for a piezoelectric energy harvesting system in presence of rain

ROMEO DI LEO[1], MASSIMO VISCARDI[1], GIANLUCA FERRINI[2] and LEONARDO LECCE[1]
[1]Department of Industrial Engineering, [2]Novaetch S.r.l.
[1]University Federico II of Naples
[1]Via Claudio 21, 80125, Naples,
[2]Via J. F. Kennedy 5, 80125 Naples
[1,2]ITALY
romeodileo@virgilio.it, massimo.viscardi@unina.it

Abstract: - The present work is focused on the proposal of the idea of a "Piezoelectric Shingle" as a new energy harvesting system, based on meteorological precipitations as the rain. It is presented a preliminary analysis about the state of art of energy harvesting systems, based on piezoelectric technology, showing potentiality, limits and other experiences in the field of interest. Besides the paper treats about the main features of rainy phenomena, interesting for an energy harvesting system, reconsidering some theoretical/empirical models. Models are addressed to define the limit velocity of raindrops and a distribution law between dimension of raindrops and the nature of rainfall. After considerations about the annual quantity of water, fallen in a region, the authors propose the ideation of some key patterns for a piezoelectric energy harvesting system from rainy precipitations. Each scheme is analyzed and evaluated for the selection of only one conceptual idea.

Key-Words: - Renewable energy, energy harvesting, piezoelectric material, rain, mechanical vibration

1 Introduction

Today the topic of energy is a crucial point for the future development of the human society. Humanity needs an increasing quantity of energy in the future and the interesting estimation of Energy Outlook of Energy Information Administration EIA (AA.VV. 2013) quantifies a boost of +55% for the worldwide consumption of energy in the next thirty years. All scientific community agrees about the idea that conventional sources of energy will finish a day. It is no easy to foresee this day and besides it is a strong challenge to find new energy sources able to override the conventional ones.

In this scenario there is an increasing interest for renewable energy sources as wind and solar energy, which are candidates as future potential contribute for the reduction of consumptions of conventional energy sources or for the complete substitution of them.

Instead the present paper explores the use of another renewable energy source, not really considered until now.

The proposed work is focused on meteorological precipitations for the energy production and particularly on the atmospheric phenomena of rain.

Rain falls from the clouds' level, gaining a constant limit velocity of fall when gravity force is equilibrated by the sum of the resistant force, generated from viscous friction, and by the Archimedes pushing force. In this manner raindrops have a kinetic energy. The final aim is to convert this kinetic energy in the electric one for harvesting energy from the environment.

The use of the environmental energy source of rain pursues a potential advantage as a green production of energy from a new, not conventional, energy source of renewable type but above all an advantage linked to the recent development of MEMS and intelligent systems. This development has carried to a wide use of autonomous sensors. In this field the recovery of energy from rain can bring the great advantage of feeding autonomous sensors in applications where other energy sources are not available.

In the present work the result of converting energy from raindrops is pursued through the use of piezoelectric materials.

In a particular manner flexible piezoelectric materials are interesting for power harvesting because they are able to withstand great strains. Larger strains give a major quantity of mechanical energy for the conversion in electrical energy.

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In literature a lot of research works about the conversion of environmental energy, linked to vibrations, using piezoelectric, are present.
A fundamental point to gain a better conversion of mechanical energy in the electric one is the choice of the type of piezoelectric material.
Lee, Wu and Shih (2006) affirm that although piezoceramic materials PZT are widely used in power harvesting field, they present some problematic aspects. In fact PZT materials are very brittle and this property carries strong limitations in the strain which they can sustain without damages. In a particular way PZT are sensitive to the propagation of the fatigue under a cycle of load, characterized by an high frequency.
To override these limitations of PZT piezoelectric material a new class of more flexible piezoelectric material was developed.
Poly-vinylidene-fluoride PVDF is a polymeric piezoelectric material with a great flexibility in comparison to PZT.
About the topic of a piezoelectric harvesting system for the conversion of environmental vibrating energy, there are many research works in literature.
Lee, Joo, Han, Lee and Koh (2005) test a PVDF film coated with poly/poly electrodes. PVDF film works from 10Hz to 1MHz without the presence of electrode damage and it obtain an increasing capacity to harvest power during its lifespan.
Mohammadi, Khan and Cass (2003) study the power generation ability of piezoelectric lead zirconate titanate fibres composites.
They highlight that thicker fibrous plates present larger displacements of fibres and samples with smaller diameter of fibres have the highest d33 piezoelectric coefficient and lowest dielectric constant, which are both contributes for a more power conversion and consequently for a more efficient harvesting systems.
Sodano, Lloyd and Inman (2004) and Sodano, Park and Inman (2004) in their works perform a comparison on the efficiency of three different types of piezoelectric materials. Classical PZT, macro-fibre composite MFC and a quick pack actuator are considered. Each type of material is excited at resonance, subjected to a 0-500Hz chirp and then each material is subjected to random vibrations. They find that efficiency of PZT is better than other two systems in all conditions, resonance, chirp and random vibrations.
Besides the choice of the more adequate material, another method of improving the energy converted by a piezoelectric harvesting system is the use of a more efficient coupling mode. There are two coupling modes 31 mode and 33 mode. In the first one the force is applied at the piezoelectric material in a perpendicular direction to the poling orientation. In the second mode the direction of applied force and of poling is the same. The influence of coupling mode is well described by Baker, Roundy and Wright (2005). Authors analyse alternative geometries for increasing power density in vibration energy scavenging for wireless sensor networks. They load up a cantilever configuration, working in 31 mode, with a stack configuration, working in 33 mode, with the same small force. Authors find the result that a cantilever configuration produces more power (two orders of magnitude) than a stack configuration, subjected to the same force. Stack configuration is more robust and it has a greater coupling coefficient but it is less productive because the stack has an elevated mechanical stiffness. For this reason strains of stack configuration are small. In conclusion for small loads, for low level of vibrations the 31 mode of cantilever configuration produces best performances in the energy conversion.
Many of the researches in the last years are also focused on improving the efficiency of piezoelectric circuitry and energy removal techniques as in Han, Von Jouanne, Mayaram and Fiez (2004) or in Lefeuvre, Badel, Richard, Petit and Guyomar (2006).
Premount (2006) highlights the importance of improving the difference between the consumption of energy by electronics used for storing the harvested energy and the capability of generation of the energy harvesting system.
Previous rows show that in literature are present a lot of research works about the conversion of environmental energy, linked to vibrations, using piezoelectric structures, but there are very few works on the topic of a piezoelectric harvesting system functioning with rain.
Guigon, Chaillout, Jager and Despesse (2008) propose a theoretical study on a possible harvesting raindrop energy system based on a polymeric piezoelectric bands with a length of 100 mm and a width of 3 mm, supported on both the ends.
Guigon, Chaillout, Jager and Despesse (2008) in another paper complete the study, presenting an experimental work on the piezoelectric system of energy conversion from rain.
Biswas, Islam, Sarkar, Desa, Khan and Huq (2009) analyze the solution already proposed by the work of Guigon, Chaillout, Jager and Despesse (2008), evaluating the application of this system in the Bangladesh region where the monsoon produces massive rainfall from June to September.

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The present work focuses its attention on the proposal of the idea of a "Piezoelectric Shingle" as a new energy harvesting system, based on raindrops.
The paper presents a preliminary theoretical and simulative study for the system. The final aim is the conversion of the mechanical kinetic energy of a meteorological precipitation as the rain in electrical energy.
The new studied harvesting system results different from the device of Guigon, Chaillout, Jager and Despesse (2008), adopting a completely different constructive scheme. In fact the studied system isn't based on long piezoelectric wires of the Guigon's solution. Besides the final aim of the research activity will be the presentation of a finite harvesting system, inserted in a shingle for roof, for this reason the name "Piezoelectric Shingle". The present paper, after a preliminary treatment about the potential features of rainy phenomena interesting for an energy harvesting system, analyzes some basic conceptual ideas for the proposition of a Piezoelectric Shingle. Then a conceptual idea is selected and chosen.
This study is the first theoretical step for a next work regarding the definition of the system, experimental tests in laboratory for the proposed system and a future final realization of the Piezoelectric Shingle.

2 Modeling of main features of rainy precipitations for the energy harvesting system

The final aim of the research is the creation of a new piezoelectric device, able to the conversion of the mechanical kinetic energy of rain in electrical energy.
For this reason are fundamental two parameters of rainfall: the mass of water and the final limit velocity of fall.
Clearly we are not interested simply to the total mass of water of a rainfall (measured in mm of water/m^2) but it is also important to know each share of this mass which falls with a given final limit velocity.
The final limit velocity is related to the diameter of raindrop.
By this preliminary considerations, the fundamental parameters of raindrop for the research project are: the dimension of raindrop (expressed by the value of its diameter) and the limit velocity of the drop.
For the first point it's a focal point to define a distribution law between dimension of raindrops and the nature of rainfall. For this reason authors conducted a revision of the state of art in the scientific literature available.
In 40's years of the past century Marshall and Palmer (1948) realize experimental measures, using coloured filters of paper. Authors correlate these measures with measures obtained with a radar by Marshall, Langille and Palmer (1947). Considering these results, they affirm that in the proximity of the ground the distribution of the medium dimension of raindrops can be presented by a simple equation proposed by authors.

$$N = (N_0 e^{-\Lambda D})*\delta D \qquad (1)$$

where:
N is the number of drops with diameter inside the interval [D, D + δD] in a unitary volume;
D is the diameter of the drop;
N_0 is an asymptotic value for diameter D which tends to 0.
This parameter is experimentally estimated by authors and it is evaluated equal to 0.08 cm-4.
Λ consider the relation with the intensity R (mm/hr.) of the rain

$$\Lambda=41R^{-0.21}cm^{-1} \qquad (2)$$

This equation is an evolution of the model previously proposed by Laws and Parsons (1943).

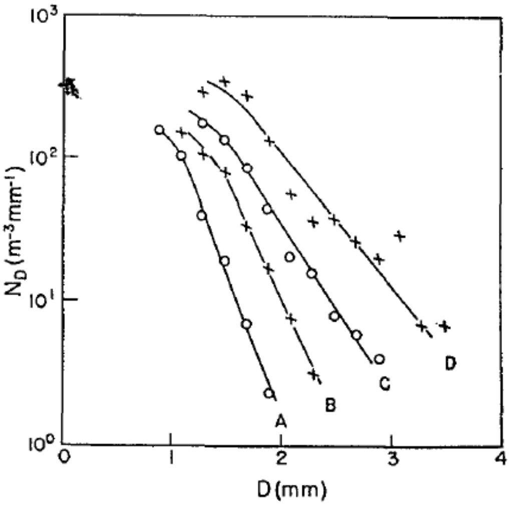

Figure 1: Curves of Law and Parson in a mtaching with experimental data

Ryde (1951), develops the model of Marshall and Palmer (1948), introducing the limit velocity of raindrops. He obtains curves of distribution which link the contribution to the mass of water, generated by drops of a defined diameter. These curves are parameterized in function of the intensity of rainfall (mm/hr.) and they present a "bell shape" (Figure 2).

The maximum of these curves are approximately distributed on an hyperbolic curve.

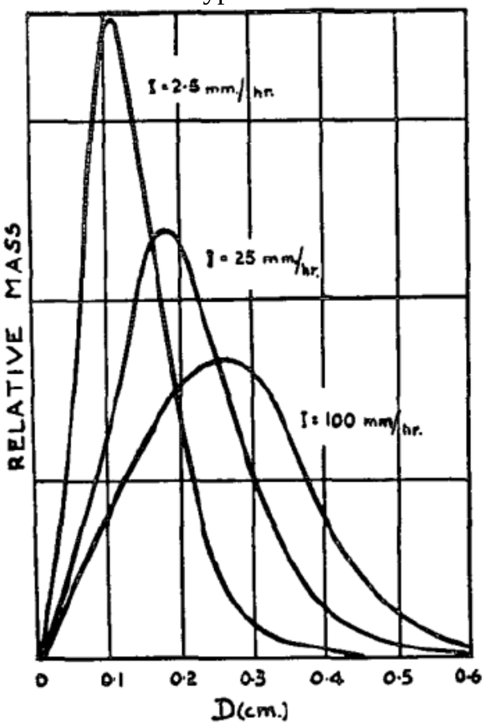

Figure 2: Ryde's curves about the distribution of raindrops

Best (1950) presents a summary and a comparison about all works on the topic and results obtained.
After the study of Marshall and Palmer other researches have been conducted to improve the method.
Shekon and Srivastava (1971) conduct an analysis based on a great number of experimental observations, performed with a Doppler radar. For the curves of Marshall and Palmer they identify a new value of intercept with axis D=0 and this value result increasing with the parameter R.
Willis (1984) analyses more than one hundred sets of experimental data, obtained by the methodology of the optical spectroscopy. He normalizes dimensional distributions and he finds that their trend deviate from the exponential tendency.
The author considers five types of functions to gain a best fit of data: three exponential functions (as Marshall-Palmer type) and two are a "gamma distribution" type. One of the "gamma distribution" gains the best result about the fitting to the experimental data.
In this way he proposes a modification to the widely used Marshall and Palmer method.
In the subsequent curves a comparison is proposed and the behaviour of new model (left side of Figure 3) is better than that of Marshall and Palmer (right side of Figure 3), which present a good matching with observed data for raindrops of medium size but it separates oneself by experimental data for greater or smaller raindrops.

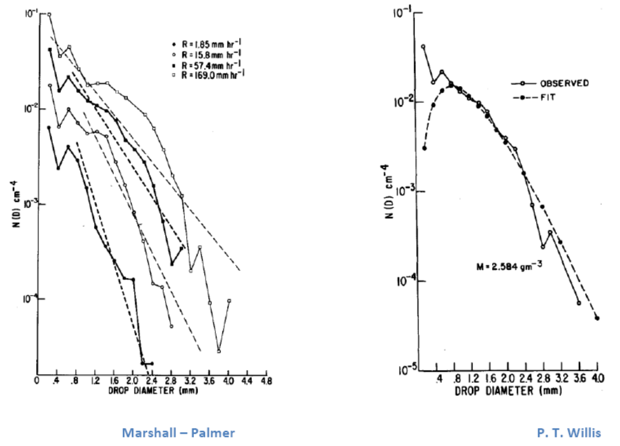

Figure 3: On the left side a comparison between experimental data and Marshall and Palmer curves for different level of rain rate. On the right side a comparison between experimental data and Marshall and Willis curve.

In Israel, Feingold and Levin (1986) carry out two years of measures about the dimensional distribution of raindrops. They confirm that experimental data can be described in a better manner by a not exponential function. They identify a lognormal distribution with a suitable choice of parameters as a better choice than an exponential one (as the equation of Marshall and Palmer). Besides these description present the advantage of a physical meaning for their parameters.
In 90's years Sempere Torres, Porram and Creutin (1994) demonstrate that it is possible to find an unifying frame for the parameterization of the distribution for the size of raindrops (rainDrop Size Distribution – DSD). This distribution presents all features of a "law of scale". The same authors (1998) subsequently confirm this idea with a greater number of experimental experiences.
The "law of scale" is clearly function of diameter of raindrop D and of rain rate R.
Following the formalism of "laws of scale" the DSD can be expressed as

$$N(D,R) = R^{\alpha} g(D/R^{\beta}) \qquad (3)$$

Where:
$N(D,R)$ ($mm^{-1}m^{-3}$) is the rainDrop Size Distribution DSD, expressed as a function of diameter of the sphere D (mm) equivalent to the raindrop and the rain rate R ($mm\ h^{-1}$);
α e β are the "exponents of scale" (not dimensional);

g(x) is the general distribution of dimensions of raindrops, expressed in function of the scaled diameter of raindrops $x = D/R^{\beta}$

In accordance with the common practice, the rain rate R is generally considered as the reference variable but every macroscopic variable of rain can be used for this aim (for example the factor of radar reflectivity Z).

It is fundamental to highlight that values of α e β and the shape and dimensions of g(x) depend from the choice of the reference variable but they are independent from its value.

At the beginning of the present paragraph we highlighted that the second fundamental parameter of raindrop for the research project is its limit velocity.

The first measures about limit velocity were conducted in 70's years when in wind gallery the limit velocity of drops of water was measured in saturated air for different number of Reynolds (0,2-200). Beard and Puppacher (1969) measure the dependence of final velocity by Reynolds number of airflow. He highlights the difference of this final velocity from that of a classical Stokes condition (low Reynolds numbers).

For a rigid sphere in Stokes condition the drag force is:

$$D_S = 6\pi a \eta V_\infty \quad (4)$$

where:

a is the radius of the rigid sphere;

η the dynamic viscosity;

V_∞ is the limit velocity.

The value of Ds can be used to obtain a not dimensional graph of real drag force on the raindrop, dividing the measured value of drag force D to the theoretical value Ds. The ratio D/Ds is the inverse ratio of Vs/V.

Measuring experimentally this last ratio it is possible to evaluate the drag coefficient CD, which is required for a prevision of the limit velocity:

$$V_\infty = \left(\frac{16}{3}\right)\left(\frac{g(\rho_s - \rho_m)}{\eta}\right)\left(\frac{a^2}{C_D R}\right) \quad (5)$$

with ρ_s and ρ_m respectively the density of the water drop and air (environment in which raindrop fall).

The subsequent image (Figure 4) shows the estimation of CD, based on experimental measures in function of Reynolds number in a comparison with the theories of Stokes and Oseen for the velocity of fall.

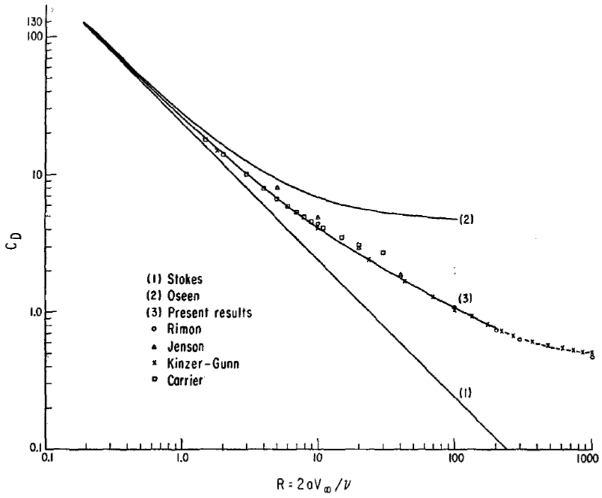

Figure 4: Measured drag coefficient in a comparison with the results of theories of Stokes and Oseen

This measure through the Reynolds number depends by many physical parameters (diameter of the drop, temperature, humidity and atmospheric pressure).

This measure is a useful manner to estimate the limit velocity in fact the subsequent quantity is a function only of environmental parameters and raindrop's diameter:

$$C_D R^2 = \left(\frac{32}{3}\right) a^3 (\rho_s - \rho_m)\left(\frac{\rho_m g}{\eta^2}\right) \quad (6)$$

Assigned the value of ρs, ρm and dynamic viscosity η (function of humidity and temperature) and the raindrop's radius a, it is possible to estimate the Reynols number, inverting the previous expression. In this way using the known value of CD and R, it is possible to estimate the limit velocity with the expression

$$V_\infty = \frac{R\eta}{2\rho_m a} \quad (7)$$

Figure 5 reports some estimations, made with this technique.

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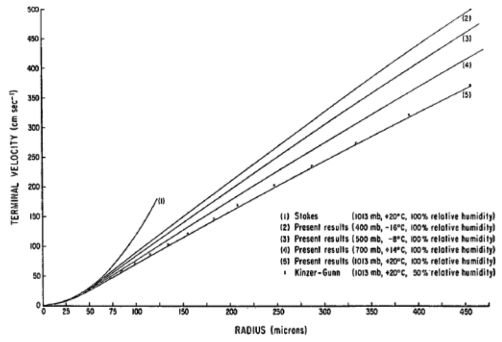

Figure 5: Limit velocity of raindrops calculated with the procedure presented by Beard and Pruppacher

In a rainy phenomena not all drops fall effectively at their limit velocity. Recent studies as Montero-Martinez, Kostinski, Show and Garcia (2009), which use new techniques for the measure of the falling drops, show that some drops have a limit velocity of one order of magnitude greater than the expected limit velocity. These drops, called "Super-terminal", carry to an increase of the real energy available against the expected one. For this reason in the case of an harvesting application these "Super-terminal drops" can be neglected in the energy estimation in a first approximation.
In the present work to estimate the limit velocity of raindrops we use the relation, obtained by Guigon R (2006).
Guigon R (2006) considers weight "W", viscous friction "R" and Archimedes' push "A" as forces acting on the raindrop.
Solving the second equation of dynamic

$$\vec{A} + \vec{W} + \vec{R} = m\vec{a} \qquad (8)$$

Solving the second equation of the dynamic, it is possible to calculate the velocity of a drop in function of its height of fall.

$$V(H) = \frac{1}{\alpha} * \sqrt{1 - 4 * e^{-H*\alpha*b+a+b*A}} \qquad (9)$$

with:

$$m = \rho_{water} * \frac{\pi D^3}{6}; \qquad m' = \rho_{air} * \frac{\pi D^3}{6};$$

$$k = \frac{1}{8}\rho_{air} * \pi D^2 * C_D; \qquad \mu = \frac{m - m'}{m}$$

$$\alpha = \sqrt{\frac{k}{\mu*m*g}}; \qquad a = ln\frac{1+\alpha*V_{init}}{1-\alpha*V_{init}};$$

$$b = 2*\alpha*\mu*g; \qquad A = \frac{-2\ln(e^{a}+1)}{b}$$

The third fundamental feature of rainy precipitation, interesting for an energy harvesting system is the annual quantity of water fallen in a region.
Figure 6 shows that the region with the greatest annual rainfall (measured as mm/year for every on a square meter) are located in South America, Africa and South-east of Asia (regions of monsoons) with an annual precipitation of about 3000mm/year.
In a detail about Italy, Alpine arch and Apennines ridge are the zones with the greatest annual rainfall (about 1500 mm/year).

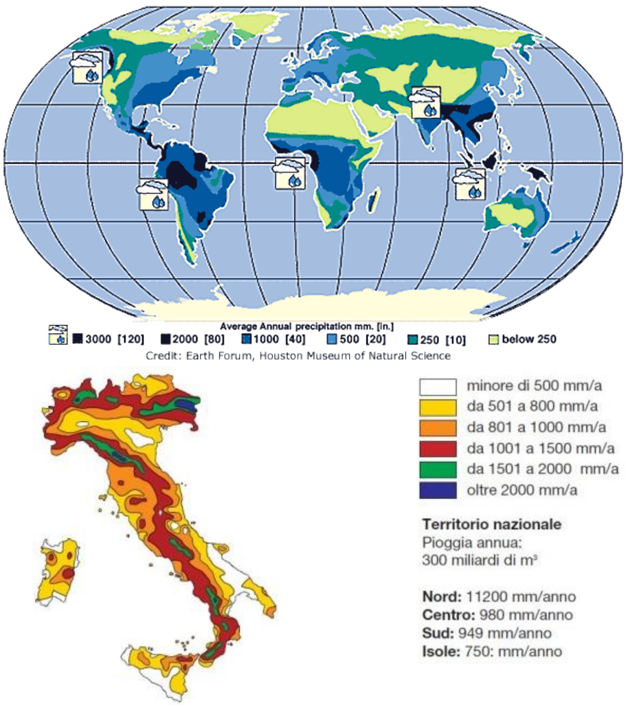

Figure 6: Annual rainfall in the world and in Italy (mm/a)

Clearly the system proposed in the present study presents a more potentiality in the region with high annual rainfall with a consequent higher temporal density of energy.
All considerations about features of rain, interesting to the energy harvesting system, exposed in the rows of this paragraph will be useful not only for the study of the system but also for an analysis about economic, social and environmental impact of the proposed piezoelectric energy harvesting system.

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This analysis of impact will be performed in a new future paper after a later development of the research activity.

3 Ideation and evaluation of key patterns for a piezoelectric energy harvesting system

Some key patterns for the realization of a piezoelectric energy harvesting system, using rainfall, has been evaluated.

The first ideal pattern contemplate the implementation of a piezoelectric patch, bonded by a glue to a membrane.

The membrane has a fixed constrain on its four edges.

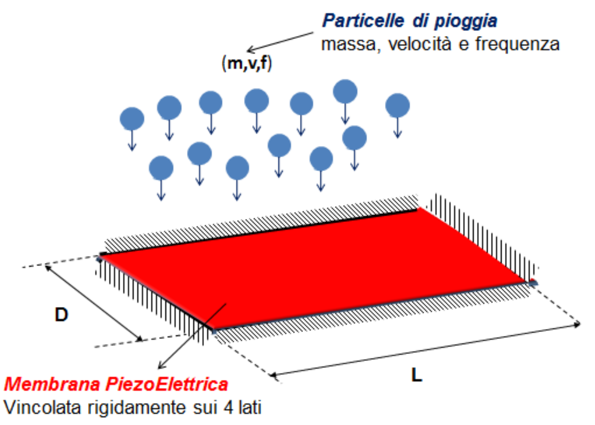

Figure 7: Ideal concept n°1

The membrane subjected to the loads, generated by impacts of raindrops with its surface, generates a deformation of the membrane and consequently of the bonded piezoelectric patch.

The second key patter is based on a piezoelectric stack, which support a collector plate raindrops. The edge of the plate are free and the only constrained region is the linking interface between the plate and the piezoelectric stack. This pattern follow the conceptual scheme of a piezoelectric scale.

In Figure 8 the second patter is depicted with a spring kp, representing the stiffness of the piezoelectric stack.

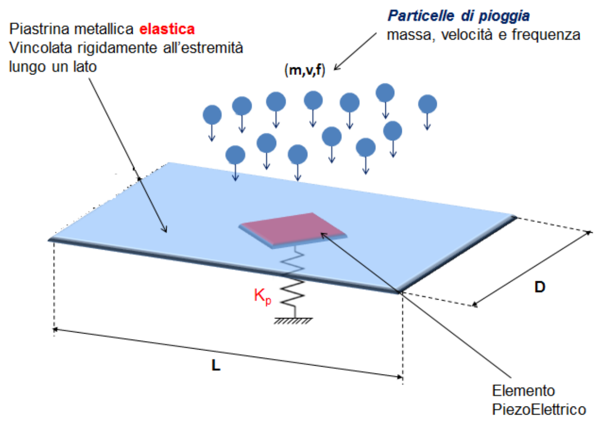

Figure 8: Ideal concept n°2

A third key pattern, which is a variation of the previous one with the addition of a spring for each corner of the membrane, has been presented (Figure 9)

The last proposed key pattern is a system without an elastic membrane or a plate but composed by the piezoelectric patch alone.

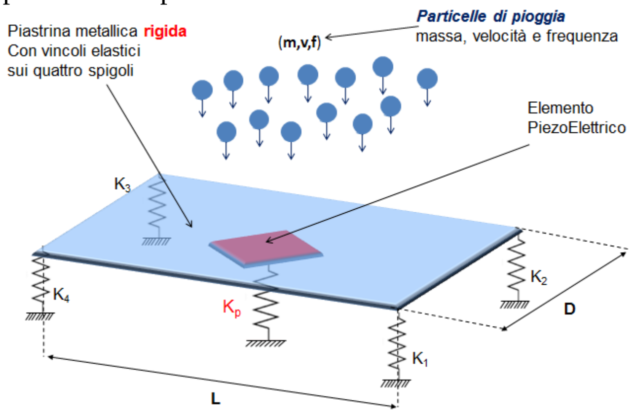

Figure 9: Ideal Concept n°3

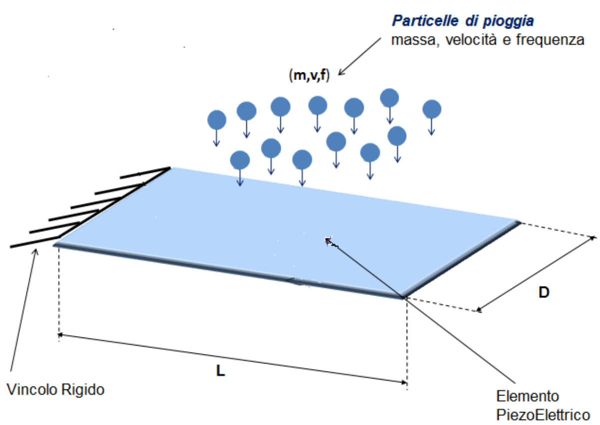

Figure 10: Ideal concept n°4

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The patch is constrained on a short side in a fixed way, reproducing the scheme of a cantilever beam.
The system, stricken by raindrops, work in a bending way.
Considering the type of load, acting on the harvesting, and the considerations of previous pages the second and third key pattern results inadequate to the proposed aim. In fact the slightness of the exciting force, produced by the raindrop's impact, don't produce a significant deformation on a stack piezoelectric transducer. As we reported in the first pages, there is a direct relation between the quantity of mechanical energy deformation of piezoelectric unit and the converted one, for this reason the strongly reduced deformation means a negligible conversion of energy by the piezoelectric system. In the market research, reported in the next paragraph, the piezoelectric stack with the smallest axial stiffness present a value of 12N/mm with dimensions of 2x3x18mm and a resonant frequency of 70 kHz.
These considerations, which lead to discard the second and third configuration, are confirmed by the statements, reported in technical state of art of the first paragraph. In fact for small loads and for low level of vibrations, Baker, Roundy and Wright (2005) highlight better performance of the 31 mode than 33 mode (the last one is the functionality of the stack configuration).
The first configuration with the glued patch has been discarded too. In fact the presence of a plate, where the patch is glued, carries to an higher stiffness of the system and consequently to lower deformation in presence of small forces, produced by the impact of raindrop and a very lower energy converted.
At this point an alternative idea was proposed. Instead of using a plate with a glued piezoelectric patch it is possible to adopt directly a piezoelectric membrane, eliminating in this manner the plate.
Also this choice has not been selected for two reasons.
In any way the constraints on all sides of material reduce the deformations of the system, achievable with the presence of a constraint on only one side. Besides this configuration of a membrane, linked on each side, create a "swimming pool effect". Raindrops amass themselves in the central zone of the membrane, generating a constant deformation. In this manner the conversion of energy is zero the variation of deformation in the time is necessary because to convert energy in the time.
Finally for all previous reasons the fourth configuration has been adopted.
The literature, as previously seen, support this choice, suggesting the 31 mode as the optimal working mode in the case of low exciting forces. The presence of the piezoelectric patch alone (without any support) and with the minimum number of constraints (only on one side in the cantilever beam configuration) would guarantee the maximum deformations under the low exciting bending actions of raindrops.

4 Conclusion

In the present work is proposed a preliminary study for the idea of a new system, called "Piezoelectric Shingle" as a new energy harvesting system, based on meteorological precipitations as the rain. The system will be based on the conversion of the mechanical kinetic energy of raindrops in electrical energy.
The first section, after the consultation of the literature, has presented a deep analysis about the state of art of energy harvesting systems, based on piezoelectric technology, showing potentiality, limits and other experiences in the field of interest. Then the main features of rainy phenomena, interesting for an energy harvesting system have been defined. In a particular way were presented some models to define the limit velocity of raindrops and a distribution law between dimension of raindrops and the nature of rainfall. After considerations about the annual quantity of water, fallen in a region, authors proposed four ideal concepts for a piezoelectric energy harvesting system based on rainy precipitations. Each conceptual scheme is analyzed and evaluated, highlighting eventual advantages and limits of each solution. In conclusion the forth ideal scheme was adopted because it works in a 31 mode with a minimum number of constraints. It would guarantee the maximum deformations under the low exciting bending actions of raindrops.
This ideal scheme it will be used for the next step of activity.

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