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HARNESSING RAINDROP ENERGY IN BANGLADESH

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ABSTRACT

The kinetic energy of raindrops can be converted into electricity by using piezoelectric materials. This paper explains behavior of raindrops at impact and of piezoelectricity. The physics of monsoon and rain pattern are also described in detail. It has been found that Polyvinylidene Fluoride called PVDF is the most suitable type of material for power harvesting application. Raindrops of 1 to 5 mm diameter are suitable for harnessing energy in Bangladesh. According to the data in Bangladesh we have around four months (June-September) of massive rainfall. In Bangladesh this time is very potential for harnessing this kind of energy.

Keywords: Energy Harnessing, Piezoelectric material, Mechanical vibration

1. INTRODUCTION

Energy is the most important issue in the world and in Bangladesh also. It is true that it is not easy to override the conventional energy sources. But to meet the large energy demand we need some substitutes. And due to recent environment concern issue the energy should be greener. So it is true that we need to try to move towards harnessing the energy from the nature which can be very much potential in some respect. There are some energy which are low in energy density but can provide sufficient energy to our sensors and MEMS. One of the energy sources is raindrop energy. We are trying to explore the possibility and probability of raindrop energy potential in Bangladesh.

Several experiments and theory have been developed [1, 2]. The idea is rain falls from a significant height which has significant kinetic energy. It is possible to convert this kinetic energy into electric power by using piezoelectric materials which converts the stress into electrical energy. Basically it is vibration energy. Because of rain drop impact is being converted to electrical energy the amount of rain and the size of the rain drop is very important. In France raindrop size can vary from 1mm to 5 mm [1].The terminal velocity of raindrop also has a major role play.

In Bangladesh June July August and September (JJAS) we have large amount of rain falls all over the country [3]. So there is a huge potential to collect the rainfall energy in the four months where other popular non conventional energy (e.g. solar energy) may not play a major role at that time.

2. REVIEW

2.1 Behavior of raindrops at impact

It is essential to understand underlying mechanisms governing the impact and spread of liquid droplets upon a solid surface for harnessing rain drop energy. Although this subject has been studied for more than a century, it is still not fully understood and therefore not perfectly modeled.

In general, three different types of behaviors are observed during drop impact on a solid surface: splashing, spreading and bouncing as illustrated in Fig 1 [4-5]. Drops impinging on solids can adhere to or bounce off the surface and can break up after impact or it can spread smoothly. An obvious difference is between processes that cause a disintegration of the drop and those that do not. Typically, the former case is called a splash. Often the conditions leading to splashing and spreading, respectively, are of particular interest. Hence, the desired behavior depends on the objectives of the particular process.

Many studies have been carried out to predict the behavior of a drop during its impact. Stow and Hadfield [6] established a splash parameter for the occurrence of splash, which depends on the surface roughness. The correlation for splashing/deposition limit expressed as $Re^{.31}We^{.69} = \xi$, where ξ, splash deposition value is dependent upon the surface roughness. Mundo *et al* [7] determined the limit between the splash and deposition modes for rigid impact surface based on experiments.

$$K = Oh^{*}Re^{1.25} > 57.7 \qquad (1)$$

If K is larger than a critical empirical value of 57.7, then it is in splashing regime. However, this empirical formula does not include other factors such as surface roughness, which is known to affect the contact angle between liquid drop and solid surface. Thoroddsen and Sakakibara's [8] experiments on a rigid impact surface showed that some of their test conditions in Mundo's splashing regime but close to the splashing line did not splash. They suspected that surface roughness plays an important role and caused the ineffectiveness of Mundo's criteria, i.e., rougher solid surface will trigger splashing for drops in conditions near the splashing line.

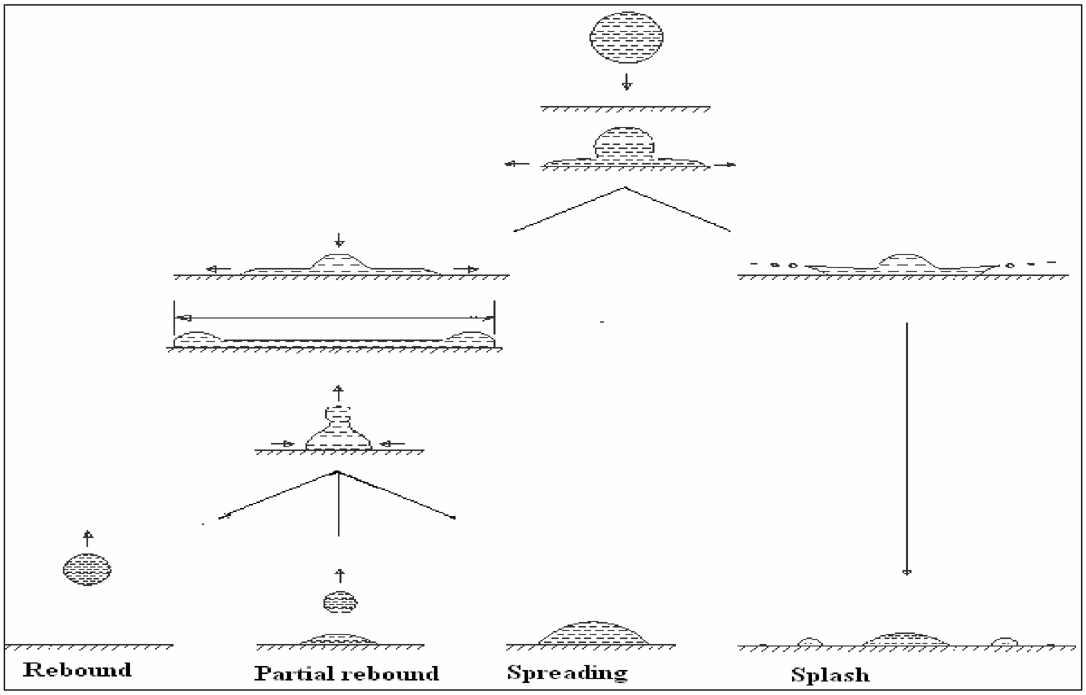

Fig 1. Scenarios of drop impact on a solid surface [5]

2.2 Piezoelectricity

Piezoelectricity describes the phenomenon of generating an electric charge in a material when subjecting it to a mechanical stress (direct effect); conversely, generating a mechanical strain in response to an applied electric field (converse effect).

The type of piezoelectric material selected for a power harvesting application can have a major influence on the harvester's functionality and performance. The most common type of piezoelectric used in power harvesting applications is lead zirconate titanate, a piezoceramic, known as PZT. Although PZT is widely used as a power harvesting material, the piezoceramic's extremely brittle nature causes limitations in the strain that it can safely absorb without being damaged. Lee et al [9] note that piezoceramics are susceptible to fatigue crack growth when subjected to high frequency cyclic loading. Another common piezoelectric material PVDF is a piezoelectric polymer that exhibits considerable flexibility when compared to PZT. Though the piezoelectric strain constant (d_{31}) and coupling coefficient (k_{31}) for PVDF is lower than that of PZT, PVDF is flexible, lightweight, tough, ecological properties (it does not contain lead) (Table 1).

A method of increasing the amount of energy harvested from a piezoelectric is to utilize a more efficient coupling mode. Two practical coupling modes exist; the −31 mode and the −33 mode. In the −31 mode, a force is applied in the direction perpendicular to the poling direction, an example of which is a bending beam that is poled on its top and bottom surfaces. In the −33 mode, a force is applied in the same direction as the poling direction, such as the compression of a piezoelectric block that is poled on its top and bottom surfaces.

Conventionally, the −31 mode has been the most commonly used coupling mode: however, the −31 mode yields a lower coupling coefficient, *k*, than the −33 mode [12, 13]. Table 3.4 shows a few of the most promising piezoelectric materials and their key properties. It was concluded that in a small force, low vibration level environment, the −31 configuration cantilever proved most efficient [13].

Table 1: Comparison of Properties of Standard Piezoelectric Polymer and Ceramic Materials [10]

	d_{31}, pm/V	k_{31}	Salient features
PVDF	28	0.12	Flexible, lightweight, low acoustic and mechanical impedance
PZT	175	0.34	Brittle, heavy, toxic

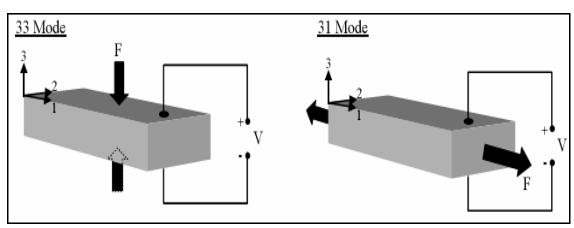

Fig 2. Illustration of 33 mode and 31 mode operation of piezoelectric material [11]

2.3 Energy harnessing from raindrop

Harnessing rain drop energy is a very recent research. Guigon *et al.* [1, 2] have recently developed a system that scavenges the vibration energy from a piezoelectric structure impacted by a water drop. In their papers they describe in detail the theoretical study undertaken to optimize the mechanical system and present an experimental device that validates the theoretical results.

Piezoelectric materials are widely used to convert mechanical energy into electrical energy. Majority of studies focus on the harvesting of vibration energy using piezoelectric beams subjected to pure bending [14,15]. For harvesting raindrop energy Guigon *et al.* [2] consider a piezoelectric membrane sensitive to surface impacts. The diagram in fig 3 shows the device used to recover the impact energy of raindrops. In the system the piezoelectric PVDF (Polyvinylidene fluoride) was used for power harvesting and it is used in -31 mode. In their study, they used mono-stretched PVDF polymers (thickness H = 25 μm, piezoelectric strain coefficient d_{31} = 15 pCN^{-1}) and bi-stretched PVDF polymers (thickness H = 9 μm, piezoelectric strain coefficient d_{31} = 5 pCN^{-1}), with a length L of 10 cm. Fig 4 shows the system with two transparent PVDF bands embedded in a Plexiglas structure, the electrodes on the surface of the piezoelectric membrane having been positioned by the manufacturer.

The impact of rain drop causes a deformation of the piezoelectric PVDF polymer membrane and a consequent strain. The resulting electrical energy in the PVDF material is formulated as [16]

$$U_{elect} = k^2 \frac{Y_{PVDF} V}{2} S^2_{aver} \quad (2)$$

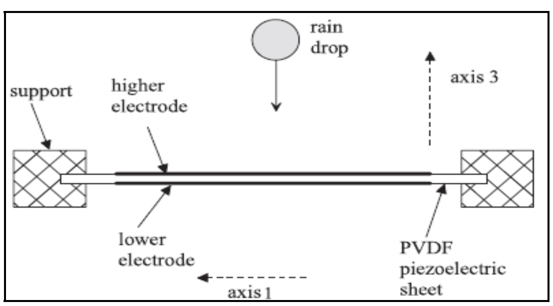

Fig 3. System of raindrop energy harvesting [2]

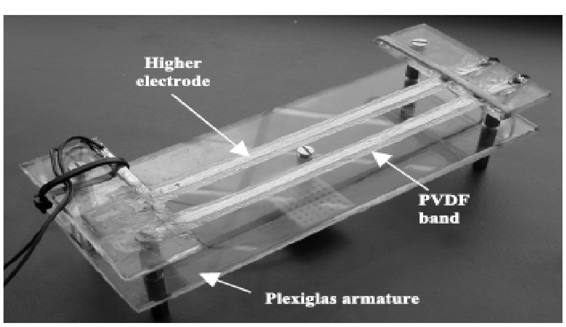

Fig 4.Mechanical system embedding the PVDF bands [2]

The electrical energy generated within the material is proportional to the deformation (Eq. 2), and thus to the amplitude of vibrations. It appears that 0.1 N pre-stressing of the cable decreases the amplitude by a factor of 10 after a water drop impact [1].

In the analysis Guigon *et al.* [1, 2] used the Mundo's [7] criteria to determine the mode of impact. They assumed that the energy balance of the splash mode drop is very close to the inelastic impact of a ball on a plate, where the energy lost during the collision is quantified by a restitution coefficient, namely the ratio of the relative speeds before and after the collision. They considered a standard rain drop of diameter 1mm and speed 3 m/s. Theoretical study shows that in order to maximize the deformation energy transferred to the material (and thus the recovered energy): the optimal width of which must be equal to approximately 2/3 of the maximum spread diameter of the drop (3.3 mm for a standard raindrop [17].

It appears that, a 25 μm thick, mono-stretched PVDF material with a piezoelectric strain coefficient d_{31} = 20 pC N^{-1} is much more effective than a 9 μm thick, bi-stretched PDVF material with a piezoelectric strain coefficient d_{31} = 5 pC N^{-1}. Table 2 shows recoverable electrical quantities in various situations, with a single drop.

The results of these impacts are very close to those produced in the simulation, as shown in table 3. Note that the higher the speed of impact, the more the experimental results differ from the simulation results. Nevertheless, the theoretical and experimental results remain reasonably close.

Table 2: Recoverable electrical quantities in various situations [1]

Types of drop	Cable dimension	Recov erable voltage	Recover able electrica l energy	Recovera ble instantan -eous power
Rain; D:1mm; v:2.8m/s	L:10cm: W:3 mm; H: 25 μm	1.6 V	1.7 nJ	0.8 μW
Medium; D:2.mm; v: 0.75 m/s	L:10cm: W:3 mm; H: 25 μm	3 V	5 nJ	2.5 μW
Downpour : 5mm; v: 5.7 m/s	L:10cm: W:1.3 cm; H: 25 μm	98 V	25 μJ	12.5 mW

Table 3: Theoretical/experimental results for high-speed impact on 25 μm thick PVDF [2]

Impact velocity and drop size	Simul ation result	Experimental result	Ratio experimental/ simulation results
4.5 m/s and 3 mm	24 V	17.2 V(≈147 nJ; 73 μW)	0.72
3.2 m/s and 1.6 mm	5.7 V	4.68 V (≈16 nJ; 8μW)	0.82

3. RAIN SCENARIO IN BANGLADESH

3.1 Physics of Monsoon in Bangladesh

The time of monsoon in South East Asia is from June to September. Prior to June, the months of May, April and March are summer months during which solar energy pours through the cloudless skies heating the South East Asia land mass which in turn heats air above the land. This hot air expands and rises. The solar energy also heats up the surface of the seas in Arabian Sea and the Bay of Bengal encouraging evaporation that generates considerable water vapor above the warm tropical water sea surface. At this time these months are autumnal months for the Indian Ocean south of the equator. The ocean is cool and the dense air settles over the surface of the ocean. This differential heating generates massive cool aerial current (Carnot Cycle) from the Indian Ocean south of the Equator heading northward to the hot land mass of South East Asia. As it passes over the Arabian Sea and Bay of Bengal, the cool dry air mass picks up tropical warm water vapor becoming moist air. The cool moist air consequently warms and rises, further picking up water vapor. As the moist unsaturated air parcel rises adiabatically, it cools and eventually reaches a relative humidity of 100%. This saturated moist air, under certain pressure and certain conditions, forms into cloud droplets when there are existing nuclei. Clouds now begin to appear. If the vapor will further condense on these cloud droplets increasing their size. This vapor condensation releases latent energy which in turns warms the air pushing it further upwards and allowing even more wet air to come in from the sea. All this heralds the growth of the dark monsoon clouds.

This massive aerial monsoon current conveying condensed cloud drops sweeps northward branching into a number of streams. It appears these streams are attached towards forested areas before making land. During their transverse over the forested areas, the monsoon cloud drops are transformed into raindrops and precipitation begins. One stream moves to Sumatra. Finally another stream moves north along the forested Arakan coast emerging into Assam (Cherapunji with nearly 300 inches annual rainfall) and Bangladesh before turning westwards over the Gangetic basin.)

The monsoon stream is made up of rain squalls. It is during the squalls that the monsoon rain comes down to earth and accounts for the intermittency in the monsoon rains. The squalls length is about 535km and speed 8m/s [18].

3.2 Rain Pattern in Bangladesh

In Bangladesh in June, July, August and September we have the maximum down pour. The interesting part is in the peak season (Jun-Jul-Aug) average rainfall in the Western Ghat of India was only 224cm, contrasted to the peak season average rainfall from the Bay of Bengal branch (Baisakkali) of the monsoon stream (Bengal, Bangladesh and Assam) amounting to 762cms, nearly three and half fold.

Table 4 exhibits the available rainfall at Dhaka. For the purpose of comparison, the available rain power in France is almost 1 Wh per square meter per year**.** If 15 raindrops of 5mm size falls per second on a square meter flat surface in Bangladesh (i.e.900 raindrops per minute), the impact energy equals to 0.18 watts.

PRECIS generated simulation data for the year of 2009 (Fig 6). Annual cycle of projected rainfall in Bangladesh projected (from year 2010-2020) (Fig 7) that the rainfall would be normally what it is in the major monsoon period.

It also shows that for the next ten years in Bangladesh the rain pattern is almost the same. Which is a good sign because we can go for long term plan and research for the technology development of harnessing rain energy in Bangladesh.

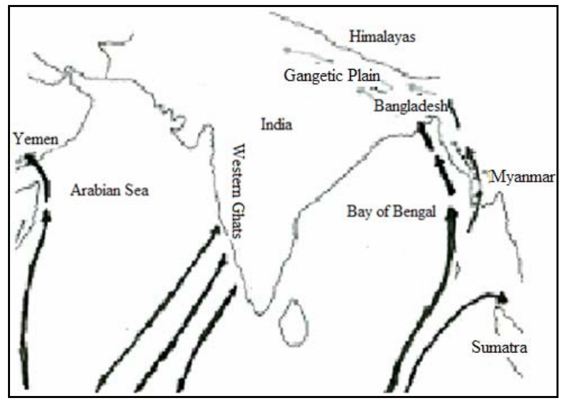

Fig 5. Map of North Asia

Table 4: Bangladesh cities monthly rainfall in mm [19]

	May	Jun	Jul	Aug	Sep	Oct	Total
Dhaka	428	348	553	282	361	368	2340
Sylhet	731	472	775	503	253	344	3078
Rajshahi	144	348	349	354	502	155	1852
Chitta-gong	463	879	491	848	203	201	3085

3.3 Rain Drop Pattern

Raindrop is common occurrence that everyone has experienced. A raindrop occurs when the water vapor from a cloud wraps itself around tiny particles during condensation. Contrary to popular opinion, raindrops are not shaped like teardrops. In fact, they are actually oblate spheroids, or spheres with the nose smashed in [20]. Different sources approximate different ranges for the measure of a diameter of a raindrop. However, on the average, a raindrop is between 0.1 to 5 millimeters. There are some exceptions; rarely, raindrops of 8 millimeters were known to occur [20]. Rain drops size normally larger than the normal doesn't occur because when they come down they break down simply or by colliding with their neighbors. Presently, precipitation is believed to be triggered by a course of action called the collision-coalescence process [20]. The cloud droplets are small in size. So motion of the air keeps them suspended. Larger droplets are faster than the small ones so on the way down they sweep the small droplets and become largr in size. Several important factors affect the diameter or size of a raindrop. First, the fall velocity of a raindrop particle is directly proportional to its diameter [20]. The larger the particle, the faster it falls. The same follows for the maximum fall distance before evaporation or the process in which a liquid turns into a gas. The larger the diameter, the greater the distance it will fall due to gravity, the force that pulls a water droplet toward the earth's surface.

As a droplet falls, it also encounters air resistance or frictional force. The magnitude of this force depends on the size of the drop's "bottom", or the surface area resisting the fall [20].As the particle accelerates the frictional drag increases. Finally the frictional and gravitational forces balance and the droplet fall at a constant speed, which is called terminal velocity. This again depends on size; smaller droplets have a lower terminal velocity than larger droplets.

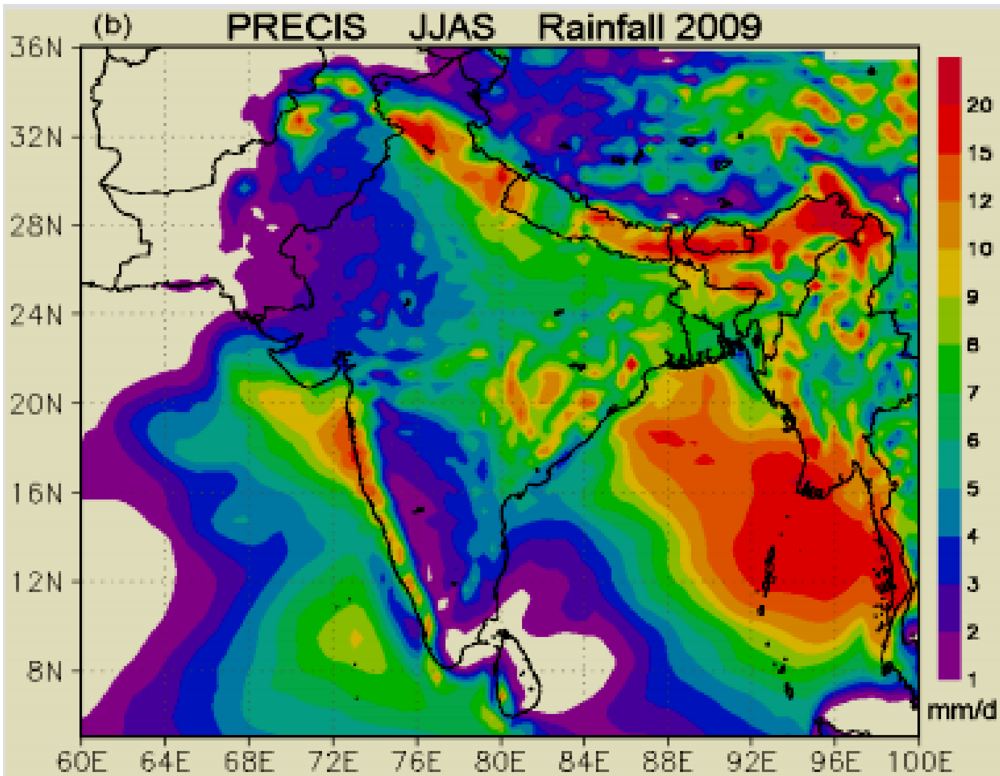

Fig 6. Projection of annual rainfall (mm/d) in the SAARC for the month of JJAS [3]

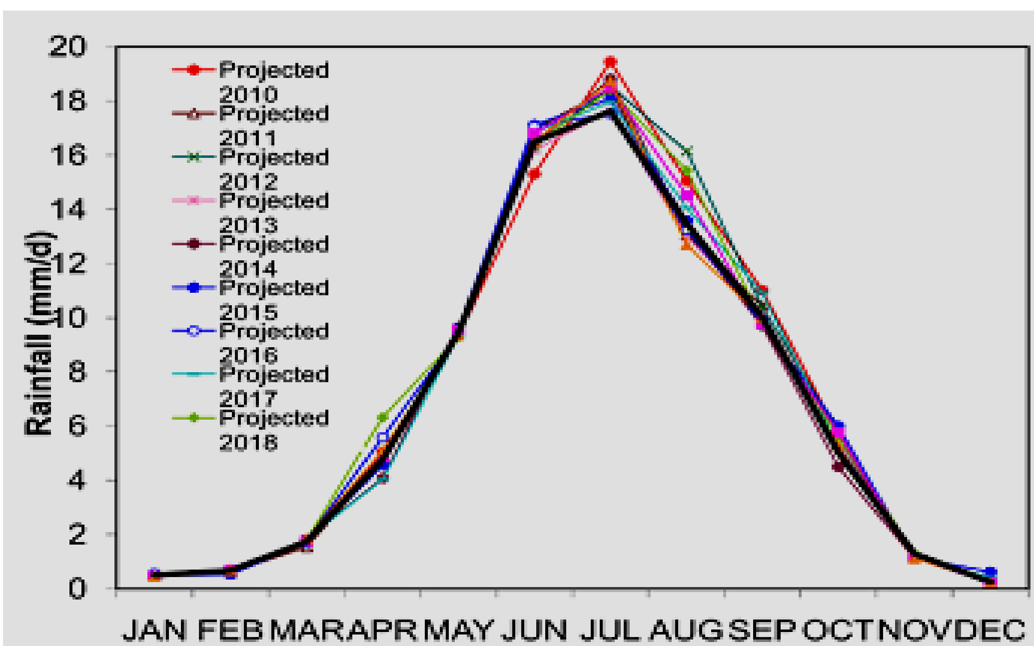

Fig 7. Annual cycle of projected rainfall (mm/d) in Bangladesh [3]

Table 5: Rain drop size assumption [20]

Bibliographic Entry	Result (w/surrounding text)	Standardized Result
"Precipitation." *Earth Science*. Illinois: Heath, 1999	"A raindrop may have a maximum diameter of 0.25 centimeter."	2.5 mm
"Rain." *Encyclopedia Encarta*.1st ed. CD-ROM. New York: Microsoft, 2000.	"Raindrops generally have a diameter greater than 0.5 mm (0.02 in.). They range in size up to about 3 mm (about 0.13 in.) in diameter."	0.5–3 mm
Davis, Neil T. "Raindrop Size Article #236." *Alaska Science Forum*. 28 June 1978.	"The 4 mm maximum diameter of raindrops probably results because raindrops larger than this size tend to break up when colliding with other large raindrops."	< 4 mm
"Characteristics of Particles and Particle Dispersoids." *Handbook of Chemistry and Physics*. 62nd Edition. New York: CRC, 1981.	"Chart"	0.5–10 mm
Formation of Raindrops. Encyclopedia.com.	"Raindrops vary in size from about 0.02 in. (0.5 mm) to as much as 0.33 in. (8 mm) in thunderstorms."	0.5–8 mm

3.4 Measurement Techniques

Because of raindrop size, terminal velocity and quantity is very important here we need to go through some measurement technique.

To determine the terminal velocity of the falling monsoon raindrops (v), we can use a stroboscopic flash lamp, adjusting the frequency to get a stationary image of the falling raindrops. The distance between successive falling drops can allow us to compute the frequency of the raindrops (f). For determining the size of the raindrops, a camera with a electronic flash and close up lens can give a reasonable idea of the size of raindrops. Random distribution of drop sizes can also be gained by rapid collection of rain on a waxed surface or a shallow pan of oil. This size distribution of raindrop should be in conformity with raindrop size distribution law, found in books on meteorology.

4. JUSTIFICATION FOR THE STUDY

In Bangladesh only 47,084 (56%) villages out of the total 84,320 villages have been electrified as of April 2009 [21]. Furthermore, the year wise village electrification has been shown in Table 6.

Table 6: Number of villages electrified in Bangladesh under the project SHS [21]

Fiscal Year	98/99	99/00	00/01	06/07	07/08
No. of Villages electrified	3399	3463	2821	926	926

To provide electricity in areas not reached by electric grid, REB is supporting a renewable energy option by making solar home system (SHS) available to households. A total of 13000 SHS has been installed.

Solar home systems are effective in the sunny months but in efficient during the monsoon months. It behooves investigate other measures to ensure electricity availability during the monsoon months to these home system. One such investigation is to explore the possibility to harness the energy of monsoon rains.

5. CONCLUSION

Energy is the major concern in the coming world. It must be remembered it is impossible to replace the mainstream energy by the use of non conventional energy. Rain drop energy is low grade energy. Due to that reason it would be used in sensors, MEMS those which consume very low amount of energy.

Because it is low grade energy the conversion mechanism should be highly efficient. Recent development in piezoelectric materials has made this energy harnessing more easy. Again the system should be sensitive to both raindrops (1mm diameter) and downpour drops (5mm diameter) because the average size of the drops are in that region.

This potential energy is under development. Some major works are being done in both raindrop energy and such kind of vibration energy. Georgia Institute of technology had made an umbrella with PVDF which is capable of harnessing energy from raindrop and powers its LED light. Researchers of the same university also have made a flexible fiber coated with zinc oxide nanowires that harvest any kind of vibration or motion for electric current.

According to the data in Bangladesh we have around four months of massive rainfall. In Bangladesh this time is very potential for harnessing this kind of energy.

6. REFERENCE

[1] Guigon, R., Chaillout, J. J., Jager, Th. and Despesse, G., 2008a, "Harvesting raindrop energy: theory", Smart Mater. Struct. 17 015038.

[2] Guigon, R., Chaillout, J. J., Jager, Th. and Despesse, G., 2008b, "Harvesting raindrop energy: experimental study", Smart Mater. Struct.17 015039.

[3] Islam, M. N., 2009, "Rainfall and Temperature Scenario for Bangladesh," the Open Atmospheric science Journal, 3, 93-103.

[4] Rein, M., 1993, "Phenomena of liquid drop impact on solid and liquid surfaces", Fluid Dynamics Research, 12(2):61–93.

[5] Rein, M., 2002, *Drop-surface interactions*, Springer, Wien; New York.

[6] Stow, C. D. and Hadfield, M. G., 1981, "An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface", *Proc. R. Soc. of London, S*er. A 373,419.

[7] Mundo, CHR, Sommerfeld, M. and tropea, C., 1995, "Droplet-wall Collisions: Experimental studies of the deformation and break-up processes", Int. J. Multiphase Flow, Vol. 21, No. 2, 151-173.

[8] Thoroddsen, S. T. and Sakakibara, J., 1998, "Evolution of the fingering pattern of an impacting drop," Physics of Fluids, Vol. 10, No. 6, 1359-1374.

[9] Lee, C. S., Joo, J., Han, S., Lee, J. H. and Koh, S. K. 2005, "Poly(vinylidene fluoride) transducers with highly conducting poly (3, 4-ethylene dioxythiophene) electrodes", *Proc. Int. Conf. on Science and Technology of Synthetic Metals,* Vol 152 pp 49–52.

[10] Harrison, J. S. and Unaies, Z., 2001, "Piezoelectric Polymers," NASA/CR-2001-211422 ICASE Report No. 2001-43.

[11] Roundy, S. J., 2003, "Energy scavenging for wireless sensor nodes with a focus on vibration to energy conversion", Ph.D. thesis, University of California, USA.

[12] Starner, T., 1996, "Human-powered wearable computing", IBM Systems Journal, 35(3) 618-629.

[13] Baker, J., Roundy, S. and Wright, P., 2005, "Alternative geometries for increasing power density in vibration energy scavenging for wireless sensor networks", *Proc. 3rd Int. Energy Conversion Engineering Conf. (San Francisco, CA, Aug.),* pp 959–70.

[14] Roundy, S., 2005, "On the effectiveness of vibration-base energy harvesting", J. Intelligent Material Systems and Structures, Vol. 16.

[15] Rabaey, J. M., Ammer, M. J., Silva, J. L., Patel, D. and Roundy S., 2000, "PicoRadio Supports Ad Hoc Ultra-Low Power Wireless Networking", IEEE Computer, Vol. 33, No. 7, pp. 42-48.

[16] Courbon, J., 1980, "R´ esistancedesmat´ eriaux—Th´ eoriedes poutres Techniquesdel'Ing´ enieur" C, 2, 010.

[17] Clanet, C.,Beguin, C., Richard, D. and Quere, D., 2004, "Maximal Deformation of an impacting drop" J.Fluid Mech., 517 199–208.

[18] Rafiuddin, M. and Islam, M. N., 2009, "Water and Flood Management", Proc. 2nd Int. Conference.

[19] Ahmed, F., 1999, "Rainwater harvesting potential in Bangladesh", *Proc. 25th WEC Conference.*

[20] Elert, G, 2001, *The Physics Factbook*, Available from URL: http://hypertextbook.com/facts/2001/IgorVolynets.shtml

[21] Chowdhury, M. N. H., 2009. African Electrification Workshop.

7. NOMENCLATURE

Symbol	Meaning	Unit
H	Thickness	(μm)
L	Length	(cm)
W	Width	(mm)
d_{31}	Strain coefficient	(pC/N)
U_{elec}	Electrical energy	J
k	Coupling coefficient	[-]
Y	Young's modulus	[-]
V	Volume	m^3
S_{aver}	Average voluminal deformation	[-]
D	Drop diameter	mm
v	Velocity	m/s
Re	Reynolds number	[-]
We	Weber number	[-]
Oh	Ohnesorge number	[-]
ξ	Splash deposition value	[-]

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