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DESIGN AND CALIBRATION OF A TRANSFORMER CONTROLLED VARIABLE RAINFALL SIMULATOR

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Abstract

A new approach for the design and construction of a variable rainfall simulator using an auto transformer which is aimed at soil erosion research was explored. The method involves using a water pump, a variable voltage regulator and a set of nozzles for the simulation of rainfall. It was found that the variation of rainfall intensity, kinetic energy and terminal velocities followed established trends such that terminal velocity and drop kinetic energy increased as rainfall intensity increased. A comparison between predicted and observed rainfall intensity for the catchment area over a period of four years showed that 57%, 45%, 61% and 57% of the natural rainfall intensity was achieved over the consecutive years. This method is therefore considered efficient and cost effective for developing countries or locations that have similar rainfall pattern.

Keywords: Variable Rainfall simulator, Variable voltage transformer, Rainfall intensity

1. Introduction

The measurement of many processes such as soil susceptibility to erosion as whether in the form of rills, interills and gullies or the measurement of soil water contamination as a result of various land use practices all depend on rainfall which is very variable in its occurrence. It is therefore important to develop a mechanism for artificially generating rainfall such that time and event controlled simulation can take place. This therefore gave rise to the design and construction of rainfall simulators.

Rainfall simulators are commonly used for outdoor experiments such as measuring soil erosion, soil water infiltration or soil-water contamination caused by pesticides or other agrochemicals as can be seen in [1]. It is also used for modeling the behavior of landscapes under long periods of natural rain [2].

The design of rainfall simulators depend on the type of experiments to be carried out [3], although the main objective is to be able to simulate the natural rainfall characteristics of a given catchment area. They can also be designed for individual experiments but may have limitations of plot size.

Rainfall simulators are broadly classified into drop simulators and pressurized nozzle simulators [4], with the pressurized nozzle simulator being the most common. The popularity of the latter is as a result of the height of about 10m required by the drop simulators before the simulated rainfall can reach terminal velocity. The attainment of terminal velocity being important as rainfall drops which do not reach terminal velocity are often highly erosive and cannot not be used as a replacement for natural rainfall. Furthermore, drop simulators do not produce a distribution of droplets unless a variety of drop forming sized tubes are used [5].

The design and operation of some nozzle type simulators which are mainly used for outdoor experiments have been shown by various researchers [5-9] and for which the variations of rainfall were achieved by the use of rotating boom and a combination of different nozzles. The use of a computer driven cam-oscillating boom which covers an area of 3.56 m^2 was employed by Blanquies et al. [5] at a cost of about seven thousand dollars ($7, 000) which is relatively high and less efficient compared to Paige et al. [6] which used a similar principle. Sawatski [7] designed a variable rainfall simulator for a slope of 2.5H: 1V and an area of 225 m^2 using a combination of seven nozzles for which the variation of rainfall can be achieved by regulating the flow through the different nozzles using different controls. A variation of rainfall ranging from 10 mm/hr to 200 mm/hr was achieved but at high man power and operating cost. Furthermore, Covert et al. [8] in order to study the effects of wildfire on runoff generation and erosion designed a simulator capable of generating an intensity of 73 ± 3 mm per hour. The intensity is varied by the alteration of water pressure and possibly nozzle type. Its major limitation however was plot size as it could only cover a 1 m^2 plot. It has also been shown that rainfall variation can be achieved by the use of a rotating disc and a solenoid controller [9].

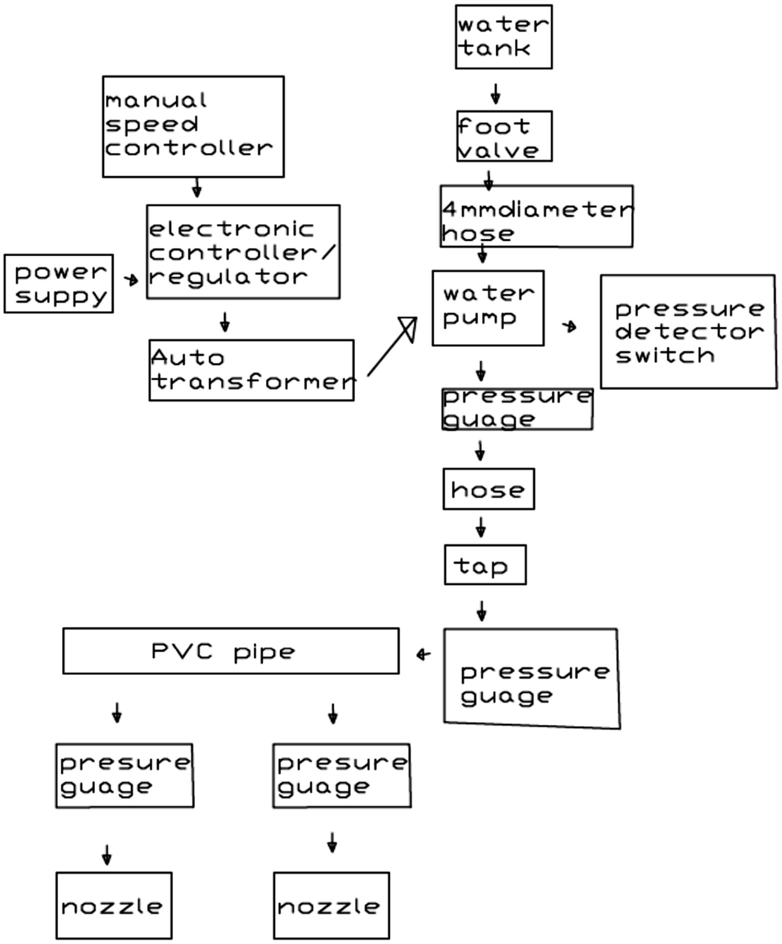

Figure 1 Schematic diagram of the variable rainfall simulator

However, a new approach of rainfall generation which is well suited for developing countries for which the materials and methods for achieving the level of automation in some of the works described above is not readily available is therefore considered in this work. A cost benefit analysis has also shown that the current approach is cheaper when compared to the ones described in [5-7] as it took about six hundred dollars ($600. 00) to produce the current rainfall simulator.

2. Materials and Methods

A combination of the various components discussed below culminated in the variable rainfall simulator whose schematic diagram is shown in Figure 1. The materials used includes two full jet nozzles, a water pump of 0.74KW, a variable voltage transformer with a combination of switching devices (the combination of the water pump and variable voltage transformer resulted in a variable speed motor), hose connections, pressure gauges and an adjustable stand. They are briefly described as follows:

2.1 Water pump

The water pump used is a 220 VAC continuous duty motor of 0.74 KW, 5 Amp input current and frequency of 50 Hz. The maximum discharge capacity is 35 L/min with a maximum head of 34 m.

2.2 Variable voltage transformer:

This is made up of a single wound transformer of 800 turns for which a 220 VAC input power is fed into as can be seen in Fig 2. It is designed in such a way that is gives a varying voltage output in a decreasing order at four discrete units of voltages labeled V_1, V_2, V_3, and V_4. The selections of these different voltages are done through electronic controllers (microcontroller integrated circuit switches) in the electronic parts. The controllers are manually triggered by a combination of variable resistors, 6V DC relays, NPN transistors and light emitting diodes (LEDs) in order to achieve the desired water pressures. The relays are arranged in such a way that after the first relay is switched on, tuning to the next relay will cause the first one to switch off. This process is continued until the last relay is reached.

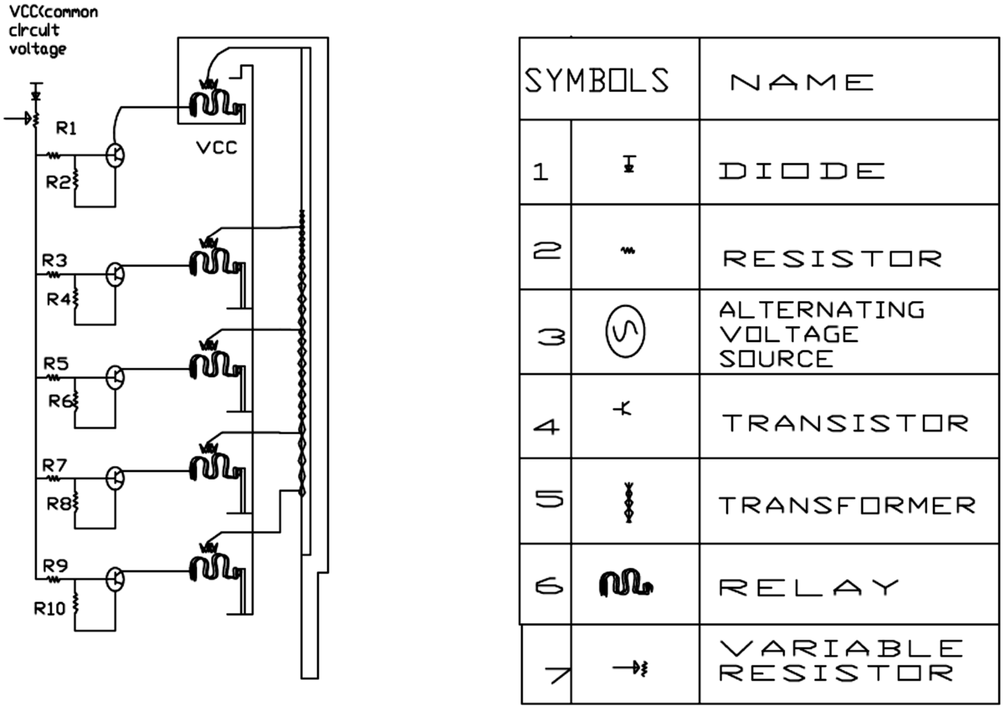

Figure 2 Circuit diagram for variable voltage transformer

2.3 Variable speed motor

The variable speed motor is a combination of the water pump mentioned above and the variable voltage transformer. The variable voltage transformer is fed from the mains and through it; the water pump is powered. By varying the voltage being fed into the water pump at discrete intervals, its pressure output is varied and by implication, the intensity of the simulated rainfall is also varied.

2.4 Hose and PVC connections

A rubber hose of 4 cm diameter supplies water from the sump to the water pump and from the water pump to a tee joint which links a set of PVC pipes. The PVC connections comprises of three pipes of different diameters (5 cm, 4 cm and 2 cm) depending on the pressure requirement and the size of the accessories in use.

2.5 Pressure gauge

Three pressure gauges of 965.3 kPa each were used in the set up. One measured the pressure at which the pump delivers water while the other two measured the pressure at which the nozzle dissipates the water.

2.6 Nozzle

The rainfall simulator makes use of two fulljet nozzles having an orifice of 5 mm diameter and spaced at a distance of 2 m. The nozzle although having an angular spray pattern were made to face each other but separated adequately so as to avoid interference from the sprays and as such no area under the spray was given an increased intensity over others.

2.7 Frame

The frame upon which the nozzles are mounted is a quadruple legged iron frame that has a minimum and maximum height of 2 m and 4 m respectively and can be extended to a horizontal length of 5 m. They possessed adequate thickness so as to avoid sagging at any given period of the experimental run.

3. Experimental Runs

Experimental tests were done at 30 minutes intervals for the various voltages and pressure intervals. This resulted in the determination of rainfall intensities, area of coverage, drop diameters, terminal velocities and kinetic energies of the simulated rainfall. The average rainfall intensity per voltage setting was obtained using a total of five rain gauges placed at different points under the simulated rainfall. The drop kinetic energy was determined using:

$$E_{KD} = 0.5 M_D V_D^2 \quad (1)$$

Where, M_D = density of water (ρ) in kg/m^3 × volume of sphere V ($4/3\pi r^3$). The terminal velocity V_D was calculated from equation (2) which was generated by Van Dijk [9] under the assumptions of air pressure being equal to 1bar, air temperature being equal to 20˚C and rain drop sizes varying from 1-7mm.

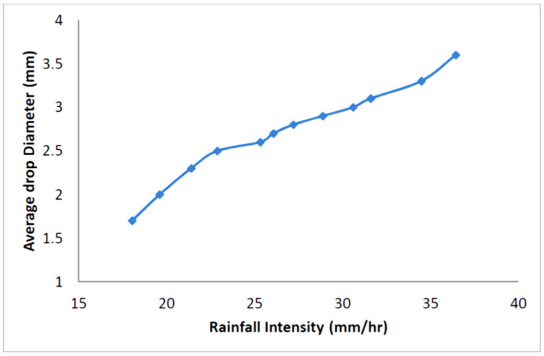

Fig 3: Variation of drop diameter and rainfall intensity

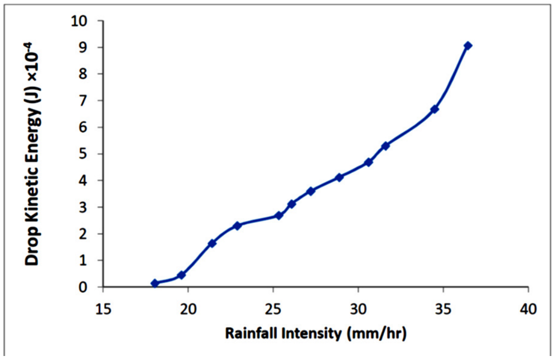

Fig 4: Variation of Drop kinetic energy and Rainfall intensity

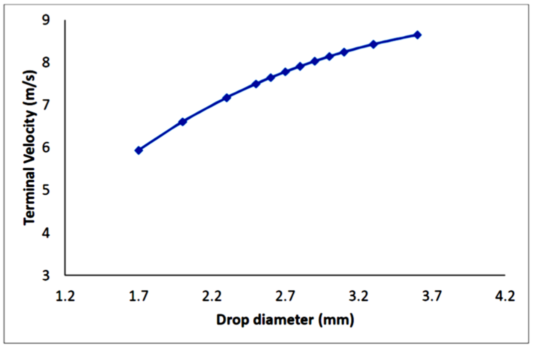

Fig 5: Variation of Terminal velocity with Drop diameter

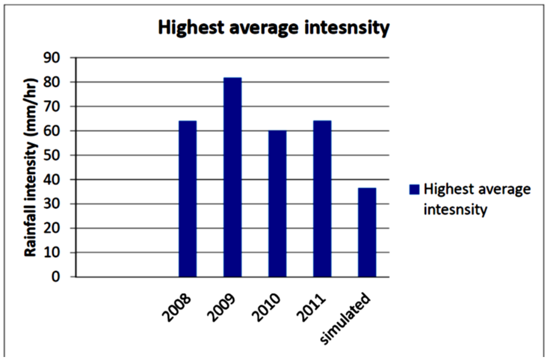

Fig 6: Comparison of observed and predicted rainfall

These conditions applied to the author's environment as shown by Eze [11] and thus the use of the equation. The drop diameters were determined using the oil method.

$V_D = 0.0561D^3 - 0.912D^2 + 5.03D - 0.254$ (2)

where D is the raindrop size in mm

5. Results

The results of the experiments are presented in Figures 3 through 6.

6. Discussion of Results

6.1 Drop diameter and Rainfall intensity

Fig 3 shows the relationship between the average drop diameter which is an equivalent of median drop diameter D_{50} for natural rain and the rainfall intensity. It can be seen that as the drop diameter increased, the rainfall intensity also increased. This is to be expected because larger diameter raindrops implies more quantity of rain over a fixed time and that invariably implies higher intensity as intensity is simply the ratio of rainfall amount to time. The relationship is described by equation (3) with coefficient of correlation $R^2 = 0.978$

$d = -0.00171I^2 + 0.1818I - 0.9178$ (3)

where d is the drop diameter in (mm) and I is the rainfall intensity in (mm/hr). This trend agrees with that shown by other researchers [12-14] at an intensity of 0-80mm/hr.

6.2 Drop Kinetic energy and Rainfall intensity

The variation of the individual drop kinetic energy determined from equation (1) and rainfall intensity is as shown in Fig 4. This relationship which shows that drop kinetic energy increases continuously with rainfall is not strictly applicable in nature as the kinetic energy of natural rainfall reaches a terminal value for any given rainfall after which it remains constant. The trend observed here is therefore attributed to the system's voltage regulation given that the variable voltage regulator gives out a range of discrete voltage units which remain constant and is responsible for the corresponding nozzle output intensity. The trend is however safe within the range of rainfall intensity that the simulator delivers.

6.3 Terminal velocity and Drop diameter

The variation of terminal velocity and drop diameter shown in fig 5 followed established trends such as [10, 15] and is expressed as equation (4) whose R^2 value is 0.9999. The variation implies that terminal velocity increases to a peak after which it remains fairly constant. This is attributed to the fact that although larger drop sizes have larger terminal velocities, the relationship does not continue infinitely but at a certain range of increase in drop size (especially when the drops become unstable in air and tend to break), the corresponding successive increase in terminal velocity is insignificant.

$$V_T = 0.0566d^3 - 0.916d^2 - 5.04d - 0.262 \qquad (4)$$

where V_T = terminal velocity in (m/s) and d = drop diameter in (mm)

6.4 Comparison of Predicted and Observed Rainfall

A comparison of the simulated rainfall intensity and that of the observed rainfall intensity within the catchment is as shown in fig 6. The data for the observed rainfall was gotten from the Centre for Basic Space Science located in Nsukka. It can be seen that 57%, 45%, 61% and 57% of the natural annual rainfall intensity was achieved over the consecutive years. Although this comparison can be improved upon by modifying some of the accessories within the simulator such as the pump capacity and nozzle type, it is worthy of note that it does not hinder the experimental use of the simulator in any way as the duration of the experimental run for instance can be increased if higher intensities are required.

7. Conclusion

The variable rainfall simulator described in this work was able to replicate to a certain degree the desired rainfall intensities of the concerned catchment area. It is simple in design and construction and also cost effective. It can therefore be used to study the various effects of rainfall such as soil erosion within the environment.

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