HOW CUSTOM-BUILT RAIN SIMULATORS COUNTER THE EFFECTS OF FAILED MONSOONS: AN AGRICULTURAL AND HYDROLOGICAL STUDY

Tushar Agarwal [a], Peeyush Khare [b], Sat Ghosh [c, d]

[a,b] Civil Engineering Department, SMBS, VIT University, Vellore, India.
[c] School of Mechanical and Building Sciences, VIT University Vellore, India,
[d] School of Earth and Environment, University of Leeds, Leeds, United Kingdom.
[a] Corresponding author: tushar090490@gmail.com

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Abstract: In this paper, we present new research results on hydrological and agricultural applications of a cost effective Rain Simulator devised by us-the first paper received world wide publicity during EGU 2011 and mainly described its fabrication, operation and uniqueness. A further careful analysis of monsoon records reveals that the years 1972, 1987, 2002 and 2009 had deficit south-west monsoon precipitations in India. This not only slowed down the country's economy, but also saw a spurt of needless farmer suicides, which could have been averted with the use of Rain Simulators. We suggest that with government subsidies, our rain simulators, particularly suitable for cultivating crops such as cotton grown on individual plots, be used every time the nation experiences a deficit monsoon. Costing only USD 300 a piece, our simulators are affordable by an average Indian farmer (based on his purchasing power parity).

This study ensured that the resultant drop size distributions for both the north-east and the south-west monsoons broadly matched recently measured rain droplet spectra. At a constant nozzle pressure (varying between 17 to 35 psi), for different cross-wind speeds (varying between 1.5 ms^{-1} to 4.5 ms^{-1}), there is a critical nozzle angle at which the areal coverage is optimum at 45 square feet. This suggests that with a government subsidy, if five of these portable simulators are used, then an average Indian cotton farmland can be hydrated during lean seasons. These results can inform manufacturers worldwide to design products matching a nation's precipitation profile.

Keywords: Rainfall Simulator, Drop size distribution, Monsoon

INTRODUCTION

The Indian economy, growing at an annual rate of 9 percent in recent years, is one of the fastest growing in the world [6]. Even so, a large proportion of the Indian society is Agrarian with approximately 600 million people dependent on agriculture out of a total of 1.2 billion. The agricultural industry constitutes 16% of the Indian GDP and is dependent on the monsoon rains for sufficient crop production. The monsoon rains typically start from Southern India during the month of June and sweeps over the nation and thereafter spreads over the nation in the following three to four months. Termed the 'South-west' monsoon, this seasonal rain hydrates crops sown during the June-September period. This is followed by the 'North-east' monsoon. It begins in September and continues for the next two to three months. Many parts of southern India receive intense rainfall from the North-east monsoon. Along with the eastern coastal states, Karnataka, Kerala and Lakshadweep on the west coast also receive significant rainfall from the North-east monsoon. Tamil Nadu, in particular, receives nearly half its annual rainfall during this monsoon period. Both these monsoons drive the production of major food and cash crops in India. These crops are sown in two major seasons- Kharif and Rabi. The Kharif season prevails during the south-west monsoon.

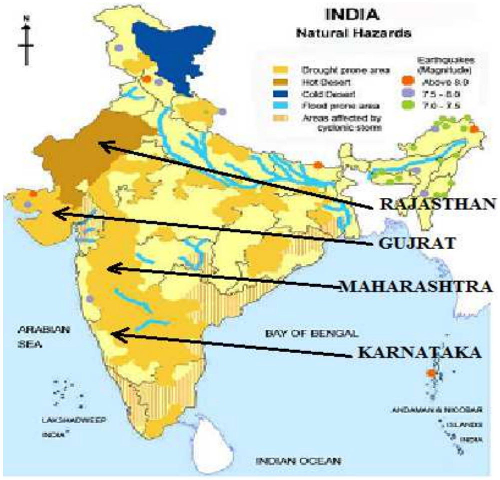

Figure 1: The drought prone regions of India[4]

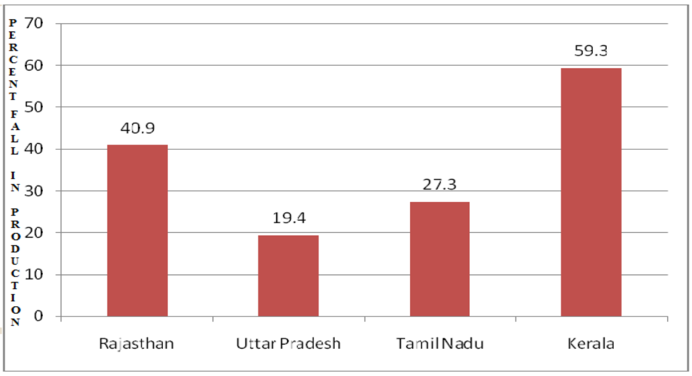

Figure 2: Percentage of fall in the production of Kharif Crops during the year 2002 [4].

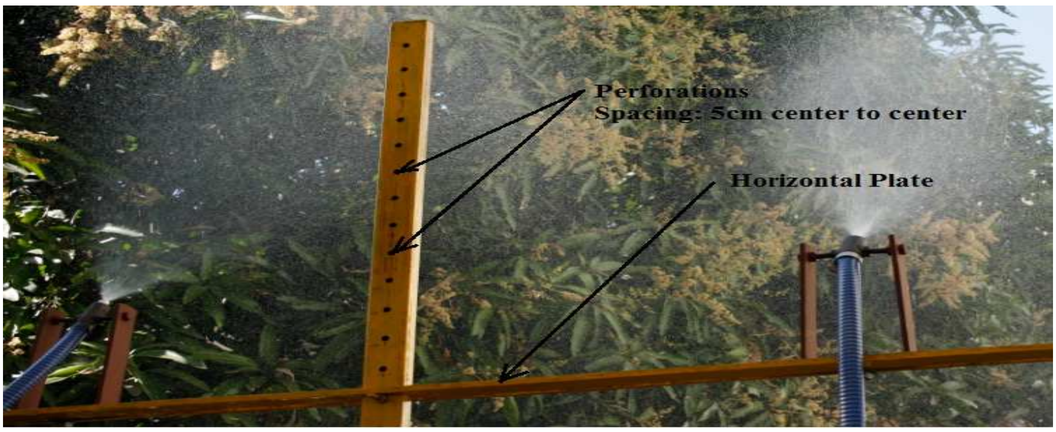

Figure 3: Arrangement of nozzle and horizontal plate resting on a vertical perforated prong.

During this season, agricultural activities take place both in rain-fed and irrigated areas. Most important Kharif crops are paddy and cotton. While paddy is a staple crop, cotton drives the textile industry of the nation. The Rabi season occurs during the winter months (October to December), when agricultural activities take place only in irrigated areas. Rabi crops are generally sown between October to February and are harvested by June. The most important Rabi crop is wheat, which is consumed extensively throughout the country. Most of the crop production in India relies heavily on monsoonal activity and any failure in the monsoons can severely affect the lives of a large number of people.

In the developed economies such as the U.S, access to irrigation and electricity permits the farmers to easily overcome drought conditions. In contrast, in

India, more than 68% of the total landmass is vulnerable to droughts (Fig.1). 33% of it receives rainfall less than 750mm a year. Another 35% is among the drought prone areas with rainfall ranging from 750-1125 millimeters a year [4]. Fig.1 shows that a large proportion of land in peninsular India falls in the category of a drought prone area. Karnataka, Andhra Pradesh, Maharashtra and Gujarat are the most vulnerable states. Rajasthan is an arid state covered by vast expanses of the Thar Desert and receives the lowest level of precipitation in the country.

India had been hit by severe droughts during the years 1877, 1899, 1918,1972, 1987, 2002 and 2009 [4]. The drought of 1987 was recorded as one of the worst droughts of the century with an overall rainfall deficiency of 19%. The rainfall deficiency is defined as the total decrement in rainfall of a region from the average rainfall received by that region. It affected more than 55% of the crop area and approximately 300 million people throughout the country.

However, the country suffered the steepest fall in its food grain production in the year 2002. The total production dropped from 212 million tonnes in 2001 to 183 million tonnes in 2002. More than 18 million hectares of arable area was left unsown during the Kharif season. Fig.2 shows the fall in the Kharif crop production in the major states of India in the year 2002. It is evident from the figure that Kerala suffered the most in the production of Kharif crops as its total yield dipped by a staggering 59.3% [4].

Kerala was followed by Rajasthan where productivity fell by approximately 41% from its average. The agricultural industry of Tamil Nadu (27.3%) and Uttar Pradesh (19.4%) also suffered heavy losses.

Owing to a large population, the aftermath of the drought goes beyond crop failures and rising food prices. In the past century, farmers in India were able to prepare for drought as it occured once in four or five years. But India’s increasingly erratic climate and failing monsoons have now led to a deterioration of the lives of the agricultural community. Between 1995 to 2009, about 241,679 farmers committed suicide [5], with almost 40% due to crop failure. Out of this 40%, the majority were small farmers with less than 3 acres of land in their possession. They earned their livelyhood by sowing cash crops such as cotton for export. It is clear from these discussions that agrarian farmlands require crop specific artificial hydration mechanisms when the monsoons fail. This establishes the fact that livelihood of a large number of people in India is dependent on agricultural production. An infraction in monsoon activity that has the potential to cause crop failure can therefore significantly impact their financial status and jeopardize their growth and development in the society. It can even force them to take extreme steps such as suicides. This mandates that agriculture and all related issues are considered vital for smooth and unhindered progress of the country. Further since agriculture in India is largely dependent on monsoons, the uniformity and characteristics of monsoons become an equal concern in the Indian context.

Therefore, the main thrust of this paper is to elucidate the design, construction and application of an ingenious rain simulator. It is anticipated that this particular design is best suited for small farmlands owned by a single farmer or a commune of farmers. We emphasize strongly that this unique design is not only robust, easy to operate (even by farmers who are not educated) and cheap (the assembly line production cost of this equipment is slated to be under USD300). As the subsequent section will show the generated rain spectrum mimics monsoon showers (the northeast as well as the southwest) reasonably well. We recommend the use of this equipment for applications on crops that are usually cultivated on small farmlands by individual farmers. Secondly, the dropsize distributions match actual dropsize distributions more favorably for droplet sizes beyond 0.8mm. We do not recommend the use of this equipment for greenhouse plants which require fine mists. Again we do not recommend the use of this simulator to hydrate the vast expanses of rice and wheat fields. Most of the individual farmers in India cultivate crops in fields approximately measuring 2 acres or less; thats precisely the domain of application that this unique rainsimulator covers.

So far we have been elaborating upon the use of this equipment during times when the monsoon fails. However, this can be used for other applications as well i.e. crops can be grown in seasons not covered by the two monsoons. They can be grown during any season for any part of the subcontinent that receives an uninterrupted sunshine. Farmers can be provided with this equipment to augment their non-monsoon crop productivity very cheaply. This has an added advantage which we now describe. Crops in India are usually grown with the use of NPK (Nitrogen-Phosphorus- Potassium) fertilizers and pesticides and the preferred mode of cultivation is furrow irrigation. Since farmers do not have a control over the intensity of rain showers, during periods of intense precipitations, furrow irrigation exacerbates the problem of fertilizer leaching which is an environmental hazard leading to the degradation of the quality of the top soil. On the other hand, by adjusting the application rates, the nozzle orientation angles, the volumetric flow rates and the cross wind speeds, a farmer can optimize these simulated showers without encountering any leaching problems.

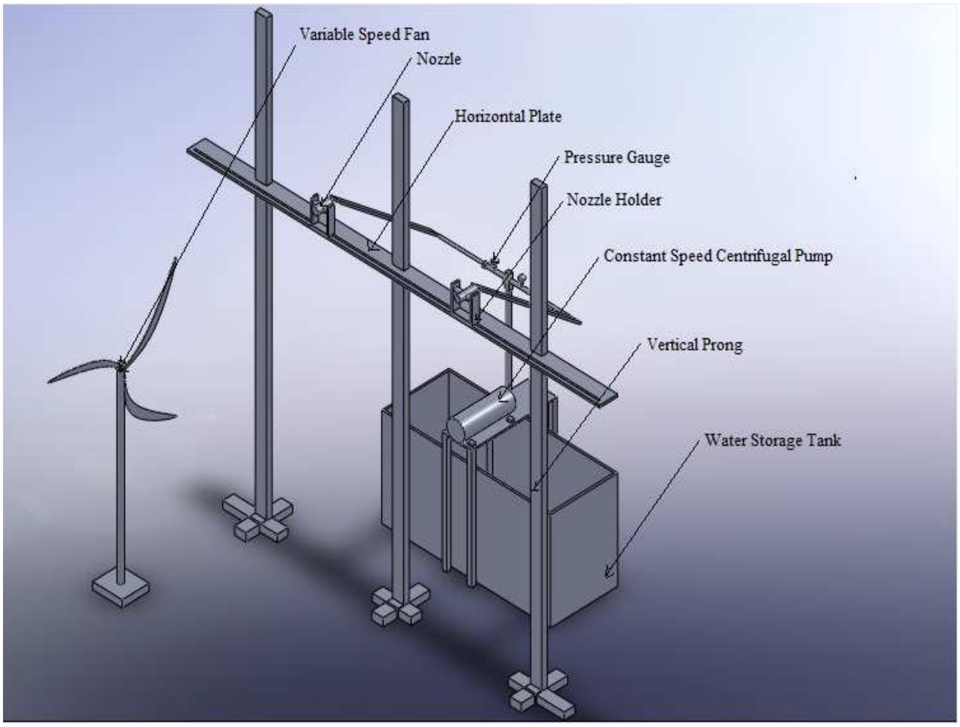

Figure 4: Computer Aided Design of Rain Simulator

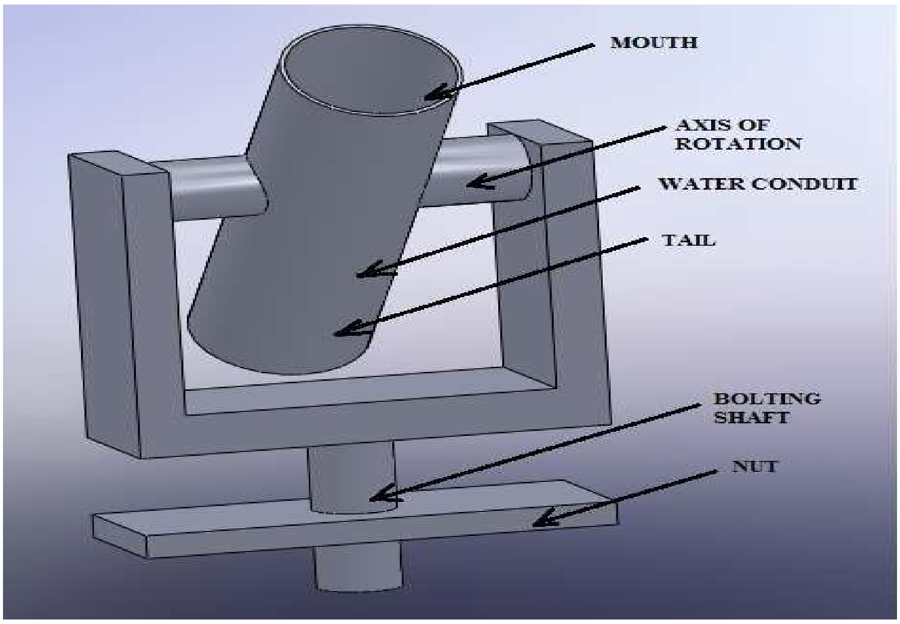

Figure 5: Computer Aided Design of a Nozzle Holder

MATERIALS AND METHODS

The basic concept involved in the construction of this simulator is to design a system which can be a reasonable proxy for monsoon showers. This is essentially a system comprising of a pumping unit and two nozzles. The pumping unit includes a centrifugal pump which is capable of delivering water up to a head of 30 meters discharging at the rate of 1 litre per second. It delivers water to a pipe network which distributes it to two standard full cone nozzles. The nozzles have a spray angle of 30 degrees and can produce droplets of varying diameters ranging from 300 microns to 5 millimetres. The network comprises of a main delivery pipe measuring 1 inch in diameter which further bifurcates to two section-pipes. Each pipe measures ½ inch in diameter and connects to the tail of the nozzle. The section pipes are flexible and thus provide manoeuvrability to nozzles along the length of the horizontal plate. A pressure gauge is attached to each of the two section pipes enabling one to measure pressure at the nozzle.

The nozzles are placed on a horizontal plate (See Fig.2) measuring 3 meters in length with a breadth of 0.075 meters. A 15 millimetres wide slit is cut along the length of the plate to fix the nozzles. It allows the movement of the nozzles along the plate. The horizontal plate rests on a three metres tall three-pronged system. Each prong is perforated with the first perforation starting at 2 metres from the ground level. Holes are provided every 5 centimetres (See fig.4). Thus nozzle height can be adjusted according to the crop specifications. This ensures that the droplets are airborne for a sufficiently long time which increases the areal coverage. The design allows for a minimum nozzle height of 2 metres to a maximum of 2.95 metres from the ground level. The suction pipe from the pump is immersed in a tank measuring 0.8 metre x 0.8 metre x 0.6 metres that supplies water to the system. The flow of water through the simulator is controlled by a 'Gate Valve' which is attached to the main delivery pipe. The pressure at the nozzles is regulated by operating the valve. This helps in attaining rain showers of different intensities and also puts a check on the wastage of water during irrigation. The simulator is designed such that it can be dismantled easily for transportation and can be quickly reassembled on the field.

An important feature of new design is the 'nozzle holder' (See Fig.6.). The nozzle holder is designed to provide a three dimensional manoeuvrability to the nozzle. It is mounted on the horizontal plate with the help of a bolting shaft (See Fig.6). The bolting shaft provides freedom of rotation to the nozzle in the horizontal plane. The components of the holder include a mouth and a tail that are connected to each other by a water conduit. The water conduit is 3 inches in length and is threaded at the mouth to fix the nozzle. The two legs of the holder are 15 centimetres in height and 6 centimetres apart. It provides an axis of rotation to the nozzle in the vertical plane. The holder is made of 3 millimetres thick G.I sheet with screws to fix it on the horizontal plate. The section pipe is attached to the tail of the conduit and is held tightly with a steel clutch. This is done to prevent any leakage of water and to maintain constant pressure at the nozzle. The orientation of released water jet is fixed by axis of rotation of the nozzle. Therefore, the nozzle holder plays a very important role in adjusting the rainfall intensity and areal coverage. Fig.6 shows the picture of a working nozzle fitted on a nozzle holder on the field.

A variable speed fan is used to simulate the cross-wind conditions during natural rainfall. The wind velocity is measured by an anemometer. The experiments are performed for cross-winds of 1.5, 3 and 4.5 ms^{-1} at different combinations of nozzle pressure and orientation. These wind velocities were specifically chosen after a literature research which specifies them as wind velocities in calm, normal and gusty atmospheric conditions respectively during natural rainfall. The rain simulator hence mimics the exact conditions that are found to exist during natural rain showers on the field.

RESULTS AND DISCUSSION

Recreating monsoon showers

The raindrop size distributions recorded by Rao et. al [3] for the south-west and north-east monsoons at Gadanki are compared with the drop size distributions obtained from rainfall simulator. Each Drop size distribution (DSD) data set was fitted with a lognormal distribution function of the form:

$$N(D)=N_T/[(2\pi)^{1/2}(\log \sigma)]\exp[(-\log D/D_m)^2/2(\log \sigma)^2] \quad (1)$$

where: N_T is calculated from the Marshal Palmer Distribution using the measured rain rates from the simulator, D, D_m and σ represents the total number of droplets, droplet diameter, equivalent diameter and the spread of distribution respectively [1, 2]. It is to be noted that the rainfall intensities measured by the collector depends on the cross-winds which are produced by a portable table fan. The wind speed is controlled by a regulator and is measured by an anemometer.

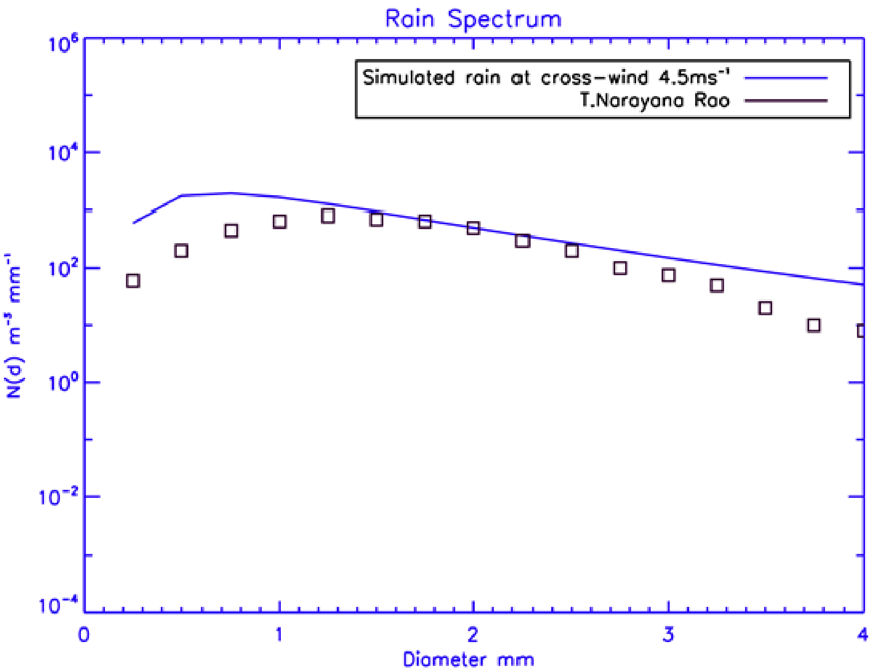

Figure 7: Drop-size distribution of the simulated rain showers compared with natural rainfall recorded at Gadanki

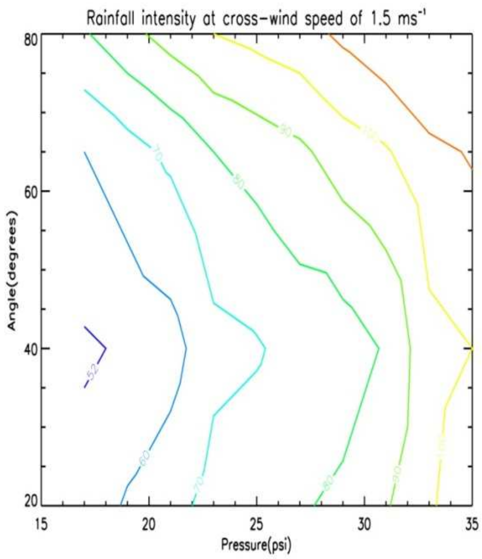

Figure 8: Variation in Rainfall intensity with nozzle angle and nozzle pressure

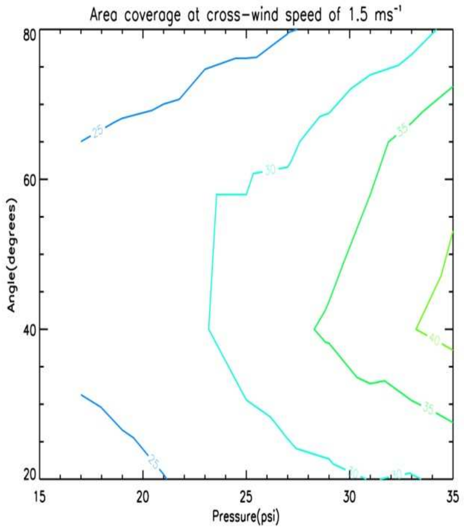

Figure 9: Variation in areal coverage with nozzle angle and nozzle pressure

An increase in the cross-wind velocity reduces the droplet intensity, although it increases the area of dispersion. This can be understood by the effect of wind advection of the droplets, increasing the horizontal component of their fall velocity.Fig.8 shows a comparison between lognormal distributions of natural rainfall and the simulated rain showers. N(d) on the "y-axis" denotes the total number of rain droplets present in one cubic metre of air for one millimetre of rainfall and "x-axis" represents the droplet size. A cross-wind speed of 4.5 ms^{-1} is chosen to simulate wind conditions during natural rainfall. The simulated spectrum closely matches with the recorded spectrum for a droplet diameter ranging from 0.8 mm to 3.2 mm. There are small disagreements in the smallest and the largest sizes. The over-prediction of the large sizes is because of the fact that the extent of coalescence is much larger in the real rain owing to the larger fall distances. The over-prediction for small droplets is because the exit at high nozzle pressure results in drop break up, causing separated droplets which do not happen in an actual rain shower. However, as one can appreciate the agreement is extremely encouraging for most other droplet diameter and in particular for the median droplet diameter. A novel feature of this rain simulator is its tri-directional manoeuvrability, an upwardly pointing nozzle with an optimal liquid discharge rate ensures that the droplets rise up, then attain a transient zero velocity, and finally fall like actual rain showers as if they fell from a real cloud base.

Range of Applicability and Ground Coverage

The rain-showers produced are dependent on nozzle pressure, orientation and cross-wind speed. Nozzles are placed at 20, 40, 65 and 80 degrees and nozzle pressures are maintained between 17 psi to 35 psi. Under these conditions, the simulator created rain-showers ranging from 36mmhr^{-1} to 135mmhr^{-1} for cross-wind speeds of 1.5, 3 and 4.5 m/s.

Fig.9. shows the dependence of rainfall intensity on nozzle angles and nozzle pressures. The readings are obtained for a cross-wind speed of 1.5 m/s. At a fixed pressure, the rainfall intensity falls as nozzle angle is increased from 20 degrees to 40 degrees. However, the trend reverses as the nozzle angle is increase beyond 40 degrees. This is because for a projectile, the maximum range, and hence the effective wetted area by the simulator, occurs at around 40 degrees of the nozzle tilt. Further increasing the angle directly reduces the wetted area concomitantly increasing the intensity of rain. It is also observed that at a critical nozzle angle of 40 degrees, a higher pressure is required to maintain the same rainfall intensity. With a fixed nozzle angle, the rainfall intensity is directly proportional to the nozzle pressure, because of an increase in the discharge over the hydrated area.Fig.10 shows the dependence of the areal coverage on nozzle orientation angles and nozzle pressures at a cross-wind speed of 1.5 m/s. It is observed that with a fixed nozzle pressure, the areal coverage increases to a critical nozzle angle of 40 degrees and thereby with a further increment in nozzle angle orientation; there is a reduction in the areal coverage.

CONCLUSIONS

In this paper we have described the design and operation of a novel rain simulator built by us to be used particularly in monsoon dominated developing nations. It is portable and robust and yet economical, costing under USD300. Owing to its international appeal, the product received attention during the EGU 2011 in Vienna. A patent has been applied for vide patent number (3623/CHE/2011). The uniqueness of the design rests in its tri-directional manoeuvrability, unlike any other rain simulators of its kind in the world. In addition, this is perhaps the first product where a simulated spectrum was compared with a real measured spectrum. The agreement is particularly good over most of the droplet diameters. As far as its hydration efficiency is concerned, we would like to point out a couple of these units will be able to aerate a small farmer's personal cropland. As many as 2 billion people worldwide depend on them for their food and livelihood. Small hold farmers in India produce 41% of the country's food grains, and other food items that contribute to local and national food security. Small farmers cannot be ignored and special attention must be given to the most vulnerable groups [7]. We believe this product will be a boon to such hapless farmers.

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