A simple low-cost water sprinkling nozzle for field crop irrigation

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For low-cost pressurized irrigation system for field crops, researchers and manufacturers are continuously in the quest to develop a simple, low-cost nozzle which requires low operating pressure, and can be manufactured using relatively unsophisticated manufacturing facilities and locally available resources. In view of these, here we present a concept and methodology for developing a simple, low-cost irrigation nozzle using PVC pipe. To corroborate the concept, a nozzle was developed and tested for its performance. Performance indicators showed that the nozzle can be operated satisfactorily over the pressure range 0.4–0.6 kg/cm^2 with application rate of 17–15 mm/h. Due to high application rate, field crops can be irrigated more efficiently compared to nozzles requiring very high operating pressures, ranging from 1.5 to 3.5 kg/cm^2. Low pressure requirement facilitates the use of low rating pipe network, low capacity pump and other accessories and therefore the overall system cost can be reduced substantially.

For pressurized irrigation system, the use of technology has resulted in more specialized and intricate hardware. These sophisticated technologies require high operating pressures and therefore high pressure pumps, high pressure rating pipes and other system components which translate into high initial investment on pumping, pipes, energy, labour and maintenance[1–3]. If modern irrigation technologies are indeed to be adopted by small growers, then it should be of low cost, simple in design and operation, equipped with few manufacturing parts, should be manufactured locally, easy in maintenance and require low energy for operation[4,5]. In addition, it should be divisible and applicable for field crop irrigation at small plots as small holders inherently grow field crops to meet their household food requirement. Several attempts have been made earlier to develop simple irrigation technologies with major emphasis on reducing operating pressure, using low-pressure bearing pipe network, modifying pipe network system, emitters/nozzles, filters, fittings, accessories, etc. to reduce overall system cost[6–9]. Despite many apparent benefits none of them could be popularized among the small holders either due to high mechanization, large farm applicability or other reasons. Here, we present the developmental methodology of a simple and low-cost water sprinkling device for field crop irrigation.

A simple 'T'-shaped device is made using a plastic pipe and holes are drilled on the two arms in opposite direction. The reactions of emitting jets provoke rotary motion if pivoted on a riser using socket and bush arrangement and water is allowed to run through it at a certain pressure. Rotary motion breaks the jets into droplets due to the resistance encountered with the surroundings[10]. If this device is used for irrigating crops, then its external hydraulic properties such as discharge, radial throw, sprinkling uniformity, etc. should be optimized over a range of pressures. At the outset, it seems that the length and diameter of the pipe, number, size and distribution of holes and the operating pressure could have direct a bearing on the overall performance of the device. Therefore, the effect of these parameters on the performance indicators of the device needs to be examined.

In pipe flow, sudden change in pipe diameter causes energy loss and variation in pressure[11]. Therefore, the diameter of the pipe should be equal to the diameter of the riser. However, in commonly used sprinklers[1], the diameter of risers is 25 mm. Therefore, for the device, pipe diameter should be 25 mm. Also, since the jet reaction produces torque, if some holes are not placed at enough distance from the riser, then at low pressure, rotary motion may not be provoked; however, if provoked, then rotational speed may not be sufficient for the desired jet breaking. Hence, the device length should be sufficiently large. Further, as the device is of sizeable length, it cannot pick up very high speeds due high air drag resistance; hence the size of holes should be such that choking is avoided and it produces thin jets, easily breakable under small rational speed. Since the hole size is relatively small, more number of holes is required to tolerate the incoming flow. Otherwise, the device will be pressed upwards and rotation may be stopped. Again, since enough holes are to be placed on the device, these should be distributed along the length to maintain high distribution uniformity.

While in operation, the device behaves as a non-inertial frame; therefore, many pseudo forces govern the paths of jets/droplets. The magnitude of these forces depends on the position of the holes and the trajectory angle which is made by a hole at the axial line of the pipe with respect to the horizontal plane containing the axis. The pseudo forces are the Euler force, centrifugal force, and Coriolis force[12,13]. Mathematically, $F_{\text{Coriolis}} = -2m\Omega \times v$; $F_{\text{centrifugal}} = -m\Omega \times (\Omega \times r)$ and $F_{\text{Euler}} = -m(\mathrm{d}\Omega/\mathrm{d}t) \times r$, where v is the velocity of jet, r the position vector of a jet element or the droplet with respect to the riser or the rotation axis, m the mass of a jet element/droplet and Ω is the angular velocity of the device of magnitude ω (refs 14, 15). In static condition ($\Omega = 0$), all the three forces are absent. The Euler force remains active till Ω is variable. The centrifugal force acts radially outwards and pulls the jets/droplets away from the riser. The Coriolis force is perpendicular to both v and the axis of rotation and is responsible for curling of the jets around the rotation axis[16]. If v is parallel to the rotation axis, then Coriolis force is zero; however, if it is against the direction of local rotation (as it happens in the present case), then it acts inwards to the axis.

Therefore, if all the holes are given 0° trajectory angle, then torque will be maximum, as all the jets are directed horizontally. However, with this angle, Coriolis force is maximum, and therefore, all the jets/droplets tend to reach near the axis of rotation or the riser, which diminishes the water application uniformity as well as throw diameter. Again, if the holes are placed at the trajectory angle of 90°, the Coriolis deflection will be negligible but rotation would cease in the absence of horizontal component of v. Hence, for better performance, trajectory angles should be more than 0° and less than 90°. If few holes are placed at trajectory angle of 45°, i.e. the arithmetic mean of two extremities, then jets emitted from these holes could achieve maximum throw, thus contributing water to the outer periphery of the wetting area. To improve the water application uniformity, the remaining holes should be given low trajectory angles for watering the inner zones of the wetting area. The holes with high trajectory angle should preferably be placed near the riser for throw optimization, as relatively high pressure makes v near the riser high and effective centrifugal force (which pulls the jets/droplets horizontally) is less, making the jets/droplets to achieve maximum throw.

Figure 1 is a schematic representation of the nozzle developed by us. The device with 14 holes (on each side) was found appropriate for 45 cm long and 25 mm diameter pipe for the desired discharge over the operating pressure range 0.4–0.8 kg/cm^2. In view of the droplets size and radial throw, the hole diameter of 1.5 mm was found most appropriate.

Holes were placed in three rows on the pipe. The first row contains six holes, whereas second and third contain four holes each. The first row was to assign the trajectory angle of 45°. The trajectory angle at which maximum throw can be achieved is generally less than 45° due to air resistance encountered by the water jet[17]. Therefore, instead of 45°, low trajectory angles were tried; it was found that the trajectory angle of 37° was most suitable for better performance. To contribute water near the riser, the third row was to assign a trajectory angle slightly more than 0°. However, testing showed that 10° was the suitable value to adjust water near the riser, and finally an angle of 9° was found most appropriate. Further, to contribute water in the middle region of the wetting area, the second row was assigned a trajectory angle of 23°, the mean of the angles of other two rows. Hole-to-hole spacing in first and second rows was kept 1.0 cm, while in the third row it was kept incremental to distribute the holes over the remaining length of the arm. The hole-to-hole spacing in the third row was adjusted in such way that the spacing between second and third holes was twice that of the first and second holes, and so forth. This arrangement was followed to avoid excess ponding near the riser. The paths of the jets/droplets emitted from various holes of different rows are shown in Figure 2.

The nozzle (see Table 1) for design parameters was tested for performance indicators such as discharge, radial throw, water application rate and coefficient of uniformity. These indicators can be determined by single nozzle tests and by block tests in terms of percentage catch can uniformity (CU%)[18–21]. All the tests were conducted in an indoor laboratory established under the National Agriculture Technology Programme at ICAR Research Complex for Eastern Region, Patna, with standard guidelines, tools and methodology[21–24]. In block test, the nozzle-to-nozzle spacing was taken as 6 m × 6 m. In all the testing, riser height was kept 1.0 m. The repeated testing and observations show that the nozzle can be operated satisfactorily over the operating pressure range at 0.4–0.6 kg/cm^2 with throw diameter of 6–8 m, average water application rate of 17–15 mm/h, surface uniformity of 55–65%, and subsurface uniformity more than 90% when operating pressure was 0.5 kg/cm^2 or more. During developmental process of the nozzle, the performance of the device was evaluated for different riser heights.

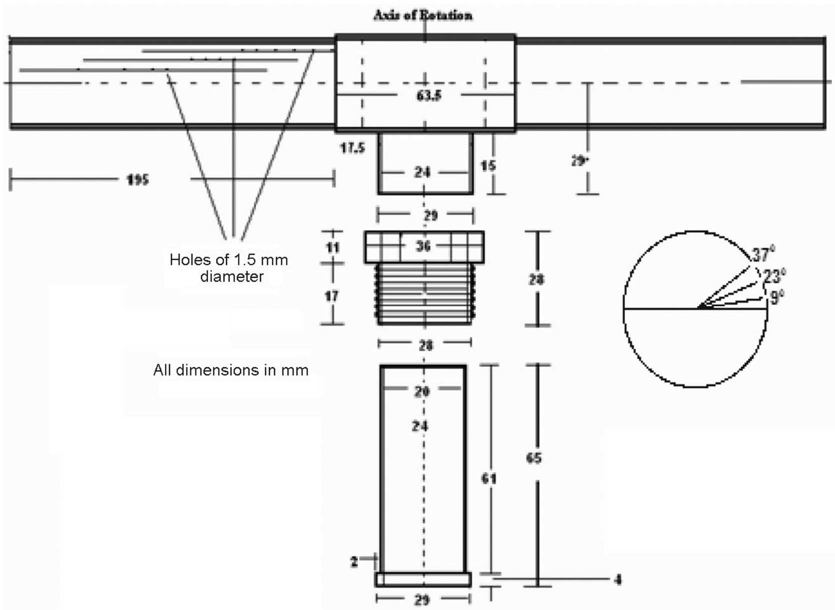

Figure 1. Schematic of water sprinkling device with bush and socket arrangement.

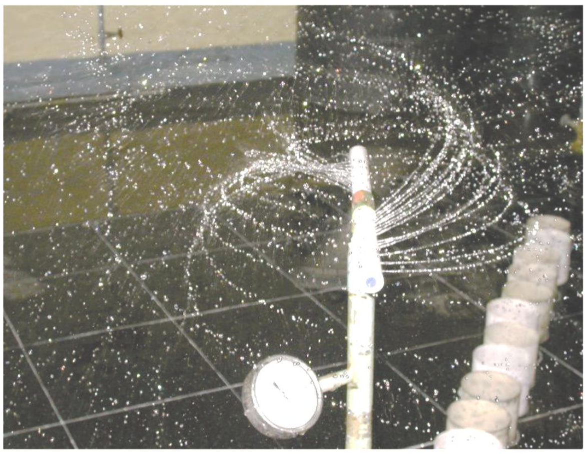

Figure 2. View of trajectory paths of developed nozzle while in operation.

Table 1. Design parameters of nozzle

Length of rotating arm	:	45.0 cm
Number of holes	:	Total 28 holes (14 at each arm of the 'T')
Diameter of holes	:	1.5 mm
Arrangement of holes	:	In three lines or rows with different trajectory angles
Hole-to-hole distance	:	1.0 cm in the first two lines or rows; 1.0 cm between the first and second holes; 2.0 cm between the second and third holes, and 3.0 cm between the third and fourth holes
Row-to-row separation along pipe axis	:	1.0 cm between the first and second lines, and 1.5 cm between the second and third lines
Trajectory angles for three sets of holes	:	37°, 23°, 9°

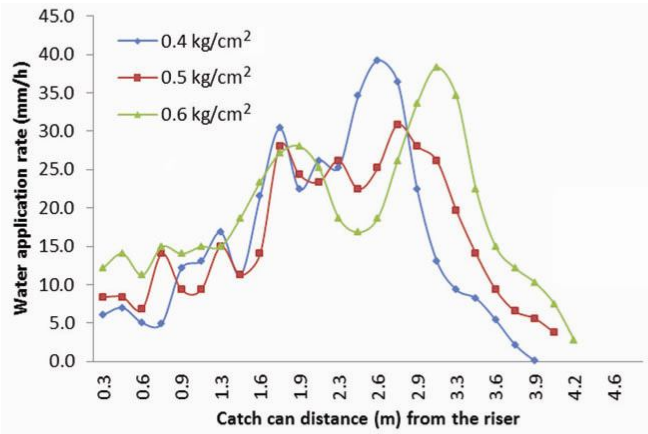

Figure 3. Water application rate of nozzle at different operating pressures.

It was observed that, over the recommended operating pressure range, the wetted area coverage was maximum if the riser height was 1 m. Further increase in riser height resulted in a decrease in the wetted area coverage but increase in CU value due to shrinkage in the wetted area. However, the decrease in wetted area was more prominent than increase in CU value. Again, decrease in riser height resulted in decrease in the wetted area as well as CU value. Since most of the cereal crops hardly attain the height of 1 m before maturity, the optimum riser height of 1 m is preferred.

The radial water application rate of the nozzle, over the operating pressure range 0.4–0.6 kg/cm^2, is shown in Figure 3. Though the surface uniformity of the nozzle is not high, the high discharge rate makes the subsurface uniformity much higher. Therefore, successful irrigation of the field crops would be performed by this nozzle. In view of external hydraulic performance, the developed nozzle is well applicable for irrigating field crops such as rice, wheat, oilseeds, etc. as application rate of the nozzle is quite high compared to impact sprinklers; it is always desirable to keep application rate of the nozzle more than the soil infiltration rate. High application rate for short duration quickly exceeds the infiltration rate of the soil; therefore, some amount of water is stored on the soil surface to saturate the soil quickly without any substantial loss of water through deep percolation or infiltration[7]. Storing of some amount of water on the soil surface for short duration allows the water to redistribute across the soil surface, facilitating better soil water movement beneath the surface, thereby making the subsurface uniformity comparatively high compared to that of catch can value.

The rotation rate or the angular speed, ω, of the nozzle has a direct bearing on droplets size[25]. At high speed of rotation smaller droplets are formed, which further improves the application uniformity. If operating pressure is fixed, it is interesting to explore the design parameter(s) which can have maximum effect on ω. In a rotary nozzle, water entering the device has no moment of momentum as no external torque is supplied to it; therefore, the moment of momentum leaving the nozzle must correspond to the frictional torque experienced by the nozzle[26]. Therefore, frictional torque (Γ) of device can be expressed as

$$\Gamma = 2\rho \sum_t \left\{ \sum_k q_{t,k} r_{t,k} \times \left(\frac{q_{t,k}}{A} \cos\alpha_t - r_{t,k}^2 \omega \right) \right\}, \quad (1)$$

where ρ is the density of water, $q_{t,k}$ the discharge from kth hole on tth line, A the cross-section area of a hole, $r_{t,k}$ the position of mth hole on tth line from the riser, and α_t is the trajectory angle of tth line.

If the device is held stationary, i.e. $\omega = 0$, eq. (1) yields

$$\Gamma = 2\rho \sum_t \left\{ \sum_k q_{t,k} r_{t,k} \left(\frac{q_{t,k}}{A} \cos\alpha_t \right) \right\}. \quad (2)$$

This is the torque required to hold the nozzle stationary while water is being discharged through it. This shows that, maximum torque is produced when the nozzle is stationary. However, for a free-running condition, i.e. if the arrangement is free from friction ($\Gamma = 0$), and the socket and bush arrangement is frictionless, the device achieves maximum value of ω. Further, if all the holes are of same discharge and $\Gamma = 0$, then eq. (1) transforms as eq. (3)

$$\omega = \left[\frac{q}{A} \left[\left\{ \sum_{i=1}^{i=6} r_{1i} \cos\alpha_1 \right\} + \left\{ \sum_{j=1}^{j=4} r_{2j} \cos\alpha_2 \right\} + \left\{ \sum_{k=1}^{k=4} r_{3k} \cos\alpha_3 \right\} \right] \right] \Bigg/ \left[\left\{ \sum_{i=1}^{i=6} r_{1i}^2 \right\} + \left\{ \sum_{j=1}^{j=4} r_{2j}^2 \right\} + \left\{ \sum_{k=1}^{k=4} r_{3k}^2 \right\} \right]. \quad (3)$$

This expression shows that ω is a function of the discharge from a hole, cross-section

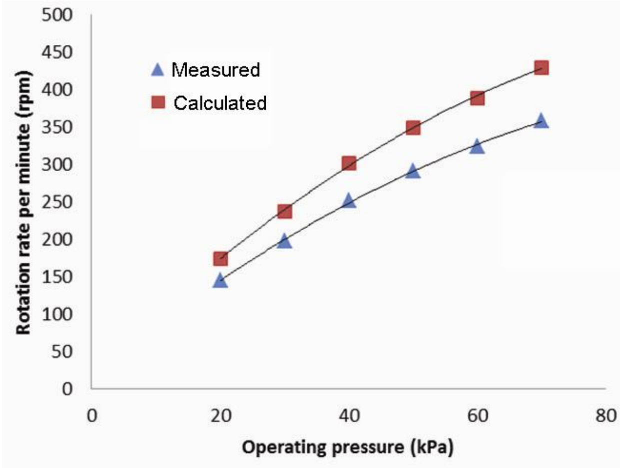

Figure 4. Rotational rate of nozzle at different operating pressures.

area of a hole, the positions of the holes from the riser, the number of holes and the trajectory angles of the holes. If in eq. (3), λ is substituted for the remaining factors, then we get $\omega = \lambda(q/A)$. This shows that once λ is fixed, ω varies with discharge flux (q/A), i.e. the speed of the jets. Therefore, if operating pressure is fixed, then ω can be varied by altering the cross-section area of the holes.

The measured and calculated rotations per minute (rpm) of the nozzle were plotted over the operating pressure range 0.4–0.6 kg/cm^2 (Figure 4) to authenticate eq. (3). The plot shows that the variation trends of both the curves are congruent with the exception that, at each of the pressures, the measured rpm is always less than the calculated rpm. This fact could be attributed to the assumption of frictionless arrangement, which does not hold truly, but reasonable.

Thus, in view of the growing scarcity and rising cost of irrigation water, the water productivity is to be increased substantially to fulfil the irrigation needs, particularly in field crops irrigation. The production cost of the nozzle developed in this study with its rotating mechanism was estimated to be approximately Rs 125 each against conventional single-nozzle impact sprinkler, which costs about Rs 400–450 each. Low operating pressure requirement facilitates the use of low-cost, flexible, flat hose pipes, other system components and accessories, therefore making the system divisible for small plot irrigation. It is estimated that an irrigation system developed with this nozzle and low-cost, flexible hose pipe may cost 30–40% less than the hand move impact sprinkler, and thus is affordable to medium to smallholders.

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