Parametric study on flow dispersion of water sprinkle

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Abstract. Although water sprinkler is used extensively in agriculture, little effort had been made to improve its performance, resulting in many sprinkler head available at market having less optimum design. Thus, this study aims to improve the basic design of water sprinkler head by conducting a parametric study on the effect of model geometry due to different flow characteristics. A common type of water sprinkler is modelled with computer aided design software and various changes such as enlarging nozzle diameter from 4mm to 8mm, changing vane angle from 70 degrees to 45 degrees are made to the original model. The models were simulated with computational fluid dynamics (CFD) software to investigate how the variation in geometry affects the flow of water and the performance of sprinkler head. The performance of water sprinkler is compared to original model in terms of watering distance, area of spray and velocity of water jet in air. The result of this study shows that enlarge the nozzle diameter have a positive effect on the velocity of water jet in air and the area covered by water jet but it drastically decreases the watering distance of sprinkler. Besides that, changing the angle of vane from 70 degrees to 45 degrees decrease the watering distance slightly and it concentrates the water into a fine jet that cover a small area. To reduce the effect, grooves can be added to the vane to increase the divergence of water spray. Reducing the angle of curvature from 10 degrees to 5 degrees improves the watering distance. The angle of curvature can be reduced more to increase the watering distance further.

1. Introduction
Water sprinkler is a device to distribute water to a large area automatically. Irrigation technology involving water sprinkler had been developed since late 1800s and later modified for orchards, commercial green houses and high-profit vegetable crops [1]. Nowadays, it is mostly used in agriculture field to irrigate crops or fire safety field to extinguish fire [2].

Water sprinkler came in many shape and sizes, but it can be classified into the following two major types on the basis of the method of water distribution, which is rotating sprinkler system and drip irrigation system. In rotating sprinkler system, nozzles are placed on riser pipe at uniform intervals. The riser pipe is connected to lateral pipe, and the lateral pipe to a water source. When water flow through rotating sprinkler, part of the flow energy is converted into rotating kinetic energy to change the direction of flow. Examples of rotating sprinkler are impact sprinkler, which rotate the sprinkler with a small impact hammer; and rotating vane sprinkler [3]. The advantage of rotating sprinkler is it the lower initial installation cost [4]. However, rotating sprinkler consume more power and is less water efficient compared to perforated pipe system [5].

The second type of water sprinkler is drip irrigation. This method consists of drilled holes that act as nozzles along pipe length through which water is sprayed. The advantage of perforated water sprinkler
is it requires less pumping power since the pipes are laid near to the crops’ root. Furthermore, this irrigation system can maximise water efficiency by reducing water loss by vaporisation [5].

There are many ways to improves the performance of water sprinkler system, such as upgrade the flow rate and pressure of water supply [6]. The use of drip irrigation with center pivot and lateral move sprinkler system is another method to save cost in water usage [7]. However, little study had investigated the possibility of using a sprinkler head that has better performance to reduce cost on installation. Thus, many type of water sprinkler commonly found on market did not have the optimum design to improve water usage and its performance in terms of distance and coverage area.

Although there are many innovations made to rotating water sprinkler, such as an adjustment ring and throttling element to adjust the distance and coverage area in one recent patent [8], the basic design of water sprinkler head had remain the same for many years [9]. Its basic component includes a deflector (or vane), a nozzle and a housing (or holder). Therefore, current study aims to improve the performance of water sprinkler by carrying out a parametric study with the basic component of a common type of rotating water sprinkler. This study employed the technique of computational fluid dynamics to simulate the flow characteristics of water sprinklers to compare the effect of various changes made to the basic design of water sprinkler.

To simulate the flow of water jet from nozzle and its dispersion from deflector, a similar model of water sprinkler head [10] is used as the reference. The boundary condition and fluid domain definition is mainly based on the previous model.

2. Methodology

2.1. Geometry of water sprinkler

A common type of water sprinkler available at the market was “825”. It has the basic design of a rotating water sprinkler with a vane, a nozzle and a holder. The water sprinkler is shown in figure 1. Its size is about 80mm width, 30mm length and 100mm height.

![Figure 1. Original model of rotating water sprinkler.](image)

Three dimensional models of water sprinkler (the original model and the modified models) were developed by using computer aided design software (CAD) SOLIDWORKS (Dassault Systemes Ltd). The comparison between original model and modified models are shown in table 1. The models were exported into ANSYS Workbench (ANSYS Ltd) in STEP file format to be simulated with computational fluid dynamics CFX software.
| Model name | Modification |
|------------|--------------|
| a          | Original geometry. Control model. |
| b          | Enlarge the nozzle diameter from 4mm to 8mm. |
| c          | Change the angle of vane from 70° to 45°. |
| d          | Change the vane’s angle of curvature from 10° to 5°. |
2.2. Governing equations
The governing equations of the models are continuity equation and momentum equation. The energy equations are not included since the temperature factor is not investigated in this study.

Continuity equation (differential form):
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]  
(1)

Where \( \rho \) is the fluid density, \( t \) is time, \( \nabla \) is the vector differential operator, and \( \mathbf{u} \) is the velocity of fluid.

Momentum equation:
\[
\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla \cdot \mathbf{p} + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g}
\]  
(2)

Where \( \rho \) is the fluid density, \( \mathbf{u} \) is the flow velocity, \( \nabla \) is the del operator, \( \mathbf{p} \) is the pressure, \( \mathbf{I} \) is the identity matrix, \( \boldsymbol{\tau} \) is the deviatoric stress tensor, which has order two, and \( \mathbf{g} \) represents body accelerations acting on the continuum, for example gravity, inertial accelerations, electrostatic accelerations, and so on.

2.3. Boundary condition
A square enclosure of 2m each side was chosen as the fluid domain. For fluid model, homogeneous model was switched on. Standard free surface model was selected to simulate the free flow of water spray in air without any solid obstacle. Since water sprinkler is fully turbulent, k-epsilon turbulence model was used to reduce the simulation time required. The reference density for the buoyancy model is set as density of air, \( 1.2 \text{kg m}^{-3} \). In fluid pair model, the surface tension coefficient of water-air interphase is set as \( 0.072 \text{N m}^{-1} \). The interphase transfer type of free surface was chosen.

The sprinkler head solid surface is defined as standard no slip wall. Since the vane is smooth steel sheet, smooth wall roughness was selected. Hence, the vane can act like a solid surface that redirect the water jet.

A circular area where water should flow in was defined as the inlet. The inlet is a circle with diameter of 26mm. The boundary of the enclosure was defined with opening pressure with zero relative pressure to simulate the open air condition that water jet flow. The direction of flow is normal to the surface.

The fluid volume fraction of air at the boundary of enclosure is one while the volume fraction of water is zero because the fluid at enclosure surface is air. The inlet location is shown in figure 2.

![Inlet location of water sprinkler model](image)

**Figure 2.** Inlet location of water sprinkler model (highlighted in green).
2.4. Grid independence test
To eliminate the effect of grid size on the simulation result, grid independence test was carried out. The model is mesh with an initial mesh of medium size. The simulation is run with increasing number of refinement. The result is shown in table 2 and plotted in figure 3. From figure 3, the maximum velocity at the nozzle increase slightly from one refinement onward. Thus, one refinement on the model is sufficient to produce accurate result.

Table 2. Maximum velocity, number of nodes and maximum velocity of test model 1 through 4

| Test model | number of nodes | refinement | maximum velocity |
|------------|----------------|------------|------------------|
| 1          | 99117          | 0          | 12.9936          |
| 2          | 150046         | 1          | 13.102           |
| 3          | 240532         | 2          | 13.1014          |
| 4          | 462635         | 3          | 13.1035          |

Figure 3. Maximum velocity against number of nodes.

3. Result and discussion

3.1. Experimental data
An experiment is carried out to validate the accuracy of simulated data. The water sprinkler is connected to pipe with same mass flowrate and the valve is opened. Distance of water sprayed is measured.

Table 3. Experiment data (continued)

| Experiment | Distance |
|------------|----------|
| 1          | 2.09     |
| 2          | 2.17     |
| 3          | 2.15     |
| 4          | 2.03     |
| 5          | 2.06     |
| Average    | 2.11     |
The average value of water jet distance in experiment is 2.11m. Compared to the simulated result of model (a), which is 1.983m, the experimental result is higher than expected.

\[
error(\%) = \frac{2.11 - 1.983}{2.11} \times 100\% = 6.02\%
\]

However, the error is small (about 5%). Thus, the model can be considered to be accurate for the purpose of simulation experiment.

3.2. Velocity distribution
High velocity in water spray for agriculture use is not desirable. The water spray may damage plant leaves and erode soil, reducing crop yield. The velocity of water jet in air from simulation is shown in figure 4 as streamline, contour in figure 5, and tabulated in table 4.

**Figure 4.** Streamline of water flow from sprinkler head with velocity of water along the streamline. (a) Original model, (b) Enlarged nozzle, (c) 45-degree vane angle, (d) 5-degree vane curvature.
Figure 5. Contour of water velocity at the bottom of enclosure. The sprinkler head is located at top left corner. (a) Original model, (b) Enlarged nozzle, (c) 45-degree vane angle, (d) 5-degree vane curvature.

Table 4. Velocity of water jet in air

| model | velocity of water jet (m/s) | percentage difference (%) | Rating |
|-------|-----------------------------|---------------------------|--------|
| a     | 0.35913                     | 0                         | 0      |
| b     | 0.29905                     | -16.73                    | 2      |
| c     | 0.41162                     | 14.61                     | 1      |
| d     | 0.33658                     | -6.28                     | 0      |

Model (a) and model (d) has similar water velocity while travelling in air. This shows that decreasing angle of curvature does not seem to have a large impact on water velocity in air. However, model (c) shows a significant decrease in velocity. Decreasing vane projectile angle does seem to make water lose
more momentum when it collides with vane to be redirected. In short, model (b) has the best performance in terms of water velocity in air.

3.3. Watering distance
Distance of the water spray can be measured from the simulation result. Distance of water spray is the most important performance factor for water sprinkler as larger distance means lesser number of sprinkler need to be used for a same area. The result is shown in table 5.

| Table 5. Distance of water jet |
|-----------------------------|
| model | Distance (m) | difference (%) | Rating |
|------|--------------|----------------|--------|
| a    | 1.983        | 0              | 0      |
| b    | 0.5          | -74.79         | -2     |
| c    | 1.573        | -20.676        | -1     |
| d    | 2.117        | 6.757          | 1      |

Increasing diameter of nozzle decrease the distance of water spray enormously (-75%). Water velocity after the jet exit the nozzle in model (b) is too low to achieve a satisfactory range of water spray. Thus, the increase in nozzle diameter should be reduced to raise the distance of water spray to an appropriate value.

Decreasing the angle of projectile from 70 degrees to 45 degrees shows a decrease in the distance of water spray. This may be due to the angle of departure of water jet from vane is too low and it shorten the range of water jet distance. Although the angle of vane is 45 degrees, when water jet hit the vane, it is deflected to about 40 degrees. Thus, the angle of vane should be adjusted to 50 degrees to ensure that water jet have a projectile angle of 45 degrees.

Decreasing the curvature of vane increase the distance by 6.7%. When the vane has a lower curvature, a larger portion of initial kinetic energy is converted into linear kinetic energy instead of rotational kinetic energy at vane due to the lower curvature. Thus, water can travel further albeit the sprinkler spin slower. The curvature angle of vane can be reduced further to increase the watering distance more.

In conclusion, changing the curvature angle of vane from 10 to 5 degrees increase the distance of water spray slightly. However, increased diameter and 45 degrees’ vane angle decrease the distance of water spray.

3.4. Watering area
The watering area is a measure of how dispersed is the water jet. In general, the larger the watering area, the smaller the water droplet. Besides that, a larger watering area can provide better coverage of crops.

| Table 6. Angle of water stream |
|-------------------------------|
| model | Area (m^2) | percentage difference (%) | rating |
|------|------------|---------------------------|--------|
| a    | 9.348E-4   | 0                         | 0      |
| b    | 2.256E-3   | 141.34                    | 2      |
| c    | 1.442E-5   | -98.46                    | -2     |
| d    | 2.433E-4   | -73.97                    | -2     |
Increased diameter of nozzle results in much larger cross sectional area of water jet. When the larger water jet is defected by vane, it splits into a large water spray covering a huge area. However, decrease vane projectile angle concentrates the water stream into a smaller diameter water jet that cover a small area only. On the other hand, decrease angle of curvature of vane did not diverge water jet as much as the original model.

In short, increased diameter can cover the largest area with a single water jet. Other variation does not do as well as the original model in diverging water jet.

3.5. Performance evaluation

The rating of original model as well as other variation is shown in the evaluation matrix below.

| Performance criteria | Weightage | Model a | Model b | Model c | Model d |
|----------------------|-----------|---------|---------|---------|---------|
| Distance             | 0.6       | 0       | -2      | -1      | 1       |
| Velocity in air      | 0.2       | 0       | 2       | 1       | 0       |
| Area                 | 0.2       | 0       | 2       | -2      | -2      |
| Total rating         | 1         | 0       | -0.4    | -0.8    | 0.2     |

The table above shows that model (b) and model (c) did not perform better than the original model, mainly because they perform worse in distance of water jet travelled.

Changing the angle of vane curvature from 70 degrees to 45 degrees and double the nozzle diameter had change the parameter too much such that it does not perform well. A smaller change in vane angle and nozzle diameter should

Modifying the angle of vane from 70 degrees to 45 degrees increase the velocity of water jet in air, making the spray less gentle and reduce area covered. Thus, grooves can be added to the vane to split up the water into a more diverged jet.

Increasing the nozzle diameter produce a beneficial result on the area covered by water spray and lower velocity of water jet in air, at the cost of greatly reducing the distance of watering. Hence, a slight increase in diameter of nozzle such as 4mm to 4.5mm is recommended as a compromise value between the three performance criteria.

Lowering the curvature of sprinkler can increase the watering distance. Hence, the curvature angle of vane can be reduced further to increase the watering distance more.

4. Conclusion and recommendation

In conclusion, the original model of water sprinkler and 3 variation of the original model is simulated. The result from simulation showed that:

a) Enlarge the nozzle diameter have a positive effect on the velocity of water jet in air and the area covered by water jet but it drastically decreases the watering distance of sprinkler.

b) Changing the angle of vane from 70 degrees to 45 degrees can decrease the watering distance slightly and it concentrates the water into a fine jet that cover a small area. To reduce the effect, grooves can be added to the vane to increase the divergence of water spray and the vane angle should be adjusted to 50 degrees.

c) Reducing the angle of curvature from 10 degrees to 5 degrees improves the watering distance. The angle of curvature can be reduced more to increase the watering distance further.
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