The Irrigation Uniformity Analysis Based on Translation Variable-Rate Sprinkler

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Abstract. Research and compare various modeling of three-dimensional model, the paper chooses CATIA software to model the translation irrigation machine, and analyzes its working principle, structure, mode of operation and obtains to various parts of the structure size parameters, organize and remove redundant parameters, to facilitate the establishment of the model. We proposed here two indexes which were spray shape and water distribution uniformity to evaluate hydraulic performance of variable-rate sprinkler. And analyzed the influence of the throw radius caused by working pressure, nozzle area and trajectory angle. By calculating instantaneous application rate, it is indicated that the irrigation uniformity will go bad when change single factor to accomplish variable-rate irrigation.

1. Introduction

Variable irrigation is the key technology in the precision irrigation, and variable-rate sprinkler is one of the ways to accomplish variable irrigation. There has been lots of researches variable-rate sprinklers both from home and abroad, but according to the existing products, the common variable-rate sprinklers have the disadvantage of complicated structure, unreliable performance and so on. The design of the existing variable-rate sprinkler is to add a variable-rate device to the strike sprinkler. The variable-rate device adjusts the structural parameter to accomplish the variable-rate spray [1]. The undesirable irrigation uniformity was a common problem for those variable-rate sprinklers. In order to improve the irrigation uniformity of the variable-rate sprinkler, a new kind of variable-rate sprinkler with a pressure and flow rate adjusting device and a nozzle-changeable device was put forward in this dissertation. The pressure and flow rate adjusting device was utilized to adjust the working pressure of the sprinkler and the nozzle-changeable device was used to change the discharge area. By regulation the two factors synchronized, the water distribution uniformity of the variable-rate sprinkler will be improved. Meanwhile, this dissertation also studied the water distribution of the variable-rate sprinkler applied in slope land with small angle. The results showed that this kind of sprinkler can dove the water distribution problem caused by the factor of the terrain.

Our freshwater resources are currently available not only effective, but utilization is also low, polluted and warming caused by the greenhouse effect, resulting in below normal rainfall combination of factors, seriously hamper the development of China's economy, the largest of which agricultural water used, conservation and control are very essential therefore can be performed on agricultural water [2]. In this paper, with reference to the market-related parameters of translated sprinkling machine, the design of a large span translated irrigation machine, according to research purposes,
either to reduce the occupied area of farmland irrigation machine translation, to maximize the use of land, but also to ensure the uniformity of crop irrigation, increase production, and save water resources. This paper will use CATIA software to design three dimensional modeling which a sprinkling machine structural parameters of structural stability analysis to ensure a structure design to meet the design requirements. By ANSYS FLOTRAN software to structure of sprinkling machine will be simplified with the mesh, and using its own fluid simulation software ANSYS FLOTRAN pipeline fluid simulation analysis, flow rate at the inlet certain circumstances, each outlet relations between the velocity distribution. Experimental prototype in the field of five test groups to testing, the resulting distribution of water, irrigation water depth data to analysis are calculated based on the calculated results to determine the design of translation sprinkler irrigation uniformity Meets "Irrigation engineering design specifications" requirement.

2. Structure of paper
The status of freshwater resources and the significance of the development of agriculture sprinkler irrigation, and domestic and foreign research and test methods for translation sprinkler machine irrigation uniformity of structure and other aspects of the analysis.

The use of CATIA software, to finite element analysis, unit setup, mesh, other loads and constraints imposed on the translation irrigation machine which across the whole body and structural stability was analyzed and the corresponding results obtained proposed structure optimization tips.

Refer to the relevant literature and standards, and summarized translation impact of sprinkler irrigation uniformity factor by calculation and analysis, fluid analysis to determine the relevant parameters, including the inlet pressure, flow rate, emitter selection, emitter spacing parameter.

Using ANSYS FLOTRAN software to simplifies structures of translation irrigation machine. Meshing pipes were simulations to determine the translation irrigation machine which the relationship between of job stress, emitter operating pressure, speed, and flow, etc.

The experimental prototype testing in the field trials, collected and organized testing data to calculate the irrigation uniformity coefficient span translation irrigation, and then with ANSYS FLOTRAN simulation data are compared to determine the large-span sprinkler irrigation uniformity performance meet the design requirements under the corresponding emitter spacing, sprinkler operating pressure, inlet flow rate and other parameters.

3. Influence factors of sprinkler irrigation uniformity and evaluation of hydraulic performance
Based on equal nozzle area theory, non-circle nozzles with four different shapes were designed and their hydraulic characteristics were compared through experiments. The result indicated that for the star shaped nozzle, the range rarely decrease and the tendency of the water distribution under different pressure were of the same [3]. The hydraulic characteristics were compared between the star shaped nozzle and the circle nozzle, as shown in Figure 1. The result showed that water distribution of the star-shaped nozzle was better than that of the circle nozzle.
Figure 1. Donald developed the nozzle

Variable-rate sprinkler BPY series with nozzle-regulator were designed. This kind of sprinkler uses a pressure and flow rate adjusting device to adjust the working pressure, and a nozzle-changeable device to change the discharge area [4]. By regulation of these two factors synchronized, the water distribution uniformity of the variable-flow rate sprinkler will be improved. Through feasibility analysis on this sprinkler, the relation among nozzle area, the range and the working pressure was obtained. The result indicated that, when the spray shape is square, the range of the working pressure for BPY20 is 0.54 to 1, and for BPY30 is 0.57 to 1, for BYP with nozzle-regulator is 0.46 to 1. When the spray shape is triangle, the range of the working pressure for BPY30 is 0.33 to 1, and for BPY20 is 0.21 to 0.8, for BYP with nozzle-changeable device is 0.21 to 1. The variable-rate sprinkler with nozzle-changeable device could accomplish given spray area under a smaller range of pressure.

\[ Q_p = 3600 \mu A \sqrt{2gH} \]  

(1)

Three kinds of nozzle-changeable device with different orifice areas for the sprinklers BPY20 and BPY30 were designed respectively. Impact of the nozzle-regulators to the stress introduced on the spring, the discharge coefficient of the sprinkler, the shape factor, and the throw radius were tested. It was obtained that: the premium radius of the orifice for the nozzle-regulator in BPY20 is D=6mm, for BPY30, it was D=7mm. The hydraulic performance of the variable-rate sprinkler with nozzle-regulator was measured. By compared with that of the star-shaped variable-rate sprinkler, the variable-rate sprinkler with nozzle-regulator provided better anticipated areas so that the water distribution uniformity was improved.

\[ R = \frac{2v^2 \sin 2\alpha}{g} = 2\varphi^2 H \sin 2\alpha \]  

(2)

Based on the kinetic equations of the rain drops, a mathematic model for the transformation from the water distribution pattern on a flat ground to that on a sloping land was derived. Through the comparison between the field test and calculation data, it was found that: among 50200, obtains from the transformation model were in good consistence with that from test. Based on the transformation from the water distribution data on the flat ground, a large amount of data on the sloping land were acquired to provide an experimental basis for the study of irrigation on the sloping land.

\[ \rho = \frac{\sum_{i=1}^{n} S_i p_i}{\sum_{i=1}^{n} S_i} \]  

(3)
4. Experiments

According to the water distribution model, the impact of slopes on the hydraulic performance was investigated. For the sprinkler on the slopes of 50-200, the variable-rate sprinkler can help to solve the problem of non-uniform distribution caused by the terrain conditions on an upslope or an downslope. The variable-rate sprinkler suitable to the slope of 100 was designed and the hydraulic performance in field operation was tested. The test indicated that: the variable-rate sprinkler will solve the problem of long range, high sprinkler intensity on the upslope and short range, low sprinkler intensity on the downslope.

\[
\bar{\rho} = \sum_{i=1}^{n} \frac{2i}{n(n + 1)} \cdot \rho_i
\]  

(4)

The low energy consumption has become one of the focuses in the development of sprinkler irrigation systems under the growing water shortage and energy consumption problem worldwide. In China, the terrain conditions, the crops and the rural economic levels are various across the land. Hence, the diversity in the configuration of Small-Scale Sprinkler Irrigation Systems is a trend. The increasingly shrinking farm labor as a result of urbanization, combined with the large-scale operations of farmland have challenged the present sprinkler irrigation machines with one-line pipe layout which is accompanied with inconvenience in transferring the pipeline to the next location. Therefore, the flexibility in the combination of components and the possibility in the application of larger areas within limited power need to be improved, and the energy consumption needs to be reduced so as to provide some basis for the further promotion of Small-Scale Sprinkler Irrigation Systems. The theoretical simulation and experimental validation were used in the optimization design and experimental study of Small-Scale Sprinkler Irrigation Systems with Low Energy Consumption and Multi Purposes. Spray water distribution curve was shown in Figure 2.

![Spray water distribution curve](image.png)

**Figure 2.** Spray water distribution curve

A Fixed-Movable Multi-Purpose Sprinkler Irrigation System was proposed to improve the flexibility of the small-scale sprinkler irrigation system and the adaptability to the crops. The key parts in the system were designed and produced including a quick-connect coupling for connection of the riser and the pipe tee, and a fixture for the sprinkler and the pipe in the system.

A Multiple-Sprinkler Irrigation System with Pairs of Laterals was developed. Theoretical analyses show that it has the minimal operation time, the minimal total cost in the life span, the highest
irrigation uniformity coefficient and proper energy consumption compared to the traditional systems with one pipeline or two parallel lines.

Eleven kinds of pipe layouts were summarized for different areas according to the combination of different lateral layouts used in the two new irrigation systems, and the mobility of components of the system. These will provide various alternatives of pipe networks for different users and applications. The stress figure of Cross-body pipes was shown in Figure 3.

![Figure 3. The stress figure of Cross-body pipes](image)

A multi-criteria evaluation model of small-scale irrigation system considering technical, economic, environmental and social aspects with ten sub-criteria and processed with Grey Relational Analysis (GRA) was developed. The Analytical Hierarchy Process and entropy method was employed in the evaluation of irrigation systems to take into account the subjective and objective aspects. Analyses indicate that the evaluation model can be adjusted easily and will provide an efficient method for the multi-criteria and multi-objective evaluation of irrigation systems.

And the impact factors of the evaluation indicators of irrigation system were explored. For the technical aspect, the impact of working pressure and sprinkler spacing on the overlapping irrigation uniformity were investigated to provide a basis for the optimization of the system. For the economic aspect, the components of Life Cycle Cost of irrigation systems were analyzed. Results show that: the energy consumption accounts for the major part of LCC of the systems, followed by the initial cost and the labor cost. Thus, the configuration optimization of irrigation system is very important to the reduction of cost and energy consumption. For the environmental aspect, the orthogonal design of four factors on three levels considering the interaction between factors was applied in the study of impacts of configuration parameters on the energy consumption. The results demonstrate that the impact of working pressure at the end sprinkler comes first, followed by that of pipe diameter, the impact of number of sprinklers is also obvious, and that of sprinkler spacing is manifested in the interactions with the other factors. Therefore, the multi-objective optimization of irrigation systems is needed.

The traditional hydraulic model was improved. And three models were developed according to the co-operation characteristics of pump-pipeline-sprinkler in the Small-Scale Irrigation Systems for there were generally no pressure regulators in the systems. They are the back step method, and the forward method considering the constraint of discharge of pump for the system with one line. And combination of both with the Golden Section Search was first used for the complicated networks. Results show that: the forward method will reflect the characteristics of irrigation pipelines better compared with the back step method. In a sprinkler irrigation system, the outlets are far less and the flow rate for each is far higher compared to a micro-irrigation lateral, thus there is an abrupt pressure drop at some length along the pipeline, not as continuous as that calculated by the back step method. The newly-designed forward-backward method will better meet the requirement of minimal pressure at the end sprinkler on each lateral in a pipe network compared to previous researches. The Von*Mises stress at maximum force diagram was shown in Figure 4.
Ant Colony Optimization (ACO) was originally introduced in the optimization of sprinkler irrigation systems for the lowest specific energy consumption and compared with Genetic Algorithm (GA) and the field tests. Results show that the optimal number of sprinklers and pressure profiles along the pipeline calculated with ACO are closer to the experimental results compared to that by GA. The multi-objective optimization model of small-scale irrigation systems was then built with Linear Weight Sum Method based on the analyses of impact factors of indicators.

Figure 4. Von*Mises stress at maximum force diagram

Figure 5. Setting the analysis options dialog
The specific energy consumption and the irrigation uniformity are the major criteria in the environmental and technical aspects, and will reflect the operation condition and the irrigation quality of the system, respectively. Moreover, they are more sensitive to the change of configuration parameters. Hence, the field experiment was carried out on the system typed PC45-4.4 equipped with sprinklers 15PY to investigate the impact of configuration parameters of system on the energy consumption and irrigation uniformity, to validate the practicability of model and optimization method, and to derive the optimal configuration in the test condition. The analyses on the impact factors of energy consumption demonstrate that: the theoretical analysis method is generally practical. But in the field test the energy consumption the pipe diameter is increased for the pressure head of sprinklers provided by the pump are higher. This indicates the interaction between the pump-pipeline-sprinkler, which is neglected in the theoretical analyses.

The analyses on the impact factors of irrigation uniformity coefficient show that: for the application of irrigation systems in the areas with wind speed lower than 2.7 m/s (the maximum value in the experiment), the combination of rectangle layout, paper sprinkler spacing and lateral spacing, and Lower pressure can be used to ensure a high irrigation uniformity and a lower energy consumption. But for the application of irrigation systems in the areas with more frequent wind or higher wind speed, the combination of triangle layout, closer sprinkler and lateral intervals and higher sprinkler pressure is suggested to minimize the effect of wind on the irrigation uniformity. The interactions between the impact factors of specific energy consumption and irrigation uniformity are obvious, thus the configuration parameters should be chosen considering different aspects.

5. Conclusion and results
To validate the computational model, field experiments were carried out under low stable wind speed conditions (less than 1.5 ms⁻¹) following the American Society of Agricultural and Biological Engineering (ASABE) standard. Two categories of experiments were carried out at the same operating pressure concurrently. The first category of experiments consisted of four sprinklers with an array of catch cans equally spaced and placed between the sprinklers constituted the experimental area.

| No. | Pressure Kpa | High mm | Index % |
|-----|--------------|---------|---------|
| 1   | 200          | 12.72   | 91.01   |
| 2   | 250          | 14.50   | 95.21   |
| 3   | 300          | 19.35   | 96.27   |
| 4   | 350          | 25.80   | 96.63   |
| 5   | 400          | 35.89   | 96.11   |

Table 1. Irrigation Uniformity under tables test pressure
The second, category consisted of isolated sprinkler experiments with catch cans placed along eight radii at equal distance from each other within the radius of throw of the sprinkler forming an orthogonal pattern as shown above in Table 1. Same operating pressure conditions were ensured with the aid of pressure gages and valves. This ensured that the distribution pattern of the isolated sprinkler experiments were as much as possible similar to each of the four overlapping sprinklers. This is a necessary requirement for comparison with the simulated overlaps with the measured pattern for similarity of the contributing sprinklers.

The highest absolute error registered was 2.9% for the 16x1.8 rectangular layouts which also recorded the least measured coefficient of uniformity. This observation may be attributed to the relatively larger spacing. The lowest absolute deviation from the measured was 0.736% for the 17x15 rectangular layouts. The relatively small overall mean absolute error is an indication of the efficiency of the model to overlap the single leg distributions to mimic field situation.

The 14x14 rectangular spacing gave the highest coefficient of uniformity values of 85% and 83.45% for both measured and simulated overlaps and the rectangular layout of 1bx18 registered the lowest simulated coefficient of uniformity value of 79%. And the lowest uniformity coefficient for the measured data was registered by the 18x18 triangular layout. In general the coefficient of uniformity increased as the spacing between sprinklers reduced for both observed and computed patterns (Figure 5-6).

From the generated overlap data other comparative performance indices such as distribution uniformity, Heerman and Hein's uniformity coefficient, standard deviation and statistical uniformity could be evaluated either from original expressions or from established empirical relationships to support decision making. Simulated and observed 3D plots for four overlapping sprinklers are shown in Figure 7, for square and triangular layouts. The vertices of the plots are the locations of the sprinkler positions. The plots show the effect of sprinkler spacing at the operating conditions.

For the single sprinkler field experiment, catch cans were placed in the form of a grid with the sprinkler head mounted on a riser of height 1.4 m from the ground, placed in the middle of the grid. Cans were placed 2 m apart from each other. In the solid-set experiments, layouts of 16x16, 16x18, 16x20 and 16x22 were performed to determine the relationship between spacing and uniformity of application while varying the operating pressure. Catch cans were placed in the center of the four overlapping sprinklers. Water application rates were determined for both single sprinkler and solid set experiments, concurrently, at pressures of 200, 250, 300 and 350 kPa respectively by means of
graduated measuring cylinders. For each operating pressure configuration, the sprinkler flow rate was measured by connecting flexible rubber hose to the sprinkler nozzle and the time required to collect a known volume of water into a bucket was measured.

The maximum, minimum and average wind speed (m/s), air temperature and relative humidity (%) that prevailed during the field test were as shown in Table 1. They were typical of the weather conditions at the test site at the onset of summer. The measured sprinkler flow rates ranged from 3.45 to 4.15 m/hr, with an average of 3.98 m³/h within operating pressure range of 200 to 350 kPa. CU values were computed according for each experiment. In general the field data exhibited an inherent variability depending on the wind speed category, operating pressure and spacing.

The first step was to set the reference conditions and numerically compute the droplet drift for the reference conditions; droplet diameter of 2.5 mm, wind speed of 2.5 m/s, initial droplet velocity of 23.79 m/s and nozzle height of 1.2 m. Subsequently, one parameter was varied from the reference value, while the remaining independent variables were held constant. The droplet drift was then computed. The sensitivity of the droplet drift to each of the influencing factors was similarly, assessed.

6. Conclusions and results
By reference to market-related entity machine parameters to determine the structure of sprinkling machine design parameters and three-dimensional modeling, using of CATIA software prototype assembly and using of their finite element analysis for structural stability analysis, in order to verify the design reliability of the translation irrigation machine, provide a theoretical basis for the future market to product.

Research on the design of translation sprinkler irrigation uniformity in case emitter spacing of 2.9m, fluid simulation analysis and field testing to determine the impact of different design working pressure of the inlet of the irrigation uniformity, the translation irrigation machine from further research and development is important.

7. References
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