DEVELOPMENT OF A SYSTEM DISCHARGE MODEL FOR A GRAVITY-FLOW DRIP IRRIGATION TECHNOLOGY IN GREENHOUSE CULTIVATION

[1]Adeogun, E. O., M. Y. Kasali[1] and A. O. Ogunlela[2]
[1]Department of Land and Water Management Engineering,
National Centre for Agricultural Mechanization, Ilorin, Nigeria.
manuelaolu2016@gmail.com
[2]Department of Agricultural and Biosystems Engineering
University of Ilorin, Ilorin, Nigeria

ABSTRACT
This paper focuses on determination of a system discharge model for a gravity-flow drip technology in greenhouse cultivation carried out at the irrigation research field of the National Centre for Agricultural Mechanization (NCAM) Ilorin, Nigeria. The adoption of greenhouse cultivation for agricultural production in research field of NCAM Integrated Farm Project (NIFAP) was considered paramount as a viable solution for off-season cultivation which provides a controlled environment of high value crops for better result. The developed model was used to describe and analyse the performance of water discharge by the system using dimensional analysis of irrigation parameters based on Buckingham's pi theorem. The predicted equation for system discharge of a gravity-flow drip technology was established from the formulated equations. The measured system discharge was determined within the range of 2.44×10^{-4} to 5.86×10^{-2} l/s, while the predicted system discharge was found to be between 2.68×10^{-3} and 0.184 l /s. A high correlation coefficient was obtained between measured and predicted system discharge in the order of 0.95.

KEYWORDS: model, drip technology, greenhouse

1. INTRODUCTION

1. INTRODUCTION

Greenhouse cultivation is a new alternative technology for agricultural practices which is currently being used to enhance production under normal and adverse climatic condition other than usual traditional methods of agricultural practices which is being impeded by climatic changes. Presently, the cultivable area is decreasing rapidly due to urbanization, encroachment of nomadic farming and infrastructural development taking place on agricultural lands (Castilla, 2000). This however leads to a need for adopting an improved and a new alternative technology that can guarantee increasing productivity at higher rate to mitigate the effect of food shortages experienced as a result of the challenges faced in agricultural production.

The use of greenhouse techology in vegetable production is gradually taking a welcoming development among peasant farmers in Nigeria. This technology, although with initial investment on a high side, its proper management would in no doubt yield a high dividend for recovering its initial cost in little or no time. According to Nalliah et al. (2009), the investment on greenhouse technology has strenghtened food security by promoting sustainable crop production intensification, which aims at producing more from the same area of land while conserving resources and reducing negative impacts on the environment. With the availability of adequate irrigation system such as sprinkler and trickle irrigation system, agricultural production would be increased to guarantee food production all year round for the fast growing population (Nalliah et al., 2009).

Greenhouse cultivation is therefore a viable solution to meet the worldwide demand of enhanced production. This technology facilitates off-season cultivation and protects crop from unfavorable outdoor condition by providing a controlled environment for high value crops for better results. It also encourages proper growth and fruiting as compared to open field cultivation. Apart from aforementioned benefits, the following advantages could also be considered. Greenhouse is a better option for nursery raising and hardening of tissue cultural plants. It is viable for cultivation in regions which are prone to soil problems and extreme climatic conditions that are unfavourable for agricultural production and it also helps to create favorable microclimate condition where production of fruits and vegetables are made possible throughout the year.

A model equation was developed for the drip irrigation system used in the greenhouse under gravity flow to describe water discharged by the system. This model however helps to describe and analyse the performance of the drip irrigation system under gravity flow in the greenhouse cultivation.

The objective of this study was to determine system discharge model for the gravity-flow drip irrigation technology for greenhouse cultivation in National Centre for Agricultural Mechanization (NCAM), Ilorin, Nigeria.

2. METHODOLOGY

A number of greenhouse recently developed and installed in NCAM Integrated Farm Project (NIFAP) research field with the installation of gravity-flow drip irrigation system was used for this study. A system discharge model equation was developed using dimensional analysis based on Buckingham's pi theorem (Langhaur, 1980).

2.1 Description of Single Tunnel Greenhouse

Each single tunnel greenhouse kit measures 30 m x 8 m (240 m^2). The framework is made of hot galvanized steel pipe which is anti-rust treated. The greenhouse is covered with 200µ thick Solarig material with plant support system attached (Figs. 1 and 2). A 32 mesh UV insect net was used to cover the front of the greenhouse with a provision of roof ventilation. Access door of 2 m x 1 m serves as the entrance to the greenhouse.

Fig. 1. Drip discharge and flow rate measurement

Fig. 2. The cultivated greenhouse

2.2 Water supply
Irrigation water flow by gravity from a 1.7 m height overhead tank which was installed beside the greenhouse that supply water to the dripper lines installed in the greenhouse.

2.3 Discharge rate of Drippers
This was carried out by measuring the total flow rate of water with a flow meter (El Awardy et al., 2003). The average flow rate was calculated by determining the flow rate per number of drippers (Ibragimov et al., 2007).

2.4 Coefficient of variation of the dripper
This was carried out by determining the collection of dripper discharge in a calibrated container and the time taken for each dripper to fill container. Therefore the dripper discharge was determined by finding the ratio of calibrated volume of container to the time taken.

2.5 Determination of model parameter for drip irrigation system
In developing the model (system discharge) for the drip irrigation system, two important sub-system are identified. These are the hydraulic system and the crop-soil system while the variables affecting water transportation in the hydraulic system are classified as the fluid factors and the hoseline factors.

2.6 Fluid factor
Factors determining the concept of fluid flow as used in this study are categorised as fluid velocity (μ), velocity of flow (v), gravitational acceleration (g) and height of water in tank (h), while the hoseline factors are hose length (ℓ), hose diameter (d), and water discharge by the system (Q_s).

2.7 Determination of Functional Relationship
The general relationship between the dependent variable, water discharge by the system (Q_s) and the independent variables (ℓ, g, h, d, v) can be expressed as follows:

$$Q_s = f(\mu, \ell, g, h, d, v) \qquad (1)$$

Where f = functional notation for system discharge.

2.8 Construction of dimensional set

Table 1. Dimensional quantity by listing the relevant variables

Variable	Symbol	Dimension
Fluid viscosity	μ	$kgm^{-1}s^{-1}$
Velocity of flow	v	ms^{-1}
Acc. due to gravity	g	ms^{-2}
Length of hose	ℓ	m
Diameter of hose	d	m
Height of water	h	m
System discharge	Q_s	m^3s^{-1}

There are seven variables (N) with three dimensions (B) as outlined in Table 1. Accordingly, the dimensional matrix is given as affirmed by Ibragimov (2007).

Table 2. Structure of dimensional matrix

$$\begin{array}{c|c}
 & \begin{array}{cccc} Q_s & \ell & d & h \end{array} \quad \begin{array}{ccc} g & \mu & v \end{array} \\
\hline
\begin{array}{c} M \\ kg \\ S \end{array} & \underbrace{\begin{pmatrix} 3 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}}_{\text{B Matrix}} \underbrace{\begin{Bmatrix} 1 & -1 & 1 \\ 0 & 1 & 0 \\ -2 & -1 & -1 \end{Bmatrix}}_{\text{A matrix}}
\end{array}$$

Where, sub matrices A and B are as indicated in the apprentices (Thomas, 2006)

In order to complete the structure of dimensional set, two other matrices (C matrix and D matrix) are also composed. By using the fundamental formula as given by Thomas (2006).

$$C = -(A^{-1}.B)^T \qquad (2)$$

From the theorem of the inverse of a matrix, Thomas, (2006) affirmed that if a matrix is non-singular, then its inverse is

$$A^{-1} = \frac{adjA}{|A|} \qquad (3)$$

Where, adjA is the determinant of the cofactor matrix A and the denominator is the determinant of the matrix.

For simplicity, matrix D is chosen to be a unit matrix of order four and treated as an identity matrix with products of variables of prescribed dimensions as (π)pi value.

Table 3. Structure of the dimensional set developed for Matrices A, B, C and D

	Q_s	ℓ	d	h	g	μ	v
m	3	1	1	1	1	-1	1
kg	0	0	0	0	0	1	0
s	-1	0	0	0	-2	-1	-1
π_1	1	0	0	0	5/3	0	-7/3
π_2	0	1	0	0	1/3	0	-2/3
π_3	0	0	1	0	1/3	0	-2/3
π_4	0	0	0	1	1/3	0	-2/3

Matrix B

Matrix A

Matrix D

Matrix C

The matrix A is non-singular, hence the rank of the dimensional matrix is 3. The C matrix is obtained by fundermental formular expressed in equation 2.2. Using Buckingham Pi theorem, the number of Pi terms S for each equation are

S = N – B = 7 – 3 = 4

i.e., there are four dimensional variables supplied by the above dimensional set and their values are given as follows (Langhaur, 1980).

$$\pi_1 = \frac{Q_s g^{5/3}}{v^{7/3}} \qquad (4)$$

$$\pi_2 = \frac{\ell g^{1/3}}{v^{2/3}} \qquad (5)$$

$$\pi_3 = \frac{d g^{1/3}}{v^{2/3}} \qquad (6)$$

$$\pi_4 = \frac{h g^{1/3}}{v^{2/3}} \qquad (7)$$

This is possible by using dimensional analysis to obtain a functional relationship between the variables and the Pi terms.

From the relation $\pi_1 = f(\pi_2, \pi_3, \pi_4)$. The functional relationship can be expressed as:

$$\frac{Q_s g^{5/3}}{v^{7/3}} = f\left(\frac{\ell g^{1/3}}{v^{2/3}} \quad \frac{d g^{1/3}}{v^{2/3}} \quad \frac{h g^{1/3}}{v^{2/3}}\right) \qquad (8)$$

For simplicity, this relation is minimized by relating π_3 and π_4 to form π_{34}.

$$\pi_{34} = \frac{d}{h} \qquad (9)$$

2.9 Solution Analysis

The three Pi terms used in the model formulations are π_1, π_2 and π_{34} are relating as

$$\pi_1 = f(\pi_2, \pi_{34}) \qquad (10)$$

The relationship existing in the determined function is hereby expressed as follows:

$$\frac{Q_s v^7}{g^5} = f\left(\frac{g^{1/3} l}{v^{2/3}} \quad \frac{d}{h}\right) \qquad (11)$$

Buckingham Pi theorem verified that for Equation (11) to be correct, there is a need to conduct at least 2m – 3 tests. In this case, m = 3. In order to develop a model equation for the system discharge using the formulated component equations, functional relationship existing between the π terms were established. This was determined by creating dimensionless plots of π_1 against π_2 holding π_{34} constant and π_1 against π_{34} holding π_2 constant (Figs. 3 and 4). Also derived were equations showing the relationships between π_1 against π_2 holding π_{34} constant twice and π_1 against π_{34} holding π_2 constant twice. The data used for π terms were obtained from drip irrigation parameters in the greenhouse.

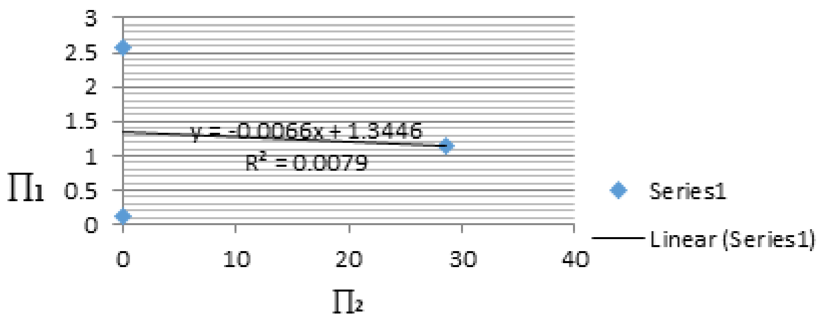

Fig. 3 Graph of Π_1 vs Π_2 holding Π_{34} constant

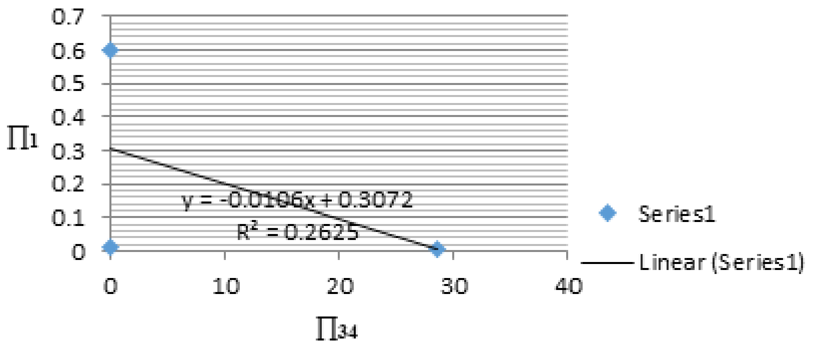

Fig. 4 Graph of Π_1 vs Π_{34} holding Π_2 constant

3. RESULTS AND DISCUSSION

3.1 Model equation

One way to develop model equation is to assume that π_{34} is the product of component equations with the functional relationship developed graphically (Langhaur, 1980).

Table 4. Greenhouse drip irrigation parameter

Irrigation Parameter	Mainline	Submain	Lateral/Dripper
d (m)	0.03	0.02	0.006
ℓ (m)	0.025	0.392	0.036
h (m)	0.05	1.68	1.68
A (m^2)	7.069×10^{-4}	3.143×10^{-4}	2.83×10^{-5}
v (m/s)	0.2802	0.1868	0.0173
π_1	0.0437	0.1120	28.642
π_2	0.125	2.566	1.1528
π_{34}	0.6	0.012	0.0036

3.2 Component Equations

The component equations derived from plotted graph of Figs. 3 and 4 are as follows:

$$(\pi_1)\text{-}2 = -0.01\pi_{34} + 0.307 \quad (12)$$
$$(\pi_1)\text{-}34 = -0.006\pi_2 + 1.344 \quad (13)$$
$$(\pi_1)_{-2} = -0.01\pi_{34} + 1.153 \quad (14)$$
$$(\pi_1)_{-34} = -0.006\pi_2 + 0.00 \quad (15)$$

In order to determine water supply prediction equation for the system, the general prediction equation for the system involving π terms is formed by summation of the component equation given as follows (Langhaur, 1980)

$$F(\pi_2, \pi_{34}) = f(\pi_2) + f(\pi_{34}) \quad (16)$$
$$F(\pi_2, \pi_{34}) = f(\pi_2, \pi_{34}) + f(\pi_2, \pi_{34}) + C \quad (17)$$
$$F(\pi_2, \pi_{34}) = A\pi_2 + B + P\pi_{34} + Q + C \quad (18)$$

The functional relationship of the π term can then be established as follows:

$$\pi_1 = A\pi_2 + B + P\pi_{34} + Q + C - (B + A\pi_2) \qquad (19)$$

By substituting the values of Equations (12 to 15) in Equation (19)

$$\pi_1 = -\,0.006\pi_2 + 1.344 - 0.01\pi_{34} + 0.307 - (0.01 - 0.006 + 0.004)$$

$$\pi_1 = -\,0.006\pi_2 - 0.01\pi_{34} + 1.651 - 0.008$$

$$\pi_1 = -\,0.006\pi_2 - 0.01\pi_{34} + 1.643 \qquad (20)$$

By substituting the values of Equations (4, 5 and 9) into Equation (20)

$$Q_s g^{5/3} / v^{7/3} = -\,0.006(\ell g^{1/3} / v^{2/3}) - 0.01(d/h) + 1.643$$

$$Q_s = -\,0.006(\ell g^{1/3} / v^{2/3})(v^{7/3} / g^{5/3}) - 0.01(v^{7/3} / g^{5/3})(d/h) + 1.643(v^{7/3} / g^{5/3})$$

$$Q_s = v^{7/3} / g^{5/3}\,[1.643 - 0.006(g^{1/3} l / v^{2/3}) - 0.01(d/h)]$$

Chart Area

$$Q_s = v^{7/3} / g^{5/3}\,[1.643 - 0.006(v^2 / gl^3)^{-1/3} - 0.01(d/h)]$$

$\left(v^2 / g\ell^3\right)^{-1/3}$ where, the expression in parentheses is a Froude number, Fr.

The system discharge model equation for a gravity-flow drip technology in greenhouse is given as:

$$Q_s = v^{7/3} / g^{5/3}\,[1.643 - 0.006(v^2 / gl^3)^{-1/3} - 0.01(d/h)] \qquad (3.21)$$

Where, Q_s is the water discharge by the drip irrigation system in greenhouse, v is the velocity of flow, ℓ is the dripper length, h is the water head from the reservoir, d is the internal dimeter of the hose and g is the acceleration due to gravity.

Table 5. Predicted and Measured System Discharge [$(Q_s)_p$ and $(Q_s)_m$]

$(Q_s)_p$ (l/s)	$(Q_s)_p-(Q_{\bar{s}})$	$(Q_s)_m$ (l/s)	$(Q_s)_m-(Q_{\bar{s}})$	$[(Q_s)_p-(Q_{\bar{s}})][(Q_s)_m-(Q_s)]$
1.841	9.371	5.364×10^{-2}	5.09×10^{-2}	0.4769
0.71	0.7169	2.932×10^{-2}	-2.662×10^{-2}	-0.01908
2.68×10^{-3}	2.79×10^{-3}	2.443×10^{-4}	2.436×10^{-3}	6.796×10^{-6}

3.3 Model verification and validation

3.3.1 Model Verification

Verification of the system discharge model equation for a gravity-flow drip technology in greenhouse cultivation is important before it could be utilized for any research purposes. This verification involves comparing predicted model with measured experimental results of the existing system.

The extent of agreement between predicted model output and physically measured data can be established, thereby leading to the determination of significant difference between predicted and measured data.

3.3.2 Model Validation

The data set that are used in model development are employed to carry out model validation. The measured data are therefore used to determine the values of πs for the system. Comparison of the result of the predicted water supply model with the measured experimental result from the system is also carried out. The measured water supply was compared with the predicted system discharge model by applying the hypothesis b – β = 0 which will only happen when $(Q_s)_p = (Q_s)_m$.

$$S^2_{y,x} = \frac{\sum y^2 - \frac{(\sum xy)^2}{\sum x^2}}{n-2} \qquad (22)$$

$$t_b = \frac{b}{\sqrt{\frac{S^2_{y,x}}{\sum x^2}}} \qquad (23)$$

Also by considering the hypothesis that a = α_0

$$t_a = \frac{a-\alpha_0}{\sqrt{S^2_{y,x}\left(\frac{1}{n} + \frac{\bar{X}^2}{\sum x^2}\right)}} \qquad (24)$$

Analysis of adequate of fit to test the significance of α and β by applying the hypothesis $a = \alpha_0$ and $b - \beta = 0$ is carried out by determining the level of significant difference between the predicted and the measured value.

Table 6. Analysis of adequate of fit at different significant level

Level of sig.	Computed t_a	Computed t_b	Tabular t value
5%	0.0002585	0.8174	4.303
1%	0.01123	1.588	9.925

In analysing the adequate of fit by applying the hypothesis, the tabular t value at 1% and 5% level of significance indicated that the computed t_a value of 0.0002585 is less than the tabular t values with 4.303 and 9.925 respectively. This imply that there is no significance difference between a and α. β is judged significantly different from zero if the absolute value of the computed t_b value is greater than t value at the prescribed level of significance. Since the tabular values are greater than the computed values, there is no significance difference between the predicted and measured slope. In this case, the hypothesis $b - \beta = 0$ is verified.

Therefore the tests showed that the predicted system discharge model is not significantly different from the measured system discharge. Figure 5 showed the graph of measured discharge against the predicted discharge for the system.

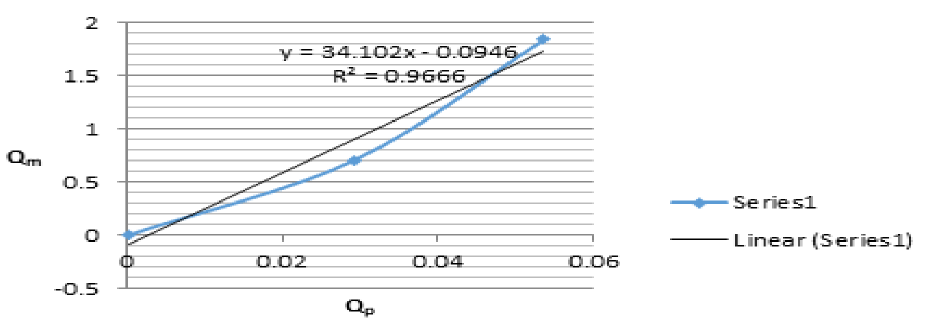

Fig. 5 Graph of Measured system discharge vs Predicted system discharge

4. CONCLUSIONS

A system discharge model was developed for a gravity-flow drip technology in greenhouse cultivation to monitor, analyse and predict the efficient use of crop water requirement data for irrigation purposes.

This model is capable of predicting system discharge of the installed drip irrigation system for greenhouse cultivation. From the data, the system is capable of discharging water within the range of 2.68×10^{-3} and 0.184l/s over an area of $240m^2$ of a greenhouse cultivated with crops.

This model provides an avenue for determining the amount of water discharged in a given time under gravity flow for irrigation practices. Consequently, the water application rate can be well maximized, based on crop water need at various stage of crop growth for adequate yield.

ACKNOWLEDGEMENT

The work reported here form part of a research programme on greenhouse research activities sponsored by National Centre for Agricultural Mechanization (NCAM), Ilorin; with due acknowledgement to the Executive Director of the Centre and the staff of the department of Land and Water Management Engineering for their unflinching support in the course of the study.

REFERENCES

Castilla, N. (2000). Greenhouse drip irrigation management and water saving. Cashiers options Mediterranean's vol 13.

El Awardy, M. N., M. F. Ahd El Salam, M. M.lL Nawawy, and M. A lL Farrah. (2003). Surface and subsurface irrigation effects on Spinach and Sorghum. The 11th Annual Conference of Misr Society of Agric., Engr. Pp. 118 – 130.

Ibragimov, N., S. R. evett, Y. Esanbekov, B. S. kamilov, L., Mirzaev and J. P. A. Lamers. (2007). Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agric. Waterr manage, 90:112 – 120.

Langhaur, A. R. (1980). Dimensional analysis and Theory of models. Huntington N, Y. Kroieger publishing.

Nalliah, V., R. S. Ranjarn and F. C. Kahimba. (2009). Evaluation of a plant controlled subsurface drip irrigation system. Biosystems Engineering, 102:313 – 320.

Thomas, S. (2006). Applied Dimensional Analysis and Modelling. Elsievier book aid international Sabre Foundation. 820 pages.