UNIVERSITI PUTRA MALAYSIA

MODELING OF CAPILLARY WICK IRRIGATION SYSTEM FOR POTTED PLANT AND SMALL SCALE PLANTATION

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By

HADI HAMAAZIZ MUHAMMED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

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DEDICATION

This thesis is dedicated:

To my lovely wife (Didar Hama) who has helped and encouraged me during my study.
To my beloved daughter (Ilyan) who has missed me for more than two years.

To my sweet son (Aga) who has become my dearest and nearest friend.

To my beloved mother (Nasrin Karim) who has been my supporter since my childhood.
To dearly missed my late father (Hamaaziz Muhammed).
To my sisters and brothers.

Abstract of Thesis Presented to the Senate of Universiti Putra Malaysia in Fulfillment of the Requirement for the Degree of Master of Science.

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Chairman: Md Rowshon Kamal, PhD
Faculty : Engineering

Limited availability of fresh water supplies worldwide demonstrates the urgent need to develop and adopt efficient irrigation methods and proper irrigation management strategies. The relatively high performance of drip irrigation is no doubt. It saves a substantial amount of water and labor, increases yields, and often also improves the quality of the produce. However, the higher investment and energy cost limit the development of the low-cost irrigation system for subsistence farmers. There has been an immense interest in developing and promoting the low-cost drip irrigation system appropriate for small-scale crop growers and greenhouse crop production. This study, by conducting laboratory experiments, investigated hydraulic characteristics and performance of cotton-bonded non-woven material to be used as the wick emitter. Furthermore, greenhouse experiments were carried out to simulate water movement and solute dynamics under root water uptake for potted eggplant crops. To determine proper water application strategies, three irrigation schedules were evaluated. The wick emitter provided the uniformity coefficient of 95.65% and distribution uniformity of 92.67% in applying irrigation in two growing media: peatgro (peat), coconut coir dust and sandy clay loam soil. The growing media and the soil were wetted in an axially symmetric pattern under the wick emitter; in traditional and modern watering methods, growing media are wetted in one-dimensional pattern. HYDRUS simulation of water distribution revealed the dependency of the spatial extent of the wetted zone in the growing media on water application period and hydraulic properties of the media. Furthermore, the results demonstrated that the solutes are transported very slowly, and most of the nutrient solution remains within the middle and bottom of the pots. The results from this study revealed that the eggplant growth showed insignificant differences for the three irrigation schedules when fresh water was used because all the three irrigation schedules provided with enough water content for the crop. In contrast, the eggplant growth showed differences between the treatments relatively when nutrient solutions were used. In terms of wick water application strategies, although 202 ml/day of nutrient solution was applied for the Management Allowed Deficit (MAD) treatment and 155 ml/day was applied for Evapotranspiration (ET) treatment. The total leaf area of the ET schedule (1252.9 cm^2) was higher than the total leaf area of the MAD (1007.8 cm^2). The result suggests that the ET schedule is the best under wick irrigation. Discharge of the wick emitter followed an inverse linear relation with a capillary height of water in the wick. This relation led to the development of an equation for compensating wick emitter discharge by replacing the pressure head of a drip emitter with capillary height of the wick emitter. The measured water volume found the close match with the simulated water and solute movement using HYDRUS 2D/3D in a container planted with brinjal plant and for various porous mediums. The findings from this study invoke opportunities to develop an effective Capillary Wick

Irrigation System (CWS) for small-scale crop production. Further investigation would provide generalized broader evidence on CWS performance based on techno-economical performance of the wick under diverse conditions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains.

PEMBANGUNAN SISTEM PENGAIRAN PEMANCAR KAPILARI UNTUK TUMBUHAN PASU DAN PERLADANGAN BERSKALA KECIL

Oleh

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Bekalan air tawar yang terhad di seluruh dunia menyebabkan perlunya pembangunan dan penggunaan kaedah pengairan yang cekap dan strategi pengurusan pengairan yang betul. Prestasi pengairan titisan yang bagus tidak disangkal. Ia menjimatkan sejumlah besar air dan tenaga kerja, meningkatkan hasil, dan juga meningkatkan kualiti hasil. Walau bagaimanapun, kos pelaburan dan tenaga yang tinggi telah menghadkan pembangunan sistem pengairan kos rendah untuk petani sara diri. Terdapat minat yang besar dalam membangunkan dan mempromosikan sistem pengairan titisan kos rendah yang sesuai untuk penanam tanaman berskala kecil dan pengeluaran tanaman rumah hijau. Melalui kajian ini, dengan menjalankan eksperimen makmal, ciri-ciri hidraulik dan prestasi bahan kapas terikat bukan tenunan diuji untuk digunakan sebagai pemancar sumbu. Tambahan pula, eksperimen rumah hijau telah dijalankan untuk mensimulasikan pergerakan air dan bahan larut dinamik di bawah akar pengambilan air untuk tanaman terung pasu. Untuk menentukan strategi aplikasi air yang betul, tiga jadual pengairan telah dinilai. Pemancar sumbu memberikan 95.65% pekali keseragaman dan 92.67% pengedaran keseragaman apabila diaplikasikan pada pengairan pada dua media penanaman: peatgro (gambut), habuk sabut kelapa dan tanah liat berpasir gembur. Media penanaman dan tanah telah dibasahkan dalam corak paksi simetri di bawah pemancar sumbu; menggunakan kaedah penyiraman tradisional dan moden, media penanaman dibasahkan dalam corak satu dimensi. Simulasi pengagihan air HYDRUS mendedahkan kebergantungan takat ruang zon dibasahkan dalam media penanaman dalam tempoh aplikasi air dan sifat hidraulik media. Tambahan pula, keputusan menunjukkan bahawa bahan larut diangkut terlalu perlahan, dan kebanyakan nutrien terus kekal pada bahagian tengah dan bawah pasu. Hasil daripada kajian ini menunjukkan bahawa pertumbuhan terung menunjukkan perbezaan yang tidak ketara bagi tempoh tiga jadual pengairan apabila air tawar telah digunakan kerana ketiga-tiga jadual pengairan disediakan dengan kandungan air yang mencukupi untuk tanaman. Sebaliknya, pertumbuhan terung menunjukkan perbezaan apabila larutan nutrien digunakan. Dari segi strategi aplikasi air sumbu, walaupun sebanyak 202 ml / hari larutan nutrien digunakan bagi rawatan Pengurusan Defisit Dibenarkan (MAD) dan 155 ml / hari diaplikasikan rawatan penyejatpeluhan (ET). Jumlah keluasan daun untuk jadual ET (1252.9 cm^2) adalah lebih tinggi daripada jumlah keluasan daun untuk MAD (1007.8 cm^2). Keputusan menunjukkan bahawa jadual ET yang terbaik adalah di bawah pengairan sumbu. Pelepasan pemancar sumbu adalah tidak linear dengan ketinggian kapilari air di sumbu. Hubungan ini menghasilkan suatu persamaan untuk membayar pampasan pelepasan pemancar sumbu dengan menggantikan kepala tekanan daripada pemancar titisan dengan ketinggian kapilari pemancar sumbu. Jumlah isipadu air yang diukur didapati hampir sama dengan air yang disimulasi dan pergerakan bahan larut menggunakan Hydrus 2D / 3D dalam bekas yang ditanam dengan tanaman terung dan untuk

untuk pelbagai medium berliang. Dapatan daripada kajian ini memberi peluang untuk membangunkan Sistem Pengairan Pemancar Kapilari (CWS) untuk pengeluaran tanaman berskala kecil. Kajian lanjutan akan menyediakan bukti umum yang lebih luas berkenaan prestasi CWS berdasarkan prestasi tekno-ekonomi pemancar di bawah pelbagai keadaan..

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Only at the very end, one realizes that the completion of a work such as this study, could never have been achieved without a lot of teamwork and support of others. Therefore, I guess, time has come to thank those who have helped me, making this thesis what it is now.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirements for the degree of Master of Science.
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LIST OF ABBREVIATIONS

ΔS	Soil volume
^0C	Temperature
2D/3D	Two-dimension/ Three-dimension
ai	experimental coefficient
ALAM	Automatic leaf area meter
AS	Air space
c	Concentration
CC	Container capacity
CDE	Convection-dispersion equation
CM	centimeter
CWS	Capillary wick irrigation system
D	Drainage
DB	Bulk density
DU	Distribution uniformity
ε	Dielectric permittivity
EAW	Easily available water
Ebb	Ebb and flow irrigation system
EC	Electrical conductivity
Eq	Equation
ET	Evapotranspiration
ET_0	Potential evapotranspiration
ET_A	Actual evapotranspiration
ET_C	Evapotranspiration of the crop
g	Gramme
h	Pressure head
h_e	Pressure head of emitter
hr	Hour
$h\phi$	Osmotic head
I	Irrigation
IAE	Irrigation application efficiency
IE	Irrigation efficiency
$K(\theta)$ or $K(h)$	Unsaturated hydraulic conductivity
K_C	Crop coefficient
k_e	Emitter discharge coefficient
Kpa	Kilopascal
K_s	Saturated hydraulic conductivity
l	Pore-connectivity parameter
LF	Leaching fraction
$M\ M^{-1}$	Mass per mass
$M^3\ M^{-3}$	Volume per volume
MAD	Management allowed deficit
MAE	Mean absolute error
MCH	Maximum capillary height
M_D	Mass of dry wick
mm	Millimeter
M_s	Mass of wet wick
NFW	Nutrient-flow wick culture
p	Experimental constant
pD	Particle density
pH	Power of the concentration of the hydrogen ion
PVC	polyvinyl chloride

q	Water flux
q_e	Discharge of emitter
R	Rainfall
RAW	Readily available water
RC	Water retention curve
RMSE	Root mean square error
S	Sink term
Se	Effective saturation
SM	Soil moisture
SPAC	Soil-plant-atmosphere continuum
TP	Total porosity
UC	Uniformity coefficient
VG	Van Genuchten
VWC	Volumetric water content
WBC	Water buffering capacity
WHC	Water holding capacity
x	Exponent
α, n, m	Van Genuchten fitting parameters
ε_L	Longitudinal dispersivity
ε_T	Lateral dispersivity
θ	Water content
θ_r	Residual water content
θ_s	Saturated water content
Ψ_m	Matric potential
ω	Water stress index
ωc	Critical water stress index
ΩR	Root zone

CHAPTER 1

INTRODUCTION

1.1 Background

Availability and adequate freshwater water supplies to the irrigated agriculture will be the dominant issues globally in the 21st century. With ever-increasing population and climate change scenarios, the demand for water will continue to increase for agriculture, especially irrigation, and other economic uses to meet food, fiber and energy security needs of the society (Ramesh, 2010). Composition of growing medium and fertigation methods underwent through enormous changes lately. Due to environmental regulations, there is an increasing interest in growing systems in which there is no leaching of water and nutrients into the subsurface of soil and in which the leaching to surface water is minimized. Plant production has changed from mineral soils to new growing medium as a result of the developments in the growing system. Many different types of growing mediums are produced by the manufactures. Peat-based substrates are frequently used in the growing systems, but sometimes inorganic substrates like rockwool and perlite are used in potted plant production. These growing media can be differed in their physical and chemical properties. It is important to optimize the conditions in the root zone of potted medium. Although researchers paid considerable attention to the chemical and physical characteristics of the substrates during past years, there is still little knowledge on modeling water and solutes in the root zone of potted plants. It is not well understood of the effectiveness of different micro irrigation methods on water and nutrient transport through potted medium. To achieve high yield with minimal wasting water and fertilizer, it is important for irrigation time to be scheduled. Because the laboratory and greenhouse experiments are costly and time consuming, the numerical models are mostly used to predict water and solute transport. Recently the two- and/or three- dimensional simulation model HYDRUS 2D/3D, which numerically solves the Richard’s equation for saturated-unsaturated water flow and the convection-dispersion equation for solute flow has been applied to micro irrigation systems and proven to be a reliable predictor for modeling water and solutes (Gärdenäs et al., 2005)). Precise estimation of temporal and spatial root-water uptake characteristics is necessary to determine irrigation efficiency and solute transport to the subsurface of soil. Therefore, root water uptake is an important factor in moving and dynamics of soil water when accounting for the root system. A number of effective irrigation methods such as drip, the pitcher and capillary irrigation are well-known as high-water application efficiencies for conserving water, reducing fertilizer losses and distributing water uniformly. In addition, the world water crisis is inevitable, yet surprisingly little work has reported to promote, develop and understand more efficient, low cost irrigation systems. Despite being drip is considered the ‘choice’ but it is not suited for remote areas for smallholder without modern technology for unfiltered water systems. Since most of the growing medium is characterized by coarse texture, they cannot retain irrigation water and nutrients. Consequently, the water and fertilizers can infiltrate down through the growing medium quickly. Therefore, using drip irrigation system for growing medium, especially for peat substrates may result in wasting water and fertilizer.

The uniform distribution is one of the most important parameters in design, management and adoption of microirrigation. A well-designed irrigation system provides the approximately equal amount of water to each plant and is economically feasible. The uniformity describes how evenly an irrigation system distributes water over the root zone. Wick irrigation is very promising, either in capillary wicking (slow), gravity fed (moderate), or pressurized (fast) wick mode. Nylon wicks made with woven (not braided), washed and weathered nylon or polyester rope have been best (Brainbridge, 2014). The flow rate depends on the type of system and wick. A gravity flow rate using 11 mm new washed solid braid nylon and the hose clamp tightened one turn past snug released about 1 liter/hour. It can tighten further for a release rate of 20 liters in 3-5 days. These require some attention to adjust as plant demand, and flow rate varies over time. The flow rate is an important factor in designing irrigation systems that non-uniformity in the water application will be minimum and non-exccessive (Wesonga et al. 2014). However, irrigation systems with improved performance are still needed, especially to apply water to the potted plants. Excess irrigation applications to the potted plants cause disease, contamination of ground water and low yield (Klock-Moore and Broschat, 2001b). Many studies have been conducted to find efficient water application approaches to the potted plants (Dole et al. 1994). A drip irrigation system is a widely used method to irrigate crops as efficiently under protected cultivation. The sub-irrigation system is an efficient water application model to save wage, time and water than other methods (Dole et al., 1994). Due to high installation cost it has yet to find its way and the smallholder farmers have limited capital to install the drip irrigation system (Wesonga et al., 2014). Three types of capillary irrigation have been reported since introduced 1970's. Recirculating irrigation system, ebb-and-flow has been presented as a good technique to decrease runoff. However, it needs accurate skill to make water flooded evenly over concrete floors than other systems (Kwon et al. 1999). The mat moistened with nutrient solution is another method to irrigate pot plant production. This method has a problem that the plant roots may come out of the pots through the bottom and perforate the mat (Klock-Moore and Broschat, 2001a). The roots are damaged while transporting (Kwon et al., 1999). Myung et al (2007) analyzed the water contents of root media for different wick lengths, pot sizes and media compositions to determine the adequate irrigation conditions in a nutrient-flow wick culture (NFW) system. This study found that the fluctuation of water content became greater with a decrease in pot size in the NFW system. All factors, such as wick length, pot size, and medium composition, influenced the water content of the medium in the NFW system. The water content in the media was increased by more than 8% and 5% in 2 cm and 3 cm wick lengths within 15 minutes respectively.

Unfortunately, there are few studies about the optimal moisture content of soilless substrates in pots, the hydraulic characteristics and water content of growing medium in wick irrigation systems. However, Kirkham and Powers (1972) reported that optimum moisture content for plant growth in mineral soils is 25% of the soil volume. Son et al. (2006) reported that the water content range of 30% to 60% in growing medium produced good growth in Kalanchoe. The capillary wick system consists of a fabric strip which is put on the pots from the bottom and absorbs water from a water reservoir delivering to the root zone. Research has already been carried out on a capillary wick irrigation system (CWS) for potted plants in Japan and South Korea (Kwon et al., 1999). This system cannot raise water to more than 20 cm. In relation to this issue, (Wesonga et al., 2014) reported that the maximum capillary height of wick materials ranged from 14 to 19 cm. Therefore, the precise water application will continue to be of great importance, and global society needs to develop strategies on developing efficient methods for water use for agriculture. In this present study, we conducted some experiments to determine hydraulic characteristics of the capillary wick irrigation system from the top such as uniformity coefficient and distribution uniformity as the relevant parameters for irrigation management. Also, until now, very limited attention was given to the hydraulic characteristics and water content of different growing media for potted plant cultivation under CWS. So, there is a need for making agricultural water use less wasteful and more efficient through enhancing and applying the existing irrigation science and technologies (Hsiao et al., 2007). Therefore, this study investigated the hydraulic characteristics of cost-effective water-saving capillary wick irrigation system, and evaluated its performance for the best management practices in smallholder farming.

1.2 Problem Statement

The value of farming is on the rise again. After years of neglect, smallholder farmers are resuming their position as a major focus for development (World Bank, 2013). In part, this reflects a broad international consensus that land, soil, and water are part of an emerging ‘critical nexus’ of issues facing the world’s population. The high performance of drip irrigation is no doubt. It saves a substantial amount of water and labor, increases yields, and often also improves the quality of the produce. However, the higher investment and energy cost limit the development of the low-cost irrigation system for subsistence farmers. There has been an immense interest in developing and promoting the low-cost and water-saving drip irrigation system appropriate for smallholder farmers and greenhouse crop production.
Lee et al. (2010) investigated subirrigation using capillary wick system for specialized pot with wick in the bottom (13.5 cm diameter x 10.5 cm height). It seemed in the investigation that the height of the pots were limited due to the wick ability to rise water to the upper part of the pots. Moreover, Wesonga et al. (2014) conducted experiments on capillarity action, water holding capacity and maximum capillary height for five types of wick materials. They concluded that the maximum height of capillarity is less that 20 cm. However, wick irrigation system can be applied in the bottom and from the top of the pot, but studies have not been bublished on wick irrigation from the top. To conclude, this work focused on applying wick irrigation from top to deliver enough water for the medium size pots provided the system assembly does not cost a lot.

1.3 Aim and Objectives

The aim of this study is to investigate the water and solute movement and the hydraulic characteristics for the development of the cost-effective water-saving capillary wick irrigation system in potted growing media and the best management practices. The specific objectives are:

1. To develop of an equation for compensating wick emitter discharge by replacing the pressure head of a drip emitter with capillary height in wick emitter

2. To develop wick water application strategies in response to plant growth.
3. To simulate two-dimensional water movement and solute transport in potted media under capillary wick irrigation system.

1.4 Importance of Study

The equation developed for cotton-bonded non-woven wick material will help to determine the discharge rate of the wick material. Also, the amount of water is discharged from the wick emitter can be quantified and controlled by the developed equation. The methods used for determining the hydraulic characteristics of the wick material, can be used to evaluate the performance of the other wick materials such as woven wick and nylon wick. Moreover, simulation of water movement and solute transport under wick irrigation enable farmer and researchers to schedule irrigation time and fertigation for the best management practices.

1.5 Scope of Works

The research approach included developing the equation of compensating drip emitter into the equation of wick emitter, and evaluating capillary wick irrigation system under greenhouse experiments.

1. Laboratory experiments conducted to determine the hydraulic characteristics of the wick material.
2. Finding the governing factors affecting the wick discharge rate.
3. Replacing the coefficients of compensating drip emitter with the new coefficients found for the wick material.
4. Developing water application strategies based on three irrigation schedules.

5. Simulation of 2D-water movement and solute transport using HYDRUS 2D/3D.

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