Modeling hydraulic performance of a drip irrigation network directly coupled to a photovoltaic pumping system

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Abstract: Drip irrigation network coupled to photovoltaic pumping system presents an alternative solution that can efficiently improves use of water and energy by small and medium irrigated farming systems compared to conventional energy use for water pumping. Standalone photovoltaic water pumping systems (PVWPS) coupled to drip irrigation network constitute the best technico-economical solution compared to PVWPS using electrical or water storage demanding additional cost for the storage device. However, the standalone PVWPS need adequate process control to optimally be coupled with a drip irrigation network as adaptation between variable irradiance inputs and hydraulic outputs are needed to overcome problem of emission uniformity instability that can affect the hydraulic network performance. This study aims to improve the performances of a drip irrigation network coupled to a standalone photovoltaic water pumping system by evaluating the impact of irradiation variation on the hydraulic performances of microirrigation networks based on the calculation of emission uniformity coefficients (five indicators). A Matlab/Simulink hydraulic model was developed to simulate a drip irrigation network confronted to variable hydraulic behaviours due to irradiance change. Evaluation of the hydraulic performances showed that irradiance change affects water distribution uniformity of the irrigation network. Emission miss uniformities up to 10% were showed when lower irradiance input occurs. This problem can be solved by proposing hydraulic point tracking that adjust the network impedance with the photovoltaic generator input and irradiance occurrence.

Keywords: drip irrigation, standalone, photovoltaic pumping system, performances, hydraulic, emission uniformity.

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1 Introduction

Drip irrigation is a powerful alternative compared to traditional irrigation systems despite it generates energetic effects resulting from conventional sources of energy (Arya et al., 2017). Then, the use of photovoltaic water pumping system (PVWPS) could be considered as a promising solution for small and medium-irrigated farming systems (Tamoli et al., 2017). Use of photovoltaic energy for water pumping is perceived as an interesting option for drip irrigation systems to satisfy water requirements during high demand periods (Barlow et al., 1993). Moreover, Photovoltaic energy is available at any point for use and don't need supplementary costs for supply and transportation. The PV solution allows small and medium-sized farmers to reduce energy costs as operating and maintenance of PV systems are the lowest compared to others energy sources (Abu-Aligah, 2011). Farmers have to choose between three types of PVWPS: standalone PV system coupled directly to microirrigation network (1), PV system with storage of electrical energy (2) or with storage of hydraulic energy (3). The first PV system can represent the best techno-economic solution as no additional cost is required for

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storing energy (Bhatia, 2014). However, the PVWPS coupled directly to irrigation network cannot be easily adopted if the hourly variations of incident irradiance are not managed to avoid variations of operating pressure and its impact water emission uniformity in the hydraulic networks (Mashay and Abbood, 2019).

This study consists on evaluating pressure variation and its impact on hydraulic performance of a microirrigation network coupled directly to a PVWPS. It aims to develop a hydraulic model to evaluate hydraulic performance of a microirrigation network using Matlab/Simulink software.

2 Materials and methods

A small microirrigation network coupled directly to PVWPS (water tank, DC pump, manifold and laterals) was approached as matrix of control volumes (CV) for each dripper. A succession of equidistant drippers along an irrigation lateral is subject to decreasing gradients of friction loss, pressure and flow rate from upstream to downstream sides. The pressure decrease along the flow axis of a lateral can be approximated by computing consecutively pressure drop and pressure gradient from on CV to another by applying the laws of mass conservation and energy on each control volume.

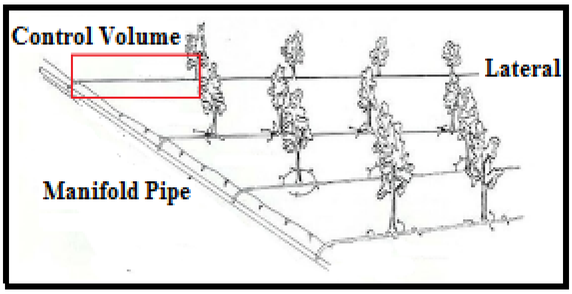

Figure 1 Representation of a control volume on a lateral microirrigation (Zella et al., 2003)

A computing model is based on CV to solve equations of the conservation of mass and energy (Equation 1) and relative friction loss (Equation 2):

$$\frac{dQ}{dx} = -q = -F_Q \frac{k}{s} \times h^{k_1} \quad (1)$$

Where q, kh^{k_1}, k and k_1, h, s, and F_Q are discharged flow per unit length in (L h^{-1}), exponential relationship of the dripper, constants depending on the type of the dripper and its flow regime, pressure head (m), distance between drippers (m), conversion factor from L h^{-1} to m^3 s^{-1} ($F_Q = 2.7777 \times 10^{-7}$), respectively.

The Darcy-Weisbach equation is used for computing friction losses:

$$h_L = f \times \frac{L}{D} \times \frac{V^2}{2g} \quad (2)$$

Where f, L, D, V, and g are friction factor, length of pipe (m), diameter of the pipe (m), average flow rate (m s^{-1}), and acceleration of gravity (m s^{-2}), respectively.

Estimation of the friction factor f is done using Equation 3 for a laminar flow and Colebrook-White equation (Equation 5) for a turbulent flow:

$$f_{lam} = \frac{64}{Re} \quad (3)$$

$$Re = \frac{\rho V D}{\mu} = \frac{VD}{\vartheta} \quad (4)$$

Where Re, ρ, μ, and ϑ are Reynolds number, density of the fluid (kg m^{-3}), dynamic viscosity (kg m^{-1} s^{-1}), and kinematic viscosity (m^2 s^{-1}), respectively.

$$\frac{1}{\sqrt{f}} = -2\, log_{10}\left(\frac{\varepsilon/D}{3{,}7} + \frac{2{,}51}{Re\sqrt{f}}\right) \quad (5)$$

With ε as absolute roughness of the pipe wall (mm)

2.1 Hydraulic model layout

An algorithm has been developed to compute pressure drop coefficient and flow rate in order to be integrated into the main hydraulic model developed in Matlab/Simulink.

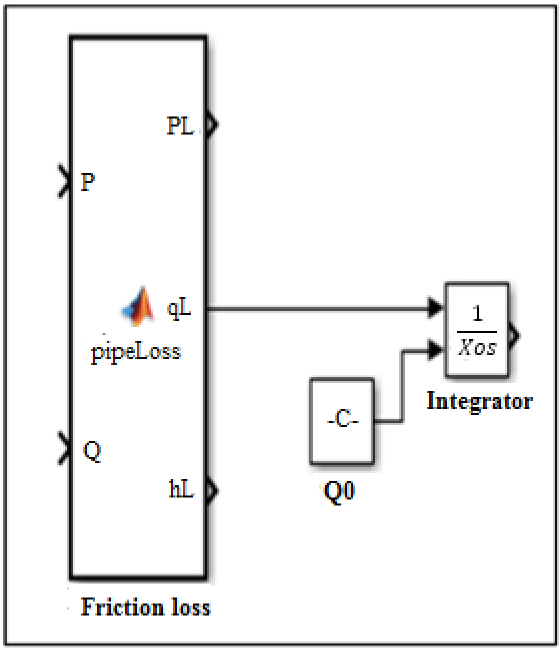

Figure 2 Structure of the hydraulic model under Matlab/Simulink

2.2 Hydraulic model input data

Data of the dripper "NETAFIM Typhoon 16250 Dripline" (NETAFIM™) were used to simulate a case of a hydraulic network of 100 CVs in the developed Model:

Nominal flow rate of 8 L h^{-1},

Distance between drippers of 1 m,

CV length of 1 m,

Lateral internal diameter of 15.5 mm and

Flow coefficients of the dripper (Equation 1 and 3) are k = 2.773 and k_1 = 0.46.

2.2.1 Configuration of the CV model

The CV model requires two inputs for hydraulic computing; an initial flow rate for the integration modules and an initial pressure to compute relative friction loss and deduce the output pressure.

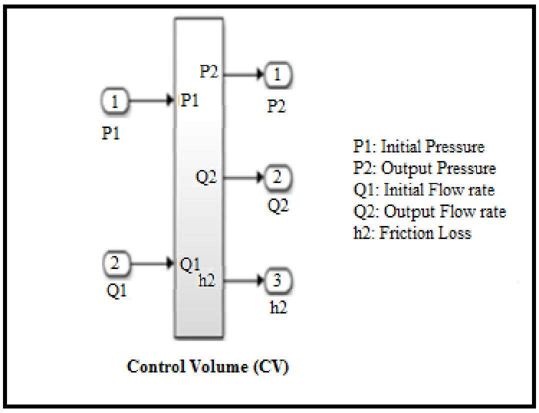

Figure 3 Layout of CV model in Matlab / Simulink

The CV model has three outputs of pressure, flow rate and friction loss.

2.2.2 Configuration of the lateral model

Computation model of a lateral is designed as a set of interconnected CVs (Outputs of a previous CV (CV_{i-1}) are the inputs of the following CV (CV_i)). The lateral model has two inputs of pressure and flow rate. The lateral inputs are the inputs of the first CV (CV_1) of the lateral.

Figure 4 Layout of lateral Model in Matlab / Simulink

2.2.3 Configuration of the manifold model

A case of a hydraulic model is presented to simulate an irrigation manifold of 10 CVs deserving 10 lateral booms. The 10 CVs of the manifold model are interconnected (Outputs of a previous CV (CV_{i-1}) are the inputs of the following CV (CV_i)) to transfer data of pressure, flow and friction loss as inputs of the next manifold CV and of the derivative lateral from this CV.

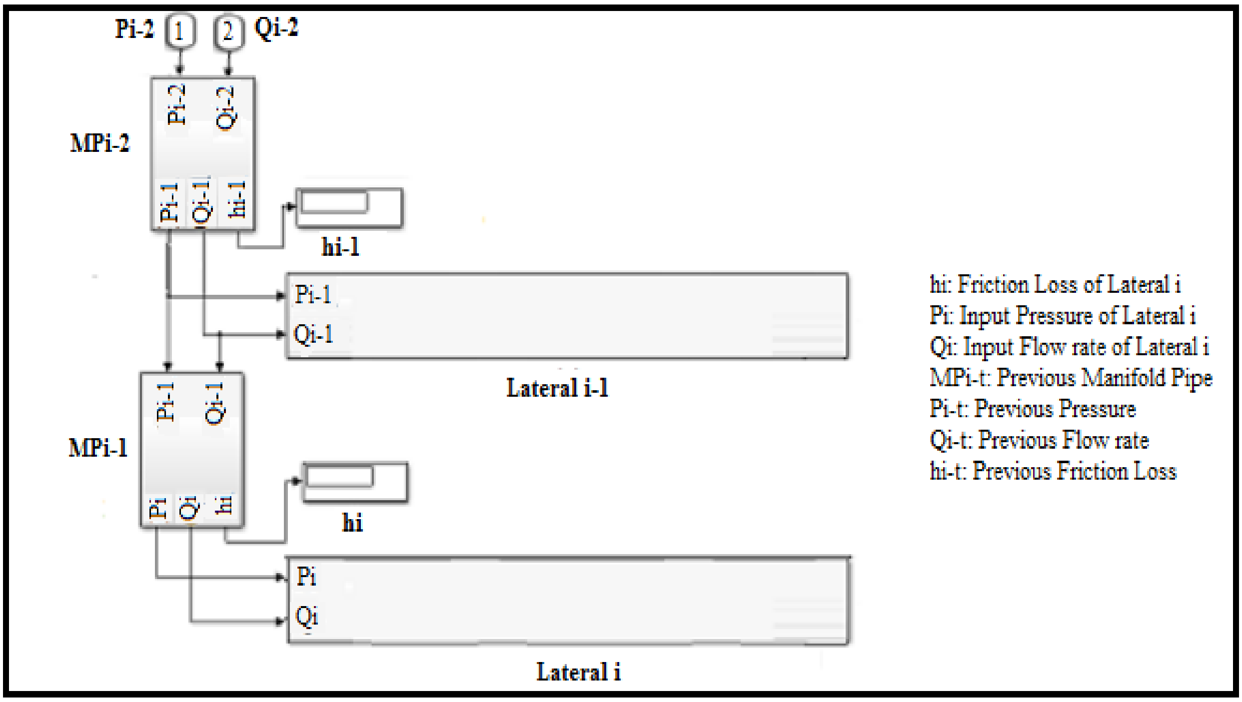

Figure 5 Layout of Manifold CV and derivated lateral in Matlab/Simulink

2.2.4 Configuration of the network model

A study case of a hydraulic network model of 100 CVs (10 lateral booms of 10 CVs) is implemented using

Matlab / Simulink. It concerns crop irrigation network having a standard spacing of 1 m between drippers. A network of 100 m^2 (one manifold of 10m connected to 10 laterals having length of 10 m, coupled directly to DC pump supplied by PV generator is computed to provide outputs of 100 values of pressure, flow rate and friction loss for each CV.

The outputs were used for approaching the network emission uniformity using five indicators: Coefficient of Christiansen uniformity CU (Christiansen, 1942; Zoldoske and Solomon, 1988; Keller and Bliesner, 1990; ASAE, 1983; Kang and Nishiyama, 1995), Field emission uniformity EU_f (Keller and Karmeli, 1974; Merriam and Keller, 1978; Kruse, 1978; Almehmdy, 2011; Mistry et al., 2017), Absolute emission uniformity EU_a (Keller and Karmeli, 1974; Mistry et al., 2017), Coefficient of variation Cv (Hart and Reynolds, 1965; Solomon, 1979; ASAE, 1996; Mistry et al., 2017) and Statistical uniformity coefficient SUC (Bralts et al., 1981; Bralts and Kesner, 1983; ASAE, 1996; Mistry et al., 2017).

Those indicators were used to evaluate effect of variable pressure at the upstream level of the irrigation network directly coupled to the PVWPS with reference to trend of daily irradiance variation. The pressure variation impacted performance of the microirrigation network.

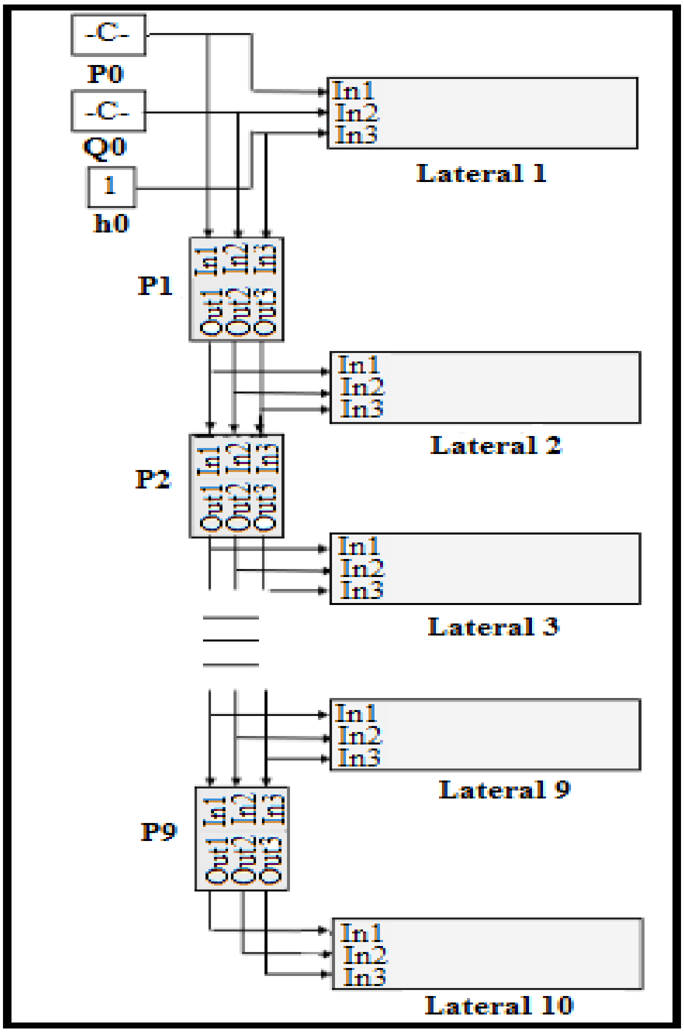

Figure 6 Layout of the irrigation network model in Matlab / Simulink

3 Results and discussions

A simulated case of a microirrigation network of 100 m^2 is done using experimental output data (Table 1) taken from experimental test of a PVWPS (Harkani et al., 2019). Output datas of the PVWPS were used as input data for modeling performance of the microirrigation network (Table 1). Pressure and flow rate data timely vary as a function of daily irradiance.

Distinction between three levels of input pressure was done to simulate three cases of the network performances:

High pressure (1.5 bar < P < 3 bar),

Normal pressure (0.7 bar < P<1.5 bar),

Low pressure (P< 0.7 bar).

Table 1 Input data (Harkani et al., 2019)

Hour	Irradiance (W m^{-2})	Pressure (bar)	Flow rate (L min^{-1})
8 h	90	0.33	3.84
9 h	280	1.10	7.2
10 h	540	2.78	11.7
11 h	610	3.30	14.04
12 h	520	2.66	11.46
13 h	280	1.12	7.27
14 h	520	2.67	11.47
15 h	514	2.20	10.36
16 h	370	1.70	9.04
17 h	130	0.69	5.68
18 h	68	0.05	1.36

Hydraulic performance indicators of three levels of high, normal and low pressure were presented (Figures 7, 8 and 9) to show high, normal and low distribution profiles. These figures show that the pressure and flow rate values decrease with increasing boom and boom carrier length.

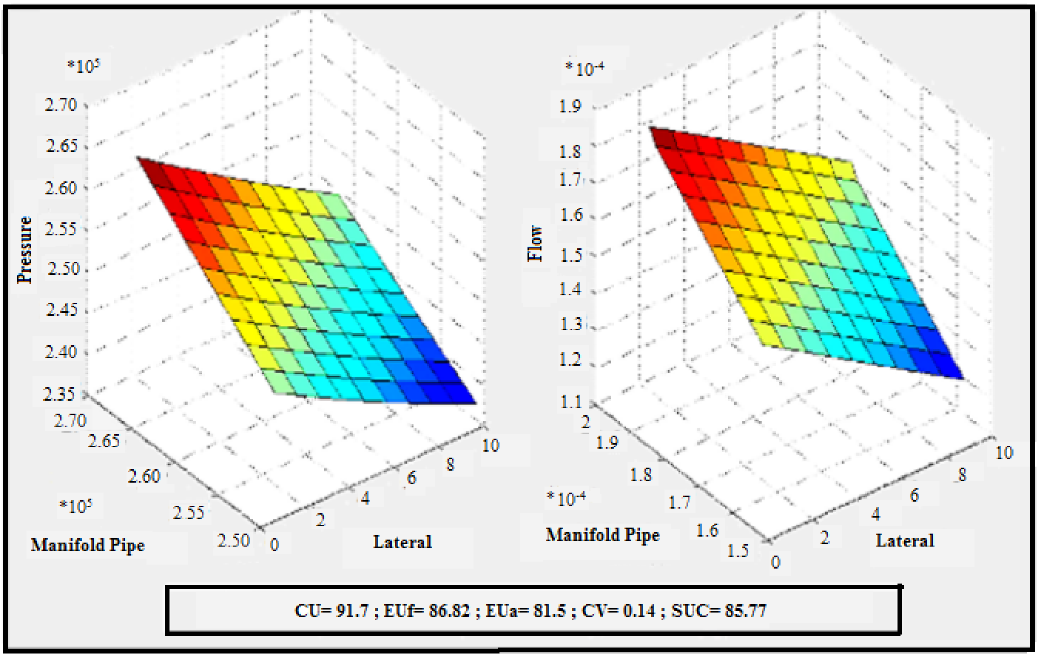

Figure 7 Pressure and flow profiles for the case of high pressure

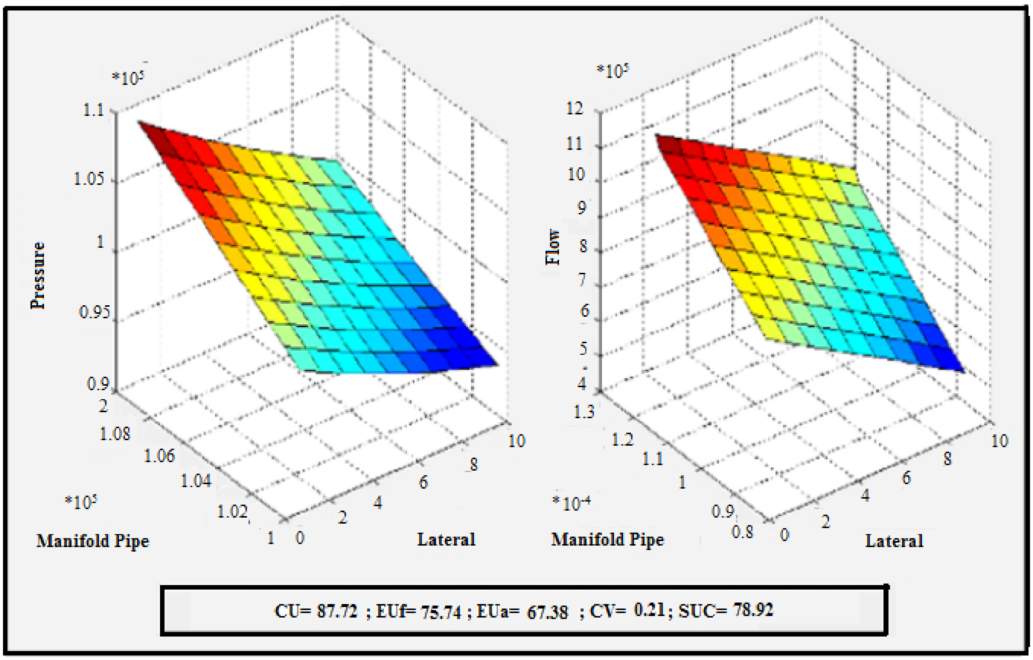

Figure 8 Pressure and flow profiles for the case of normal pressure

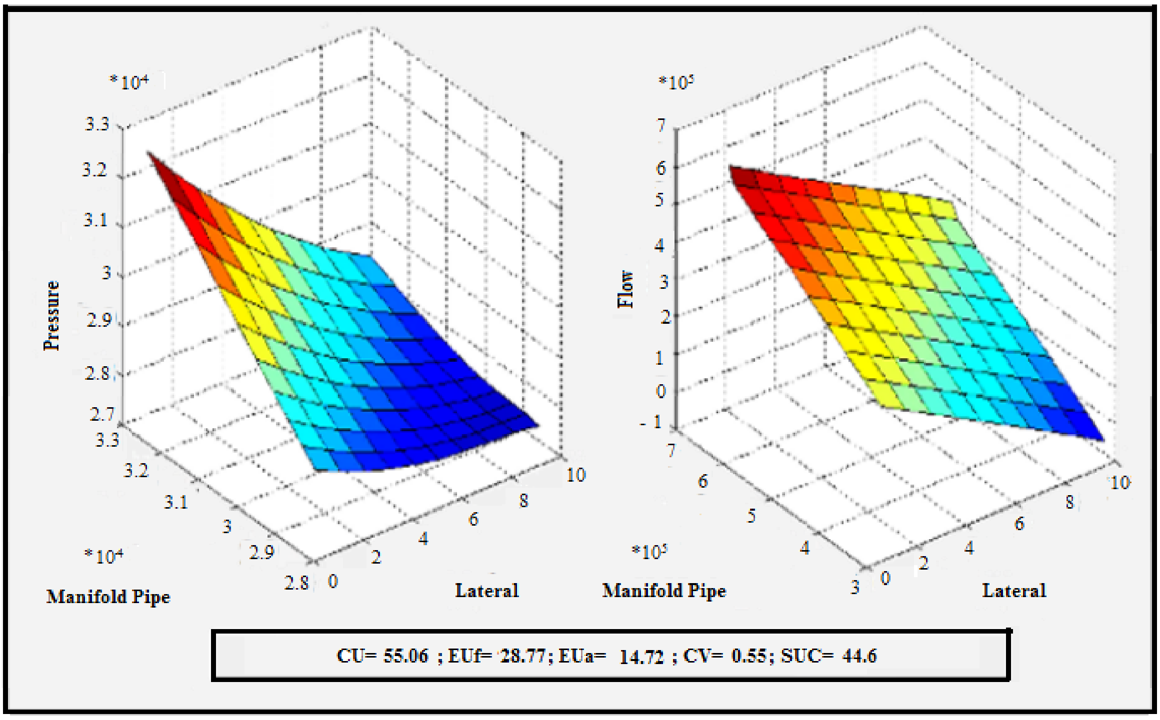

Figure 9 Pressure and flow profiles for the case of low pressure

3.1 High pressure case

Figure 7 shows profiles of pressure, flow for the case of high pressure (P = 2.67 bar). The indicators of emission uniformity (Fig. 10) showed good network performance. The coefficient of variation (Cv= 0.14) for this case is considered as good to show better performance of water distribution compared to standard (Cv_s= 0.15).

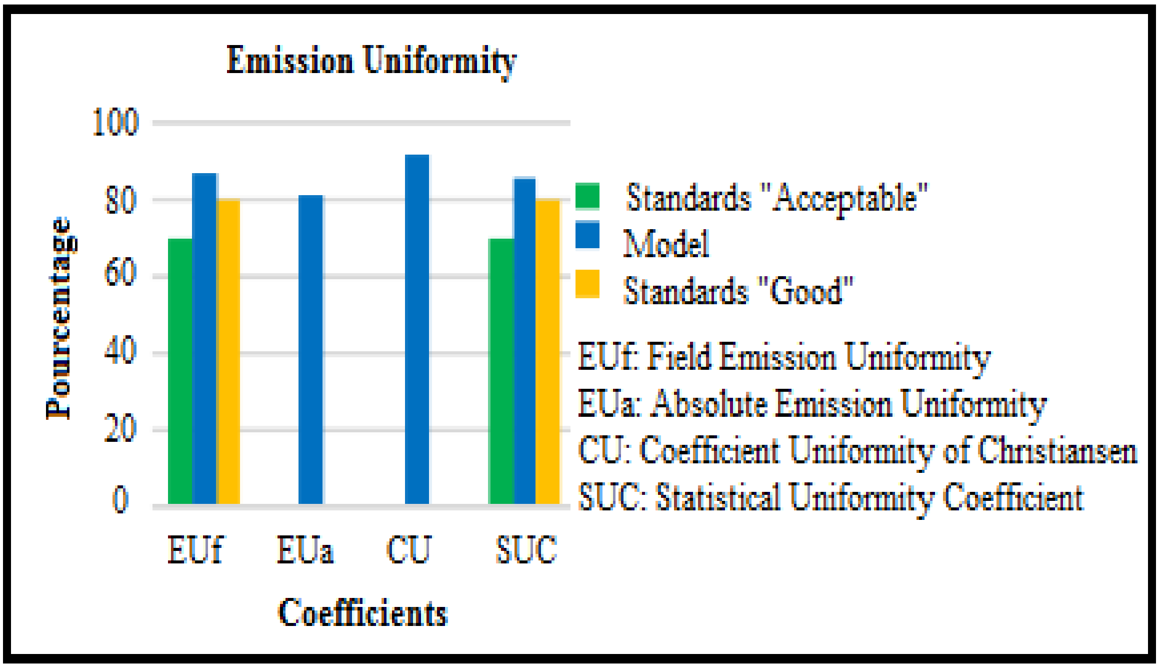

Figure10 Network emission uniformity (Case of high pressure input)

3.2 Normal pressure case

Figure 8 shows profiles of pressure and flow distribution for the case of normal pressure (P = 1.1 bar). Figure 11 illustrate as in the previous case, that emission uniformity indicators are good to show that water distribution is good for better network performance (Figure 11). However, the computed Cv for this case of normal pressure is 0.21 to show relatively low water distribution compared to standard (Cv_s= 0.15).

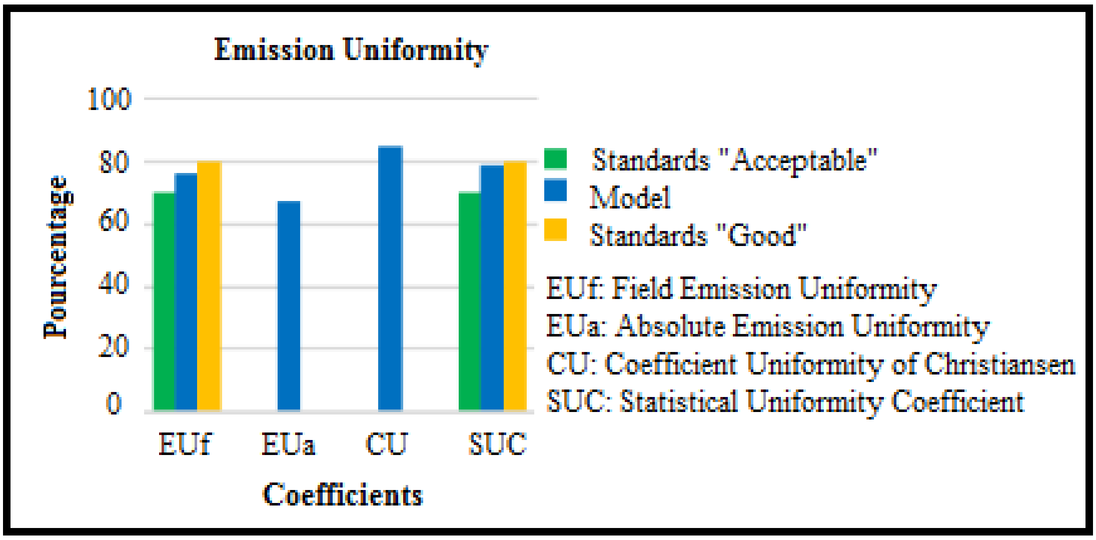

Figure 11 Network emission uniformity (Case of normal pressure input)

3.3 Low pressure case

Figure 9 illustrates pressure and flow profiles for the case of low pressure (P = 0.33 bar). Negative flow values are observed in the last laterals. Figure 12 represent the emission uniformity coefficients for the case of low pressure (P = 0.33 bar) to show that water distribution in the network is low.

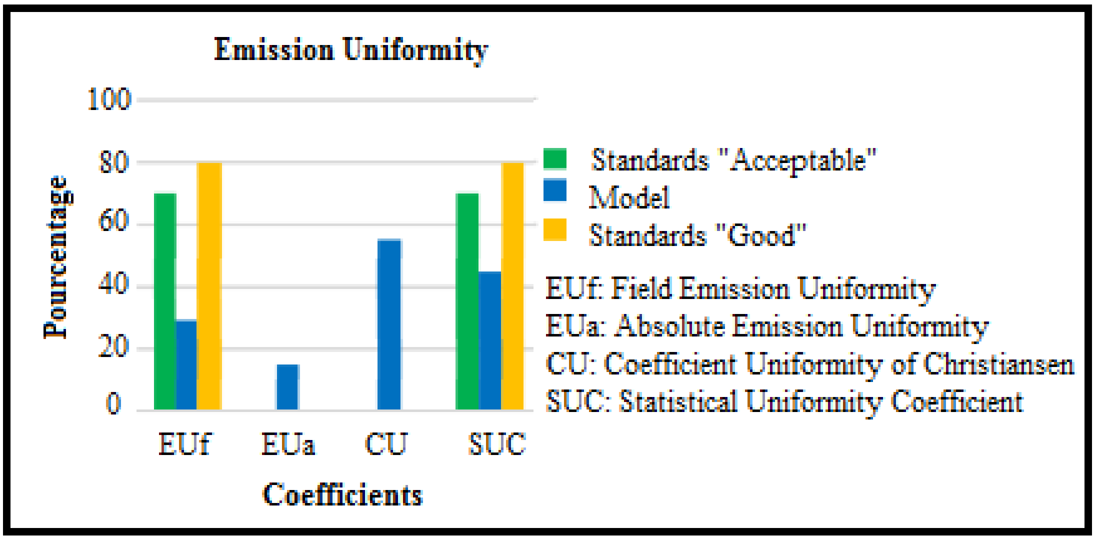

Figure 12 Network emission uniformity (Case of low pressure input)

For this case of low pressure, the emission uniformity indicators are the lowest to show effect of low pressure on water distribution in irrigation network. This case can occur when irradiance is low.

The statistical uniformity coefficient (SUC) is the lower to be unacceptable. The Cv is 0.55 considered as bad compared to standard (Cv_s= 0.15).

4 Conclusions

This study aimed to evaluate the hydraulic performance of a PVWPS coupled to a microirrigation network by means of emission uniformity coefficients of water. A model of calculation has been developed in Matlab/Simulink environment to simulate water uniformity distribution in microirrigation networks. Simulation of three cases of operating the hydraulic network at high, normal and low pressure levels proportionally to three levels of high, normal and low irradiance was carried out.

Results showed better water emission uniformity for high and normal pressures compared to the case of low pressure. The coefficients for the case of low pressure are below the acceptable standards to show impact of operating irrigation network when low irradiance is occurring. This problem can be solved by proposing hydraulic point tracking to adjust the network impedance with the photovoltaic generator input and irradiance occurrence. In perspective of this work, it will be interesting to generalize the simulation approach to be the subject of a study to simulate a modular hydraulic network in terms of width, length and an undetermined number of laterals.

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Nomenclature:

Symbol Meaning

PVWPS: Photovoltaic water pumping system

PV: Photovoltaic

CU: Coefficient uniformity of Christiansen

EU_f: Field Emission Uniformity

EU_a: Absolute Emission Uniformity

Cv: Coefficient of Variation

SUC: Statistical Uniformity Coefficient

CV: Control Volume

Cv_s: Coefficient of variation standard

P: Pressure

q: Discharged flow per unit length in (L h^{-1})

k and k_1: Constants depending on type of dripper and its flow regime

h: Pressure head (m)

s: Distance between drippers (m)

F_Q: Conversion factor from L h^{-1} to m^3 s^{-1}

f: Friction factor

L: Length of pipe (m)

D: Diameter of the pipe (m)

V: Average flow rate (m s^{-1})

g: Acceleration of gravity (m s^{-2})

Re: Reynolds number

ρ: Density of the fluid (kg m^{-3})

μ: Dynamic viscosity (kg m^{-1} s^{-1})

ϑ: Kinematic viscosity (m^2 s^{-1})

ε: Absolute roughness of the pipe wall (mm)