World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:6, No:1, 2012

Effect of Greywater Irrigation on Air-Water Interfacial area in Porous Medium

A. H. M. Faisal Anwar

Abstract**—**In this study, the effect of greywater irrigation on air-water interfacial area is investigated. Several soil column experiments were conducted for different greywater irrigation to develop the pressure-saturation curves. Surface tension was measured for different greywater concentration and fitted for Gibbs adsorption equation. Pressure-saturation curves show that the reduction of capillary rise stops when it reaches its critical micelle concentration (CMC). A simple theory is derived from pressure-saturation curves for calculating air-water interfacial area in porous medium during greywater irrigation by introducing a term 'hydraulic radius' for the pores. This term diminishes any effect of pore shapes on the air-water interfacial area. The air-water interfacial area was calculated using the pressure-saturation curves and found that it decreases with increasing moisture content. But no significant effect was observed on air-water interfacial area for different greywater irrigation. A maximum of 10% variation in interfacial area was observed at the residual saturation zone.

Keywords**—**Greywater, Irrigation, Interfacial area, Surface tension, Porous medium.

I. Introduction

IN many countries, use of greywater in irrigation is increasing for the preservation of potable water. Greywater is a non-toilet component of household wastewater that is generated from bathtubs, showers, sinks, washing machines and dishwashers. Among these sources, laundry greywater are frequently used for irrigation because greywater originating from other sources (especially kitchen) may contain oil and grease [1-2]. Reuse of greywater is now becoming common in many arid and semi-arid regions in the world including Australia. In a typical household in Western Australia, total generation of greywater is 117 l/d per person [3]. Laundry and bathroom greywater contributes about 89% of this volume, which can be reused for the lawn/gardening watering. The domestic wastewater may generate effluents with reduced level of nitrogen, solids and organic matter, but often contain higher level of surfactants, oils, boron and salt [4-5]. These components of greywater may have harmful effects on soil, plants and underground water. Surfactants are the major components of detergents found in domestic wastewater which have hydrophilic head and hydrophobic tail [4-6]. Surfactant molecules in aqueous solution accumulate onto the interfaces and thus reduce interfacial tension [7-8]. Reduction of surface tension in greywater may change the underlying soil structure and thus the capillary pressure in soil.

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The interaction between laundry greywater and the saturated soil has been studied to quantify the soil hydraulic conductivity [9] in different soil samples. Shafaran et al. [4] suggested that accumulation of surfactants from greywater may lead to water repellent soil. But still limited information is available regarding the effects of surfactants, commonly present in laundry and household detergents, on hydro-physical properties of aquifer including air-water interracial area. Air-water interfacial area (a_i) is an important parameter that describes the pore scale distribution of air and water inside the porous media which may be affected due to the irrigation of surfactant-rich laundry greywater. The relationship between air-water interfacial area, water saturation and capillary pressures are of interest for many reasons such as, modeling of water and solute transport in vadose zone. Such relationships have been investigated using several methods include: thermodynamic treatment on pressure-saturation relationship [10], pore network model [11-12], and simplification of pore geometry [13-15]. Verifications or comparisons of most of these models were far away with that of experimental results because of experimental inaccessibility to this parameter for a long time. Successful experiments include: use of interfacial tracer technique [7, 16-18], imaging technique [19-20] and more recently, the use of Synchrotron X-ray Microtomography [21-22]. But to date, there is no study showing the effect of greywater irrigation on air-water interfacial area in unsaturated soil. In this paper, drainage pressure-saturation relationships are developed for different greywater irrigation in a laboratory column. Surface tension of different greywater solution was measured and Gibbs adsorption equation was fitted. Air-water interfacial area was calculated using the soil characteristics curves and corresponding surface tension from Gibbs equation. Results are obtained for different greywater irrigation and air-water interfacial area is presented with moisture content for variably saturated soil.

II. Theoretical Background

A. Estimation of air-water interfacial area

A porous medium is composed of solid matrix and a numerous number of interconnected pores of various sizes and shapes. During the wetting process of porous media, first the smaller pores begin filling up and successively larger pores become saturated. During the drainage process, the system becomes reverse. As the drainage proceeds, from larger to smaller pores are drained leaving the pore walls covered with a thin liquid film. This assumption was first used by Cary [15] and later Anwar and Matsubayashi [23] for determining fluid-fluid interfacial area in porous medium. The simplest model for describing pore structure is the capillary bundle tube consisting of numerous cylindrical capillary tubes with different diameters but same lengths [24]. In reality, the capillary pores may be of any shapes. In order to avoid the differences in pore shapes, a term “hydraulic radius (R)” is introduced for pores. The R is defined as the ratio between the cross-sectional areas of pores of any shape to their wetted perimeter. The introduction of hydraulic radius could diminish any shape effects arising from the pore shapes. After drainage, the hydraulic radius R (cm) of drained pore may be calculated as:

$$R = \frac{\sigma}{\psi \rho g} \tag{1}$$

where ψ is capillary rise (cm), and σ is surface tension (dyn/cm), ρ is the fluid density (gm/m^3) and g is the gravity (m/s^2) . The specific air-water interfacial area (a_i) is defined as the ratio of total interfacial area between air and water to the total volume of porous medium which can be expressed as [23]:

$$a_i = \frac{\rho g}{\sigma} \int_0^{\theta_a} \psi \, d\theta_a \tag{2}$$

where $d\theta_a$ is the incremental volumetric air content (cm^3/cm^3) in the pressure-saturation curve. Hence, the Eq. (2) needs only drainage pressure-saturation (ψ-θ) curve to calculate air-water interfacial area in unsaturated porous medium.

B. Surface tension and surfactant adsorption

Surface tension in surfactant-rich greywater is reduced because of the accumulation of surfactant monomers onto the air-water interface. Thus the concentration of surfactant at the air-water interface is larger than the concentration of surfactant in the bulk. The excess concentration of surfactant at the surface is called the Gibbs surface excess and is designated by Γ (mol/cm^2). It is generally determined by Gibbs adsorption equation, using the relationship between surface tension, σ (dyn/cm) and the bulk surfactant concentration, C (mol/cm^3) [25]. As the specific surfactant is unknown in the laundry greywater in this study, concentration C was taken as the greywater concentration. The Gibbs equation is expressed as [25]:

$$\partial\sigma = -RT\Gamma\partial(\ln C) \tag{3}$$

where T is absolute temperature (^{0}K) and R is the ideal gas constant. Since σ is a linear function of ln$C$ in the region of C< CMC (critical micelle concentration), Γ can be taken as constant in this region for a specific surfactant.

III. Materials and Experiments

A. Materials

A medium sand (d_{50}=0.48mm; ρ_b=1.68 g/cm^3; n=0.40 cm^3/cm^3) was selected as the porous matrix for this study. The soil medium was washed for several times using tap water and oven dried (at 105°C for 24 hrs) before sieve analyses (Method AS1289). The DUO 2X Ultra Concentrated Top Loader Aromatic Detergent Powder is selected as laundry detergent for greywater preparation based on the availability of required information in the literatures [26]. The concentrations of laundry greywater were calculated based on the full washing capacity of a washing machine and following the given instructions of DUO washing powder. Normal load wash and three cycles of wash and rinse were assumed and the greywater concentrations used in the experiments were, 0.1g/L, 0.26g/L, 0.44g/L and 0.6g/L respectively.

B. Column Experiments

The experiments were conducted in a laboratory soil column composed of several PVC rings of 9 cm inner diameter and 3 cm length as shown in Fig. 1. The column was packed successively with the soil in small increments under water saturated condition and tapped at the bottom. This procedure ensured the elimination of any trapped air and layer formation during the packing process. The effective length of the soil column was 54cm. The column was kept saturated for 1 hour and the outlet tank was brought down and kept the water level of the outlet tank at the same level of the bottom of the soil column. This arrangement could maintain the water level at the bottom of the soil column referring to groundwater table. The column was kept in this position for 24 hours to equilibrate the system. After establishing equilibrium in the system, the greywater of known concentration was flushed through the column and pH and EC at column outlet were measured in every two minutes interval. Total pore volume of the column was calculated as 1374 cm^3. Greywater irrigation continued until the EC of the column effluent became constant. To get constant EC at the column outlet, approximately 7.5 number of pore volume of greywater solution was flushed into the column for 120 minutes. The flow velocity of greywater flushing was on an average 3.27cm/min. The column was again kept 24 hrs to establish equilibrium in the system and then the column was dismantled [7]. The moisture content in each ring was measured gravimetrically and the suction head corresponding to each ring was taken as the distance between the ring’s mid-point and the bottom water level [7]. The same experiment was repeated for different greywater concentration and one experiment was done with tap water at the beginning to compare with the greywater irrigation. The porosity of soil was taken as the saturated moisture content and the bulk density was calculated for each ring gravimetrically. All the experiments were conducted at room temperature (22±1^{0}C).

C. Surface Tension Measurements

Surface tension of greywater with different concentration was measured by the Wilhelmy plate method [7], with the help of a surface tensiometer (Sigma 700). First, the platinum Wilhelmy plate was cleaned, burned on a Bunsen burner and 3/4 of the plate was wetted by the greywater solution. The plate was positioned hanging on a balance and the solution level was automatically increased until it touched the plate. The increase of the weight was recorded by the electronic balance and was converted to surface tension directly. The measurements were taken at the room temperature of 22±1^{0}C for a range of greywater concentrations (0-500 mg/l).

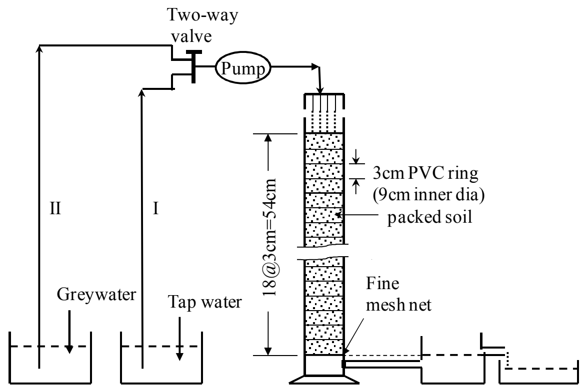

Fig. 1 Experimental setup

IV. RESULTS AND DISCUSSION

A. Surface Tension Reduction

Accumulation of surfactant molecules onto different interfaces reduces the interfacial tension. As greywater contains substantial amount of surfactant, it also reduces the surface tension. In this study, surfactant present in laundry detergent is unknown. For this reason, surface tension of greywater (as a whole) was measured for different concentration and presented in Fig 2. The concentration was converted to logarithmic value in order to fit the Gibbs adsorption equation [Eq 3]. When all the interfaces are saturated with surfactant molecules, there is no reduction of surface tension and hence the concentration refers to critical micelle concentration (CMC). The CMC value for the greywater used in this study was found as 280 mg/L. Usually CMC is determined for a specific surfactant but the surfactant in the detergent is unknown in this study. As the interfacial area is calculated for greywater irrigation, it is reasonable to look at the surface tension reduction for the greywater as a whole.

B. Pressure-saturation relationship (ψ-θ curve)

During each column experiments, the moisture contents in each ring were measured gravimetrically and the capillary rise was taken as the distance between the groundwater table and the mid-point of each ring. The pressure-saturation curves for each experiment are plotted in Fig. 3. Capillary rise is a phenomenon that can have both beneficial and detrimental effects on the soil. It is a main mechanism by which plants can draw water from below the root zone, but it is also a mechanism contributing to the accumulation of salts in the soil. The reduction of capillary rise with increasing greywater concentration is mainly because of the surface tension reduction as described by the capillary theory. Figure 2 revealed that the surface tension reduction continues until the greywater concentration reaches its CMC value. The reduction of surface tension consequently changes the migration pattern in the soil pores. Figure 3 revealed that the capillary pressure decreases sharply at the lower concentration of greywater but have a little effect at the higher concentration. This is because the surfactant monomers form micelles when the entire interfaces are saturated with monomers and the concentration reaches its critical value. Though the specific surfactant in DUO detergent is unknown in this study but several studies show that anionic and non-ionic surfactants are present in detergents [4-5]. Shafran et al. [4] reported that it is only the surfactant in laundry detergent has the influence on the reduction of surface tension, not any other ingredients present in it. Another explanation for decrease in capillary pressure is embedded in the mechanism of surfactant adsorption onto the soil surfaces. Shafran et al. [4] performed experiments with the pure surfactants normally present in laundry detergent such as linear alkylbenzene sulfonate (LAS) and found that the electrostatic bonds of negatively charged sulfonate groups interact with the positively charged sand surfaces causing the adsorption of hydrophobic tails of LAS monomers and protruding into the aqueous phase.

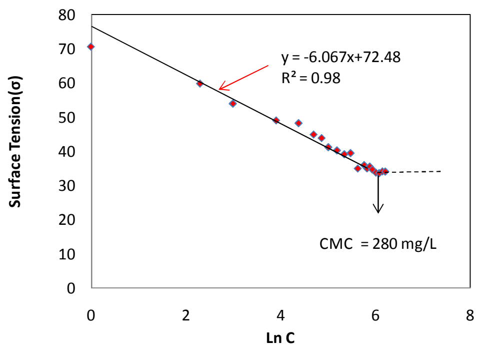

Fig. 2 Surface tension reduction with greywater concentration

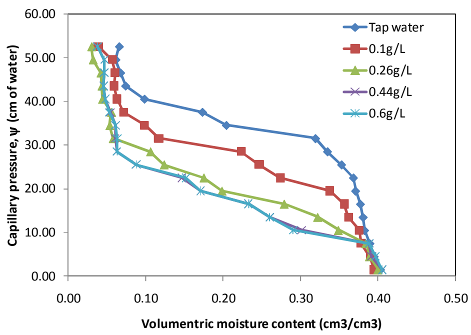

Fig. 3 Pressure-saturation (ψ-θ) curves for different greywater irrigation

C. Air-water interfacial area

The air-water interfacial area was calculated using Eq. (2) for different ψ-θ curves and presented in Fig. 4. Most of the pressure saturation relationships only describe the region where both fluids are continuous. It does not provide any information below the residual saturation. Thus the interfacial area calculated using Eq (2) is strictly valid for variable region of saturation. The air-water interfacial area must pass through a maximum and return to a zero value when saturation tends to zero [14]. It may be explained as the saturation increases from zero, interfacial area should also start from zero and pass through a maximum value and return to zero at the saturated condition. Results revealed that the interfacial area increases with decreasing water saturation up to residual condition. This provides the general behavior of the system that available interfacial area should decrease with increasing saturation. However, quantitative behavior of interfacial area in the residual zone of saturation has not yet been investigated [14]. According to Eq (2), air-liquid interfacial area is related to $\rho\psi/\sigma$ where ρ/σ is the chemical property of the liquid (solute). Again, capillary pressure or suction head (ψ) is inversely proportional to ρ/σ. Thus the term $\rho\psi/\sigma$ in Eq (2) would be the same for a particular porous media using any liquid to develop ψ-θ curve. Thus air (or gas)-liquid interfacial area for the porous media calculated by Eq (2) may be true for any air-liquid system present in the porous medium. In the current research, the surface tension is reduced until it reaches its CMC value and thus it follows the capillary reduction accordingly. Thus, theoretically there should not be any effect on the air-water interfacial area for capillary reduction as long as the assumption of capillary theory is valid. For this reason, the interfacial area found in this study for different greywater irrigation does not show any significant variation. However, a maximum of 10% variation was observed at the residual saturation zone.

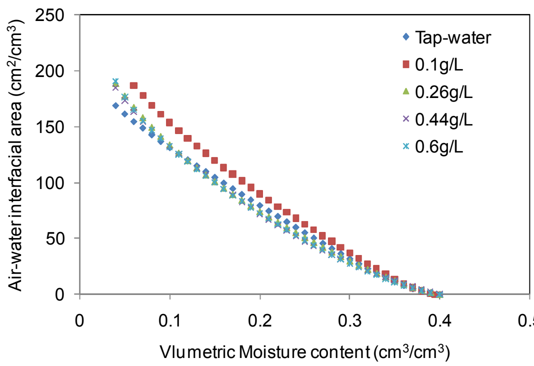

Fig. 4 Effect of greywater irrigation on air-water interfacial area

V. Conclusion

The use of greywater in irrigation is rapidly increasing in many countries but it may change the underlying soil hydrologic parameters. In this research, the effect of laundry greywater irrigation on air-water interfacial area is investigated. A soil column composed of several PVC rings were used to develop the pressure saturation curves for different greywater concentration. Results revealed that the capillary rise is reduced for greywater irrigation due to the surface tension reduction. Separate experiments were done for Surface tension measurements for greywater and the CMC value was obtained fitting the Gibbs adsorption equation. Results revealed that the reduction of capillary rise stops when it reaches towards the CMC value. The air-water interfacial area was calculated using a simple method derived from soil characteristics curve. The results revealed that the greywater irrigation does not have significant effect on the air-water interfacial area. The maximum variation in estimation was found 10% at the zone of residual saturation.

Acknowledgment

Author would like to acknowledge that most of the laboratory experiments were performed by Mr. Henry Hartono Gunawan.

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