SOLOS E IRRIGAÇÃO

GASEOUS IRRIGATION CONTROL SYSTEM: DESCRIPTION AND PHYSICAL TESTS FOR PERFORMANCE ASSESSMENT ([1])

ADONAI GIMENEZ CALBO ([2*]); WASHINGTON LUIZ DE CARVALHO E SILVA ([3])

ABSTRACT

Irrigas is a water tension measuring system made out of a porous cup (sensor), connected to a gas pressurizing/measuring device by a flexible tube. Water tension (T) is obtained from the equation T=Td-p or T=Ts-p, where Td is the sensor desorption critical water tension (bubbling beginning), Ts is the sensor sorption critical water tension (bubbling ceasing) and p is the applied gas pressure. Differently from conventional tensiometers, the irrigas porous cup cavity is filled with air. This characteristics makes the irrigas system nearly maintenance free and also eliminates the need of making hydrostatic pressure corrections for sensor depth. The system was tested both in the desorption and sorption modes. In the first case the Richards pressure chamber was used to adjus)t the soil water tension which makes the porous cup air permeable. The water tension thus obtained was always practically equal to the Td values measured by the bubbling method, observation that is a physical validation of the barrel immersion technique for irrigas usage for irrigation management. Important for instrument dimensioning, porous cup water loss as a function of water tension measured from zero to Td was diminutive, increased with the soil water tension and was smaller in higher Td porous cups. In the sorption mode, functioning as a gaseous tensiometer, driven by a steady air-flow source, irrigas sensors yielded, directly, water tension readings ranging from zero to Ts. For irrigation scheduling purposes, commercial irrigas water tension systems can be selected according to crop critical water tension requirements.

Key words: irrigas, irrigation scheduling, porous cup, tensiometer, water tension.

RESUMO

SISTEMA GASOSO DE CONTROLE DE IRRIGAÇÃO: DESCRIÇÃO
E TESTES FÍSICOS PARA AVALIAÇÃO DE DESEMPENHO

Irrigas é um sistema para medir tensão de água (T) constituído de uma cápsula porosa (sensor) ligada a um dispositivo de aplicar/medir pressão de gás. T é obtido com as expressões: T=Td-p e T=Ts-p, sendo Td a tensão crítica de dessorção da água (início de borbulhamento); Ts é a tensão crítica de sorção (fim de borbulhamento) e p a pressão gasosa aplicada. Diferentemente dos tensiômetros comuns, por ter sua cavidade cheia de ar, não requer adição de água e tampouco correção de pressão hidrostática. O sistema foi testado, tanto no modo dessorção quanto sorção. No primeiro caso, a câmara de Richards foi utilizada para ajustar a tensão da água na qual o sensor irrigas se torna permeável ao ar. Os valores de

([1]) Recebido para publicação em 1.º de junho de 2005 e aceito em 9 de junho de 2006.
([2]) Embrapa Instrumentação Agropecuária, Caixa Postal 741, 13560-970 São Carlos (SP), Brasil. E-mail: adonai@cnpdia.embrapa.br. *Autor correspondente.
([3]) Embrapa-SPD, Av. W3 Norte (Final) - 70770-901, Brasília (DF), Brasil. E-mail: washington.silva@embrapa.br

tensão de água verificados foram praticamente iguais aos valores de Td determinados por borbulhamento, resultado que é prova física do correto funcionamento do método da imersão da cuba em recipiente com água usado em manejo de irrigação. A perda de água das cápsulas, característica importante para o dimensionamento de instrumentos, foi ínfima, aumentou linearmente com a tensão de água aplicada e foi menor nas cápsulas com maior Td. No modo sorção, acionado por fluxo continuo de ar, os sensores irrigas geraram valores de tensão de água de maneira linear e direta entre zero e Ts. Para fins de manejo de irrigação, sistemas irrigas comerciais de medir tensão de água podem ser selecionados de acordo com a tensão critica de água para a cultura.

Palavras-chave: cápsula porosa, irrigas, manejo de irrigação, tensão da água, tensiômetro.

1. INTRODUCTION

Adoption of sound irrigation scheduling techniques remains a challenge despite the existence of several methods based on climate, soil and plant properties. Usually, most farmers have the perception that irrigation scheduling procedures are expensive and time consuming, while beneficial effects on crops, water and energy savings are usually disregarded.

Marshall (1959) stated that an indirect method based on the pressure required to force air through the water-filled pores of a given porous cup was an example of procedure for irrigation control yet to be developed. More recently a new water tension measuring system for irrigation control has been developed, patented (Calbo, 2000 and 2004) and released by Embrapa (Calbo and Silva, 2001). This system, named irrigas, is simple, cheap, reliable and requires little or no maintenance at all. Irrigas consists of a porous cup, which is the water tension sensor, connected to an air pressurizing / measuring device. An irrigas system with the porous cup inserted into the soil and connected to a transparent barrel by a flexible tube is illustrated in figure 1. In wet soil the porous cup pores are filled with water and an air pressure higher or equal to the bubbling pressure is necessary to force air passage through the porous cup. As the soil dries, water tension builds up and the pressure necessary to force air through the porous cup reduces. As soil water tension becomes greater than porous cup bubbling pressure (Td) air permeates the pores freely and the small pressure provided by the barrel immersion (Figure 1) is sufficient to force air passage through it.

Differently from the irrigas system for measuring porous media water tension, Kemper and Amemya (1958) used the increase in the porous cup air permeability when submitted to soil water tension greater than Td to evaluate soil water tension. That method, however, is difficult to be employed because the air permeability increases as a sigmoidal function of the soil water tension and the exact behavior of this curve is a characteristics of each particular porous cup.

No water filled tensiometers are available for irrigation scheduling in tensions above those an conventional tensiometer works. For special mechanical engineering and geological applications, however, the unstable tensiometer of Ridley and Burland (1993) measures soil water tensions way above 100 kPa, for periods of few hours or less. The Ridley and Burland (1993) tensiometer, also studied by Tarantino and Mangiovì (2001), requires a 24-hour pre-hydration phase in a high pressure chamber, at 4000 kPa, to dissolve air bubbles. That system stops working suddenly as soon as cavitation occurs. The Ridley and Burland (1993) tensiometer is, nonetheless, an important tool for measuring porous media water tension, but it is not appropriate for irrigation management purposes.

Used as a tensiometer the irrigas system works within a linear water tension range that extends from zero to Td (Calbo and Silva, 2003). In this range the sensor was considered stable and maintenance free, much different from water filled conventional tensiometers. These devices usually work properly only in the range between zero and 70 kPa, but require frequent water addition which is certainly a limitation to the construction of unattended automatic irrigation scheduling systems.

The objective of this work was therefore to present a description and to perform physical tests to assess the response and the linearity of the irrigas system used for irrigation control.

2. MATERIAL AND METHODS

Irrigas system assembling and tests

The system (Figure 1) is made out of a porous cup, which is the sensor, a plastic lid, a plastic tube and a transparent barrel to evaluate pressure. The plastic lid is firmly attached to the porous cup by water resistant glue. A plastic tube of about 1.6 m is connected at one end to the porous cup lid tip and at the other, to a transparent barrel (Calbo and Silva, 2001). In order to work properly, the system must be leakage free, and to detect undesirable leaks the porous cup is immersed in water for about 30 seconds. After that it is removed from the water, and then the transparent barrel dipped into water. The water must not enter the barrel, if the system is leakage free.

Experimental irrigas sensors

In order to examine the system response to adjusted water tension values, small irrigas sensors were manufactured with a wide range of critical water tensions (Td). These experimental irrigas porous cups had a diameter of 17 mm, a length of 9 to 10 mm and an internal cavity 8 mm in diameter by 6 mm in length. The lid was made of a 5 mm thick PVC plate (ϕ 17 mm) and had a central orifice (ϕ 3 mm) and a small diameter copper tube 15 mm in length was fixed to it. A flexible PVC tube connected the irrigas porous cup to an 1.0 ml barrel.

Irrigas fundamental expressions

According to the capillary theory the water tension in a porous medium is related to the water surface tension (σ) by:

$$T = (2\sigma \cos \alpha) / r \qquad (1)$$

where α is the contact angle and r is the pore radius (Reichardt, 1985). In glass and other very hydrophilic materials, especially if textured (Bico el al., 2002) α is close to zero, cos α is close to one, which, as a consequence, reduces equation 1 to $T=2\sigma/r$ (Marshall, 1959; Libardi, 1995).

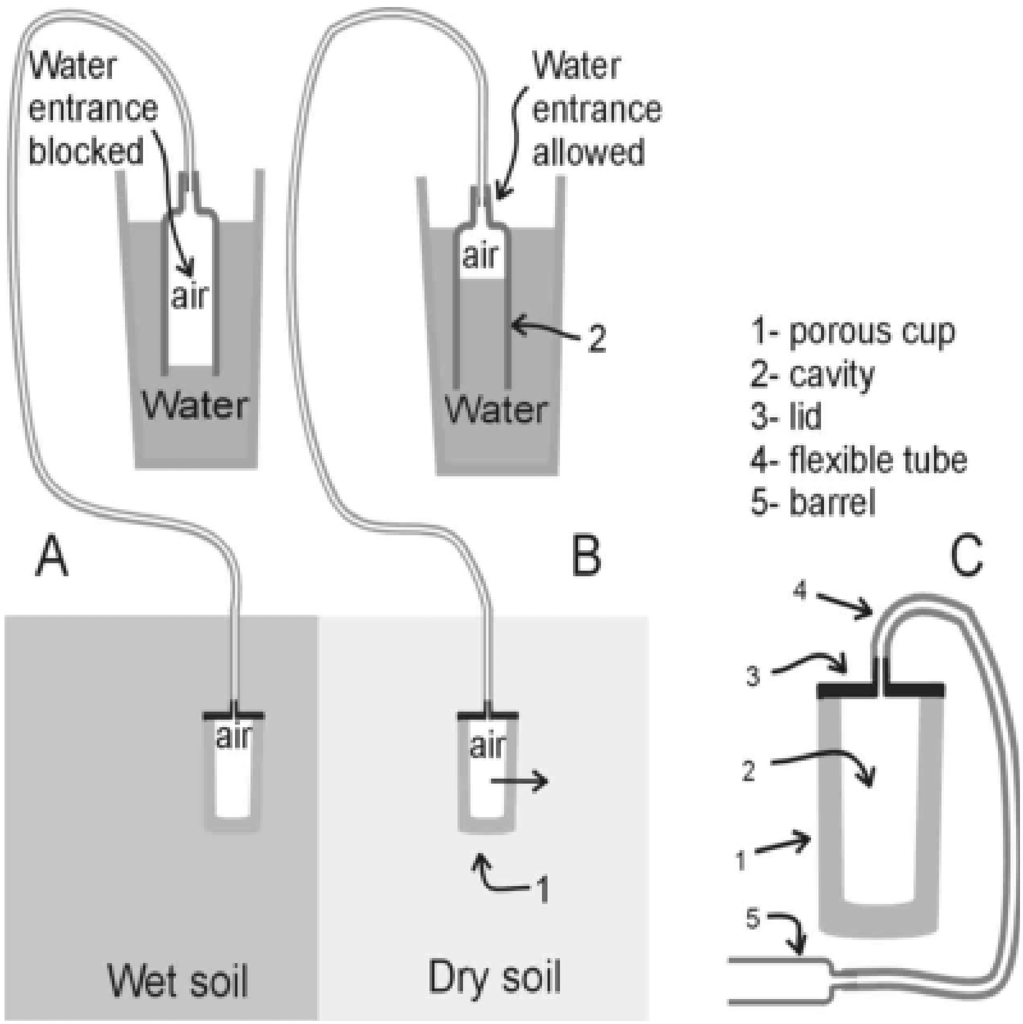

Figure 1. Illustration of the irrigas system to control irrigation. On the left side (A), in wet soil, the porous cup water imbibition does not allow the air permeation and water does not enter the barrel as it is immersed. In the center (B), in dry soil, there are opened paths for air permeation in the porous cup and, consequently, water enters the barrel during the immersion. On the right (C) an enlarged porous cup with details.

If a pressurizing system is used to force gas through the porous cup of the irrigas, a measure of soil water tension within the linear water tension range which extends from zero to Td is obtained. In the desorption approach, the soil water tension (T) in which an irrigas porous cup starts to be permeated by gas, as a separate phase, can be represented by the expression:

$$T = Td - p \quad (2)$$

Where p is the applied gas pressure. Similarly, in the sorption approach the soil water tension is measured with the expression:

$$T = Ts - p \quad (3)$$

Where Ts is the sorption critical water tension, that can be represented by the pressure p in which the irrigas porous cup (immersed) returns to the air-impermeable state.

Negative pressure chamber

In order to demonstrate that irrigas sensor becomes permeable to air in a desorption process under water tensions higher than Td, modified Richard pressure chambers (Richards, 1941; 1949) were prepared, as illustrated in Figure 2. In this set up, an conventional tensiometer reading stabilization was used as an indicator of water tension equilibrium.

Before using the apparatus, a thin clay layer was applied to the porous plate wall with two purposes: first, to conduct water to the tensiometer and to the irrigas porous cup, and second, to impede air entrance into the porous plate. These properties of clay are recognized by Marshall (1959). The water level inside the chamber was adjusted to about 3 mm above the porous plate base (Figure 2). A fine 20 mm layer of cotton fabric was then placed at the bottom of the porous plate of the tensiometer and of the irrigas porous cup. This layer which does not cause measurable delay in the water tension response, according to preliminary assays, had the purpose of avoiding cleaning the porous cup before weighing it for water exchange tests. For the measurements, the irrigas sensor was firmly pressed by a metallic cylindrical weight. The base of the tensiometer was abraded to improve the contact with the cotton fabric, in a second chamber (Figure 2). The firm contact of the tensiometer was obtained using a holder. Circular plastic sheets were placed over the Richards pressure chamber to block water evaporation from the tensiometer surface and from the irrigas porous cup during the measurements.

Water tension equilibrium was reached very fast according to the tensiometer reading, in a matter of few minutes. Irrigas porous cups with bubbling pressure (Td) between 7 and 60 kPa feature hydraulic conductivities ranging from 4 to 100 times than the used tensiometer porous cup, in accordance with the Poiseuille equation (Marshall, 1959) applied to these porous cups. For this reason, tensiometer stabilization was used as indicator of water tension equilibrium in these assays.

Soil water tension, irrigas permeation and Td

The irrigas porous cups were kept in a 5 mm water layer for at least two hours, in order to fill up the pores. irrigas sensors with Td measured with the bubbling pressure technique were submitted to a soil water tension increase simulated in Richards pressure chambers, up to the point it becomes air permeable. Those measurements were performed at 25 ± 1 °C with the objective of testing the hypothesis that the irrigas sensor turns air permeable as the soil water tension becomes greater than Td.

For the bubbling pressure measurements these irrigas porous cups were immersed in water and submitted to a slow gas pressure increase, which was obtained from a steady air-flow source. Bubbling pressure was read in a Hg manometer as soon as bubbling started, and the reading was then recorded as a Td value.

The estimate of the water tension in which irrigas sensors with different Td become air-permeable was made in a Richards pressure chamber. For this procedure the water tension was increased in steps of about 1 kPa followed by the barrel immersion test, to check whether air-permeation occurred in the irrigas sensor (Figure 2). In order to perform such test the transparent barrel (Figure 2) was immersed in water and its meniscus was observed during one minute. If no meniscus movement were detected, then the irrigas sensor was considered impermeable to air, and a new water tension increase step was then applied. Steps of water tension increments were added up to the point the irrigas sensor became air permeable.

Water tension versus irrigas sensor water content

The porous cup water loss as a function of water tension was evaluated after water tension adjustment. To do so, the tested porous cup was removed from the Richards pressure chamber, placed in a small closed flask, to avoid evaporation, and immediately weighed to the nearest milligram. For this measurement, the pressure chamber setup illustrated in figure 2 was used as described before.

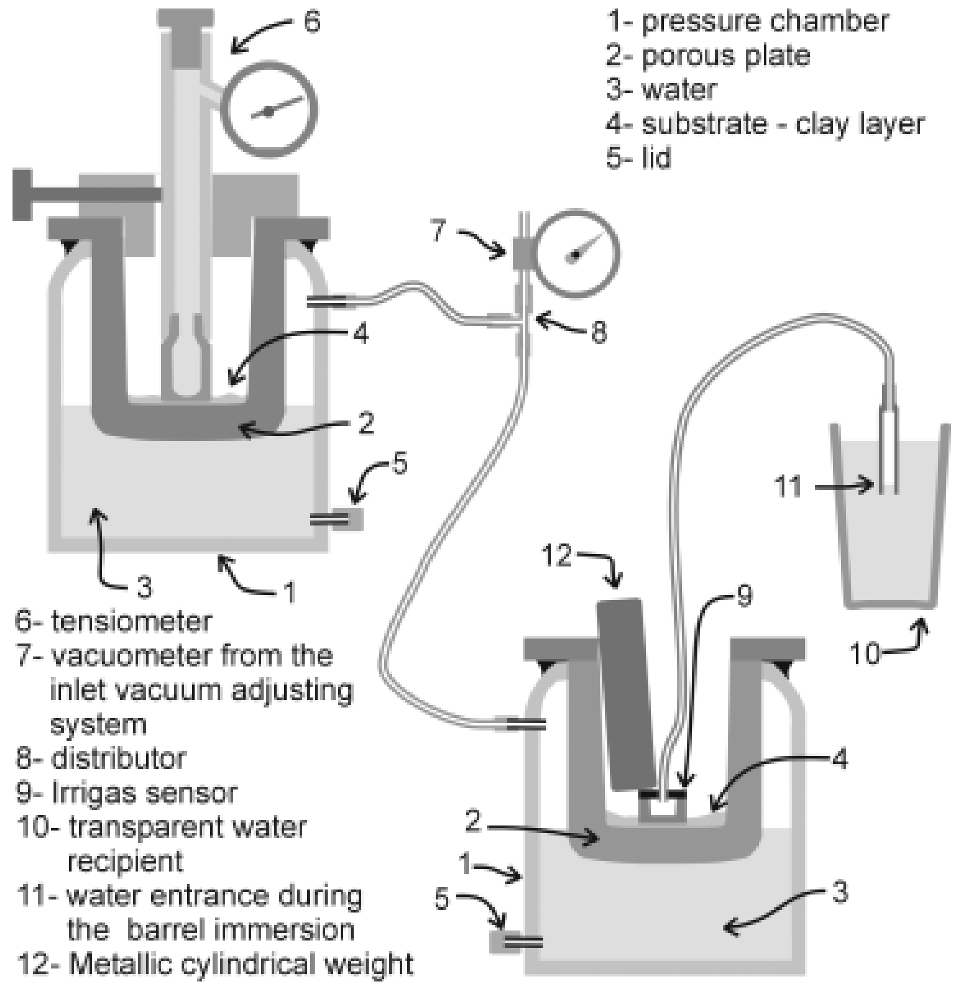

Figure 2. Illustration of two modified Richards negative pressure chambers, in which water tension of an irrigas sensor and of an conventional water filled-tensiometer are controlled simultaneously.

Pressure induced air-flow

The air flow through the porous cup induced by the use of increasing level of gas air tension was monitored with a calibrated capillary flowmeter (SLAVICK, 1974). For this purpose the gas tension was adjusted with a needle valve in the experimental arrangement illustrated in figure 3.

Steady air-flow induced pressure

In figure 4 a system devised to estimate soil water tension using equations 2 and 3 is illustrated. In this system water tension is measured according to the induced pressure caused by a steady gas flow out of the reference and of the measuring tubes, which are usually adjusted to equal values. For the experimental irrigas sensors herein described a 0.5 ml per minute flow was adjusted in both tubes with use of gas needle valves. A soap bubble flowmeter was used to monitor this gas flow. Typical air-flow induced pressure traces were obtained with the irrigas porous connected to the measuring tube, while the reference tube was kept open, without the porous cup.

In order to obtain direct soil water tension readings by this air-flow induced pressure method, the equipment (Figure 4) was used in the differential mode. For this purpose, similar irrigas sensors were connected to the reference side, which remained immersed in water, and to the measuring side which is usually placed in contact with the soil. For this study, the measuring irrigas sensor was placed in the adjusted water tension substrate (Figure 2) and water tension measurement was obtained in a matter of few minutes after pressure reading stabilization. Since the reference sensor was kept permanently immersed in water, as a consequence, the differential manometer reading was a direct substrate water tension estimate.

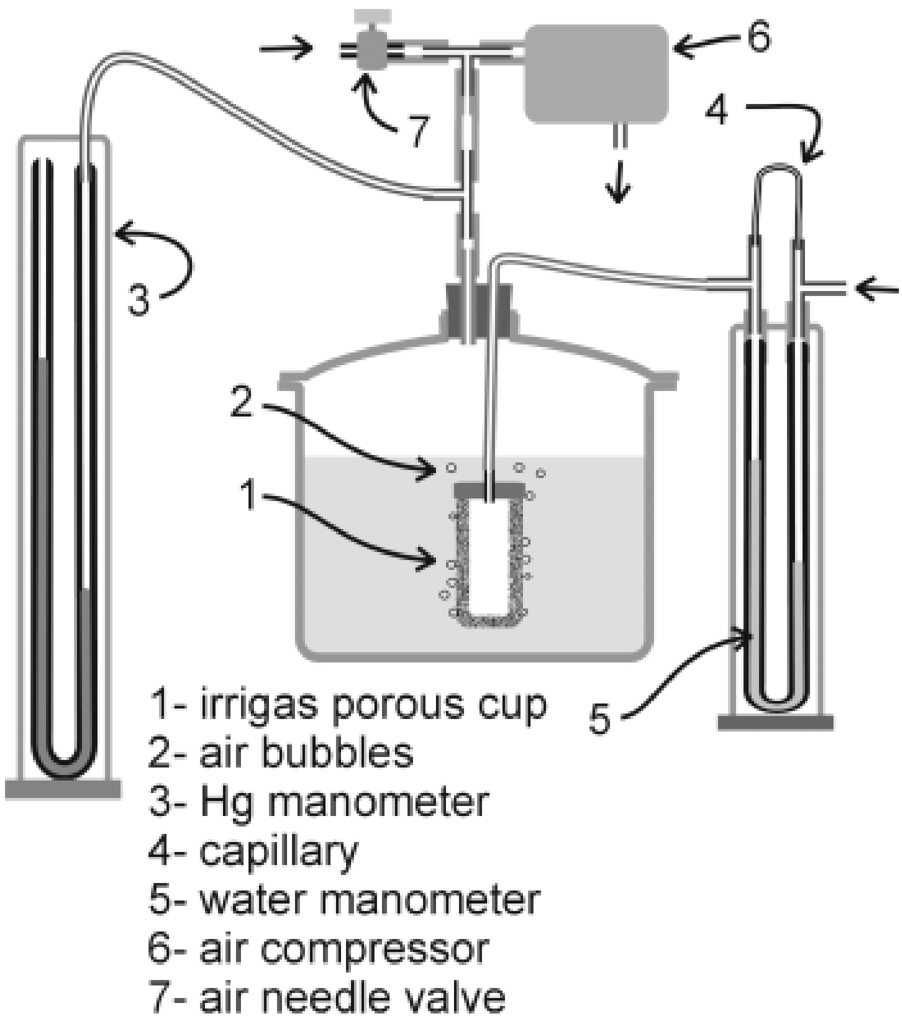

Figure 3. System with a capillary flowmeter to measure air-flow through an irrigas porous cup as a function of the applied gas tension. Arrows without numbers indicate the air flow direction in the system.

Statistics

Representative traces of pressure induced air-flow and of steady air-flow induced pressure were selected from at least five replicates. The physical evidence that the barrel immersion test yields permeable irrigas response, the relative porous cup water content versus water tension, and a typical water tension curve obtained with two 20 kPa-irrigas porous cup, were all submitted to analysis of variance followed by linear regression.

3. RESULTS AND DISCUSSION

Barrel immersion test evaluation

The physical validation of the barrel immersion technique used for irrigation management by Brazilian growers (Figure 1) was performed using irrigas sensors with different Td values. Richards pressure chambers, where the soil water tension was increased up to the point the irrigas porous cup becomes air permeable were used for the tests. The smallest soil water tension in which the porous cup became air permeable in the barrel immersion test occurred practically at the irrigas sensor Td value as it is illustrated in figure 5. This result is consistent with that obtained by KEMPER and AMEMYA (1958), who employed bubbling pressure and Richards pressure chamber methods for testing porous cups from different North American makers.

Pressure traces versus air-flow traces

A typical air-flow induced pressure trace response obtained for an immersed irrigas porous cup is illustrated in figure 6A. In this trace the maximum value is an estimate of Td and the stabilized value is an estimate of Ts. Whenever these irrigas sensors are placed in a soil and submitted to a given water tension, the pressure trace obtained is of lower magnitude and such traces can be used to estimate water tension with equations 2 and 3.

Furthermore, as increasing air-pressure is applied the porous cup loses water and air-bubbling starts as the applied air-pressure (p) becomes slightly larger than Td. This air-pressure induced air-flow through the porous cup increases dramatically as p is further increased (Figure 6B).

These air-flow / pressure porous cup behavior has been considered useful for automation purposes and considering these physical responses a gaseous system to control irrigation was patented by Embrapa (CALBO, 2000; 2004). This system has now been used with and without automation in field applications using different set ups such as the barrel immersing technique. (CALBO and SILVA, 2001), the irrigation signaling device (CALBO and SILVA, 2003a), the gaseous tensiometer (CALBO and SILVA, 2003b), the automatic tensiometric irrigation controllers (CALBO et al., 2004) and new commercial irrigation products such as the MRI 03 (POZZANI, 2004).

Porous cup water exchange

For instrument design aiming at rapid response the porous cup water exchange in a given water tension measurement is very important. The larger the required water exchange, the larger is the instrument response time in any considered water tension range. The irrigas functioning depends on water exchange between the soil and the porous cup. This implies that the porous cup has its own water retention characteristic curve, which strongly depends on Td. The measured water tension range for this study was the irrigas range, which is at most from zero to Td.

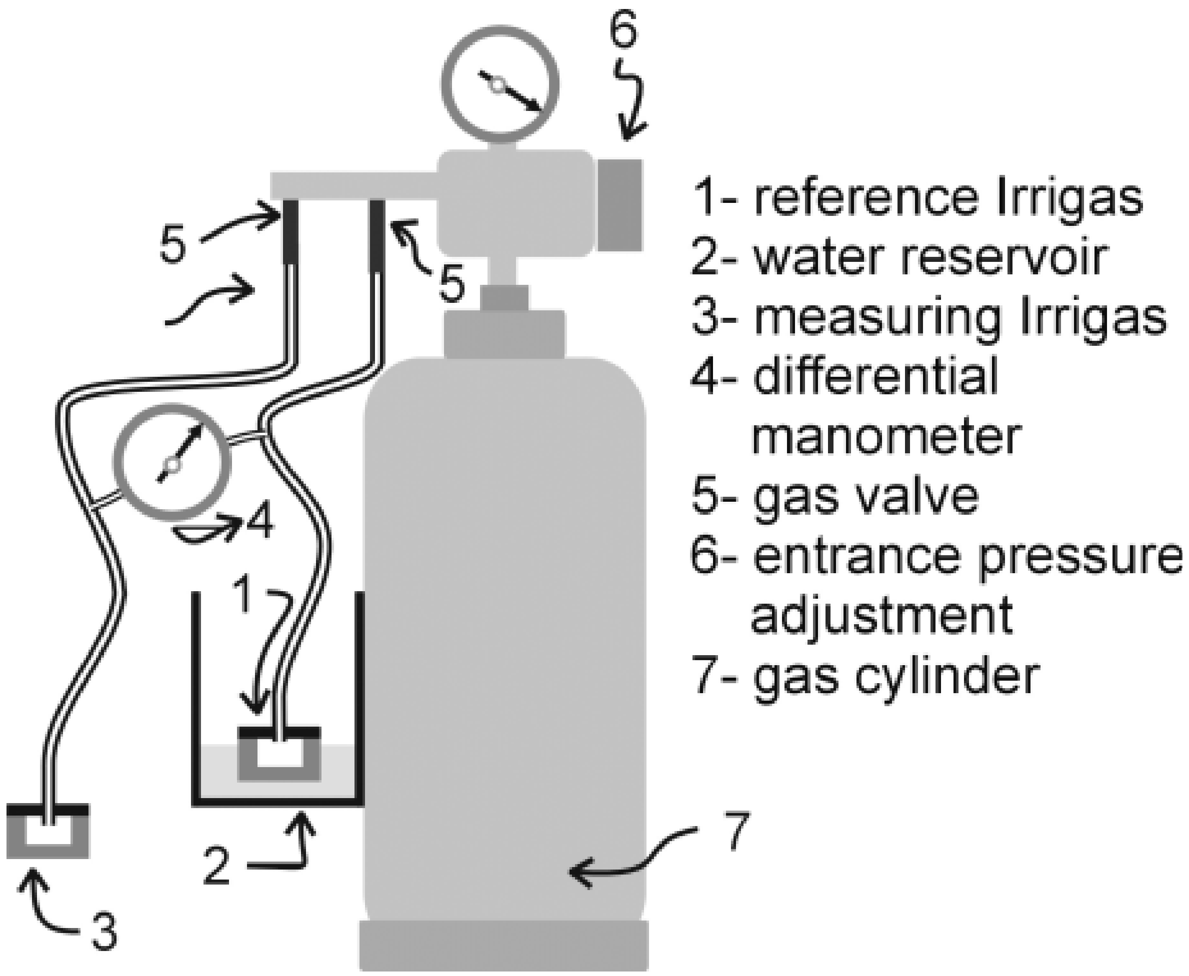

Figure 4. Differential steady gas flow driven irrigas tensiometer for direct soil water tension measurement.

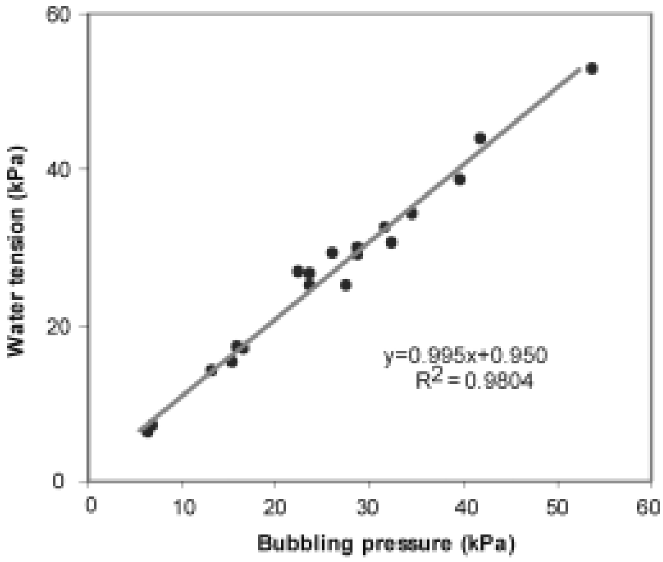

Figure 5. Soil water tension in which irrigas porous cups featuring different Td values (bubbling pressure) became air permeable.

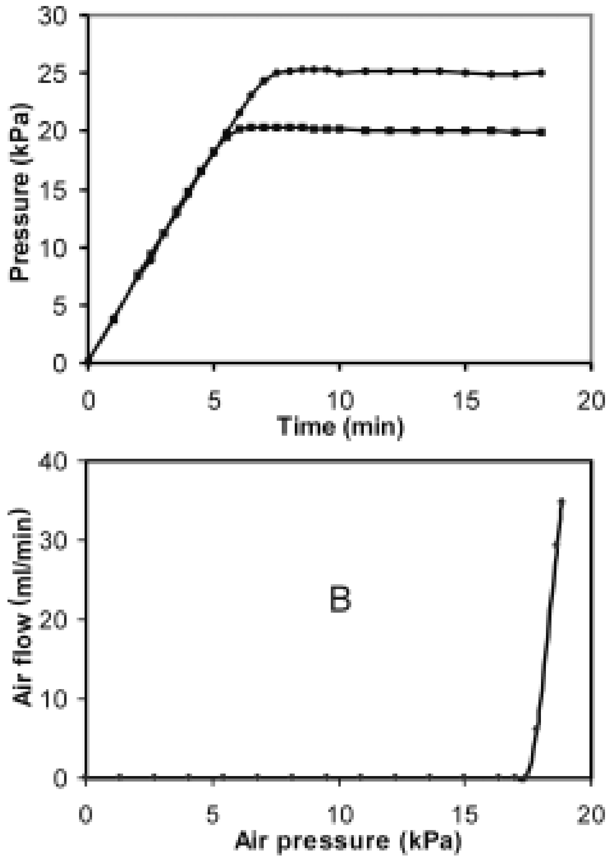

Figure 6. A- Typical trace for pressure as a function of time for a 25 kPa E-design irrigas porous cup immersed in water and subjected to an air-flow of 1.0 ml min^{-1}. Circle (•) is for a irrigas porous at an water tension adjusted to zero and square (■) for the same irrigas porous cup at a water tension adjusted to 5 kPa. B- Typical trace for air-flow as a function of the applied air-pressure for a 17 kPa irrigas porous cup from the same maker immersed in water.

Figure 7 illustrates the water loss of three porous cups, with different Td, as function of the soil water tension. It can be observed in Figure 7 that porous cup with finer pores (higher Td) exchanges less water with the soil as compared to porous cups with larger pores. This feature is much valuable because the soil hydraulic conductivity decreases very rapidly as the water tension increases. Moreover, the near saturated hydraulic conductivity condition remains in the sensor while the water tension is lower than Td, which is a condition that favors rapid soil / porous cup water tension equilibrium. The porous cups used in this work featured a porosity ranging from 20 to 35%. For these porous cups hydraulic conductivity is proportional to the square of the effective pore radius, according to the Poiseuille equation (MOORE, 1972). This radius could be estimated from Td (Eq. 1) and inferring from the modified Poiseuille equation, a 12 kPa porous cup should be 100 times more water permeable than an conventional 120 kPa tensiometer porous cup, a fact which is already well known (MARSHALL, 1959), and that indicates that hydraulic equilibrium in the studied porous cups can be fast (minutes) due to the small water exchange required for the irrigas sensor response (Figure 7).

Gas driven soil water tensiometer

Both desorption and sorption methods employed to estimate soil water tension as a function of the applied gas pressure yielded nearly linear responses, as it is illustrated in a sorption case (Figure 8). In this differential operation mode, the gas tensiometer (Figure 4) is very convenient to operate, it is portable and measures water tension directly, either instantaneously or continuously.

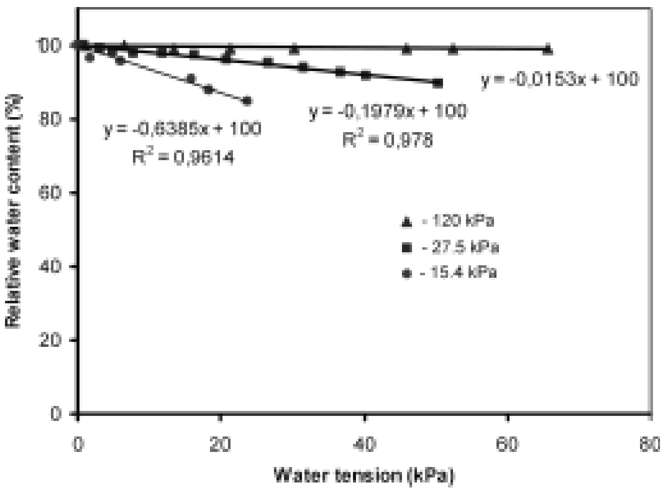

Figure 7. Relative water content of three porous cups as a function of water tension. The desorption critical water tension (Td) of the cups are • -15.4 kPa, ■ - 27.5 kPa and ▲ - 120 kPa.

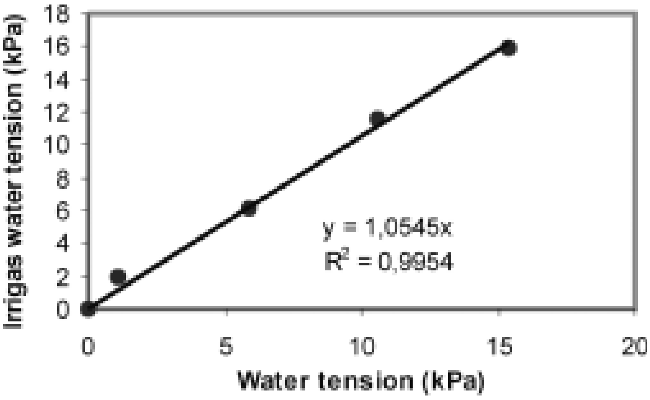

Figure 8. Typical response for a differential gas flow driven irrigas tensiometer to soil water tensions adjusted with a Richards pressure chamber.

These results obtained with an improved irrigas system strengthen the initial work of first irrigas gaseous tensiometry made by CALBO and SILVA (2003b) who used two different approaches to apply the sorption method. In one of these approaches a small steady gas flow was used and the stabilized pressure (p) was used to calculate the water tension.

Integrating remarks

Differently from water filled conventional tensiometers, the porous cup cavity and the tube of the irrigas system are filled with air (CALBO and SILVA, 2001; 2003b). This differential feature is advantageous because this system does not require water filling maintenance to remain operational. This means that irrigas can be kept unattended, sampling continuously the soil water tension. These properties make irrigas an unique system for modern precision water management techniques. Initial and promising research results of irrigas usage for a coffee crop were presented by SANTANA (2003) and VIANA (2004), for fresh-market tomatoes by PASCHOLD and MOHAMMED (2003) and for bell peppers by MAROUELLI et al. (2003).

Two other features of being a gas filled water tension system are: First, two or more irrigas sensors may be easily connected, in parallel, to be read using a single tube-barrel system. This is a simple way to increase the assurance that plant will not suffer from water stress since a "dry" response will be obtained as soon as soil becomes dry enough in the vicinity of one or more sensors. A second usage consequence, is that there is no need of hydrostatic pressure correction when irrigas sensors are placed at different depths in the soil, while for conventional tensiometers, placing position differences have to be carefully corrected for (MARSHALL, 1959, RICHARDS, 1942).

For irrigation scheduling purposes, growers may look for current tensiometric irrigation scheduling guidelines, such as those found in MAROUELLI et al. (1996), and based on those critical plant water tension values search for the appropriate irrigas water tension controlling sensors and systems.

4. CONCLUSIONS

1. Irrigas can be used to yield wet and dry responses required for water management, in which case "dry" is a soil submitted to water tensions higher than Td.

2. In steady air-flow driven systems the irrigas sensor can be used as a gas tensiometer, which measures soil water tensions ranging from zero to Ts.

3. Irrigas is a near maintenance-free sensor which does not require correction for porous cup placing depth, differently from conventional, water filled tensiometers.

4. For irrigation scheduling purposes, growers can use irrigas water tension controlling systems based on the available plant critical water tension guidelines.

REFERENCES

BICO, J.; THIELE, U.; QUÉRÉ, D. Wetting of textured surfaces. **Colloids and Surfaces**. A: Physicochemical and Engineering Aspects, v. 206, p. 41-46, 2002.

CALBO, A.G. **Sistema de controle gasoso de irrigação baseado na determinação de umidade do solo por meio de capsulas porosas**. Patente BR PI 0004264-1, 2000.

CALBO, A.G. **Gas irrigation control system based on soil moisture determination through porous capsules.** Patent US 6705542B2, 2004.

CALBO, A.G.; SILVA, W.L.C. Irrigas: novo sistema para o controle da irrigação. In: CONGRESSO NACIONAL DE IRRIGAÇÃO E DRENAGEM, 11., Fortaleza, 2001. **Anais**... Brasília: Associação Brasileira de Irrigação e Drenagem, 2001. p. 177-182.

CALBO, A.G.; SILVA, W.L.C. Controle da irrigação facilitado - sinalizador de irrigação para uso com o Irrigas®. In: CONGRESSO BRASILEIRO DE OLERICULTURA, 43., Recife, 2003. **Anais**... Botucatu: Sociedade Brasileira de Olericultura, 2003a. 1 CD-ROM.

CALBO, A.G.; SILVA, W.L.C. Novo tensiômetro: rápido, contínuo e opera em tensões superiores a 100 kPa. In: CONGRESSO BRASILEIRO DE ENGENHARIA AGRÍCOLA, 32., Goiânia, 2003. **Anais**... Jaboticabal: Sociedade Brasileira de Engenharia Agrícola, 2003b. 1 CD-ROM.

CALBO, A. G.; MAROUELLI, W. AP.; SILVA, H. R. Uso de controladores automáticos de irrigação na aplicação da tensiometria irrigas. **Horticultura Brasileira**, Brasília, v. 22, n. 2, jul. 2004. Suplemento 2.

KEMPER, W.D.; AMEMIYA, M. Utilization of air permeability of porous ceramics as a measure of hydraulic stress in soils. **Soil Science**, Madison, v.85, p.117-124, 1958.

LIBARDI, P.L. **Dinâmica da água no solo**. Piracicaba: ESALQ / USP, 1995. 497p.

MAROUELLI, W.A.; CALBO, A.G.; CARRIJO, O.A. Viabilidade do uso de sensores do tipo Irrigas® para o manejo da irrigação de hortaliças cultivadas em substratos. **Horticultura Brasileira**, Brasília, v.21, n.2, p. 286.

MAROUELLI, W.A.; SILVA, H.R. da; SILVA, W.L.C. **Manejo da irrigação em hortaliças**. 5.ed. Brasília: EMBRAPA, SPI, 1996. 72p.

MARSHALL, T.J. **Relations between water and soil**. Harpenden: Commonwealth Bureau of Soils; Bucks: Commonwealth Agricultural Bureaux, 1959. 91p. (Technical Communication, 50)

MOORE, W.J. **Physical chemistry**. New Jersey: Prentice-Hall, 1972. 977p.

NOBEL, P.S. **Physicochemical and environmental plant physiology**. Sydney: Academic Press, 1991. 635p.

PASCHOLD, P.J.; MOHAMMED, A. Irrigas® - a new simple soil moisture sensor for irrigation scheduling. **Journal of Applied and Irrigation Science**, Kassel, v.38, p.22-28, 2003.

POZZANI, E.R. **Produtos Irrigas E-design**. Disponível em: http://www.e-designindcom.com.br/PROD.HTM. Acesso em: 11 dez. 2004.

REICHARDT, K. **Processos de transferência no sistema solo-planta-atmosfera**. 4.ed. Campinas: Fundação Cargill, 1985. 466p.

RICHARDS, L.A. A pressure-membrane extraction apparatus for soil solution. **Soil Science**, Madison, v.51, p.377-386, 1941.

RICHARDS, L.A. Soil moisture tensiometer materials and construction. **Soil Science**, Madison, v.53, p.241-248, 1942.

RICHARDS, L.A. Methods of mounting porous plates used in soil moisture measurements. **Agronomy Journal**, Madison, v.41, p.489-490, 1949.

RIDLEY, A.M.; BURLAND, J.B. A new instrument for the measurement of soil moisture suction. **Géotechnique**, London, v.43, p.321-324, 1993.

SANTANA, M.S. Crescimento inicial de duas cultivares de cafeeiro adensado influenciado por níveis de irrigação localizada. 2003. 50p. (Dissertação – Mestrado) – Universidade de Brasília, DF.

SLAVICH, S. **Methods of studying plant water relations**. Berlin: Springer-Verlag, 1974. 449p. (Ecological Study, 9)

TARANTINO, A.; MONGIOVÌ, L. Experimental procedures and cavitation mechanisms in tensiometer measurements. **Geotechnical and Geological Engineering**, New York, v.19, p.189-210, 2001.

VIANA, J.L.B. **Manejo da irrigação por gotejamento durante o segundo ano de cultivo do cafeeiro adensado**. 2004. 44f. Dissertação (Mestrado) - Universidade de Brasília, DF.