Hysteretic behaviour of thermal properties on porous media

C. M. Rubio [1,2], R: Josa [1], D. Cobos [3,4], C. Campbell [3,4], F. Ferrer [1]

(1) Departamento de Ingeniería Agroalimentaria y Biotecnología, Universidad Plitécnica de Cataluña, Parque Mediterráneo de la Tecnología, 08860 Castelldefels (España). E-mail: carles.rubiol@upc.edu
(2) Departamento de Biofísica Ambiental y Suelos, LAB-FERRER Soils and Environmental Consulting, 25.200 Cervera (España).
(3) Department of Crop and Soil Science, Washington State University, (WA, USA.)
(4) Decagon Devices, Inc., Pullman, (WA, USA).

ABSTRACT

In order to partly fill the thermal soil properties studies, we focused this work in the relation between thermal and hydrodynamic soil properties for several soil textural classes. This study was divided in two different objectives; (i) to determine and to analyze soil thermal and hydrodynamic properties, and (ii) to explore the impacts of hysteresis on soil thermal properties under experimental controlled conditions. Samples were obtained from Llobregat delta plain (Spain). To measure soil thermal properties, simple needle sensors were used. The samples were repacked in a soil column device. Volumetric water content and thermal conductivity were monitored continuously. The results allowed a rather complete understanding of the relation between thermal and hydrodynamic properties at laboratory scale for silt loam soils. Differences in thermal properties at a given water content were interpreted as a results of different hysteretic paths observed, arising in turn from different wetting and drying processes. Reasonably, we support that, in observed water contents, a change has taken place in the internal structure of the soil water, and how the water was adsorbed. This fact produced differences in the thin water films around the particles, and affected heat transport. This topic needs further theoretical and experimental investigation, and moreover to establish comparison with other variables that could cause effect on the thermal properties.

Keywords: water content, water potential, thermal conductivity, thermal diffusivity, volumetric heat capacity, soil samples

INTRODUCTION

Soil thermal properties are influenced, among other variables, mostly for particle size distribution, water content and bulk density. The particle size and its distribution have an effect on the manner in which the moisture is held (Singh and Devid, 2000). Soil water content has an important role in determining soil thermal properties, due the conduction through the soil is largely electrolytic. Thus, when the soil moisture increase the thermal conductivity rise, because water is a good conductor (DeVries, 1963). Frequently, the statement is made that thermal properties of soils at the same moisture content for different textural class is highest in sand, intermediate in loam and lowest in clay.

On the other hand, in laboratory conditions thermal properties largely should be influenced for drying and wetting processes driven by water potential differences, being the relationship between water potential and water content a consequence of wetting and drying history (Hillel, 1980). This effect of a non-unique water-retention curve, i.e. the soil water hysteresis, is relevant for the gas-phase continuity, which influence on soil thermal properties. The hysteresis phenomenon has been well documented in the literature beginning with the work of Haines (1930), and followed by other authors, such as Philip (1964); Kutilek and Nielsen (1994), and Bristow (1998) who related thermal properties with water potentials.

The purpose of our research is to explore the influence of hysteresis as one of the decisive factors to cause differences on the heat transport. Thus, the aim of our work is divided in two different task; **(i)** to measure and to analyze soil thermal and hydrodynamic properties, and **(ii)** to explore the impacts of hysteresis on soil thermal properties under experimental controlled conditions.

METHODOLOGY

Sampling plot was located in Can Solé Road, sited in the Llobregat delta plain (Northeast of Spain). The samples were obtained between surface and 30 cm depth. To characterize the soil physical variables, particle size distribution, bulk density, total organic carbon content, and calcium carbonate content were measured.

To determine the thermal properties a SH-1 small dual-needle sensor (Decagon Devices Inc.) was employed. The SH-1 thermal sensor combined with KD2-Pro (Decagon Devices, Inc.) reader-logger, allowing to obtain a continuous large thermal data soil, and yielding reliable and accuracy soil thermal diffusivity (α) and thermal conductivity (λ) estimations. Volumetric heat capacity (C_v), was determined from thermal conductivity and diffusivity data, following the expression:

$$C_v = \frac{\lambda}{\alpha} \qquad (1)$$

To determine the volumetric water content (θ) and the water potential (ψ), the soil column was monitorized with two EC-5 frequency domain probes (Decagon Devices Inc.) and two T-5 minitensiometer (UMS GmbH). The sensors were placed in couples (one T5 and one EC-5) at the same level. [$\theta(\psi)$] data from saturation to -83 kPa with minitensiometer (Vandervaere et al., 1997) were measured. However, to measure the driest data a WP-4 device (Decagon Devices) was used (Thakur et al., 2005). Both data set were used to estimate the water retention curve during the drying process.

RESULTS AND DISCUSSION

The studied soil was classified as silt loam textural class (USDA, 1998), with a particle size distribution for silt content always higher than 60%, mean sand content about 34%, and mean clay content about 4%. Mean bulk density is 1.47 g·cm^{-3} and total porosity 45%. Mean total organic carbon content was about 3.1%, and mean calcium carbonate content was 40.3%. Soil water retention curve was obtained fitting the observed data to the Van Genuchten equation (1980). The results showed a volumetric water content close to saturation about 0.45 cm^3·cm^{-3}. The values of water content for field capacity and permanent wilting point were 0.20 and 0.09 cm^3·cm^{-3}, respectively. The fitted curve obtained a $r \cong 0.98$ for $p \leq 0.01$.

In Fig. 1a, 1b and 1c, we show the wetting and drying cycle related with the thermal properties data, which were observed for the studied soil. All thermal properties in Fig. 1 were determined for a same spatial-temporal scenario. Existed, in general, good agreements between the thermal conductivity measurements and the soil hysteretic behaviour (Fig. 1a), which was subject to drying and wetting cycles (Bristow, 1998; Bristow et al., 2001). Thermal conductivity measurements at the end of the wetting process showed a linear increasing with the soil water contents. Whereas, during the drying cycle, Fig. 1a showed a fast reaction increasing the values of the soil thermal conductivity. When the water in porous media began to decrease, then the thermal conductivity started a rapid decreasing, in parallel to the wetting process. Experiences performed with thermal properties in the laboratory have presented an unclear phenomena. The changes in the soil temperature produced during the drying process, controlled certain divergences in the thermal dynamic behaviour, as is the case of the Fig. 1, where the temperature decreased 12 Celsius degrees inside the column device (due to changes in the environmental room temperature) during half drying cycle, involving that the evaporative demand decreased.

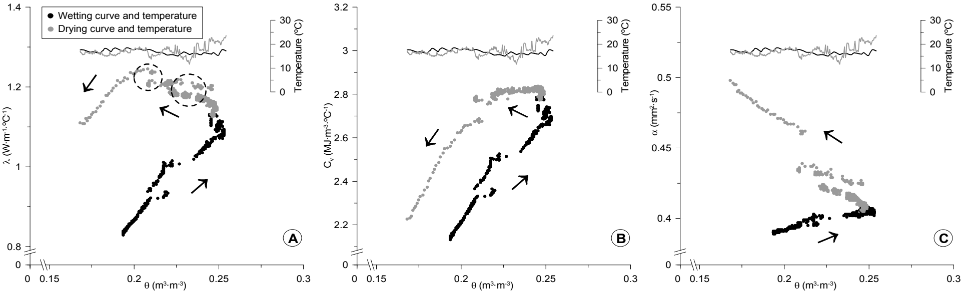

Figure 1. Wetting and drying curves of the relation between A: thermal conductivity, B: volumetric heat capacity, C: thermal diffusivity and volumetric water content. The lines are the temperature curves oscillation during both cycles (black corresponds to wet, grey corresponds to dry), the arrows mean the direction of the process.

On the other hand, the temperature oscillation during the wetting process was negligible, maintaining steady-state conditions all time. Although, several studies carried out by Campbell et al. (1994), Campbell and Norman (1998) about the effects of the temperature on the thermal properties, maintain that in a moist soil at room temperature 10 to 20% of the total heat transport is as latent heat through the pores. This portion of the heat transport is strongly temperature dependent, roughly doubling for each 10°C temperature rise. Therefore, the variable temperature produced a small effect on the thermal conductivity when the temperature decreased 12ºC, such that the heat transport was reduced (see dot circles in Fig. 1a).

Fig. 1b and 1c, showed the influence of water content in volumetric heat capacity and thermal diffusivity, respectively. Volumetric heat capacity (Fig. 1b) presented a well-defined hysteresis process, and the variations of the temperature during dried curve did no affect to both cycles either. However, Fig. 1c shown greatest differences between both moisture cycles. Thermal diffusivity increased whereas the water content was increasing in the porous media. But, an unexpected fact occurred when the moisture cycle was opposite. During the dried curve, the values of α shown a constant increasing. The divergences in α values might be explained by the relation between water content and porous media diameter, and the spatial interaction between heat transfer and soil moisture. The most important factor is the thickness and geometry of the water layer around the particle (Al Nakshabandi and Kohnke, 1965), which determined the heat transfer in the system. λ and especially α values would depend highly on the manner in which the best conducting mineral particles were interconnected by the less conducting water phase, and were separated by the poorly conducting gas phase (Koorevaar et al., 1983). Therefore, the heat transport in the soil taken place mainly through the narrow points of contact between the particles. The water around contact points formed very effective "bridges" for conduction of heat. However, the thin film formed around the soil particles during both processes, involved different λ and α values for the same water content, such as were shown in Fig. 1a and 1c. Also, the variations in the volume of the air fraction explained much of the variation in thermal diffusivity data rather than other variables, just that in driest measures for this soil the relationship was not typically linear. Also, the variations of the temperature would influence in the rate of latent heat, yielding significant differences in the gas phase, and controlling the different scenarios occurred on both cycles. Therefore, we could assume that the values of thermal properties varied according to the thermal state of the system.

CONCLUSIONS

The laboratory-scale study of heat flow and water produced a unique and comprehensive data set useful for quantifying the spatial-temporal dynamics of λ, C_v and α based on moisture levels. Thermal properties showed an acceptable relationship with water content, being directly proportional the increase of water content with the increase of the observed thermal conductivity and diffusivity, and therefore with the calculated volumetric heat capacity. Also, the influence of the hysteretic behaviour on soil thermal properties shown in **Fig. 1a, 1b and 1c**, was related with several important factors: saturation and non-saturation degree, changes on temperature and its influence on the heat transport, and the geometry of the water layer around the particle. However, we are fully aware that additional experiments are indispensable to validate in different soils the partly conceptual and partly empirical basis of the schematization elaborated in this work. Also, it would be convenient to be continued the investigations of the thermal hysteretic behaviour studying more variables (e.g. the effects on compacting), which can be especially sensitive on these type of data.

ACKNOWLEDGMENTS

This research was funded by the Lab-Ferrer Environmental Biophysics and Soils Consulting Center. We thank the Ministerio de Educación y Ciencia for the Torres Quevedo award to Dr. C. M. Rubio.

REFERENCES

- Al Nakshabandi G., Kohnke H. 1965. Termal conductivity and diffusivity of soils as related to moisture tension and other physical properties. Agricultural Meteorology, 2: 271-279.
- Bristow K.L. 1998. Measurement of thermal properties and water content of unsaturated sandy soil using dual-probe heat-pulse probes. Agric. Forest. Meteorol., 89: 75–84.
- Bristow K.L., Kluitenberg G.J., Goding, C.J. Fitzgerald T.S. 2001. A small multi-needle probe for measuring soil thermal properties, water content and electrical conductivity. Computers and Electronics in Agriculture, 31: 265-280.
- Campbell G. S., Jungbauer Jr. J.D., Bidlake W.R., Hungerford R.D. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Sci. 158:307-313.
- Campbell G. S., Norman J. M. 1998. An Introduction to Environmental Biophysics, 2nd Ed. Springer Verlag, New York.
- DeVries D.A. 1963. Thermal properties of soils. In: W.R. van Wijk (Editor), Physics of plant environment. North-Holland Publishing Co., Amsterdam, pp. 210-235.
- Haines W. 1930. Studies in the physical properties of soil: V. The hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith. J. Agric. Sci. 20, 97–116.
- Hillel D. 1980. Fundamentals of Soil Physics. Academic Press, New York, 413 pp.
- Koorevaar P., Menelik G., Dirksen C. 1983. Elements of soil physics. Develpments in soils science 13. Elsevier, New York, 230 p.
- Kutilek M., Nielsen D.R. 1994. Soil hydrology. Catena, Cremlingen-Desdedt, Germany. 370 p.
- Philip J.R. 1964. Similarity hypothesis for capillary hysteresis in porous materials. J. Geophys. Res., 69 , 8: 1553–1562.
- Singh D.N., Devid K. 2000. Generalized relationships for estimating soil thermal resistivity. Experimental Thermal and Fluid Sci., 22: 133-143.
- Thakur V.K.S., Sreedeep S., Singh D.N. 2005. Parameters affecting soil–water characteristic curves of fine-grained soils. Journal of Geotechnical and Geoenvironmental Engineering, 131, 4: 521-524.
- Vandervaere J.P., Peugeot C., Vauclin M., Angulo Jaramillo R., Lebel T. 1997. Estimating hydraulic conductivity of crusted soils using disc infiltrometers and minitensiometers. Journal of Hydrology, 189: 203-223.