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Compensation of temperature effects for in-situ soil moisture measurement by DPHP sensors

Vinay S. Palaparthy [a], Devendra N. Singh [b], Maryam Shojaei Baghini [c,*]

[a] Centre for Research in Nanotechnology and Science, Indian Institute of Technology Bombay, India
[b] Department of Civil Engineering, Indian Institute of Technology Bombay, India
[c] Department of Electrical Engineering, Indian Institute of Technology Bombay, India

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ABSTRACT

Dual probe heat pulse (DPHP) sensors are economical solutions for soil moisture measurements. However, in agriculture fields the temperature significantly changes from time to time during 24 h, which affects response of the soil moisture sensor. This paper, analyzes and models the error produced in the response of the DPHP sensors due to variation of the soil temperature. For this purpose, first effect of the soil temperature on the response of the sensor is studied using eight different soil samples. Accordingly, the existing soil moisture model, used for DPHP devices, is modified and used for the temperature compensation. A low power DPHP sensor comprising one heater probe and one temperature sensor probe, placed 0.003 m apart, is fabricated. A low power, automated system, dissipating average power of 30 mW, is also developed for the field measurements to validate the proposed model. The developed system is deployed in the field and soil moisture is measured for 38 h at every 1 h interval. Field measurements indicates that volumetric moisture content measured without temperature compensation leads to error of about 3% and with temperature compensation the error is reduced to 0.5%.

1. Introduction

Timely irrigation of agricultural field and soil moisture measurements are required for the proper yield of crops. Dry farming is carried out in locations in which costs for IT applications/sensors are not affordable by farmers. Moreover, the need of monitoring soil moisture is not only related to dry farming but, more generally, in all locations in which irrigation is expensive or waste of water is forbidden. In-situ regular soil moisture monitoring is one of the major requirements in many agriculture fields. Most of the soil moisture sensors which are accurate are costly and not affordable by the many farmers (SushaLekshmi et al., 2014). Soil moisture determines the quantity of water present in the soil, which can be expressed either in terms of gravimetric moisture content (w) or volumetric moisture content (θ_v) (SushaLekshmi et al., 2014). Gravimetric techniques are limited to the lab and volumetric measurement is used in both lab and in situ measurement (Zazueta and Xin, 1994; ASTM D 2216, 2008). Volumetric soil moisture measurement techniques like neutron scattering probe technique, time domain reflectometry (TDR), and frequency domain reflectometry (FDR), are considered to be accurate techniques (Topp et al., 1980; Li et al., 2003; Rao and Singh, 2011). However, the major drawback of these sensors is that they are very expensive (SushaLekshmi et al., 2014).

Many researchers have reported the dual probe heat pulse (DPHP) technique as one of the affordable techniques to measure the soil thermal properties and soil moisture content (Campbell et al., 1991; Bristow et al., 1993, 1995, 1994a, 1994b; Kluitenberg et al., 1993, 1995; Valente et al., 2004, 2006, 2010; Tarara and Ham, 1997; Heitman et al., 2003; Song et al., 1998; Ochsner et al., 2003; Jorapur et al., 2015; Olmanson and Ochsner, 2006; Young et al., 1995). DPHP sensors are extensively calibrated for the lab and field measurements to measure the soil moisture with an accuracy of ±3% with reference to the standard gravimetric technique (Valente et al., 2004, 2006; Tarara and Ham, 1997; Heitman et al., 2003; Song et al., 1998; Ochsner et al., 2003; Bristow et al., 1994a, 1994b). Measuring soil moisture with an accuracy of ±3% is acceptable because most of the commercial systems available in the market measure soil moisture content with this accuracy (e.g. gs3, gs1 and ec-5 sensors from Decagon Devices, Inc.) Cost of the dual probe heat pulse (DPHP) sensors is almost three times less than commercially available volumetric moisture sensors like FDR and TDR. Among various soil moisture

* Corresponding author.
E-mail address: mshojaei@ee.iitb.ac.in (M.S. Baghini).

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sensors, DPHP sensor has potential to be a suitable candidate for the soil moisture measurements considering price and accuracy. DPHP sensor has two probes, the heater probe and the temperature sensor probe, which are placed at a distance 'r' apart as shown in Fig. 1(a). A voltage pulse is applied to the heater for a finite time (fixed energy) due to which heat flows in all directions shown in the Fig. 1(b) and rise in the temperature (ΔT) is measured by the temperature sensor probe. In agriculture field soil temperature varies from time to time during 24 h and response of the sensor deployed in the field should not affect the measurements (Heitman et al., 2003). Few works have reported an effect of the soil temperature. Bristow et al. (1994a, 1994b), have studied the effect of the initial soil temperature on the soil thermal properties, but they have not gone further to explore those effects on the soil moisture measurement. Jorapur et al. (2015), simulated the effect of soil temperature on the DPHP sensor and concluded that ΔT decreases with increase in the soil temperature. Olmanson and Ochsner (2006), studied the dependency of the temperature on DPHP sensor across 5–45 °C and concluded that variation in the sensor response is due the specific heat of the solids, liquids and gases in the soil. Young et al. (1995) proposed few approaches for correcting the ambient temperature effects on DPHP sensors (manufactured by East 30 Sensors, Inc. (Pullman, WA)). These researchers proposed a single probe method (SPM) in which the energy lost during the measurement is added to the soil by providing more heating to the DPHP heater probe. SPM measurements led to 10% variation in the moisture measurement during field measurements. For SPM approach extra temperature sensors were deployed for measuring the soil temperature, which adds additional cost to the system. (Young et al., 1995) also proposed a complex Levenburg–Marquardt (LM) corrected optimization model, which led to 0.5% variation in the moisture measurement during field measurements. In LM corrected model, optimization on temperature drifts, critical moisture content and apparent needle spacing 'r' is applied. In LM method, optimization of needle spacing is crucial because 2% deviation in 'r' leads to 4% relative error in the moisture content (Kluitenberg et al., 1993). Measuring soil moisture with accuracy ±3% is acceptable for agriculture applications. Even most of the commercial systems available in the market measure soil moisture content with accuracy of ±3% (gs3, gs1 and ec-5 sensors from Decagon Devices, Inc.). Moreover, measurement accuracy depends on the type of the soil. For clayey soils ±3% is acceptable because of wide window between the field capacity (FC ≈ 40%) and the permanent welting point (PWP ≈ 20%). For the sandy soils ±3% is not acceptable, because of the small window between the FC (≈6%) and PWP (≈2%) (Veihmeyer and Hendrickson, 1931; Rao et al., 2013). Thus, developing a simple model to minimize the effect of soil temperature without additional hardware for soil temperature sensing and measure soil moisture accurately is an essential requirement.

In this work, low power DPHP sensor is used. Then effect of soil temperature on the DPHP sensor has been analyzed first under laboratory conditions on eight different soils and model is established for temperature compensation. Further, field measurements are performed to validate the proposed model. An automated and self-sustained system is designed and developed for the field measurements. The developed system measures soil moisture and soil temperature using the DPHP sensor. Volumetric moisture content measured without and with temperature compensation using DPHP sensor is benchmarked with the commercially available soil moisture sensor. Furthermore, we estimated the specific heat of solids in the soil using the DPHP sensor, which is an important factor required to measure θ_v. The presented DPHP automated system has been filed as an Indian patent application (IPA) number (IPA No. 3054/MUM/2015).

2. Materials and methods

2.1. Theory of heat pulse technique

DPHP sensor uses solution of heat conduction equation for an infinite line of heat source in an isotropic and homogeneous medium to derive the volumetric heat capacity of the soil, C (J m^{-3} °C^{-1}) as given by (1) (Bristow et al., 1994a, 1994b).

$$C = \frac{q'}{4\pi k(\Delta T)}\left[\mathrm{Ei}\left(\frac{-r^2}{4k(t_m - t_0)}\right) - \mathrm{Ei}\left(\frac{-r^2}{4k(t_m)}\right)\right] \quad (1)$$

In (1), k is the thermal diffusivity of the medium (m^2 s^{-1}), $t_m$is the time (s) required to reach the maximum temperature change ΔT (°C), t_0 is the duration of heat pulse (s), r is the distance between the probes (m), q′ is heat input per unit length of the heater (W m^{-1}), Ei(x) represents the exponential integral function of input x. Thermal diffusivity is determined by using (2) (Bristow et al., 1994a, 1994b).

$$k = \frac{r^2}{4}\left\{\frac{\left(\frac{1}{t_m - t_0} - \frac{1}{t_m}\right)}{\ln\left(\frac{t_m}{t_m - t_0}\right)}\right\} \quad (2)$$

C is related to the volumetric moisture content θ_v by using (3) (Bristow et al., 1994a, 1994b).

$$C = \rho_b c_s + \rho_w c_w \theta_v \quad (3)$$

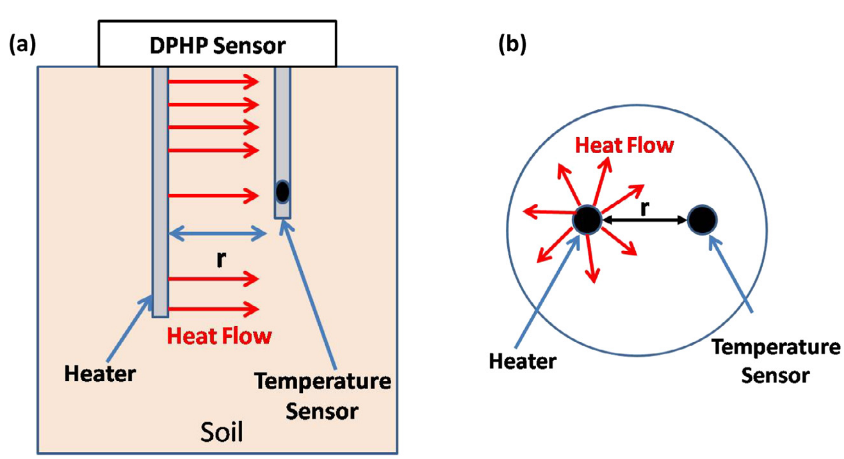

Fig. 1. (a) Conventional DPHP sensor; (b) heat flow from the heater probe due to applied voltage.