農地の熱特性推定のための熱パルスプローブの検量

Heat Pulse Probe Calibration for Thermal Property Estimation in Agricultural Fields

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Introduction Accurate estimation of soil thermal properties including thermal conductivity (λ), diffusivity (κ), and volumetric heat capacity (C_v), is essential for understanding surface energy balance, especially in agricultural fields influenced by irrigation and crop growth. Dual Probe Heat Pulse (DPHP) probes are commonly used, but their accuracy in estimating thermal properties depends on precise calibration of rod spacing. Recent sensor designs with thicker rods challenge the assumptions of the conventional infinite line source (ILS) theory. The Identical Cylindrical Perfect Conductor (ICPC) model addresses this by accounting for rod geometry and heat capacity. This study aimed to evaluate rod spacing calibration using both models in reference media, water and ice.

Materials and Method A DPHP was constructed following Kamai et al. (2015) with modifications, including thicker stainless-steel rods. The central rod housed a resistance heater, and the outer rods (Ta and Tb) had thermistor at mid-length. Both ILS and ICPC models require the rod spacing value between the heater and the thermistor rods, which slightly deviates from the physically measured value (rphy), and rather a fitting parameter as apparent rod spacing value (rc), determined by the calibration medium with known thermal properties. Calibration into agar-stabilized water at room temperature (21°C) was compared with the calibration in the air-free ice (–21°C). The details of creating air-free ice was demonstrated by Naruke et al. (2021). Temperature response analysis for the DPHP calibration and thermal property estimation using the ILS and ICPC models were followed

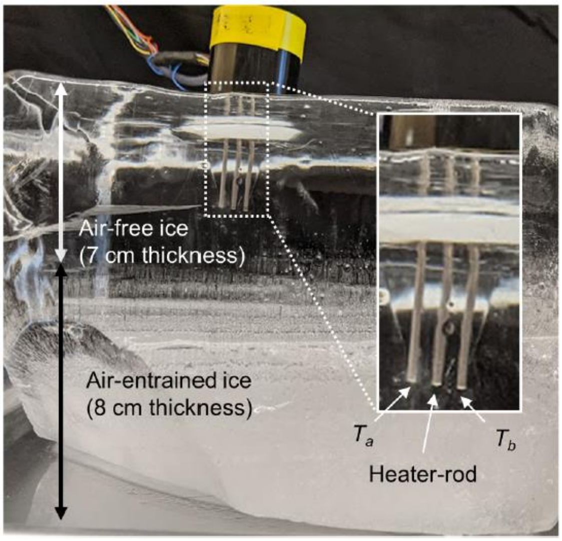

Figure 1. DPHP rods (the heater rod and two thermistor rods, Ta and Tb) in the air-free portion.

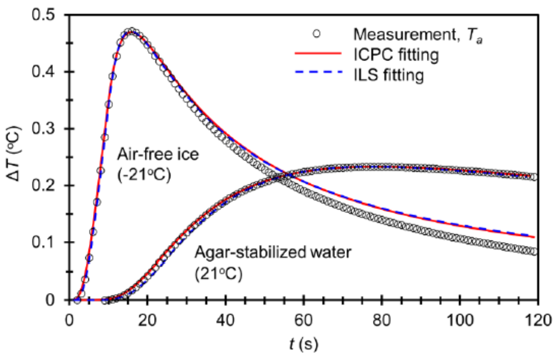

Figure 2. Measured and fitted temperature rise at the thermistor rod, Ta, in ice and water.

Table 1. Measured rphy and determined rc_i and rc_w values between the heater and at the thermistor rod, Ta, using the ILS and the ICPC model.

rphy	ILS		ICPC	
	rc_i	rc_w	rc_i	rc_w
mm				
6.87	7.37	6.92	7.01	6.96

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as Kamai et al. (2015), which uses ±5 s fitting window around the peak temperature.

Results and Discussion All results presented here are based on data from thermistor Ta, although both thermistors showed close agreement. Figure 2 compares the measured temperature rise (ΔT) at the thermistor with fitted curves from the ILS and ICPC models in both air-free ice (–21°C) and agar-stabilized water (21°C). The rapid peak of ΔT in air-free ice was nearly double that in water, attributed to ice's lower C_v and higher λ and κ. Both models fit the observed ΔT data well. Table 1 shows the physical rod spacing (rphy) and the calibrated spacing from both models in ice (rc_i) and water (rc_w). In water, both models produced rc_w values close to rphy. However, the ILS model substantially overestimated rc_i, whereas the ICPC model showed only a slight change. This supports prior findings that ICPC-based calibration is less affected by differences in C_v between calibration media.

Table 2 presents reference and estimated values of C_v, λ and κ, after calibration in the ice. The ICPC model consistently yielded more accurate estimates than the ILS model. Notably, calibrating in media with similar C_v to the target medium (e.g., wet soil) improves accuracy in thermal property estimation. Since ice's C_v (1.93 MJ m^{-3} °C^{-1}) is closer to that of wet soil than water's C_v (4.18 MJ m^{-3} °C^{-1}), air-free ice could potentially serve as a more suitable calibration medium, although the creation of air-free ice is time-consuming.

Figure 4 illustrates the accuracy of ICPC-based estimates of all three thermal properties using rc_i, compared with reference value for ice and water at the temperature range roughly between –25 and 25°C. Error bars reflect standard deviations from repeated measurements, confirming the ICPC model's robustness. These results support the potential use of air-free ice and the ICPC model for accurate DPHP calibration.

Table 2. Thermal property validation in water using calibrated DPHP in ice.

	C_v MJ m^{-3} °C^{-1}		λ W m^{-1} °C^{-1}		κ mm s^{-1}	
	Ref.	Avg.	Ref.	Avg.	Ref.	Avg.
ILS	4.18	3.80	0.60	0.67	0.14	0.18
ICPC		4.26		0.62		0.15

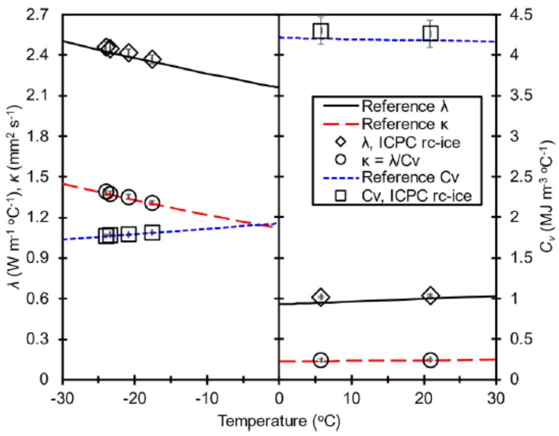

Figure 3. Estimated all three thermal properties with calibrated DPHP in air-free ice using the ICPC model.

Conclusion The ICPC model provided more accurate thermal property estimates than the ILS model in both air-free ice and agar-stabilized water. By accounting for rod diameter and heat capacity, the ICPC model produced calibrated rod spacings that were closer to the actual physical spacing and less affected by the thermal properties of the calibration medium. However, using the physical spacing value without calibration still introduces significant errors. This study demonstrates that applying the ICPC model with proper calibration, especially in reference media like air-free ice, can improve the reliability of heat pulse probe measurements in soils. These findings support the broader use of the ICPC model for soil thermal property assessments across different environments and conditions.

References Kamai et al. (2015). Soil Sci. Soc. Am. J., 79(4), 1059–1072.; Naruke et al. (2021). Agric. For. Meteorol., 308–309, 108610.

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