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Method for Maintaining One-Dimensional Temperature Gradients in Unsaturated, Closed Soil Cells

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Abstract

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Disciplines

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ABSTRACT

One-dimensional temperature gradients are difficult to achieve in nonisothermal laboratory studies because, in addition to desired axial temperature gradients, ambient temperature interference (ATI) creates a radial temperature distribution. Our objective was to develop a closed soil cell with limited ATI. The cell consists of a smaller soil column, the control volume, surrounded by a larger soil column, which provides radial insulation. End boundary temperatures are controlled by a new spiral-circulation heat exchanger. Four cell size configurations were tested for ATI under varying ambient temperatures. Results indicate that cells with a 9-cm inner column diameter, 5-cm concentric soil buffer, and either 10- or 20-cm length effectively achieved one-dimensional temperature conditions. At 30°C ambient temperature, and with axial temperature gradients as large as 1°C cm^{-1}, average steady-state radial temperature gradients in the inner soil columns were <0.02°C cm^{-1}. Thus, these cell configurations meet the goal of maintaining a one-dimensional temperature distribution. These cells provide new opportunities for improving the study of coupled heat and water movement in soil.

Heat and water redistribution in soil are closely linked. Water moves in response to thermal gradients, while water redistribution both carries heat and alters soil thermal properties. These processes have been studied in the field setting (e.g., Jackson, 1974; Cahill and Parlange, 1998), but the complexity of field conditions often demands that fundamental work be conducted in a controlled laboratory setting. Theory has been developed to describe coupled heat and water movement (e.g., Philip and de Vries, 1957), but mathematical complexity usually limits analysis to one dimension. Providing one-dimensional temperature conditions in laboratory soil columns remains challenging.

Prunty and Horton (1994) noted that laboratory studies aimed at one-dimensional temperature conditions (e.g., Nassar and Horton, 1989; Bach, 1992) often demonstrated evidence of ATI. This interference creates a radial temperature distribution, in addition to the axial temperature distribution from imposed boundary conditions, thus altering the coupled processes of heat and water movement within the column. The two-dimensional temperature distributions of these studies limit thorough analysis and comparison to one-dimensional theory. In response, Prunty and Horton (1994) developed closed soil cells to reduce ATI and produce one-dimensional temperature distributions. Their cells were small (5-cm length, 2.5-cm i.d.) and required 8 cm of radial insulation. They found that, with restricted ATI, steady-state axial temperature distributions for unsaturated soil cells were concave between boundary temperatures (cf. Prunty, 1992), unlike the linear or convex distributions frequently reported in the literature (cf. Nassar and Horton, 1989). This concavity comes from the nonlinear distribution of thermal properties associated with water redistribution in response to thermal gradients (Prunty and Horton, 1994).

The cells recommended by Prunty and Horton (1994) reduce ATI, but their small size imposes experimental limitations on both the separation of boundary temperatures and the in situ instrumentation needed to study water redistribution. Larger cells have been implemented to provide experimental flexibility (Prunty, 2003), but without addressing ATI. To both remove size limitations and address ATI, we designed a new type of closed soil cell. We hypothesized that we could reduce the effects of ATI by radially insulating the control volume soil with an additional concentric layer of the same soil material, exposed to the same end boundary conditions. Because water redistribution creates nonuniform thermal properties in the soil control volume, static insulation creates a mismatch in the thermal properties between control volume soil and insulation. Having a concentric soil layer as the insulation allows water redistribution and thus provides a better match in thermal properties between insulation and the control volume. Our goal in this design was to develop larger cells (greater diameter and length) than those recommended by Prunty and Horton (1994). To test our hypothesis, we evaluated several sizes and configurations of these soil cells for the effect of ATI. We also developed a new heat exchanger for end boundary temperature control. Ambient temperature interference was evaluated by measuring steady-state axial and radial temperature distributions in the new cells under unsaturated conditions.

MATERIALS AND METHODS

Soil Cells

Laboratory experiments used closed soil cells with controlled boundary temperatures. Two cell lengths and two cell

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Abbreviations: ATI, ambient temperature interference; F38, 3.8-cm fiberglass insulation; L, long; N, narrow; R16, 1.6-cm Reflectix insulation; R48, 4.8-cm Reflectix insulation; S, short; TC, thermocouple; W, wide.

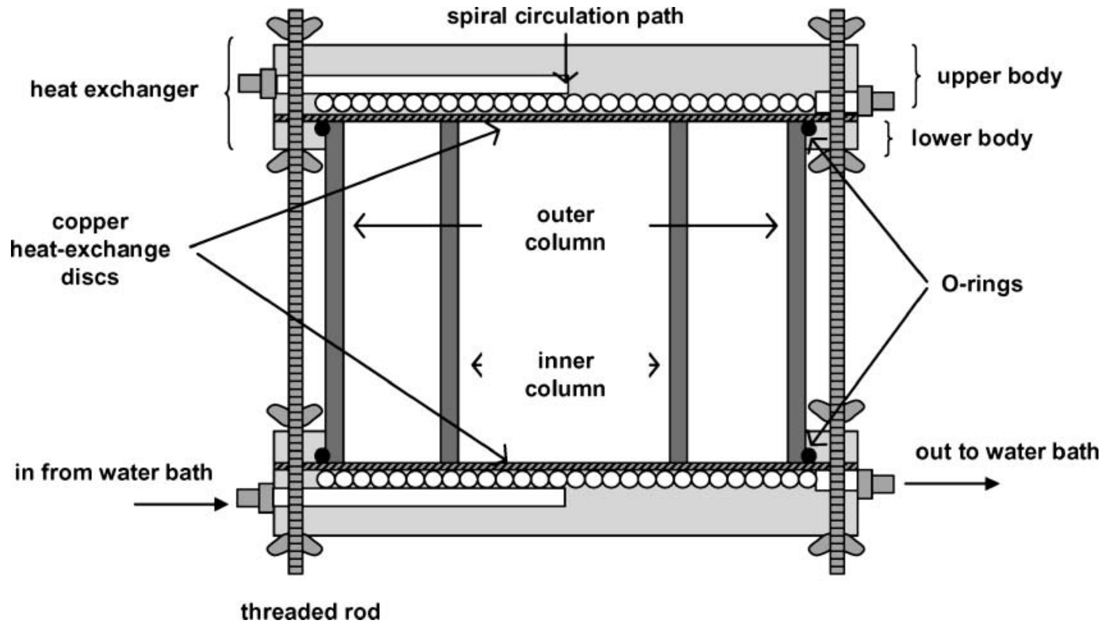

Fig. 1. Cross-section of the cell tested in the experiments, shown without soil, insulation, and thermocouples. Heat exchangers positioned at the top and bottom of the cell are identical except for orientation. The diagram is not drawn to scale.

diameter configurations were tested, giving a total of four cell designs. Each cell consisted of a smaller soil column contained within a larger soil column (Fig. 1). Both inner and outer columns were made from Schedule 40 PVC (polyvinyl chloride) pipe, cut to the same length. The smaller column was uniformly packed with soil, and placed inside the larger column. The outer column was packed with identical soil material to provide radial insulation.

Cell lengths were 10 cm (S, short) and 20 cm (L, long), respectively. The cell diameter configurations were wide (W): 20.2-cm outer column diameter, 8.9 cm inner column diameter; and narrow (N): 8.9-cm outer column diameter, 5.2 cm inner column diameter. The W and N configurations gave a soil buffer thickness between the inner and outer columns of 5.1 and 1.5 cm, respectively. Cell configurations (Table 1) are hereafter referred to by their length and width combination, for example, SW denotes short and wide.

In an effort to minimize the effects of ATI, additional insulation was placed around the outer column for each cell configuration. Two insulation methods were used for each cell under each set of experimental temperature conditions (Table 2). The first method consisted of a single layer of fiberglass pipe insulation (Insulation World, Hopewell, VA) with thickness of 3.8 cm (hereafter F38). The second method also used F38, around which were wrapped layers of Reflectix bubble insulation (Reflectix Inc., Markleville, IN) with nominal thickness of 0.8 cm per layer. Two layers of Reflectix insulation were used for the S cells (1.6 cm total thickness of Reflectix insulation, hereafter R16) and six layers were used for the L cells (4.8 cm total thickness, hereafter R48). Insulation was fit tightly around the cells and held in place with tape. For further comparison, additional runs were made under a subset of ambient temperature conditions using no cell insulation for the S cells and F38 plus R16 for the L cells.

Table 1. Cell configurations for columns constructed from Schedule 40 PVC (polyvinyl chloride).

		Outer column		Inner column	
Cell	Length	Inner diam.	Wall	Inner diam.	Wall
	cm				
Long, wide	20.0	20.2	0.8	8.9	0.6
Long, narrow	20.0	8.9	0.6	5.2	0.4
Short, wide	10.0	20.2	0.8	8.9	0.6
Short, narrow	10.0	8.9	0.6	5.2	0.4

Temperature Control and Measurement

The ends of each cell were sealed with heat exchangers (Fig. 1). The heat exchangers consisted of a Plexiglas body with an inner channel for water circulation, a thin copper plate (0.5-mm thick) for heat exchange with the soil, and an O-ring to provide a seal between the heat exchanger and the cell (Fig. 2). The upper body of the heat exchanger was a disk (2.5 cm thick), with a diameter 7 cm larger than the outer diameter of the soil cells. The lower side of the body was shaped with a ball mill to create a spiral channel (6.3-mm i.d.) for water circulation from temperature-controlled water baths

Table 2. Experimental conditions for cells containing Hanlon sand packed at a water content of 0.072 m^3 m^{-3} to a bulk density of 1.6 Mg m^{-3}. Each ambient temperature condition was maintained for 2 d.

	Boundary temperature			
Cell	Upper	Lower	Ambient temperature	Insulation†
	°C			
Long, wide	35	15	20	F38, F38 + R48
			30	F38, F38 + R48
			40	F38, F38 + R48
Long, narrow	35	15	20	F38, F38 + R48
			30	F38, F38 + R48
			40	F38, F38 + R48
Short, wide	30	15	10	F38, F38 + R16
			20	F38, F38 + R16
			30	F38, F38 + R16
			40	F38, F38 + R16
Short, narrow	30	15	10	F38, F38 + R16
			20	F38, F38 + R16
			30	F38, F38 + R16
			40	F38, F38 + R16

† Two insulation methods were used for each cell. The first method used fiberglass insulation 3.8 cm thick (F38). The second method used F38 plus Reflectix insulation 1.6 cm thick (F38 + R16) or 4.8 cm thick (F38 + R48).

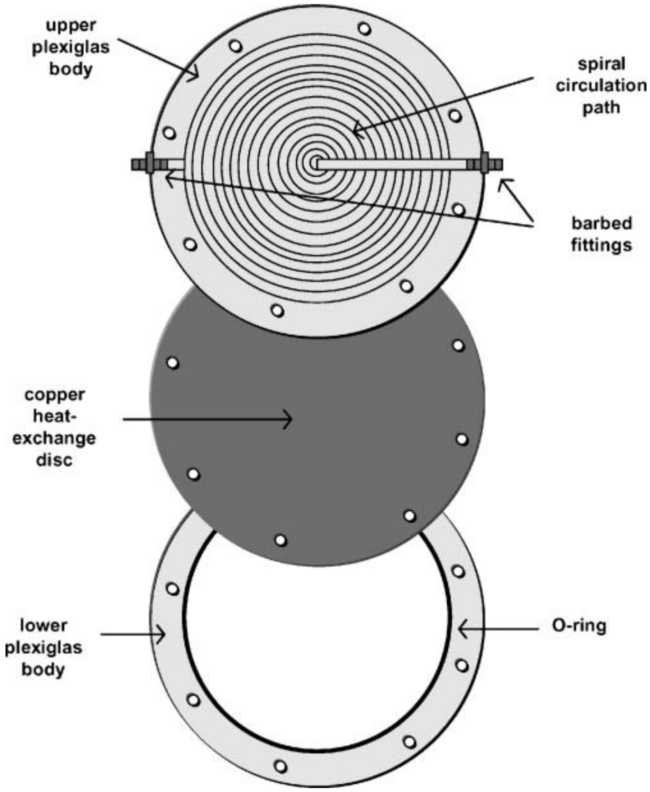

Fig. 2. Components of the heat exchanger as arranged on the top of the soil cell. Identical heat exchangers were placed on the top and bottom of each cell. The diagram is not drawn to scale.

(Programmable Digital Circulator, Model 9512, PolyScience, Niles, IL) via barbed fittings. Water was circulated from the water bath to the center of the spiral channel, and returned from the outer edge of the spiral to the water bath. The diameter across the entire width of the spiral loop matched the diameter of the soil cells; the circulation path frequency was approximately one path per 0.7 cm. A copper plate was held in place between the soil and the spiral channel by the lower body of the heat exchanger, which consisted of a Plexiglas ring (2.5 cm thick). The inner diameter of the ring matched the outer diameter of the cell, thus seating the packed cells in contact with the copper plate. An O-ring between the outer column and the Plexiglas ring provided a seal. Threaded rods with wing nuts were used to secure the entire system. Two sizes of heat exchangers, identical except in diameter, were used for the four cell configurations.

Temperature distributions in the cells were measured with copper-constantan (Type T) thermocouples (TCs) made from 28-gauge insulated wire. Thermocouple temperatures were recorded using a datalogger (Model 21X, Campbell Scientific, Logan, UT) and two multiplexers (Model AM16/32, Campbell Scientific). The TCs were installed during column packing with leads running through small portals in the walls of the column. After installation, the portals were sealed with putty. For all cells, TCs were placed in contact with the heat-exchanger disks at both ends of the cell and at 2-cm increments along the length of the cell. At each depth increment, TCs were installed radially at the center of the inner column and within 1 cm of the outer column wall. For the W cells, a third TC was installed within the inner column, within 1 cm of the wall, at each depth increment.

The cells and water baths were placed within a growth chamber during experimental runs to maintain constant ambient temperature conditions. Ambient temperatures within the growth chamber were recorded with an additional TC.

Experimental Conditions

All experimental runs used the same soil material, initial volumetric water content (θ), and bulk density (ρ_b). The soil was collected from the subsurface of an area mapped as Hanlon sand (coarse-loamy, mixed, superactive, mesic Cumulic Hapludoll; Soil Conservation Service, 1984) near Ames, IA. The soil was air dried, passed through a 2-mm screen, and mixed thoroughly before use. Results from particle-size analysis by the pipette method (Soil Survey Staff, 1972) showed that the soil was composed of 91.7% sand, 7.2% silt, and 1.1% clay. Organic matter content was <1%. Before packing, the soil was wetted to achieve an initial θ of 0.072 $m^3 m^{-3}$ at a packing ρ_b of 1.6 Mg m^{-3}. The soil was carefully packed into the cells in 2-cm depth increments in an effort to achieve a uniform ρ_b and to allow placement of the TCs.

The cells were oriented vertically throughout the experiments. Boundary temperatures were constant for each cell throughout the experiments, but ambient temperatures were changed to assess the effect of ATI (Table 2). For the 20-cm cells (LW and LN), the upper and lower boundary temperatures were 35 and 15°C, respectively. For the 10-cm cells (SW and SN), the upper and lower boundary conditions were 30 and 15°C, respectively. Ambient temperatures tested included 10, 20, 30, and 40°C (depending on cell configuration). Each ambient temperature was maintained for 48 h before moving to the next warmer temperature. Temperatures within the cells were recorded throughout the experiments, but here we focus on steady-state temperatures recorded during the last few hours of each 48-h period.

Cells were disassembled at the end of the experimental runs, and soil in both the inner and outer columns was sectioned into 2-cm depth increments. These sections were weighed, dried at 105°C for 24 h, and reweighed to determine the final θ distribution within the cells.

RESULTS AND DISCUSSION

Performance of the Heat exchangers

The heat exchangers used in these experiments differed in design from those typically used in column studies. Temperature-controlled water baths have been used by others (Bach, 1992; Prunty, 1992; Prunty and Horton, 1994), but water is typically circulated through a void space, similar in lateral extent to the heat-exchanger plate. Using a void space creates uncertainty in the uniformity of imposed boundary temperatures because of the potential for incomplete mixing within the void. Circulation of water through a spiral loop eliminates the issue of mixing and ensures that temperature-controlled fluid comes into thermal contact with the entire surface of the heat-exchanger plate.

A preliminary experiment was conducted to test the uniformity of imposed temperatures along these new heat exchangers. A single column, identical to the outer column of a LW cell, was packed with the Hanlon sand. Five TCs were installed radially at each end of the column, in contact with the heat-exchanger plates. The TCs were positioned with one at the center of the column, two on opposite sides of the column within 1 cm of the wall, and two spaced equally between the center and the column wall. Water bath temperatures were maintained at 35 and 15°C for 24 h, and temperatures were recorded every 10 min.

Steady-state radial temperature along the soil and heat-exchanger boundaries was achieved within 6 h after changing temperatures from the initial 20°C ambient temperature. For the remainder of the 24-h period, the coefficient of variation for boundary temperatures was <0.3 and <1.2% for the warm and cold ends, respectively. Temperatures showed a slight decrease from the center of the column outward (<0.2°C across the 10-cm radius) for the warm end and a slight increase from the center of the column outward (<0.4°C across the 10-cm radius) for the cool end. This slight radial temperature change was consistent with expectations from the design; heat was lost or gained by the heat exchanger fluid along its spiral circulation path from the center of the heat exchanger outward. Additional heat loss or gain may have also occurred near the edge of the heat exchanger where there was limited insulation from ambient temperature conditions. Temperatures at the two inner positions of the heat exchanger, which represented the end boundary conditions of the inner soil column in the two-column cell design, differed by an average of <0.04 and <0.06°C for the warm and cool ends, respectively. The heat exchangers provided an average axial thermal gradient of 1°C cm^{-1} within the soil column. For the soil boundaries, the heat exchangers gave a worst-case radial thermal gradient of 0.04°C cm^{-1}. At the inner soil column end boundaries, the heat exchangers gave a worst-case radial thermal gradient of 0.015°C cm^{-1}. Thus, the heat exchangers demonstrated an ability to provide stable and uniform boundary temperatures, particularly across their inner 8-cm diameter sections.

Temperature Distributions with Variable Insulation

Steady-state temperatures were reached for all cell configurations within 48 h following changes in ambient temperature or insulation. The coefficient of variation for temperature during the last 6 h of each 48 h period was <0.3% for all TC positions. The consistency of the axial steady-state temperature profile across insulation methods for a given cell was used as a standard to determine the degree of ATI (Prunty and Horton, 1994). Comparison of the temperature profiles indicates that the soil buffer alone did not adequately limit ATI for all cells (Fig. 3). At 30°C ambient temperature and F38,

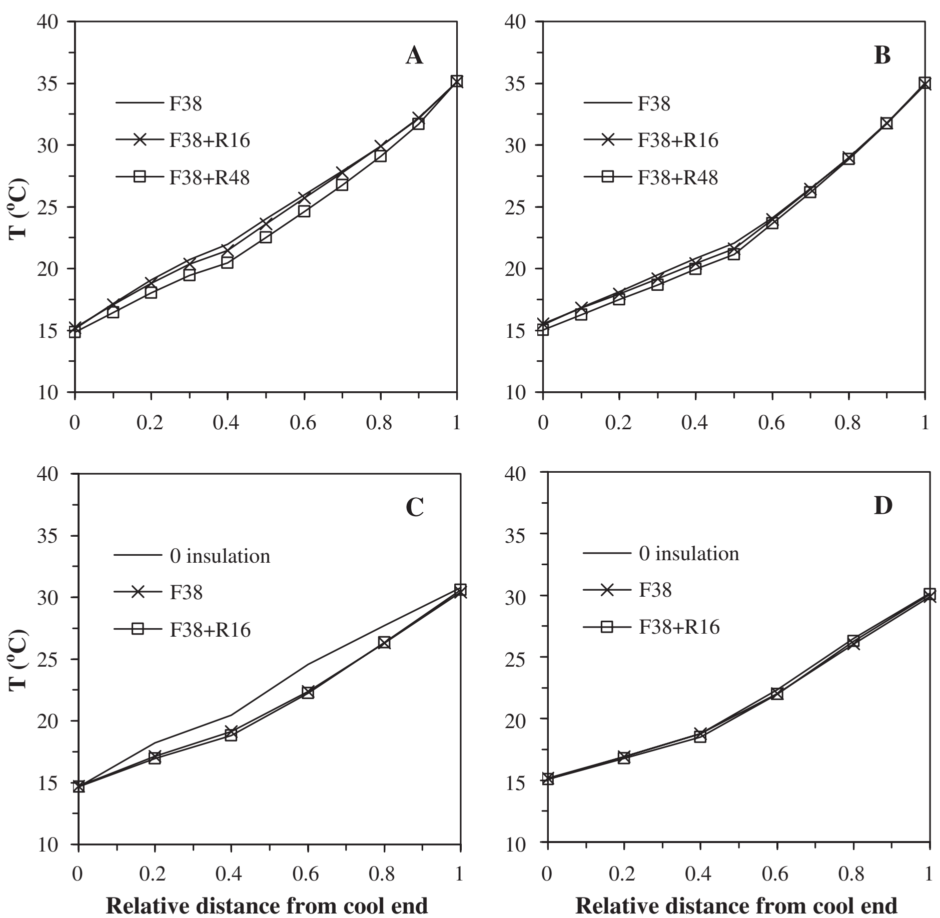

Fig. 3. Steady-state temperature (*T*) profiles as affected by insulation thickness for 30°C ambient temperature: (A) the long, narrow cell, (B) the long, wide cell, (C) the short, narrow cell, and (D) the short, wide cell. Insulation methods included fiberglass insulation at 3.8 cm (F38) and Reflectix insulation at 1.6 (R16) and 4.8 (R48) cm (Table 2).

the LN cell showed a nearly linear temperature profile (Fig. 3A). Increasing the thickness of insulation led to the concave temperature profile described by Prunty and Horton (1994). Because the temperature distribution continued to change at the maximum insulation thickness tested (F38 plus R48), it is unclear whether ATI was effectively eliminated. The LW cell showed a concave temperature profile at 30°C ambient temperature for all insulation thicknesses (Fig. 3B). Temperature profiles changed slightly with increasing insulation thickness, but their relative stability indicated that ATI was greatly reduced by the soil buffer.

The SN cell showed a nearly linear temperature profile with zero insulation at 30°C ambient temperature (Fig. 3C). But the temperature profile became concave with F38 and showed little change with further insulation. The SW column had concave, consistent temperature profiles across all tested insulation thicknesses (Fig. 3D). For this cell, the soil buffer, even without additional insulation, appeared to adequately reduce ATI to nearly undetectable levels. By comparison, the SN cell showed limited ATI with F38; the total thickness of soil buffer and insulation for this configuration is nearly equal to the thickness of the soil buffer alone for the SW cell.

Radial Temperature Differences

From comparisons with varying insulation thickness, the LW cell with F38 plus R48 and the SW cell with F38 showed limited ATI. Radial temperature differences within these cells at 30°C ambient temperature were examined as a further indicator of ATI (Fig. 4). The radial temperatures at the two positions within the inner columns of the cells were quite similar. The average temperature difference between the center and outer edge of the inner column was only ~0.08°C for the LW and SW cells. Thus, these two cell configurations appear to approach the design goal of a one-dimensional temperature distribution for 30°C ambient conditions. Radial temperature differences between the inner and outer (insulation) columns were also small (data not shown in Fig. 4) with a maximum difference between the center and outer radial temperatures of 1°C for both the LW and SW cells.

Temperature Distributions with Variable Ambient Temperatures

From the previous comparisons of insulation and radial temperature, the minimum effective insulation thickness for the cells was determined to be F38 plus R48 for the LN and LW cells, F38 plus R16 for the SN cell, and F38 for the SW cell. These configurations are compared for all tested ambient temperatures in Fig. 5.

The temperature profile for the LN cell shifted from nearly linear at 40°C ambient temperature to concave at 20°C ambient temperature (Fig. 5A). Clearly even the maximum insulation thickness tested did not alleviate the effects of ATI. The SN cell showed a concave shape across all ambient temperatures, with only a small shift at different ambient temperatures (Fig. 5B). The LW cell gave a consistent shape to the temperature profile and showed only a small shift with changing ambient temperature (Fig. 5C). The SW cell showed nearly identical temperature profiles for all ambient temperatures, indicating well-controlled ATI (Fig. 5D). The mean shift in soil temperatures across the range of ambient temperatures was 2.21, 0.57, 0.54, and 0.25°C for the LN, SN, LW, and SW cells, respectively. Thus, the SW cell clearly provided the best performance of the four cell configurations tested. The SN and LW cells were similar in effectiveness of controlling ATI, while the LN cell failed to effectively control ATI.

To further verify these results, a subset of experimental conditions was repeated for the LW and LN cells. At the conclusion of the initial experiments, the LW and LN cells were again subjected to ambient temperatures of 20 and 30°C with F38 insulation. Results were consistent with previous measurements. The mean shift in soil temperatures between these ambient temperatures was <0.5°C for the LW cell, but was >1.5°C for the LN cell. These results confirmed previous observations about the relative effectiveness of the LW and LN

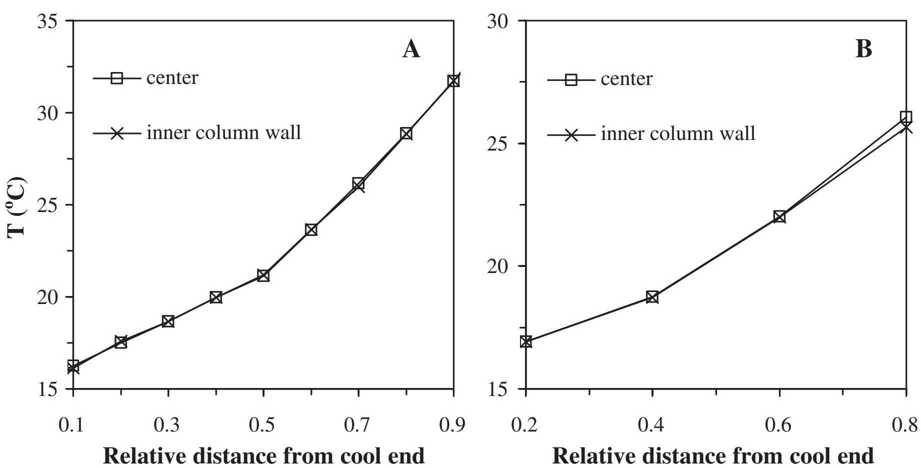

Fig. 4. Steady-state temperature (*T*) profiles at two radial positions for 30°C ambient temperature in (A) the long and wide cell with 3.8 cm of fiberglass plus 4.8 cm of Reflectix, and (B) the short and wide cell with 3.8 cm of fiberglass insulation.

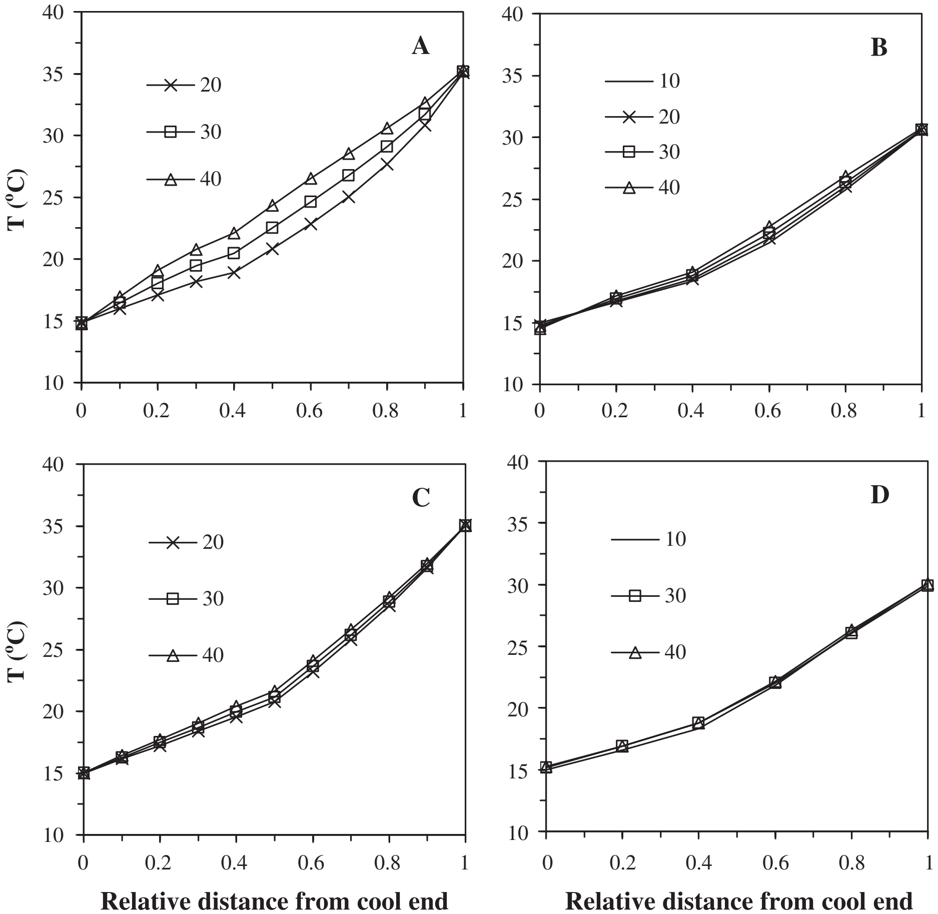

Fig. 5. Steady-state temperature (*T*) profiles as affected by ambient temperatures of 10 to 40°C: (A) the long, narrow cell with 3.8 cm of fiberglass plus 4.8 cm of Reflectix; (B) the short, narrow cell with 3.8 cm of fiberglass and 1.6 cm of Reflectix; (c) the long, wide cell with 3.8 cm of fiberglass and 4.8 cm of Reflectix; and the short, wide cell with 3.8 cm of fiberglass insulation, respectively.

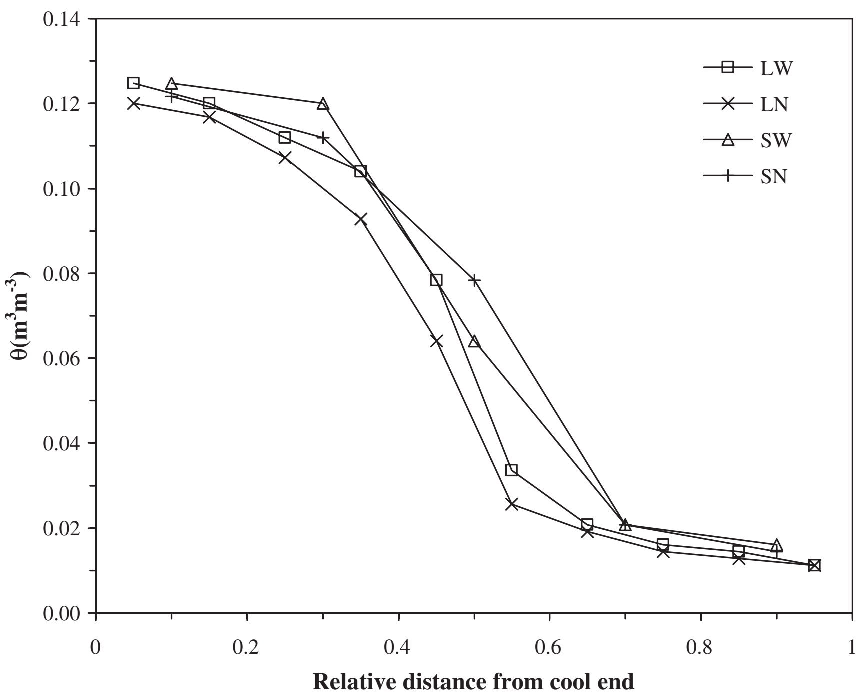

Fig. 6. Final water content (θ) distributions within the long and wide (LW), long and narrow (LN), short and wide (SW), and short and narrow (SN) cells.

cells and indicated repeatability in the measured effect of ATI.

Water Content Distributions

At the end of the experiment, columns were disassembled and final θ distributions were determined. Water recovery was ~85% for the LW and LN cells and ~95% for the SW and SN cells. It is expected that most water loss occurred during cell packing or during end-of-experiment column sectioning; the long columns required more time for both packing and sectioning. The minimum water recovery was 93% with the cell design of Prunty and Horton (1994).

The purpose of the two-column cell configuration is to provide insulation of the control soil volume using material having similar thermal properties. To have similar thermal properties, the soil in the outer column in each cell must have a similar water content distribution to the inner column. For each of the four cell configurations, outer and inner column θ at each depth were within 0.01 $m^3\ m^{-3}$. Thus, despite small temperature differences between the outer and inner columns, ATI appears to have had little impact on outer and inner column θ distributions.

Because cell end temperatures were maintained for >12 d during tests with various insulation thicknesses and ambient temperatures, the short-column θ distributions probably approached steady state. The θ distributions in the long columns may not have reached steady state. Final θ distributions were similar between the four cells, however, even with different lengths and slightly different end temperatures (Fig. 6). The slightly more abrupt change in θ near the ends in the short cells (SW and SN) may be related to the longer equilibration time required by the LW and LN columns. The θ distribution for all four cells was similar to that shown in Fig. 5A of Prunty and Horton (1994) for a sand at similar initial θ.

CONCLUSIONS

The primary objective of this study was to develop soil cells with limited ATI for use in experiments to monitor one-dimensional coupled heat and moisture transport phenomena. The new cells described here consisted of an inner soil column surrounded by a buffer of the same soil material. Cell end temperatures were controlled by a spiral circulation heat exchanger, which provided near-uniform imposed end-boundary temperatures. Several cell configurations were tested for the effect of ATI on steady-state temperature profiles. Results indicate that both the LW and SW cells (with appropriate insulation) sufficiently limit ATI to create a near one-dimensional temperature distribution within the control volume.

From these experiments, it appears that cells can be expanded from the 5-cm-length, 2.5-cm-diameter size described by Prunty and Horton (1994). Cells with control volumes as large as 10-cm length with 9-cm diameter, or even 20-cm length with 9-cm diameter, are able to provide approximate one-dimensional temperature distributions when a concentric 5-cm soil buffer is used. These cell designs provide new opportunities for improving the study of coupled heat and water movement in soil.

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