

Postprint: Simulation of Soil Water-Heat Distribution Characteristics and Influencing Factors in Vertical Tube Surface Drip Irrigation

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Abstract

In desert environments, soil water-heat conditions are key factors affecting the healthy growth of sand-fixing plants in vegetation-based sand-fixation projects. Vertical pipe surface drip irrigation is a novel water-saving and temperature-control conservation technology proposed to alleviate the combined stress of soil drought and high surface temperature on sand-fixing plant seedlings. Its soil water-heat distribution and migration patterns remain unclear, and its application to plant sand-fixation areas lacks theoretical foundation. To investigate the effects of irrigation parameters (dripper flow rate and irrigation water temperature) and vertical pipe parameters (vertical pipe diameter and burial depth) on soil water-heat distribution and migration patterns under vertical pipe surface drip irrigation, a mathematical model for soil water-heat migration under vertical pipe surface drip irrigation was constructed using HYDRUS-2D software. The reliability of the established model and its solution method was verified through indoor experiments. Building upon this, nine simulation scenarios were designed using single-factor analysis, considering four influencing factors: dripper flow rate (1, 2, 3 L · h⁻¹), irrigation water temperature (10, 20, 30 °C), vertical pipe diameter (9.6, 11.6, 13.2 cm), and vertical pipe burial depth (15, 20, 25 cm), to obtain soil water-heat distribution characteristics and migration patterns under different parameter combinations for vertical pipe surface drip irrigation. The results indicated: (1) Throughout the irrigation process, soil water-heat changes at nine representative points within the wetted body were all achieved through water-heat coupling realized by regulating temperature through water. During the initial irrigation stage, dynamic changes in soil water-heat inside the vertical pipe were most pronounced, particularly at the intra-pipe surface layer; as irrigation duration increased, soil water-heat conditions inside the pipe gradually stabilized, with water permeating laterally through orifices at the pipe bottom, causing soil moisture at various points outside the pipe to increase rapidly and stabilize, while temperature fluctuated

slightly under the influence of irrigation water temperature. (2) During the drip irrigation period, vertical pipe diameter had no significant effect on soil water-heat conditions, while vertical pipe burial depth primarily affected soil moisture conditions, with no obvious influence on the soil thermal environment. Under different vertical pipe burial depths, moisture distribution in the soil wetted body outside the pipe was demarcated by the pipe bottom: soil water content at the same point above the pipe bottom decreased with increasing burial depth, while soil water content at the same point below the pipe bottom increased with increasing burial depth. (3) Dripper flow rate had relatively limited influence on soil temperature distribution, but served as a key parameter affecting soil moisture conditions; the greater the dripper flow rate, the higher the soil water content at the same point outside the pipe. (4) Irrigation water temperature had relatively weak influence on soil moisture distribution, but constituted a direct factor affecting soil temperature conditions; the higher the irrigation water temperature, the higher the soil temperature at the same point both inside and outside the pipe. (5) When vertical pipe diameter and burial depth are fixed and difficult to adjust, effective regulation of root zone soil water-heat conditions can be achieved by adjusting dripper flow rate and irrigation water temperature. This study can provide a scientific basis for the design, operation, and management of vertical pipe surface drip irrigation projects for sand-fixing plants.

Full Text

Simulation of Soil Hydrothermal Distribution Characteristics and Analysis of Influencing Factors in Vertical Tube Surface Drip Irrigation

Abstract: The success of sand fixation projects in desert environments critically depends on soil hydrothermal conditions, which fundamentally affect the healthy growth of sand-fixing vegetation. Vertical tube surface drip irrigation represents a novel water-saving and temperature-control conservation technology designed to alleviate the combined stresses of soil drought and high surface temperatures on sand-fixing seedlings. However, the mechanisms governing soil hydrothermal distribution and migration patterns remain unclear, limiting the theoretical foundation for widespread application in sand fixation areas. To elucidate the effects of irrigation parameters (drip head flow rate and irrigation water temperature) and vertical tube parameters (tube diameter and burial depth) on soil hydrothermal distribution and migration under vertical tube surface drip irrigation, this study developed a mathematical model of soil water-heat transport using HYDRUS-2D software. The reliability of the constructed model and its solution method was verified through laboratory experiments. Building upon this validation, a single-factor analysis was conducted considering four influencing factors—drip head flow rate (1, 2, and 3 L · h⁻¹), irrigation water temperature (10, 20, and 30°C), vertical tube diameter (9.6, 11.6, and 13.2 cm), and burial depth (15, 20, and 25 cm)—across nine simulation scenarios to char-

acterize soil hydrothermal distribution patterns and migration dynamics under various parameter combinations.

The results revealed several key findings: (1) Soil hydrothermal changes throughout the irrigation process were achieved through water-temperature coupling, with the most pronounced dynamic variations occurring during the initial irrigation stage, particularly within the inner surface layer of the tube. As irrigation progressed, the hydrothermal conditions inside the tube gradually stabilized, with water infiltrating laterally through bottom holes while soil moisture outside the tube increased rapidly and stabilized. Temperature exhibited slight fluctuations influenced by irrigation water temperature. (2) During drip irrigation, vertical tube diameter showed no significant effect on soil hydrothermal status, whereas burial depth primarily influenced soil moisture conditions without substantially affecting the thermal environment. The soil moisture distribution in the wetting body outside the tube was demarcated by the tube bottom, with moisture content at points above the bottom decreasing as burial depth increased, while moisture content at points below the bottom increased with greater burial depth. (3) Drip head flow rate represented the critical parameter affecting soil moisture status, though its influence on temperature distribution was limited. Higher flow rates resulted in greater soil moisture content at identical points outside the tube. (4) Irrigation water temperature had minimal impact on soil moisture distribution but served as the direct factor influencing soil temperature. Higher irrigation water temperatures led to elevated soil temperatures at identical points both inside and outside the tube. (5) When vertical tube diameter and burial depth were fixed and difficult to adjust, effective regulation of root zone soil hydrothermal conditions could be achieved by modulating drip head flow rate and irrigation water temperature. This research provides a scientific basis for the design, operation, and management of vertical tube surface drip irrigation systems for sand-fixing vegetation.

Keywords: irrigation; infiltration; hydrothermal transport; numerical simulation; vertical tube surface drip irrigation

Introduction

Wind-sand disasters represent a major ecological and environmental challenge confronting human society, attracting widespread international attention. Implementing effective wind-sand control measures constitutes an essential response to these disasters. Among various control strategies, vegetation-based sand fixation has emerged as an ecologically friendly and sustainable approach for combating wind-sand hazards and establishing ecological barriers in sandy regions. In desert environments, soil hydrothermal conditions critically influence the healthy growth of sand-fixing plants. During summer months, clear skies and direct solar radiation frequently generate surface temperatures exceeding 50°C, causing basal stem burns in plant seedlings. Combined with drought conditions in sandy soils, these factors pose severe challenges to seedling survival.

To simultaneously mitigate the combined stresses of high surface temperatures and soil drought on sand-fixing seedlings, Fan Yanwei et al. integrated pipe protection technology with surface drip irrigation systems to propose vertical tube surface drip irrigation. Compared with conventional surface drip irrigation, this technology partially shields the soil surface, significantly suppressing evaporation to only 7.0% of traditional systems. Compared with non-irrigated treatments, it provides cooling effects that reduce surface temperatures by 7.0°C at midday peak temperatures (15:00), creating more favorable growth environments for seedlings. These advantages demonstrate the exceptional performance of vertical tube surface drip irrigation in water conservation and temperature control, offering an effective technical solution for sand fixation projects.

Current understanding of vertical tube surface drip irrigation has been limited to soil water movement patterns, primarily through laboratory experiments and numerical simulations. Experimental studies have investigated cumulative infiltration and wetting front migration under various influencing factors through both vertical tube ponded infiltration and vertical tube surface drip irrigation tests using aeolian sandy soil. Numerical simulations have examined infiltration rate changes under ponded conditions and wetting front migration patterns under drip irrigation scenarios. However, research on soil hydrothermal distribution characteristics and influencing factors under vertical tube surface drip irrigation remains limited, particularly regarding the dynamic coupling processes of soil moisture and temperature. This knowledge gap restricts comprehensive understanding of the hydrothermal coupling mechanism and hinders further technological development and application.

The HYDRUS software package has been widely applied to simulate soil hydrothermal transport processes, demonstrating reliable performance in reflecting transport patterns. Previous studies have validated HYDRUS models for various irrigation scenarios, including subsurface drip irrigation, furrow irrigation, and surface drip irrigation under mulched conditions. These investigations have successfully simulated soil moisture dynamics and thermal transport, optimized hydraulic and thermal parameters through inverse modeling, and achieved satisfactory results. The software's proven applicability in simulating soil hydrothermal distribution under drip irrigation conditions provides a robust methodological foundation for numerical simulation of vertical tube surface drip irrigation.

The distinctive feature of vertical tube surface drip irrigation lies in the tube wall's horizontal restriction and vertical guidance of soil water movement, creating infiltration patterns that differ substantially from conventional surface drip irrigation. Currently, no dedicated HYDRUS-based research exists for hydrothermal transport under vertical tube surface drip irrigation conditions. To address this research gap, this study developed a mathematical model for soil water-heat transport in vertical tube surface drip irrigation using HYDRUS-2D, validated the model reliability through laboratory soil box experiments, and systematically investigated the effects of irrigation parameters (drip head flow

rate, irrigation water temperature) and vertical tube parameters (tube diameter, burial depth) on hydrothermal migration patterns and distribution characteristics. The findings aim to provide theoretical guidance for soil hydrothermal management and promote the application of vertical tube surface drip irrigation in sand fixation areas.

1.1 Laboratory Experimental Setup

The experimental soil was collected from the Babusha Forest Farm in Gulang County, Wuwei City, Gansu Province. The soil was air-dried, crushed, uniformly mixed, and sieved through a 2 mm mesh to prepare the test samples. Particle size distribution analysis using a laser diffraction instrument (MS2000) revealed sand particles accounted for 97.68% of total mass, with silt and clay comprising 2.32%. According to the international soil texture classification standard, the test soil was classified as sand.

The experimental apparatus consisted of four main components: a soil box, water supply system, vertical tube, lighting system, and soil temperature-moisture monitoring system [Figure 1: see original paper]. The soil box was constructed from 12 mm thick acrylic panels with internal dimensions of 60 cm × 60 cm × 65 cm. Monitoring holes were drilled on one side for inserting temperature-moisture sensors, while ventilation holes at the bottom prevented air entrapment. The water supply system comprised a water storage tank, inlet pipe, peristaltic pump, outlet pipe, and height-adjustable stand, with the peristaltic pump controlling drip head flow rate. The lighting system included 275 W infrared lamps and mounting brackets to simulate desert surface temperature conditions. The monitoring system consisted of soil temperature-moisture sensors and a data logger.

Prior to testing, monitoring holes were sealed with tape and ventilation holes were covered with gauze to prevent soil loss. The soil sample was packed in layers at a predetermined bulk density of $1.54 \text{ g} \cdot \text{cm}^{-3}$ and initial water content of $0.031 \text{ cm}^3 \cdot \text{cm}^{-3}$, with interfaces between layers scarified to ensure hydraulic continuity. When packing reached 40 cm height, the vertical tube was installed at the predetermined burial depth against the perforated side at the center. Packing continued in both the soil box and tube until reaching 5 cm below the top surface. Temperature-moisture sensors were then inserted through the monitoring holes, and the box was sealed. To approximate actual desert surface temperature conditions, infrared lamps heated the soil box surface. During heating, the distance between lamps and surface was adjusted while controlling heating location and intensity with independent switches. Irrigation commenced only after surface and internal temperatures and moisture contents stabilized. Throughout the preheating and irrigation periods, soil moisture and temperature were recorded at 1-minute intervals using the monitoring system.

1.2 Mathematical Model

Vertical tube surface drip irrigation can be conceptualized as an axisymmetric two-dimensional infiltration process. The governing equation for soil water movement is the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[rK(h) \frac{\partial h}{\partial r} \right] + \frac{\partial}{\partial z} \left[K(h) \frac{\partial h}{\partial z} \right] - \frac{\partial K(h)}{\partial z}$$

where θ is volumetric water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), t is time (min), r is radial coordinate (cm), z is vertical coordinate (positive downward) (cm), h is pressure head (cm), and $K(h)$ is unsaturated hydraulic conductivity ($\text{cm} \cdot \text{min}^{-1}$).

The relationship between θ , h , and K was described using the Van Genuchten-Mualem model:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}$$

$$K(h) = K_s S_e^{0.5} [1 - (1 - S_e^{1/m})^m]^2$$

where θ_r is residual water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), θ_s is saturated water content ($\text{cm}^3 \cdot \text{cm}^{-3}$), α is the inverse of the air-entry value (cm^{-1}), n and m are fitting parameters related to soil physical properties ($m = 1 + 1/n$), K_s is saturated hydraulic conductivity ($\text{cm} \cdot \text{min}^{-1}$), and S_e is effective saturation defined as $(\theta - \theta_r)/(\theta_s - \theta_r)$.

The basic equation for soil heat transport can be expressed as:

$$\frac{\partial C(\theta)T}{\partial t} = \frac{\partial}{\partial x_i} \left[\lambda_{ij}(\theta) \frac{\partial T}{\partial x_j} \right] - C_w q_i \frac{\partial T}{\partial x_i}$$

where $C(\theta)$ is soil volumetric heat capacity ($\text{J} \cdot \text{cm}^{-3} \cdot ^\circ\text{C}^{-1}$), T is soil temperature ($^\circ\text{C}$), λ_{ij} is soil thermal conductivity ($\text{J} \cdot \text{cm}^{-1} \cdot \text{min}^{-1} \cdot ^\circ\text{C}^{-1}$), C_w is water specific heat capacity ($\text{J} \cdot \text{cm}^{-3} \cdot ^\circ\text{C}^{-1}$), and q_i is water flux ($\text{cm} \cdot \text{min}^{-1}$).

The simulation domain was a rectangular region with radial length of 30 cm and vertical depth of 60 cm. The time step was 0.1 min and spatial step was 1 cm. The Galerkin finite element method was used for spatial discretization, while an implicit difference scheme handled temporal discretization. [Figure 2: see original paper] illustrates the simulation domain for vertical tube surface drip irrigation.

Initial conditions were established based on measured soil moisture and temperature values. The inner boundary infiltration process involved complex transformation from three-dimensional (water entry from a point) to one-dimensional

(tube wetting) flow. Given the relatively small tube diameter and rapid wetting of the tube section, the 3D-to-1D transition was simplified by assuming uniform water infiltration from the tube bottom as a constant flux boundary. The upper boundary (BC) was treated as an atmospheric boundary with zero infiltration or evaporation rates, while the lower boundary (DE) was a free drainage boundary. Left and right boundaries (AB , EF) and tube walls (AE) were zero-flux boundaries. Temperature boundaries were specified as third-type Cauchy boundaries that varied with irrigation. The initial and boundary conditions were expressed as:

Initial conditions:

$$\theta(r, z, 0) = \theta_i, \quad T(r, z, 0) = T_i \quad (0 \leq r \leq 30 \text{ cm}, 0 \leq z \leq 60 \text{ cm})$$

Boundary conditions:

$$\left\{ \begin{array}{ll} -K(h) \left(\frac{\partial h}{\partial z} - 1 \right) = 0, & BC \\ -K(h) \left(\frac{\partial h}{\partial r} \right) = 0, & AB, EF \\ -K(h) \left(\frac{\partial h}{\partial z} - 1 \right) = \frac{Q}{\pi D^2/4}, & AE \\ h(r, 0, t) = h_0(t), & AE \\ -K(h) \left(\frac{\partial h}{\partial z} - 1 \right) = 0, & DE \\ -\lambda_{ij} \frac{\partial T}{\partial n_i} = 0, & AB, BC, DE, EF \\ -\lambda_{ij} \frac{\partial T}{\partial n_i} = C_w q_i n_i (T - T_w), & AE \end{array} \right.$$

where n_i is the outward unit normal vector, Q is drip head flow rate ($\text{L} \cdot \text{h}^{-1}$), D is tube diameter (cm), and T_w is irrigation water temperature ($^{\circ}\text{C}$).

1.3 Model Parameterization and Simulation Scenarios

1.3.1 Parameter Calibration The soil water characteristic curve was determined using the centrifuge method. Pretreated soil samples were packed into rings at predetermined bulk density, saturated, and then subjected to sequential centrifugation at preset rotational speeds and time intervals using a CR21N high-speed refrigerated centrifuge. Soil mass was recorded at each speed interval, and the Van Genuchten-Mualem model was fitted to derive hydraulic parameters. Saturated hydraulic conductivity was measured using the constant head method.

Thermal transport parameters were obtained through HYDRUS inverse modeling. Temperature values at all observation points under $Q = 1.0 \text{ L} \cdot \text{h}^{-1}$ conditions were used for parameter inversion, with initial values set to HYDRUS-2D defaults. The inverse module identified optimal thermal parameters through iterative computation. presents the calibrated soil hydraulic and thermal transport parameters.

1.3.2 Numerical Simulation Scenarios Following model validation, simulations were conducted using Babusha Forest Farm aeolian sandy soil. A single-factor analysis examined four influencing factors—drip head flow rate, irrigation water temperature, tube diameter, and burial depth—each at three levels, totaling nine scenarios. Simulations analyzed the effects of flow rates (1.0, 2.0, 3.0 L · h⁻¹), water temperatures (10, 20, 30°C), tube diameters (9.6, 11.6, 13.2 cm), and burial depths (15, 20, 25 cm) on hydrothermal migration and distribution patterns. Initial soil hydrothermal conditions were based on measured data from laboratory experiments.

1.4 Statistical Analysis

Data were processed using Excel and Origin software. The root mean square error (RMSE) and Nash-Sutcliffe efficiency coefficient (NSE) were employed for error analysis:

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (O_i - S_i)^2}$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^N (O_i - S_i)^2}{\sum_{i=1}^N (O_i - O_m)^2}$$

where N is the total number of data points, O_i and S_i are the i -th observed and simulated values, respectively, and O_m is the mean observed value. RMSE values approaching zero and NSE values approaching one indicate smaller deviations and higher agreement between simulated and observed data.

Results and Analysis

2.1 Model Validation

The HYDRUS-2D model was validated using measured soil temperature and moisture data from the $D = 11.6$ cm, $B = 20$ cm, $Q = 1.5$ L · h⁻¹ scenario. Nine representative characteristic points within the wetting body were selected for comparison [Figure 3: see original paper]. The simulated and observed values showed consistent trends across all points. Point 1 (inner tube surface) first contacted irrigation water, exhibiting rapid moisture increase and temperature decline before stabilizing. Point 2, located directly below Point 1, showed delayed water arrival, rapid moisture increase, and a temperature pattern of initial increase followed by decrease and stabilization. Points outside the tube displayed similar moisture dynamics and gradual temperature stabilization.

Statistical analysis using t-tests yielded P values greater than 0.05 for all nine points, indicating no significant differences between simulated and observed values. RMSE values averaged 0.46°C for temperature and 0.018 cm³ · cm⁻³ for

moisture content, while NSE coefficients approached 1. These results confirm that the developed mathematical model accurately represents the hydrothermal transport process in vertical tube surface drip irrigation.

2.2 Effects of Influencing Factors on Soil Hydrothermal Migration

2.2.1 Drip Head Flow Rate Single-factor analysis of flow rates ($1.0, 2.0, 3.0 \text{ L} \cdot \text{h}^{-1}$) with $T = 20^\circ\text{C}$, $D = 11.6 \text{ cm}$, and $B = 20 \text{ cm}$ revealed that flow rate primarily affected temperature during early irrigation stages, particularly at Point 1 [Figure 4: see original paper]. Higher flow rates accelerated cooling from initial surface temperature to irrigation water temperature. Throughout the irrigation period, flow rate showed minimal influence on Point 1 temperature (maximum difference: 1.1°C). However, flow rate significantly impacted soil moisture. Larger flow rates shortened the time for water to reach specific points. For Points 1-2 inside the tube, moisture content increased with flow rate, though the wetting effect diminished during later stages as soil approached saturation. For Points beneath and outside the tube, higher flow rates resulted in greater moisture content during later irrigation stages, while early-stage moisture remained at initial values until water arrival. During later stages, soil moisture at all points stabilized near saturation ($0.377 \text{ cm}^3 \cdot \text{cm}^{-3}$), except Point 1 at low flow ($1 \text{ L} \cdot \text{h}^{-1}$) which showed slightly lower moisture ($0.359 \text{ cm}^3 \cdot \text{cm}^{-3}$), likely due to insufficient water supply relative to infiltration capacity.

2.2.2 Irrigation Water Temperature Analysis of water temperatures ($10, 20, 30^\circ\text{C}$) with $Q = 2.0 \text{ L} \cdot \text{h}^{-1}$, $D = 11.6 \text{ cm}$, and $B = 20 \text{ cm}$ demonstrated that irrigation water temperature significantly influenced soil temperature [Figure 5: see original paper]. Temperature at all points increased with irrigation water temperature, with the most pronounced effects at Points 1-2 inside the tube. When irrigation water temperature exceeded initial soil temperature, soil temperature increased, reaching 28.78°C at Point 1. Conversely, lower irrigation water temperatures caused soil cooling. The influence of water temperature on soil moisture was minimal, with moisture content decreasing slightly as temperature increased (maximum difference: $0.013 \text{ cm}^3 \cdot \text{cm}^{-3}$ at Point 5). This minor effect may be attributed to temperature gradient-induced suction gradients driving water migration from high to low temperature zones.

2.2.3 Vertical Tube Diameter Examination of tube diameters ($9.6, 11.6, 13.2 \text{ cm}$) with $Q = 2.0 \text{ L} \cdot \text{h}^{-1}$, $T = 20^\circ\text{C}$, and $B = 20 \text{ cm}$ showed minimal diameter effects on soil temperature, confined primarily to early irrigation stages at Point 1 [Figure 6: see original paper]. Maximum temperature difference across diameters was only 0.19°C . During later stages, temperature control by tube diameter disappeared, with all points stabilizing between irrigation and initial soil temperatures ($20\text{--}22^\circ\text{C}$). Tube diameter exhibited minor influence on soil moisture. At Points 1-2 inside the tube, moisture content decreased slightly with increasing diameter during early stages, but converged to saturation during later stages. At Points 3-7 outside the tube, moisture content decreased slightly

with increasing diameter, with maximum differences of $0.017 \text{ cm}^3 \cdot \text{cm}^{-3}$. This pattern reflects Darcy's law relationship where increased cross-sectional area reduces flow velocity, delaying water arrival at specific points.

2.2.4 Vertical Tube Burial Depth Analysis of burial depths (15, 20, 25 cm) with $Q = 2.0 \text{ L} \cdot \text{h}^{-1}$, $T = 20^\circ\text{C}$, and $D = 11.6 \text{ cm}$ indicated that burial depth had minimal impact on soil temperature, affecting only Point 1 slightly [Figure 7: see original paper]. Temperature at Points 2-8 showed initial increase followed by decrease with increasing burial depth, with maximum difference of 1.58°C at Point 2. Burial depth significantly influenced soil moisture distribution. Moisture content at Points 3-8 increased with burial depth, while Point 9 showed the opposite trend, decreasing with depth. At irrigation conclusion, moisture content at 25 cm depth was 8.91% and 23.11% higher than at 15 cm and 20 cm depths, respectively. This pattern occurs because greater burial depth lengthens the infiltration path, enhancing the tube wall's horizontal restriction and vertical guidance, thereby promoting deeper water movement. The contrasting behavior at Point 9 reflects its relative position adjustment with changing burial depth, moving to the upper region outside the tube bottom where wall restriction weakens, causing preferential downward flow along the tube exterior.

Discussion

Vertical tube surface drip irrigation effectively combines pipe protection technology with surface drip irrigation systems, demonstrating excellent water-saving and temperature-control performance that provides scientific solutions for sand-fixing seedlings facing extreme drought and high temperatures. When tube diameter and burial depth are fixed during seedling establishment and difficult to adjust during maintenance, regulation of root zone hydrothermal conditions can be achieved through drip head flow rate and irrigation water temperature adjustments.

Throughout the irrigation process, soil hydrothermal changes at all characteristic points occur through water-temperature coupling. The most dynamic variations appear during early irrigation stages inside the tube, particularly at the inner surface layer. As irrigation proceeds, hydrothermal conditions stabilize, with water infiltrating through bottom holes while soil moisture outside the tube increases rapidly and stabilizes, and temperature fluctuates slightly according to irrigation water temperature.

Drip head flow rate and irrigation water temperature significantly influence hydrothermal migration processes. Flow rate is the key parameter affecting soil moisture status, while water temperature directly determines soil temperature. During early irrigation, increased flow rate accelerates cooling at Point 1 and causes initial warming followed by cooling at Point 2, while Point 9 shows minimal change. This occurs because irrigation water temperature is lower than initial soil temperature, and higher flow rates introduce more cool water, absorbing greater soil heat and causing more pronounced temperature decline.

During later stages, flow rate effects on temperature diminish as all points stabilize between irrigation and initial soil temperatures. Flow rate directly affects moisture distribution and transport—increased flow delivers more water per unit time, expands wetting front migration distance, and extends water arrival time at specific points, collectively increasing soil moisture content. This aligns with findings by Tan Junli et al. that larger flow rates shorten irrigation duration and reduce water diffusion time and distance in sand layers. Notably, Points 1-2 inside the tube approach saturation during later stages, with only Point 1 at low flow ($1 \text{ L} \cdot \text{h}^{-1}$) showing slightly reduced moisture, likely due to insufficient water supply relative to infiltration capacity.

The relative relationship between irrigation water temperature and soil temperature determines heat transfer direction and magnitude. When irrigation water enters soil, water-soil heat exchange occurs. Higher irrigation water temperatures release heat to soil, raising soil temperature, while lower temperatures absorb heat from soil, causing cooling until thermal equilibrium is achieved. Irrigation water temperature shows minimal influence on soil moisture, with slight moisture decreases observed at higher temperatures, consistent with Liu Lihua et al.'s conclusion that temperature gradients generate suction gradients driving water from high to low temperature zones.

Tube diameter and burial depth are structural parameters of the vertical tube system. Diameter shows minimal influence on hydrothermal migration, while burial depth primarily affects moisture conditions through altered infiltration pathways, with negligible thermal effects. At constant flow rate, increased diameter expands the infiltration channel area, reducing unit area flux and delaying water arrival at specific points. This reflects the inverse relationship between flow velocity and cross-sectional area in Darcy's law: increased area reduces velocity, extending travel time. Consequently, moisture content at Points 3-7 decreases slightly with increasing diameter. During early irrigation, the increased diameter also slows water velocity, prolonging water-soil contact time and enhancing heat transfer, resulting in slightly higher temperatures.

Increased burial depth lengthens the infiltration path within the tube, strengthening the tube wall's horizontal restriction and vertical guidance on soil water movement, thereby promoting deeper water migration. This explains why moisture content at Points 3-8 increases with burial depth. The contrasting behavior at Point 9 reflects its position adjustment relative to the tube bottom—at greater burial depths, Point 9 moves to the upper region outside the tube bottom where wall restriction diminishes, causing preferential downward flow along the exterior tube wall. This demonstrates the high sensitivity of soil moisture distribution to geometric boundary conditions, consistent with experimental results showing decreased wetting volume with increasing tube diameter and burial depth.

Practically, while larger drip head flow rates are generally preferable as they increase average moisture content and irrigation uniformity outside the tube, design must balance wetting expansion against ponding risk. The maximum

flow rate is constrained by the critical stable infiltration rate inside the tube to prevent seedling submergence. In sand fixation areas where daytime soil temperatures are high, cool water irrigation can effectively reduce soil temperature and alleviate heat stress, while warm water irrigation during cooler nighttime periods can promote plant metabolism. Future research should investigate plant responses to soil moisture and temperature environments to provide theoretical guidance for selecting optimal flow rates and irrigation temperatures.

Conclusions

This study developed and solved a mathematical model for soil water-heat transport in vertical tube surface drip irrigation using HYDRUS-2D software. Model reliability was verified through laboratory data, and the effects of irrigation and tube parameters on hydrothermal processes were simulated. The main conclusions are:

1. The model accurately simulated soil hydrothermal transport, with RMSE values of 0.46°C for temperature and $0.018\text{ cm}^3\cdot\text{cm}^{-3}$ for moisture content, and NSE coefficients approaching 1. The model realistically reflects the hydrothermal migration process in vertical tube surface drip irrigation.
2. During early irrigation stages, soil hydrothermal dynamics inside the tube were most pronounced, particularly at the inner surface layer. As irrigation progressed, internal hydrothermal conditions stabilized, with water infiltrating through bottom holes while external soil moisture increased rapidly and stabilized, and temperature fluctuated slightly according to irrigation water temperature.
3. Drip head flow rate was the critical parameter affecting soil moisture status, with higher flow rates increasing soil moisture content at identical points outside the tube. Irrigation water temperature was the direct factor influencing soil temperature, with higher temperatures elevating soil temperature at identical points inside and outside the tube. However, flow rate had limited effect on temperature distribution, and water temperature had minimal impact on moisture distribution.
4. Tube diameter showed negligible influence on soil hydrothermal status during irrigation, while burial depth primarily affected moisture conditions without significantly impacting the thermal environment. The moisture distribution pattern outside the tube was demarcated by the tube bottom, with moisture content above the bottom decreasing as burial depth increased, and moisture content below the bottom increasing with greater depth.
5. When tube diameter and burial depth were fixed and difficult to adjust, effective regulation of root zone hydrothermal conditions could be achieved by modulating drip head flow rate and irrigation water temperature.

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