NUMERICAL SIMULATION ON SOIL MOISTURE AND HEAT TRANSFER IN COTTON FIELD UNDER MULCHED DRIP IRRIGATION CONDITION

SIMULATION NUMERIQUE DU TRANSFERT DE LA TENEUR EN EAU DU SOL ET DE LA CHALEUR DU SOL DANS LES CHAMPS DE COTON DANS LE SYSTEME D'IRRIGATION GOUTTE A GOUTTE EN PAILLIS

Zhi Zhang[1], Fuqiang Tian[2], Heping Hu[3]

ABSTRACT

Soil heat and moisture condition is of critical importance for crop growth and yield. Mulched drip irrigation can improve the water use efficiency and root zone soil heat content. This is less studied through soil moisture and heat transfer simulation. In this study, field experiments were conducted in irrigation experimental station in Xinjiang Province of China during 2008 and 2009 (for cotton crop under mulched drip irrigation), and the software VS2DHI developed by the U.S. Geological Survey (USGS) was used to explore the movement and distribution of soil moisture and heat on a daily basis. The software result was calibrated using the monitored data. The study confirms the sinusoidal pattern of soil temperature during the crop growth period, which is primarily driven by solar radiative force, while the fluctuation of soil temperature is flattened at the deeper soil. The calibration and validation results show that both soil moisture and temperature simulated by VS2DHI agree well with the field data. The influence of mulching on soil moisture is analyzed by the model which shows that the film plays an important role of conserving soil moisture, especially for the surface soil of 40cm depth. More work should be done to improve VS2DHI by coupling ground surface energy processes to evaluate the influence of mulching on soil temperature.

Key words: *Moisture and heat transfer, mulched drip irrigation, VS2DHI simulation, Zinjiang province, China.*

1 PhD Candidate, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Haidian District, Beijing 100084, China. Fax: +86-10-62796971. E-mail: z-zhang05@mails.tsinghua.edu.cn. Telephone: +86-13466598727.

2 Associate Professor, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Haidian District, Beijing 100084, China. E-mail: tianfq@tsinghua.edu.cn.

3 Professor, State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Haidian District, Beijing 100084, China. E-mail: huhp@tsinghua.edu.cn.

RÉSUME ET CONCLUSION

Cet article présente le travail que nous avons fait sur le transfert d'humidité et de chaleur dans le sol sous la condition de goutte irrigation sous pellicule dans les champs de coton, en se basant sur les donnés d'essais sur champs et sur l'étude numérique faites par logiciel (VS2DHI). Les résultats de simulation sont calibrés avec les données observées d'essais sur le champ qui sont effectués dans la région autonome ouïgoure Xinjiang de Chine 2008 et 2009. La comparaison entre les données d'essais et les résultats de simulation montre que le modèle est pertinent.

Les essais sur champs sont effectués dans la région aride avec grande fluctuation de la température diurne. Les types de sols principaux sont sable de limon et sable fine. Le style de plantation de coton et d'arrangement de tuyaux est nommé « un tuyau, une pellicule et quatre ranges de coton », qui veut dire que le tuyau en dessous de la pellicule de couverture est au milieu de quatre ranges symétriques de coton.

Dans cette étude, il est supposé que la goutte irrigation sous pellicule soit un problème plan de deux dimensions, que la goutte irrigation soit une source linéique, que le sol soit uniforme et homogène, et qu'aucun flux latéral ne traverse la limite ni gauche ni droite de la zone due à la symétrie. Il y a trois différents types de condition de limite de la borne supérieure, qui sont : aucun flux sous la zone couverte, flux déterminé sous la zone considérée, et flux d'évaporation sous la zone inter-pellicule. Deux types de condition limite de la borne supérieure pour la température sont appliqués y compris température spécifiée de la surface du sol pour la condition dominante de la diffusion (la période de non-irrigation) et température spécifiée de l'eau entrée pour la condition dominante d'advection (la période d'irrigation) respectivement. La zone de simulation est définie comme une section rectangulaire de largeur de 75cm et de profondeur de 200cm.

La simulation numérique est réalisée par le logiciel VS2DHI, qui est développé par U.S. Geological Survey. La calibration et la validation des résultats montrent que l'humidité et la température du sol simulées par VS2DHI concordent bien avec les données de champ. L'analyse de données confirme le modèle sinusoïdal de la température du sol pendant la période de croissance de cultures, qui est principalement dominé du forçage radiatif du soleil, en tant que la fluctuation de la température du sol est aplanie quand on se déplace vers le fond du sol. Les résultats de simulation assurent le phénomène découvert dans l'analyse de données précédente. La gamme de la fluctuation de la température du sol observée est de 16.0ºC et 6.4ºC à la profondeur de 5cm et 25cm, respectivement, tandis que des gammes de fluctuation de16.0ºC et 6.4ºC sont obtenues de la simulation numérique de la température du sol.

Les résultats de simulation indiquent l'existence d'un décalage du temps dans la variation d'humidité du sol à la profondeur plus importante lors d'irrigation. L'humidité maximum est atteinte 20 heures plus tard à la profondeur de 35cm qu'à la profondeur de 5cm. En échelle journalière, les distinctions de la température du sol existent dans des différentes parties le long de la direction horizontale. Le sol en dessous de pellicule a une fluctuation de la température moins importante que celle du sol inter-pellicule due à la teneur élevée d'eau et à la grande capacité thermique, et la pellicule de couverture a également un effet sur la distribution de la température du sol.

L'influence de la couverture sur l'humidité du sol est analysée par le modèle qui montre que la pellicule joue un rôle importante de conservation d'humidité du sol, notamment pour la surface du sol à 40cm de profondeur. Cependant, plus de travail doit être fait pour améliorer VS2DHI par le couplage de la procédure d'énergie de la grande surface afin d'évaluer l'influence de couverture sur la température du sol. Les conditions spécifiques aux limites qui sont appropriées sont nécessaires pour obtenir un résultat de simulation plus raisonnable et plus juste. De plus, le modèle peut être adopté pour guider les pratiques agricoles de différentes cultures et dans les différentes conditions météorologiques lorsque la croissance de cultures sera prise en compte et le modèle de plante sera intégré dans le système de transfert d'humidité et de température du sol dans le futur.

Mots clés: *Transfert de l'humidité et de la chaleur, système d'irrigation goutte à goutte en paillis, simulation VS2DHI, province de Zinjiang, Chine.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

Water availability for agricultural use is declining all over the world due to the scarcity of water resource. In China, the northwestern part suffers the most due to water scarcity. Therefore, it is imperative to popularize the water-saving irrigation options and improve water use efficiency in this arid region (Hou and Wang et al., 2009; Wan and Kang et al., 2010). Both soil moisture and heat have significant influence on plant growth and on the crop yield (Baghour and Moreno et al., 2002; Bauerle and Smart et al., 2008; Hou and Wang et al., 2009). Drip irrigation in fields with film mulch cover has been widely used in Xinjiang Province (Xu and Li et al., 2003; The Statistics Bureau of China, 2008). This agronomic measure can improve soil moisture and heat content in the root zone (Ham and Kluitenberg et al., 1993). This aspect is less studied through soil moisture and heat transfer simulation.

Several experiments have been conducted to investigate the effects of film mulching and drip irrigation on the moisture and heat distribution in the subsurface soil. The results indicate that film plays a key role in conserving soil moisture and increasing soil temperature (Hu and Li, 2003; Dai and Zhang et al., 2007; Zhang and Lv et al., 2008). Canopy temperature is usually used as the criteria to schedule drip irrigation of cotton and 28^0C is the threshold canopy temperature in Texas cotton field to start drip irrigation without mulching (Wanjura and Upchurch et al., 2002). Subsurface soil moisture is obviously increased due to total elimination of evaporation by the film cover (Cai and Shao et al., 2002; Li and Kang et al., 2007). Moreover, radiative balance between atmosphere and land surface is changed due to the mulched condition. Soil temperature of mulched land is higher than that of bare land, especially during the night, if both have the same moisture content. The seed germinating rate and cotton yield have been improved because of the appropriate soil environment (moisture and temperature) under mulched drip irrigation (Li and Wang et al., 2001; Li and Shao, 2004; Hu and Zhang, 2005; Zhang and Cai, 2005).

Many researchers conducted studies based on numerical simulation of moisture and heat transfer. The complexity of moisture and heat flow in natural environment requires the use of numerical models to evaluate the processes and to analyze interactions between the various controlling parameters. Mahrer (1979) studied the heat and moisture flow through soil with transparent polyethylene covering. The coupled soil moisture and heat flow governing equation developed by Philip-De Vries in 1984 was incorporated into film mulching problem (Mahrer, 1984) and reasonable results were obtained. Scanlon and Milly (1994) developed a model, which considered the vapor transfer mechanism. Sui and Zeng et al., (1992a, b) set up and validated a mathematically based model coupling moisture and heat transport in film mulched system. Wu and Huang employed a four-layered SMPAC model to simulate moisture and heat transport in a wheat field covered by transparent polyethylene, and the results showed remarkable consistency between the simulated and the observed data (Wu and Huang et al., 2000; Wu and Chau et al., 2007).

The researches mentioned above are mainly based on the field experiments. Few numerical studies were carried out for both soil moisture and heat transfer simulation, and even fewer under the mulched drip irrigation condition. This paper demonstrates the characters and regimes of soil moisture and heat transfer, which are obtained by simulation results of VS2DHI. In contrast to the previous studies that alternatively considered agronomic measures of drip irrigation or film mulch, we make attempt to simulate the transfer processes with respect to both of them. Simulated results are calibrated and validated from the observed data from the field experiments, which were conducted in Xinjiang province in 2008 and 2009 (for cotton field under mulched drip irrigation). Focusing on the practical problems, some substantial guidance for scheduling irrigation is achieved on the basis of the simulation results. Our study gives a more comprehensive view of soil moisture and heat transfer processes, although lots of assumptions have been introduced into the simulation.

2. NUMERICAL SIMULATION

2.1 Description of the model

VS2DHI is a computer program developed by the U.S. Geological Survey (USGS) for solving problems of water flow and energy transfer in variably saturated porous media (Healy and Ronan, 1996; Hsieh and Wingle et al., 2000). This software has a user-friendly interface. Boundary and initial conditions can be easily chosen based on real situations. The grid consists of vertical and horizontal lines forming a rectangular array of cells. The error control mechanism varies the time step size in an attempt to take minimum number of steps while satisfying the error tolerance.

2.2 Governing equations

The model description is fully documented by Lappala and Healy et al., (1987); Healy and Ronan, (1996); and Hsieh and Wingle et al., (2000). However, the governing equations are provided here for convenience. The governing equation for water which is derived from Richard's equation is given as follow:

$$v\{\rho[c_m + sS_s]\}\frac{\partial H}{\partial t} - \rho\sum_{k=1}^{\widehat{m}} A_k K K_r(h)\frac{\partial H}{\partial n_k} - \rho q v = 0 \quad (1)$$

where, v is a volume of porous medium, ρ is the water density, c_m is the specific moisture capacity, which is the slope of the moisture retention curve, s is saturated, S_s is the specific storage, *H* is the total head, and *h* is the pressure head. *t* is time, *K* and K_r is the saturated hydraulic conductivity and relative hydraulic conductivity, respectively. *q* is the volumetric source-sink term. $\hat{m}$ is the number of faces of the volume, and A_k is the area of the k^{th} face to which n_k is orthogonal.

The advection-dispersion heat transfer equation is:

$$\frac{\partial}{\partial t}[\theta C_w + (1-\emptyset)C_s]T = \nabla \cdot K_T(\theta)\nabla T + \nabla \cdot \theta C_w D_H \nabla T - \nabla \theta C_w \upsilon T + qC_w T^* \quad (2)$$

where, θ is the volumetric moisture content, ∅ is porosity, C_w and C_s is heat capacity of water and dry solid, respectively. is the temperature, K_T is thermal conductivity of the water and solid matrix (a tensor), D_H is hydrodynamic dispersion tensor, υ is water velocity, T* is temperature of fluid source. The other notation is defined as above.

Development of the heat equation ignores the heat capacity of the air phase in the porous medium when moisture content is less than porosity. However, this heat capacity term is small relative to that of water and therefore should be of little practical concern.

VS2DHI model adopts finite difference method to solve the governing equations mentioned above. Because temperature is a variable within both the flow and transport equations, the two equations could be solved simultaneously. However, VS2DHI is set up to solve the equations sequentially (Lei and Yang et al., 1988; Healy and Ronan, 1996). VS2DHI maintains the sequential solution algorithm, necessitating iterative solution of both equations within each time step. The flow equation is solved first, assuming a temperature equal to that at the previous time step. Next the transport equation is solved to update the value of temperature. The flow equation is then resolved with the updated temperature. This iterative process is continued within the time step until the value change between subsequent solutions of the flow equation is less than tolerance at every node.

2.3 Initial and boundary conditions

In this study, we assume the mulched drip irrigation as a two dimensional plane problem, and therefore, drip irrigation is a linear source (Skaggs and Trout et al., 2004), the soil is assumed to be homogeneous, and no lateral flux across the left and right borders of the zone due to the symmetry. Evaporation is negligible in mulched zone due to the film. The simulated section of unsaturated zone is defined as a rectangle 75cm wide and 200cm deep, and it is represented by 1675 elements which has 3cm uniform intervals assigned to the grid space.

Initial conditions are based on moisture content and soil temperature monitored in the field experiments. The "continuous" interpolation method is employed to convert the measured point data into the initial soil moisture and heat profiles. This method performs a triangulation of the contour lines to generate a triangular mesh. The value at a point is computed by finding the triangle that contains the point, and then performing a linear interpolation over the triangle. If the point lies outside the triangular mesh, it is assigned the value of the nearest contour.
There are three different types of upper boundary conditions, i.e., no flux under mulched zone, specified flux under ponded zone, and evaporative flux under inter-film zone. Two types of upper boundary conditions associated with the temperature are employed including specified

surface soil temperature for diffusion dominated condition (non-irrigation period) and specified inflow water temperature for advection dominated condition (irrigation period), respectively. Boundary temperature, which is obtained from the measured data will not change in one period. The pond will appear when subsurface soil becomes saturated. The surface of pond is horizontal and the height of pond is negligible. Groundwater table is specified with the depth of 2m. Therefore the bottom boundary condition associated with the soil moisture is the total head of -2 m, and the bottom boundary condition associated with the temperature is 16.5^0 C. The Figure 1 shows the schematic diagram of this simulated section.

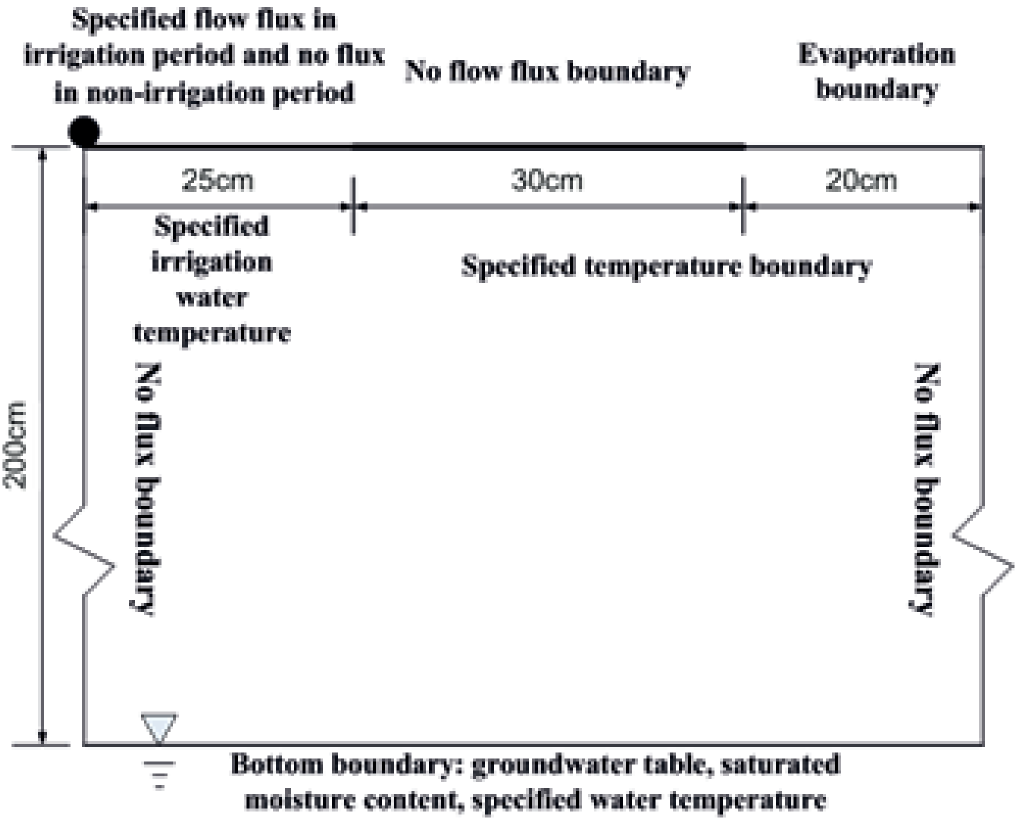


Fig. 1. Simulated section and boundary conditions in mulched drip irrigation system (La section de simulation et les conditions aux limites dans le système de goutte irrigation sous pellicule)

2.4 Parameters estimation

Soil hydraulic and thermal properties were obtained from a combination of laboratory measurements and published data (Table 1: Lei and Yang et al., 1988). Soil samples were collected from the boreholes for determination of parameters in the laboratory. The Brooks-Corey Model is used as the function of soil water retention.

Table 1. Basic parameters of soil (Les paramètres de base du sol)

Parameters	Value
Saturated hydraulic conductivity	7.5*10^{-6} m/s
Porosity	0.42
Residual moisture content	0.015
Parameters of hydraulic characteristic functions (Brooks Corey model: $\frac{\theta-\theta_r}{\theta_s-\theta_r}=(\frac{h}{h_b})^{-\lambda}$)	h_b = -0.085m λ = 0.548
Heat capacity of water	CW = 4.187E6 J/(m^{3}* □)
Heat capacity of dry solids	CS = 1.938E6 J/(m^{3}*□)
Soil thermal conductivity at residual moisture content	K_{Tr} = 0.466W/(m*□)
Soil thermal conductivity at full saturation	K_{Ts} = 1.545W/(m*□)
Grid spacing	Uniform 3cm

Numerical simulation is carried out from 8:00h July 20, 2009 to 8:00h July 27, 2009. Irrigation started in July 22 with irrigation volume of 60.96 mm and 46.44 mm for two different treatments whose total irrigation volume is 525 mm and 375mm, respectively. Values of 10.584*10^{-6} m/s and 10.75*10^{-6} m/s were assigned to the linear dripping discharge in the model, as irrigation process lasted for 12 hours and 8 hours, respectively.

There are lots of simplifications adopted to calculate evapotranspiration (ET). ET is simulated as a recurring cycle. The cycle is composed of ET periods of equal duration. ET parameters are defined at the beginning time of each period, and are assumed to vary linearly from the beginning of one period to the beginning of the next period. In this study, the values of annual potential evaporation and transpiration are estimated as 1300 mm and 2600 mm, respectively. The evaporation process will not take place in near-pipe zone and middle zone owing to the film mulching. The depth of root zone where the transpiration process affects soil moisture distribution is set as 0.5m and the spatial distribution of root is derived from the Molz (1981) model.

3. MEASUREMENTS AND MODELING RESULTS

3.1 Measurements

The field experiments were carried out in the arid area with strong diurnal temperature fluctuation, which is located in Bayangol Prefecture, Xinjiang Province of China (86012’ E, 410 36’ N). The experiments were implemented during the growing seasons in two years, i.e., from May to September in 2008 and in 2009. The primary soil types are silty sand and fine sand. The cotton cultivar is Xinluzhong #21. The style of cotton planting and drip pipe arrangement is named “one pipe, one film and four rows of cotton”, which means the drip pipe beneath the mulched film is in the middle of four symmetrical rows of cotton (Gao and Tian et al., 2010). The film width is 110cm and the inter-film zone is 40cm (Fig. 2).The zone under the drip pipe is near-pipe zone and the zone between the cotton lines is middle zone (Hu and Tian et al., 2011).

Hourly averages of air temperature, solar radiation, wind speed and absolute humidity were measured 2 m above the soil surface at a meteorological station situated in the cotton field. Soil temperature data were obtained both from geothermometer and Hydro probes. Soil moisture was measured from the samples collected from boreholes, using the gravimetric method. Spatial interval of sampling was variable and generally ranged from 0.1 m in the upper 0.5 m and increased with depth generally to 0.3m intervals till 2 m. The soil moisture data measured by Hydro probes was also available in the following analysis.

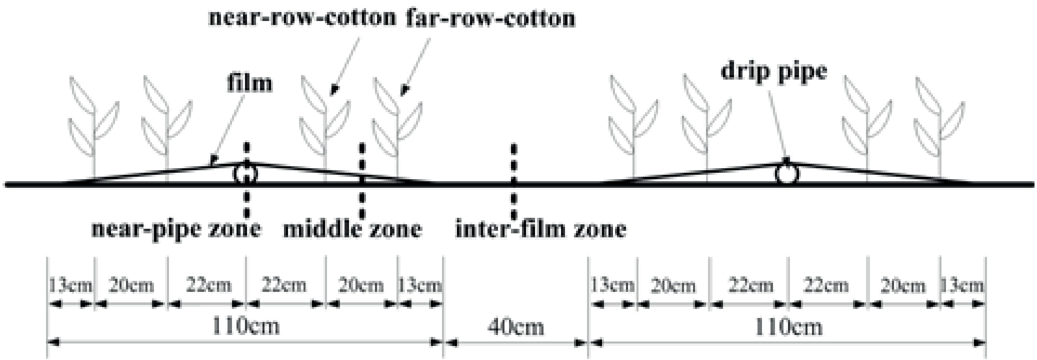


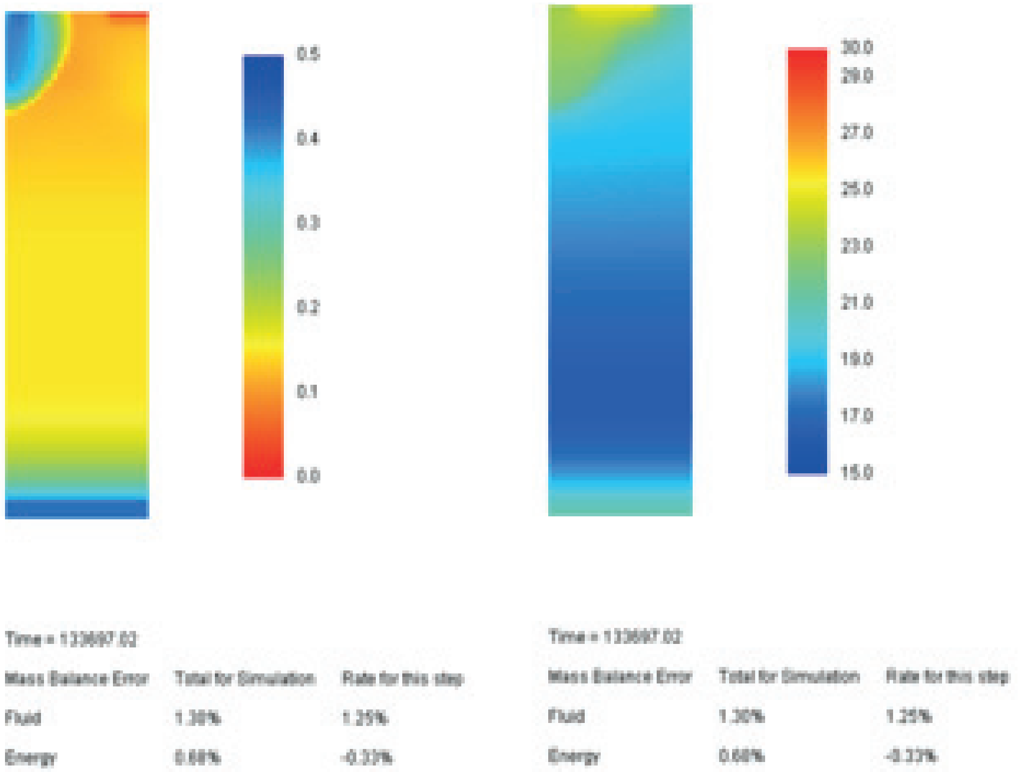
Fig. 2. The style of cotton planting and drip pipe arrangement (Le style de plantation de coton et l’arrangement de tuyaux de goutte)

3.2 Results evaluation

Once all required data mentioned above have been entered, the VS2DHI software can be invoked to run the simulation. The output variables are total head, pressure head, moisture content, saturation degree, temperature, and velocity or flux magnitude. Simulated results are displayed for each time step, and can be created automatically as a simple animation. According to the contour animation of moisture content and temperature generated by VS2DHI (Figure 3), features of soil moisture and heat transport under mulched drip irrigation condition can be obviously observed. Comparisons have been made between simulated and observed values of soil moisture and temperature, and root mean square error (RMSE, see Equation 3) is chosen to be the evaluation criteria .There is remarkable consistency between simulated and observed value, and the details are discussed below.

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n}|e_i|^2}{n}\right]^{\frac{1}{2}} \quad (3)$$

where, n is the sample number and ei is the individual model-prediction error, which is defined as $e_i = P_i - O_i$. Capital letter P and O refer to the prediction and observation data, respectively.



(a) Profile of soil moisture
(a) Le profil d'humidité du sol

(b) Profile of soil temperature
(b) Le profil de température du sol

Fig. 3. Contours of simulated moisture content and temperature in soil column (Les contours d'humidité contenue et de température dans la colonne du sol)

3.2.1 Results with total irrigation volume of 525mm

Reasonable agreement exists in the simulated and monitored values of soil moisture and temperature at depth of 15 cm in the treatment of 525mm total irrigation volume (Figure 4 and Figure 5). However, simulated values of soil temperature are somewhat higher than observed ones which are obtained by geothermometer (RMSE=1.203^0 C), and more fluctuated compared with the ones got by Hydra probes (RMSE=1.169^0 C). The soil moisture results suggest that simulated values are lower than test ones before irrigation, and higher after irrigation. There is a positive error in simulated peak moisture content at the beginning time of irrigation, despite a relatively accurate simulation of the moisture content after the time of 60 hours. The error can be attributed to soil heterogeneity in the field and errors in the prescribed hydraulic properties. The Figure 6 demonstrates the trend that simulated soil temperature is slightly higher than observed temperature at depth of 20 cm (RMSE=0.722^0 C).

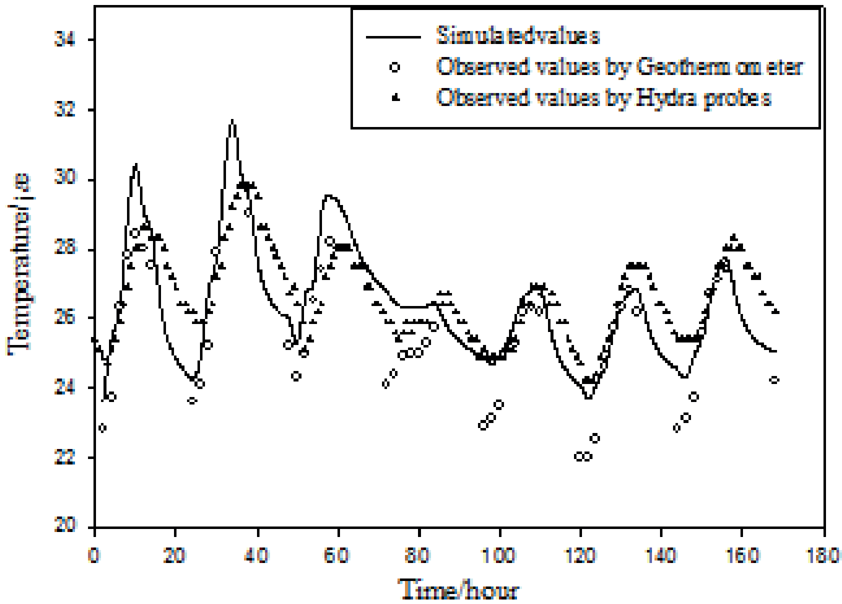


Fig. 4. Soil temperature versus time at 15cm depth in near-pipe zone (mulched treatment, 525 mm) (La température du sol en fonction de temps à 15cm de profondeur dans la zone proche au tuyau (couverte de pellicule, 525 mm))

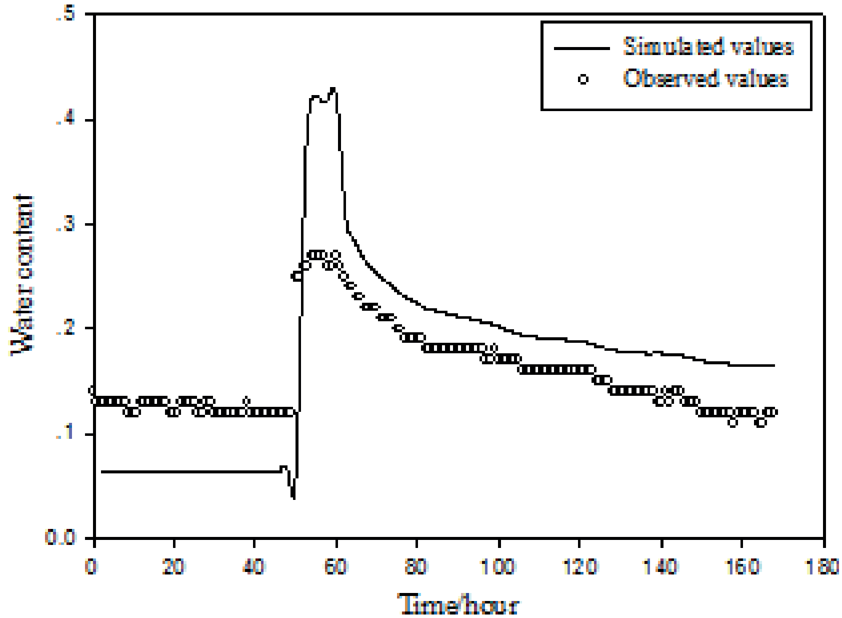


Fig. 5. Soil moisture content versus time at 15cm depth in near-pipe zone (mulched treatment, 525 mm) (L'humidité du sol en fonction de temps à 15cm de profondeur dans la zone proche au tuyau (couverte de pellicule, 525 mm))

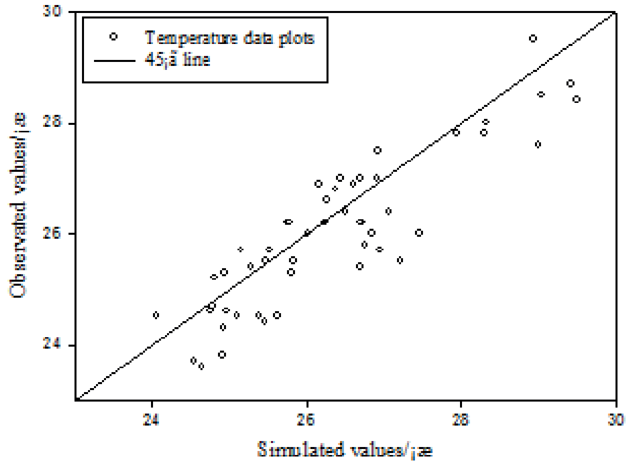


Fig. 6. Comparison of soil temperature at 20cm depth in near-pipe zone (mulched treatment, 525 mm) (Comparaison de température du sol à 20cm de profondeur dans la zone proche au tuyau (couverte de pellicule, 525 mm))

3.2.2 Results with total irrigation volume of 375mm

The simulated soil temperature versus time and Comparison chart with total irrigation volume of 375 mm are depicted in Figure 7 and Figure 8, respectively. It can be observed that the simulated and observed values are in good agreement. Lower volume of irrigation provides much better, but still far from perfect, agreement between simulated and observed soil temperature. The RMSE is 0.6940 C and 0.6830 C at 20cm depth in middle zone and in inter-film zone, respectively. These values are smaller than RMSE of 0.7220 C in the total irrigation volume of 525mm. The moisture conditions are not analyzed here for the shortage of field data for this treatment.

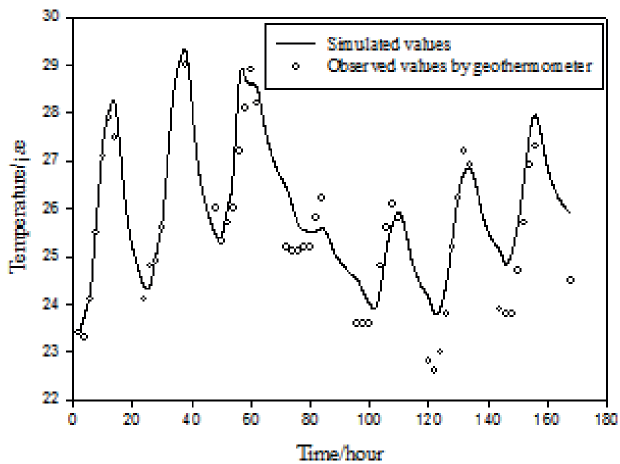


Fig. 7. Soil temperature versus time at 20cm depth in middle zone (mulched treatment, 375 mm) (La température du sol en fonction de temps à 20cm de profondeur dans la zone au milieu (couverte de pellicule, 375 mm))

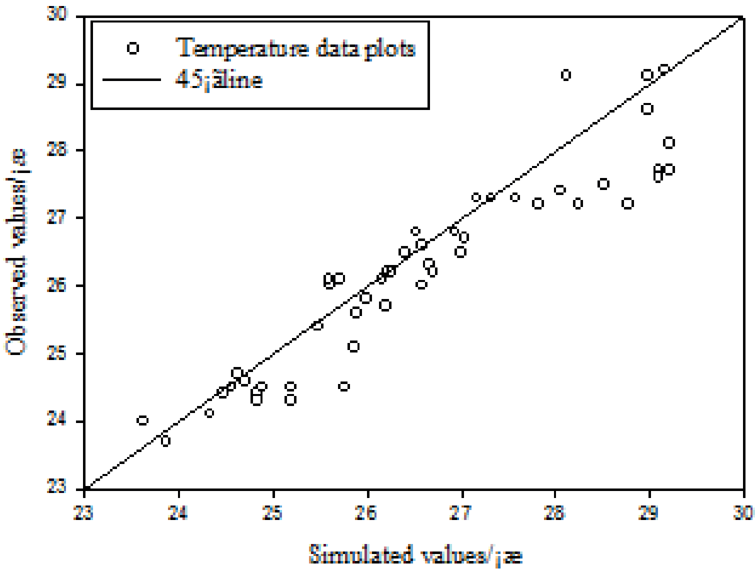


Fig. 8. Comparison of soil temperature at 20cm depth in inter-film zone (mulched treatment, 375 mm) (Comparaison de températuer du sol à 20cm de profondeur dans la zone inter-pellicule (couverte de pellicule, 375 mm))

4. MODEL APPLICATION AND DISCUSSION

4.1 Variability of soil moisture and temperature in mulched drip irrigation

Good agreement is found between the simulated and observed values of soil moisture and temperature under two treatments with different irrigation volume. The simulation research provides a greater understanding of unsaturated zone processes. The complexity of soil moisture and heat transfer in situ position required numerical models to analyze interactions and feedback mechanisms between various controlling factors. Therefore we take the approach of using numerical simulation with VS2DHI to interpret observed field data and to evaluate the transfer processes after the results evaluation.

Soil moisture and heat will be redistributed under mulched drip irrigation condition. The field data analysis confirms the sinusoidal pattern of soil temperature during the crop growth period, which is primarily driven by solar radiative force, while the fluctuation of soil temperature is flattened when we move downward to the deeper soil (Zhang and Tian et al., 2011). Simulation has been performed corresponding to the specified boundary condition mentioned above and the phenomenon is reproduced by the simulation (Figure 9). The simulative results provide a convincing support to the variability found in the previous data analysis. The fluctuation range of observed soil temperature is 16.0^0 C and 6.4^0 C at the depth of 5cm and 25cm, respectively, while 16.9^0 C and 5.1^0 C fluctuation range obtained from simulative soil temperature data.

The simulated results indicate a time lag in deeper soil moisture variation during irrigation (Figure 10). Peak moisture is achieved 20 hours later at depth of 35cm compared with that of 5cm, and the peak magnitude is reduced by a factor of 3.4.

At the daily time scale, distinctions of soil temperature exist in different positions along horizontal direction (Figure 11). Soil beneath film including the near-pipe zone and middle zone has low temperature fluctuation than inter-film soil due to high moisture content and large thermal capacity.

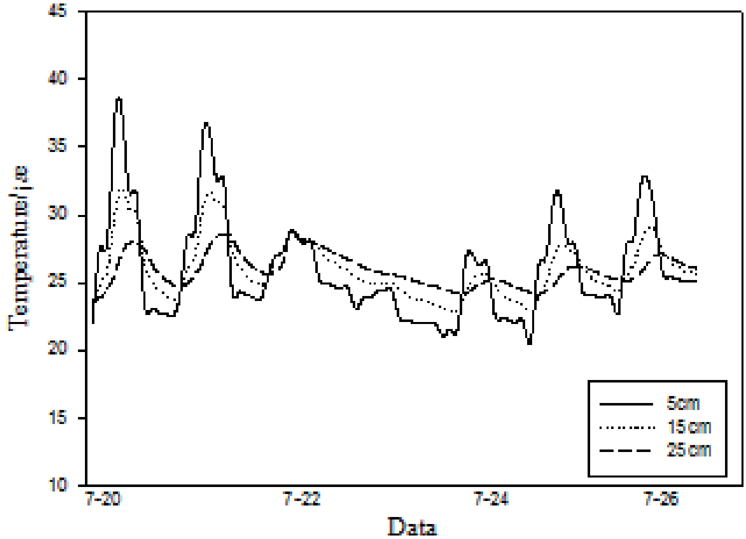


Fig. 9. Simulated soil temperature versus depth in near-pipe zone (mulched treatment, 375 mm) (La température simulée du sol en fonction de profondeur dans la zone proche au tuyau (couverte de pellicule, 375 mm))

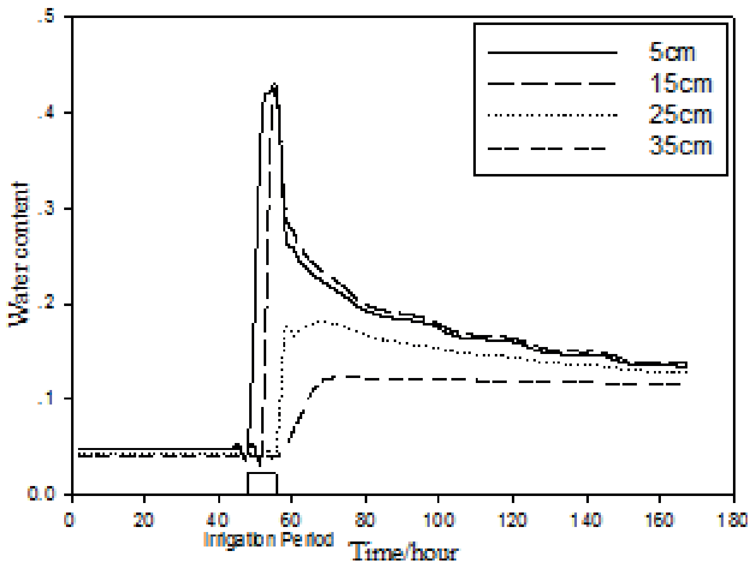


Fig. 10. Simulative soil moisture versus depth in near-pipe zone (mulched treatment, 375 mm) (L'humidité simulée du sol en fonction de profondeur dans la zone proche au tuyau (couverte de pellicule, 375 mm))

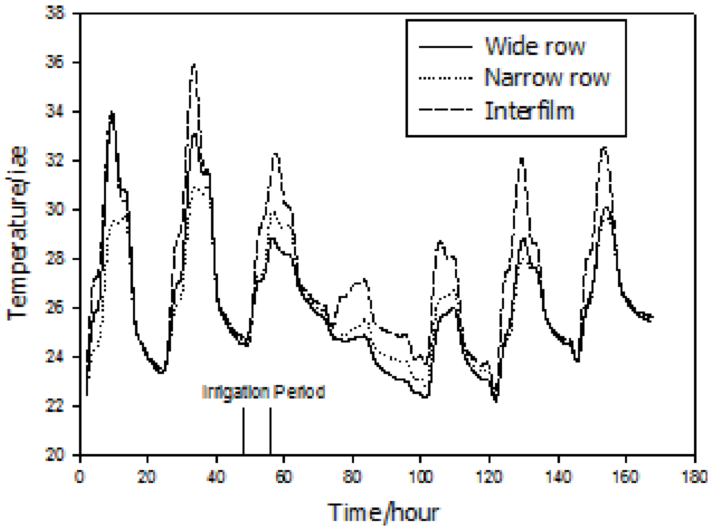


Fig. 11. Simulative soil temperature versus horizontal position (mulched treatment, 375 mm) (La température simulée du sol en fonction de position horizontale dans la zone proche au tuyau (couverte de pellicule, 375 mm))

4.2 Mulching effect on conserving soil moisture

To quantify the effect of film on soil moisture conserving, numerical simulation is implemented under bare soil boundary condition. The total irrigation volume is 375 mm. Evaporation occurs in the unmulched soil while no flow flux takes place when film exists. The results are depicted in Figure 12 and Figure 13.

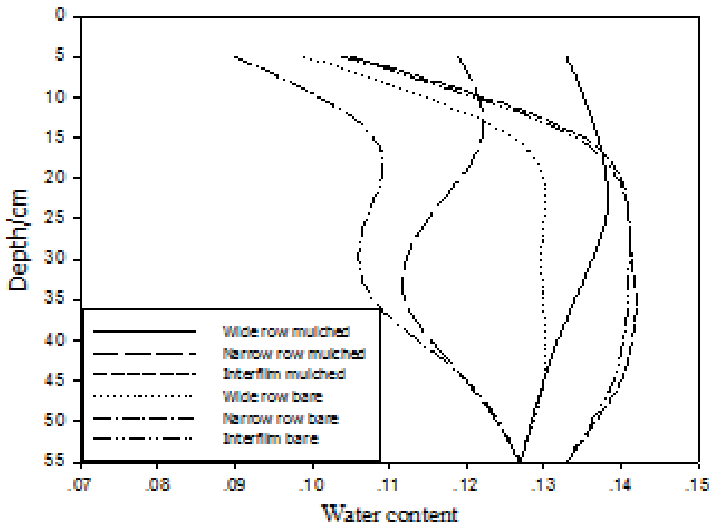


Fig. 12. Profile of simulative soil moisture content at the beginning time of irrigation (375 mm) (Le profil d'humidité simulée du sol au début d'irrigation (375 mm))

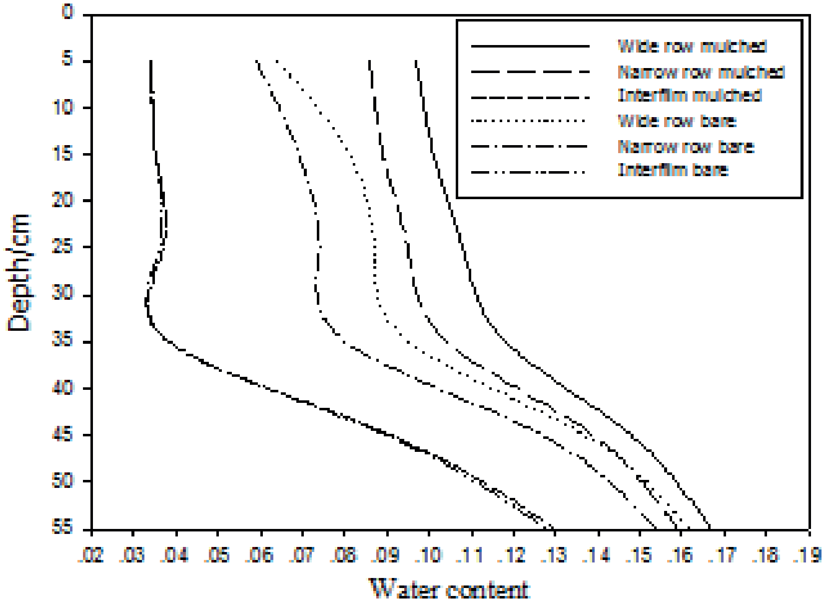


Fig. 13. Profile of simulative soil moisture content at the end time of simulation (375 mm) (Le profil d'humidité simulée du sol à la fin de simulation (375 mm))

The figures above illustrate a noticeable effect of film on soil moisture. Film has the function of conserving soil moisture, especially within the 40cm depth. The details are summarized in Table 2.

Table 2. The differences of simulated soil moisture between mulched and unmulched zone within 55cm depth (375 mm) (Les differences d'humidité simulée du sol entre la zone couverte et ouverte à l'intérieur de 55cm de profondeur (375 mm))

Time	Position			Total
	Near-pipe zone	Middle zone	Inter-film zone	
Beginning time of irrigation	0.057	0.055	0.004	0.116
End time of simulation	0.113	0.109	0.004	0.226

The difference of volumetric moisture content between mulched and unmulched zone within 55 cm depth is 0.226 at the end time of simulation, which is almost twice as large as the value at the beginning time of irrigation. The differences are attributed to the different dominant factors that influence soil moisture. At the beginning time of irrigation, the difference is mostly caused by the initial condition, while at the end time of simulation the difference is mainly caused by the irrigation. As we know, the initial condition is based on the observed data, and the irrigation process in the simulation is ideal. Therefore the comparable results generally suggest that the function of film is relatively weaker than supposed. What's more, the soil moisture difference between mulched and unmulched zone in the position of inter-film is so small that could be neglected.

5. CONCLUSIONS

This paper presents the work we have done on soil moisture and heat transfer under mulched drip irrigation condition in the cotton field based on the field experiments and numerical software (VS2DHI). Simulated results are calibrated upon filed observed data from the experiments which are conducted in Xinjiang Province of China during 2008 and 2009. The numerical simulation is performed by the software of VS2DHI, developed by U.S. Geological Survey. The calibration and validation results show that both soil moisture and temperature simulated by VS2DHI agree well with the field data. The data analysis confirms the sinusoidal pattern of soil temperature during the crop growth period, which is primarily driven by solar radiative forcing, while the fluctuation of soil temperature is flattened when we move downward to the deeper soil. The simulative results provide a convincing support to the phenomenon found in the previous data analysis. The fluctuant range of observed soil temperature is 16.0^0 C and 6.4^0 C at the depth of 5cm and 25cm, respectively, while 16.9^0 C and 5.1^0 C fluctuation range obtained from simulated soil temperature data.

The simulated results indicate a time lag existing in deeper soil moisture variation when irrigation takes place. Peak moisture is achieved 20 hours later at depth of 35cm compared with that of 5cm. At the daily time scale, distinctions of soil temperature exist in different positions along horizontal direction. Soil beneath film has low temperature fluctuation than inter-film soil due to high moisture content and big thermal capacity, and film covering also has effects on the distribution of soil temperature.

The influence of mulching on soil moisture is analyzed by the model which shows that the film plays an important role of conserving soil moisture, especially for the surface soil of 40cm depth. However, more work should be done to improve VS2DHI by coupling ground surface energy processes to evaluate the influence of mulching on soil temperature. Special boundary conditions which are suitable for mulched drip irrigation are necessary for obtaining a more reasonable and accurate results in the numerical simulation. Also, the model can be adopted to guide the agricultural practice under different crops and meteorological conditions when crop growth is considered and plant model is incorporated into the soil moisture and temperature transfer system in future.

ACKNOWLEDGEMENT

The authors thank the staffs of the experimental station in Bayangol Prefecture, Xinjiang Province who paid great efforts in field experiments. The financial support comes from “Eleventh Five-year Plan” project (No. 2007BAD38B01, 2007BAD38B09).

REFERENCES

Baghour, M. and D. A. Moreno, et al. (2002). "Influence of root temperature on uptake and accumulation of Ni and Co in potato." Journal Plant Physiology 159: 1113~1122.

Bauerle, T. L. and D. R. Smart, et al. (2008). "Root foraging in response to heterogeneous soil moisture in two grapevines that differ in potential growth rate." New Phytologist 179: 857~866.

Cai, H. and G. Shao, et al. (2002). "Water demand and irrigation scheduling of drip irrigation for cotton under plastic mulch." Journal of Hydraulic Engineering 11: 119-123. (In Chinese)

Comas, L. H. and T. L. Bauerle, et al. (2010). "Biological and environmental factors controlling root dynamics and function effects of root ageing and soil moisture." Australian Journal of Grape and Wine Research 16: 131–137.

Dai, T. and Z. Zhang, et al. (2007). "Technology and developmental trend of mulching drip irrigation." Water Saving Irrigation 2: 43-47. (In Chinese)

Gao, L. and F. Tian, et al. (2010). "Experimental research on soil water and salt movement and irrigation scheduling for cotton under mulched drip irrigation condition." Journal of Hydraulic Engineering 41 (12): 1158-1165. (In Chinese)

Ham, J. M. and G. J. Kluitenberg, et al. (1993). "Optical Properties of Plastic Mulches Affect the Field Temperature Regime." Journal of the American Society for Horticultural Science 118 (2): 188~193.

Healy, R. W. and A. D. Ronan (1996). "Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media-modification of the U.S. Geological Survey's computer program VS2DT." Water Resources Investigations Report: 96-4230.

Hou, X. and F. Wang, et al. (2009). "Duration of plastic mulch for potato growth under drip irrigation in an arid region of Northwest China." Agricultural And Forest Meteorology 150 (2010): 115~121. (In Chinese)

Hsieh, P. A. and W. Wingle, et al. (2000). "A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media." Water Resources Investigation Report: 99-4130.

Hu, H. and F. Tian, et al. (2011). "Soil particle size distribution and its relationship with soil water and salt under mulched drip irrigation in Xinjiang Province of China." Science China Technological Sciences 54 (3): 1~7. (In Chinese)

Hu, X. and M. Li (2003). "Effects of trickle irrigation under sub film on the soil conditions of rhizosphere in cotton." Chinese Journal of Eco-Agriculture 11 (3): 121-123. (In Chinese)

Hu, X. and W. Zhang (2005). "Study on micro-environment of temperature and moisture on cotton (Gossypium hirsutum.L.) under drip irrigation mulched with plastic film." Chinese Journal of Agrometeorology 26 (4): 259-262. (In Chinese)

Lappala, E. G. and R. W. Healy, et al. (1987). "Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media." Water Resources Investigations Report: 83-4099.

Lei, Z. and S. Yang, et al. (1988). Soil water dynamics, Tsinghua Press. (In Chinese)

Li, M. and S. Kang, et al. (2007). "Effects of plastic film mulch on the soil wetting pattern, water consumption and growth of cotton under drip irrigation." Transactions of the CSAE 23 (6): 49-54. (In Chinese)

Li, Y. and M. A. Shao (2004). "Spatial and temporal variation of soil temperature extremum under plastic mulch in Xinjiang." Chinese Journal of Applied Ecology 15 (11): 2039-2044. (In Chinese)

Li, Y. and W. Wang, et al. (2001). "Field characters of soil temperature under the wide plastic-mulch." Transactions of the CSAE 17 (3): 32-36. (In Chinese)

Mahrer, Y. (1979). "Prediction of Soil Temperatures of a Soil Mulched with Transparent Polyethylene." American Meteorological Society: 1263-1267.

Mahrer, Y. (1984). "Temperature and moisture regimes in Soils mulched with transparent polyethylene." Soil Science Society of America Journal 48 (2): 362-367.

Scanlon, B. R. and P. C. D. Milly (1994). "Water and heat fluxes in desert soils 2. Numerical simulation." Water Resources Research 30 (3): 721~733.

Skaggs, T. H. and T. J. Trout, et al. (2004). "Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations." Journal of Irrigation and Drainage Engineering 130 (4): 304-310.

Sui, H. and D. Zeng, et al. (1992a). "Simulation of mulch effects on soil temperature and moisture regimes part I: Mathematical model." Acta geographica sinica 47 (1): 74-79. (In Chinese)

Sui, H. and D. Zeng, et al. (1992b). "Simulation of mulch effects on soil temperature and moisture regimes part II: Finite element analysis and application." Acta geographica sinica 47 (2): 181-187. (In Chinese)

The Statistics Bureau Of China (2008). The yearbook of Statistics of China, The Statistics press of China. (In Chinese)

Wan, S. and Y. Kang, et al. (2010). "Effect of saline water on cucumber (Cucumis sativus L.) yield and water use under drip irrigation in North China." Agricultural Water Management 98 (2010): 105~113.

Wanjura, D. F. and D. R. Upchurch, et al. (2002). "Cotton yield and applied water relationships under drip irrigation." Agricultural Water Management 55: 217~237.

Wu, C. L. and K. W. Chau, et al. (2007). "Modelling coupled water and heat transport in a soil-mulch-plant-atmosphere continuum (SMPAC) system." Applied Mathematical Modelling(31): 152-169.

Wu, C. and J. Huang, et al. (2000). "A model of heat and water flow in SPAC under transparent polyethylene mulch." Journal of Hydraulic Engineering(11): 89-96. (In Chinese)

Xu, F. and Y. Li, et al. (2003). "Investigation and discussion of drip irrigation under mulch in Xinjiang Uygur Autonomous Region." Transactions of the CSAE 19 (1): 25-27. (In Chinese)

Zhang, C. and H. Cai (2005). "Dynamic patterns of soil temperature in the drip irrigation underneath mulching film." Agricultural Research in the Arid Areas 23 (2): 11-15. (In Chinese)

Zhang, W. and X. Lv, et al. (2008). "Salt transfer law for cotton field with drip irrigation under the plastic mulch in Xinjiang Region." Transactions of the CSAE 24 (8): 15-19. (In Chinese)

Zhang, Z. and F. Tian, et al. (2011). "Spatial and temporal pattern of soil temperature in cotton field under mulched drip irrigation condition in Xinjiang." Transactions of CSAE 27 (1): 44-51. (In Chinese)