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Thermal Diffusion Flow Analysis in Unsaturated Loamy Soil using UPWIND and QUICK Numerical Simulation

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Abstract**: *Understanding of energy transport in saturated porous media and unsaturated porous media provides vital information regarding the development of thermal porous reservoirs, industrial filter applications, water reservoirs and low-temperature fluid flow applications. The present paper focus is on presenting the solution of thermal energy diffusion through unsaturated loamy soil using finite difference method approach. The unsteady temperature profile comparison as time function at different spatial locations and as function of spatial location at different time interval are compared using UPWIND and QUICK approach method using thermal diffusion case. MATLAB software is used to simulate above approach for simulation.***

Keywords**: *Mathematical modeling, Finite difference method, Loamy soil***

I. INTRODUCTION

The fluid flow through complex metric of pores through medium (known as porous medium) may contain number of fluids. The applications of above case can be found in many engineering discipline applications such as thermal porous reservoirs, industrial filter applications, water reservoirs and low-temperature fluid flow applications etc. Saturated/ Unsaturated flow problems are derived from Darcy's law [1], analytical works [2], assumption modification ([3], [4], [5]), validation [6], and further extension of equation [7], [8] based on experiments were carried out by researchers. Enormous publication were published on different modeling concept such as pore-scale model ([9], and [10]) constant and variable model [11] based on properties relationships like water –clay interaction [12], soil – water characteristic curve [13]. Heat transfer analysis in packed bed using local thermal equilibrium [11], [12] *considering* and non-local thermal equilibrium (NLTE) condition [14], [15], between phases (fluid / solid) were also published. The mathematical modeling and numerical simulation/ analyses *of unsteady flow through unsaturated flow through such case are discussed in detail in* [12]. *The theoretical and practical aspects are discussed by enormous research paper but research papers based on unsaturated soil numerical simulation are few in quantity.*

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II. LOAMY SOIL ASSUMPTIONS

The unsaturated loamy soil is considered to obey perfect gas law in the presence of air entrap in soil, it's all hydraulic and thermal physical properties are assumed as homogeneous and isotropic[12].

The dimensionless water saturation is as [11]:

$$\text{Water saturation}, S_{\mathrm{e}} = \frac{c - c_{res}}{c_{sat} - c_{res}} = \left[\frac{1}{1+(\alpha h)^n}\right]^m \qquad 1$$

Modified Darcy's law for unsaturated loamy soil based on momentum equation:

$$u = -KK_r(c)\nabla h(c) \qquad 2$$

A. Mass-balance equation [12]:

$$\frac{\partial(\varepsilon s_i \rho_i)}{\partial t} + \nabla(\rho_i u_i) = 0 \qquad i = water, air \qquad 3$$

$$\frac{\partial h}{\partial t} = \frac{\mathrm{K}\frac{\partial}{\partial \mathrm{x}}\left[K_r \frac{\partial h}{\partial x}\right]}{\frac{\partial c}{\partial h}} \qquad 4$$

B. Heat transfer model

1D heat transfer model for loamy soil considering unsaturated flow having constant thermal properties as [12]*:*

$$(\rho c_p)_m \frac{\partial T}{\partial t} + (\rho c_p)_f u.\nabla T = \nabla.[(k_m).\nabla T] \qquad 5$$

C. Numerical Solution

Based on first order differencing scheme (backward), the finite difference discretization of above term is:

$$\frac{h_i^{n+1} - h_i^n}{\Delta t} = \frac{k}{\Delta x^2}[K_r^e * (h_{i+1}^{n+1} - h_i^{n+1}) - K_r^w * (h_i^{n+1} - h_{i-1}^{n+1})] * \left(\frac{dc}{dh}\right)^{-1} \qquad 6$$

Similarly, finite difference discretization of heat transfer model considering time domain (implicit) and diffusion (backward differencing) is written as [12]:

$$\frac{T_i^{n+1}-T_i^n}{\Delta t}+\frac{U_rT_r-U_lT_l}{\Delta t} = \frac{(k_m)}{(\rho c_p)_m}\left(\frac{T_{i+1}^{n+1}+T_{i-1}^{n+1}-2T_i^{n+1}}{\Delta x^2}\right) \tag{7}$$

The velocity driven term U, is numerically solved using second order upwind formulation approach (equation 8 & 9) and quadratic upstream interpolation for convective Kinematic (QUICK) formulation approach (equation 8,9,10 & 11) *as elaborated* [12]*:*

$$U_r = 0.5(U_i + U_{i+1}) \tag{8}$$

$$U_l = 0.5(U_i + U_{i-1}) \tag{9}$$

$$T_r = \left(\frac{3}{4}\right)T_i + \left(\frac{3}{8}\right)T_{i+1} - \left(\frac{1}{8}\right)T_{i-1} \tag{10}$$

$$T_l = \left(\frac{3}{8}\right)T_i + \left(\frac{3}{4}\right)T_{i-1} - \left(\frac{1}{8}\right)T_{i-2} \tag{11}$$

III. INITIAL AND BOUNDARY CONDITION

The numerical simulation of thermal diffusion based on initial and boundary condition is carried out considering negative 1 m, matric potential head and bed temperature of at 20 °C uniformly. The matric potential head at 0 m (i.e. at 1 Absolute atmospheric conditions) having temperature 50 °C is allowed to flow. The boundary conditions having a zero derivative towards outflow axial direction follow as:

h = 1 m (-ve), at $0 \le x \le L$, t = 0; T=20 °C, u = 0;
h = 0, at x = 0 t> 0; T=50 °C;
$\left(\frac{\partial h}{\partial x}\right)_{x=L} = 0$, $\left(\frac{\partial T}{\partial x}\right)_{x=L} = 0$; at x = L t > 0;

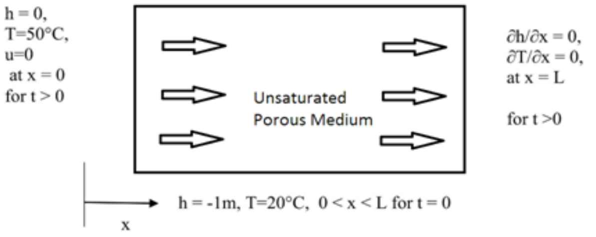

Fig. 1. Schematic representation of loamy soil

The numeric simulation are carried out using on (R) Core (TM) I^5-3230M CPU processor, WINDOW 8.1 (64-bit) system. Typical computer processing time to solve a single run was about 190 seconds.

IV. VALIDATION OF CODE

The numerically simulated code results were validated by comparing the experimental work conduct with Singh[16] considering local thermal equilibrium. The temperaturetime profiles at different spatial locations linearly agrees with the simulated results.

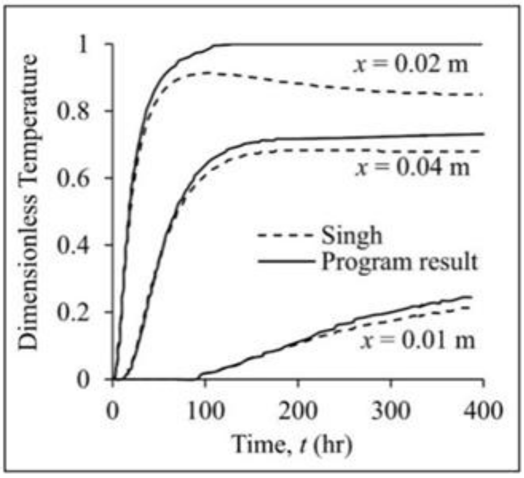

Fig. 2. Results in comparison of Singh[16] with program result at distinguish spatial locations

The loamy sand physical properties as presented in Table 1 are used as input in the program.

Table 1: Loamy sand physical properties

Sand percentage	Clay percentage	Density	Clay percentage	Porosity, ε
65 %	10 %	2650 Kg/m^3	10 %	0.453

V. COMPARISON RESULT BETWEEN SECOND-ORDER UPWIND WITH QUICK APPROACH RESULTS

The solution obtained from finite difference method solution based on UPWIND with QUICK approach are compared in this section. The comparison of loamy sand soil for unsteady-temperature as a function of time at different axial locations is presented in Fig 3 (a, b, c, and d).

On the basis of transient temperature at specific simulation time using UPWIND and QUICK approach is further presented in Fig. 4 (a, b, c, d, e and f).

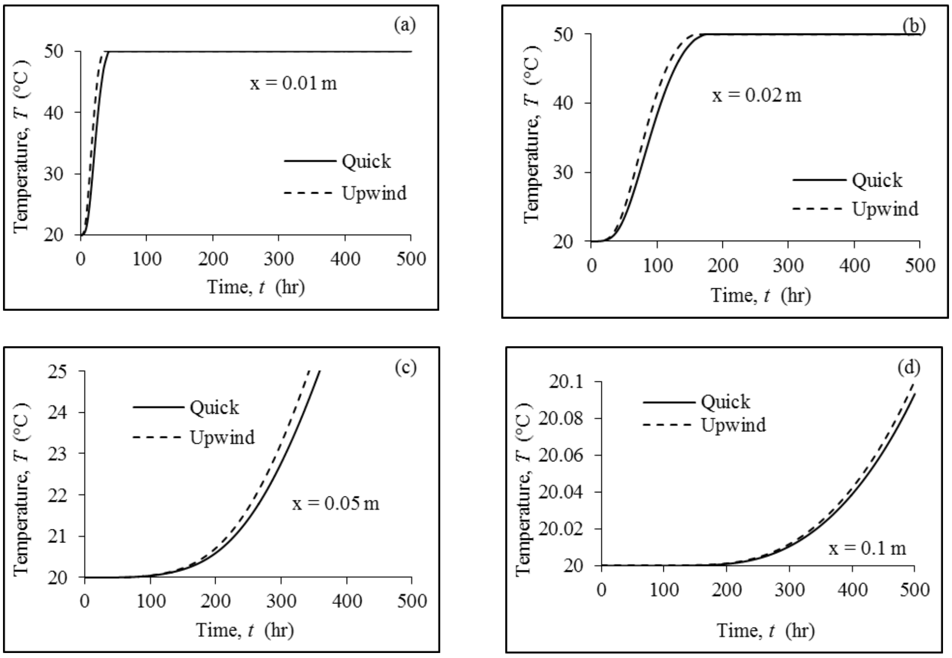

Fig. 3.Comparison of unsteady temperature profile using QUICK and UPWIND method for loamy sand soil

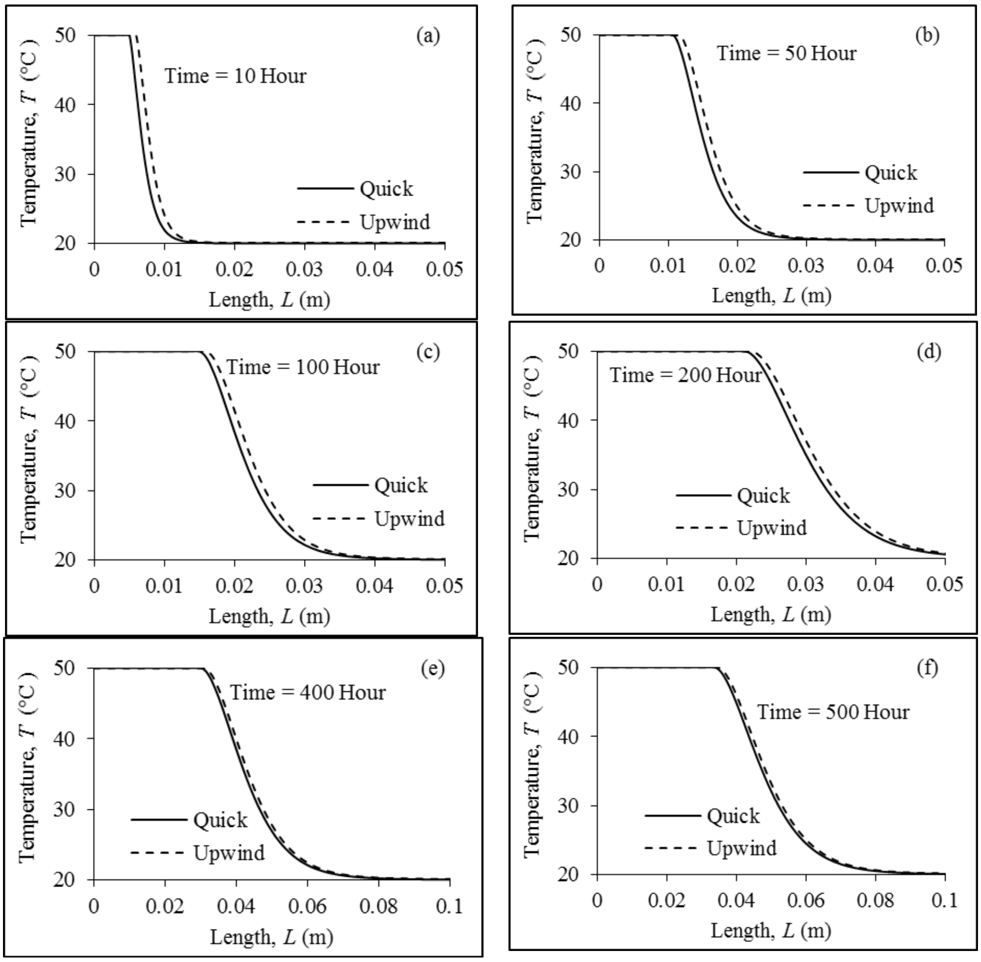

Fig. 4.. Comparison of unsteady temperature profile using QUICK and UPWIND method for loamy sand soil

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VI. CONCLUSIONS

A qualitative validation using QUICK and Upwind approach is carried out. The second order upwind and Quick approach for thermal unsteady temperature response as a function of time at different axial locations for loamy sandalong with temperature profile as a function of spatial locations at different simulation hours such as 10, 50, 100, 200, 400 and 500 hours for loamy sand soil compared and discussed. It is clearly observed that the variation of results is miniature or identical.

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