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Analysis and experimental study on thermal dispersion effect of small scale saturated porous aquifer

Guoqing Liu [a,b], Zhifang Zhou [a,*], Zhaofeng Li [a], Yanzhang Zhou [b,c]

[a] School of Earth Science and Engineering, Hohai University, Nanjing 210098, China
[b] Nanjing Hydraulic Research Institute, Nanjing 210029, China
[c] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing 210029, China

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ABSTRACT

The coefficient model of small scale thermal mechanical dispersion of saturated porous aquifer is established and it is applied in the heat transfer process of convective dispersion. Step-by-step test is conducted for the two physical processes of one-dimensional unsteady heat conduction of semi-infinite medium and convection dispersion to obtain heat physical parameters, thus achieving the verification purpose of analytical solution. On this basis, the porous aquifer thermal dispersion effect is evaluated, the results show that if coefficient of thermal mechanical dispersion 1×10^{-2} W m^{-1} K^{-1} is selected as the critical point where thermal transport is affected, the distribution of thermal mechanical dispersion coefficients can be divided into non-ignorable triangular domain and ignorable polygon domain. However, the result shows that the maximum of longitudinal dispersivity is at centimeter order of magnitude, which is significantly different from the research result of thermal dispersivity under outdoors large scale conditions. This proves the existence of scale effect of thermal dispersion, and thus shows the direction of further research. At last, under condition that the thermal dispersion is ignored, the heat transfer method of thermal transport under conditions of different seepage velocities is also defined.

1. Introduction

Thermal dispersion is a special heat transfer phenomenon in the thermal transport of porous aquifer. Due to the velocity fluctuation in the pore space of the medium, the heat is equalized and the heat transfer effect is strengthened. Therefore, the thermal transport and flow in porous media present many particular complex features, namely, the dispersion effects [1].

The early governing equation of convection conduction did not include thermal dispersion term, but with the gradual development of basic theory of heat transfer in saturated porous media, on the analogy of solute transport hydrodynamic dispersion effect, the discussion of conceptual model gradually focuses on thermal mechanical dispersion mechanism. Kwong et al. [2] proposed the concept of "effective thermal conductivity" and defined it as the sum of "stagnant liquid heat conductivity coefficient" and "thermal dispersion heat conductivity coefficient after the flow". D Marsily [3] believed that thermal dispersion was similar to mechanical dispersion of the solute, the process was closely related to the structure of the medium and flow velocity. However, there is essential difference between thermal transport and solute transport, since the existence of heat conduction enables energy transfer among solid particles in the process of thermal transport and there are other thermal transports in the molecular diffusion and absorption effect in solute transport. It is thus clear that solute transport can be used as a reference but cannot be copied. A large amount of work has been done by many scholars for pore scale conditions, the thermal mechanical dispersion coefficient in the convective dispersion heat transfer process is generally regarded as a physical quantity that relies on the fluid velocity and particle size of porous media [4–8]. Metzger et al. [9] imitated porous media aquifer with a glass ball with a diameter of 2 mm and acquired relevant expressions of thermal-dynamic dispersion coefficient. Based on this research, N. Molina [10] discussed the influence of thermal dispersion effect on the thermal plume range in the geothermal system under microscale and macroscale conditions using analytical solution. Some scholars believe that thermal dispersivity is a function of size and cases show that in the energy storage experiment of large scale porous aquifer, the simulative temperature field data fit well with the field experiment data only

* Corresponding author. School of Earth Sciences and Engineering, Hohai University, No. 1 Xikang Road, Nanjing 210098, Jiangsu Province, China. Tel.: +86 02583787140.
E-mail addresses: zhouzf@hhu.edu.cn, lgqno111@126.com (Z. Zhou).

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Nomenclature

a_x	longitudinal dispersivity (m)
a_y	transverse dispersivity (m)
α_c	thermal diffusivity of heat conduction process ($m^2\ s^{-1}$)
λ_x	effective thermal conductivity in the longitudinal direction ($W\ m^{-1}\ K^{-1}$)
λ_y	effective thermal conductivity in the transverse direction ($W\ m^{-1}\ K^{-1}$)
λ_f	thermal conductivity of water ($W\ m^{-1}\ K^{-1}$)
λ_s	thermal conductivity of the solid particles ($W\ m^{-1}\ K^{-1}$)
λ_v	mechanical dispersion coefficient ($W\ m^{-1}\ K^{-1}$)
λ_a	bulk thermal conductivity of porous medium ($W\ m^{-1}\ K^{-1}$)
α	total thermal diffusivity ($m^2\ s^{-1}$)
α_c	thermal diffusivity of heat conduction process ($m^2\ s^{-1}$)
α_f	thermal diffusivity of water ($m^2\ s^{-1}$)
x, y, z	Cartesian coordinates (m)
S	dimensionless temperature standard deviation (dimensionless)
c_f	heat capacity of water ($J\ kg^{-1}\ K^{-1}$)
c_s	heat capacity of solid particles ($J\ kg^{-1}\ K^{-1}$)
A	longitudinal dispersivity empirical constants (dimensionless)
H	aquifer thickness (m)
ΔH	head difference (m)
D	specimen diameter (m)
d	particle diameter (m)
τ	time ($m\ s^{-1}$)
n	total porosity (dimensionless)
v	Darcy velocity ($m\ s^{-1}$)
Δz	space step (m)
$\Delta \tau$	time step (s)
erfc	error function
θ	dimensionless temperature (dimensionless)
K	hydraulic conductivity ($m\ s^{-1}$)
T_0	initial temperature (K)
T_s	surface source temperature (K)
$T_{z,\tau}$	measuring temperature (K)
q_z	discharge per unit width ($ml\ h^{-1}$)
Pe	Peclet number (dimensionless)
m_1	empirical constant (dimensionless)
R_d	assumed coefficient (dimensionless)
ρ_f	water density ($kg\ m^{-3}$)
ρ_s	solid particle density ($kg\ m^{-3}$)
ρ_d	dry density ($kg\ m^{-3}$)
w	seepage velocity of test ($m\ s^{-1}$)
$(\rho c)_{fs}$	porous medium heat capacity ($J\ kg^{-1}\ K^{-1}$)
$\rho_f c_f$	heat capacity of water ($J\ kg^{-1}\ K^{-1}$)
$\rho_s c_s$	heat capacity of solid skeleton ($J\ kg^{-1}\ K^{-1}$)
Gs	specific gravity (g/cm^3)

on the premise that the thermal dispersion term is considered, there are defects for considering only the heat transfer method of convective conduction [11]. However, the dispute on convective dispersion of thermal transport in saturated porous aquifer has always existed. On the one hand, some scholars [12,13] believe that thermal dispersion $\lambda_a/(\rho c)_{fs}$ dominates in the simulative process of thermal transport and thermal mechanical dispersion is negligible relatively, on the other hand, many researches show that thermal dispersion effect is produced in micro-scale homogeneous porous media in the thermal transport process [1,14], which is of course also produced in the macro-scale heterogeneous thermal transport process [15–17], thermal dispersion effect is generally not negligible, especially under outside large scale conditions, it is generally believed that the longitudinal dispersivity is 5%–10% or one-tenth of the radius of the influence [18]. In the simulative experiment of aquifer energy storage, $\lambda_v/\lambda_a = 2$ was applied [19]. Xue et al. [11] provided the longitudinal dispersivity as $a_x = 3.3$ m in the seasonal energy storage experiment in Shanghai. However, as for the disputes on heat dispersion effect, we should take into consideration heat dispersion effect while doing calculation. From the perspective of development situation disclosed by dispersion mechanism, it is not mature yet. The bottleneck is lacking a unified calculation expression for heat mechanical dispersion coefficient. Moreover, these adjustable empirical constants are always different due to different experiment conditions and numerical simulations.

For example, Koch et al. [20] proposed a theoretical semi-empirical correlation about axial and radial thermal dispersion effect, and some scholars tried to study the dispersion effect and turbulence model in porous media through direct simulation of the fluid flow and heat transfer in space with specific geometric shapes [21,22]. Chou et al. [23] compared some of the calculation methods and found out that the deviation was up to dozens of times. Most of the empirical coefficients were obtained through their own experiment data and the models lacked generality and comparability. At present, the researches of thermal mechanical dispersion coefficient mostly rely on direct measurements in experiments and numerical simulations. Yu [24] once provided some comprehensive analysis of the calculation formula of dispersion coefficient. There are various theoretical basis for the research on thermal dispersion: fractal analytical approach [25], turbulent mixing length theory [26,27], and numerical simulation of fluid and heat transfer in porous media [28,29], volume average method [30,31] and statistical average method [32].

At present, exploration is still constantly made for the study on heat dispersion effect. More theory and test research are necessary for its development. The dissertation employs small-scale physical model to study the influence of heat dispersion effect on heat transfer through test and analysis, thus laying a foundation for subsequent further study. In addition, accurate mastering of heat dispersion effect possesses great significance for accurate prediction of temperature field for the aquifer energy storage [33,34], GSHPs (Ground Source Heat Pumps) [35–37], nuclear engineering development technology, temperature field tracer, tunneling and large hydropower construction projects. It will also offer reference for study on more complex heat transfer of liquid–solid-heat coupling.

2. Experiments

2.1. Experiment ideas

The experimental program is divided into two phases: (a) one-dimensional unsteady state heat conduction experiment of semi-infinite porous aquifer under non-convection condition, in this experiment, the heat is transported simply by heat conduction, by this physical process the thermal diffusivity α_c of saturated porous aquifer is obtained, this is an indispensable parameter which cannot be obtained by instrument measurement in the study of thermal dispersion. (b) One-dimensional unsteady state convective dispersion experiment of semi-infinite porous aquifer under fixed