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Single Phase Model of Thermal Diffusion Process in Saturated Porous Media due to Hot Water Seepage Flow

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SYNOPSIS

This paper aims to evaluate the applicability of the single phase model for thermal diffusion phenomena caused by saturated flow through porous media. These were based on the laboratory experiments using vertical glass bead columns. Since the permeability of bead is increased by seepage of hot water into cold porous media, the seepage flow under a constant head gradient becomes unsteady. In this research, a newly-devised method to fix the seepage velocity was adopted for the steady experiments. The coefficient of thermal diffusion κ, which is a main parameter of the single phase model, was identified from the experimental data. The behavior of κ values under various conditions was investigated and was used as a measure to evaluate applicability of the model. Through this research, it was clarified that κ values can be represented as a linear function of the heat transfer velocity. The relationship between the thermal dispersivity β which characterizes κ values, and the spatial scale of flow were also discussed.

INTRODUCTION

The temperature of groundwater is very stable throughout a year because the aquifer is located deep under the ground surface. This inherent property of the groundwater is extremely useful as water and energy resources. Recently, in order to utilize this thermal characteristic of groundwater, the Aquifer Thermal Energy Storage (ATES) technique[1)] by the well injection of hot or cold water has been offered from the 1980's. ATES is expected to have applicability not only as a subsidiary energy source to fossil fuels but also as a technique for the disposal of excess heat on the ground surface and for the cooling of subsurface facilities. In Northern Japan, since well withdrawal to melt away heavy snow has caused serious land-subsidence for a long time, a snow melting project by ATES using the heat-pump have been planned. The use of the ATES technique produces also a risk that artificially disturbs the subsurface environment of the basin. Therefore, a careful assessment of the regional groundwater condition should be in advance carried out for realizing ATES.

In this research, in order to analyze the thermal behaviors in aquifer by ATES, the applicability of the single phase model will be considered by comparison with accurate laboratory experiments.

SINGLE PHASE MODEL ON THERMAL DIFFUSION PROCESS

As it has not been long since research on the thermal diffusion process with seepage flow in a porous media started, the physical mechanism of this phenomena has not been sufficiently clarified. On the contrary, the solute transport process in an aquifer has been studied by many researchers in relation to the contamination problem. The analysis model for the solute transport then has been developed to some extent. These two phenomena are similar from the point of the advective dispersion phenomena in the porous media. That is, the molecular diffusion and the mechanical dispersion in solute transport correspond to the heat conduction and the thermal dispersion in heat transfer, respectively. For the sake of simplicity, let us assume that the natural convection due to the density difference in the fluid can be ignored. Provided that the temperature of the solid and liquid achieve mutual equilibrium in a short time, the single phase analysis based on the well known model for solute transport may be applied to the thermal problems.

The fundamental equation of the single phase model for heat transfer is written as follows,

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\kappa \frac{\partial T}{\partial x}\right] - u*\frac{\partial T}{\partial x} \qquad (1)$$

$$\kappa = \kappa_c + \beta \cdot u*^{n} \qquad (2)$$

where T is the temperature of the saturated porous media, κ is the coefficient of thermal diffusion, and κ_c is the conductivity of temperature. Also β is the thermal dispersivity, $u*$ is the seepage velocity that a delay due to heat exchange between solid particles and liquid is taken into consideration, and the value of n is assumed to be equal to 1.0. The first term in the right hand side of Eq.(1) represents effect by thermal diffusion such as thermal conduction and dispersion, and the second term represents the effect of flow advection. Although the natural phenomena are too complicated to be explained by the assumption described above, we would like to focus our attention here to evaluate the validity and limits of the single phase heat transfer model. For that, laboratory experiments were carried out under various conditions concerning with the particle size of porous media, temperature of seepage water and flow discharge etc., and the evaluation of the single phase model through identification of the coefficient of thermal diffusion for the experimental data has been tried.

LABORATORY EXPERIMENTS

By using the experimental apparatus as shown in Figure 1, the thermal diffusion process in a porous media is measured by thermal sensors and a data logger when hot water infiltrates into columns A and B filled with fine glass beads. The columns were set vertically to prevent occurrence of natural convection due to density difference of the fluid, and the hot water seeps downward from the top of the column under a certain hydraulic gradient. The columns have an inside diameter of 10 cm and a total length of 50 cm and are made of stainless steel pipes 1 mm thick to minimize heat loss in the lateral direction. The columns and the hot-water tank are covered with heat insulating materials to keep it warm. In the hot water tank, a pipe heater controlled by computer is provided to keep the temperature of hot water to a fixed value.

The initial condition of the experiment was made by supplying cold-water from the left tank into the column. After the temperature distribution in the column is noted, hot water from the right tank is supplied into the column. In this research, two procedures of water supply to the columns, which are the constant head method and the variable head method, are adopted. In the constant head method for the column A, since the water tank and the column are joined by saturated, hot-water flows under a constant hydraulic gradient. As the permeability of the glass bead increases by the seepage of hot water, the inflow rate will also increase gradually. Conversely, in the variable head method for the column B, the hot water flows in a narrow pipe in constant rate protruding on the top of column. This method aims to keep the constant flow rate by allowing free variation of the water level in the pipe corresponding to the change of permeability in the column. The stability of flow rate can be checked in detail by the areal flow meter installed at the bottom of the column.

The glass beads in the column are prepared from three types which have mean diameters of 0.3, 0.6, 1.0 mm and a uniformity coefficient of about 1.0. As the thermal sensor, K class thermocouples (Chino Electric Co., Inc., SUS-316) are inserted into the column to measure the temperature of fluid along the center line of column. Data of water temperature are recorded in the computer through the data logger (Eto Denki, Inc.,THERMODAC-E 5001A) with resolution of 0.1 degree. As described later, these experimental data were compared with computed results by the single phase model for the identification of the coefficient of thermal diffusion.

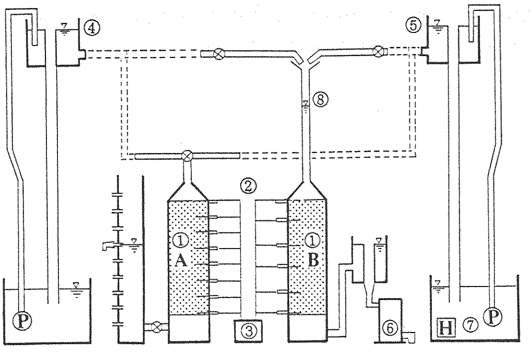

Fig.1 Schematic diagram of experimental apparatus.
1. Column of bead 2. Thermal sensor 3. Data logger
4. Hot water tank 5. Cold water tank 6. Areal flow meter
7. Heater controlled by PC 8. Pipe for adjustment of head

CONSTANT HEAD EXPERIMENTS AND THEIR PROBLEMS

As main experimental data for the seepage of hot-water, the temporal behavior of water temperature at the location of each sensor was obtained. In the rising process of temperature, the time at which the temperature reaches at 50 % value of its variation range means that the center of the front of hot water arrives at the location of sensor. Figure 2 shows the relationships between the sensor locations and the arrival time of hot water front. This figure shows that the descent velocity of the hot water front is not constant and gradually increases by intrusion of hot-water into the column.

The reason why this increase of velocity occurs under the constant head gradient is that the permeability varies with the seepage of hot water. As well known, the permeability K contains the coefficient of kinematic viscosity ν of fluid and is described as $K=kg/\nu$. Where k is a unchangeable parameter prescribed by the pore structure of porous media, called as the intrinsic permeability, and ν depends on the temperature of fluid. Figure 3 shows the relationship between the water temperature and K value which can be calculated by the above equation, with the results of the permeability test for three types of beads under various temperatures. According to this figure, the permeability K increases gradually along convex curves by the rising of the water temperature.

In this experiment, the cold water in the vertical column is excluded downward by intrusion of the hot water from the upper part of column, as shown in Figure 4. So the distribution of water temperature in the column at any time may be regarded to consist of the hot part and the cold part. The average permeability K_m for the whole column may be described by the following equation.

$$K_m = \frac{L}{x/K_2 + (L-x)/K_1} = \frac{kgL}{x(\nu_2 - \nu_1) + L\nu_1} \tag{3}$$

where L is the total length of column, x is the distance to the front of hot water from the top of column, K_1 and K_2 are the permeability of the part occupied by the cold water and the hot water, respectively, and ν_1 and ν_2 are the kinematic viscosity of the cold water and the hot water, respectively.

Figure 5 indicates the variation of K_m/K_1 calculated based on the above equation for the case that the hot water of temperature T_2 = 15 - 50 ℃ seeps into the region filled with the cold water with T_1 = 10 ℃. As shown in this figure, K_m for T_2 = 15 ℃ almost does not increase because of the small difference of temperature. In the case of T_2 = 50 ℃, however, K_m increases substantially as the fraction function and becomes more than 2 times of K_1 when the front arrives at the bottom of the column. That is, in the experiments under conditions of the constant head gradient, the phenomena are unsteady because the velocity of advective flow varies temporarily.

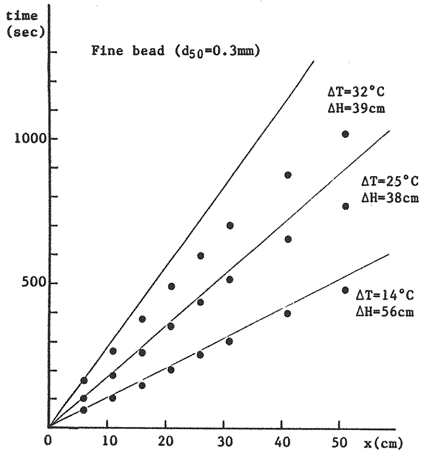

Fig.2 Relationship between sensor location and passage time of front.

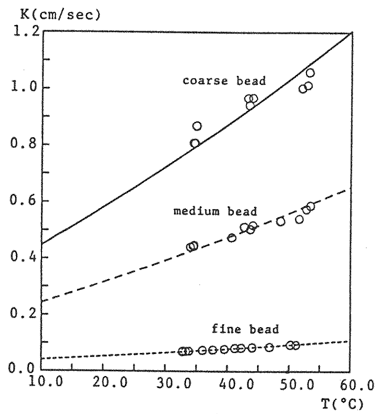

Fig.3 Increase of permeability due to rising of water temperature.

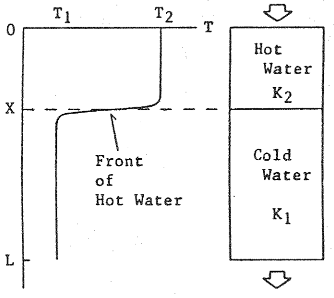

Fig.4 Distribution of temperature along column.

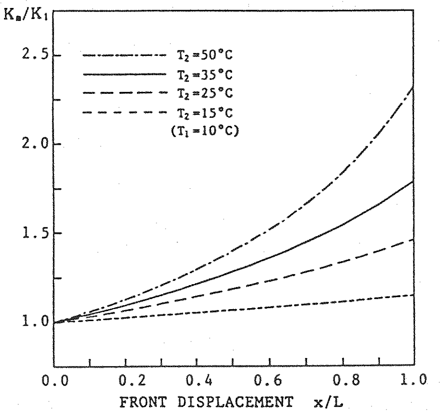

Fig.5 Increase of average permeability due to intrusion of front.

As shown in Eq.(2), the coefficient of thermal diffusion in the single phase model includes the velocity of advective transport u^* in the term of thermal dispersion. Therefore, temporal variation of the velocity affects the coefficient of thermal diffusion itself and makes the phenomena remarkably complex. For the sake of the purpose of this research, evaluating the applicability of thermal diffusion model through the stability of the parameter values is necessary to fix the advective velocity even under seepage of the hot water. As one of the countermeasures, Fujinawa[2)] has tried to move vertically the water tank for adjustment of the head. However, it is difficult to adjust accurately the head gradient in the fast phenomena finished in several minutes. This is the reason why the water supply to the column has been done by the variable head method as stated above.

VARIABLE HEAD EXPERIMENTS FOR THE PURPOSE OF STEADYING OF ADVECTIVE VELOCITY

Problems awaiting solution on the experiments

The water supply by the Variable Head Method aims to keep a constant velocity by eliminating the effect of permeability variation with the narrow pipe on the top of column, where the water level is allowed to rise and fall freely. Two problems will be pointed out for this method. The first is on the inside diameter of the pipe. If the pipe is too thick, the storage volume in the pipe due to the movement of the water table may not be ignored. Conversely if the pipe is too thin, it may happen that the pipe is stopped up by instability of flow fluids. In order to minimize these effects, an optimum diameter has been selected among the several pipes with various diameters.

The second is the problem about the length of pipe. The pipe has to be lengthened more than the distance of fluctuation of head in the pipe. However, if the pipe is too long, even if the inflow water is quickly changed from cold to hot, the supply of hot water to column will be delayed and the temperature of inflow water at the top of column will rise gradually because of the mixing of the hot water and the cold water in the pipe. That is, it is impossible to make the required boundary temperature step up. Therefore, in the analysis of experimental data, measurements of temperature by the upper sensor have been adopted as the upper boundary condition.

Steadying of the discharge

Examples of variation of the flow discharge and the head in the pipe are shown in Figure 6. In the upper figures, the symbols ● indicate the discharge Q at the end of the column and the symbols ○ show the head h in the pipe. The symbols ● in the lower figures indicate the ratio of permeability K_m/K_1 calculated by Eq.(3) based on the arrival time of the hot water front (the 50% value of temperature difference) to each location of sensors. As can be seen in these figures, though the permeability K_m keeps increasing from the start of experiment, the head gradient keeps decreasing due to falling of the head in pipe and the discharge is successfully kept at the constant rate. This device to keep discharge at a steady state gives a nearly good result to other conditions of experiments.

Unsymmetry of the variation curve of temperature

Figure 7 shows the time variation of temperature measured by each sensor under the condition of steady discharge. Seeing the figure in detail, the rising process of temperature at lower sensors is steep in the increasing part of the curves and mild as the curve approaches its maximum value. That is, the rising curves are unsymmetrical at the middle of the temperature range. Though unsymmetry in the curves has also been noted in the solute transport experiments [3][4], it is more remarkable in these experiments of heat transfer. Supposing $t_{10\text{-}30}$ to be the time elapsed for the temperature to rise from the 10 % value to the 30 % value of the temperature range and $t_{70\text{-}90}$ to be the time from the 70 % value to the 90 % value of the same, the ratio $t_{70\text{-}90}/t_{10\text{-}30}$ may be taken as an index of the unsymmetry.

Figure 8 indicates the relationship between the index $t_{70\text{-}90}/t_{10\text{-}30}$ and the mean diameter of the bead. According to this, it is found out that the unsymmetry index becomes smaller for the coarser bead. Furthermore, though other relationships between the unsymmetry, the velocity, the difference of temperature and the flow distance from top of column have been investigated, the results are varied and obscure in each experimental case. As will be described later, the unsymmetry of curves cannot be explained by the single phase model. Therefore, to understand better the phenomena it is necessary to clarify the cause of unsymmetry and rearrange the simulation model of heat transfer.

IDENTIFICATION OF COEFFICIENT OF THERMAL DIFFUSION

The thermal diffusion model used in the analysis is for the one dimensional flow in the homogeneous media and Eq.(1) has been analyzed numerically by the finite difference method. In the analysis, the initial condition is $T(x,0)=T_1$, where T_1 is the temperature of cold water. The rising curve measured by the upper sensor are used as the boundary condition. Then, calculating the temperature in the column, the coefficient of thermal diffusion κ has been identified by the measured data at each point. The seepage velocity of advective flow u^* in the equation can be computed from the travel time of the temperature front among the sensors.

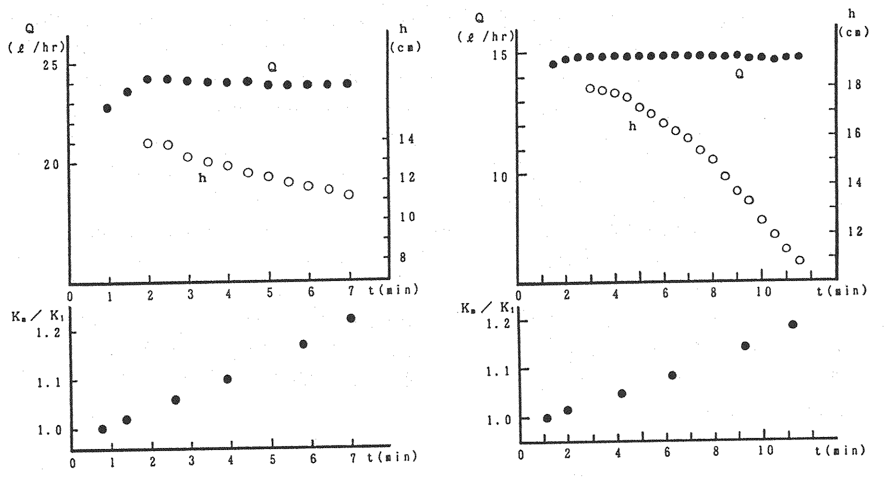

Fig.6 Steadying discharge by Variable Head Method.
Diameter of glass bead : Left 0.6mm, Right 0.3mm
Water temperature : Cold water 25℃, Hot water 35℃

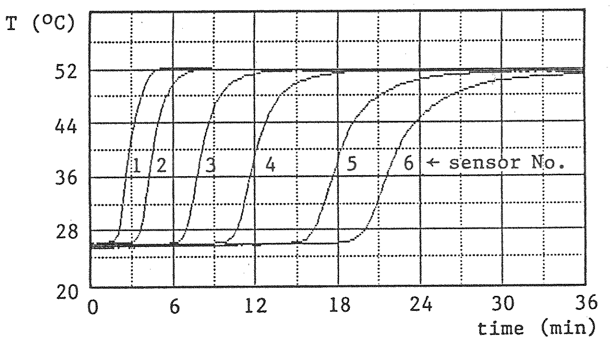

Fig.7 Examples of temperature rising under Variable Head Method.

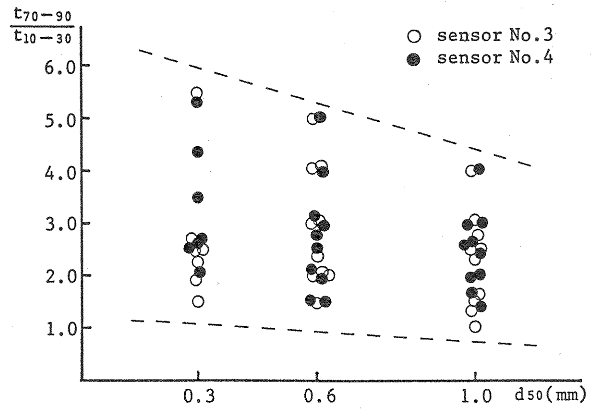

Fig.8 Relationship between unsymmetry of rising curves and diameter of bead.

Figure 9 compares the computed and the observed value in the identification of κ. The left curve in the figure is the measured data at upper sensor A used as the boundary condition, and the right curve and the symbols ○ are the computed data and the observed data at lower sensor B, respectively. Comparing the computed and the observed data at sensor B, the agreement in the latter half of the curve is not good even though the boundary condition is given by the measured data. This is because of the unsymmetry of rising curve, as mentioned above. That is, the single phase model cannot completely represent the behavior of heat transfer in the column.

Figure 10 shows the relationship between the κ value identified and the flow velocity u^*. As recognized in the figure, since there is a tendency for the κ values to increase linearly with respect to u^*, it can be assumed that the expression (2) will be best for computing κ. Applying the straight line of Eq.(2) to plots in the figure, the conductivity of temperature κ_c=7.8 x10^{-4} (cm²/sec) and the thermal dispersivity β=5.4x10^{-2} (cm) have been obtained. Comparatively, Sato[5)] had given the conductivity κ_c=2.4 - 3.5 x10^{-3} (cm²/sec) as the results of the laboratory experiments of thermal conduction in the saturated glass beads.

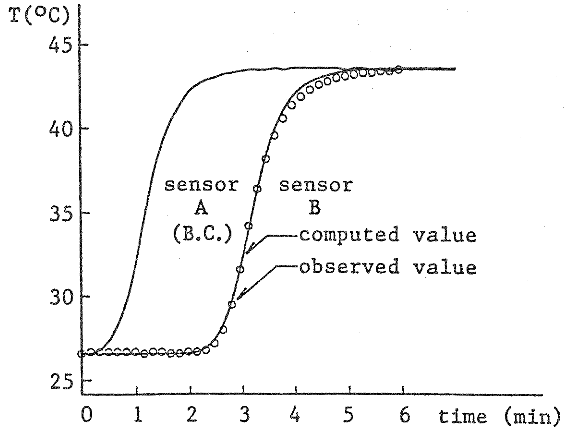

Fig.9 Example of agreement between observed data and computed data in identification of κ.

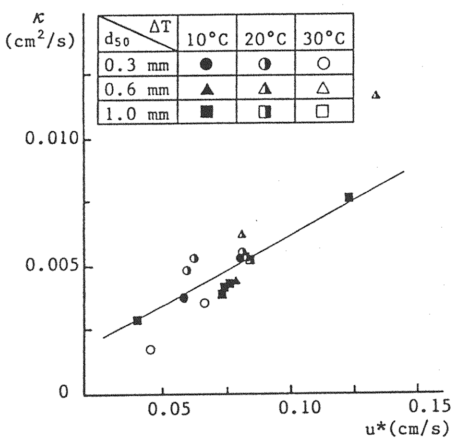

Fig.10 Relationship between thermal dispersivity κ identified and seepage velocity u *.

Next, let us consider the value of thermal dispersivity β. It has been already pointed out that the solute dispersivity α obtained by laboratory experiments depends on the geometric characteristics of the porous media and the α value is the same order as the mean diameter of the particle[6]. The β value, 0.54 (mm), obtained in this research is also approximately the same as the bead diameter (0.3 - 1.0 mm). Therefore, it seems reasonable to suppose that the α and β values in the laboratory are similar to each other. Incidentally, the authors [6] had previously clarified that the β value in the field tests of well injection is the same order as the α value. Through this research, the similarity of α and β has been recognized even in the scale of the laboratory experiments.

Plotting the α and β values obtained in previous papers and this research with relation to the spatial scale of experiments result in Figure 11. The symbols ● in the figure are the solute dispersivity α, ○ denotes the thermal dispersivity β by the field tests and ◎ is the β value by this laboratory research. According to the figure, there is a difference of 3 orders between values of symbols ○ and ◎. However, considering that the scales of these experiments differ by 2 orders with each other, it is possible to interpret the above result to be caused by the the scale effect of the diffusion phenomena. Therefore, we can confidently say that β have similar values as α and that β also have the scale effect similar to α.

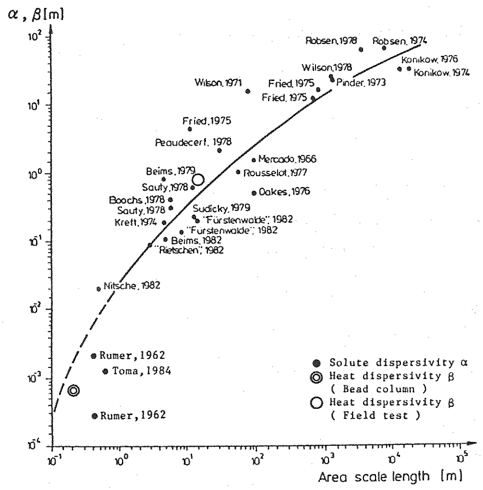

Fig.11 Spatial scale effect on dispersivity of heat and solute (modified based on literature 8).

CONCLUSIONS

The following conclusions have been obtained through this research.

(1) Since the average permeability of column increases as the fraction function with the intrusion of hot water to the bead, the seepage velocity increases remarkably under the fixed head gradient.

(2) In order to steady the discharge in the seepage of hot water, a newly-devised method, which absorbs the increase of permeability as the decrease of head gradient, has been developed.

(3) The rising process of temperature by each sensor is an unsymmetric curve, which becomes more mild in the latter half. This phenomena is marked in the case of small bead media.

(4) The identified values of the coefficient of thermal diffusion κ increase almost linearly with respect to the seepage velocity. Concrete values of the conductivity of temperature κ_c and the thermal dispersivity β have been obtained.

(5) The β values in the laboratory experiments correspond to the diameter of particle in porous media, as well as the solute dispersivity α. On the other hand, the α and β values in the field tests are larger because of the scale effect of the phenomena.

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APPENDIX - NOTATION

The following symbols are used in this paper;

g = acceleration of gravity;
k = intrinsic permeability of saturated porous media;
K_m = average permeability of total of the column;
K_1 = permeability of glass bead in part occupied by cold water;
K_2 = permeability of glass bead in part occupied by hot water;
L = total length of column;
n = a constant assumed to equal to 1.0;
T = water temperature in saturated porous media;
T_1 = temperature of cold water;
T_2 = temperature of hot water;
u^* = seepage velocity considering with a delay due to heat exchange between solid particles and liquid;
x = distance to front of hot water from top of column;
α = solute dispersivity;
β = thermal dispersivity;
κ = coefficient of thermal diffusion;
κ_c = conductivity of temperature;
ν_1 = kinematic viscosity of cold water; and
ν_2 = kinematic viscosity of hot water.

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