ON THERMAL ANOMALIES DUE TO INJECTION-WELL DISCHARGES IN POROUS AQUIFERS

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ABSTRACT

Infiltration wells discharging industrial cooling water or water from heat pumps give rise to temperature and hence density differences in the receiving groundwater. These produce buoyancy effects which may alter the outflow distribution considerably, cause vertical flow near the well and lead to temperature stratification. These effects have been investigated in a three-dimensional numerical flow and heat-transport model and verified by laboratory tank experiments. The main results of the study are presented.

RESUME

Les rejets thermiques dans le sous-sol, soit de refroidissement industriel ou de pompes de chaleur, introduisent des changements de température et ainsi de densité aux eaux souterraines. Dans les environs d'un puits d'infiltration ils provoquent des effets d'ascension ou descension et de stratification thermique qui peuvent modifier considérablement l'écoulement de l'eau infiltrée. Ces effets ont été étudiées dans un modèle mathématique de l'écoulement et de transport à trois dimensions. Le modèle a été verifié par des expériences dans le laboratoire. Les résultats principaux sont présentés ici.

1. INTRODUCTION

Anomalies of groundwater temperatures may either have natural causes or be induced by human activities. In particular, in densely populated metropolitan areas, considerable regional changes of groundwater temperatures have been observed. One of the main reasons for these changes is undoubtedly the use of groundwater for thermal purposes either for industrial cooling systems or for heat pumps. In either case, groundwater is extracted, experiences a positive or negative temperature change and is then infiltrated again into the ground. This gives rise to temperature anomalies which may affect other uses of the groundwater. Temperature anomalies may interfere with the use for drinking water supply purposes, have adverse effects as e.g. in the case of mutual interference of neighboring heat pumps or neighboring cooling systems, or also be favorable as in the combination of cooling water discharges and heat pumps. For a proper assessment of such effects, it is necessary to quantify the flow and temperature field in the vicinity of injection wells.

The development of a thermal anomaly due to a discharge of warmer or colder water into an aquifer is a highly complicated process which depends upon many parameters. Apart from the transport of heat due to convection, conduction and dispersion, one has to consider the heat exchange with the porous matrix, the temperature-dependent changes of viscosity and density and consequently of the Darcy-conductivity, as well as density-dependent buoyancy effects. Finally, the heat exchange with the atmosphere and adjacent geologic formations is important for the extent of the anomaly.

The present contribution is geared towards quantification of the density-induced buoyancy effects in the nearfield of the injection well.

2. GENERAL FLOW CONFIGURATION

We investigate the simple case of infiltration of water with a positive temperature difference ΔT through a single vertical injection well into a confined aquifer with a natural groundwater flow velocity v_o (Fig. 1). Basically, we can distinguish three zones, in which various parameters are dominant:

- The nearfield is characterized by dominant buoyancy effects. These determine the resulting outflow distribution over the depth and give rise to vertical flow components and the formation of convection rolls with a tendency towards the development of a stable temperature stratification.
- The intermediate zone is characterized by essentially horizontal flow and vertical mixing processes by dispersion and conduction with the tendency towards a uniform temperature distribution over the aquifer thickness.
- The farfield is determined by heat exchange processes through the top layer to the atmosphere and to adjacent geologic formations, which become dominant and ultimately responsible for the extent of the temperature anomaly as a whole.

The extent and importance of each of these zones depends of course upon the parameters characterizing the infiltration and the aquifer.

3. NEARFIELD PARAMETERS

How important are nearfield buoyancy effects for the development of a thermal anomaly? How do they affect the far field, and under which conditions can they be considered negligible?

The answer to these questions requires a detailed investigation of the flow- and temperature distribution in the nearfield, which necessarily has to be three dimensional in space. If we consider the aquifer to be homogeneous, isotropic and of constant thickness m and take the natural groundwater velocity v_o to be uniform and steady, then the flow and temperature field is governed (MEHLHORN) essentially by three independent dimensionless parameters: the relative infiltration rate Q^*, the relative buoyancy B^*, and the Rayleigh number Ra.

The relative infiltration rate is defined as

$$Q^* = \frac{\eta_1}{\eta_o} \frac{Q}{v_o m^2} = \frac{b_i'}{m} \tag{1}$$

and expresses the ratio of the infiltration rate to the natural groundwater discharge; it can be also interpreted as the ratio of the infiltration width b_i' (see Fig. 2) to the aquifer thickness m. The larger this parameter becomes, the more extended will be the temperature field and the less important will be local buoyancy effects.

The relative buoyancy is defined as

$$B^* = \frac{\Delta\rho}{\rho_o} \frac{\frac{g}{\nu_o} k_o}{v_o} \tag{2}$$

and represents the ratio of the buoyancy force due to density differences to the driving force of the natural horizontal groundwater flow. For larger values of this ratio the importance of buoyancy effects increases.

The Rayleigh number is defined as

$$Ra = \frac{c_w}{c} \frac{(\Delta\rho g k_o)/(\rho_o \nu_o)}{D/m} \tag{3}$$

and characterizes the ratio of vertical heat transport due to buoyancy effects to vertical heat transport due to heat conduction and mixing. If the Rayleigh number is large, buoyancy effects can produce temperature stratifications; if it is small, the equalizing effects of heat conduction and vertical mixing will dominate.

Of particular interest are the global dimensions of the nearfield and the temperature conditions at the boundary to the transition zone, as shown schematically in Fig. 2. The investigations can thus be summarized by the following relationship:

$$\left.\begin{array}{l}\text{flowfield}\\ \text{temperature distribution}\\ l_n\ ,\ b_n\ ,\ e\end{array}\right\} = f\ (Q^*,\ B^*,\ Ra) \tag{4}$$

4. MODEL STUDY OF NEARFIELD

For investigating the flow and temperature distributions, a three-dimensional numerical model has been developed. This model solves the equation of motion (BEAR)

$$\nabla\left[\frac{k_o}{\nu}(\nabla p - \rho_w \vec{g})\right] = \frac{\partial(\rho n)}{\partial t} \tag{5}$$

and the heat transport equation (BEAR)

$$\frac{\partial T}{\partial t} + \frac{c_w}{c}\vec{v}_f \nabla T - \nabla D\, \nabla T = 0 \tag{6}$$

These two equations have to be solved simultaneously, since flow field and temperature field are mutually dependent and interact because of the temperature-dependence of density and viscosity. Since changes in the temperature field are comparatively slow, the flow field will respond to such changes more or less immediately. The unsteady flow field was therefore composed from a large number of quasi-steady states and calculated by means of a difference scheme. The unsteady temperature field was calculated by the method of characteristics (KONIKOW and BREDEHOEFT; PINDER and COOPER), in which the convective and the dispersive heat transport are treated separately.

For testing and verification of the numerical model, a sand model of 0.65 m height, 1.2 m width and 2 m length was constructed. By varying the water levels in the inlet chamber and outlet chamber of the model, arbitrary uniform flow velocities v_o could be produced. In the symmetry axis of the model, water could be infiltrated at alternative locations through vertical infiltration wells. Experiments were performed with a sand of grain size of 0.4 to 0.7 mm for a large variety of flow velocities, injection well discharges and temperature differences. Through a system of 118 in situ temperature probes, the time-dependent development of the temperature field could be observed. The sand model tests showed marked buoyancy effects. The sand model experiments were simulated in the numerical model in order to verify the model and to prove that it reproduces the heat transport processes correctly.

Fig. 3 shows a comparison of numerical and experimental results (MEHLHORN). The upper part shows the steady-state temperature distribution in a cross section downstream from the injection well; the lower part gives the development with injection time for three probes in that cross section. The comparison between measured and computed values appears to be quite satisfactory.

5. RESULTS

In order to illustrate the typical nature of the nearfield configuration, Fig. 4 shows velocity and temperature distributions as calculated by the numerical model for one example case. It was assumed that warm water of 17.5° C is discharged at a rate of 7 m^3/h into groundwater with a natural temperature of 10° C. The aquifer has a thickness of 50 m and a natural groundwater Darcy velocity of 0.046 m/day. For this situation, the relevant dimensionless parameter are:

relative infiltration rate	Q^*	=	1.2
relative buoyancy	B^*	=	1.5
Rayleigh number	Ra	=	76

The figure shows a section in flow direction through the infiltration well and two cross sections, the first one through the well and the second at a distance of twice the aquifer thickness downstream. In all sections the development of a temperature stratification can be recognized. Furthermore, the cross sections show the development of convection rolls with axes in flow direction along both sides of the discharge, which enhance lateral spreading greatly.

Complete numerical calculations have been performed for the following parameter combinations:

Run No.	Q^*	B^*	Ra	Run No.	Q^*	B^*	Ra
1	1,5	0,8	43	5	1,7	0,4	22
2	0,9	2,1	109	6	3,9	0,7	43
3	0,4	5,9	296	7	3,3	1,8	108
4	0,5	3,8	193	8	1,2	1,5	76

The shape of the resulting temperature nearfield is given in Fig. 5; these block diagrams are vertically distorted by a factor of 2. The plot clearly shows the dependence of the temperature field on the parameters Q^* and B^*. Buoyancy effects are dominant for large relative buoyancy B^* and small relative infiltration rate Q^*; in some cases the discharge does not even penetrate to the bottom of the well. For large relative infiltration rates Q^* and small relative buoyancy B^* on the other hand, the distortions of the temperature field due to buoyancy become secondary.

The values of the Rayleigh number Ra were in all cases large enough to render vertical heat conduction and mixing small in comparison to the other effects. From an extrapolation of model test results, it can be assumed that vertical mixing and heat conduction overrides the development of thermal stratification when the Rayleigh number approaches the order of magnitude of one.

The calculations and experiments have been performed for positive temperature differences, relating to the case of warm cooling-water discharges. The case of negative temperature differences, as it applies to heat pumps, can be treated in analogy as the "upside down" version of these calculations.

6. EFFECTS ON FARFIELD

The development of thermal stratification due to buoyancy effects in the nearfield can have drastic consequences for the development and extent of a thermal anomaly as a whole. In a stratified flow situation, the heat is spread and transported much faster than under fully mixed conditions. Furthermore, the vertical temperature distribution is determined by these effects. The vertical temperature gradients, on the other hand, are governing the vertical heat exchange through the top layers to the atmosphere and to the lower geologic formations. Since in the farfield these heat exchange processes finally determine the extent of the thermal anomaly, nearfield buoyancy effects may markedly influence the entire temperature field.

Natural aquifers usually exhibit a layered geological structure with variations in permeability, inhomogeneities and often anisotropy with usually smaller permeabilities in the vertical direction as compared to the horizontal. These effects may have a marked influence on the horizontal spread of the temperature field; they tend to increase mixing and to decrease the relative importance of the buoyancy effects.

7. CONCLUSION

The results of the numerical and experimental investigations show clearly that discharges of water with temperature differences lead to buoyancy-induced changes of the flow and temperature field near the injection well. The relevant parameters of well discharge and aquifer characterizing these effects have been identified. The results show at which parameter combinations (relative discharge, relative buoyancy and Rayleigh number) stratification is important or vertically mixed conditions throughout the aquifer are to be expected. The results give a tool for an estimation of the extent of temperature anomalies and thus provide an aid in groundwater management as well as a prerequisite for underground heat-budget considerations.

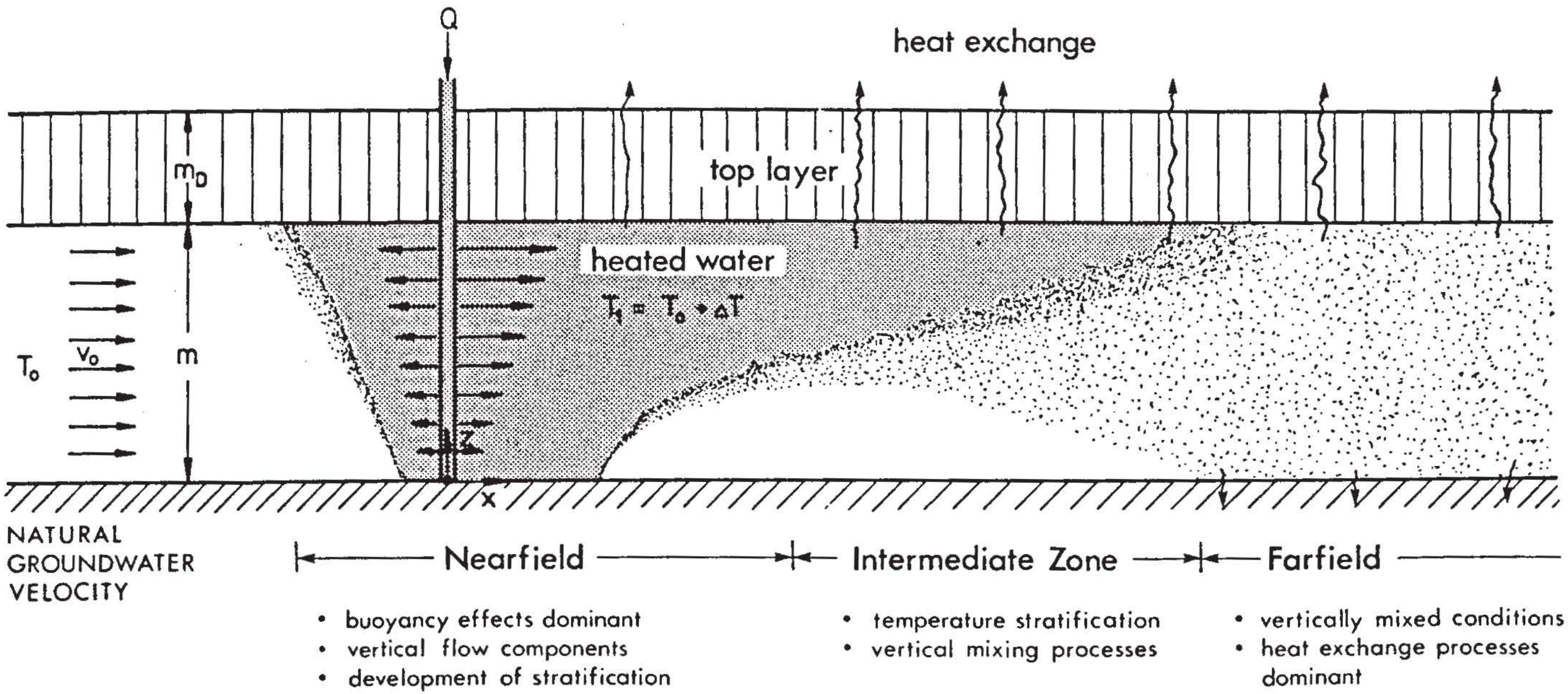
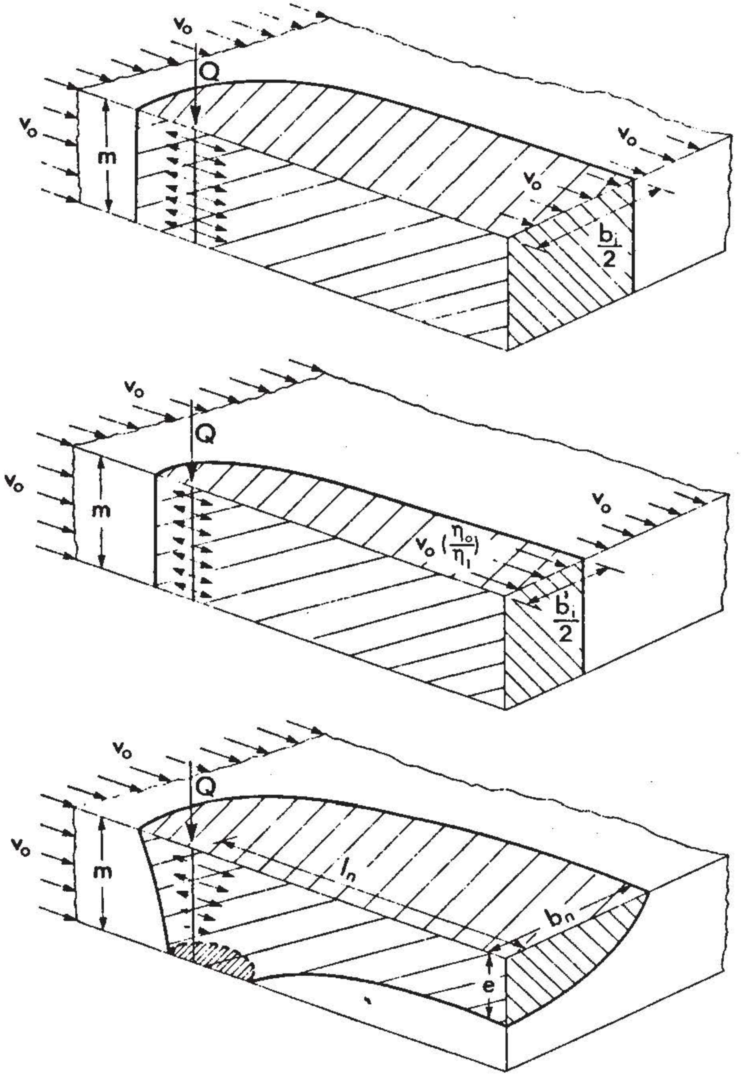


Fig. 1: Definition sketch for infiltration of heated water into an aquifer



discharge without temperature difference ($\Delta T = 0$):

infiltration width : $b_i = \frac{Q}{v_o m}$

discharge with temperature difference ΔT; mixed conditions:

temperature - corrected infiltration width

$$b_i' = \frac{\eta_1}{\eta_o} \frac{Q}{v_o m}$$

discharge with temperature difference ΔT; stratified conditions:

stratified temperature field characterized by: l_n ; b_n ; e

Fig. 2: Temperature nearfield under mixed and stratified conditions

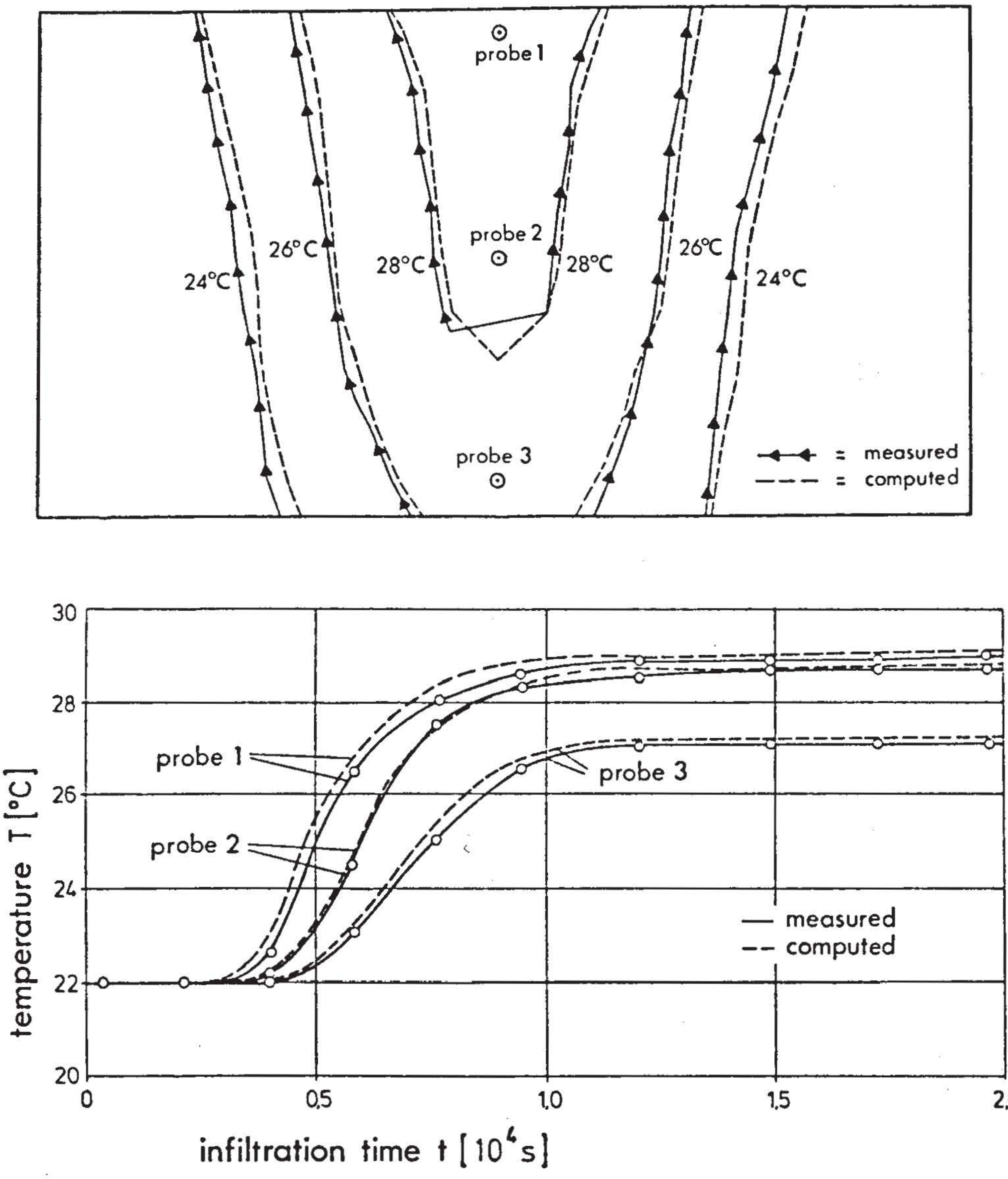


Fig. 3: Comparison of measured and computed temperature field

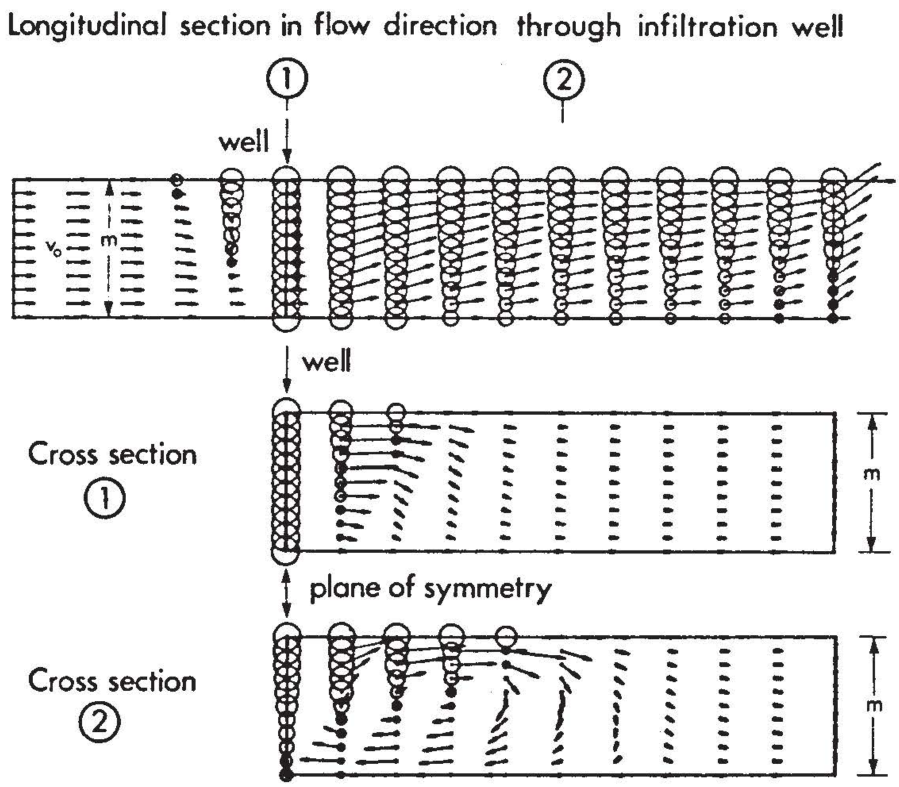


Fig. 4: Example of flow and temperature field ($Q^*= 1.2$; $B^*= 1.5$; Ra=76)

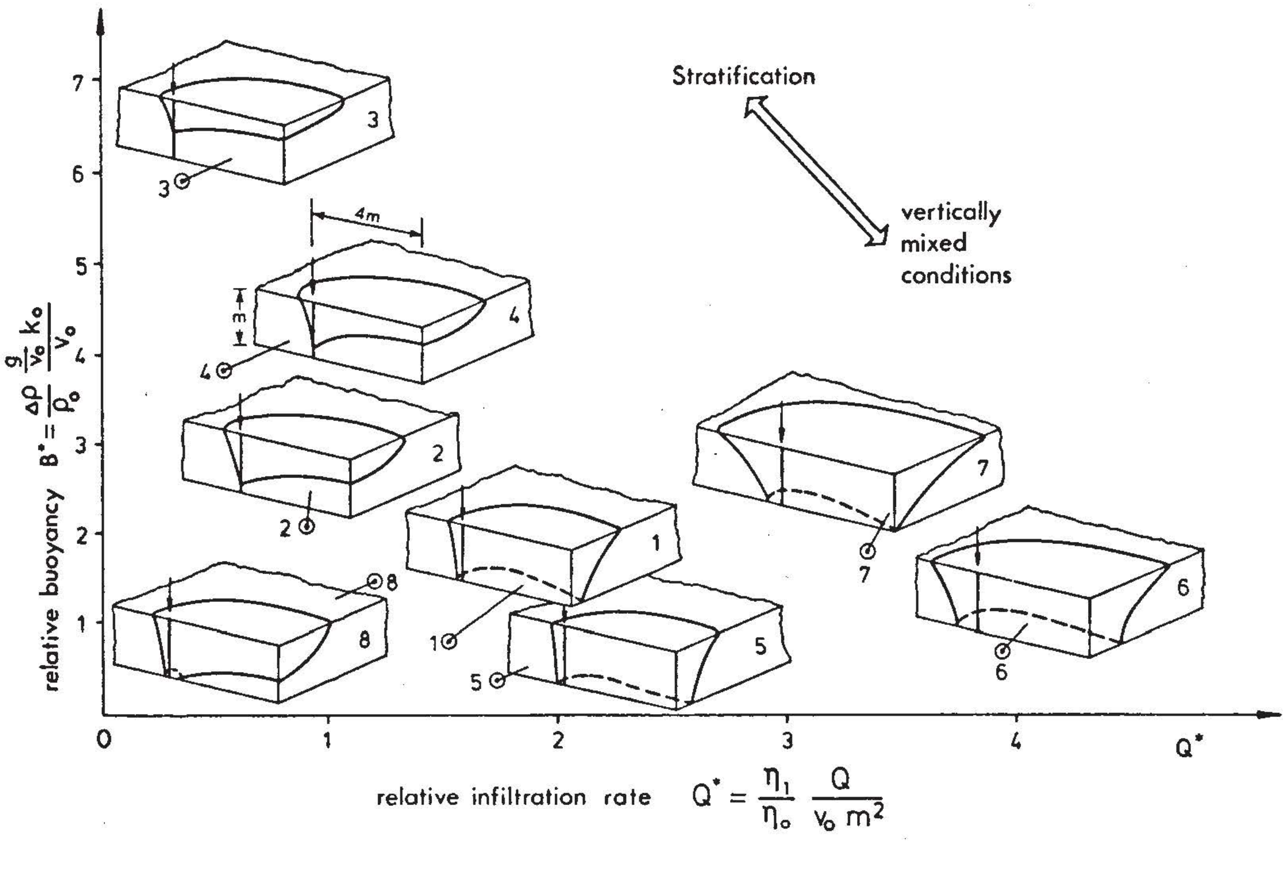


Fig. 5: Shape of temperature field as a function of relative infiltration rate and relative buoyancy

LIST OF SYMBOLS

b_i	[m]	=	$Q/(v_o m)$ = infiltration width
c, c_w	$[J/(m^3.K)]$		specific heat of saturated soil, of water
g	$[m/s^2]$	=	gravitational acceleration
k_o	$[m^2]$	=	permeability
m	[m]	=	thickness of aquifer
n	[-]	=	porosity
p	$[N/m^2]$	=	pressure
t	[s]	=	time
v_f, v_o	[m/s]	=	Darcy velocity, natural groundwater velocity
D	$[m^2/s]$	=	$\lambda/(\rho c) + \alpha \left\lvert\frac{v_f}{n}\right\rvert$ = dispersion tensor
Q	$[m^3/s]$	=	infiltration rate
T, T_o, ΔT	[K]	=	temperature, of groundwater, temperature difference between infiltration and groundwater
α	[m]	=	dispersivity
ρ, ρ_0, $\Delta\rho$	$[kg/m^3]$	=	density, of groundwater, density difference between infiltration and groundwater
η_0, η_1	$[kg/(m \cdot s)]$	=	dynamic viscosity of groundwater, of infiltration water
ν_0, ν_1	$[m^2/s]$	=	kinematic viscosity of groundwater, of infiltration water
λ	$[W/(m \cdot K)]$	=	heat conductivity

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