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USAGE OF EXISTING DEEP BORE - HOLES AS HEAT EXCHANGERS

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SUMMARY

Preliminary technical analysis has been shown in this paper. It concerns Polish deep bore - holes allowing to utilize geothermal energy as heating power. In order to attain an aim via numerical methods an algorithm has been created. It allows to estimate machinery service parameters. The problem has been solved in three-dimensional space.

LABEL INDEX

ρ	- density
τ	- time
α	- convectional heat exchange coefficient
λ (λ_x, λ_y, λ_z)	- thermal conductive coefficient (along reference system axes)
$\Delta\tau$	- time interval step
Ω, Γ	- capacity and edge of the modelled zone
Ω_e, Γ_e	- capacity and edge of an element
A_{ij}	- coefficient matrix
Bi	- Biot's criterial number
B_i	- free term matrix
c	- specific heat
d	- diameter
H	- modelled zone height
h_i	- exchanger zone height
N	- form function
Q', Q"	- the balanced zone inlet and outlet heat
Q_{a1}, Q_{a2}	- heat gathered inside a slot and inner tube
q_{slo}	- sun radiation stream density on an Earth parallel surface
q_v	- inner heat source power
r	- radius
t, T	- temperature, temperature matrix
V	- voluminosity

Bottom indexes:

1, 2, 3	- inner tube, insulating tube, external tube
i, j	- exchanger zone or an element number
i1, i2	- insulation surface of inner tube and slot sides
w (w1, w2)	- water (inside slot and inner tube)
z	- deposit

INTRODUCTION

In Europe there have been already working installations that use deep bore-holes as heat exchangers. The latter allows to utilize heat energy gathered in rock formations. The above field world leader is Switzerland that exploits about 6 000 such exchangers (Rybach et al., 1995). In spite of such item worldwide use Poland hosts no installation like that. The paper basic aim was to create operating parameter method for vertical heat exchangers using heat energy accumulated in rock formations (working under Polish geothermal conditions).
In order to attain the above a usage of existing deep bore - holes was analyzed. This assumption should significantly reduce costs of the task. It allows also to base deliberations on particular data obtained while investigation that was exercised during the hole boring.

Among miscellaneous practical applications a significant place is hold by vertical heat exchanger erection based on the Field exchanger schema (Kraft and Wetzel, 1997), (Rybach et al., 1995) (Fig. 1)

The exchanger consists of two coaxial tubes of different diameter. The colder inlet water, having t'_{w1} temperature flows through the slot between pipes and gathers heat furnished by deposit Q_z (Fig. 2) and insulating layer Q_{i1}. Flowing through the exchanger length and recuperating heat water reaches a bottom where external tube is blinded however inner tube is opened. Warmed water flows into the inner pipe and is pumped to the surface. Water speed inside inner pipe is augmented due to lessened active flow surface. Also the heat recuperation coefficient is high. The inner tube water has higher temperature than slot water and gives back heat Q_{i2} getting colder at a particular depth. Because of that exchanger outlet water temperature should be as high as possible the latter process ought to be disturbed. One of the methods that could be implemented in the task is insulating the inner tube. The insulation implementation causes a flow cross-section and slot water flow speed augmentation. It does influence the deposit heat recuperation intensity increase.

It should be remembered that flow resistance increases proportionally to the flow speed second power. The increased value forces high power pump usage. It augments the exchanger's operative costs. While exchanger exploitation a phenomenon of deposit coolness in the neighbourhood appears. It drives to the gradient of temperature between the deposit and slot water stream decrease. As consequence of the mentioned phenomenon the exchanger thermal power decrease reveals during exploitation. Basing on the operation data it was found out that thermal influence zone is usually less than 10 m (Rybach et al., 1995).

METHODOLOGY DESCRIPTION

A heat exchange in deposit and insulating layer between cold and warm water is described by following differential equation (Kenneth et al., 1995):

$$c\rho\frac{\partial t}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial t}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial t}{\partial z}\right)+q_v \qquad (1)$$

Differential equation (1) is solved numerically through *finite element method* (FEM).
To simplify mathematical description the system was divided into three elements: deposit (where heat is accumulated), insulation layer between running water slot and inner tube

water, and vertical heat exchanger. High values of *Biot`s number* (Bi > 0.1) for insulated inner tube force to consider an insulation influence of heat exchange between slot water and inner pipe water.
The process model was constructed with following assumptions:

- the process character is linear, it means that thermal conductivity coefficient values, specific heat and deposit substance density and insulation density, are not, in the certain time interval $\Delta\tau$, a temperature functions however they can vary in subsequent time steps,
- in the considered time interval $\Delta\tau$ a temperature change in a certain space element Ω_z and Ω_i runs linearly,
- the model does not consider water transfer (neither gas nor liquid phase) inside the modelled Ω_z and Ω_i zone and its influence to the heat exchange.
- a phase transformation heat of rock formation structure water has been omitted,
- a heat exchange influence of snow and grass covered contact surface between Ω_z zone and atmosphere has not been considered,
- a Field exchanger is treated as an object of sectionally concentrated parameters and ideal water mixing in every exchanger section is assumed,
- no liquid movement caused by density difference inside exchanger is considered.

Profiting of the above assumptions undefined heat exchange three-dimensional problem might be described by equation (Malinowski, 1996):

$$K_{ij}(\tau)T_j(\tau) + C_{ij}(\tau)\dot{T}_j(\tau) = G_i(\tau) \tag{2}$$

Assuming the linear temperature change in the time interval $\Delta\tau \in (\tau,\ \tau+\Delta\tau)$ and using *Galerkin formulation* a following algebraic equation system is obtained:

$$A_{ij}(\tau)T_j(\tau+\Delta\tau) = B_i(\tau) \tag{3}$$

where:

$$A_{ij} = \int_{\Omega_e}\left(\lambda_x\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + \lambda_y\frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y} + \lambda_z\frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}\right)dV + \int_{\Gamma_e}\alpha N_i N_j dS \tag{4}$$

$$B_i = \int_{\Omega_e} q_v N_i dV - \int_{\Gamma_e} qN_i dS - \int_{\Omega_e} c\rho N_i \sum_{j=1}^{NP}\left(N_j\frac{\partial T_j}{\partial\tau}\right)dV \tag{5}$$

An equation system (3) allows to estimate temperature distribution in the deposit and insulation layer in the next time step. It is solved by *Gauss elimination method*.

The *boundary conditions* were forced according to (Fig. 1). *Primary condition* estimation is executed by deposit and insulation layer temperature distribution determination using a modeled hole thermal profiling curves (if there are no such ones one can use neighboring hole curves).
An exchanger is divided into finite section number, considered as discrete elements. Inside sections an ideal water mixing is assumed.
Preparing an energy balance for i-ic exchanger section in a certain time interval $d\tau$ following equations are gotten:

- for an intertubular slot

$$dQ_z(\tau)_i + dQ_{i1}(\tau)_i + dQ'_{w1}(\tau)_i = dQ''_{w1}(\tau)_i + dQ_{a1}(\tau)_i \tag{6}$$

- for an inner tube

$$dQ'_{w2}(\tau)_i + dQ_{i2}(\tau)_i = dQ''_{w2}(\tau)_i + dQ_{a2}(\tau)_i \tag{7}$$

A solar radiation influence on the heat exchange on Earth surface was considered by including a second class boundary condition (Fig. 3) where q_{slo} indicates solar radiation stream density reaching the surface parallel to the Earth. The second class boundary condition, considering a geothermal energy stream reaching the bottom of the modeled zone Ω_z, was determined as depending on the hole localization.
Basic material constant data determining particular lithologic layers of modeled exchanger profile (specific heat, thermal conductivity coefficient, density) was taken out of papers (Plewa, 1988), (Plewa, 1994) and (Polish Standard - PN, 1981).
An important parameter involved in an exchanger application pay - off is energy amount used by circular pumps forcing water flow in the operating system. Operating data of existing installations prove that by a little stream of sufficiently cooled water let into an exchanger the latter can work without any circular pumps (Kraft and Wetzel, 1997).

EXEMPLAR CALCULATION RESULTS

The described algorithm was used to determine operating parameters of vertical, Field class heat exchanger. The latter was modeled using data from already existing hydrogeological hole WM-D in Skierniewice (geographic coordinates: longitude 20° 07’ 55” latitude 51° 58’ 02”). The hole was bored by Hydrogeological Company. The data was taken from Hydro Bank. The hole reached 645 m of depth in bottom Cretaceous deposit boring through Quaternary, Tertiary and upper Cretaceous formations.

The present deliberation aims to estimate exchanger thermal power and warmed water temperature for primary service period. Forced water temperature 6 °C and operating stream value 10 m^3/h were assumed.

Fig. 4 displays a lithological profile and basic geometric dimensions of the exchanger. In the modeled exchanger, beside insulating layer between inner tube and intertubular slot, an external tube insulation was concerned. Insulating layer was used in the atmosphere influence zone that could (in wintertime) cause forced water additional chill.

It has been evaluated that in case of 6 °C water forcing it is purposed to use the insulation down to about 5 m below the ground level. Below the mentioned depth ground temperature is already higher than forced in water and equals to about 7 °C (Pajak and Malinowski, 1998) with simultaneous insignificant year changes (standard deviation of year average soil temperature at 5m depth equals to 0.7 °C) (Pajak and Malinowski, 1998). Thermal features of insulating material are identical for all the system and refer to inorganic insulating materials (Recknagelet al., 1994) (λ=0.2 W/mK, ρ=200 kg/m^3, c=1 kJ/kgK).
Geothermal heat stream density was determined in accordance with paper (Plewa, 1988) and amounts 68 mW/m^2. Thermal features of particular formation were found on base of (Plewa, 1988), (Plewa, 1994), (Polish Standard - PN, 1981) and were assembled in Tab.1 (Fig. 4.).
Modelling time interval includes atmospheric data of heating season 1997/1998.
Calculation result for the above is displayed by Fig. 5 and Fig. 6.

For Skierniewice WM-D hole exchanger exploitation analysis was run (an option without internal pipe insulation and circular water stream increase). Modeling period was lengthened to three heating seasons: from 1st Nov. 0001 till 30th Dec. 0004.
The calculations involved two device operating modes:

a) exchanger service while heating period (1st Nov. – 1st Apr., forced water stream of 20 m^3/h, temperature 6 °C) and idle mode in summer time (the rest of the year),
b) heating service mode - winter time (1st Nov. – 1st Apr., forced water stream of 20 m^3/h, temperature 6 °C) and air conditioning in summer time (1st June – 1st Sep., forced water stream of 10 m^3/h, temperature 30 °C).

This option exchanger power distribution chart as exploitation time function is shown by Fig. 7.
Calculation results in no inner tube insulation option are displayed by Fig. 7 - Fig. 11.

CONCLUSIONS

In this paper shown schema of service parameter determination in vertical heat exchangers allows to consider a broad spectrum of factors that occur, beginning from the exchanger parameters (geometric dimensions, physical features of constructing materials) through deposit parameters (rock formation heat features), atmosphere conditions and local geothermal conditions. The model allows to consider deposit and constructing materials physical characteristics anisotropy and their fluctuations in the time.
Consideration in equation (1) of term involving inner heat source power allows to consider radiogenic heat generation. It might have been important in case of deep exchangers.
Algorithm application allows to model exchanger heat close zone natural regeneration (while exchanger idle time during summer) and artificial (usage in air-conditioning installations) and its influence upon heating period exchanger exploitation.
It is worth to mention that the model is adaptable to exchangers of different construction. Due to implemented solutions it will require only few changes in a module responsible for device heat exchange with no further transformations in deposit heat exchange describing procedures.

The results obtained in the calculative example prove a radical exchanger power decrease in the service beginning (Fig. 5, 7, 8). Temperature interval that will be reached by heated water makes it useful as bottom source for compressor heat pumps. Exchanger thermal influence range (defined as length where temperature field in the exchanger neighborhood is changed by 1°C relatively to the deposit of no heat exploitation) was at 445 m depth about 7 m long (Fig. 10, 11). By following seasons the deposit temperature decreased around the exchanger (Fig. 10, 11). It proves that during idle time the deposit temperature field does not restore.
Accepted deposit heat energy accumulation schema and exchanger service one allow significant power increase only at the beginning of a heating season (Fig. 8). The effect might be more promising in real system deposit exploitation. It is owing to the fact that the aim of the above deliberations was to determine a maximal exchanger power. In the reality we deal with power demand accommodation of exchanger connected customers. A receiver maximum power demand occurs in top heating season, it means December, January and February. Fig. 8 reveals that exchanger proposed in second calculative option furnish about 25 kW of power in this period. So when choosing a heating system (with no top demand aid) such customer can be connected whose top demand will be covered with furnished power. By the above an exchanger exploitation will run uniformly, that should effect an improvement of consequences caused by deposit heat accumulation and spread them in time, generating the exchanger heat power increase by the end of the heating season.
Inner tube insulation application effects higher temperature reached by exchanger heated water (Fig. 6, 9) causing effective power increase. A higher water temperature effects heat pump work effectiveness positively as they use exchanger warmed water as heat energy source.
The highest exchanger warmed water temperature increase, for data from calculative examples, occurs in the beginning (upper) part - Fig. 6 and 9. Fig. 6 proves insignificant temperature decrease of inner, insulated tube water running up to the surface. It witnesses a proper choice of insulation separating inner pipe from the slot.

The results of calculations run by the author as well as experimental data (e.g. (Clauser, 1997), (Rybach et al., 1995)) allow to conclude that under Polish conditions erection of vertical heat exchanger that uses geothermal energy might be profitable only on the base of already existing deep bore-holes (due to temperature range and possible thermal power). This statement's main reason is deep hole boring high cost.
The above utterance does not involve shallow (down to 90 m) vertical heat pump collectors that in fact use solar radiation energy accumulated in the ground and might be erected by method different from boring.

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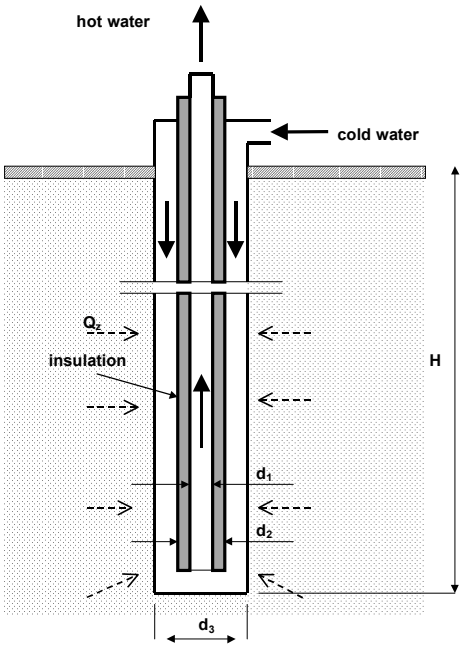


Fig. 1 General vertical heat exchanger framework that use geothermal energy

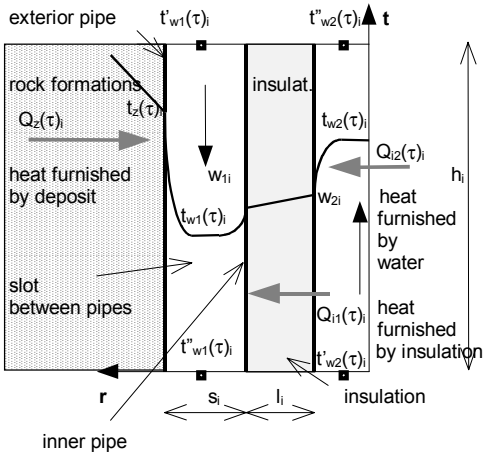


Fig. 2 Schema of heat exchange in the exchanger zone

(1981) *Polish Standard* PN-81/B-03020

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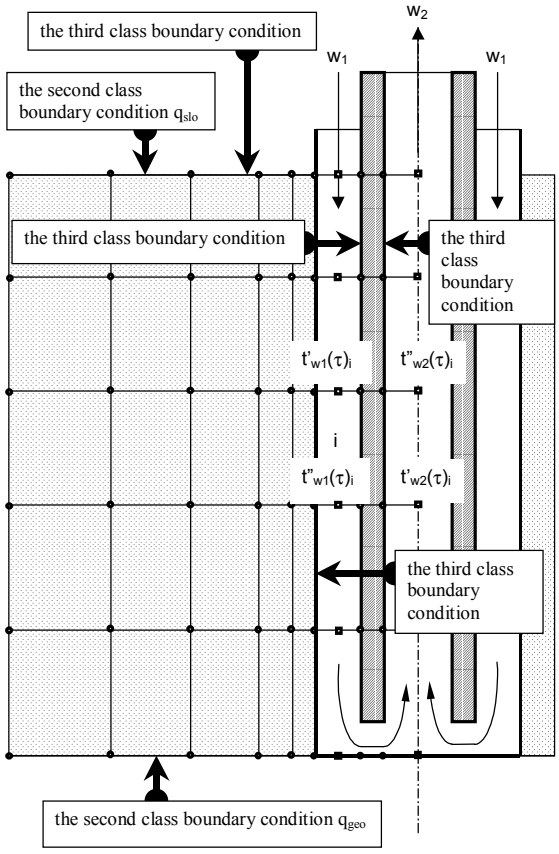


Fig. 3 Schema of boundary conditions determination and exchanger division into sections

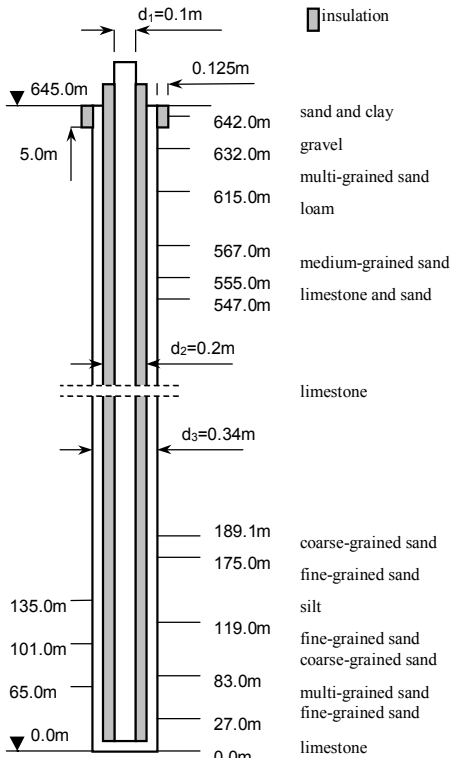


Fig. 4 Geometry and lithology of the exchanger based on WM-D hole in Skierniewice

Table 1. Thermal properties of geological layers

Name	λ [W/mK]	ρ [kg/m^3]	c [kJ/kgK]
loam	0.90	2720	0.50
silt	1.50	2600	0.79
fine-grained sand	1.50	1650	2.00
sand and clay	1.30	1600	2.00
coarse-grained sand	0.80	1500	1.20
multi-grained sand	0.93	1500	1.50
medium-grained sand	0.93	1650	1.50
limestone	2.50	2600	0.84
limestone and sand	2.30	2550	0.84
gravel	0.93	1700	1.50

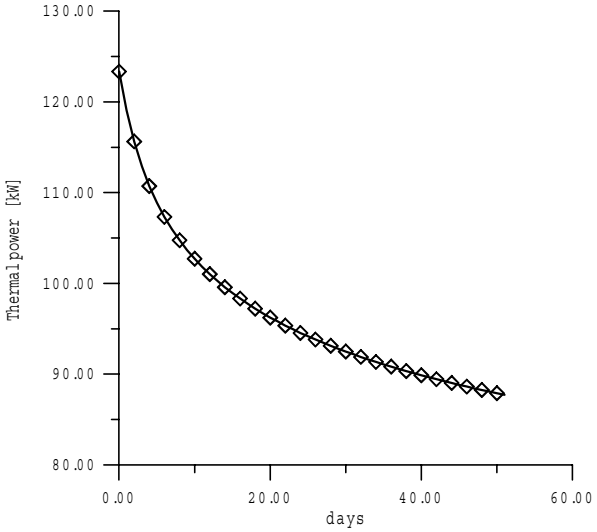


Fig. 5 Exchanger heat power change while exploitation

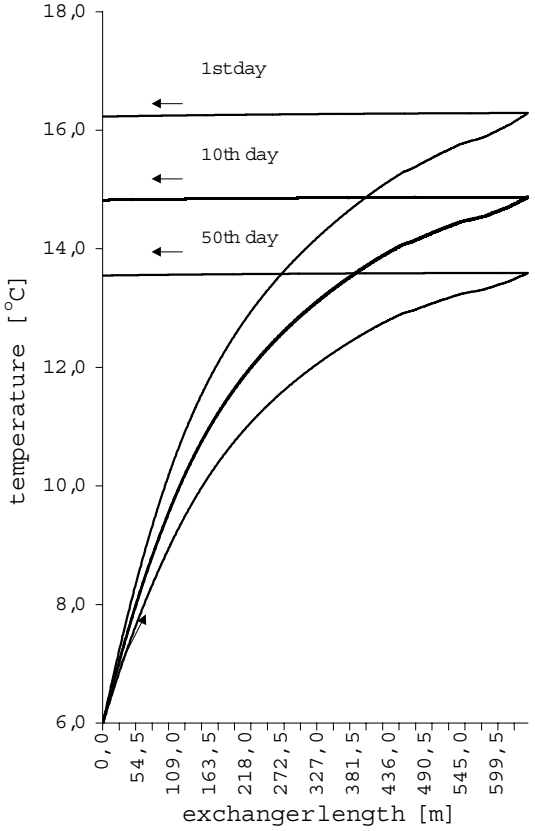


Fig. 6 Exchanger water temperature change while exploitation

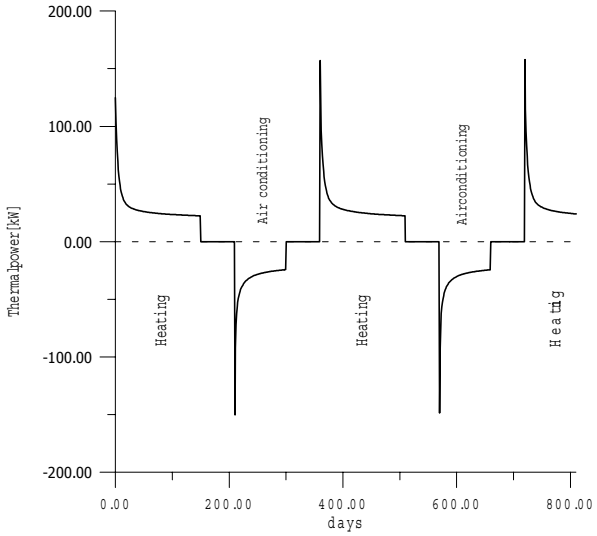


Fig. 7 Exchanger power distribution in time

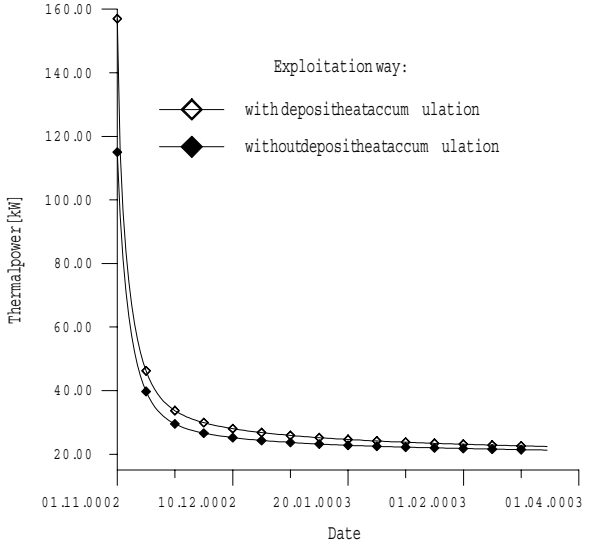


Fig. 8 Heating power assembly while second heating season

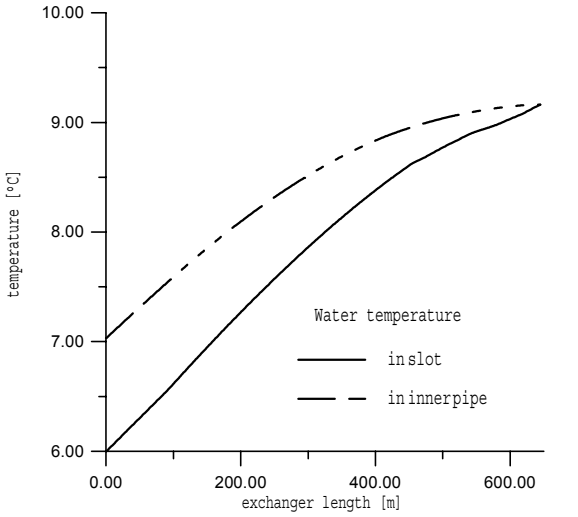


Fig. 9 Exchanger water temperature distribution as option of deposit heat accumulation without inner tube insulation on 1st Apr. 0004 (the end of the third heating season)

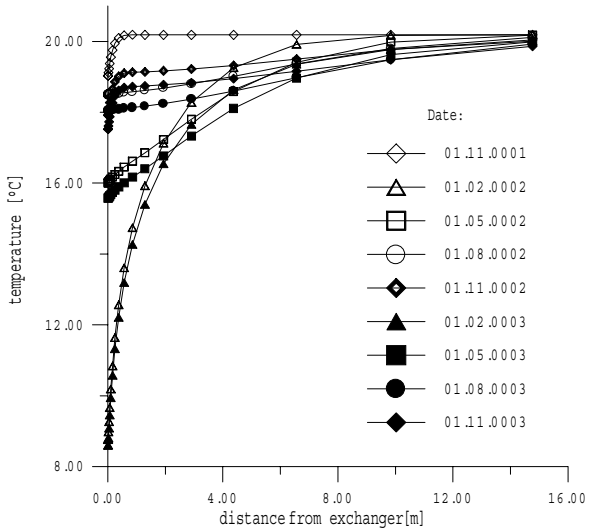


Fig. 10 Deposit temperature distribution as option of no deposit heat accumulation without inner tube insulation at 445 m depth below the ground level

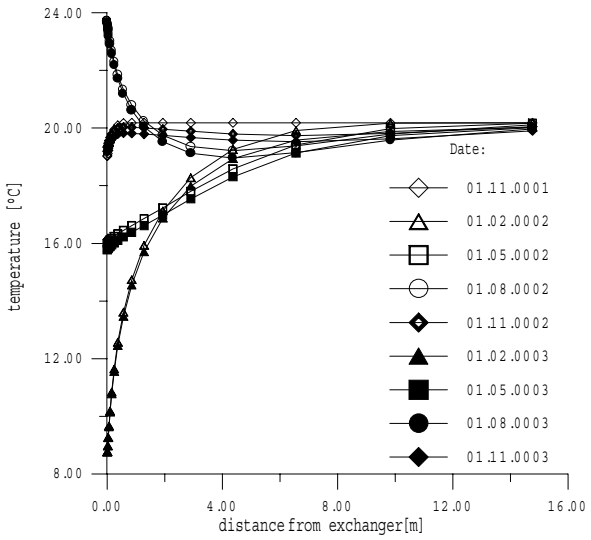


Fig. 11 Deposit temperature distribution as option of deposit heat accumulation without inner tube insulation at 445 m depth below the ground level