Comparison of Borehole Heat Exchangers (BHEs): State of the Art vs. Novel Design Approaches

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Abstract: The efficiency of borehole heat exchangers (BHEs) for geothermal purposes depends not only on material properties but also on their geometrical design. These days most used design consists of two parallel arranged U-shaped pipes which are embedded in a high-conductive shell filling out the borehole. Another common design is a pipe inside of another pipe, with fluid flowing down inside and up outwards (coaxial design). These two are compared to a new design approach consisting of a down flow pipe surrounded by six (twelve) up flow pipes, promising a better efficiency because of the larger surface compared to the double U pipes. All four designs are calculated with COMSOL Multiphysics using symmetries and numerical simplifications. The results show that the new design approach is indeed more efficient than the common designs.

Keywords: borehole heat exchangers, geothermal energy, heat transfer in porous media

1. Introduction

The high heat conductivity and elevated temperature of the subsurface in winter season is used by borehole heat exchangers to run heat pumps. The efficiency of the heat exchangers depends on the material, but also on design parameters which define the contact surface to the underground. There are two conventional designs used in most geothermal units.

There are several COMSOL Multiphysics studies about the common U pipe design. One example is the work of Acuña *et al.* [1] which is about the optimal position of the pipes in the borehole. Zanchini *et al.* [2] evaluated thermal response tests which are an essential tool in the field of geothermal energy. Here, COMSOL Multiphysics is used to compare and maximize the performance of three different heat exchangers, the two more or less conventional designs and a novel approach.

2. Geothermal Heat Exchangers

A typical heat exchanger for geothermal applications consists of two U pipes made of HDPE (High-Density-Polyethylene) and arranged parallel in the borehole which is filled with highly conductive material. A common fluid for heat transport within the pipes is water, sometimes with additional substances in order to rise the heat capacity and/or lower the freezing point. The usage of two pipes increases the effective contact surface. Another design is the coaxial pipe which consists of one centred down flow pipe embedded inside a bigger up flow pipe. Figure 1 shows the different designs.

One new developed type is the "Terra Umweltsonde" [3] consisting of a centred and insulated (down flow) pipe which leads into six surrounding (up flow) pipes. This configuration comes up with approximately 1.25 times more surface for heat exchange compared to the double U pipes, promising a more efficient operation at comparable flow rates. Another version of this design comes up with twelve up flow pipes, leading to even higher contact surface. This approach is already in use in Sweden. The exact relations between the different heat exchanging surfaces are shown in Table 1. One would assume that a higher surface correlates with higher efficiency.

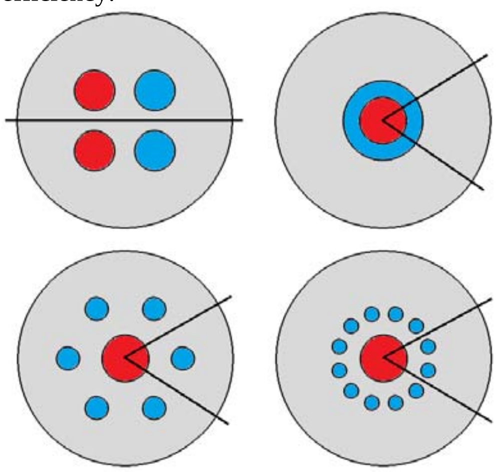

Figure 1. Cross section of four models. Colors show flow directions (red: inflow, blue: outflow); Black lines show implemented symmetry planes.

Table 1: Relative (to Double U) heat exchanging surfaces with and without isolated parts of the Terra pipes

Design	*Rel. Surf.*	*w/o Isolation*
Double U	1	-
Coaxial	0.492	-
Terra_6	1.25	0.936
Terra_{12}	1.625	1.313

High efficient BHE are characterized by a low thermal resistivity. This is important for the dimension of the borehole and so for the costs of a geothermal facility. It becomes even more important when the BHE is coupled with a solar heating system, for example for recharging the underground ambient temperature in summer.

3. Governing Equations

3.1 Heat Transfer in BHEs

There are several possible ways to create BHE models. The direct way would be to calculate the flow inside the pipes and couple this by temperature *T* with heat transfer in the geological environment. But as the length-thickness-ratio of a 70 m BHE is about 1/100, it is obvious that a fully coupled transient Navier-Stokes flow calculation is impossible or at least very drawn-out. A more efficient way to calculate the heat exchange is to assume a mean velocity in the pipe and to calculate an effective thermal conductivity of the tubes as the inverse sum of the wall conductivity and the heat transition from wall to fluid. The inverse effective conductivity then becomes

$$k_{1,eff}^{-1} = k_{HDPE}^{-1} + k_{transition}^{-1} = \frac{1}{h \cdot r_i \cdot \log\left(\frac{r_o}{r_i}\right)} + \frac{1}{k_{HDPE}},$$

with r_i, r_o as inner and outer radii of the tube and h as the convection coefficient which is typically quantified as

$$h = \frac{Nu \cdot k_w}{r_i}.$$

The Nusselt number Nu is an unknown parameter here. Depending on the flow regime in the tubes, there are estimated correlations between the Rayleigh, Prandtl and Nusselt numbers. In this case, $Nu = Nu(\mathrm{Re}, \mathrm{Pr})$ is calculated according to the Churchill-Bernstein correlation [3]

$$Nu = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left(1+(0.4/\mathrm{Pr})^{2/3}\right)^{1/4}} + \left(1+\left(\frac{\mathrm{Re}}{28200}\right)^{5/8}\right)^{4/5}$$

which gives usable values of Nu for a wide range of Re, Pr (as long as $\mathrm{Re}\cdot\mathrm{Pr} \geq 0.2$).
Finally, the effective conductivity depends on constant parameters and on the mean flow velocity.

3.2 Heat Transfer in Subsurface

Here, attention is turned on the comparison of the different BHE designs. Thus, the subsurface is assumed to be homogeneous, without any ambient flow or hydraulic head gradient. The heat transport is described by the heat transport equation. Since the porous media consists of two phases, solid material and water, it constitutes an effective heat conductivity for the two phase system, too. It depends on the volume fraction or porosity θ_s of the solid material:

$$k_{2,eff} = \theta_s k_s + (1-\theta_s) k_w$$

Effective parameters are also estimated for density and heat capacity at constant pressure. They are given in Table 2.

4. Use of COMSOL Multiphysics

Implementation of the models in COMSOL Multiphysics is done in version 4.2. All models are 3D to be able to add non-homogeneous ambient flows and parameter variations in later applications. Thus, to reduce calculation time and save RAM-space, symmetry planes are used. This reduces the number of grid points to 1/2 in the double U and 1/6th in the other three cases. Figure 1 shows the arrangements of the BHE types and the symmetry planes in a 2D cross section.

Physical mode *heat transfer (ht)* in three different ways is used; *heat transfer in porous media* for the subsurface, *heat transfer in solids* for the borehole (grey parts in Fig. 1) and *heat transfer in fluids* inside of the BHEs. Here, heat transporting fluid is water with temperature dependent parameters.

4.1 Geometry and Meshing

All four models consist of long, thin geometries. In those cases, free meshing is inefficient and even impossible. Thus, the mesh is created by adding free triangulars on the top surface and distribute them to the bottom surface using swept mesh. Highest gradients in temperature (or Darcy flow) are suggested in horizontal directions, so the vertical distribution can be coarser.

4.2 Boundary Conditions and Solvers

Fluid of 0°C is injected by adding a velocity in *z*-direction. The changeover of fluid from a down flow to an up flow pipe is realized by taking the mean temperature of the cross section and adding this as a temperature boundary condition for the up flow pipe.
The boreholes are surrounded by cylinders of large radius which form the geological ambient. Neumann conditions are used at the cylinder boundaries. The initial temperature field is determined by a common geothermal gradient:

$$\nabla T = T_0 + (-z) \cdot 0.03\,[K/m], \quad z \le 0$$

The problem is solved time dependent. It was checked that the chosen radius R is big enough to make influence of the boundaries negligible, at least in considered time scales.

4.3 Input parameters

Table 2 shows the parameters used in this study. All values are in a typical range for European subsurface conditions and BHEs. Parameters of the fluid (water) are implemented to be temperature dependent and taken from the COMSOL *material library*. The only exception is the thermal conductivity which is assumed to be very high to get a uniform horizontal heat distribution inside the BHEs (which would actually be measured in a real turbulent pipe).

5. Results

The performances of the BHEs are here compared by the mean outflow temperature T_{out} at equal conditions. Figure 2 shows the results of transient calculations, simulating all four BHE types for 5 hours with an in flow temperature $T_{in} = 0°C$, evaluating the evolution of T_{out}. In Figure 3 the performance is studied in dependence of the flow rate.

Table 2: Parameters used in this study

Properties of Ground		
Volume fraction	θ_s	0.75
Eff. thermal conductivity	$k_{2,eff}$	$2\,[W/(m \cdot K)]$
Eff. Density	ρ_{eff}	$2000[kg/m^3]$
Eff. Spec. Heat Capacity	$c_{p,eff}$	$1000\,[J/(kg \cdot K]$
Properties of HDPE-BHEs		
Double U	type	$32x2.9\,[mm]$
Coaxial (out)	type	$63x3.8\,[mm]$
Terra_6 (out)	type	$20x2\,[mm]$
Terra_{12} (out)	type	$14x2\,[mm]$
$\text{Terra}_{6,12}$, Coaxial (in)	type	$40x3.7\,[mm]$
Pipe length	l	$70\,[m]$
Therm. Conductivity	k_{HDPE}	$0.4[W/(m \cdot K)]$
Therm. Cond. Isolated Pipe	k_{iso}	$0.04[W/(m \cdot K)]$
Properties of Grout		
Therm. Conductivity	k_{grout}	$2\,[W/(m \cdot K)]$
Density	ρ_{grout}	$1680\,[kg/m^3]$
Spec. Heat Capacity	$c_{p,grout}$	$730[J/(kg \cdot K)]$

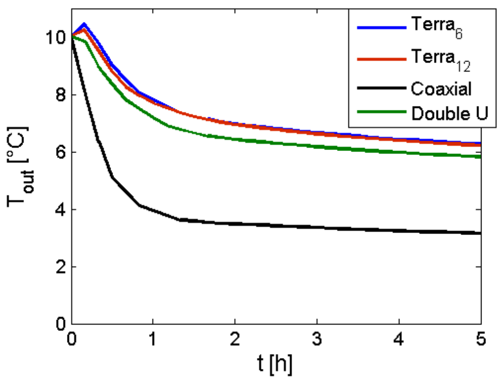

Figure 2. Time development of outflow temperature T_{out} at constant inflow temperature $T_{in} = 0\,[°C]$ for $Q = 10\,[L/\min]$

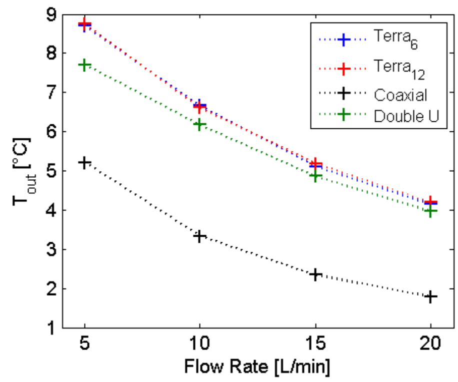

Figure 3. T_{out}-dependence on flow rate, $T_{in} = 0\,[°C]$.

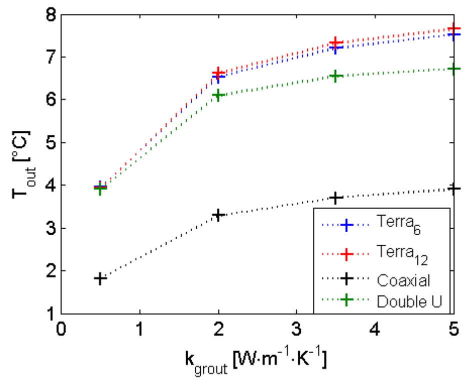

Figure 5. T_{out} for different thermal conductivities of the grout, after $t = 3\,[h]$, $Q = 10\,[L/\min]$

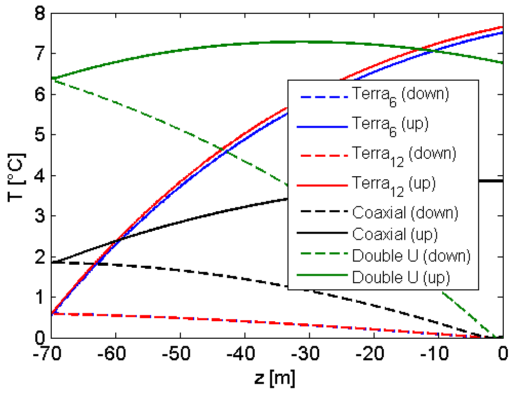

Figure 4. Temperature distribution in the center of the pipes along *z*-axis, after $t = 3\,[h]$, $Q = 10\,[L/\min]$.

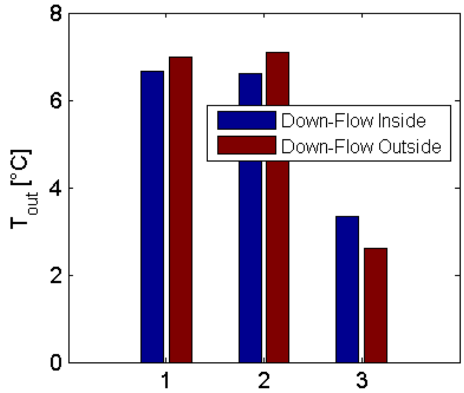

Figure 6. Conventional and inverted flow directions for 1: Terra$_6$, 2: Terra$_{12}$, 3: Coaxial, $t = 3\,[h]$, $Q = 10\,[L/\min]$.

5.1 Influence of Thermal Heat Bridges

One advantage of the new design is the isolated inner pipe. This feature reduces the effect of heat bridges between down and up flow pipes. The temperature of the fluid along the centers of the pipes is pictured in Figure 4. Figure 5 shows a comparison of the pipes in relation to a growing thermal conductivity k_{grout} of the borehole filling material. Increasing this parameter increases the effect of heat bridges.

5.2 Inverted Flow Direction

The flow direction is inverted to the system in Figure 1 to estimate its influence on the efficiency. This makes no sense for the double U pipe because it would not change anything as the U pipe is point symmetric to the borehole center.

The only possible change for it would be a crosswise operation, but this increases the heat bridge effect and is hence not recommendable. Figure 6 displays the difference of outflow temperature for the other three BHEs at both flow modes.

6. Conclusions and Discussion

The models show that the new design approach has a better performance than common designs. The reasons for this are the isolation of the downflow pipe and the bigger surface for heat exchange with the ambient. Figures 3 and 5 show that the better performance of the novel designs increases relative to the common ones when varying essential parameters. The Terra$_{12}$ design is not much better here than Terra$_6$. Experimental data (from Sweden) indicate that the performance of Terra$_{12}$ is much better than our results show. One reason for that could be that the boreholes for $Terra_{12}$ pipes in Sweden are usually filled up with water. This is only possible in granite subsurfaces and might affect convective heat exchange within the borehole, which was not considered in this study.

The reason for the better performance of the $Terra_{6,12}$ pipes is the isolation paired with surface advantages as it is obvious in Figure 4. The downflow branch of the pipes shows that they nearly keep their inflow temperature until reaching the bottom and profit by the strong temperature contrast leading to a high heat flux. The other two designs heat up much more on downward flow. Double U pipe reaches its temperature maximum at half depth of the borehole, it cools down again in the upper half. Coaxial pipe does not even heat up enough to lose much heat.

There is a noticeable worse performance of the coaxial design in all studied parameter variations. Practical experience with BHEs do not confirm these results. Field data of the coaxial pipes suggest that their performance is comparable to double U. There are two possible reasons for that: first, we did not consider all effects which might appear running the BHEs and some of the model simplifications could be fatal for the coaxial pipe. Second, the effective conductivity could be calculated not exactly enough. The other three designs are tubes while coaxial designs out flow branch is rather a bent slot, which might have an influence on the calculation of Reynolds and Nusselt numbers.

The influence of the flow direction on the performance is not too big here, as seen in Figure 6. Nevertheless, even small improvements can have a great benefit. Surprisingly, the coaxial pipe behaves contrary to the Terra pipes. At least it is recommendable to check a change of the flow direction in practical use of BHEs.

Further working with the models needs more experimental feedback.

The project objective is to simulate a field of three BHEs, embedded in a heterogeneous ambient. The long time behavior of such a field with implemented solar temperature recharge of the subsurface is one interesting research purpose which will be investigated in future work using the introduced models.

7. References

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8. Acknowledgements

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