Sub-surface Heat Rejection in Alternative Cooling Systems

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Abstract: During the operation of alternative cooling systems produced heat needs to be rejected. On option is to dissipate the heat into the sub-surface. This can be feasible under convenient temperature conditions only. Groundwater flow is an important element in considerations for the application of such a technique. Here we describe the set-up of a numerical model, using COMSOL Multiphysics®, which can be a useful tool to evaluate the possibilities and to design a system of sub-surface heat rejection.

Keywords: heat rejection, heat transport, borehole heat exchanger, coupled geometries

1. Introduction

In regions with hot climate air condition (AC) systems are one of the biggest consumers of electrical power. Power mainly stems from fossil sources. In order for societies to reach the goal of low-carbon consumption, as agreed upon in the Paris 2015 treaty, alternative cooling systems that do not rely on fossil energy, can thus deliver a major contribution. Absorption cooling systems utilize thermal energy to produce chill. Solar and thermal energy can be employed as low grade heat sources. No fluorocarbons (as in conventional refrigerants) are used in the process. Their coefficient of performance (COP) depends strongly on a chill source, for which the sub-surface is an option. Here we explore sub-surface heat rejection as part of an absorber system for residence house cooling.

The technical installation of a system for heat rejection is similar to a borehole heat exchanger (Oberdorfer *et al*. 2011). The most simple design is a pipe with U-turn. Another design is the so-called co-axial type, where small diameter inner pipe is inside an outer pipe. At the end of the pipe the inne pipe is open and connected to the annular space between inner and outer pipe. A cross-section through such a system is shown in Figure 1. The pipes, U-turn or co-axial are usually installed in a borehole.

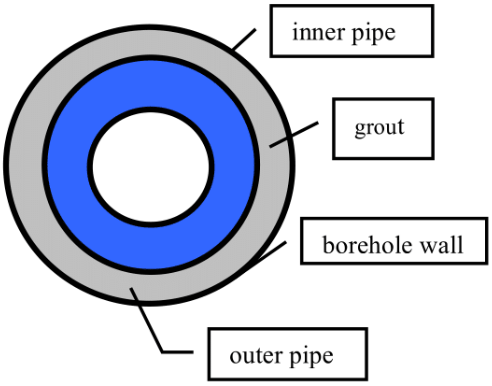

Figure 1. Sketch of cross-section through a co-axial heat exchanger

Water of elevated temperature enters at one pipe end at the ground surface. It in co-axial design in inlet is usually to the inner pipe. A fluid, usually water circulates through the pipes, while heat is dissipated. Returning water with a lower temperature can then be used in the cooling system, for example an absorber, above ground.

The task of simulating the entire system including downflow, U-turn, upflow and the connected grout and soil in a single model requires some simplifications. The major reason is, that different length and time scales are included that hardly match. For example for the heat simulation within the pipes the cm scale between the pipe center and its wall is highly relevant. For heat flux in the surrounding groundwater domain several 10th of m have to be considered. Although finite element codes nowadays are equipped with good meshing tools to combine elements of different size, there remain still limitations that simplifications of the model are required.

Here the pipe system itself is modelled by two 1D geometries, one geomery for downflow and one for upflow. The 1D models can be embedded in a 2D vertical cross-section or in a 3D model of the surrounding porous medium. In the simulations these different geometries are coupled. Details of the couplings are described below.

The presented approach is an improved version of research published by Oberdorfer *et al*. (2012) as well as Holzbecher & Räuschel (2014). Couplings have been improved due to novel options of the COMSOL Multiphysics software. Moreover in the model application we coupled to a 3D porous medium geometry, while former examples only dealt with the 2D case.

2. Model Set-up

2.1 Mathematical Description

In the presented approach the temperature T in the pipes is described by the 1D differential equation for heat transport:

$$(\rho C)_f \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left((\rho C)_f T v\right) = -\frac{\partial}{\partial x} \cdot \lambda_f \frac{\partial T}{\partial x} + j$$

with heat capacity of fluid $(\rho C)_f$, fluid thermal conductivity λ_f, flow velocity v and sinks/sources j. The different terms of the equation consider storage, advection, conduction and additional sinks or sources. The thermal regime in the ground is described similarly by the equation:

$$(\rho C)\frac{\partial T}{\partial t} + \nabla \cdot \left((\rho C)_f T\mathbf{q}\right) = -\nabla \cdot \lambda \nabla T$$

with specific heat capacity of the fluid-solid system (ρC), its thermal conductivity λ and groundwater velocity $\mathbf{q}$. In case of stagnant groundwater, the second term of the equation can be omitted. The equation is valid in 1D, 2D or 3D. In case of groundwater flow the hydraulics affects heat transport in the advection term via Darcy velocity $\mathbf{q}$:

$$\mathbf{q} = -\nabla \cdot \mathbf{K} \nabla h$$

with piezometric head h and the tensor of hydraulic conductivities $\mathbf{K}$. The piezometric head can be obtained by solving the groundwater flow equation:

$$S\frac{\partial h}{\partial t} = \nabla \mathbf{K} \nabla h + Q$$

with storage coefficient S and general sink/source term Q. h is the dependent variable in the equation. Details concerning the link between hydraulics and thermics are given by Holzbecher (2014).

Heat transfer at the interfaces between grout and pipes, and at pipe boundaries of the pipes is calculated using conductances h:

$$j_s = -h\left(T - T_{ext}\right)$$

with external temperature T_{ext}. Conductances h are calculated as inverses of resistances R. As heat flow is mainly normal across the interfaces, various resistances can be summed up (Al-Khouri 2011).

2.2 Use of COMSOL Multiphysics® Software

As noted already the entire model consists of three components: downflow, upflow and ground, in the following denoted as porous medium. The former two are 1D, the latter can be 2D or 3D. The U-turn itself at the very bottom of the pipe is neglected.

In all components we utilize heat transfer modes, as described in detail in section 2.1. For downflow and upflow we use heat transfer in fluids, for the ground heat transfer in porous media. In the simulation the components have to be coupled by extrusions, which are sketched in Figure 2. COMSOL Multiphysics® is surely the most convenient software to treat such a coupled multi-domain setting.

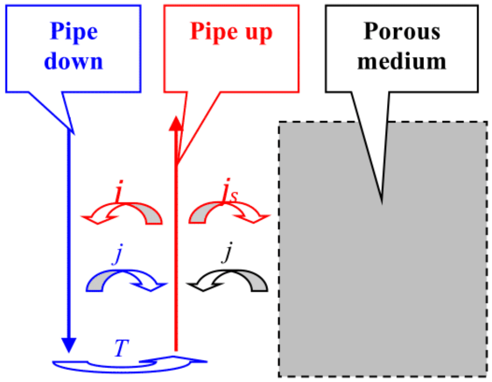

Figure 2. Sketch of components and extrusions

Upflow and downflow are coupled in two ways. (1) The calculated bottom temperature of the downflow leg is the inflow temperature for the upflow leg. (2) At all depths the temperatures of both components are utilized to compute the heat exchange between inner and outer leg, using conductances, as outlined in section 2.1. The exchange term is considered in the differential equation as source or sink (depending on the sign).

Finally the coupling between the 2D/3D region and the outer pipe is realized as follows: (1) the temperature along the outer pipe is considered in the 2D/3D component by a Dirichlet boundary condition at the pipe location; (2) the heat flux from the 2D/3D model is considered in an additional source term for the outer pipe model. In order to transform the temperatures from the 1D geometry to 2D/3D geometry, we use a general extrusion, which identifies the *x*-component along the pipe with the *z*-dimension (vertical) in the porous medium. A linear extrusion from the connected boundary of the porous medium geometry to the upward flowing pipe is constructed to transfer the fluxes.

2.3 Boundary and Initial Conditions

The 1D components have a Dirichlet condition at their inlets, and the usual Neumann condition at their outlets. The porous medium model has Dirichlet conditions at the outer boundaries, in which the geothermal gradient is taken into account. At the bottom of the porous medium model we require a Dirichlet temperature condition. At the top we use a Dirichlet condition, too, in order to account for temporally changing conditions. In general a Neumann condition may also be adequate there.

Initial condition for the temperature in all geometries is according to the geothermal gradient.

3. Results

Example simulations with the described model are shown in Figure 3. Two figures show the temperature distribution in the porous medium around a borehole of 300 m length. One result was obtained for a location without groundwater flow, the other for a location with groundwater flow. Elevated temperatures in downstream direction are clearly visible. It has to be noted that the groundwater table was modelled to lie in about 40 m depth. In the unsaturated zone above the groundwater table there is no horizontal flow component, and there are thus no elevated temperatures in any direction.

4. Conclusions

We described the set-up of a model for heat rejection in the sub-surface. The pipe system is represented by two 1D geometries, which are coupled to the geometry of the surrounding porous medium, which can be 2D cylindrical or 3D. Coupling is performed by general and linear extrusions.

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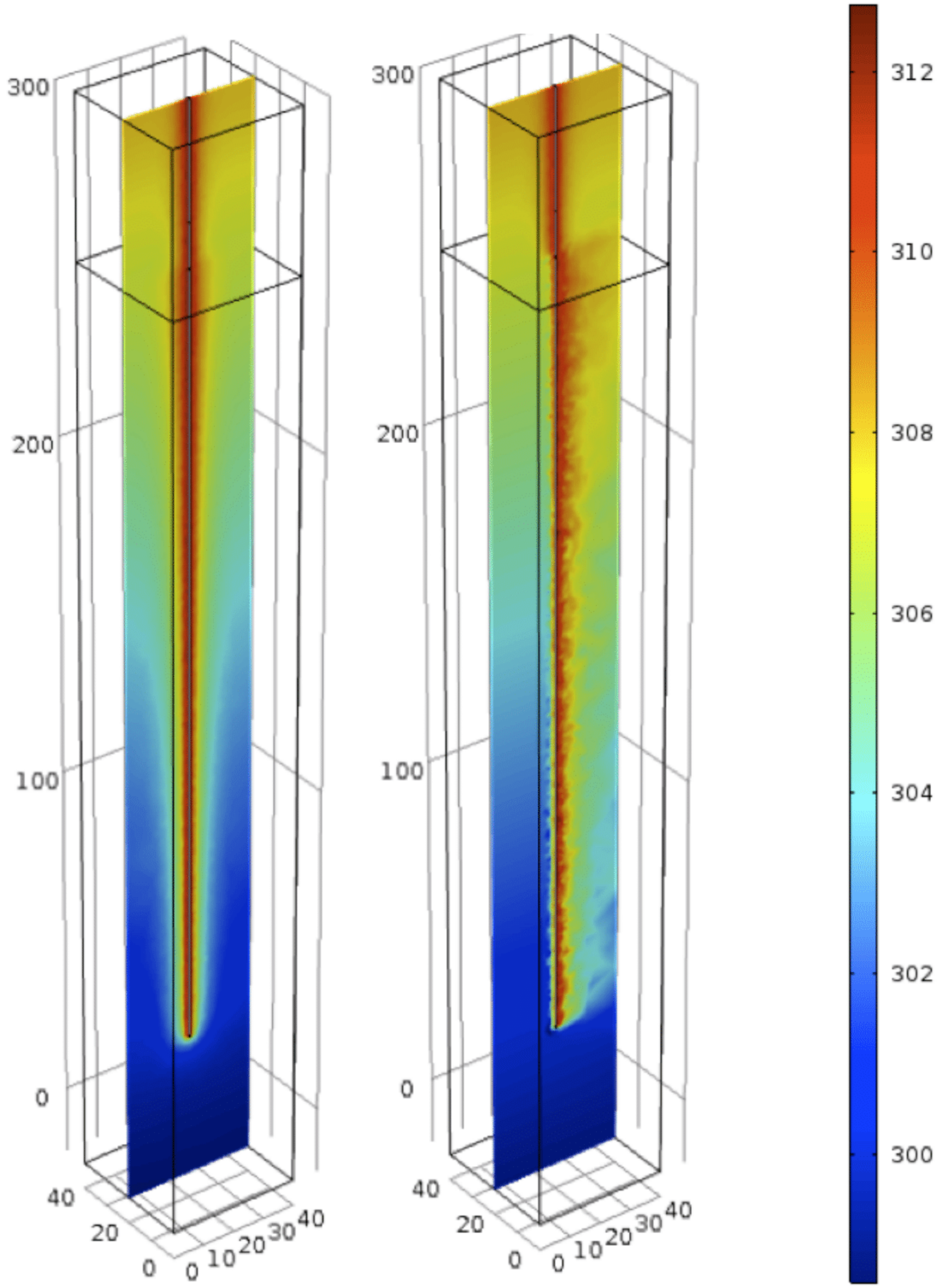

Figure 3. Temperature (°K) field around borehole; left: no groundwater flow; right: with groundwater flow