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Shallow geothermal engineering: overview and applications

Lecture 1. Introduction to shallow geothermal energy

Lecture Rules

Grading System

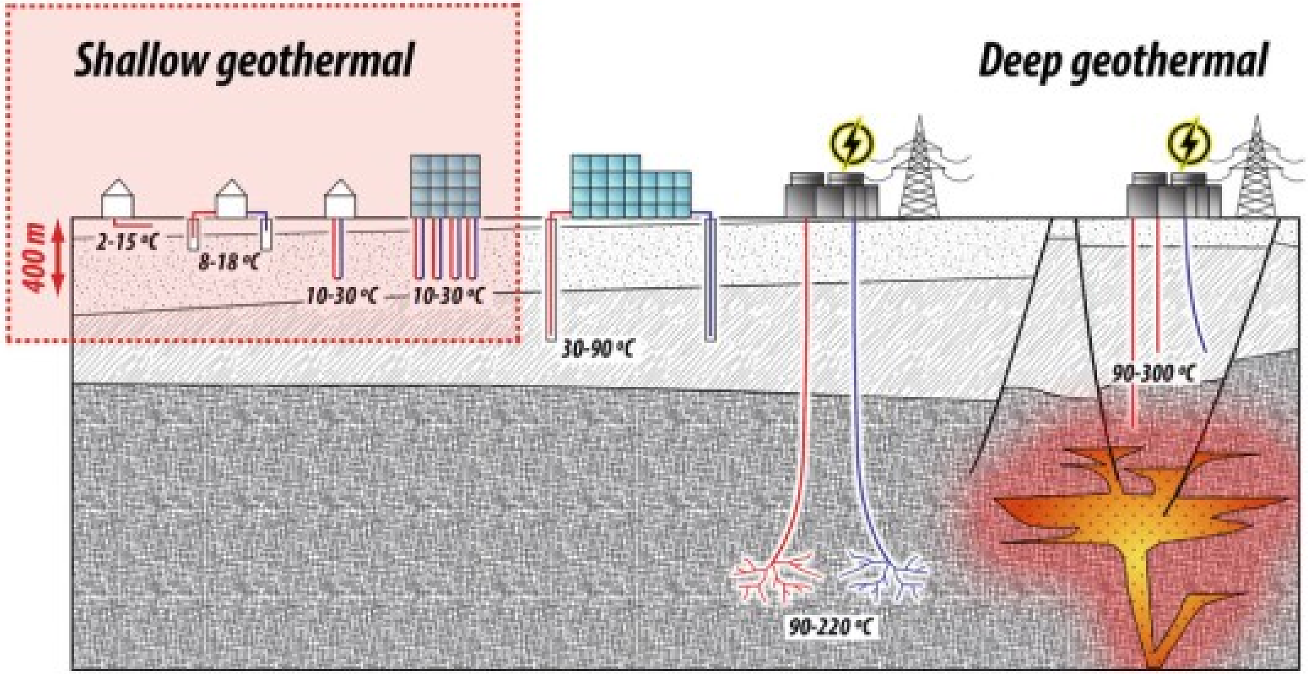
- Total: 100 Marks
- Final Exam: 60 Marks
- Classwork: 15 Marks
- Lab/Oral: 25 Marks

Content

- What is geothermal energy?
- Classification of geothermal energy.
- Ground heat Sources.
- Exploitation of shallow geothermal energy.

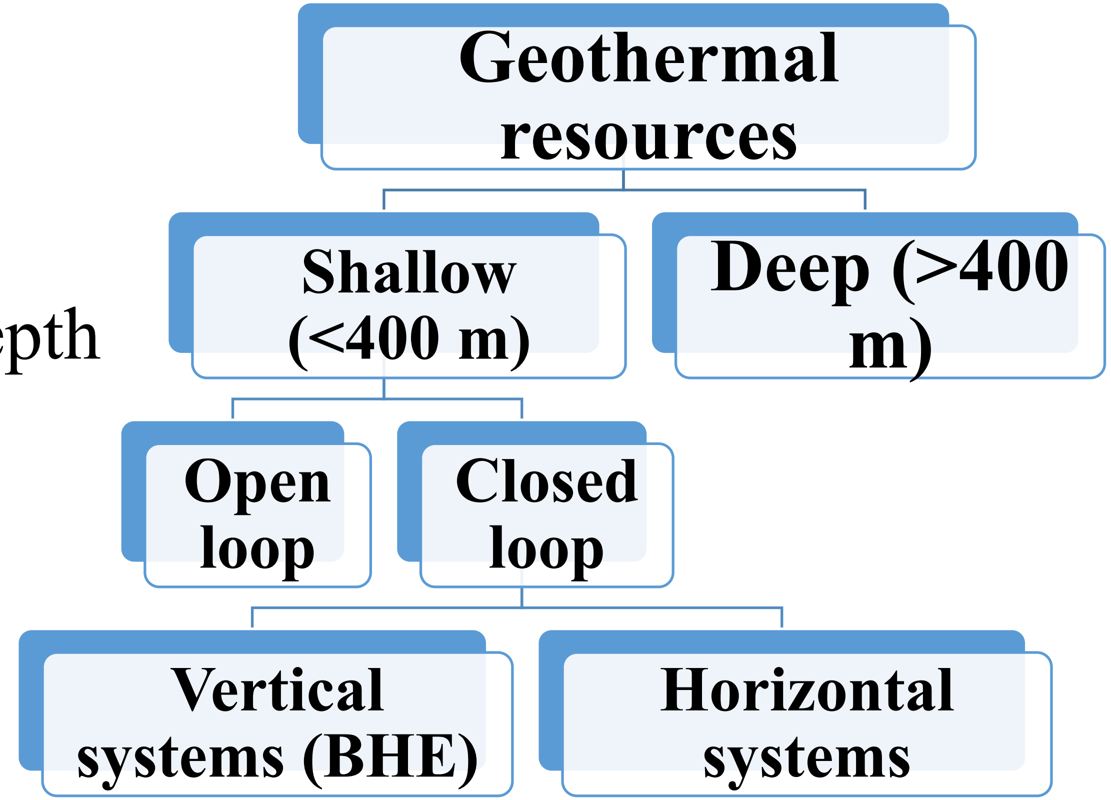
Introduction

- Geothermal energy is the energy produced and stored into the ground from the sun or during rock formation.



Classifications of geothermal resources

- According to depth



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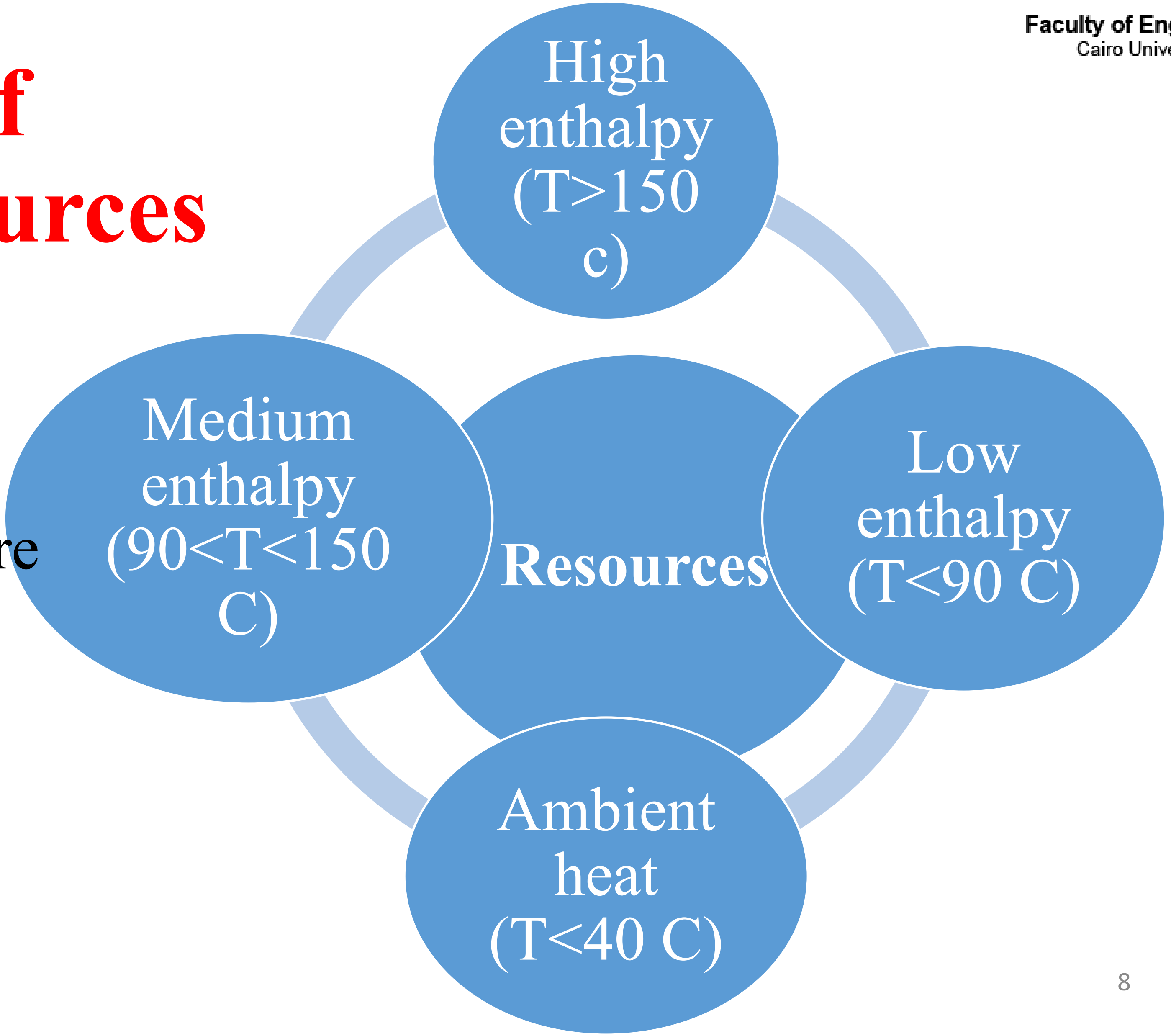
Classifications of geothermal resources

- According to Temperature



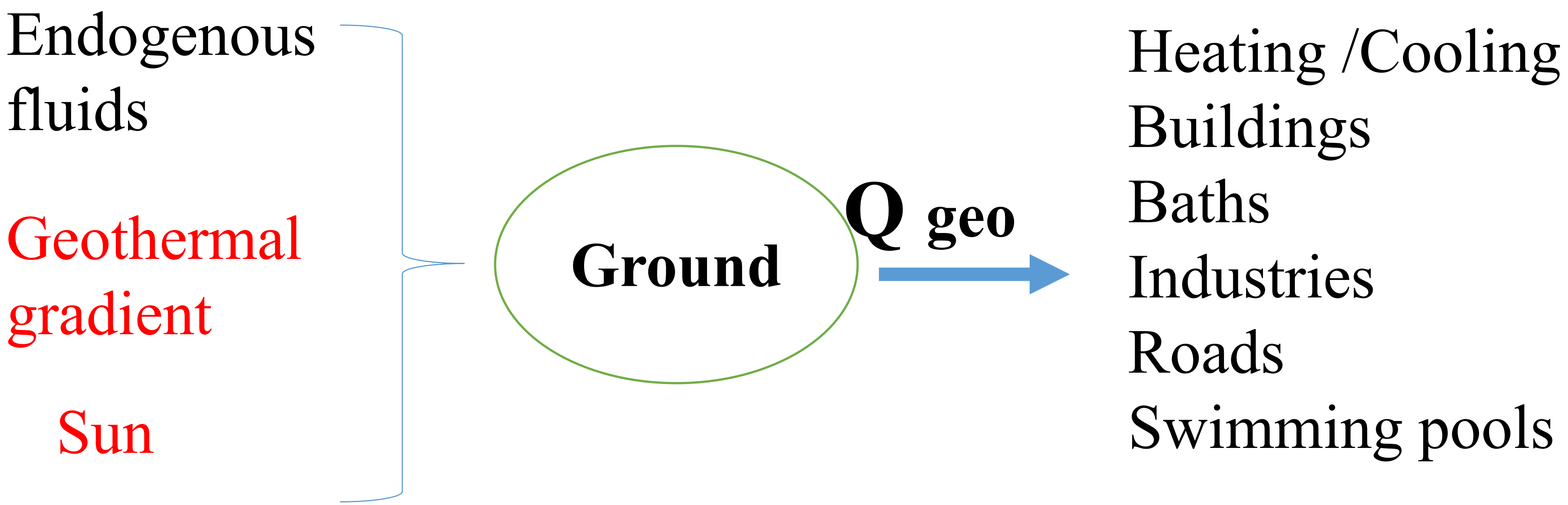
Classifications of geothermal resources

- **High enthalpy (T > 150 °C)**
  - Electric energy production
  - District heating.
- **Medium enthalpy (90<T<150 °C)**
  - Electric energy production (< 5 MW)
  - District heating (urban network)
  - Heating of industrial and commercial firms

Classifications of geothermal resources

- **low enthalpy (T < 90 °C)**
  - **District heating (neighborhood network)**
  - **Heating of industrial and commercial firms**
- **Ambient heat (T<40 °C)**
  - **Can be exploited by heat pumps.**
  - **Heating/cooling/hot water of single buildings.**
  - **Heating/cooling in the agriculture sector.**
  - **Snow melting and de-icing**

Ground Heat Sources



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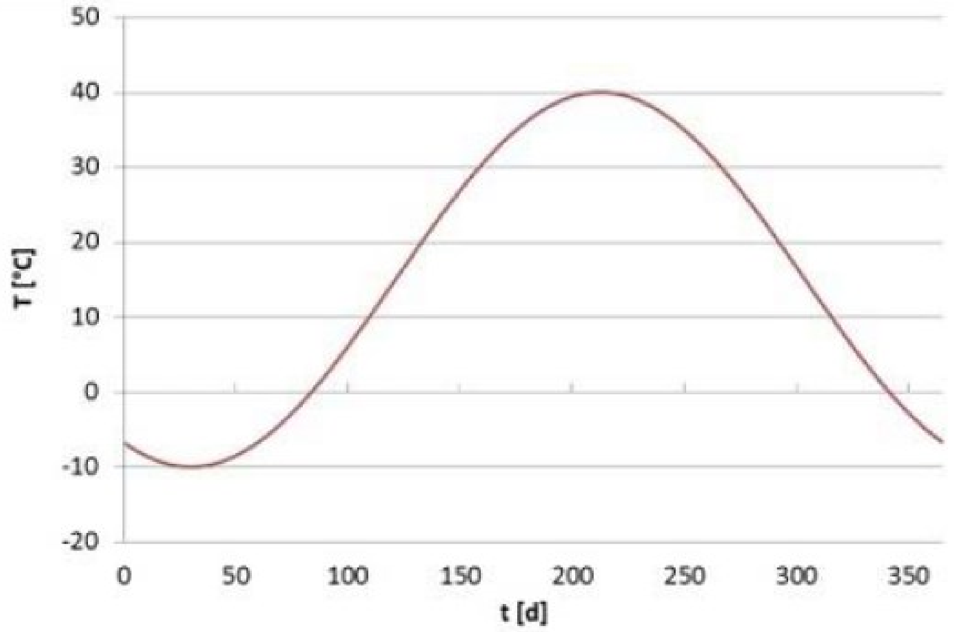
Heat gained from the sun

- Climate wave:

$$T(t) = T_m + \nabla T_m . t - A.Cos\left(\frac{2.\pi.(t-t_{t0})}{T}\right)$$



- T_m : Yearly average temperature °C
- A: Wave amplitude °C
- T : Wave period d
- t_0: day of minimum temperature d
- ∇T_m: climatic trend (°C/d)

Heat gained from the sun

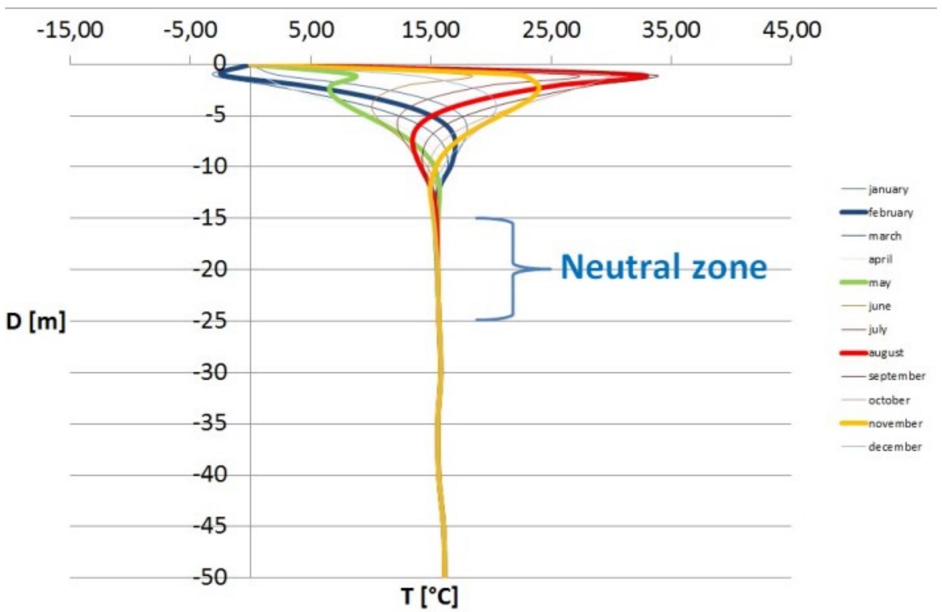
- *Heat is transferred into the ground.*

- $T_g(D,t) = T_m + \nabla T_m . t - A. exp\left[-D.\sqrt{\frac{\pi}{T.\alpha_g}}\right]. Cos[\frac{2\pi}{T}.(t - t_{T0} - \frac{D}{2}.\sqrt{\frac{\pi}{T.\alpha_g}})]$

- α_g: thermal diffusivity m^2/day
- D: depth (m)

Heat gained from the sun

- Temperature of the ground is affected by the climate until certain depth (D) then it keeps constant.
- So:
  - Geothermal energy is independent of climate
  - lasts during the year.



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Ground Heat

- Finally, the contribution of sun and geothermal gradient to the ground temperature can be expressed as:

$$T_g(D,t) = T_m + \nabla T_m . t - A.exp\left[-D.\sqrt{\frac{\pi}{T.\alpha_g}}\right].Cos[\frac{2\pi}{T}.(t - t_{T0} - \frac{D}{2} . \sqrt{\frac{\pi}{T.\alpha_g}})] + \nabla T_{Geo}(h,\lambda).D$$

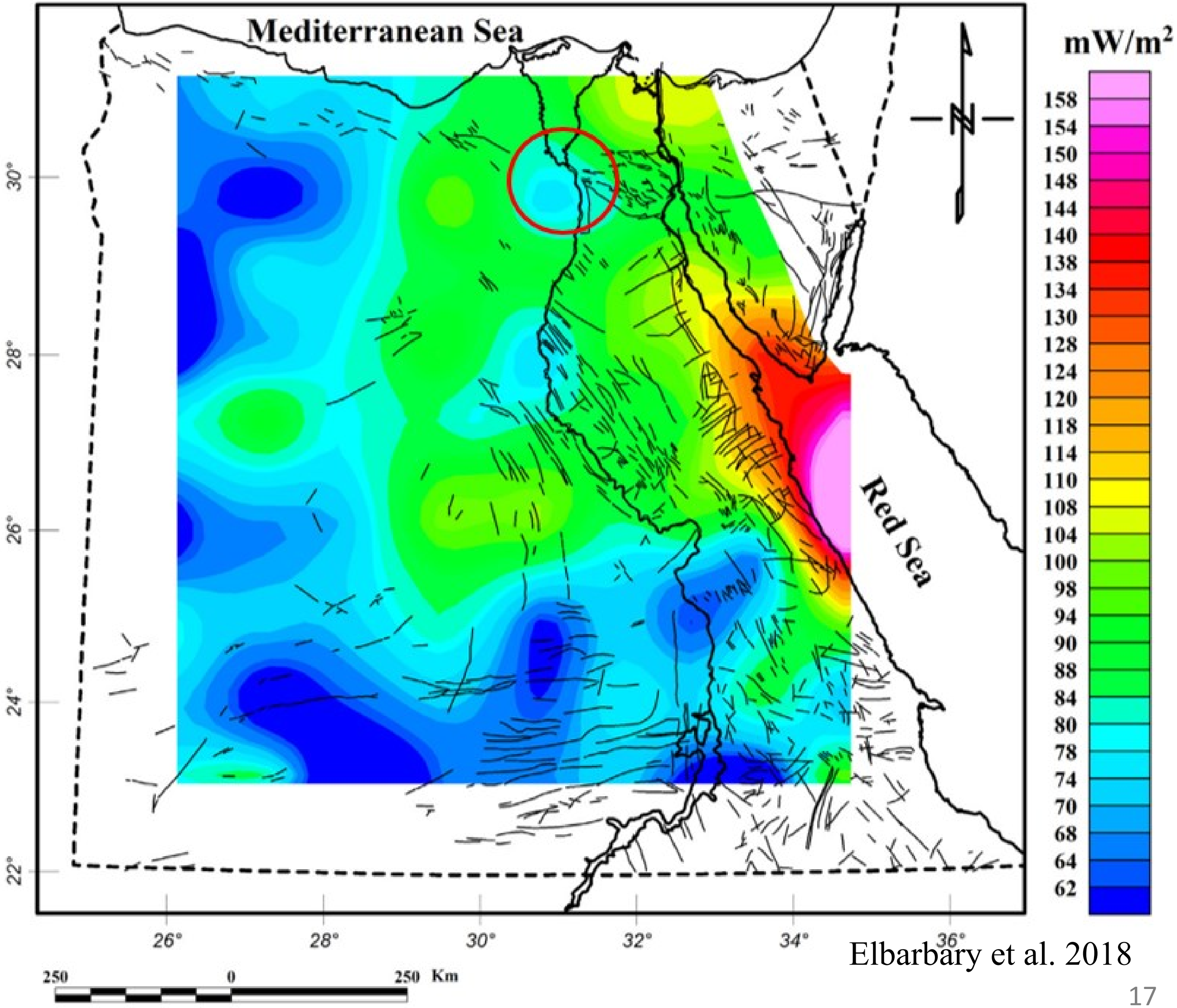
- h: heat flow density W/m^2
- λ: thermal conductivity of the layer (W/m.°C)
- ∇T_{Geo} : geothermal gradient .°C/km

Ground Heat

- The average value of the heat flow of ground is 65 m W/m^2.
  - Based on geothermal gradient value of 3 °C/100 m.
  - Based on thermal conductivity value of 2.20 W/m.°C. which depends on rock/soil type.
  - Heat flow is q = $\frac{Q}{A}$ (W/m^2).

- Q= λ.A. ∇T_{Geo}

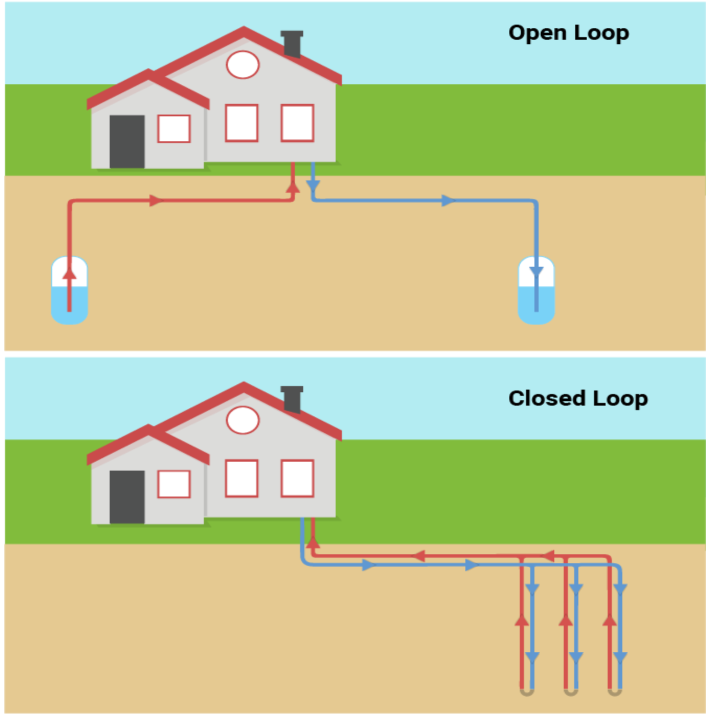
Heat flow of Egypt



Elbarbary et al. 2018

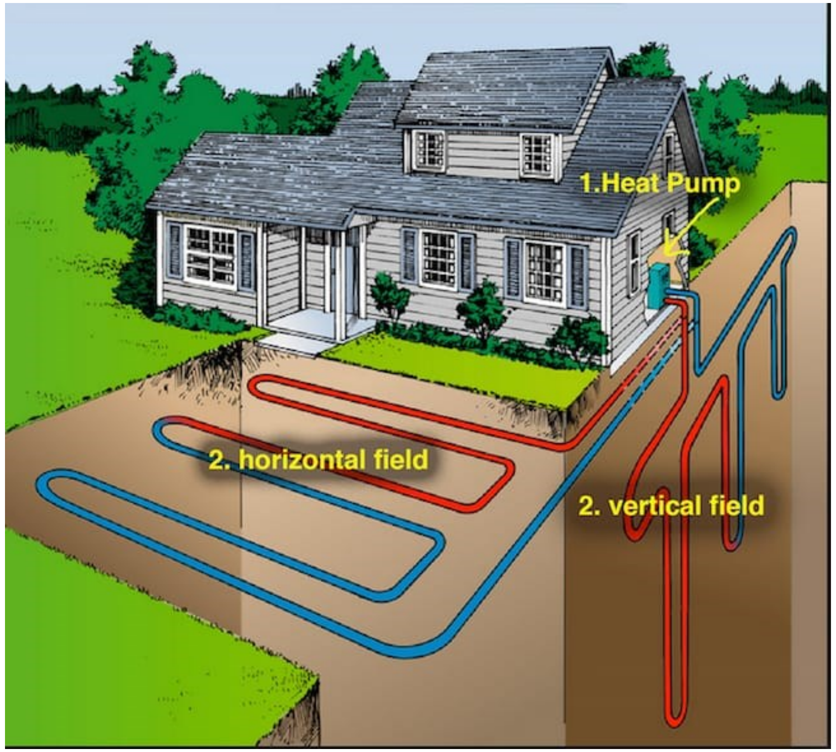
Exploitation of shallow geothermal energy

- Shallow geothermal can be exploited in different ways:
  - Closed loop system:
    - Through pipelines' loop.
  - Open loop system:
    - Through production and injection wells.
    - Lakes or seas.



Exploitation of shallow geothermal energy

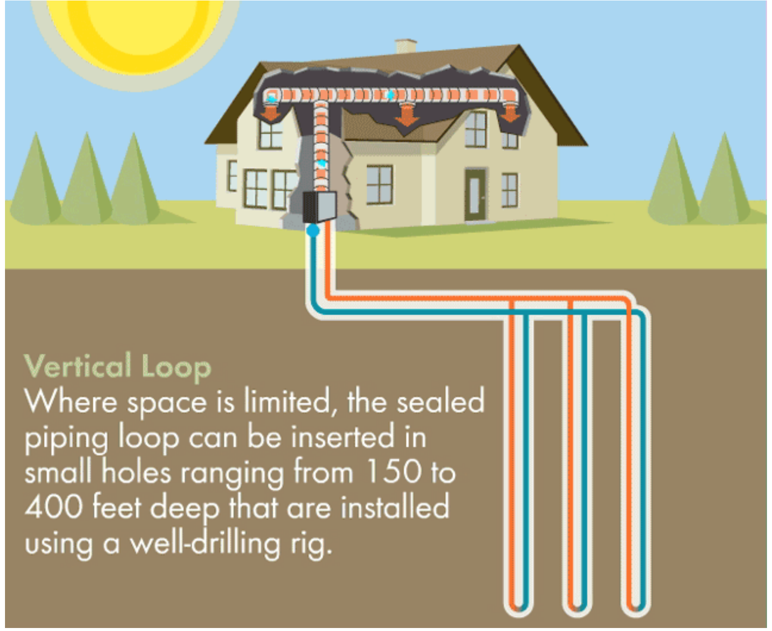
- Shallow resources can be exploited in closed loops using heat pumps through different systems such as:
  - Vertical system
  - Horizontal system



Exploitation of shallow geothermal energy

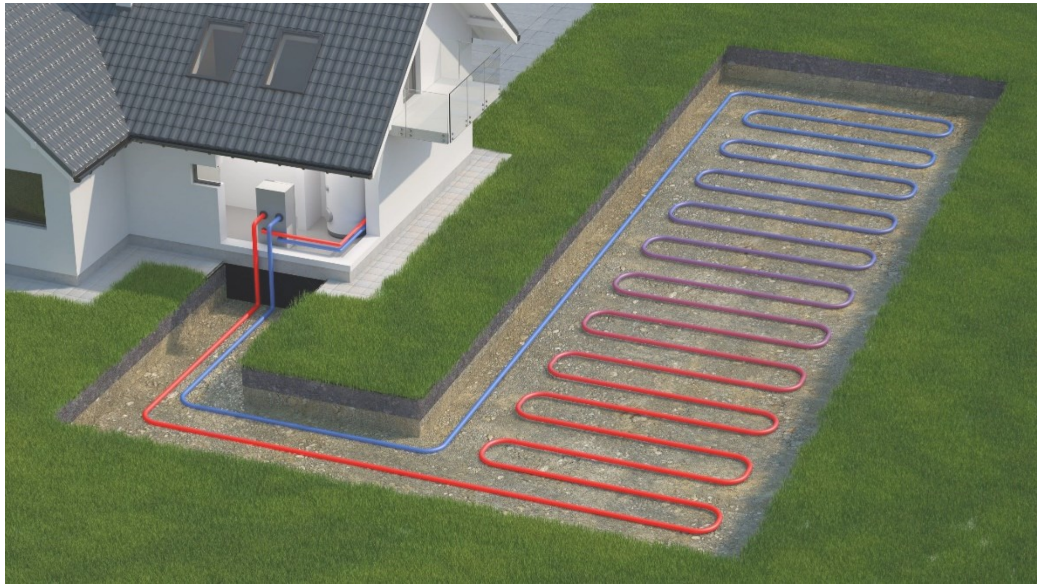
- Vertical Borehole heat exchangers (BHE):
  - Vertical boreholes are drilled and connected to the heat pump

    - Higher depth
    - Requires lower area
    - More output power
    - Climate independent.

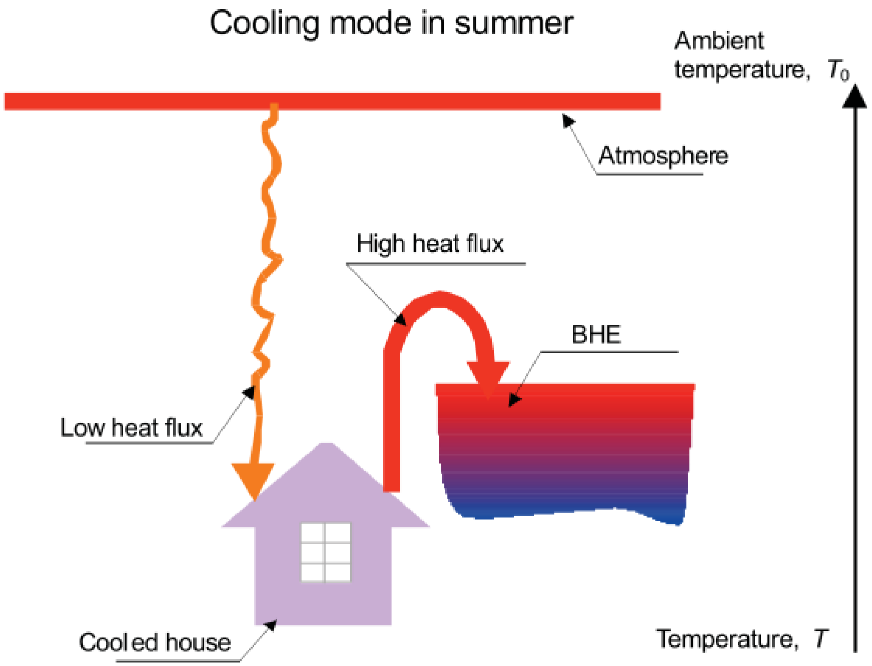


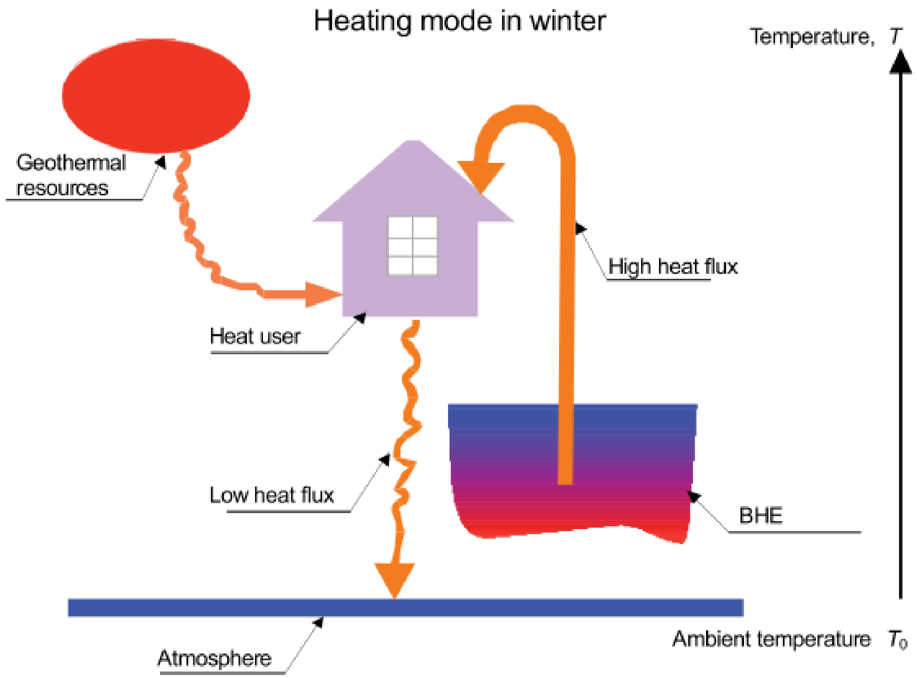
Exploitation of shallow geothermal energy

- horizontal pipe system:
  - Pipelines are drilled horizontally and connected to the heat pump
    - lower depth
    - Requires much more area
    - less output power
    - Climate dependent.



How it works?


Cooling mode in summer
Ambient temperature, T_0
Atmosphere
High heat flux
BHE
Low heat flux
Cooled house
Temperature, T

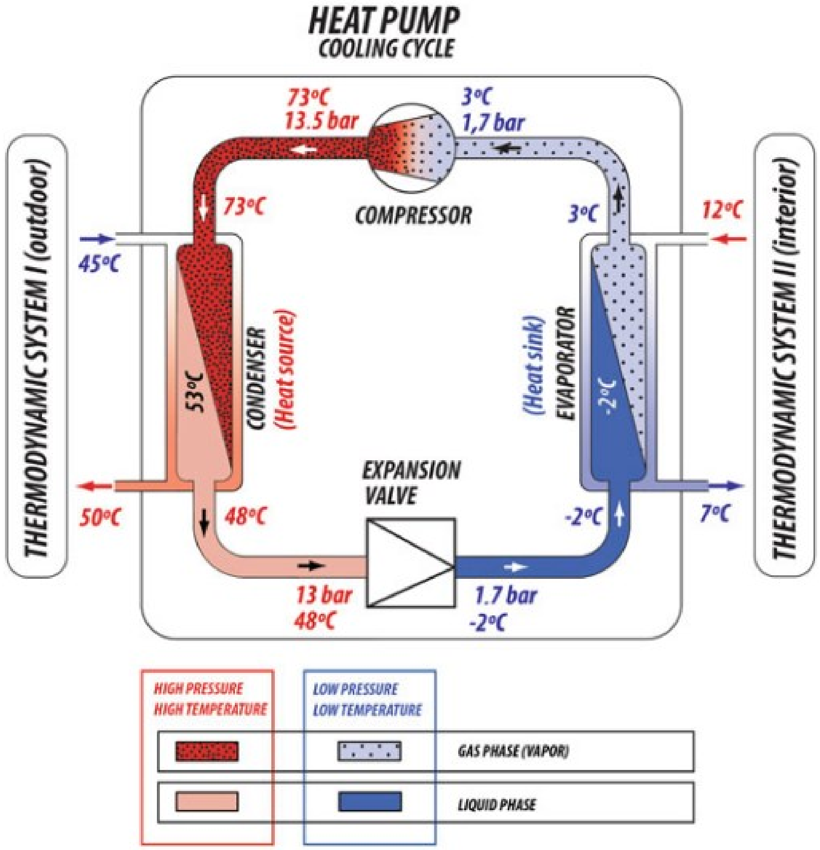

Heating mode in winter
Temperature, T
Geothermal resources
High heat flux
Heat user
Low heat flux
BHE
Ambient temperature T_0
Atmosphere

How it works?

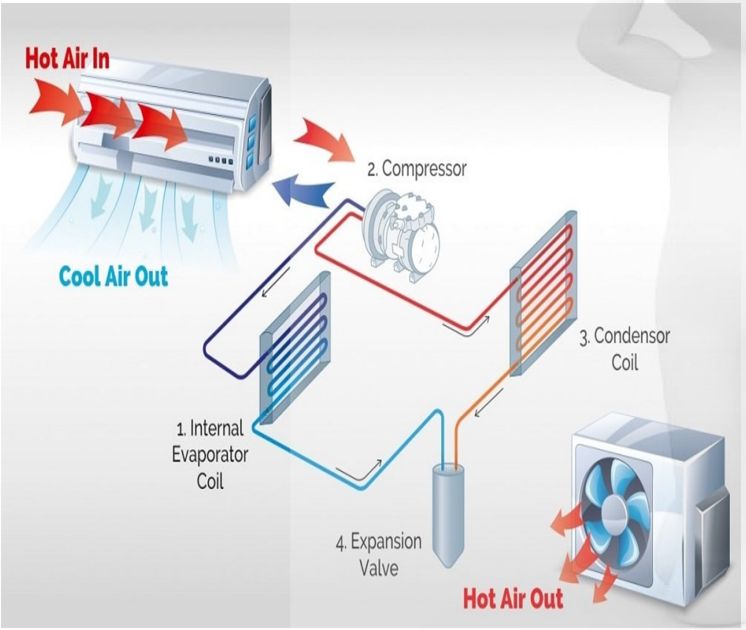
- Heat pumps are used to force the heat transfer process whatever the direction of natural heat flow through a secondary circuit.
- For cooling, the borehole is considered as a heat sink for heat disposal in summer while it is considered as a heat source in winter for heating.
- In heat pumps, heat is exchanged between a working fluid and the Fluid through the BHE connected to the heat pump.
- Heat pumps require external work (electrical power) to operate.

Ground Source Heat pump (GSHP)

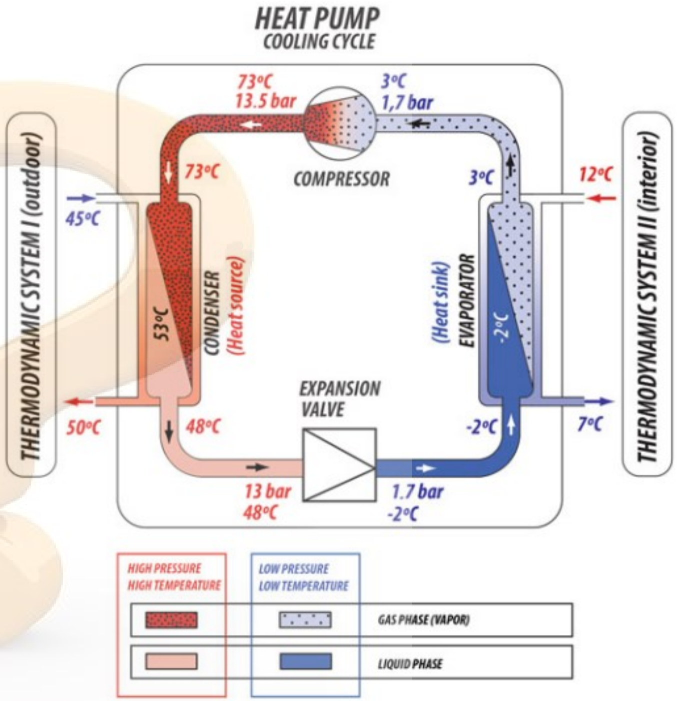
- Heat pump has 4 main components:
  - Compressor
  - Evaporator
  - Condenser
  - Expansion valve.
- It can be used for either heating or cooling.



AC unit Vs GSHP

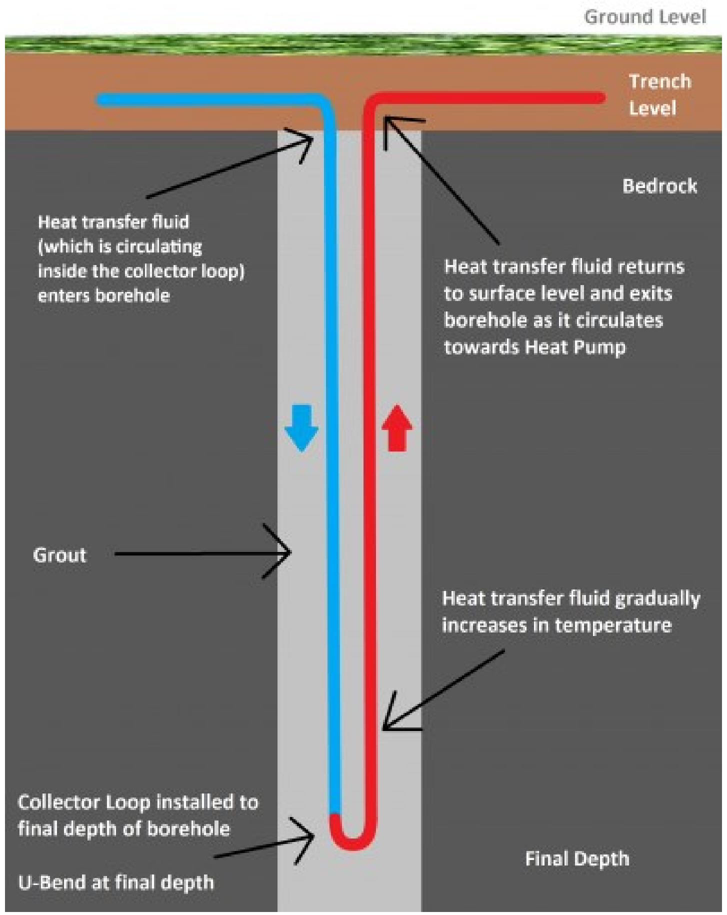


VS



Heat transfer mechanisms

- Heat is mainly transferred through convection of heat carried by the water circulating into the system.
- Heat is also transferred by conduction from the borehole wall to the grout and then the pipeline wall.



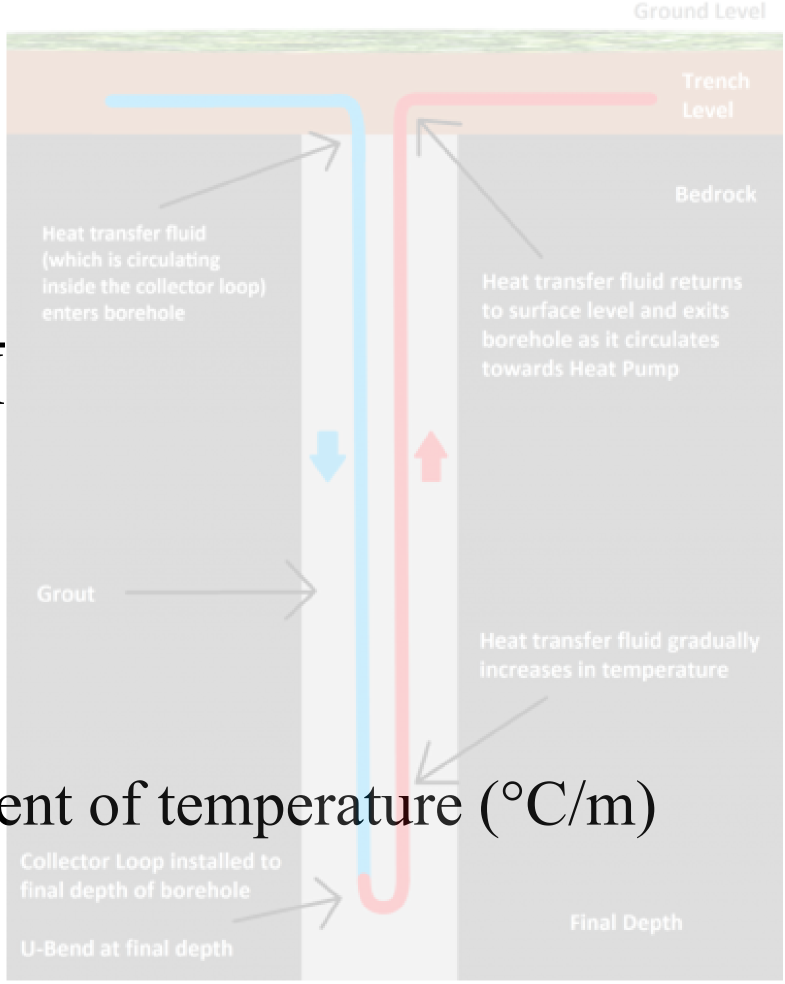
Heat transfer mechanisms

- For convection:
  - Q=h.A.ΔT
- Q: convective power (W)
- A: area of heat transfer (m^2)
- ΔT: temperature difference (°C)
- h: heat transfer coefficient (W/ m^2.C).

Heat transfer mechanisms

- For conduction:
  - $Q = \lambda . A . \frac{\Delta T}{\Delta X}$
  - Q: conduction transferred power (W)
  - λ: thermal conductivity (W/m.°C)
  - A: area of heat transfer (m^2)
  - ΔT: temperature difference (°C)
  - ΔX: depth or thickness

$\frac{\Delta T}{\Delta X}$: gradient of temperature (°C/m)



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Shallow geothermal engineering: overview and applications

Lecture 2. Ground properties for geothermal exploitation

Content

Thermophysical properties

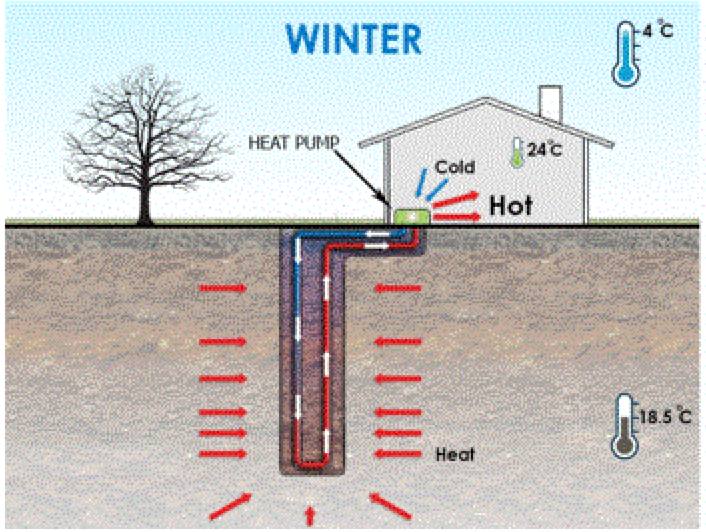
Heat flow
Thermal conductivity
Specific heat capacity
Thermal diffusivity
Ground temperature
Borehole thermal resistance

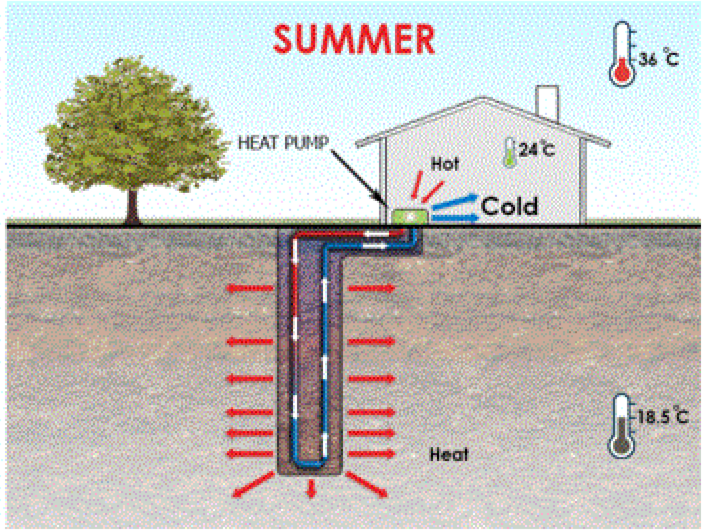
Hydraulic properties

Permeability (hydraulic conductivity)
Groundwater flow.
Pressure drop meaning

Thermophysical properties

- Thermophysical properties of ground and other components such as grout and pipeline walls are very important in geothermal energy exploitation.

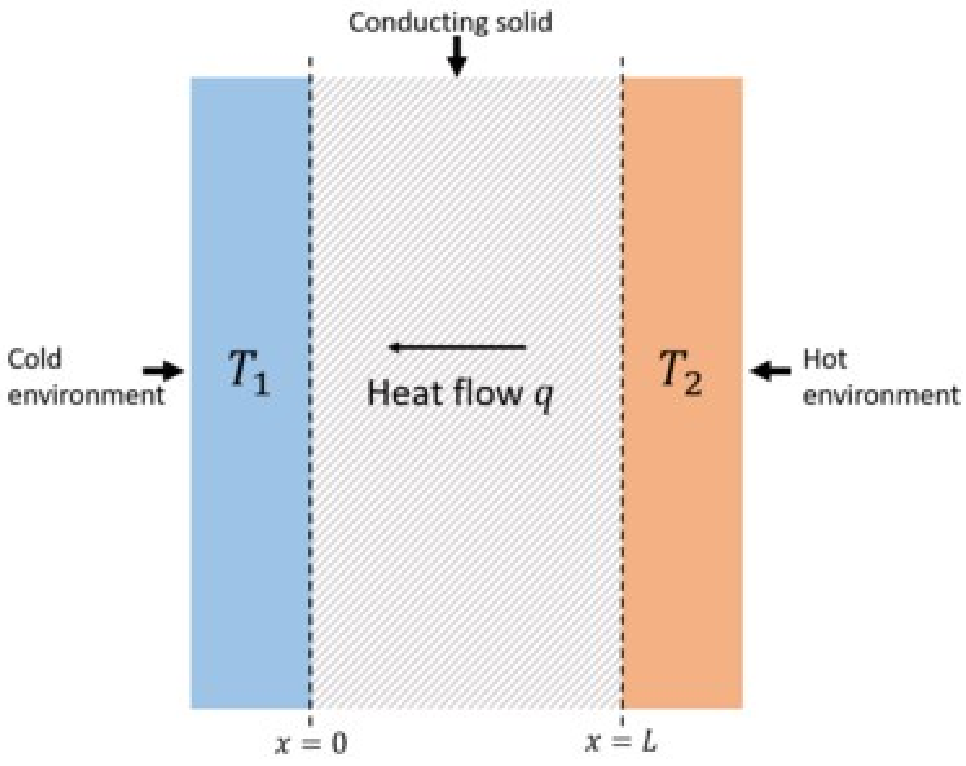




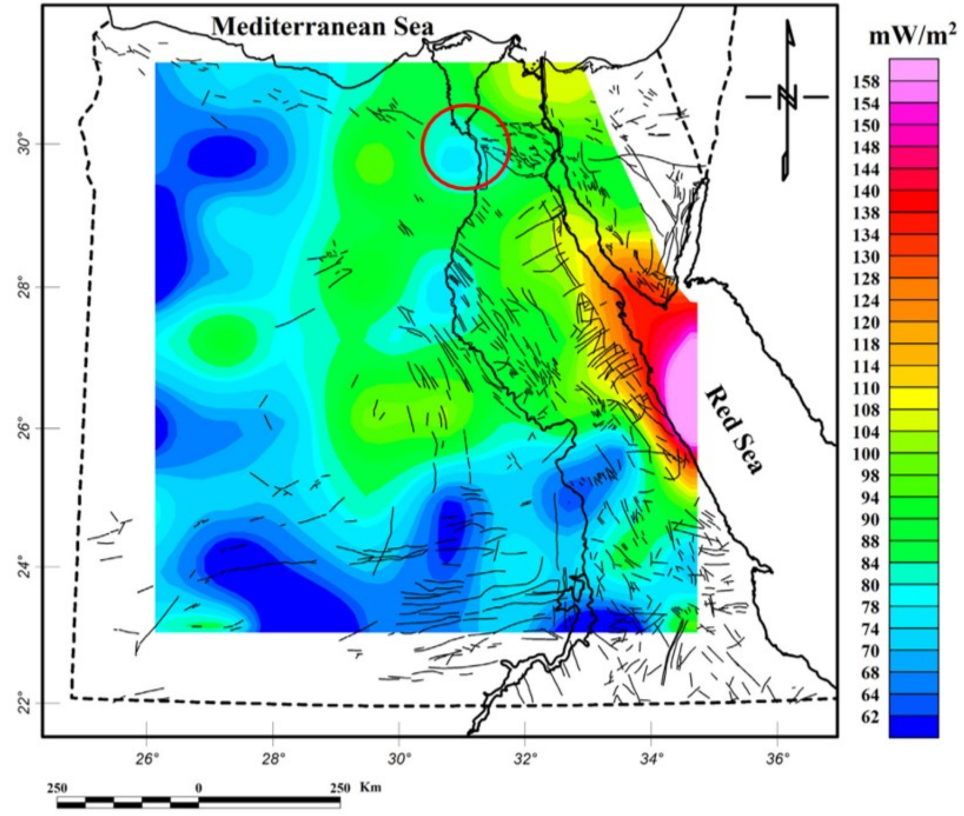
Thermophysical properties

- To calculate the **heat flow** (W/ m^2), the thermal conductivity (λ) of the ground should be measured.

  - Thermal conductivity (λ) differs according to the rock/soil type.



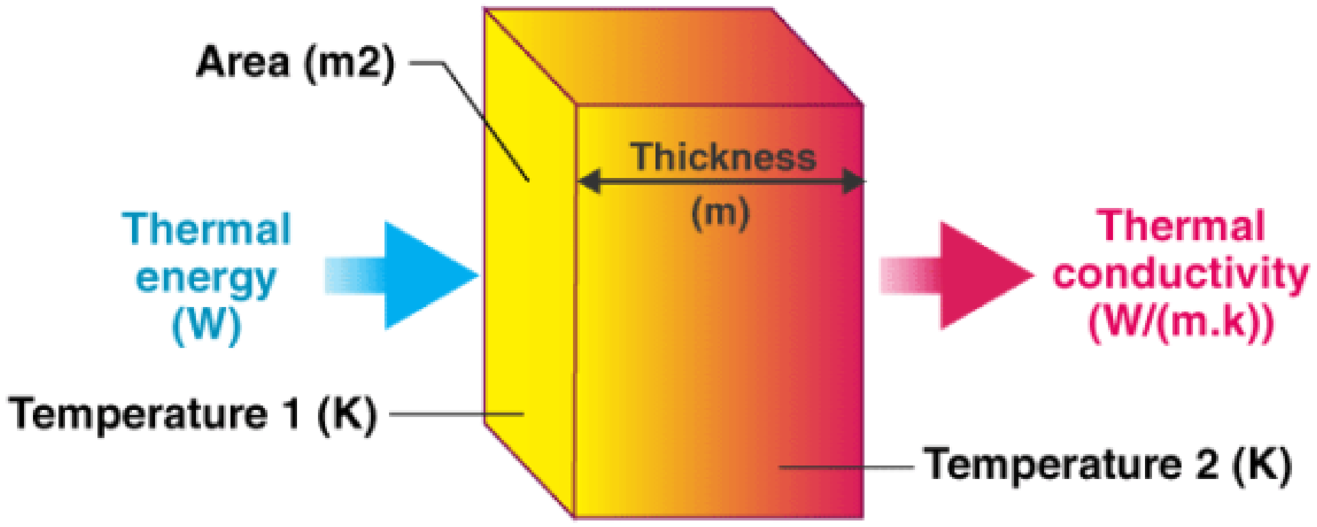
Thermophysical properties



Heat flow map of Egypt, Elbarbary et al. 2018

Thermophysical properties

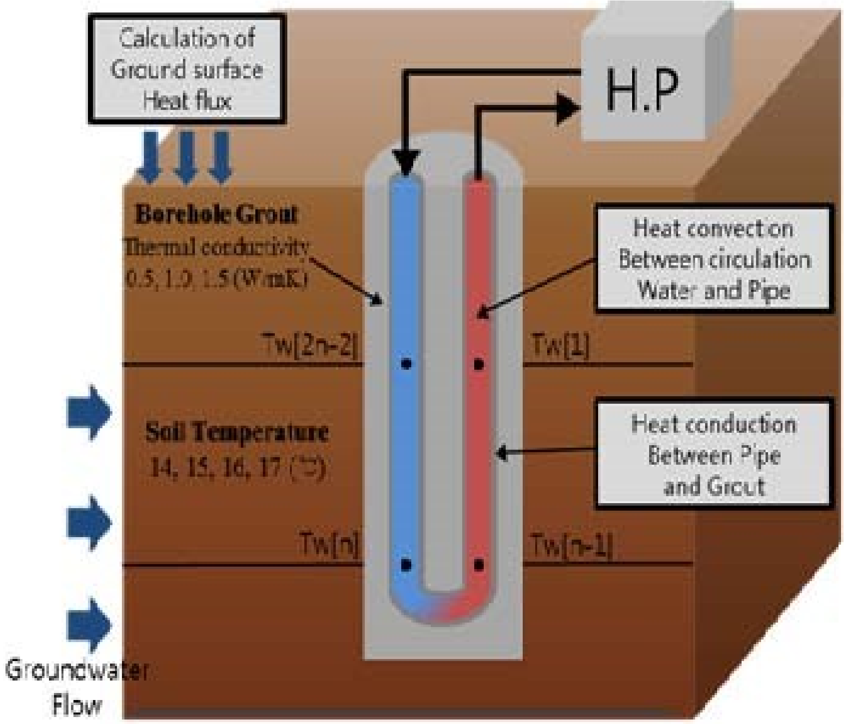
- **Thermal conductivity** represents the ability of a material to conduct heat from a hotter side to a colder one.



$$Q = \lambda . A . \frac{\Delta T}{\Delta X}$$

Thermophysical properties

- Thermal conductivity of the ground is important in transferring heat to/ from the circulating fluid.



Thermophysical properties

Table 1. Ranges of thermal properties of some minerals (Gil et al. 2020)

Mineral	Thermal conductivity (λ), W/m. °C	Heat capacity (C), KJ/ Kg. °C
Quartz	7.69 - 7.70	0.70 – 0.74
Kaolinite	2.60	0.93
Smectite	1.90	0.86
Clay minerals	1.70 - 5.95	0.5 - 0.95
Calcite	3.25 – 3.90	0.79 - 0.80
Mica	0.70 - 2.32	0.76 – 0.78
Feldspar	1.68 – 2.31	0.63 – 0.75

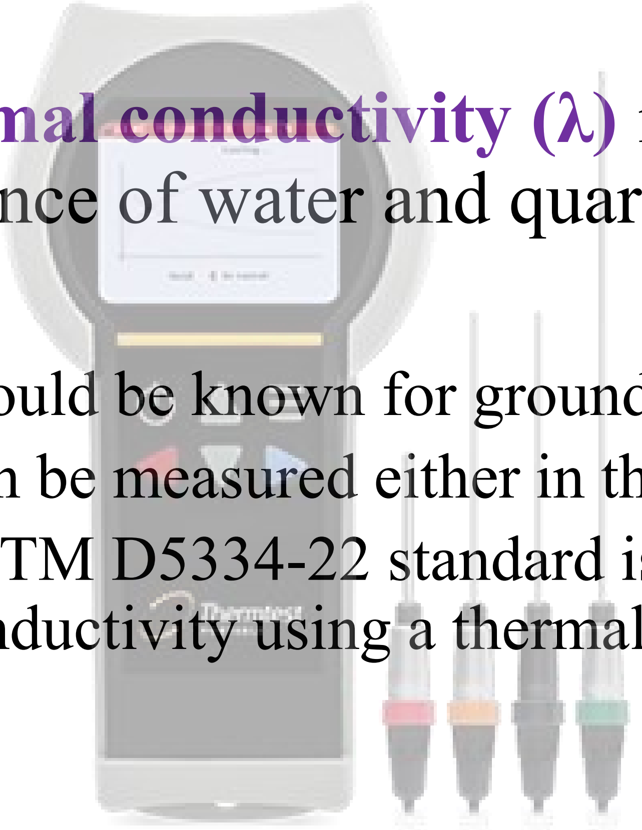
Thermophysical properties

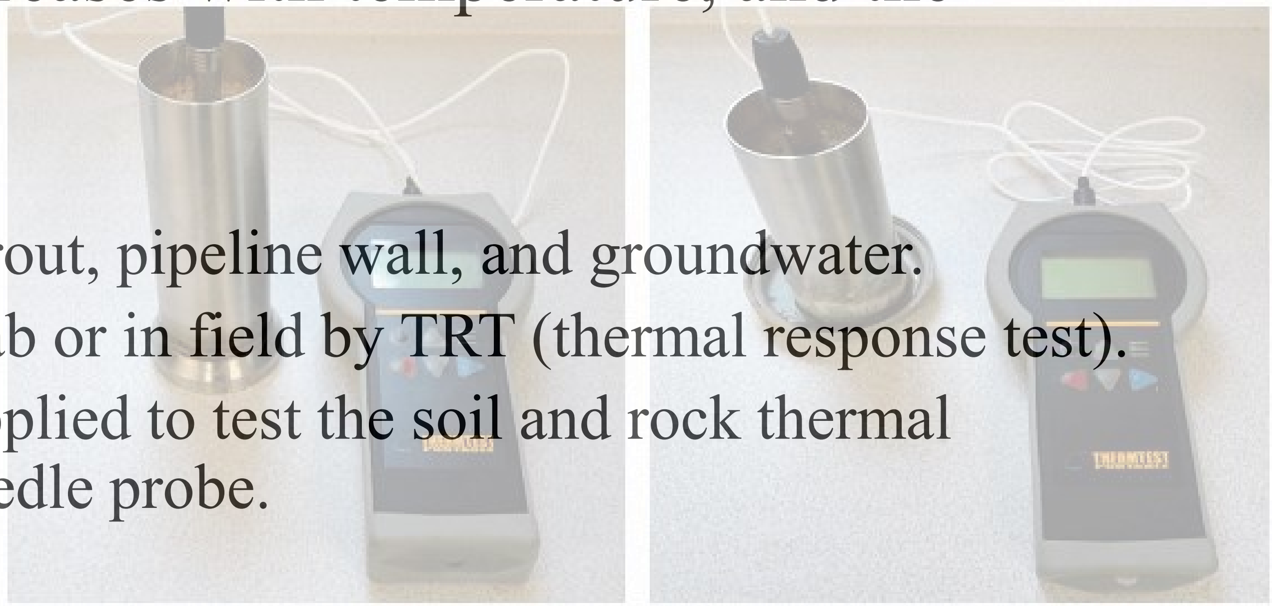
Table 2. Ranges of thermal properties of some rock types/soil (Gil et al. 2020)

Rock	Thermal conductivity (λ), W/m. °C	Heat capacity (C), KJ/ Kg. °C
Granite	1.25 - 4.45	0.67 - 1.55
Limestone	0.62 - 6.26	0.82 - 1.72
Siltstone	0.61 - 2.10	0.91 - 1.52
Shale	0.55 - 4.25	0.88 - 1.44
Soil	0.40 - 0.86	1.80 - 1.90
Clay	0.60 - 2.60	0.84 - 1.00
Basalt	1.50 - 2.50	0.84 - 1.28

Thermophysical properties

- **Thermal conductivity (λ)** increases with temperature, and the existence of water and quartz.
  - Should be known for ground, grout, pipeline wall, and groundwater.
  - Can be measured either in the lab or in field by TRT (thermal response test).
  - ASTM D5334-22 standard is applied to test the soil and rock thermal conductivity using a thermal needle probe.





Thermophysical properties

- **Heat capacity** (C, J/kg.°C) represents the amount of energy required to increase the temperature of 1 kg of a material 1°C.
- It represents the ability of a material to store energy.
- **Heat capacity** is an important parameter in heat transfer which determines the amount of energy needed to heat or cool a material.

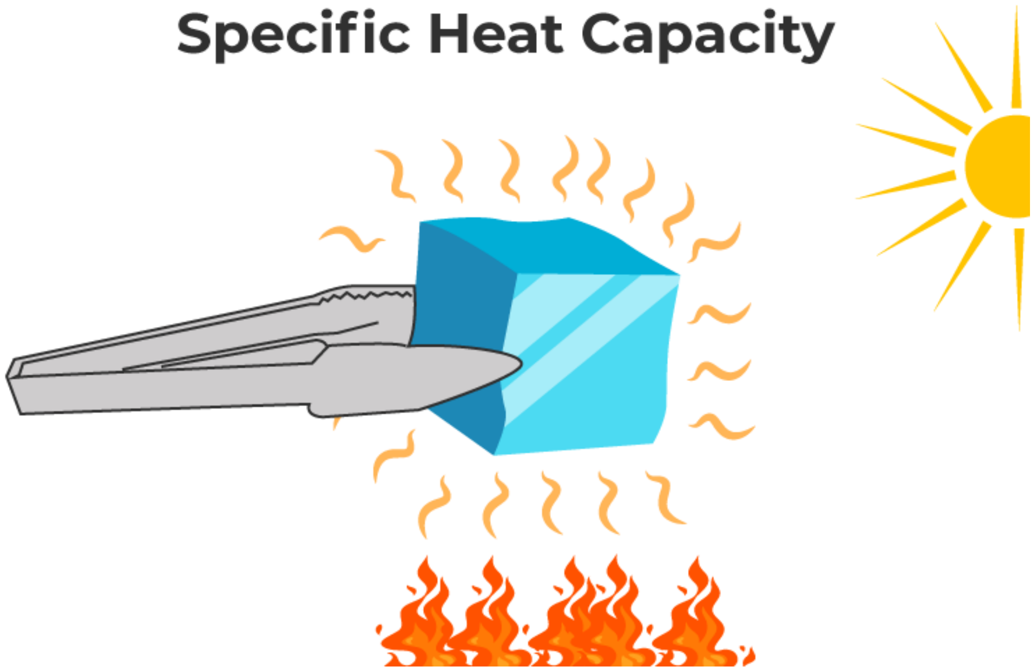
Thermophysical properties

- Thermal diffusivity ($\alpha, m^2/s$) is expressed as the rate of heat transfer via conduction.

  - Volumetric heat capacity (c, J/ m^3.°C)
  - Thermal diffusivity ($\alpha, m^2/s$) $= \frac{\lambda}{c}$
  - c =C.ρ
  - ρ: density (kg/ m^3)

Thermophysical properties

- For a BHE, Is it better to have a ground with low or high heat capacity?



Thermophysical properties

Table 3. Ranges of thermal diffusivity of some soils

Soil type	Thermal diffusivity ($\alpha, m^2/day$)
Dry clay	0.02 – 0.05
Wet clay	0.04 – 0.07
Dry silt	0.02 – 0.05
Wet silt	0.04 – 0.07
Dry gravel	0.03 -0.03
Wet gravel	0.04 – 0.06
Dry sand	0.02 – 0.05
Wet sand	0.07 - 0.15

Thermophysical properties

Table 4. Ranges of thermal diffusivity of some rock types

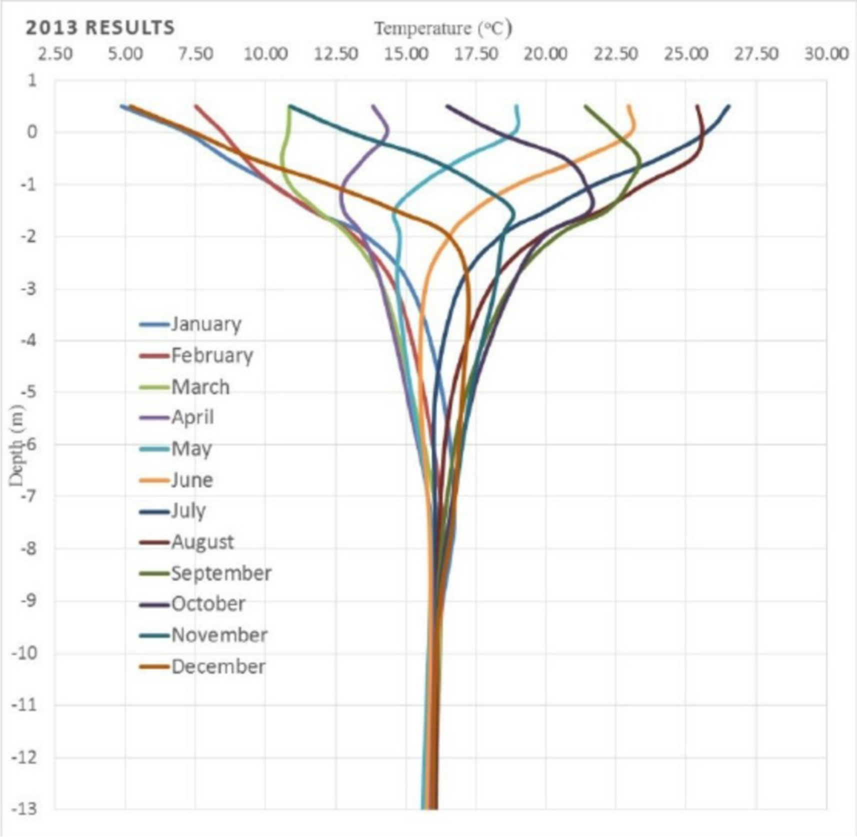
Rock type	Thermal diffusivity ($\alpha, m^2/day$)
Claystone	0.05 – 0.12
Siltstone	0.05 – 0.12
Mudstone	0.05 – 0.12
Sandstone	0.09 – 0.15
Limestone	0.08 – 0.14
Shale	0.06 – 0.11
Basalt	0.05 – 0.08
Diorite	0.06 - 0.09

Thermophysical properties

- Ground temperature should be measured as it determines the range of applications, the chosen heat pump, and the output efficiency.
- A downhole temperature sensor is used to measure the undisturbed ground temperature (T_g) along the borehole depth.

Downhole Ground temperature sensor

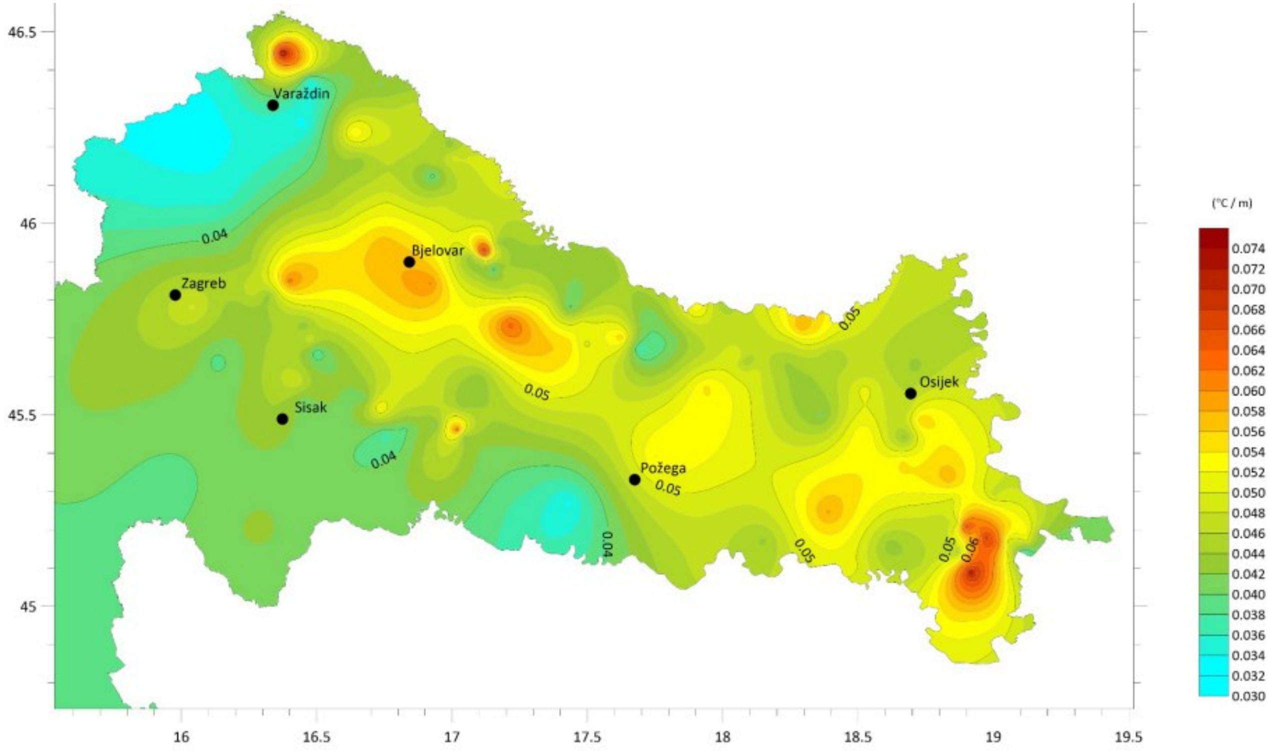
Thermophysical properties



Ground temperature vs depth, Aydin et al. 2015

Thermophysical properties

- The geothermal gradient (°C/m) is an important parameter to be known.
- It represents the rate of temperature change with depth.
- More important for deep resources.



The geothermal gradient in Croatia

Thermophysical properties

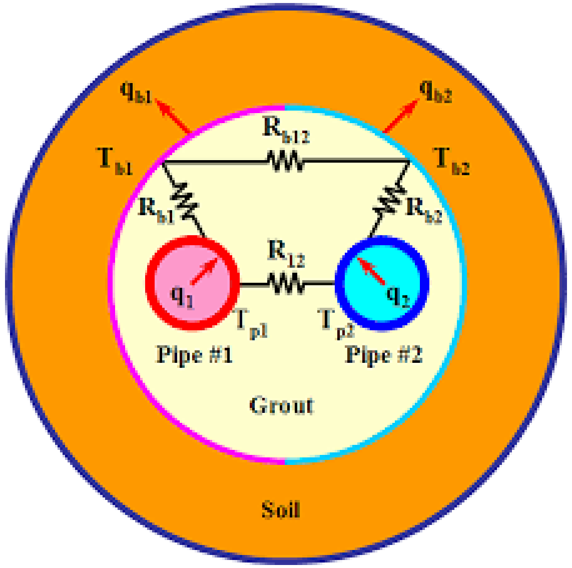
- Borehole thermal resistance [R_b]:
- Should be calculated to estimate the required depth to reach the required load.
- Describes the loss of temperature from the ground to the heat carrier fluid or vice versa.
- A lower thermal borehole resistance always increases the efficiency of the BHE.

  - Affected by:
    - Borehole diameter
    - Pipe size and configuration
    - pipelines material
    - Grouting
    - The heat carrier fluid
    - Laminar or turbulent flow

Thermophysical properties

- Resistances in a BHE are the summation of obstacles facing conduction and convection of heat transfer.

- $\Sigma R = R_{ground} + R_{ground-grout} + R_{grout-pipeline\ wall} + R_{pipeline\ wall\ -fluid} + R_{fluids}$



Borehole resistance to heat transfer

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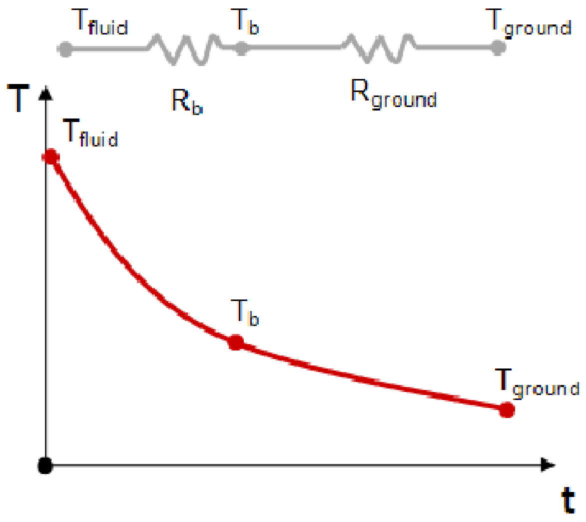
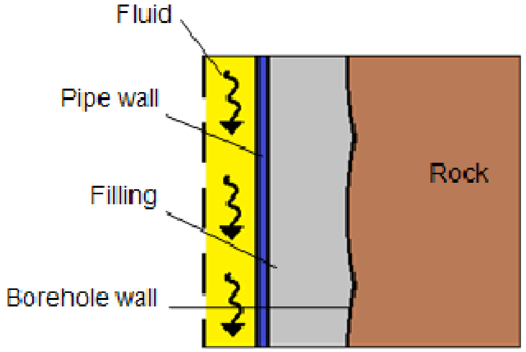
Thermophysical properties

- Borehole thermal resistance [R_b]:
  - It lowers the heat transfer and therefore the output power.

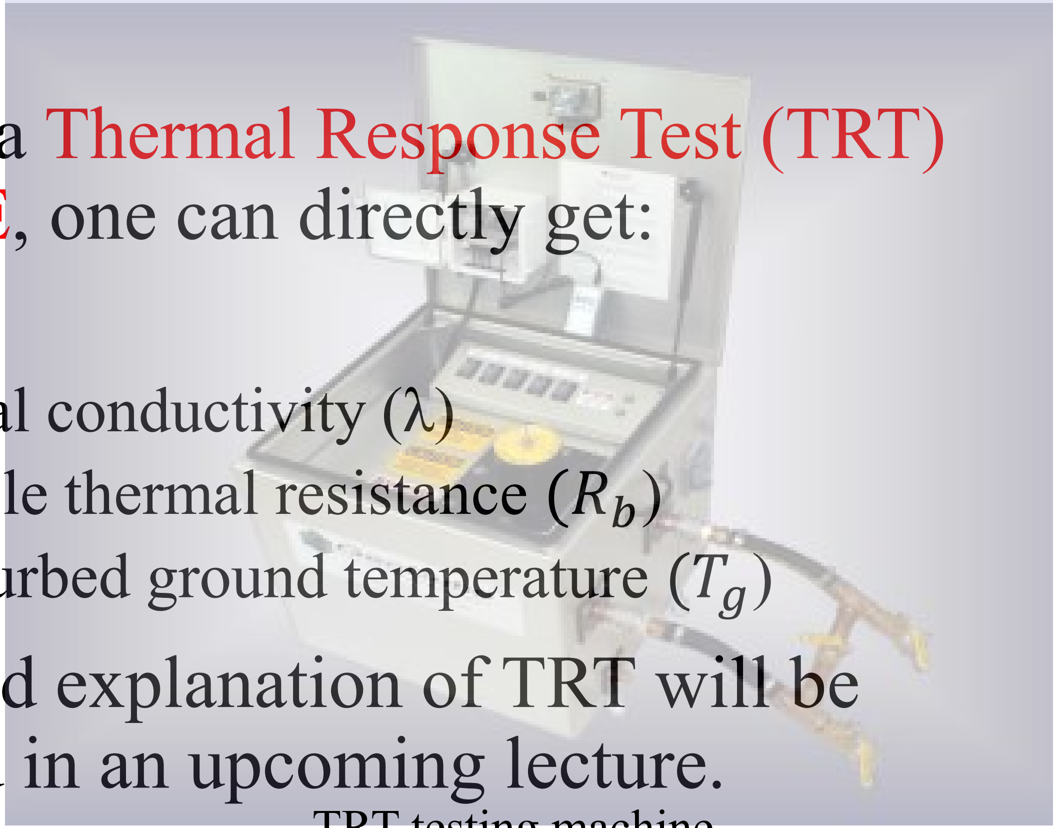


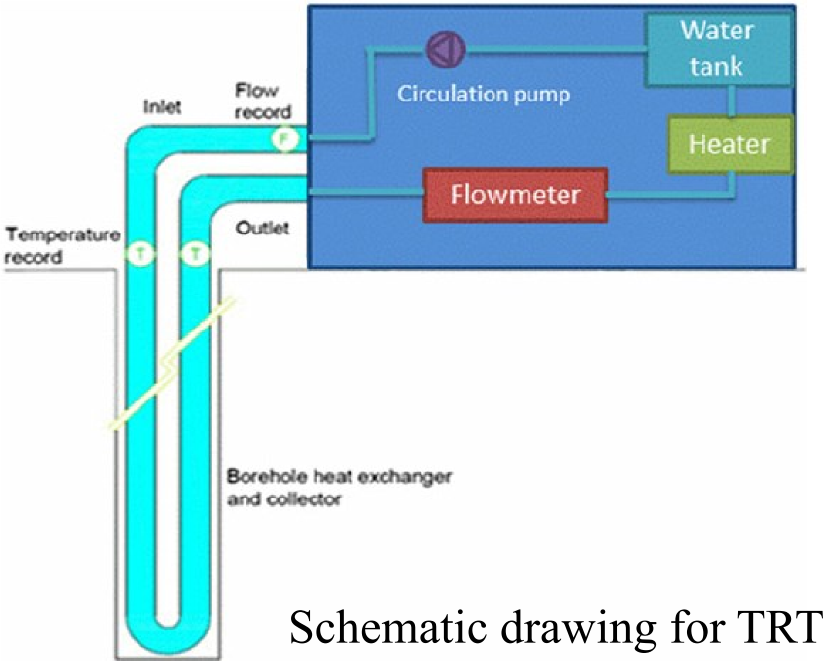


Borehole resistance to heat transfer

Thermophysical properties

- Through a Thermal Response Test (TRT) on a BHE, one can directly get:
  - Thermal conductivity (λ)
  - Borehole thermal resistance (R_b)
  - Undisturbed ground temperature (T_g)
- A detailed explanation of TRT will be discussed in an upcoming lecture.

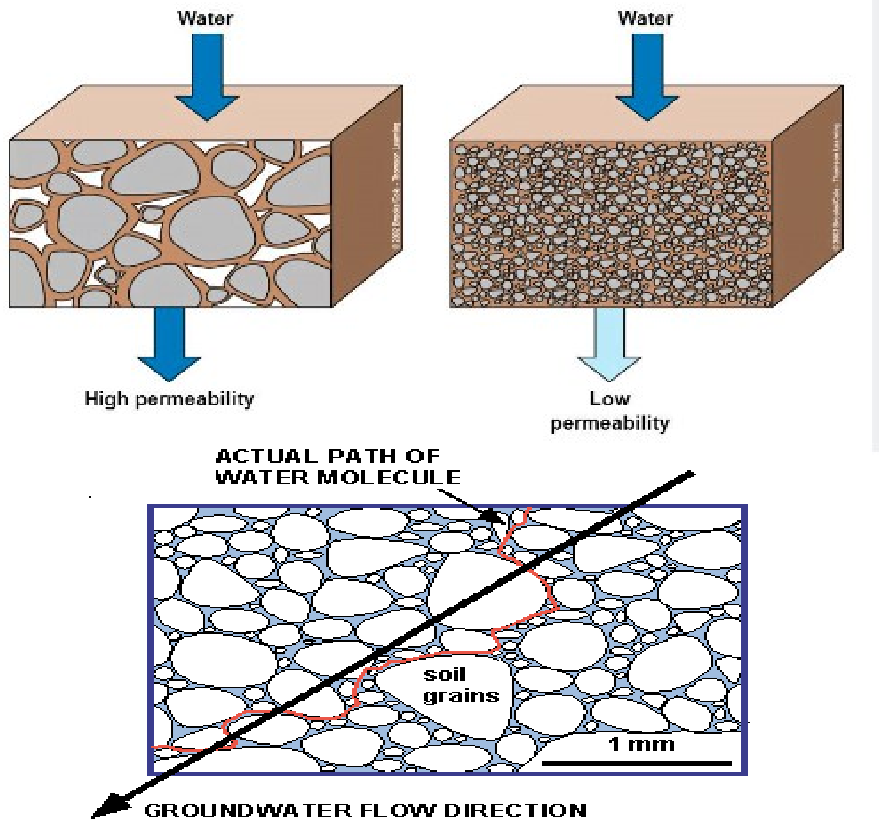

TRT testing machine



Schematic drawing for TRT

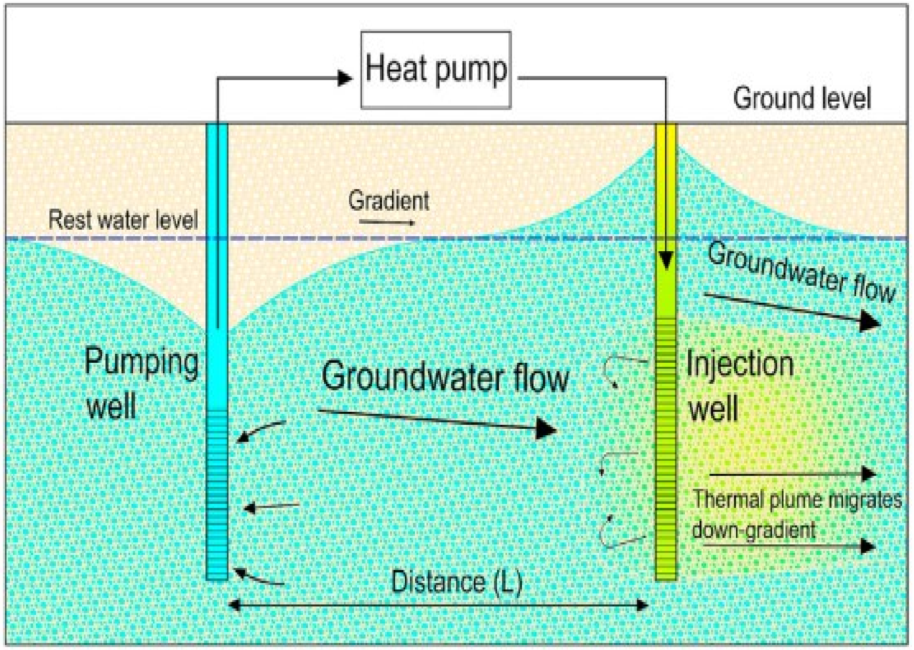
Hydraulic properties

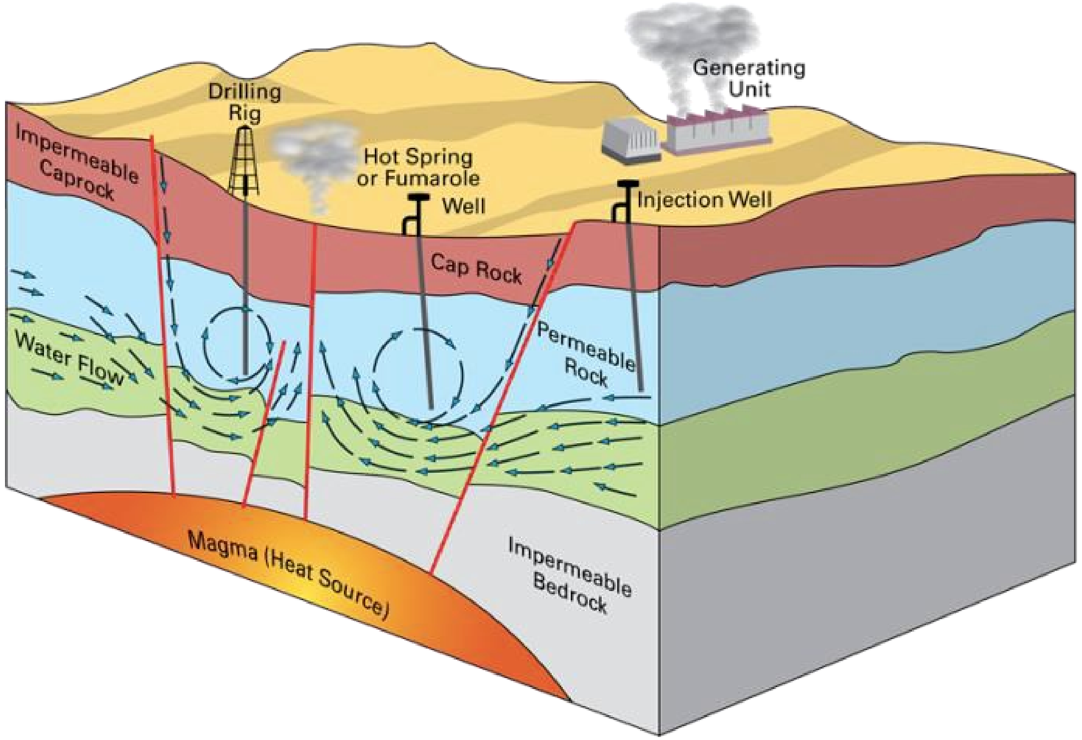
- Hydraulic/hydrogeological properties are very important in shallow geothermal energy exploitation, especially in **open-loop systems**.
- Permeability plays a vital role in open loop systems where water is pumped out through a production well and injected again through an injection well.



Grain size effect on permeability

Hydraulic properties





Groundwater flow direction and position of production and injection wells

Hydraulic properties

- Groundwater flow direction is not important for open-loop only but also for the closed-loop system.
- To avoid thermal interference between different BHEs, the Boreholes are drilled in a perpendicular line to the groundwater flow direction.

Hydraulic properties

- The pumping/flow rate (m^3/h) which is affected by the **pressure drop** in pipelines.

  - Q = m.C.ΔT

- Q: heat transferred (W)
- m: mass flow rate (Kg/s)
- C: specific heat (J/kg.°C)
- ΔT: Temperature difference (°C).

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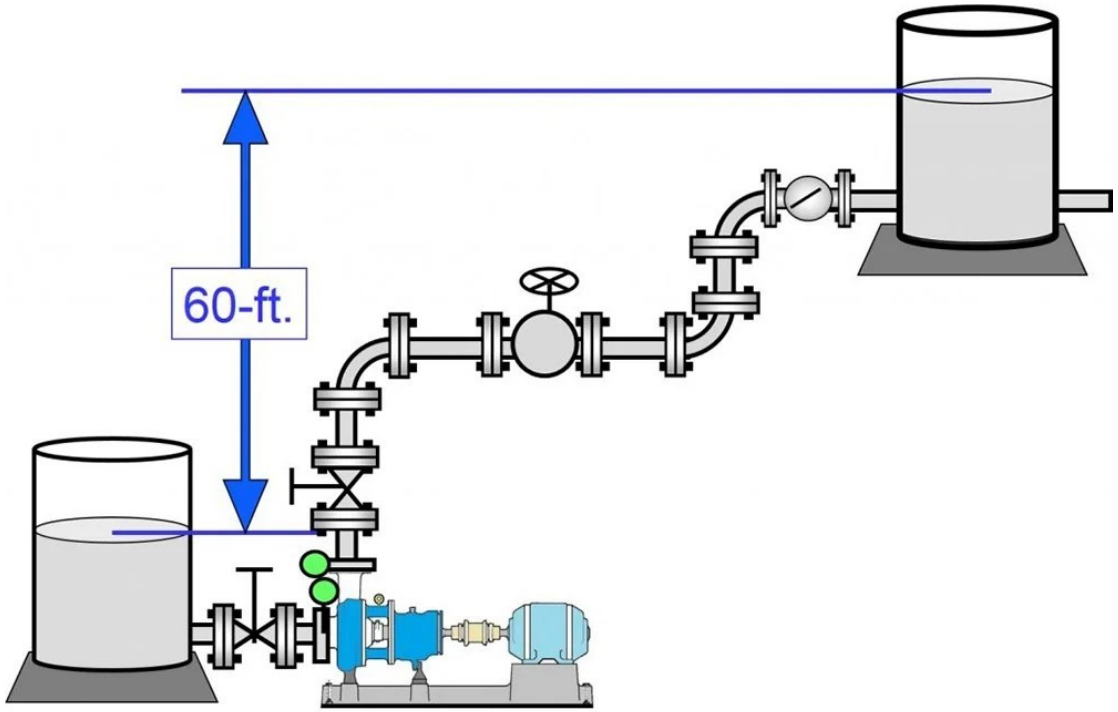
Hydraulic properties

- The pressure drop should be calculated to determine the circulation pump specification.



Pressure drop in pipes

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Shallow geothermal engineering: overview and applications

Lecture 3. Heat exchangers- part 1

Content

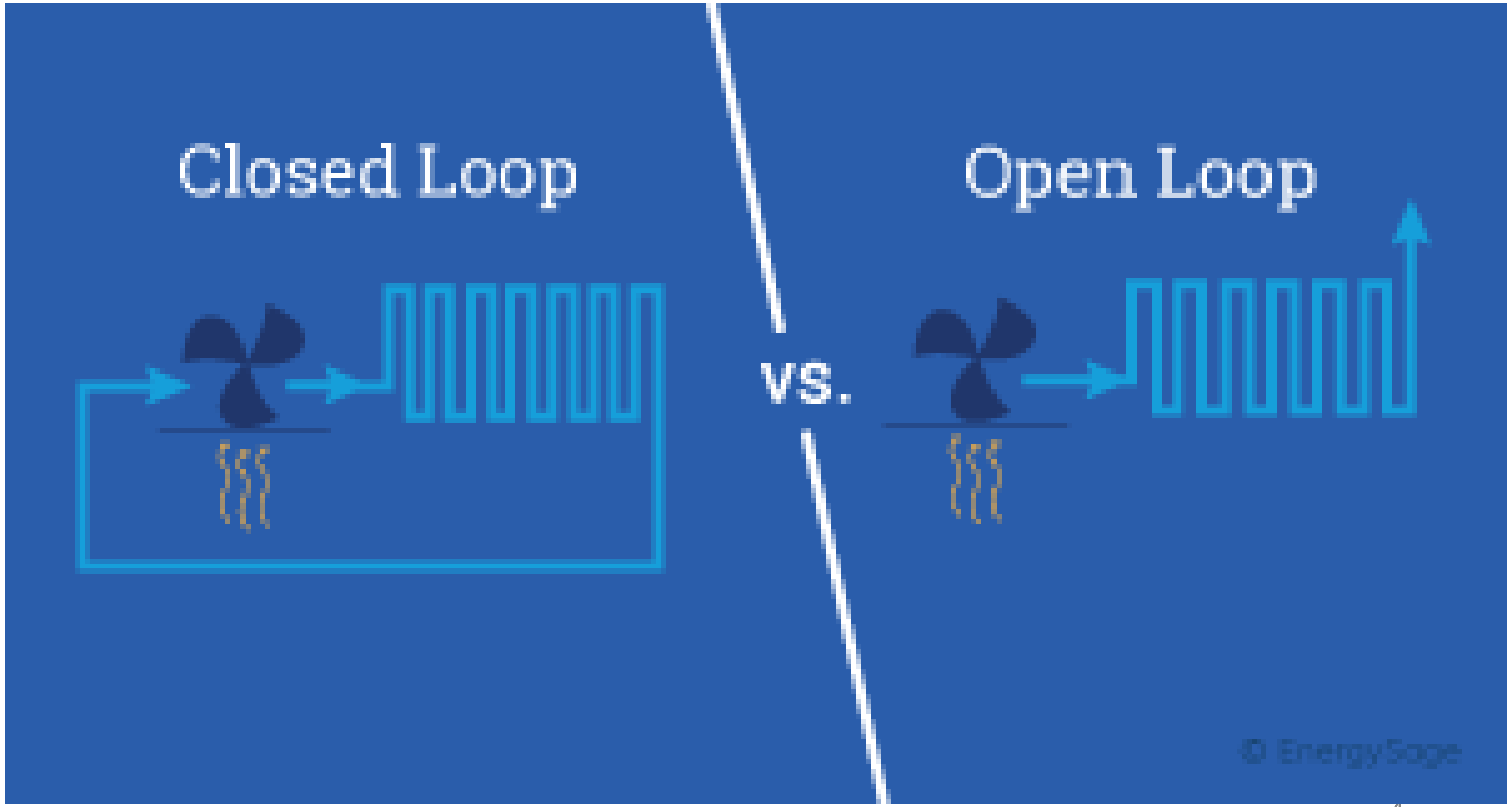
Introduction

- Heat exchangers are used to exchange the heat between two fluids one of them is hot and the other one is cold without direct contact between them.

- In shallow geothermal resources, where the fluid temperature is not high enough, heat is exchanged via heat pumps.

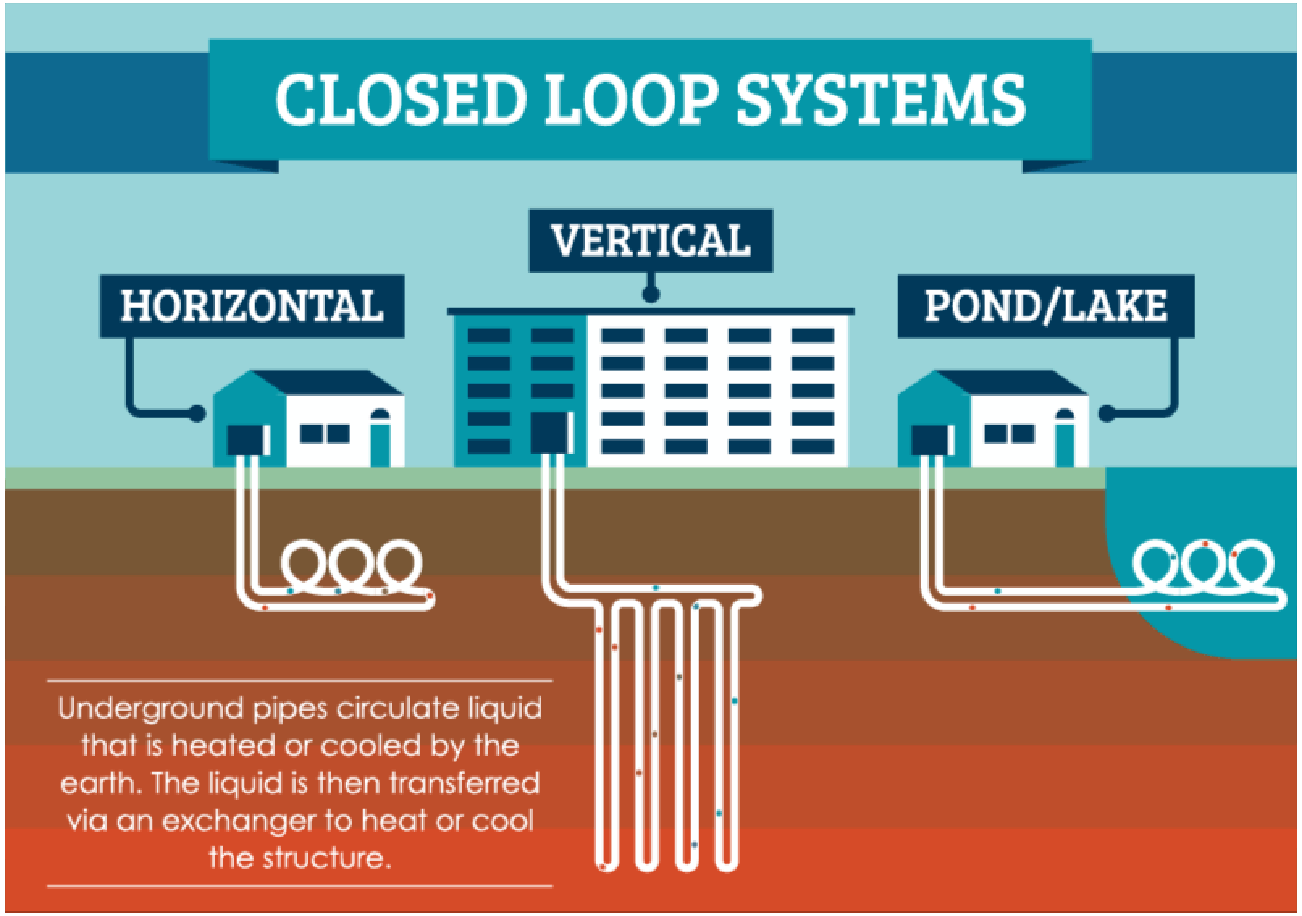
Shallow geothermal exploitation systems

- Closed loop system
- Open loop system



Shallow geothermal exploitation systems

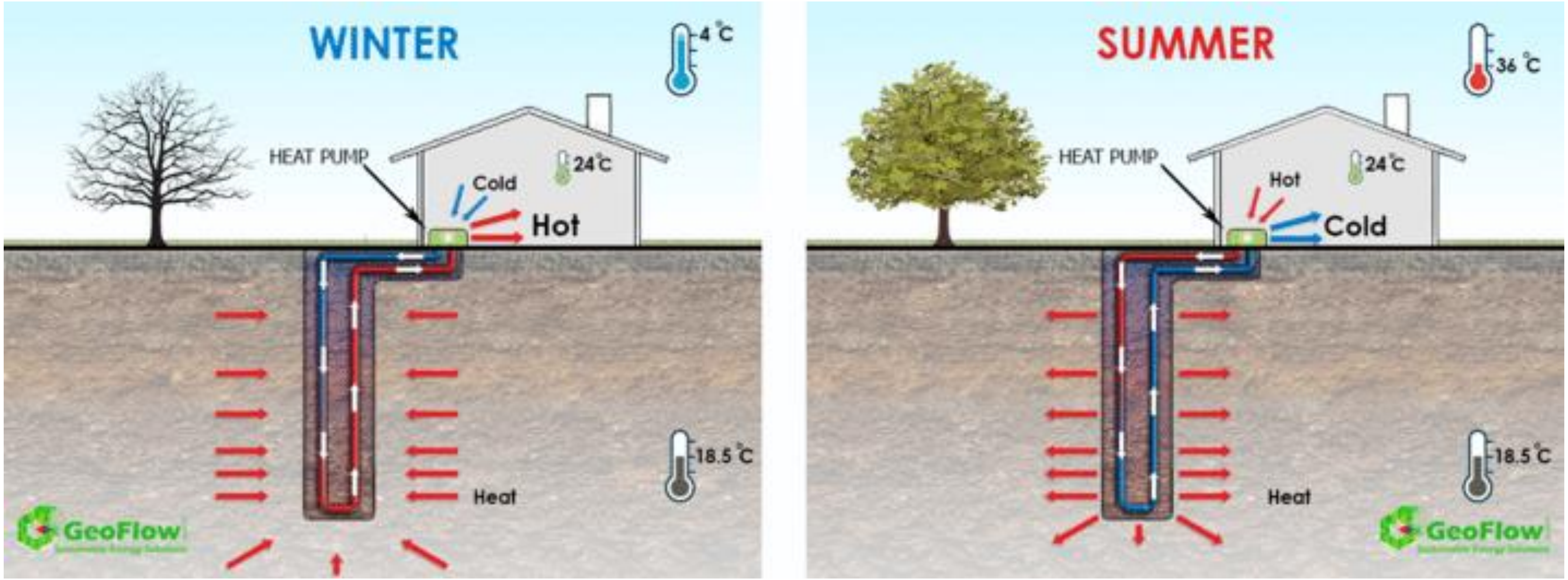
- 1- Closed loop system:
    - Vertical borehole heat exchanger (BHE)
    - Horizontal pipelines.



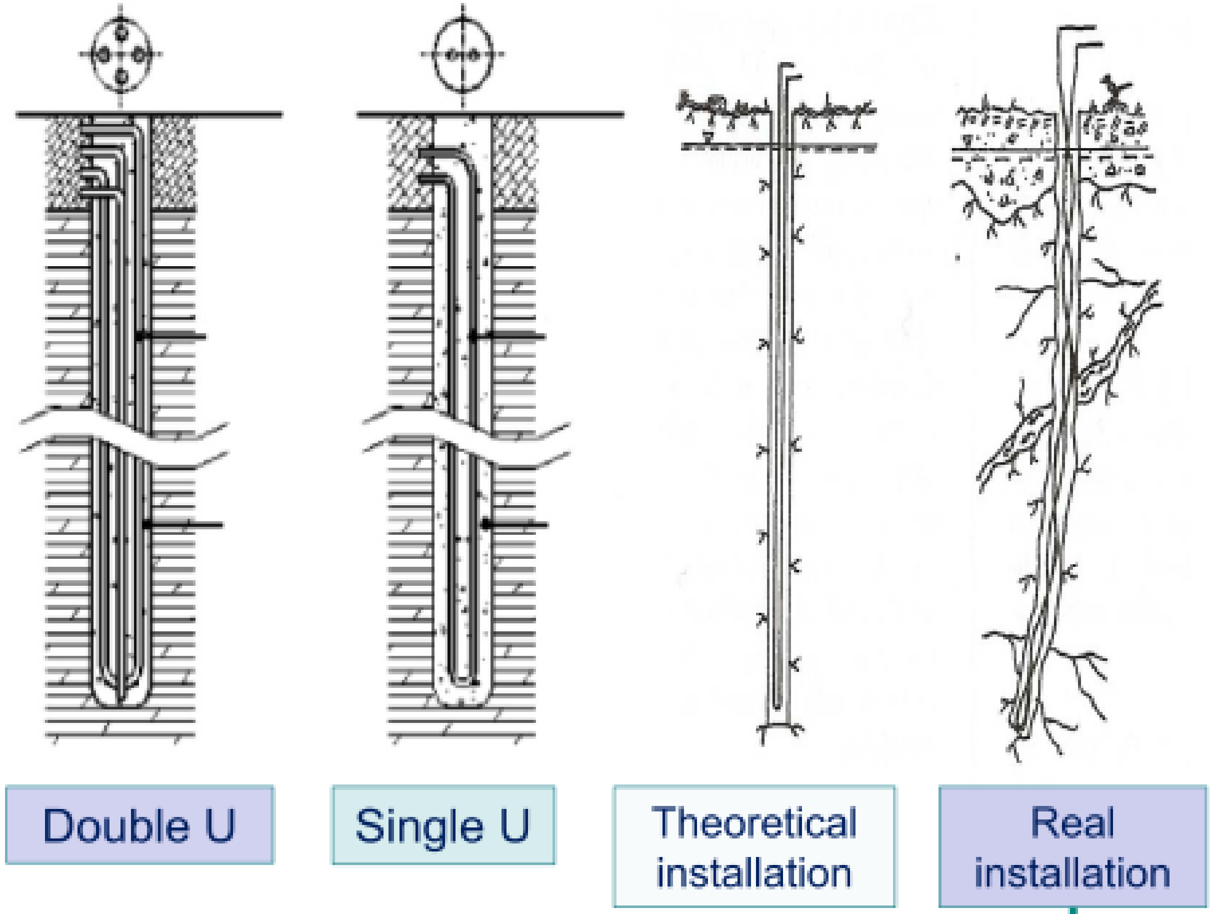
Shallow geothermal exploitation systems

- Vertical borehole heat exchanger (BHE):
  - Is the most efficient technology nowadays.
  - Heat transfer is carried out mainly via conduction.
  - Requires lower space
  - Reach higher depth.
  - Independent of weather.

Shallow geothermal exploitation systems



Shallow geothermal exploitation systems



Shallow geothermal exploitation systems

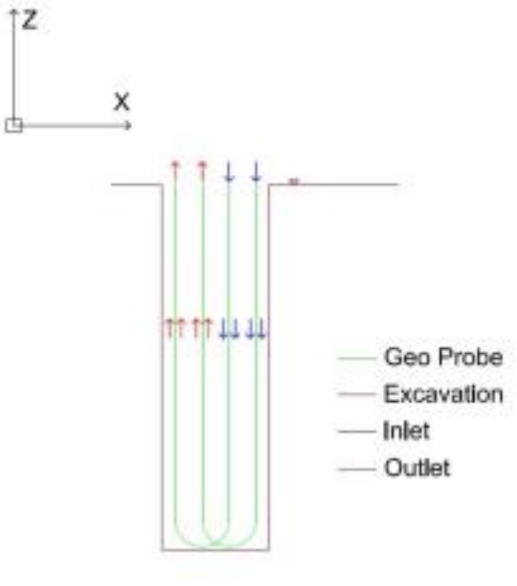
- Vertical borehole heat exchanger (BHE):
  - A BHE is made by a vertical drilling. Inside the hole, two or more pipes are installed with a U-bend at the bottom.
  - Borehole Diameter 127 -200 mm.
  - Pipe Diameter 32- 50 mm.
  - Grouting fills the annulus between pipelines starting from bottom to top using dedicated pipe.

Shallow geothermal exploitation systems

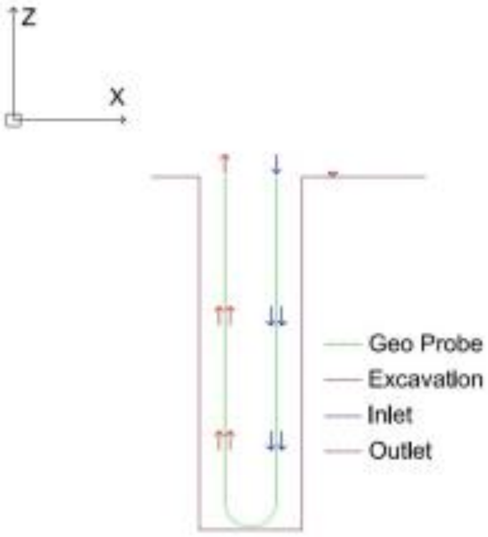
- Vertical borehole heat exchanger (BHE):
- Heating mode:
  - The circulating fluid is colder than surroundings and absorbs heat from the ground.
- Cooling mode:
  - The circulating fluid is hotter than surroundings and releases heat to the ground

Shallow geothermal exploitation systems

- Vertical borehole heat exchanger (BHE):



Double U



Single U

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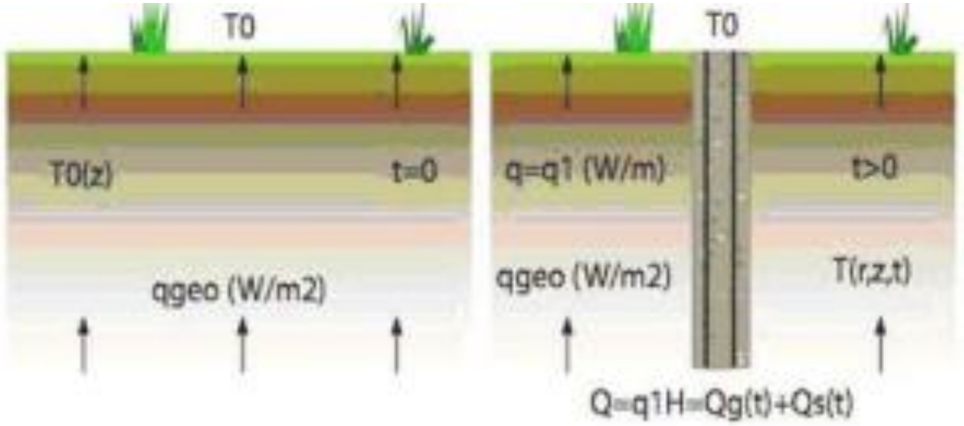
Shallow geothermal exploitation systems

- Vertical borehole heat exchanger (BHE):
  - Inside the pipe a thermovector fluid flows, which heats up or cools down depending on the system use
  - The higher the temperature difference between inlet and outlet, the higher exploited power.

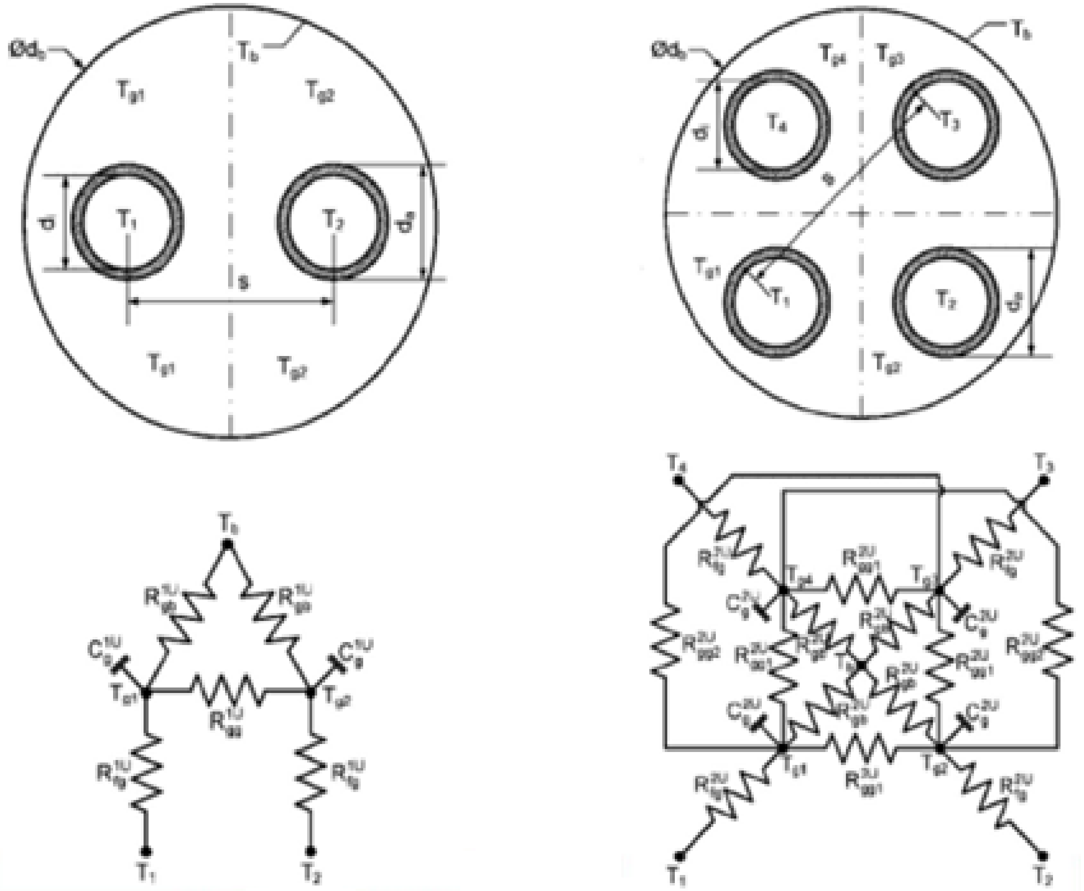


Shallow geothermal exploitation systems

- Vertical borehole heat exchanger (BHE):
  - Heat transfers modes in geothermal borehole :
    - Conduction: between ground and the geothermal pipes.
    - Convection: of the fluid inside pipes.
    - Advection: due to the ground water flow.

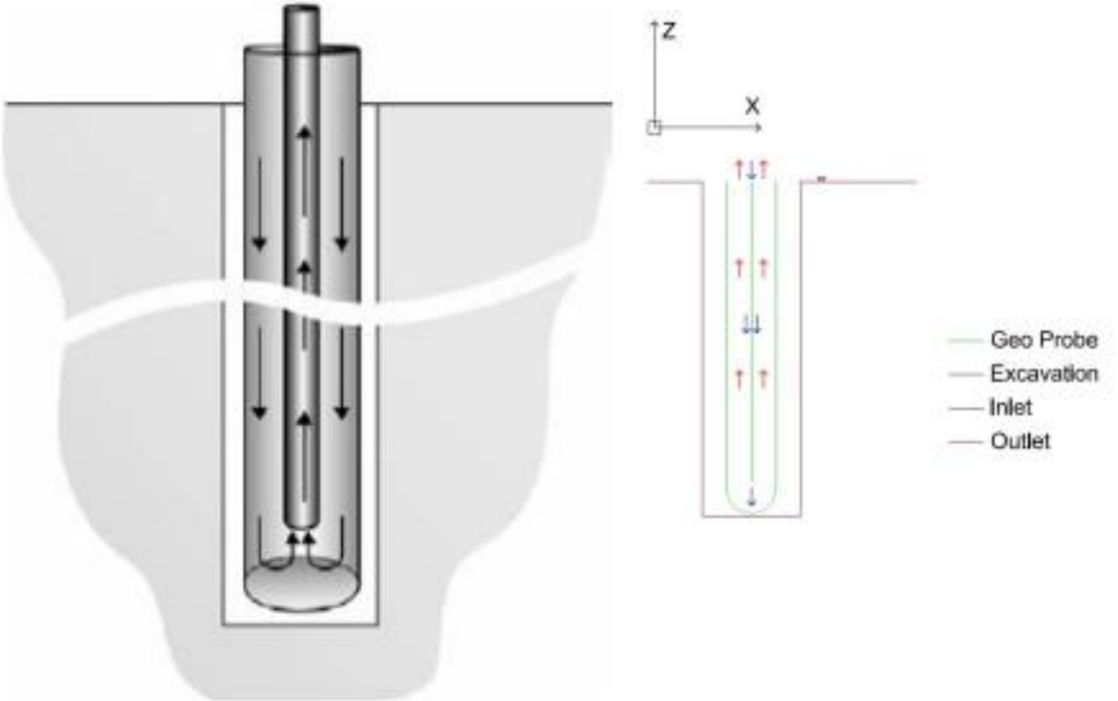
Shallow geothermal exploitation systems

- Vertical borehole heat exchanger (BHE):
  - The basis model is a conductive model.
  - Heat moving in radial direction from fluid to the ground or vice versa.
  - All materials crossed by heat are represented by thermal resistances and thermal capacities in series (pipe, grouting, ground).
  - The geological layer is represented in parallel. the usual model is called Delta Circuit



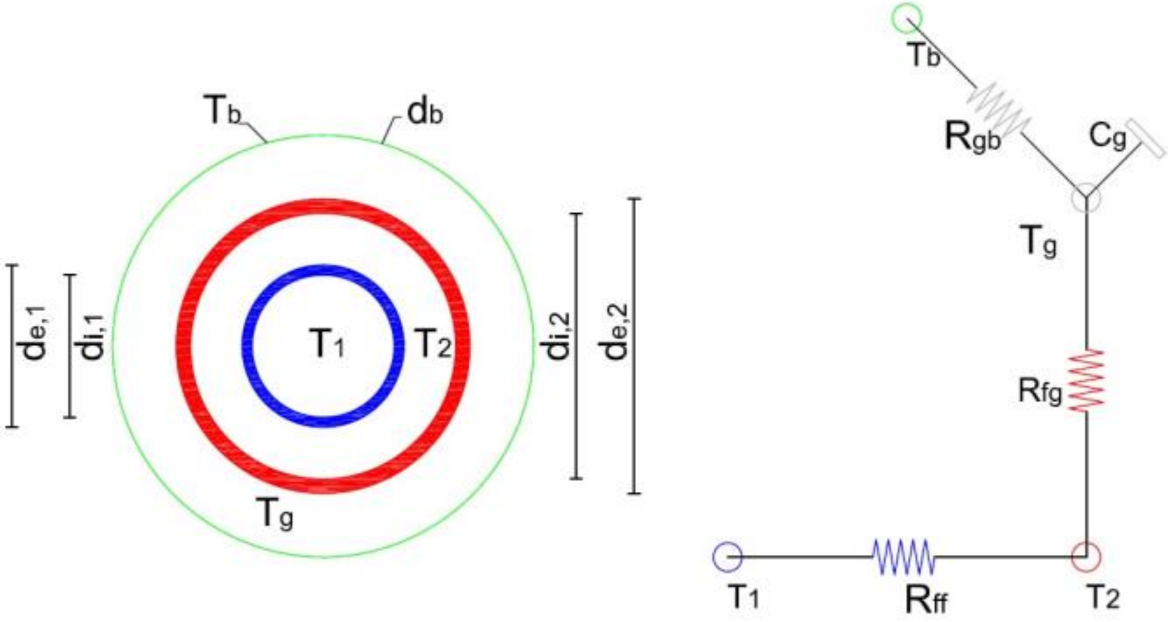
Shallow geothermal exploitation systems

- Vertical borehole heat exchanger (BHE):
  - Coaxial pipes
    - Advantage:
      - possibility or insulating the return pipe.
    - Disadvantage:
      - big external diameter (63 mm or more).
      - Difficult to be at high depth



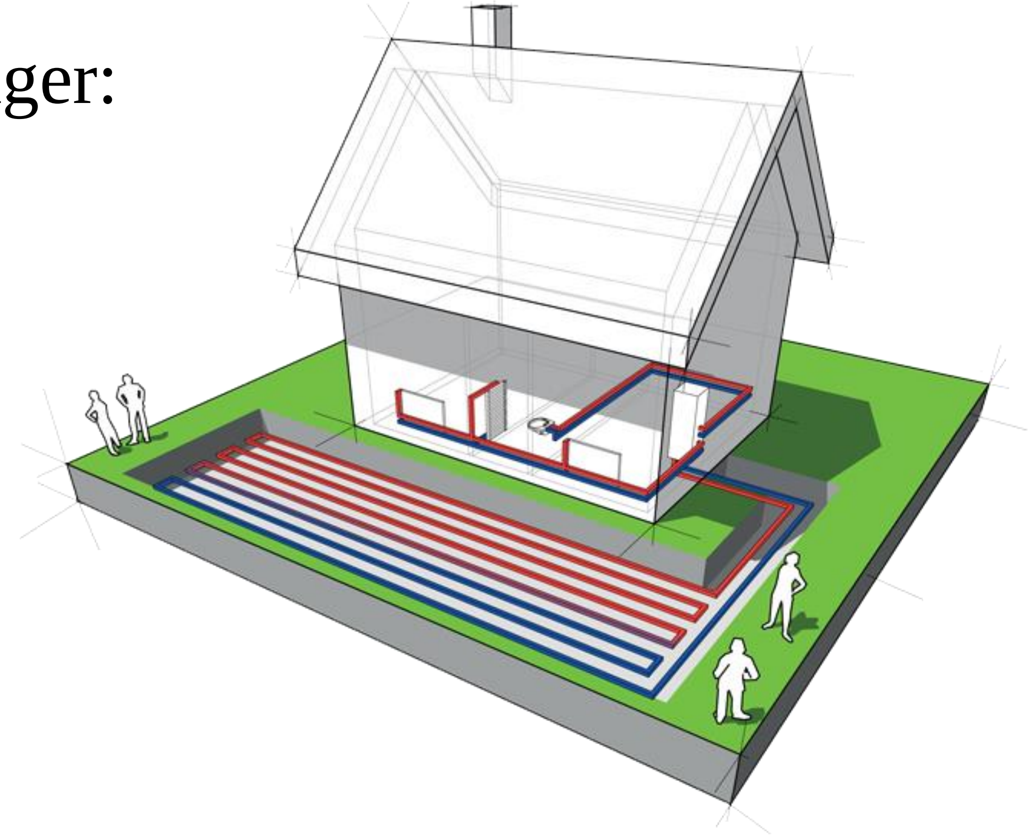
Shallow geothermal exploitation systems

- Resistances of coaxial pipes



Shallow geothermal exploitation systems

- Horizontal borehole heat exchanger:
  - Shallow pipelines.
  - Lower drilling cost.
  - Climate dependent.
  - less efficient.

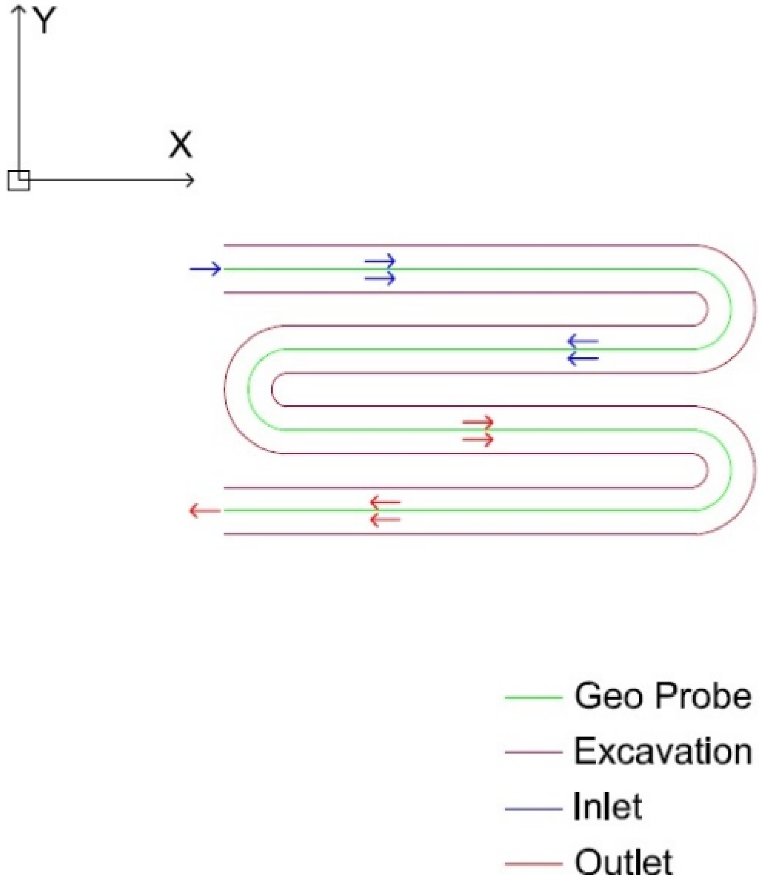


Shallow geothermal exploitation systems

- Horizontal borehole heat exchanger:

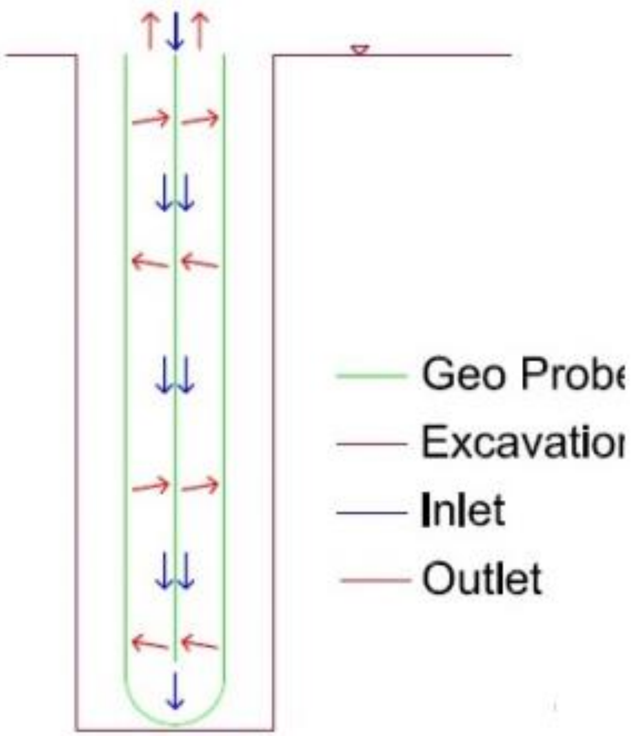
Trench installation

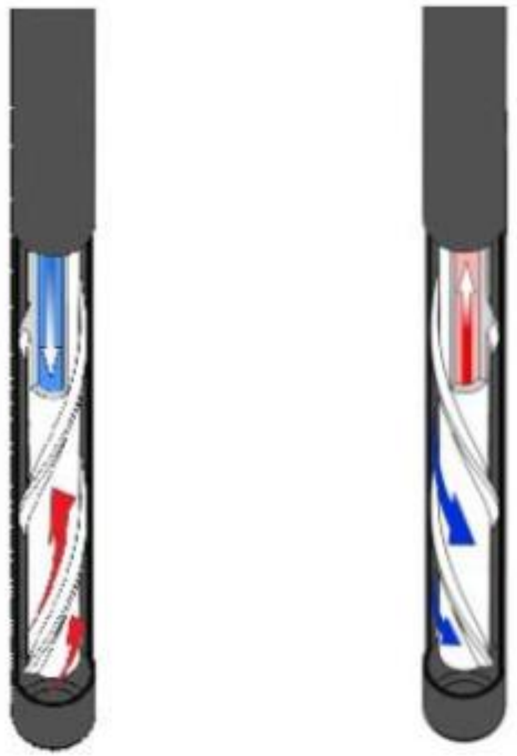
Bench installation



Shallow geothermal exploitation systems

- Spiral BHE:
  - Increase surface of heat transfer.
  - Increase heat transfer coefficient without heat drop increase.

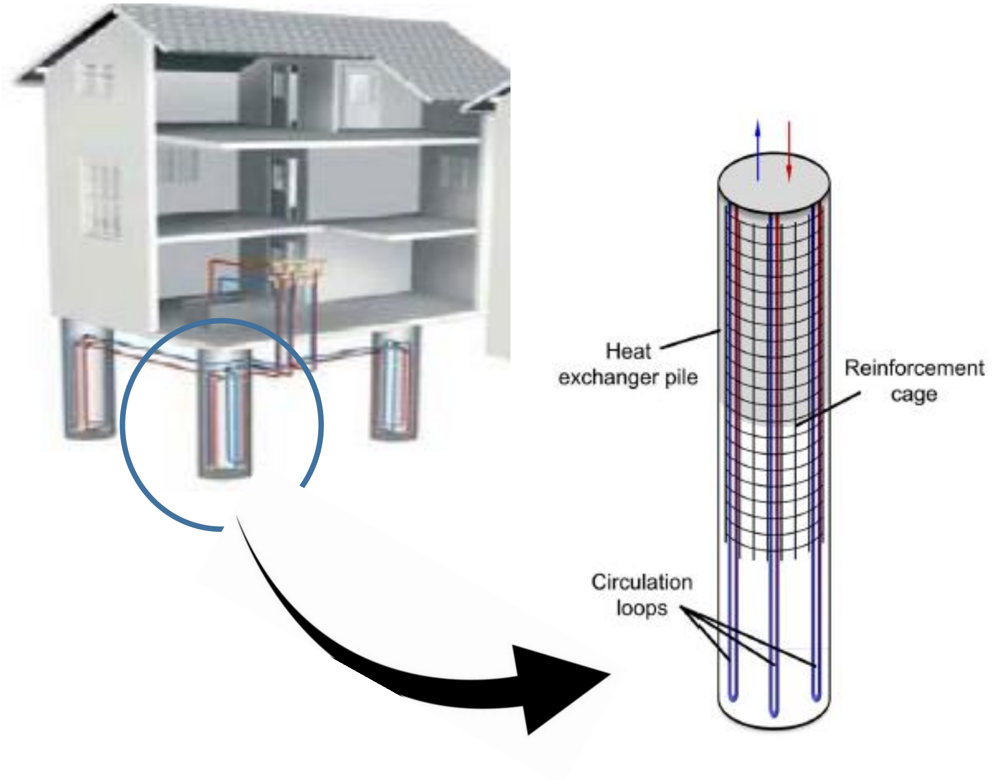




Shallow geothermal exploitation systems

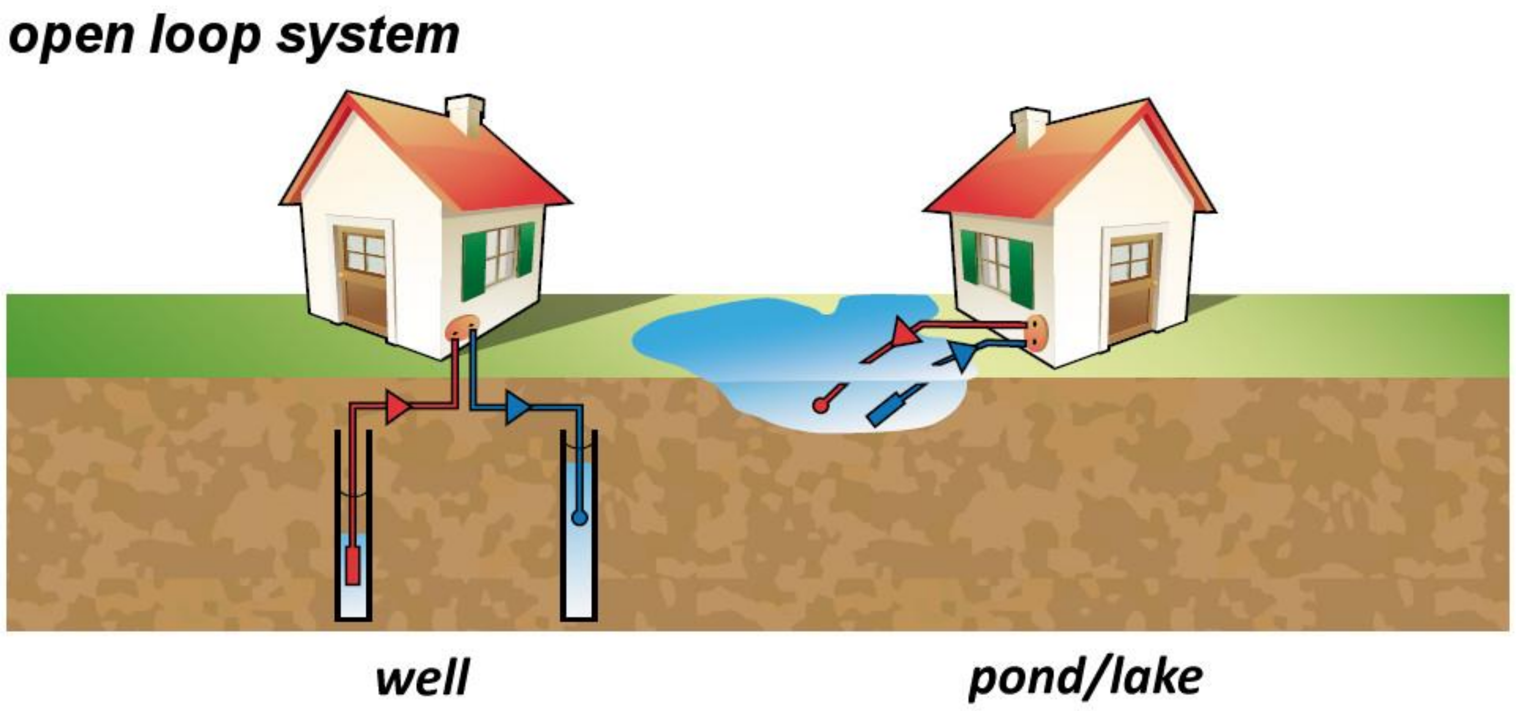
- Piles Geo-exchangers:

    - Implemented during construction into the building piles
    - Can reach 10-20 m.
    - Low output power.
    - Can work in a hybrid system to cover the required thermal load.



Shallow geothermal exploitation systems

- 2- Open loop system:



Shallow geothermal exploitation systems

- Open loop system:
  - Ground water is extracted through a production well until reaching the heat pump.
  - Then, water is re-injected into the ground through an injection well.
  - The distance between both wells must be well calculated.
  - Higher output power than BHEs.
  - Higher costs for pumping out.
  - Water quality: filters must be applied.

Shallow geothermal exploitation systems

- Both closed loop and open loop systems are connected to the heat pump where heat exchange occurs.
- In closed loop systems, heat transfers between ground and fluid into the borehole through the BHEs and then in the heat pump.
- In open loop systems, heat transfer occurs in the heat pump.

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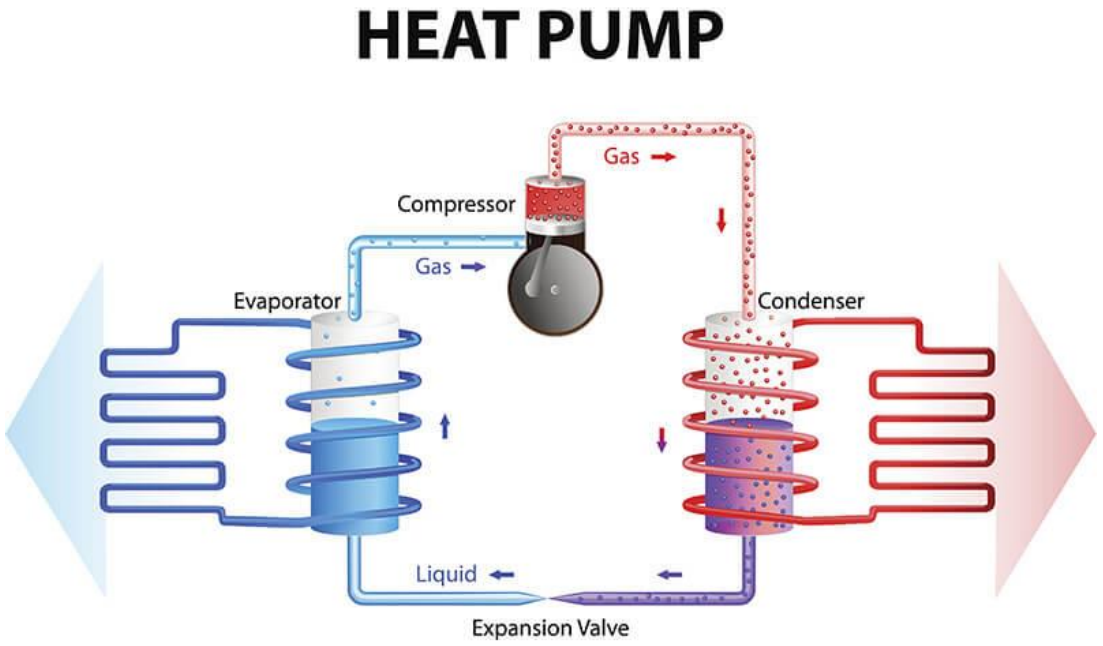
Shallow geothermal engineering: overview and applications

Lecture 4. Heat exchangers- part 2

Heat exchange in Heat Pumps

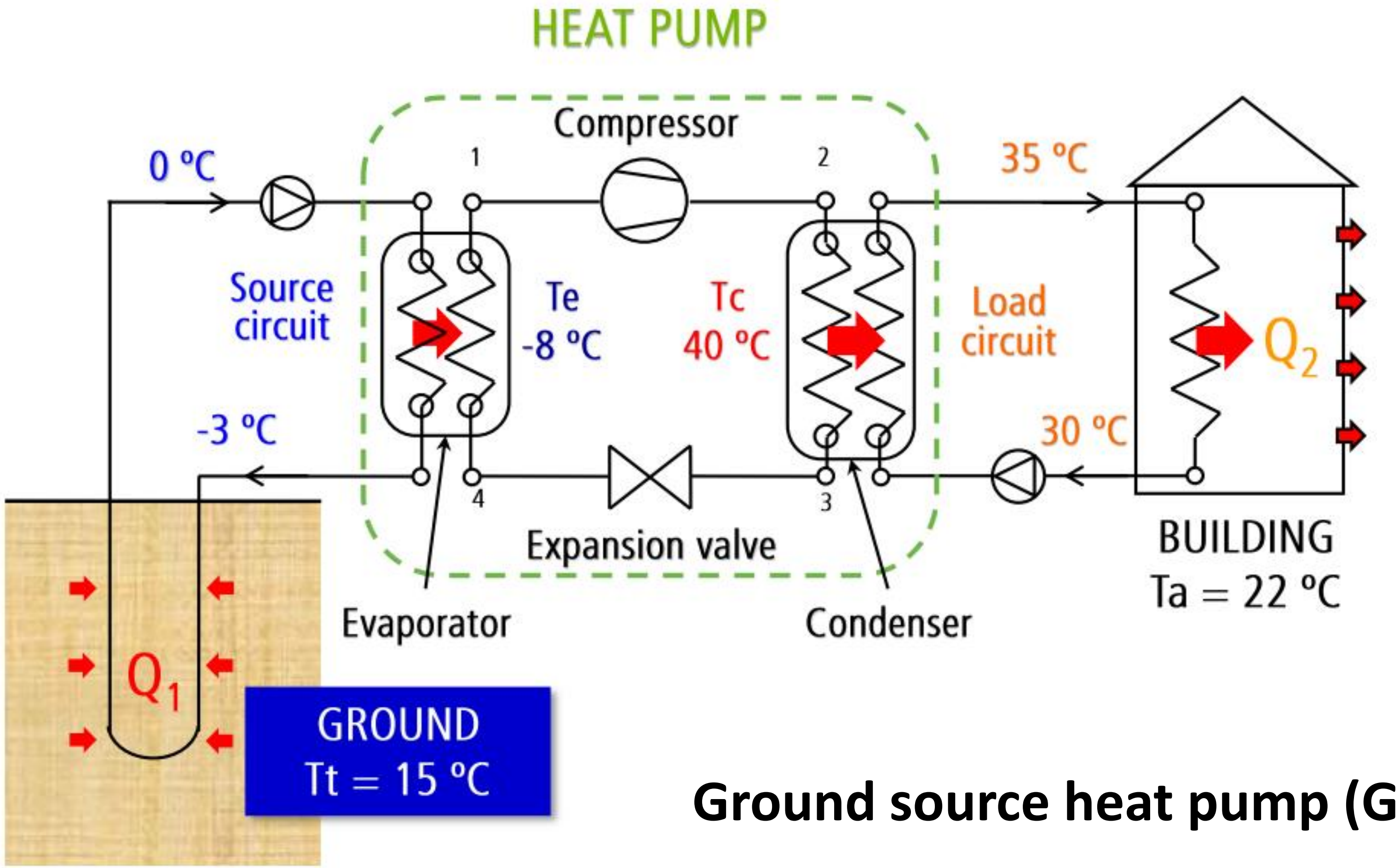
- Heat pumps absorb heat from a source and transfer it to another source with external work exerted.



Heat exchange in Heat Pumps

- Heat pumps can be classified according to the source from which heat is extracted:
  - Air-air (A-A)
  - Air-water (A-W)
  - Water-water (W-W, ground source heat pump).
  - Water-air (W-A)
- Heat pumps can be used for heating only or cooling only or both.

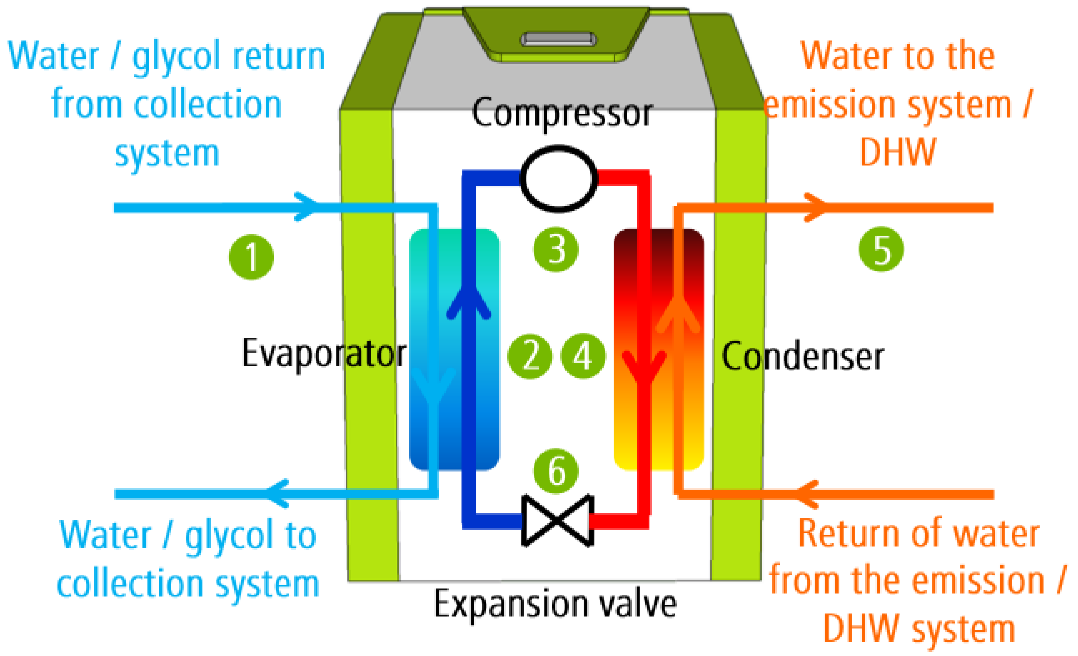
Heat exchange in Heat Pumps (GSHP)



Ground source heat pump (GSHP)

Heat exchange in Heat Pumps (w-w)- heating process

- Water with glycol (antifreeze) circulates (by pumps) into the pipes buried into the ground.
- Water has lower temperature than the surrounding ground, So heat transfers from ground to water.
- This water transfers its gained heat to a refrigerant circulating into the evaporator until this refrigerant turns into vapor (boil).

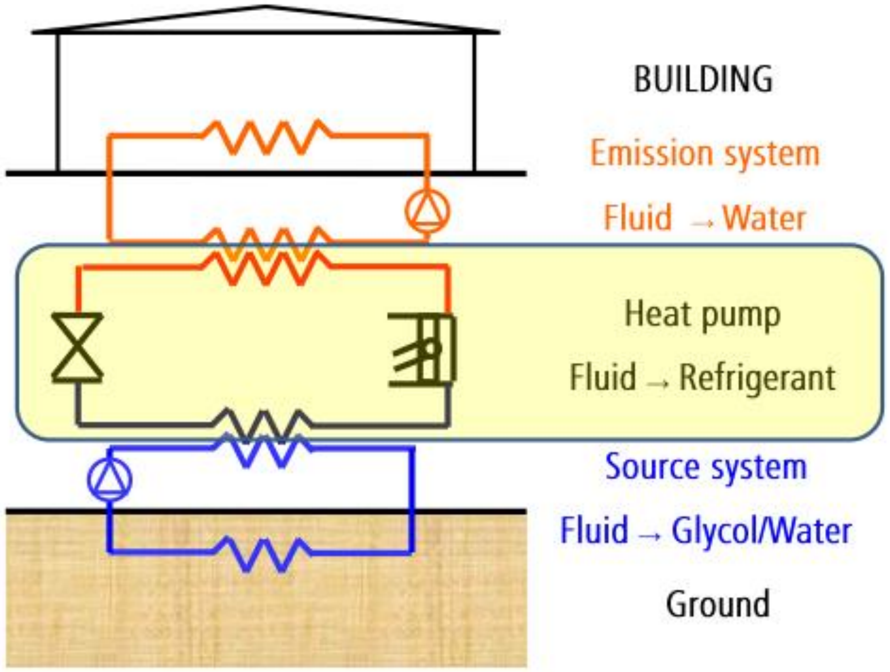


Heat exchange in Heat Pumps (w-w)- heating process

- Then, this refrigerant, in form of vapor, goes to the compressor where pressure and temperature of increases.
- After that, the compressed fluid goes to the condenser where it is cooled and condensed giving its heat to the water in the emission system (fan coils, radiators, underfloor heating/cooling) .
- This water is distributed into the building/facility which need to be heated/cooled.

Heat exchange in Heat Pumps (w-w)- heating process

- The condensed refrigerant, which had lost its heat in the condenser, passes the expansion valve, where pressure and temperature decreases.
- Finally, this refrigerant can gain heat agai from the water with glycol coming from the (BHE) and starts new cycle.



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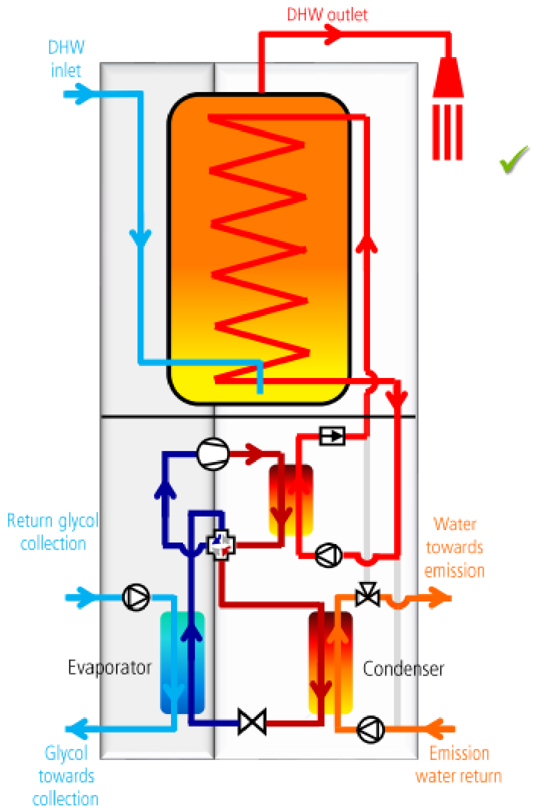
Heat exchange in Heat Pumps (w-w)-heating+ Cooling process

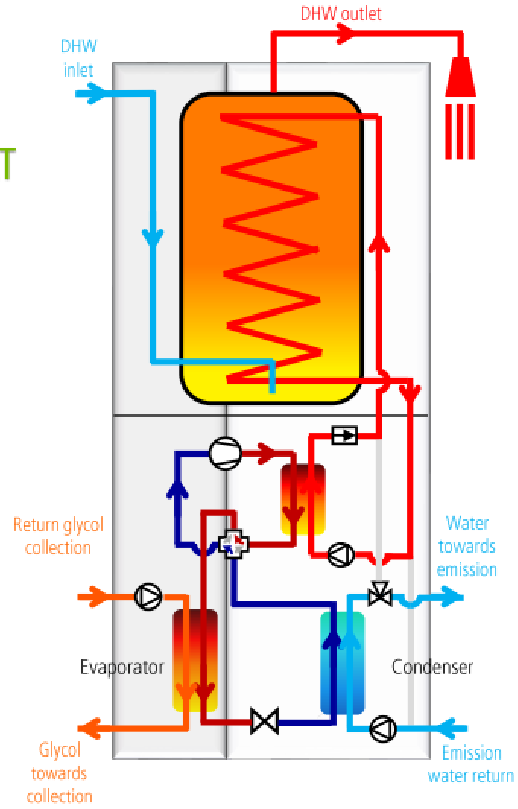
DHW: Domestic Hot Water

Heating + DHW



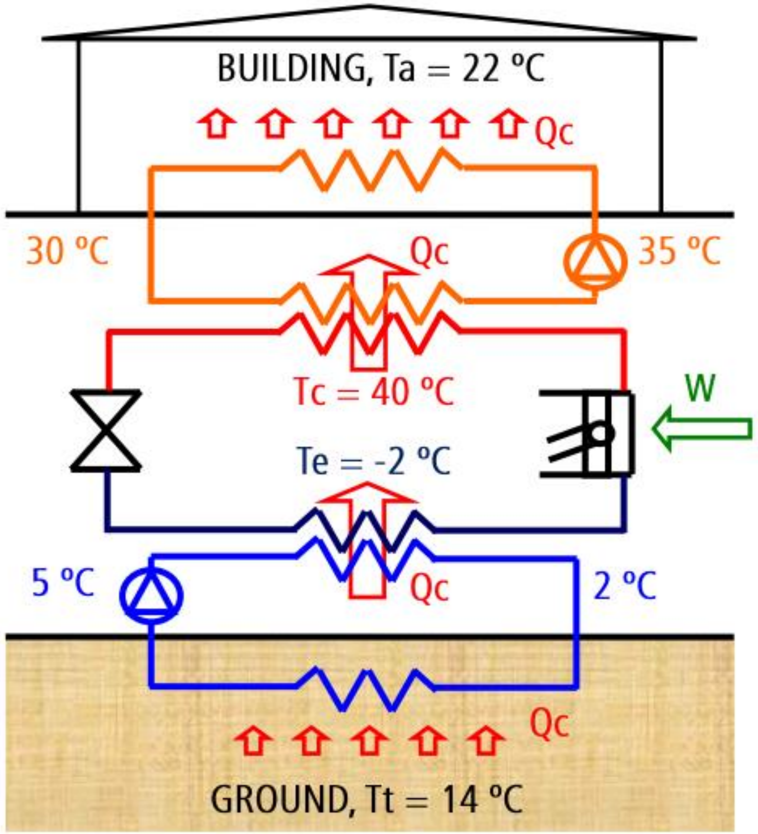
- ✓ SIMULTANEOUS HEAT / COLD AND DHW / POOL
- ✓ PERFORMANCE INCREASE UP TO 200%

Cooling + DHW



Heating efficiency of heat pumps

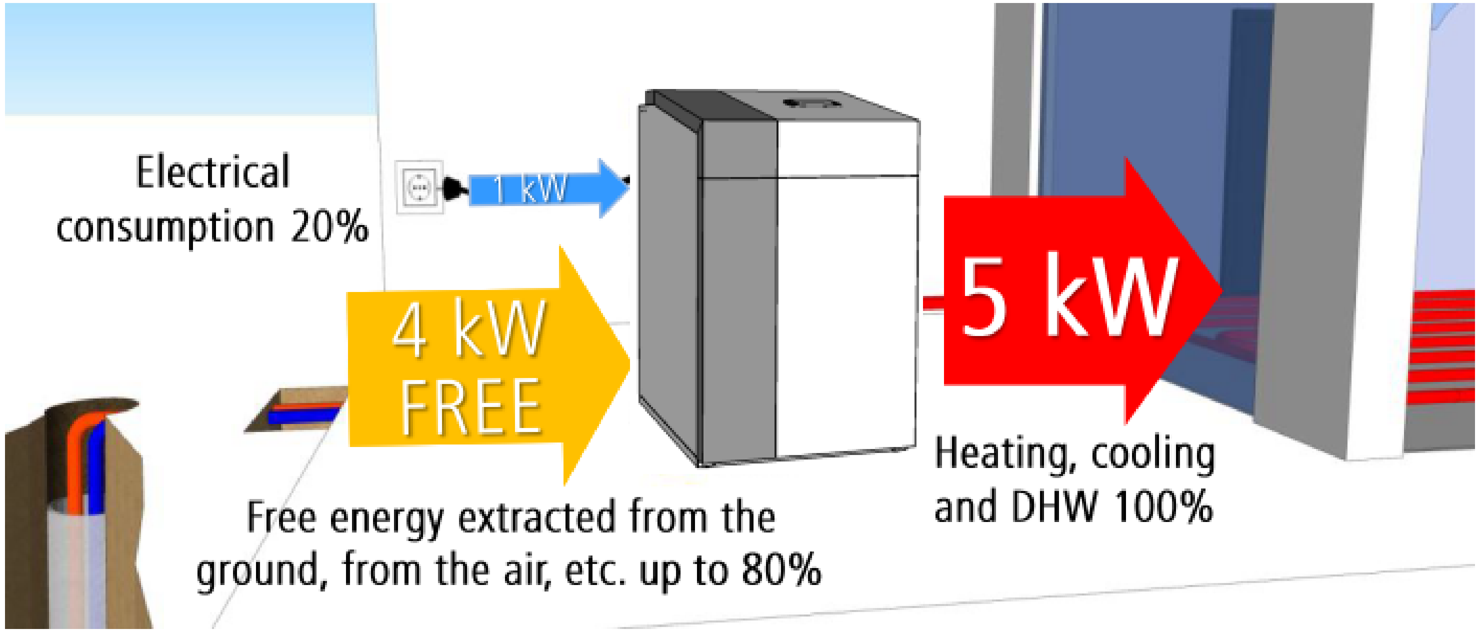
- Coefficient of performance (COP):
  - COP= $\frac{output\ power}{input\ electrical\ power} = \frac{P_H}{P_E}$
- Seasonal Coefficient of performance (SCOP):
  - Represented in certain time (energy form not power)
  - SCOP= $\frac{output\ Energy}{input\ electrical\ Energy} = \frac{E_H}{E_E}$



Cooling efficiency of heat pumps

- Efficiency energy ratio (EER):
  - EER= $\frac{output\ power}{input\ electrical\ power} = \frac{P_C}{P_E}$
- Seasonal EER(SEER):
  - Represented in certain time (energy form not power)
  - SEER= $\frac{output\ Energy}{input\ electrical\ Energy} = \frac{E_C}{E_E}$
- Seasonal performance factor (SPF): Global factor
  - SPF = $\frac{E_C+E_H}{E_E}$

Efficiency of heat pumps



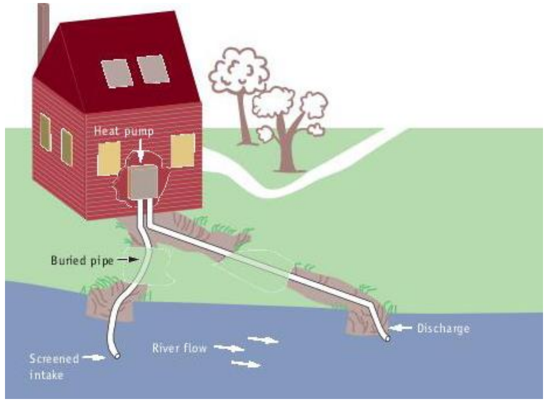
EFICCIENCY = Useful power / Electrical consumption = 5/1 = 5

Types of GSHP

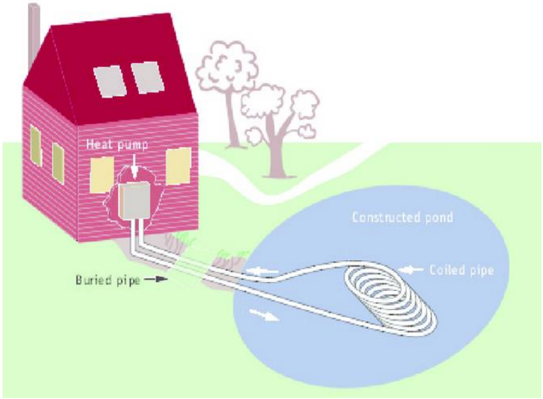
GSHP

- Surface Water Heat Pumps (SWHP)
- Ground water Heat Pumps (GWHP)
- Ground Coupled Heat Pump (GCHP)

Types of GSHP

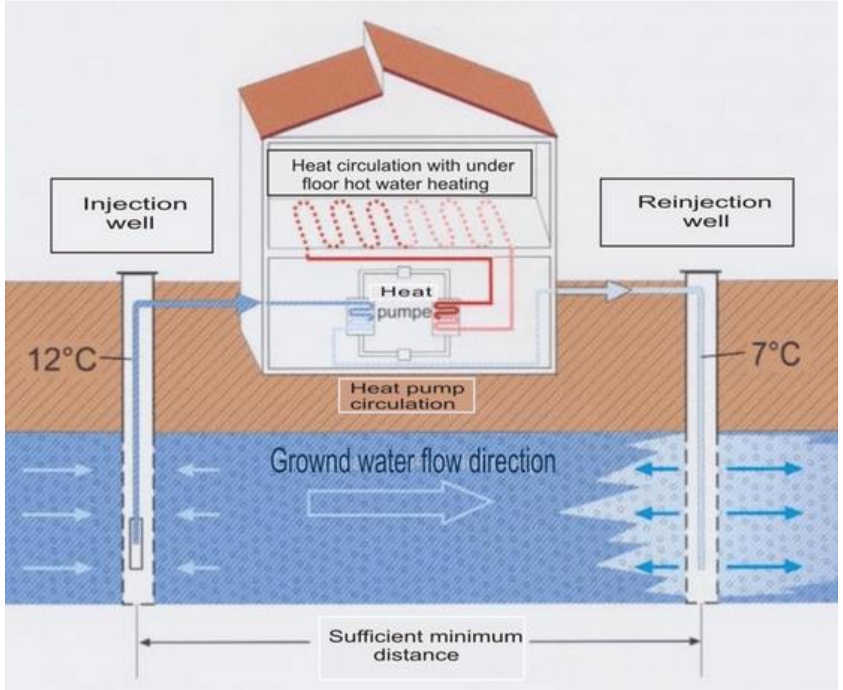


- Surface Water Heat Pump (SWHP):
  - Depends on surface water in its working cycle.
  - Is not suitable in absence of surface water or in freezing areas.



Types of GSHP

- Ground Water Heat Pump (GWHP):
  - Extracts the ground water through a production and reinject water again through another injection well.
  - Depends on the hydraulic properties of the ground (permeability,..).



Types of GSHP

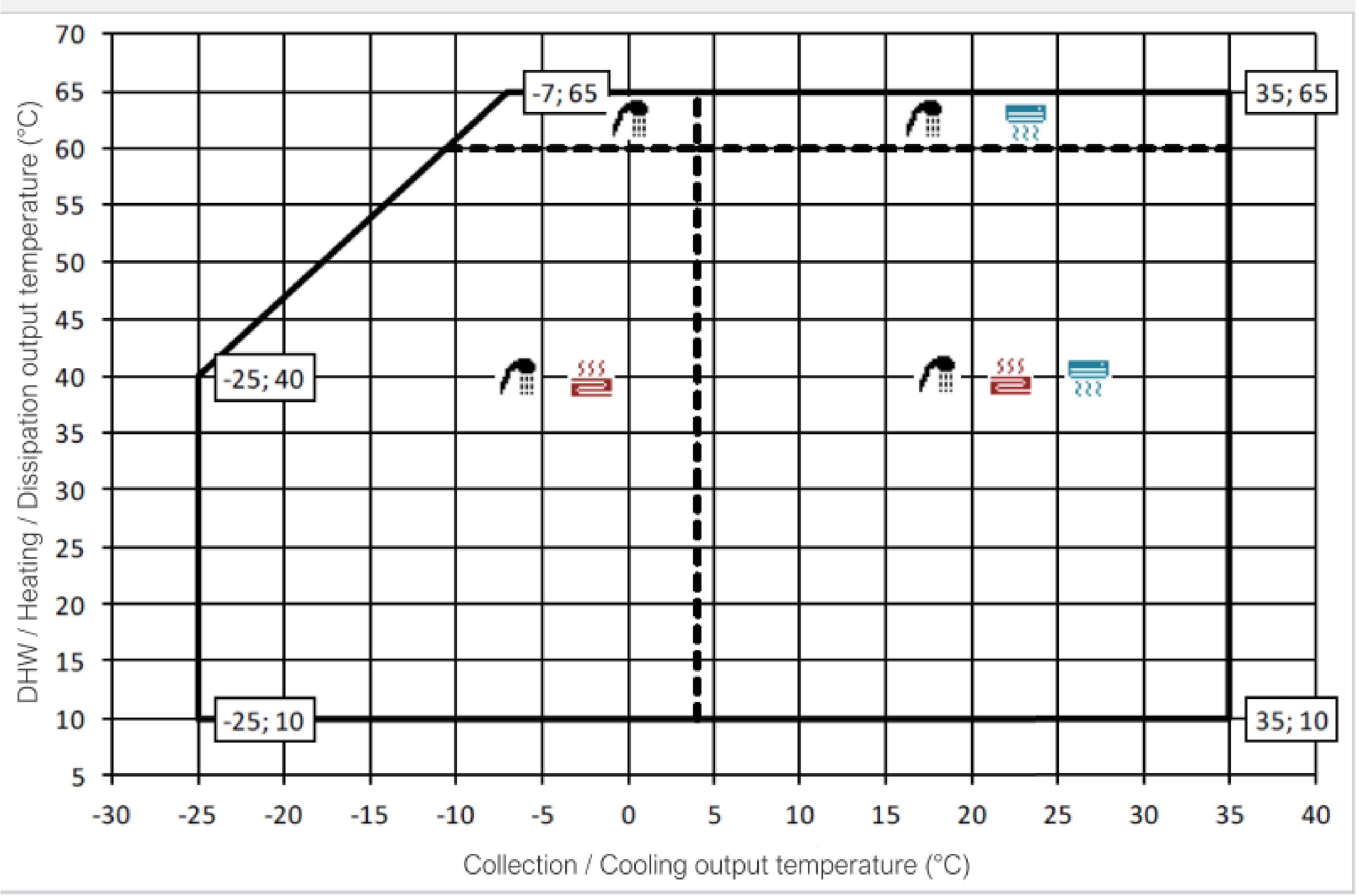
- Ground Coupled Heat Pump (GCHP)
  - Heat is exchanged between the ground and the fluid (in BHE) via conduction.
  - Depends on the thermal properties of the ground and the fluid such as thermal conductivity and ground temperature.

Selection of GSHP

- Firstly, the thermal load of the building is determined.
- The conditions that the heat pump will work within must be determined; for example temperature of the ground and the required temperature of the building or DHW.
- Each heat pump model has an output power range.

Selection of GSHP

- Example of range of temperature for a HP.
- For example, water at temperature -25 results DHW at 10 -40



Selection of GSHP

- Calculation of the required heat pump power depends on the following equation
  - $Q=m.C.\Delta T$
- m: is determined according to the type and conditions of facility.

Selection of GSHP For DHW

- According to the EU standards:

Single house:

Nº Bedrooms	1	2	3	4	5	6	>7
Nº of persons	1,5	3	4	5	6	6	7

Nº of buildings	< 3	4 - 10	11-20	21-50	51-75	76-100	>101
Simultaneity coefficient	1	0,95	0,9	0,85	0,8	0,75	0,7

Type of construction	l/day a 60°C
Single house	28
Hospitals and clinics.	55
Ambulatory and health center.	41
Hotel *****	69
Hotel ****	55
Hotel ***	41
Hotel/hostel **.	34
Camping site.	21
Hostel/pension*.	28
Residence.	41
Penitentiary center.	28
Hostel.	24
Collective changing rooms/showers.	21
School without shower.	4
School with shower.	21
Barracks.	28
Factories and workshops.	21
Offices.	2
Gymnasiums.	21
Restaurants.	8
Cafeterias.	1

Selection of GSHP for Heating/cooling

Type of construction	Thermal load (W/m^2)
Passive Housing	10
Low-energy building	40
Recent construction (as of 2005)	50
Old construction (prior to 2005)	80
Uninsulated construction	100

Distribution type	Energy rating of the house			
	A	B	C	D
Underfloor heating	35 W/m^2	40 W/m^2	45 W/m^2	55 W/m^2
Fan-coils	60 W/m^2	66 W/m^2	75 W/m^2	90 W/m^2
Low temperature radiators	50 W/m^2	60 W/m^2	70 W/m^2	80 W/m^2

Selection of GSHP for Heating/cooling

- If you have an uninsulated area of 160 m^2 classified as a low energy building (thermal load 100 W/ m^2) , a power of 100*160 =16000 W of heating is required.
- You have to look for a heat pump that can provide this amount of Kilo Watts at the available ground temperatures.
- The following information represents a heat pump from EcoForest (ecoGEO + B/C 5-22).

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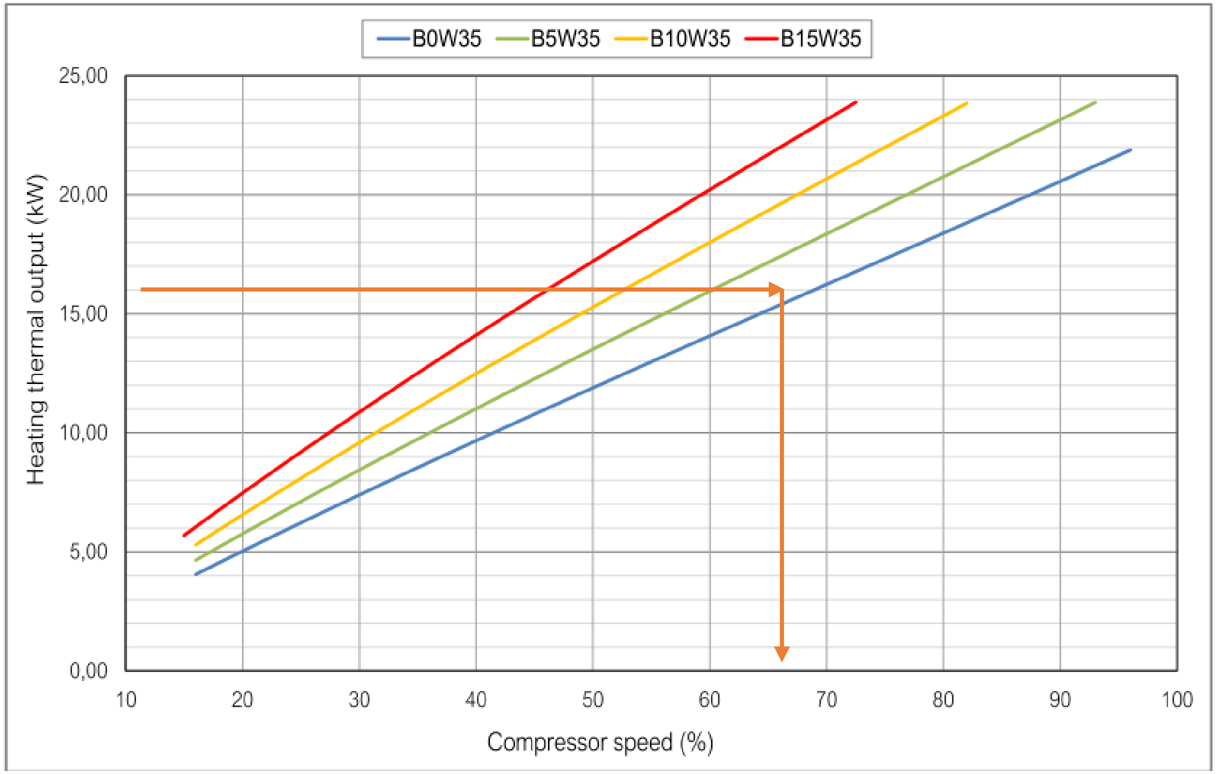
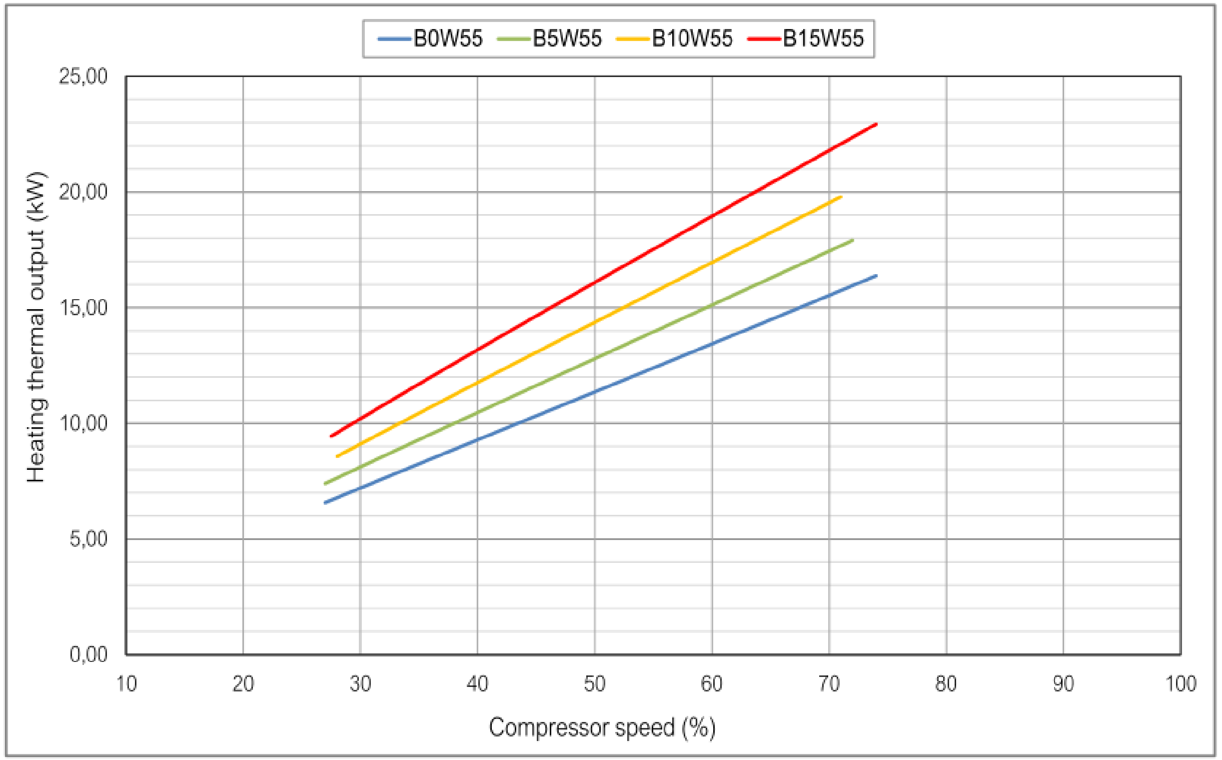
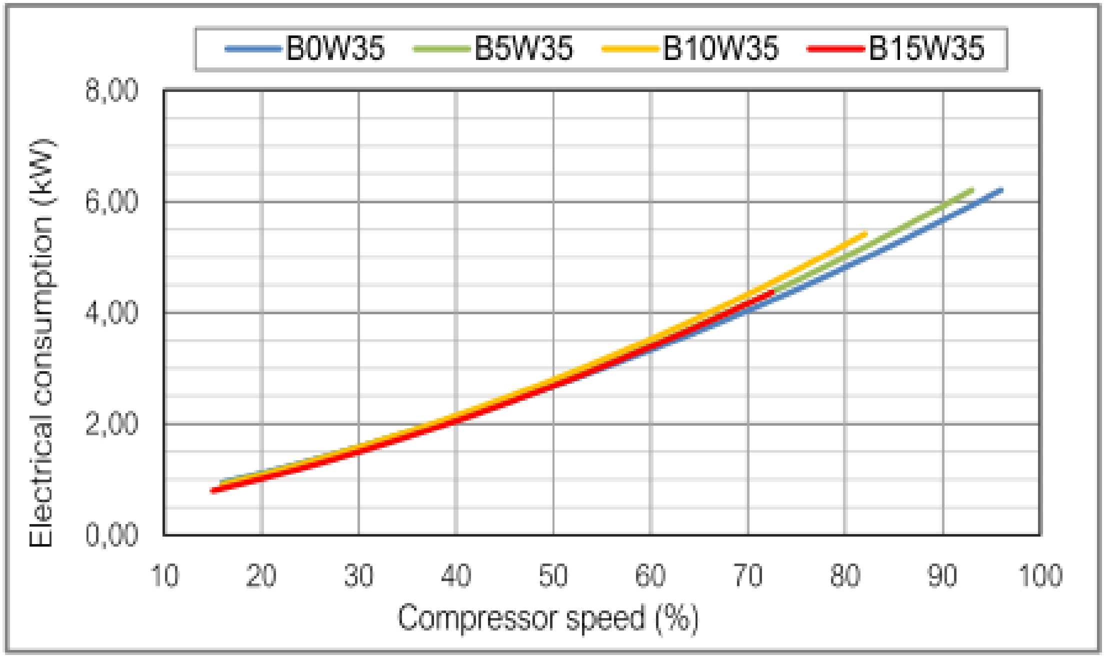
Selection of GSHP for Heating/cooling



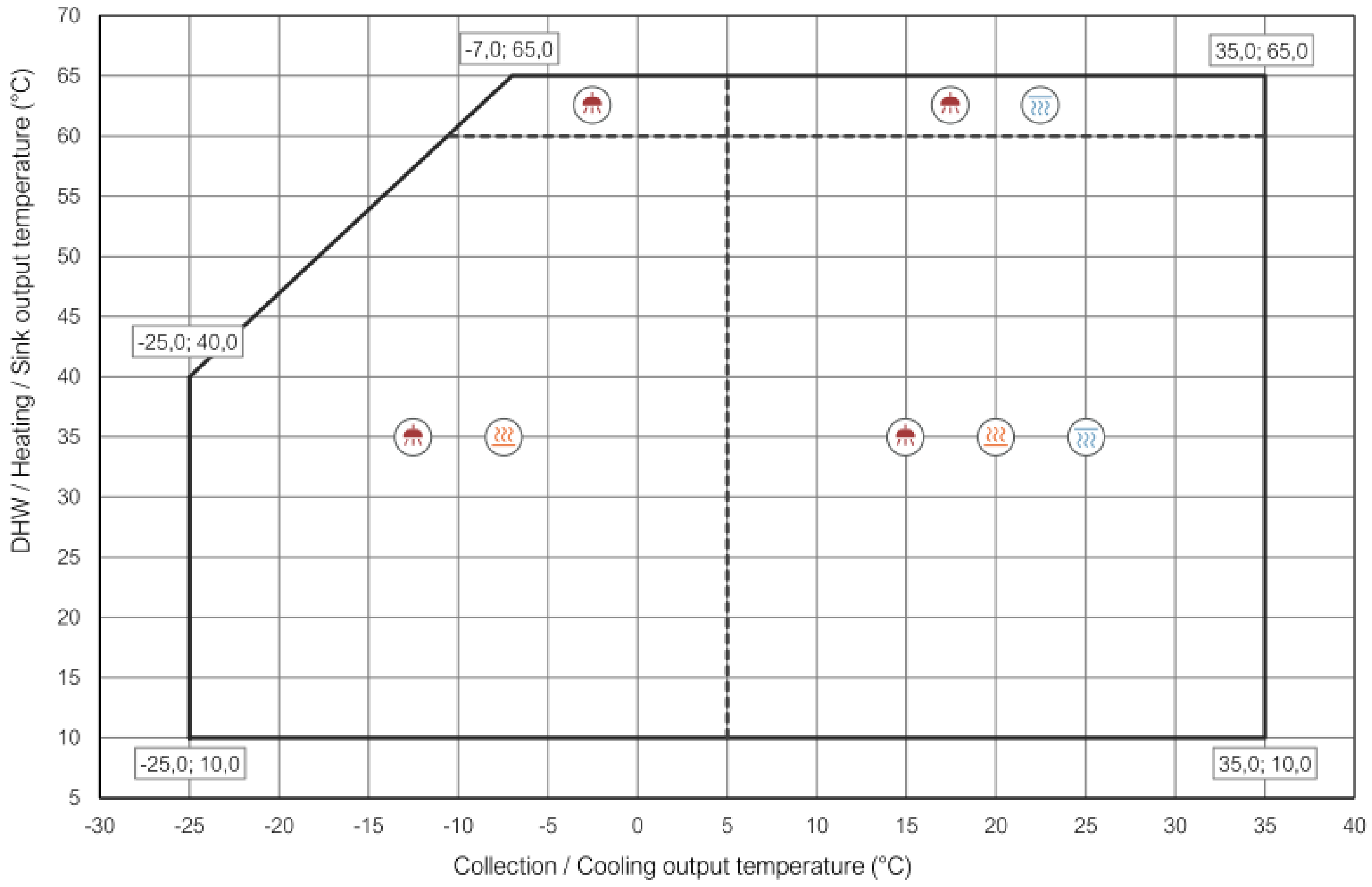


Selection of GSHP for Heating/cooling

- As shown from the previous slide, working with a brine of higher temperature can reduce the required work of the compressor.



Selection of GSHP for Heating/cooling



GEB

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Shallow geothermal engineering: overview and applications

Lecture 5. Design of shallow geothermal systems- part1

Content

- Design of Closed-loop systems
  - Design of vertical systems.
  - Worked Example with an analytical solution.

Steps of system Design

Determine the building thermal load

- Compare different exploitation systems (Open vs closed).
- Initial costs & output.

Heat pump selection

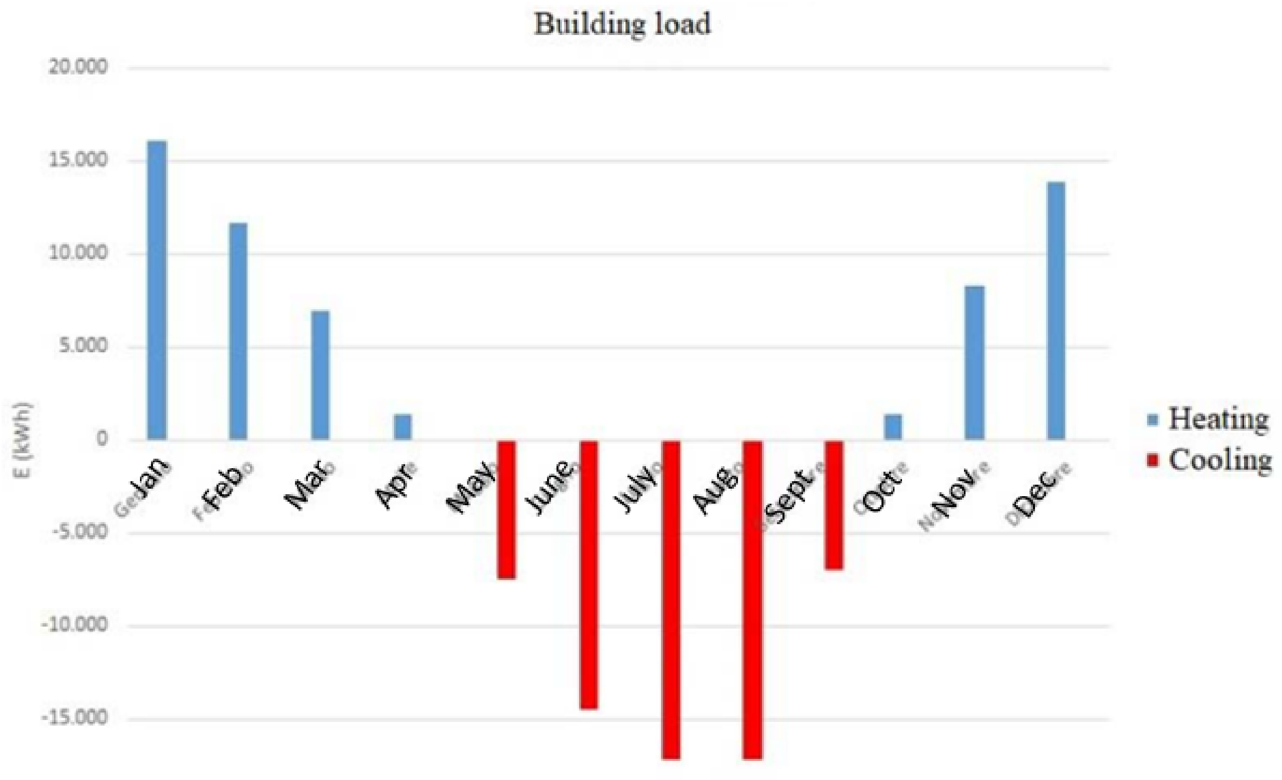
- Techno-economical comparison between heat pumps vs other alternatives.
- CO2, energy saved.

Analysis of weather

- Month of max temp that requires cooling.
- Month of min temp that requires heating .

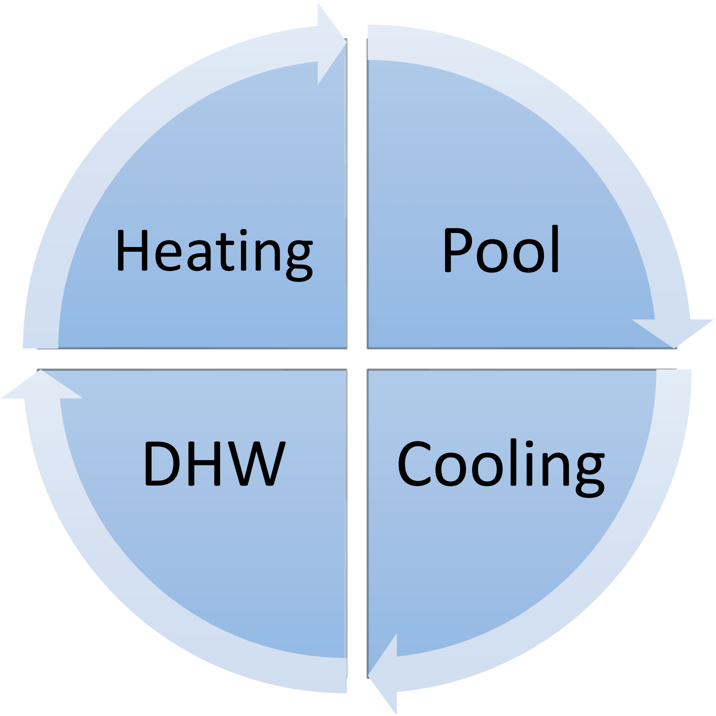
- Based on: e.g.
- Ground properties
- Hydrological data

Step 1: Building thermal load determination



Monthly Energy Consumption

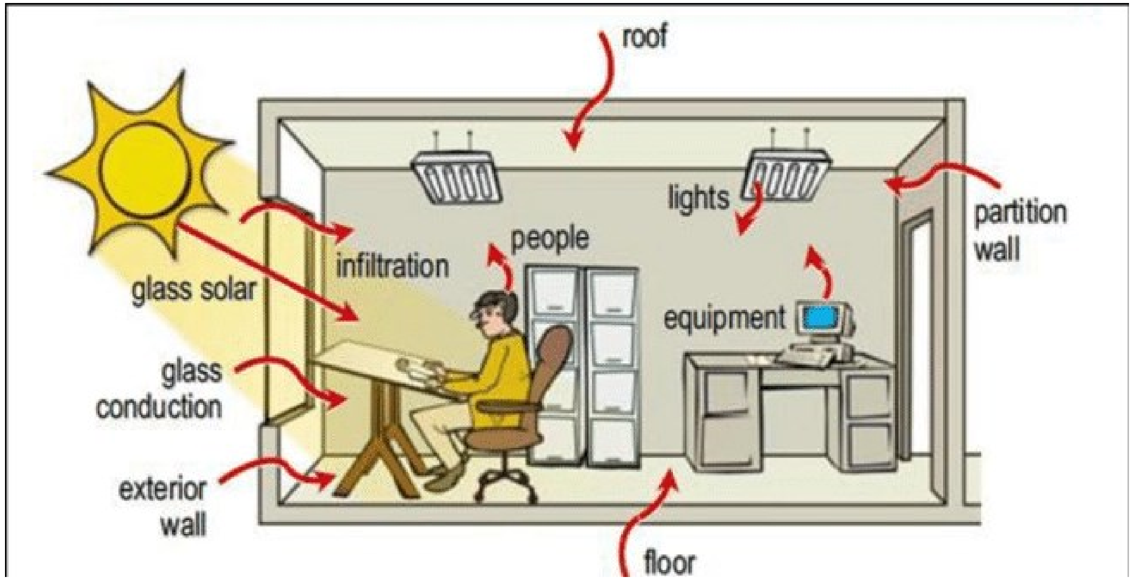
Step 1: Building thermal load determination



Step 2: calculation of peak values of power for heating and cooling

- Calculate the peak heating power for the month of Min temperature.
- Calculate the peak cooling power for the month of Max temperature.

Step 2: calculation of peak values of power for heating/ Cooling



Heat Sources in a Building

Type of construction	Thermal load (W/m²)
Passive Housing	10
Low-energy building	40
Recent construction (as of 2005)	50
Old construction (prior to 2005)	80
Uninsulated construction	100

Building thermal load according to building construction type, after ecoForest Co.

Step 2: calculation of peak values of power for DHW

Single house:

Nº Bedrooms	1	2	3	4	5	6	>7
Nº of persons	1,5	3	4	5	6	6	7

Nº of buildings	< 3	4 - 10	11-20	21-50	51-75	76-100	>101
Simultaneity coefficient	1	0,95	0,9	0,85	0,8	0,75	0,7

Type of construction	l/day a 60°C
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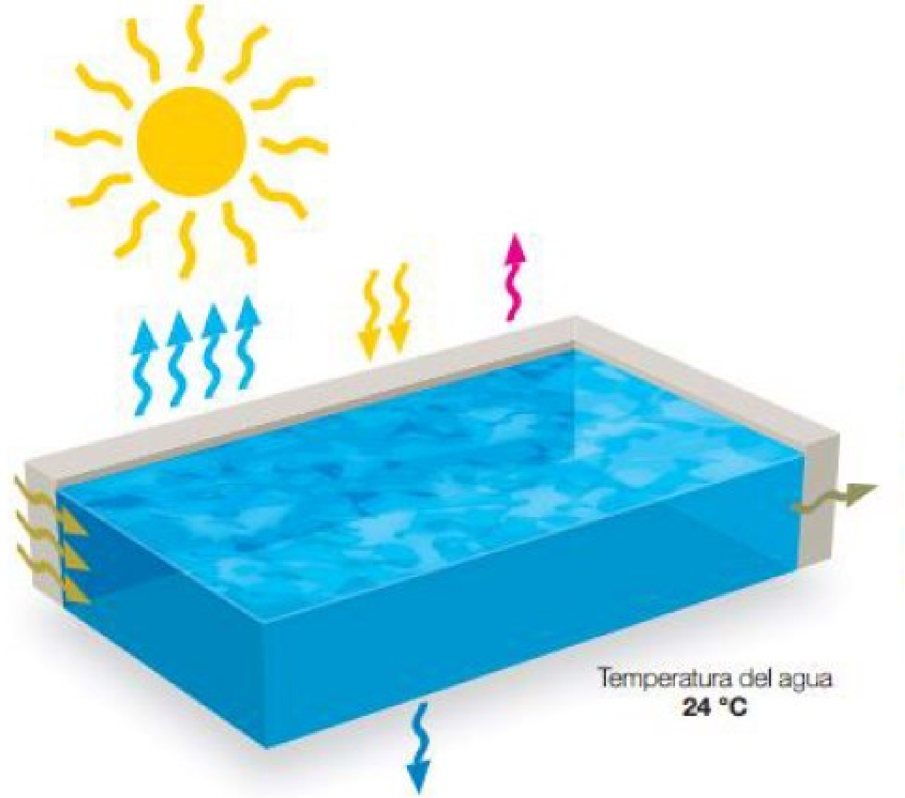
School with shower.	21
Barracks.	28
Factories and workshops.	21
Offices.	2
Gymnasiums.	21
Restaurants.	8
Cafeterias.	1

DHW needs / person According to building type, ecoForest Co.

Step 2: calculation of peak values of power for Pools

Type of pool	Water temperature		
	20°C	24°C	28°C
With cover	100 W/m²	150 W/m²	200 W/m²
With cover and wind protected	200 W/m²	400 W/m²	600 W/m²
Without cover and partially exposed to wind	300 W/m²	500 W/m²	700 W/m²
Without cover and exposed to wind	450 W/m²	800 W/m²	1000 W/m²

Heating load needs for pool, ecoForest Co.



Step 3: Min and Max temperature required by the end user

- Determination of T_{in} & T_{out} for heating.
- Determination of T_{in} & T_{out} for cooling.
- Choose a suitable heat pump.
- COP/EER

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Step 3: Min and Max temperature required by the end user Cont.

- $T_{out\ BH} = T_{in\ max} - \frac{P_{Cooling}\left(\frac{COP+1}{COP}\right)}{C_p.m}$.
  - T_{max}: the max entering water temperature (EWT).

- COP= $\frac{Max\ Output\ power}{electrical\ power\ consumed\ by\ the\ compressor\ of\ a\ heat\ pump}$

Step 3: Min and Max temperature required by the end user Cont.

- $Q_{ground} = P_{cooling} + P_{compressor}$

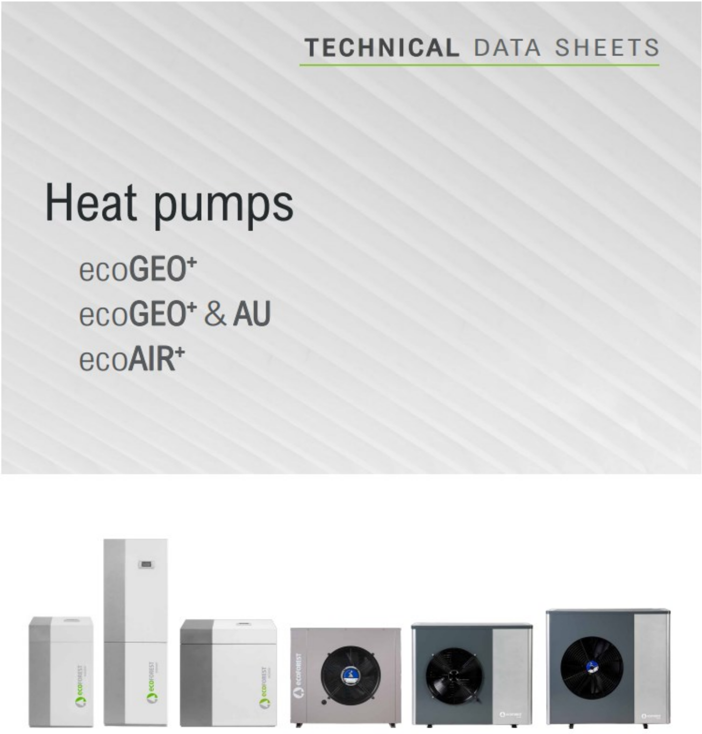
$$= P_{cooling}(1+\frac{1}{COP}) = P_{cooling}(\frac{COP+1}{COP})$$

- $Q_{ground} = P_{Heating} - P_{compressor} = P_{Heating}\,(1-\frac{1}{COP})$

$$=P_{Heating}(\frac{COP-1}{COP})$$

Step 3: Min and Max temperature required by the end user Cont.

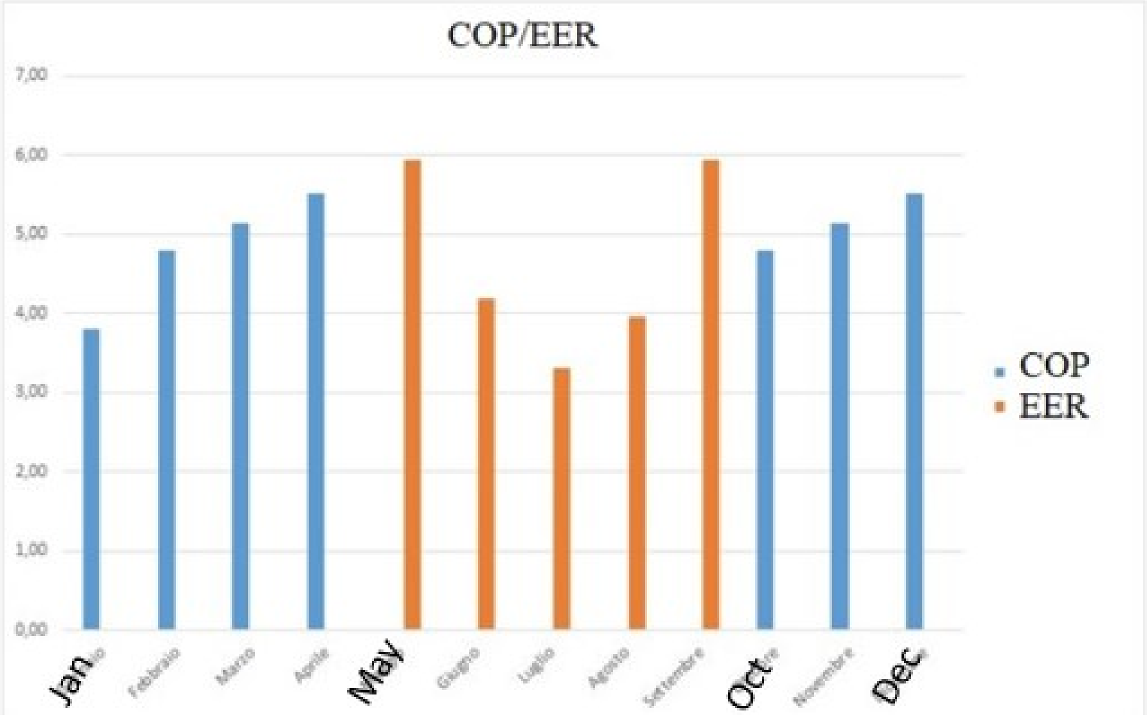
- Choice of a suitable Heat pump:
  - Based on the max required power.
  - Based on the temperature range that a heat pump can work within.



ecoForest Technical Data Sheet.

Step 4: Evaluation of COP/EER for each month

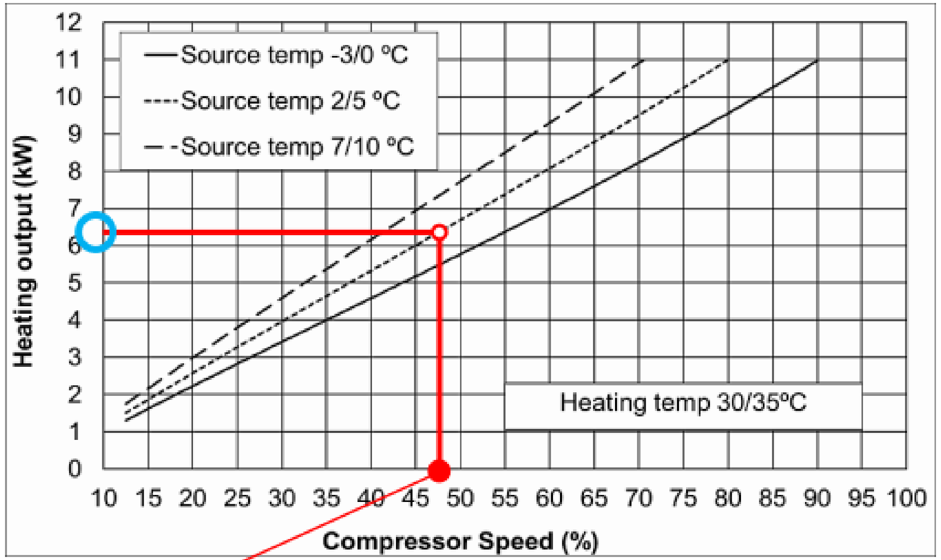
- The system's efficiency changes monthly according to the air temperature in each month.

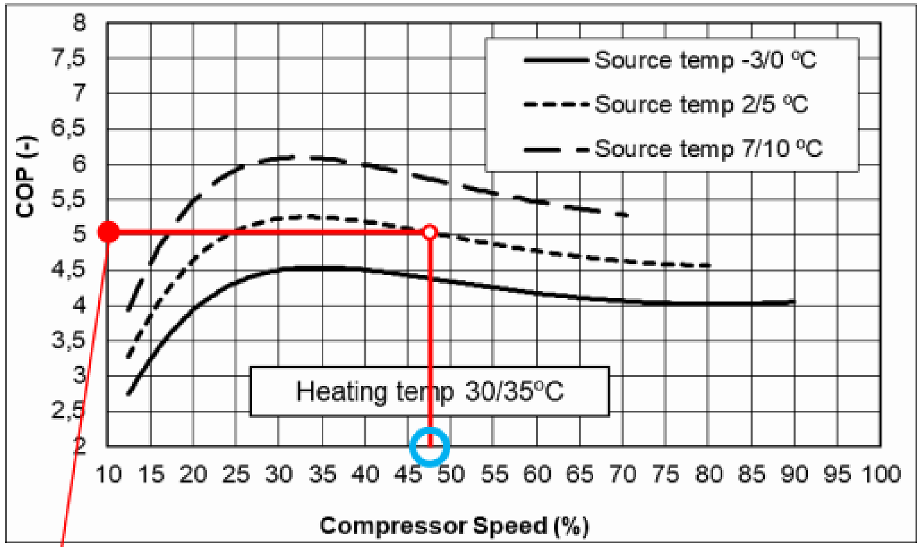


Monthly efficiency of the system

Step 4: Evaluation of COP & electrical power consumption

- After determining the demand and knowing the working temperatures, a heat pump that can provide the required thermal power is chosen.

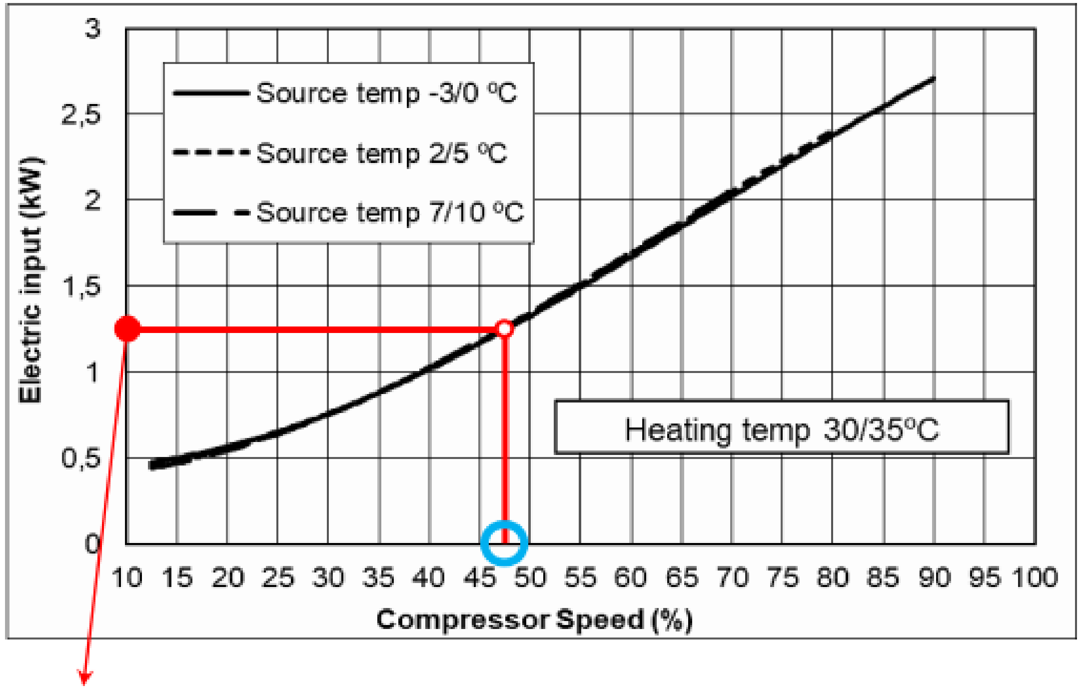




47% → ecoGEO C1 1 – 9 kW ✓

COP = 5,0

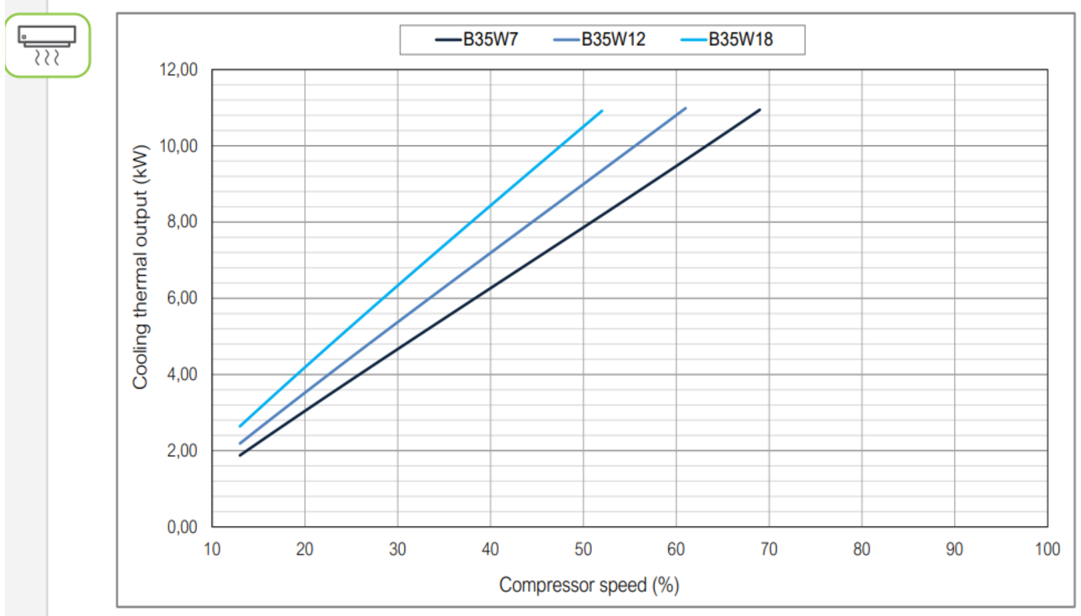
Step 4: Evaluation of COP & electrical power consumption Cont.



$P_{el} = 1,2$ kW

Step 4: Evaluation of COP & electrical power consumption Cont.

- The same concept for cooling, choose the source and distribution temperatures curve, then get the same previous data.



Step 5: Geological study

- Determination of lithology.
- Determination of thermal properties of each layer.
- Determination of ground temperature.
- Presence of groundwater flow.

Step 5: Geological study Cont.

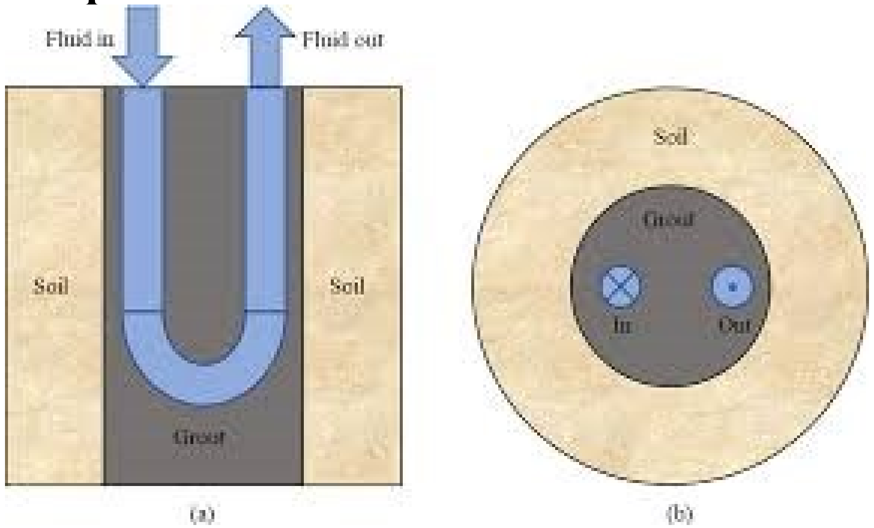
- Determination of lithology.
  - Can be carried out through logging or geophysical survey
- Determination of thermal properties of each layer.
  - Thermal conductivity of the ground can be obtained through thermal response test (TRT) or in laboratories.
- Ground temperature T_g is obtained through the TRT or field measurements.

Step 6: Estimation of Thermal Resistances

- Thermal resistance represents the obstacles that resist and reduce the efficiency of heat transfer.

- Thermal resistances depend on different parameters:

  - Ground material
  - Grouting material
  - Pipelines material
  - The circulating fluid.



Step 6: Estimation of Thermal Resistances

- Also, thermal resistances can be calculated through TRT by comparing the fluid temperatures at inlet and outlet due to constant power injection into a borehole.

Step 7: Preliminary Setting the penalty temperature

- To determine when the unbalance between injection and extraction occurs.
- This unbalance affects the source temperature over the lifetime.

Step 8: Calculations of BHE dimensions for heating/cooling

- Calculating of total length of BHE.
- Calculating the number of boreholes and depth of each one.
- Max depth of borehole should not exceed 100 m (preferable).

Step 8: Calculations of BHE dimensions for heating/cooling

- Another quick solution for (Not for commercial use):
- Length of borehole = $\frac{power\ (W)}{heat\ flow\ (\frac{W}{m})}$
- Ground material has a range of Heat flow (W/m), we calculate the length of borehole for both edges.
- Best case scenario (highest value) and worst-case scenario (lowest value).

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Step 8: Calculations of BHE dimensions for heating/cooling

Type of rock	Specific extraction capacity	
	1800 h/year	2400 h/year
Clay, loams	35-50 W/m	30-40 W/m
Sandstone	65-80 W/m	55-70 W/m
Basalt	40-65 W/m	35-55 W/m
Limestone	55-70 W/m	45-60 W/m
Granite	65-85 W/m	55-70 W/m
Gravel, dry sand	< 25 W/m	< 20 W/m
Gravel, saturated sand	65-80 W/m	55-65 W/m
Gravel and sand with high water flow	80-100 W/m	80-100 W/m
Gneis	70-85 W/m	60-70 W/m

The heat extraction rate (W/m) for different ground layers, after ecoForest

Worked Example

- A building with area =130 m^2.
- Ground temperature 22.75 °C.
- peak heating load 12.5 KW.
- peak cooling load 15 KW.
- The heating thermal loads 6000 KW.h/yr.
- Cooling thermal loads 10400 KW.h/yr.
- The electricity consumption for heating: 3.2 KW.
- The electricity consumption for cooling 4.1 KW.
- Flow 3300 Littre/hr.

Worked Example

- <u>For Cooling:</u>
  - EER (Energy Efficiency ratio) = $\frac{Peak\ cooling\ load\ (P_{cooling})}{Electrical\ power}$
  - $Q_{ground} = P_{cooling} + P_{compressor} = P_{cooling}(1+\frac{1}{EER}) = P_{cooling}(\frac{EER+1}{EER})$
    - Q_{ground}: power to be injected into the ground during cooling.
  - Q_{ground}= m. C_p . ΔT

Worked Example

- For Cooling:
  - EER= $\frac{Peak\ cooling\ load}{Electrical\ power\ consumed\ by\ compressor} = \frac{15000}{4100} = 3.6$
  - $Q_{ground} = P_{cooling} + P_{compressor} = P_{cooling}(1+\frac{1}{EER}) = P_{cooling}(\frac{EER+1}{EER})$ = 19.16 KW.

15 KW

4.10 K W

Worked Example

- $\Delta T = \frac{Q}{C_p .m}$
- $\Delta T = T_{in\ BH} - T_{Out\ BH}$
- $T_{out\ BH} = T_{max} - \frac{P_{Cool}\left(\frac{COP+1}{COP}\right)}{C_p.m} = 35 - \frac{19.16}{4.180 * \frac{3300}{3600}} = 30°C$
- Borehole Length (L):
- $L_{cooling} = \frac{P_{cool}\left(\frac{COP+1}{COP}\right).(R_P + R_S.F)}{T_{Avg} - T_{ground}}$ & $T_{Avg} = \frac{Tmax + T_{out\ BH}}{2} = 32.5\ °C$

Worked Example

- R_P: *thermal resistance of pipe*
- R_s: $thermal\ resistamce\ of\ soil$
- F: $cooling\ factor$ *(proportion of cooling months/year)*

Worked Example

- L= $\frac{19160*0.145}{(32.5-22.75)} = 284.94\, m$

- So we can use 3 BH with depth 95 m for each

- In case of unbalance between heating & cooling loads, Factor B is introduced
- L_{new}=L*$F_B = 285 * 1.2 = 350\, m$

- So 4 BH with depth 87 m for each is drilled.

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Worked Example

- There are other analytical solutions;
  - e.g. to solve twice for heating and cooling separately.

- You must choose the longer borehole solution such as in Ashrae method.

2.Design methods

2.1. ASHRAE method

The ASHRAE method is an analytical one. The sizing equations are basically obtained by solving for the total BHE length L the following steady state equation for the heat transfer in the ground:

$$Q = L\frac{(T_g - T_f)}{R} \quad (1)$$

where Q is the heat rate, T_g the undisturbed ground temperature, T_f the average fluid temperature and R is the BHE thermal resistance. The total length for the heating (L_h) and the cooling (L_c) mode are calculated separately according to equations (2) and (3) respectively:

$$L_h = \frac{Q'_a R_{ga} + Q'_{g,h,D}(R_b + PLF_{m,h,D} R_{gm} + R_{gd} F_{sc})}{T_g - \left(\frac{T_{f,in} - T_{f,out}}{2}\right) - T_p} \quad (2)$$

$$L_c = \frac{Q'_a R_{ga} + Q'_{g,c,D}(R_b + PLF_{m,c,D} R_{gm} + R_{gd} F_{sc})}{T_g - \left(\frac{T_{f,in} - T_{f,out}}{2}\right) - T_p} \quad (3)$$

Full citation: M. Staiti and A. Angelotti, "Design of borehole heat exchangers for ground source heat pumps: A comparison between two methods," *Energy Procedia*, vol. 78, pp. 1147–1152, 2015, doi: 10.1016/j.egypro.2015.11.078.

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Shallow geothermal engineering: overview and applications

Lecture 6. Design of shallow geothermal systems- part 2

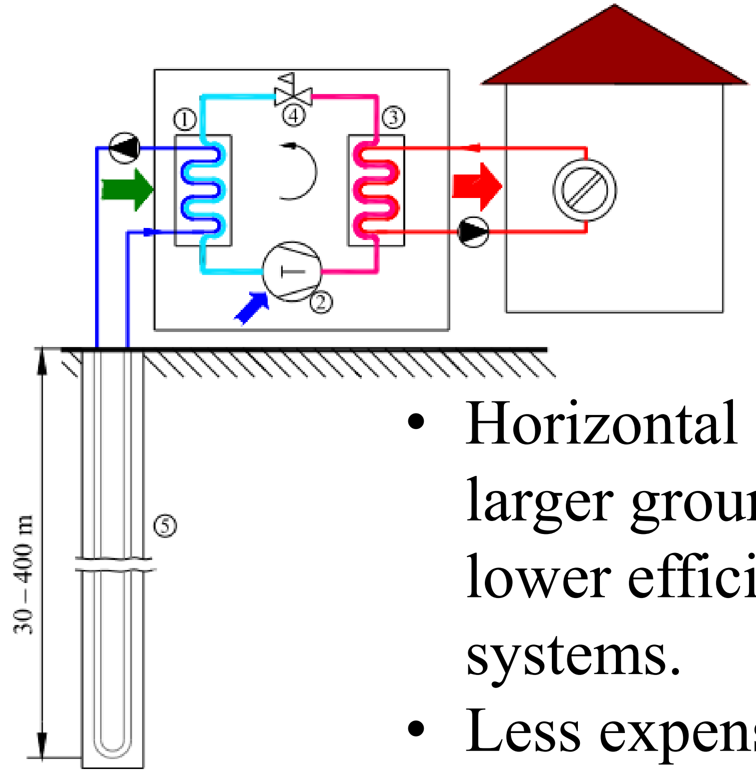
Content

- Tutorial on EED designing tool (Software).
- Vertical vs Horizontal heat exchangers.
- Horizontal ground heat exchangers.
- Tutorial on GHX toolbox (Spreadsheet).
- Open loop systems
- How are parts connected together?
- Circulating fluid properties.

Tutorial on EED designing tool (Software)

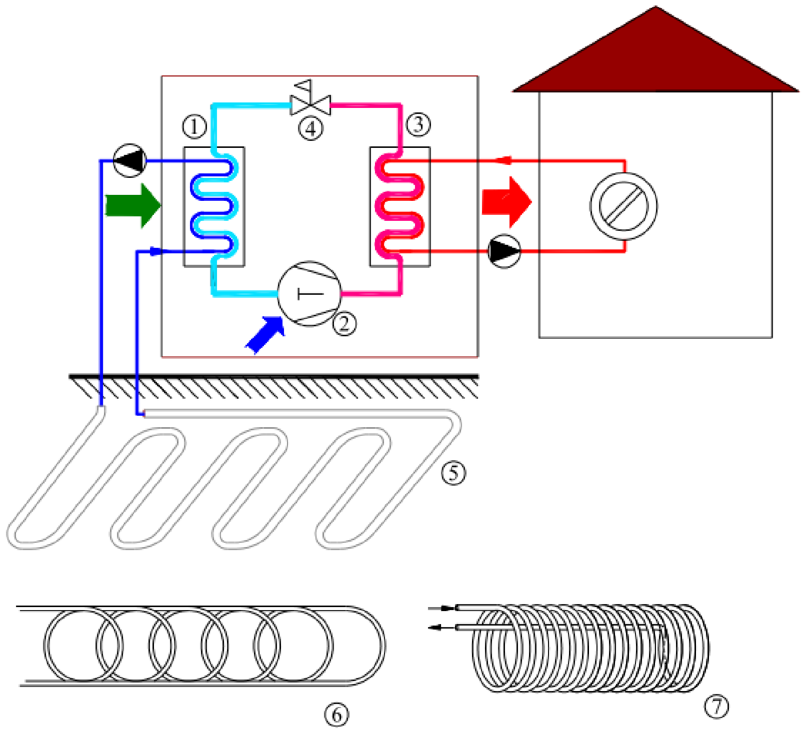
- Begin using the software following the instructor's steps.

Vertical vs Horizontal heat exchangers



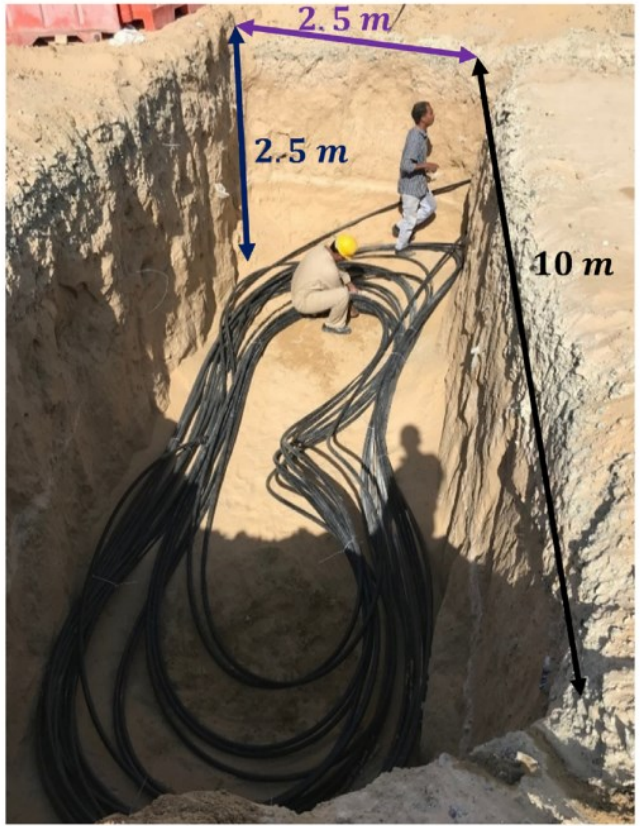
Vertical borehole heat exchanger

- Horizontal systems require a larger ground area and produce lower efficiency than vertical systems.
- Less expensive.



Horizontal Ground heat exchanger types

Horizontal ground heat exchangers



Atwany et al. 2020

Horizontal Ground Heat Exchanger (GHX)

Horizontal ground heat exchangers

- The efficiency of a Ground Heat Exchanger (GHX) can be calculated according to the relationship:

$$\epsilon = \frac{T_{in} - T_{out}}{T_{in} - T_g}$$

- When connected to heat pump system:

$$\epsilon = \frac{P_{out}}{P_{Comp} + P_{Cir.pump} + P_{fan}}$$

Horizontal ground heat exchangers

Calculations of Demand

- Power can be simply estimated with the same methodology of vertical BHEs.
  - Power (W) = thermal load (W/ m^2)* building Area (m^2).

  - Area of extraction, pipe spacing, and pipe size are estimated according to the soil type.

Horizontal ground heat exchangers

- $Q_{ground} = P_{cooling}(\frac{COP+1}{COP})$ for cooling mode.
- $Q_{ground} = P_{Heating}(\frac{COP-1}{COP})$ for heating mode.
- The extraction area (m^2)= $\frac{Q_{ground}\ (W)}{Extraction\ Capacity\ (\frac{W}{m2})}$

Horizontal ground heat exchangers

Soil type	Placement factor	Extraction capacity
Cohesive soil, residual moisture	50 m^2/kW	20 W/m^2
Dry, non-cohesive soil	75 m^2/kW	13,5 W/m^2
Cohesive, wet soil	25 m^2/kW	40 W/m^2
Sand saturated with water, gravel	20 m^2/kW	40-50 W/m^2

Determination of the extraction area, ecoForest Co.

Calculations of extraction area

- Heat Capacity of GHX:

$$Q\ (W) = m^{\cdot} C_p \Delta T$$

$\Delta T = T_{in} - T_{out}$ in cooling mode

$\Delta T = T_{out} - T_{in}$ in heating mode

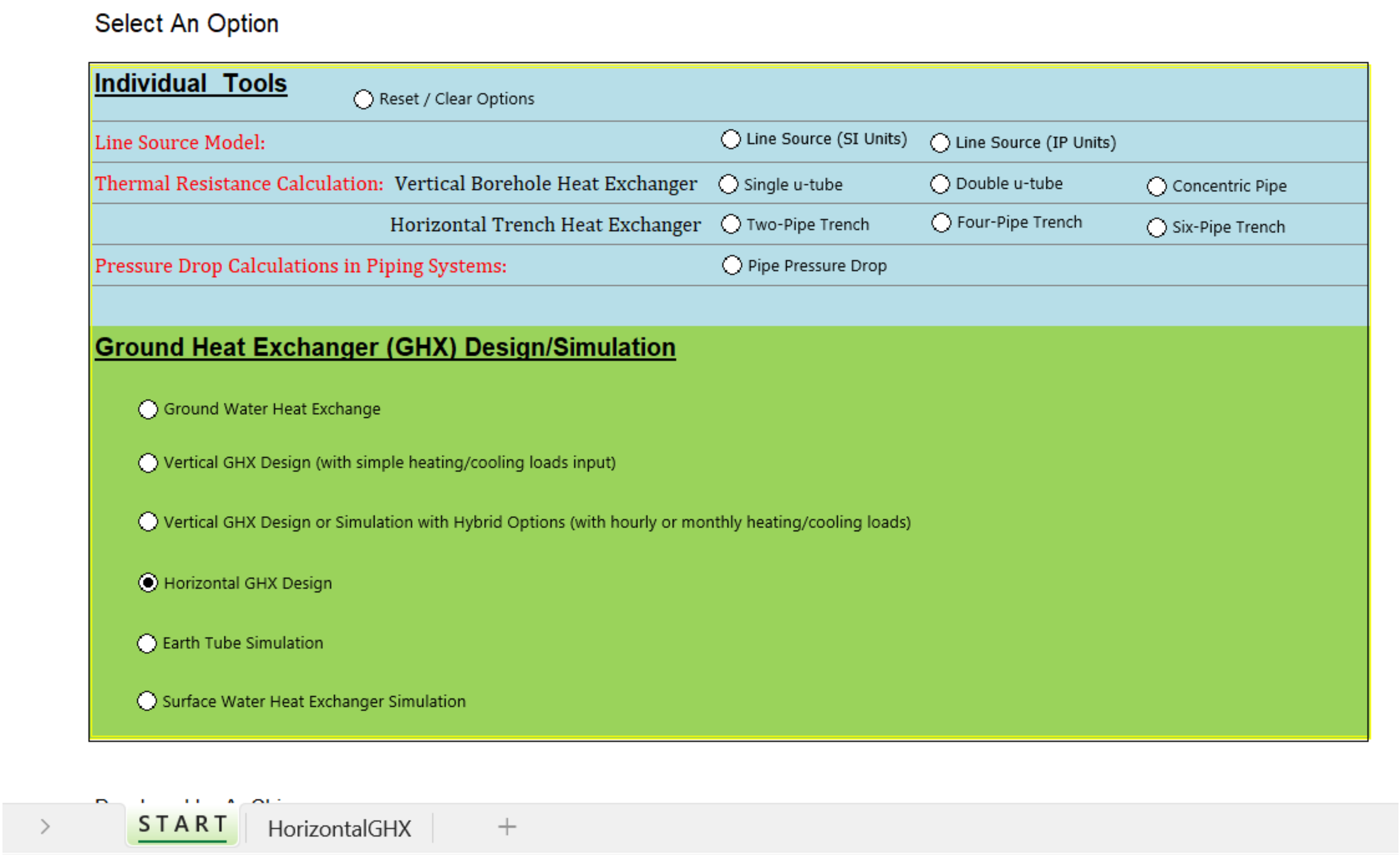
$m^{\cdot}$: mass flow rate (Kg/s)

C_p: 4187 J/Kg.k for water

Soil type	Pipe distance	Pipe size
Dry soil	0,5	DA 25
Normal soil	0,7	DA 32
Wet soil	0,8	DA 40

Tutorial on GHX toolbox (Spreadsheet).

- Begin using the spreadsheet following the instructor's steps.



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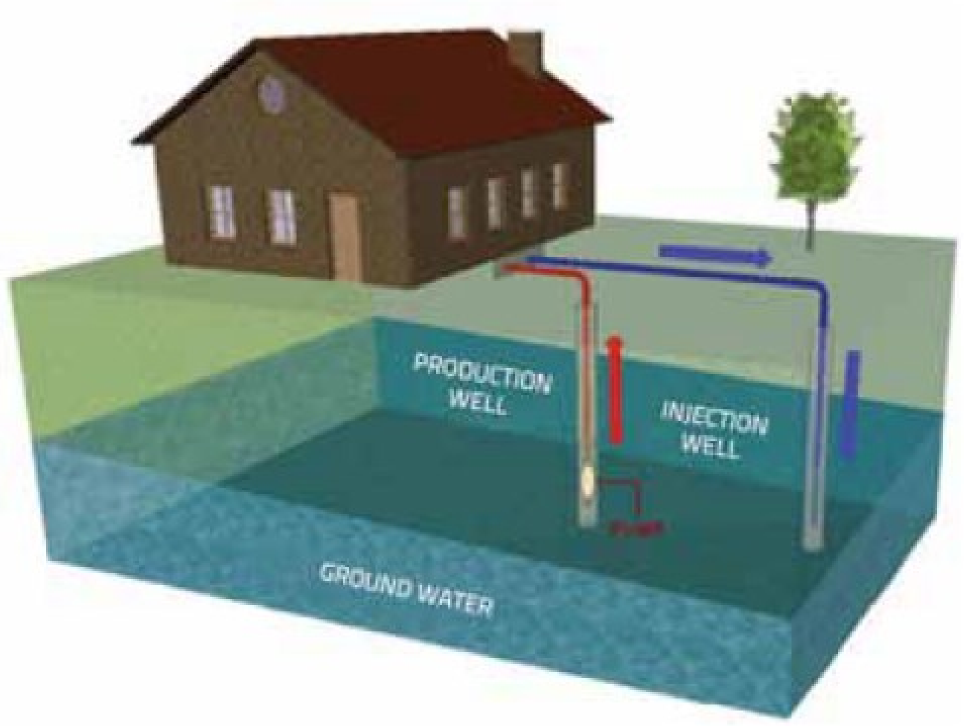
Design of Open loop systems

Open loop systems



Open loop systems

- In open-loop systems, the main heat transfer does not occur in the pipelines, but in the heat pump itself.

- At least one extraction well and one injection well.

Calculations of water flow

- $Q_{ground}\,(W) = m{\cdot}C_p\Delta T$

- For groundwater:
  - $C_p = 4187\,\frac{J}{kg.°C}$ & ΔT may be set as 3°C
    - Flow rate of groundwater through the ground heat exchanger

$$(L/sec) = \frac{Power\ (W)}{C_p\ \Delta T}$$

How are parts connected together?

How are parts connected together?

After designing the borehole number and dimensions, and the heat pump capacity, all parts are connected to act in an integrated system.

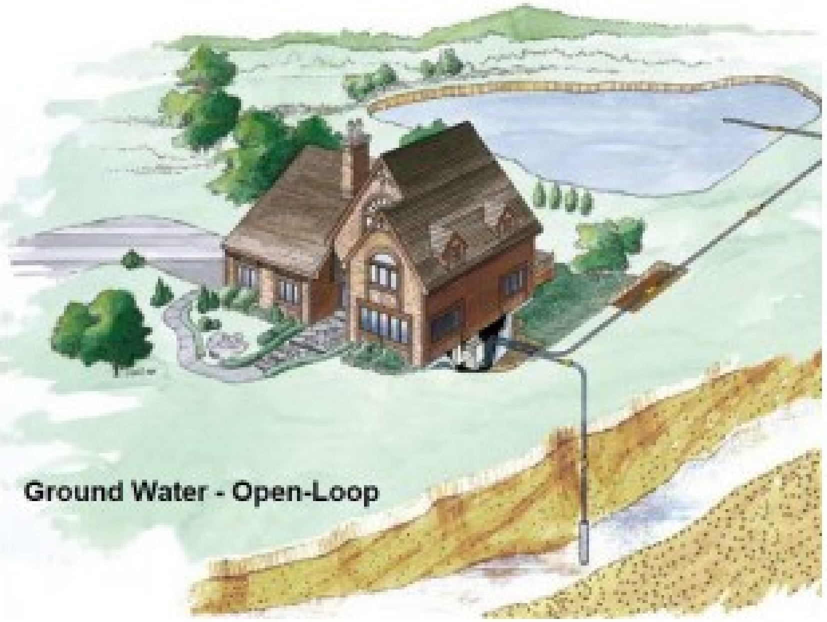
How are parts connected together?

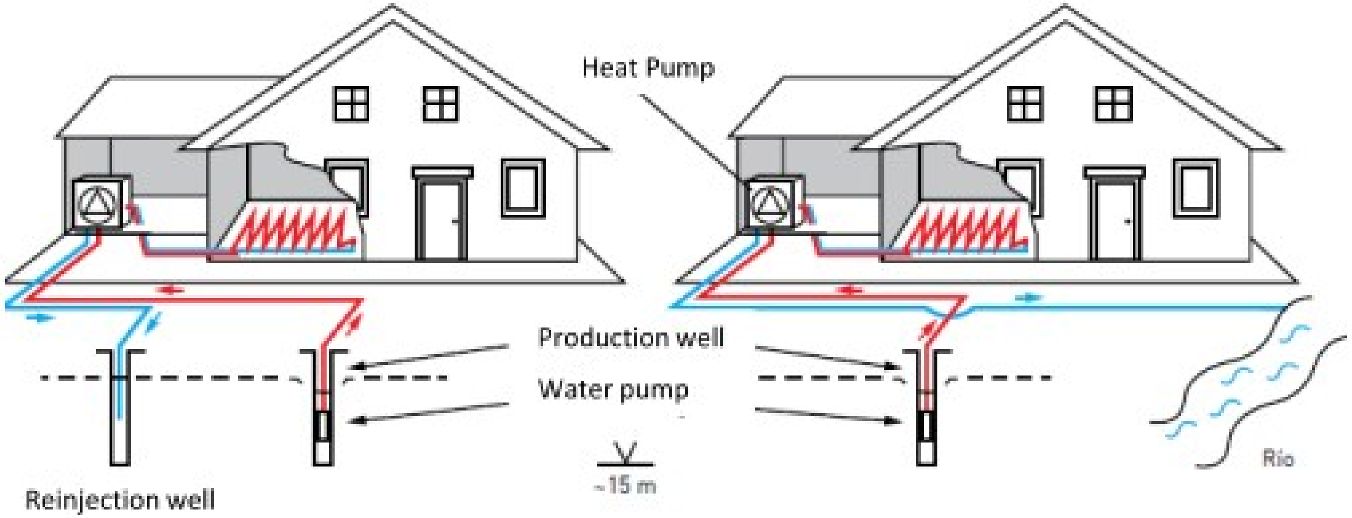
AFTER DRILLING

How are parts connected together?

- In case of multiple boreholes, central connector is used to combine all boreholes into one inlet and one outlet.

How are parts connected together?





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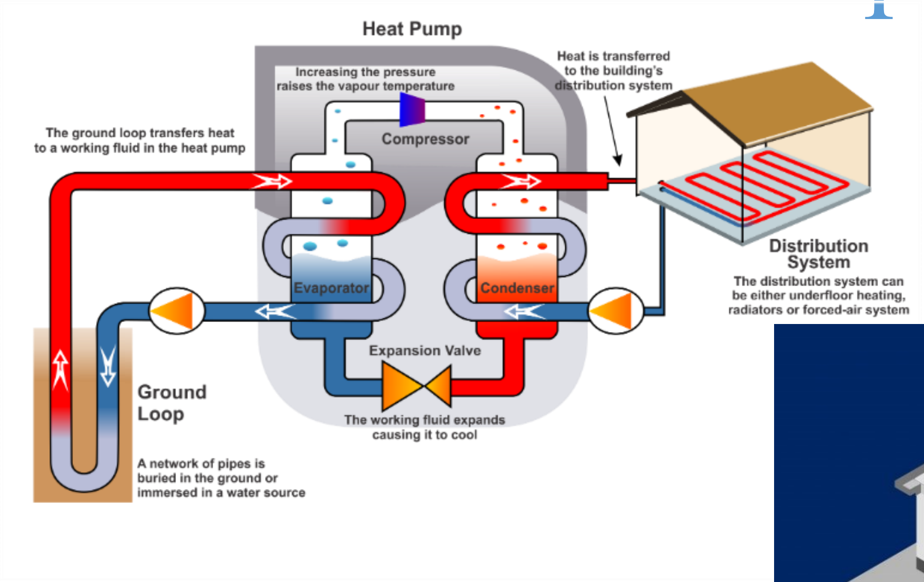
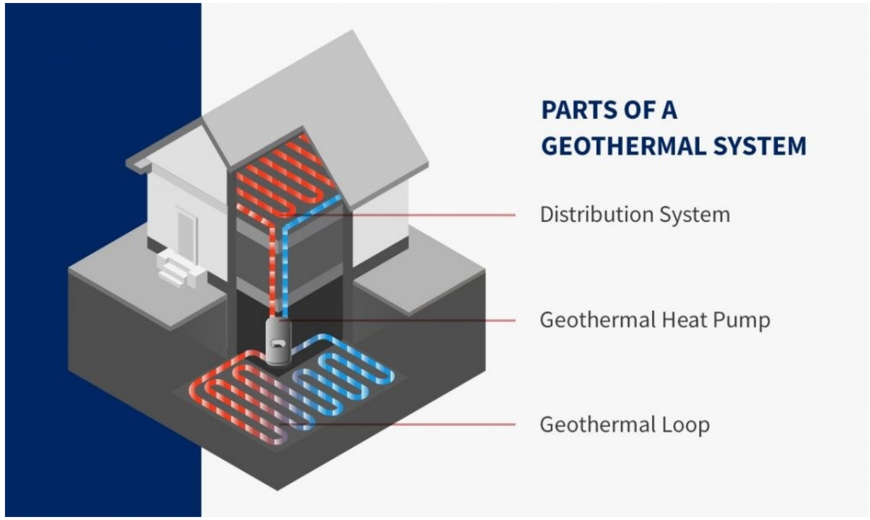
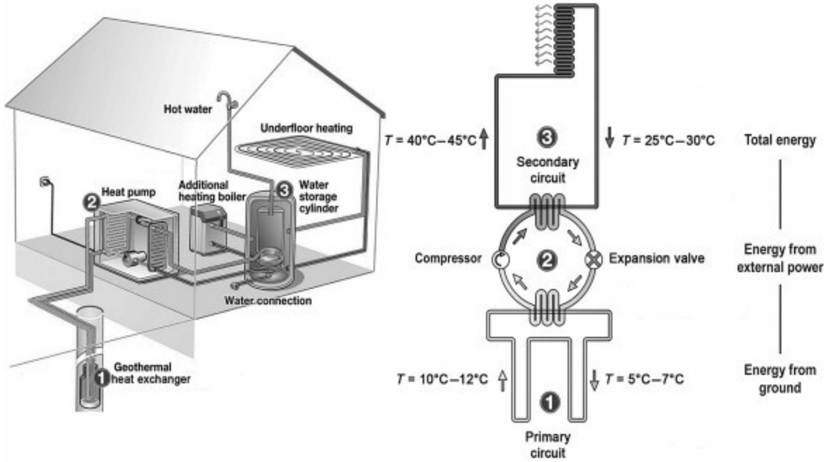
How are parts connected together?





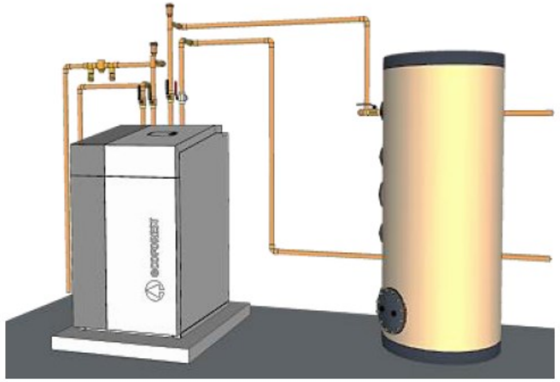


Schemes for a GSHP system for heating/cooling

How are parts connected together?

Direct connection

4 pipe buffer



Heat pump + Buffer tank

Indoor heat pump and tanks

Chilled water fan coil unit (FCU)

Circulating Fluid properties

- For BHEs, water freezes at 0 °C. In order to avoid freezing, glycol is added to water as an antifreeze to lower the freezing temperature.

- Adding Glycol enhances the properties of the used brine.

% Propylene glycol	Freezing temperature°C
0%	0
10%	-3
20%	-8
30%	-14
40%	-22
50%	-34
60%	-48
100%	-59

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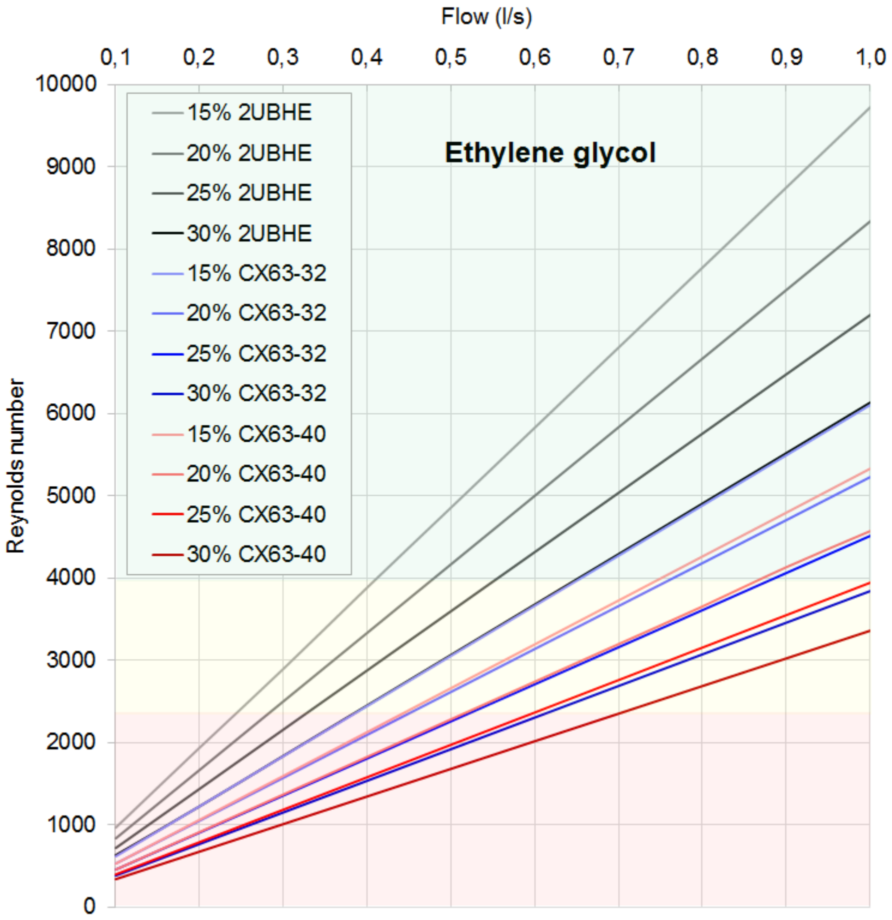
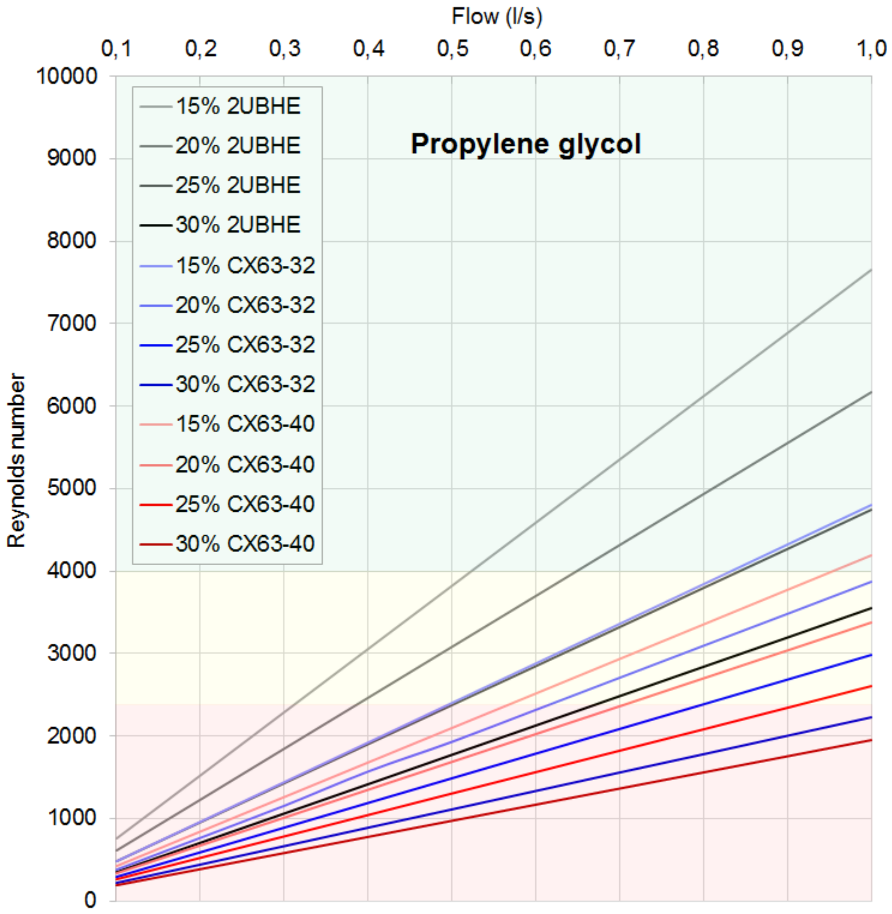
Circulating Fluid properties





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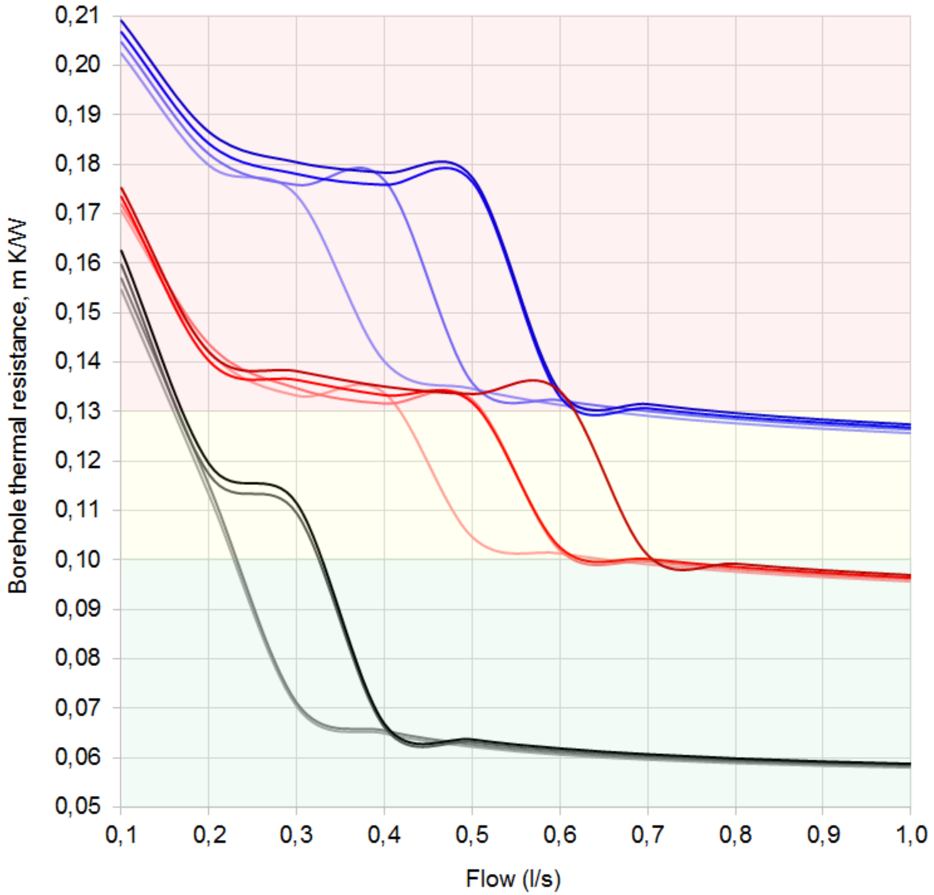
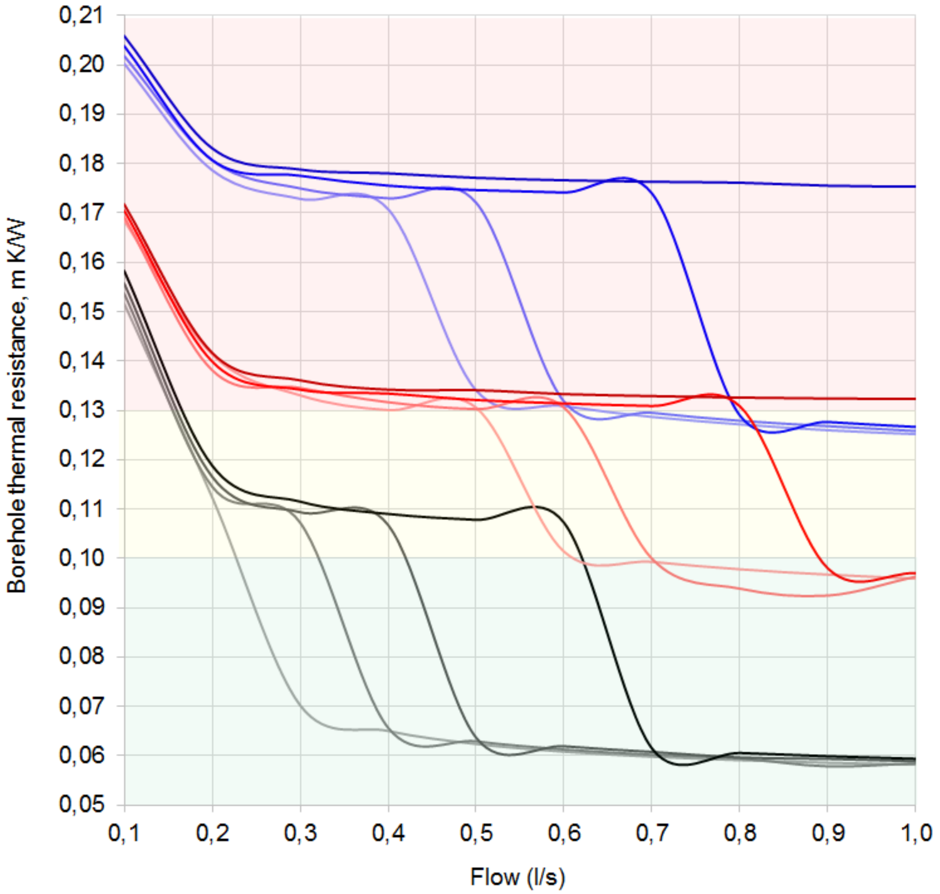
Circulating Fluid properties





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Shallow geothermal engineering: overview and applications

Lecture 7. Thermal Response Test (TRT)

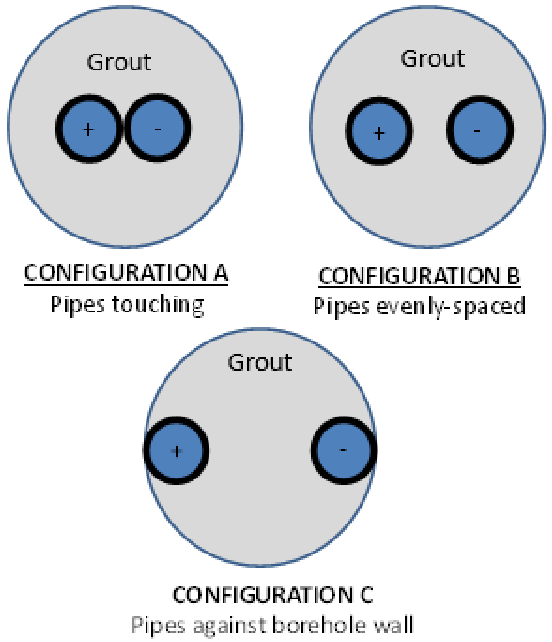
Content

Thermal Response Test

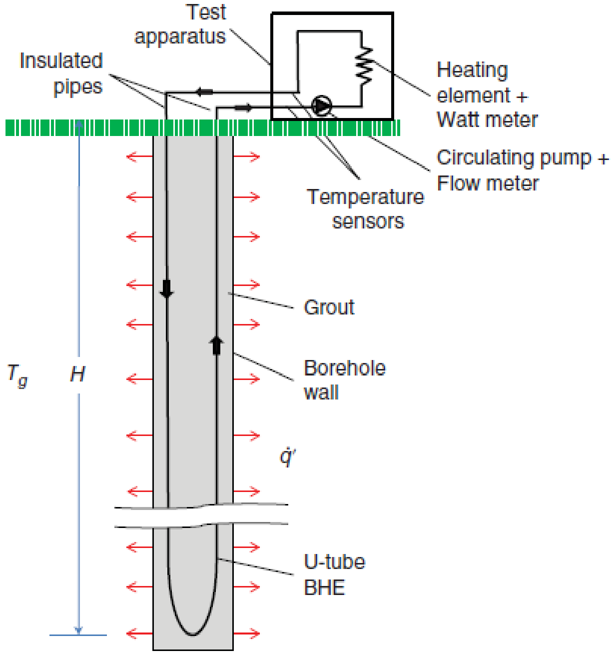
- A Thermal Response Test (TRT) is carried out to obtain accurate values of these properties such as:
  - Thermal conductivity
  - Undisturbed ground temperature (average ground temperature over BHE depth).

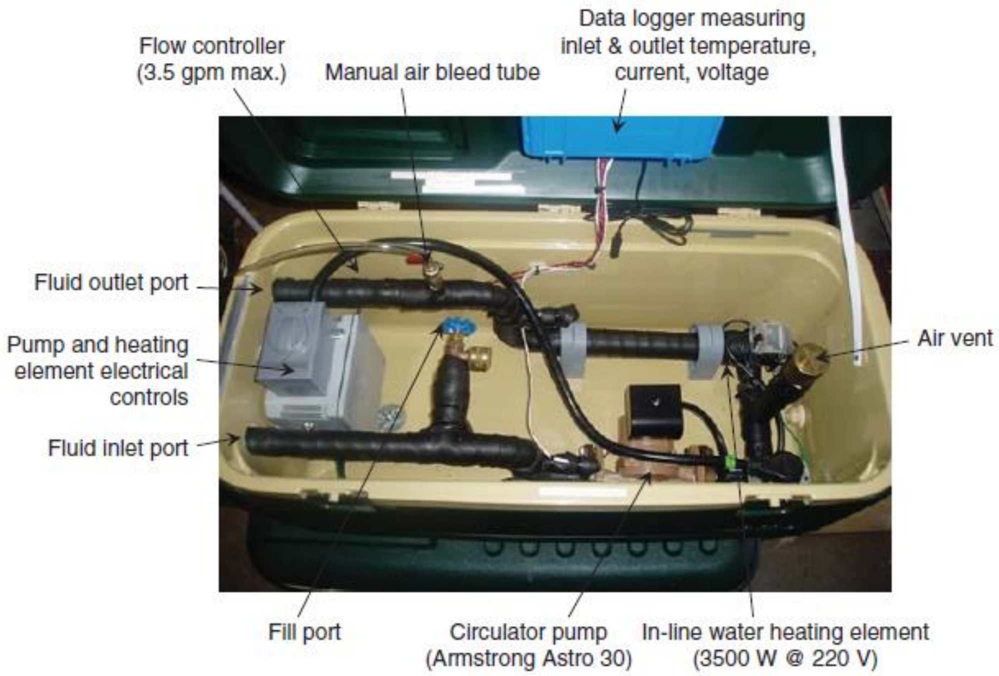
Thermal Response Test

- Lower thermal resistances means higher heat transfer efficiency.
- It depends on:
  - borehole diameter
  - pipe size and configuration
  - pipe material
  - grouting
  - heat carrier fluid
  - laminar/turbulent flow



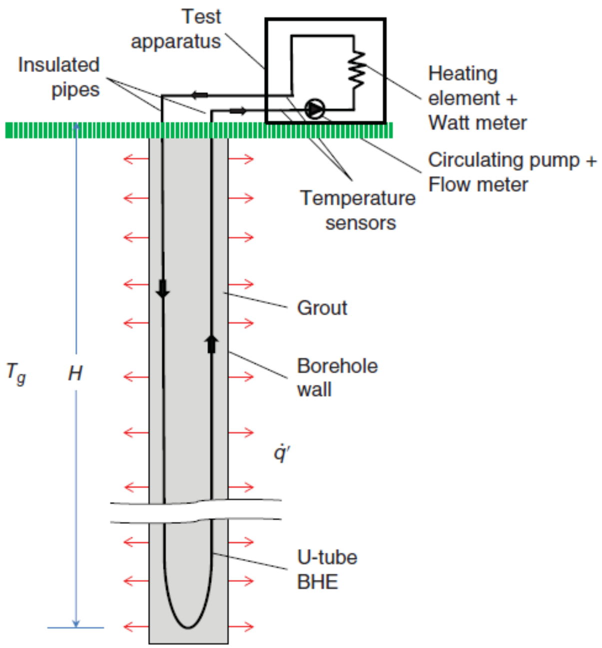
Thermal Response Test

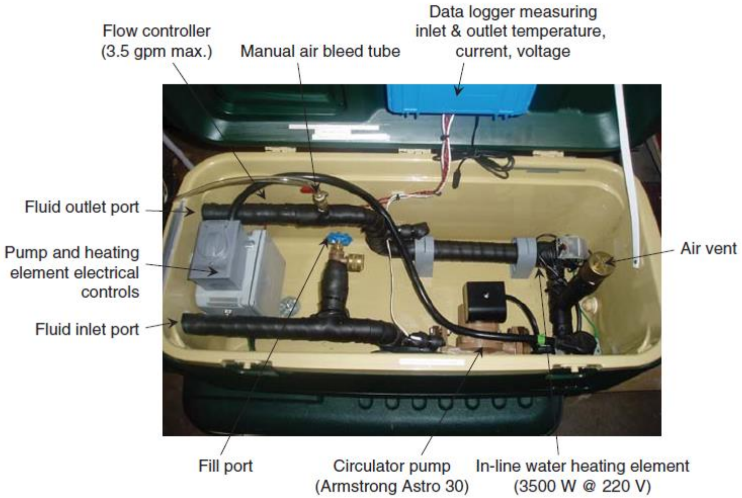




Thermal Response Testing (TRT)

- The test procedure involves application of a constant heat rate to the fluid flowing through a BHE.
- A data logger records the inlet and outlet fluid temperatures and some tests are also designed to record fluid flow rate and power added to the fluid stream.
- The heat rejection or extraction rate must be known in order to evaluate the test data.
- Research suggests that test duration should be of the order of 40 h.
- An accurate measurement of the average subsurface Earth temperature prior to the start of the test must be conducted. it represents the initial condition of the subsurface temperature field.





Thermal Response Test

- **Undisturbed ground temperature**

(i) using a temperature probe to measure the temperature of the standing fluid in the BHE with depth

And/or

(ii) circulating the BHE fluid with the test pump with no heat addition, and recording the stabilized fluid temperature.

- Thermo-phreatimeter is used to measure the ground temperature before carrying out TRT.
- Enough duration between completion of BHE and TRT onset.

Thermal Response Test

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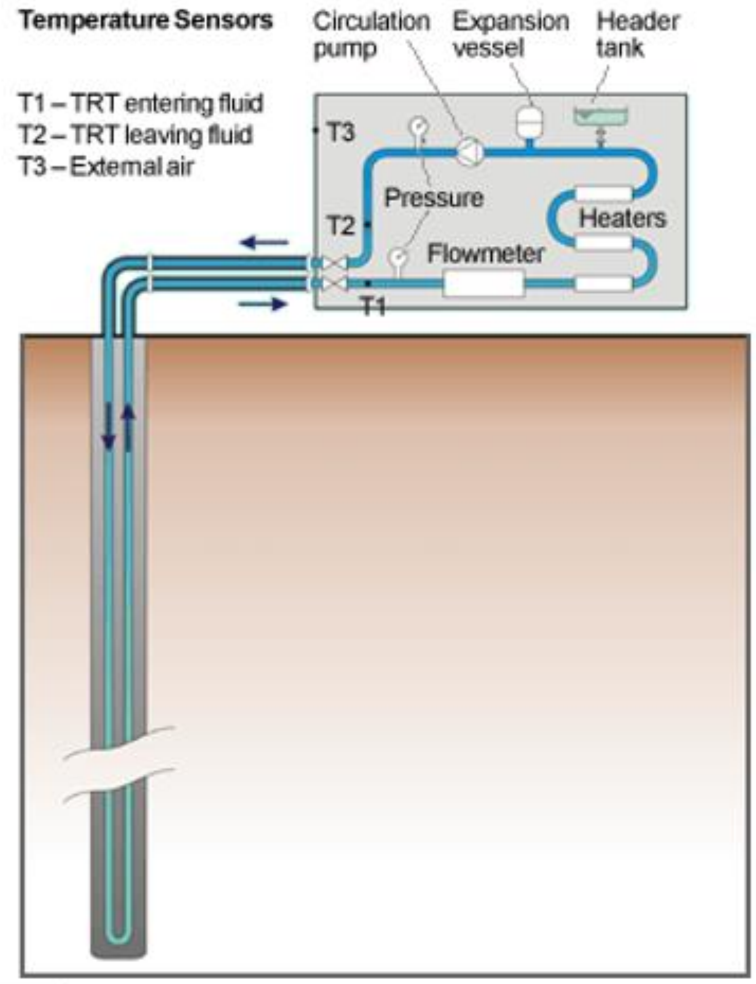
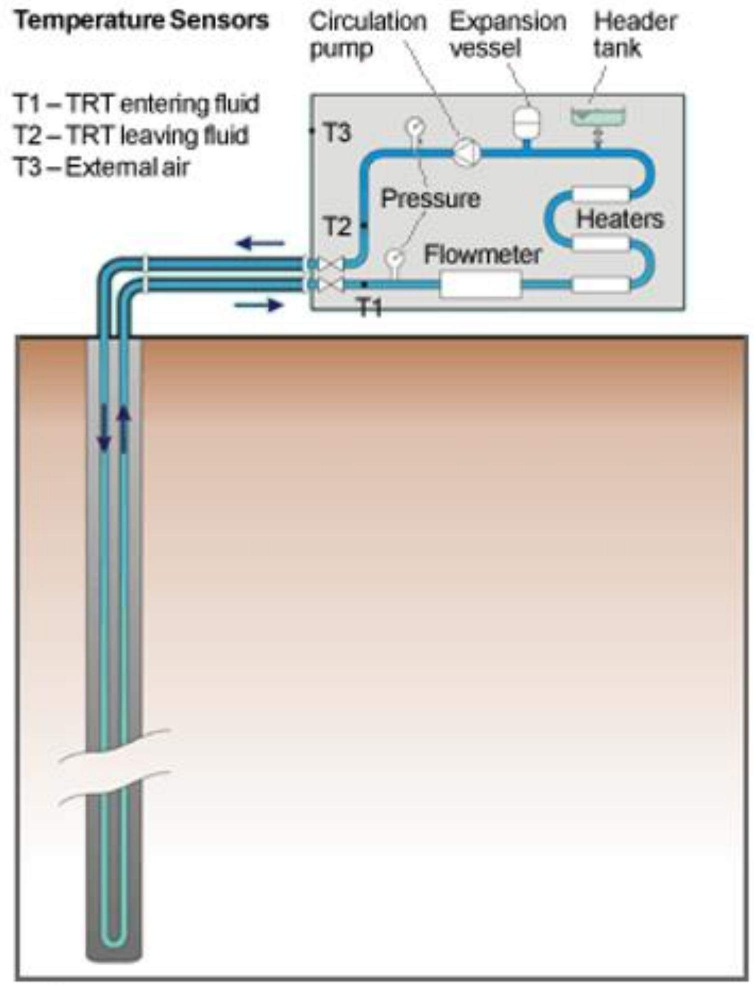
Thermal Response Test

- A constant heat injection rate will be provided by a heater.
- The thermal energy is transported with the water injected into the ground through circulating pumps.
- For 100 m borehole depth, 50 W/m heat injection rate, the constant injected power is 5KW.



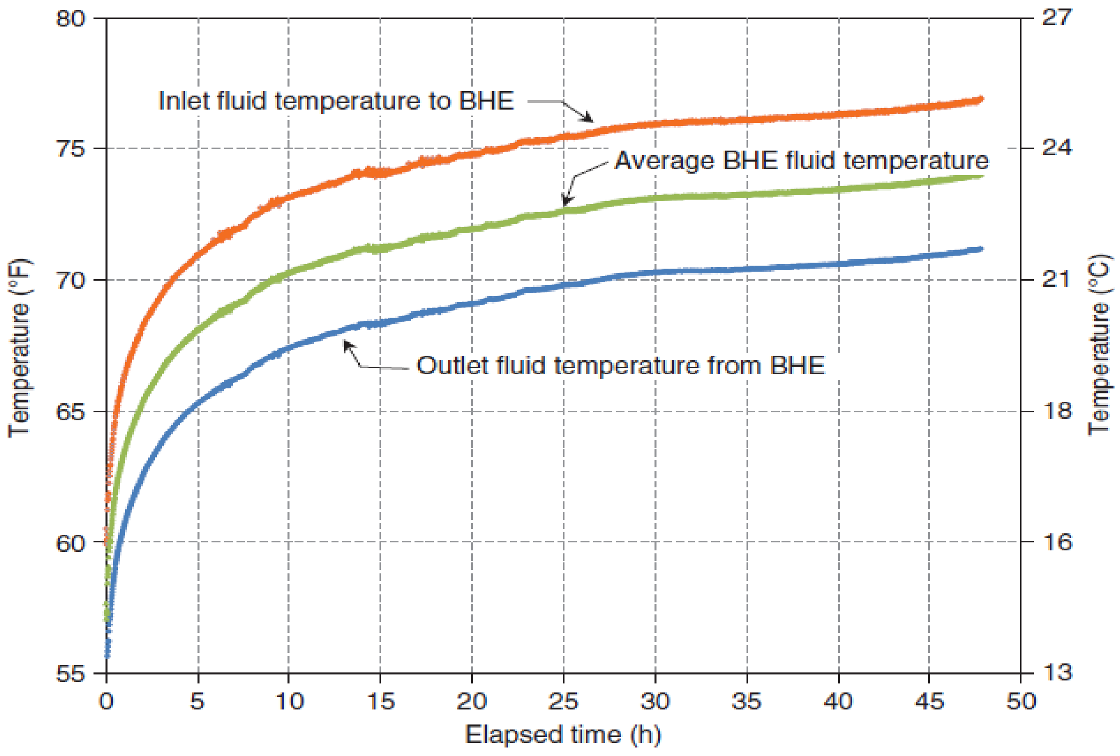
Thermal Response Test



- From the development of the temperatures (response of the underground to the heat injection) the thermal conductivity can be calculated.

Thermal Response Test

- The constant heat injection causes a continuous increase of fluid temperature for both inlet and outlet.
- This increase follows a logarithmic behavior, being sharp in the beginning period (transient state) and slow down for the rest of heat injection (quasi-stationary state).
- On the long term, a stable condition of inlet/outlet temperature is reached, with the radius of heat bulb in the ground enough to dissipate the requested energy.



Thermal Response Test

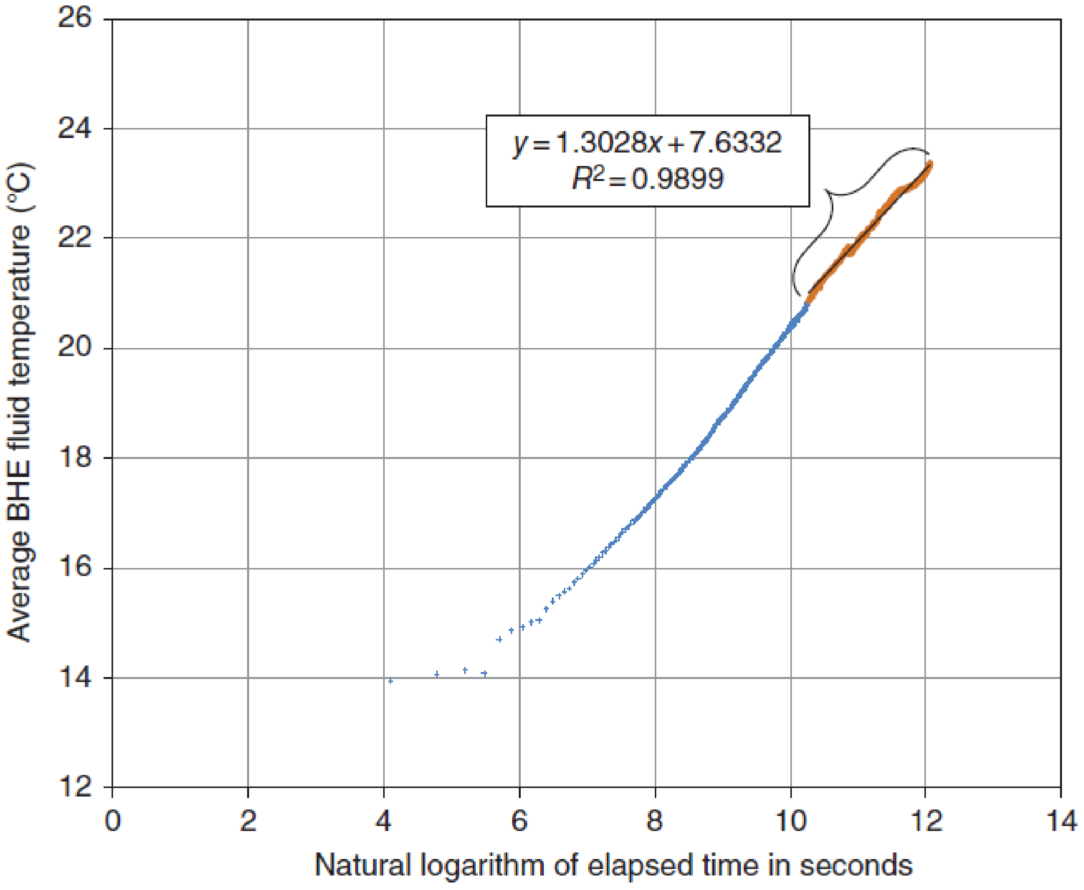
- Important notes:
  - The injected power must be constant during the test period.
  - No interruption.
  - Flow in BHE should be turbulent.
  - Pumping rate 1-2 m^3/h
  - Accuracy of temperature measurement: at least 0,1°C, better 0,01°C.
  - TRT lasts for more than 48 h.
  - Max. recording interval: 10min. Better 1 or 3 min.
  - NO drilling activities near TRT area, this will affect the groundwater flow.

Data interpretation: analytical model

- A Graphical method

$$T_{fluid}(t) = m \cdot lnt + b$$

$$m = \frac{\dot{q}'}{4\pi k}$$



Data interpretation: analytical model

- Inverse Modeling: minimizing the difference between experimentally obtained results and results predicted by a mathematical model by adjusting inputs to the model.
- A two-variable optimization is needed to solve for the thermal conductivity of the ground and the borehole resistance.
- Objective function: to minimize the sum of the squared error (SSE), given by:

$$SSE = \sum_{1}^{N} \left(T_{experimental} - T_{model}\right)^2$$

- A mathematical model: any adequate mathematical model that describes heat transfer in BHEs coupled to an optimization routine is suitable
- Adequate mathematical model: Infinite Line Source model (ILS).

Mathematical Models of Heat Transfer around BHEs

- The thermal diffusion equation for cylindrical coordinates:

$$\alpha\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}+\frac{\partial^2 T}{\partial z^2}\right]+G=\frac{\partial T}{\partial t}$$

- There are two models for BHES design:

- the line source model:(infinite $(\partial^2 T/\partial z^2=0)$ & finite line source models).

(Note: the term $\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}$ is not applicable for both models)

- the cylinder source model.

Infinite Line Source Analytical Models of Heat Transfer in the Ground

- a classic solution to calculate the temperature distribution around an imaginary vertical line in a semi-infinite solid medium, initially at a uniform temperature.

$$\alpha\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right]+G=\frac{\partial T}{\partial t}$$

The initial condition:

$$T(r,t)=T(r,0)=T_g$$

the boundary conditions:

$$T(r,t)=T(\infty,t)=T_g$$

$$\lim_{r\to 0}\left(r\frac{\partial T}{\partial r}\right)=\frac{\dot{q}'}{2\pi k}$$

Infinite Line Source Analytical Models of Heat Transfer in the Ground

$$\Delta T_r = \frac{\dot{q}'}{4\pi k}\int_u^{\infty}\frac{e^{-u}}{u}du$$

Where: $u = \frac{r^2}{4\alpha t}$

$$\Delta T_r = \frac{\dot{q}'}{4\pi k}W(u)$$

$$W(u) = \ln\left(\frac{\exp(-\gamma)}{u}\right) + 0.9653u - 0.1690u^2 \quad \text{for } u \le 1$$

$$W(u) = \frac{1}{ue^u}\frac{u+0.3575}{u+1.280} \quad \text{for } u > 1$$

where γ is Euler's constant = 0.5772

The final equation can also be expressed as:

$$\Delta T_r = \dot{q}' R_g'$$

where: R_g' is the ground thermal resistance per unit length of borehole

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Borehole Heat Exchangers

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Determining the BHE Fluid Temperature

- calculate the temperature at the borehole wall by substituting the value of r_b in place of r in the above equations.
- calculate the ground thermal resistance (R'_g)
- calculate the thermal resistance of the borehole elements (R'_b) (the pipe configuration within the borehole, the borehole grout, and the fluid thermal properties)

$$\Delta T_f = \dot{q}' R'_g + \dot{q}' R'_b$$

The average BHE fluid temperature is then simply calculated by:

$$T_{f,avg} = \Delta T_f + T_g$$

Borehole Heat Exchangers

Mathematical Models of the Borehole Thermal Resistance

- We cannot engineer the ground.
- The borehole thermal resistance is one of the main features over which BHE designers have control.
- the borehole thermal resistance is assumed as a steady-state value.
- the thermal storage effects of the heat carrier fluid, pipe, and grout are ignored.
- This has been shown to be a reasonable approximation where *rb/H* ratios are small, of the order of 0.0005
- The main goal is to minimize the borehole thermal resistance within practical limits.

Mathematical Models of the Borehole Thermal Resistance

$$R'_b = \frac{T_f - T_b}{\dot{q}'}$$

Where:

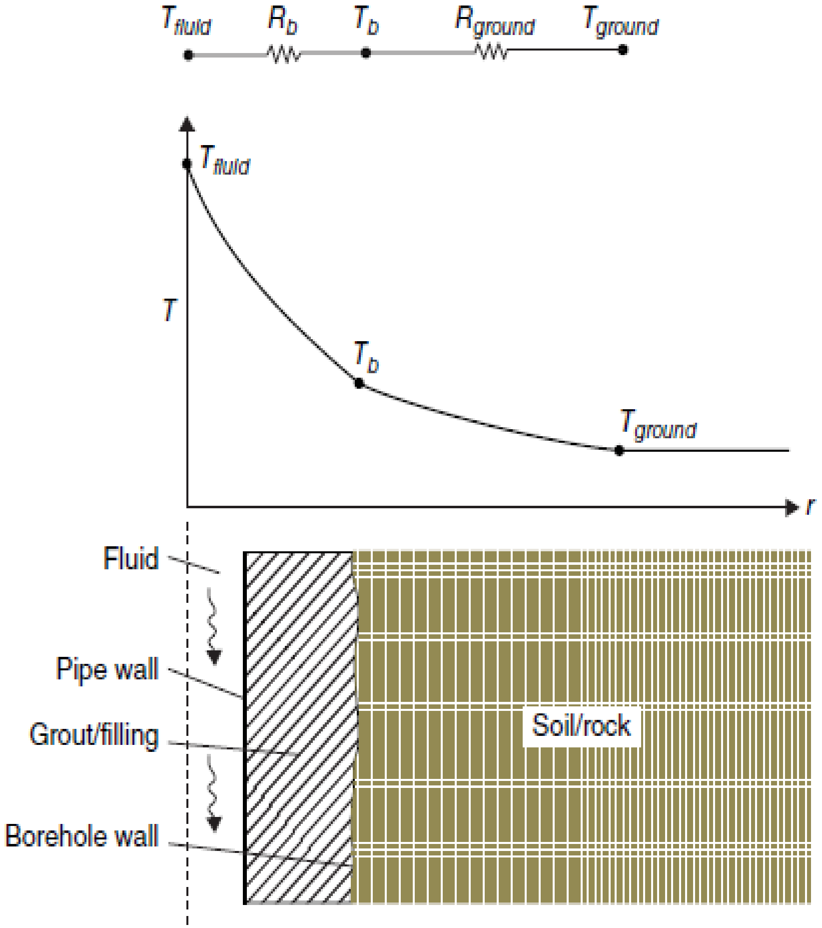
- R'_b is the borehole thermal resistance per unit length
- T_f is the average fluid temperature
- T_b is the average temperature at the borehole wall
- $\dot{q}'$ is the thermal pulse per unit length

Borehole Heat Exchangers

Mathematical Models of the Borehole

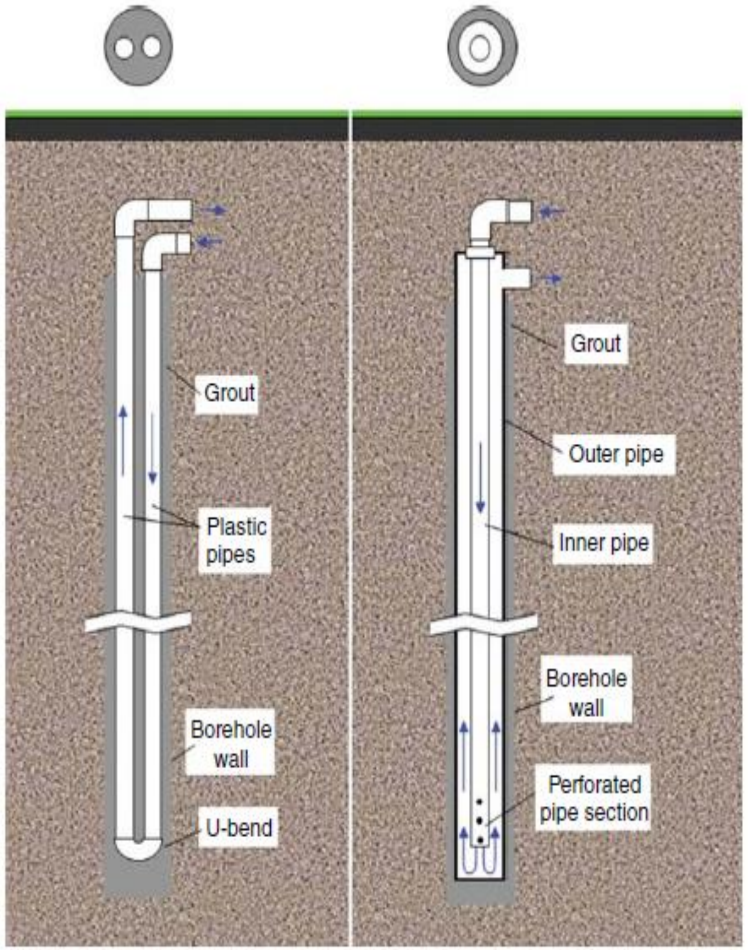
Thermal Resistance

- heat first must be transferred by fluid convection
- then by conduction through the pipe
- And then through the borehole filling material
- The filling material may be either grout or natural groundwater.



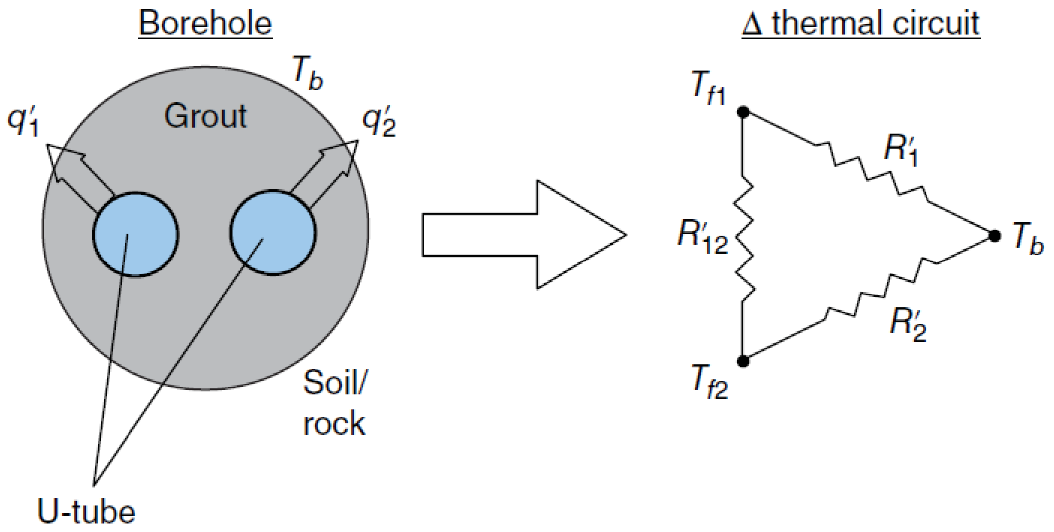
Mathematical Models of the Borehole Thermal Resistance

- The borehole thermal resistance is also dependent on the type and arrangement of flow channels in the borehole
- there are many configurations of BHEs such as U-tube or concentric tube (coaxial tube) configuration



Mathematical Models of the Borehole Thermal Resistance

- The heat fluxes associated with each leg of the U-tube are not equal (except at the borehole bottom) and vary with depth.
- Each leg thermally interacts with the surrounding ground, as well as with each other.
- Calculation of the borehole thermal resistance is further complicated with multiple U-tubes (i.e., two U-tubes or three U-tubes).



Borehole Heat Exchangers

Mathematical Models of the Borehole Thermal Resistance

The Pipe Thermal Resistance:

- the most common material of construction for BHEs is high-density polyethylene (HDPE)
- Crosslinked polyethylene (PEX) is also gaining market strength
- the thermal resistance of the BHE pipe per unit length of bore:

$$R'_p = \frac{1}{\pi D_{p,in} h_{in}} + \frac{\ln\left(D_{p,out} / D_{p,in}\right)}{2\pi k_p}$$

- the convection coefficient (*h*) for internal flow in pipes:

$$h = \frac{Nuk_f}{D_{p,in}}$$

Mathematical Models of the Borehole Thermal Resistance

The Pipe Thermal Resistance:

- ❑ Under laminar flow conditions, Nu = constant = 4.36
- ❑ Under turbulent flow conditions (i.e., Re > ~2300), Nu = f(Re, Pr).
- ❑ Over a wide range of 0.5 < *Pr* < 2000 and 3000 < *Re* < 5 × 106:

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

- ❑ The heat transfer fluid used in BHEs ranges from pure water to an aqueous antifreeze mixture with various proportions of, most commonly, propylene glycol.

Mathematical Models of the Borehole Thermal Resistance

The Thermal Resistance of Grouted Single U-Tube BHEs:

- ❑ An ideal BHE bore grout would protect groundwater from contamination, promote heat transfer, be easy to install, and have a reasonable cost.
- ❑ The most commonly used grouting materials: either bentonite based or cement based.
- ❑ The higher-thermal-conductivity materials result in lower borehole thermal resistance, which translates to less drilling required.
- ❑ for a single U-tube take the arithmetic average of the two cases of a uniform borehole wall temperature ($R'_{1,effective}$) and a uniform heat flux on the borehole wall ($R'_{1,effective}$):

$$R'_{b,single\ \ U\text{-}tube} = \left(R'_{1,effective} + R'_{2,effective}\right)/2$$

Borehole Heat Exchangers

Mathematical Models of the Borehole Thermal Resistance

The Thermal Resistance of Grouted Single U-Tube BHEs:

$$R'_{1,effective} = R'_2 + \frac{1}{3R'_{1,2}}\left(\frac{H}{\dot{m}c_p}\right)^2 + \frac{1}{12R'_2}\left(\frac{H}{\dot{m}c_p}\right)^2 \text{ and } R'_{2,effective} = R'_2 + \frac{1}{3R'_1}\left(\frac{H}{\dot{m}c_p}\right)^2$$

$$R'_1 = \frac{1}{\pi k_{grout}}\left[\beta + \ln\left(\frac{2S}{r_p}\right) + \sigma ln\left(\frac{r_b^2 + S^2}{r_b^2 - S^2}\right)\right] - \frac{1}{\pi k_b}\frac{\frac{r_p^2}{4S^2}\left[1 + \sigma\frac{4r_b^2 S^2}{\left(r_b^4 - S^4\right)}\right]^2}{\left\{\frac{1+\beta}{1-\beta} + \frac{r_p^2}{4S^2} + \sigma\frac{2r_p^2 r_b^2\left(r_b^4 + S^4\right)}{\left(r_b^4 - S^4\right)^2}\right\}}$$

$$R'_2 = \frac{1}{4\pi k_{grout}}\left[\beta + \ln\left(\frac{r_b}{r_p}\right) + \ln\left(\frac{r_b}{2S}\right)\right] + \sigma\ln\left(\frac{r_b^4}{r_b^4 - S^4}\right) - \frac{1}{4\pi k_b}\frac{\frac{r_p^2}{4S^2}\left[1 - \sigma\frac{4S^4}{\left(r_b^4 - S^4\right)}\right]^2}{\left\{\frac{1+\beta}{1-\beta} + \frac{r_p^2}{4S^2}\left[1 + \sigma\frac{16r_b^4 S^4}{\left(r_b^4 - S^4\right)^2}\right]\right\}}$$

$$R'_{1,2} = \frac{R'_1 R'_2}{R'_2 - 0.25R'_1} \qquad \beta = 2\pi k_{grout} R'_p \qquad \sigma = \frac{k_{grout} - k_{ground}}{k_{grout} + k_{ground}}$$

Borehole Heat Exchangers

Mathematical Models of the Borehole Thermal Resistance

The Thermal Resistance of Grouted Double U-Tube BHEs:

$$R'_{b,\ double\ u-tube} = R'_{sf} + \frac{1}{3}\frac{1}{R'_a}\left(\frac{H}{C}\right)^2$$

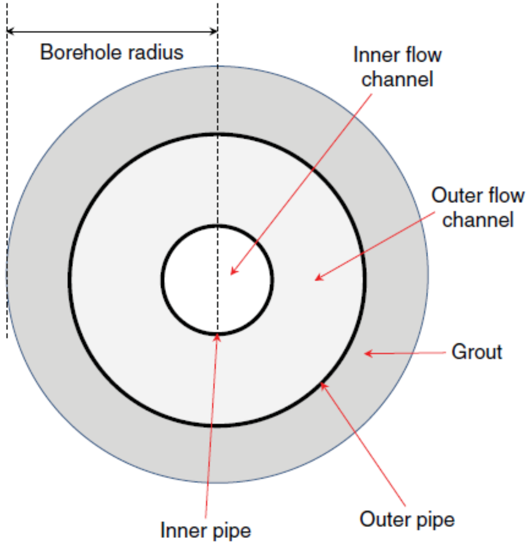
$$R'_{sf} = \frac{1}{2\pi k_{grout}}\left[\ln\left(\frac{r_b}{r_{p,out}}\right) - \frac{3}{4} + b^2 - \frac{1}{4}\ln\left(1-b^8\right) - \frac{1}{2}\ln\left(\frac{\sqrt{2}br_b}{r_{p,out}}\right) - \frac{1}{4}\ln\left(\frac{2br_b}{r_{p,out}}\right)\right] + \frac{R'_p}{4}$$

$$R'_a = \frac{1}{\pi k_{grout}}\left[\ln\left(\frac{\sqrt{2}br_b}{r_{p,out}}\right) - \frac{1}{2}\ln\left(\frac{2br_b}{r_{p,out}}\right) - \frac{1}{2}\ln\left(\frac{1-b^4}{1+b^4}\right)\right] + R'_p$$

Mathematical Models of the Borehole Thermal Resistance

The Thermal Resistance of Concentric Pipe (Coaxial) BHEs

$$R'_{b,\ concentric\,pipe} = R'_{sf} + \frac{1}{3}\frac{1}{R'_a}\left(\frac{H}{C}\right)^2$$



$$R'_{sf} = \frac{1}{2\pi k_{ground}} \left[\frac{k_{ground}}{k_{grout}}\left[\left(1+\xi\pi r_p\right)^2 \ln\left(\frac{r_b}{r_p}\right) - \xi\pi\left(1+\xi\pi r_p\right)^2\left(r_b^2 - r_p^2\right) + \frac{1}{4}\left(\xi\pi r_b^2\right)^2 - \frac{1}{4}\left(\xi\pi r_p^2\right)^2\right]\right] + R'_p$$

- Objective function: to minimize the sum of the squared error (SSE), given by:

$$SSE = \sum_{1}^{N} \left(T_{experimental} - T_{model}\right)^2$$

- **The optimization steps:**

(a) First, make some initial guesses of the thermal conductivity and borehole thermal resistance. Enter the remaining values needed to calculate the BHE fluid temperature (i.e., ρc_p, undisturbed temperature, average heat input during the test (in W or Btu/h), borehole depth, borehole radius).

(b) At each time interval, calculate the average *measured* borehole fluid temperature $T_{avg} = (T_{in} + T_{out})/2$ and plot on a graph,

(c) At each time interval, calculate the ground thermal resistance (R'_g).

- If using the well function, R'_g is given by $W(u)/(4\pi k)$.
- If using Eskilson's analytical g-function, R'_g is given by $g/(2\pi k)$.

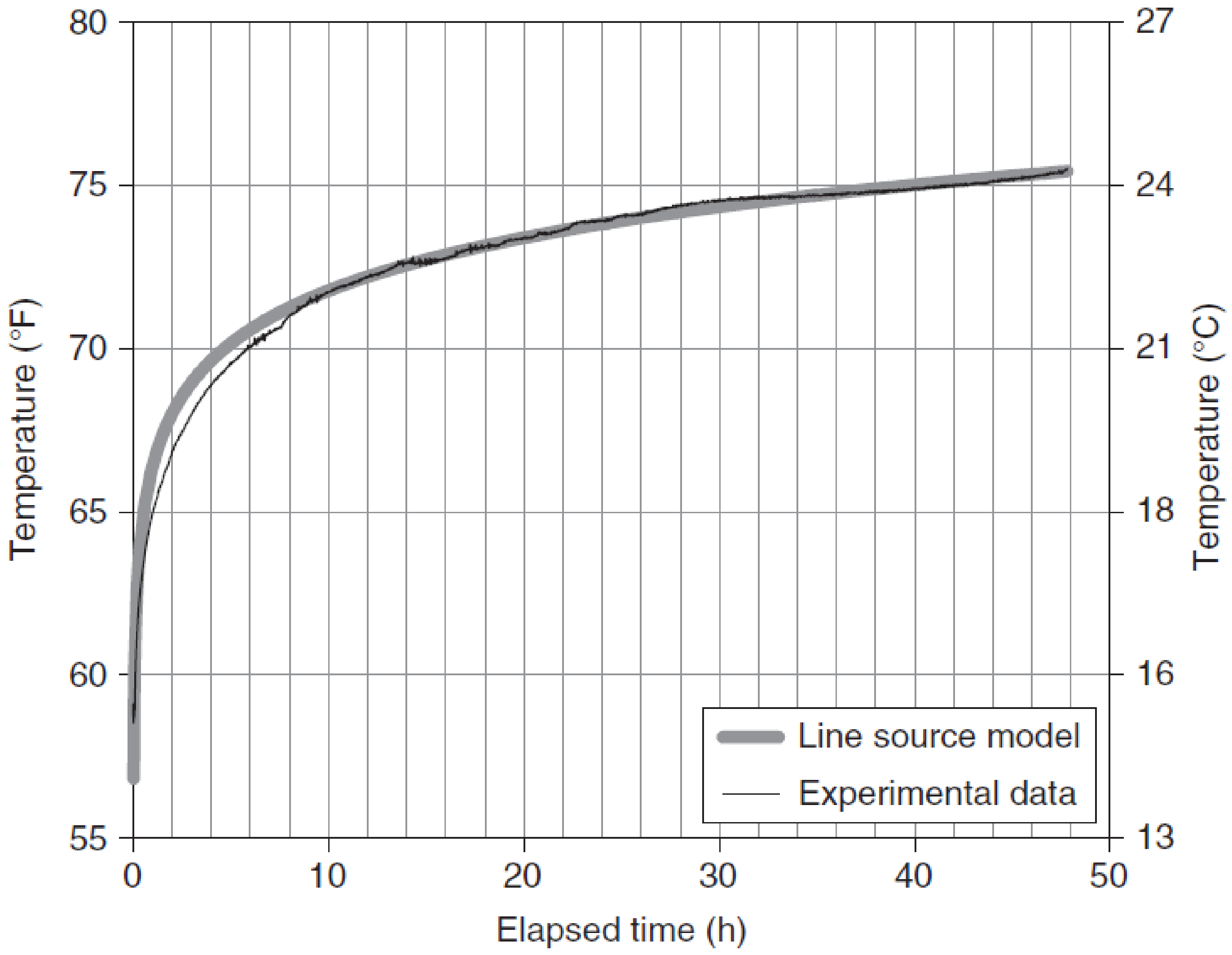
- **The optimization steps:**

(d) At each time interval, calculate the BHE fluid temperature ($T_{f,\ avg}$) using equations (5.18) and (5.19). Thus, $T_{f,avg} = \dot{q}' R_g' + \dot{q}' R_b' + T_g$. Plot the calculated $T_{f,avg}$ on the same graph as the measured data.

(e) At each time interval, calculate the squared error between the experimental and modeled fluid temperatures. Sum the squared errors for times greater than $5 r_b^2 / \alpha$.

(f) Use the Excel Solver to minimize the sum of all the squared errors, with the Solver being set up to adjust the thermal conductivity and the borehole thermal resistance. Report the thermal conductivity and borehole thermal resistance when the sum of squared error is minimized.

- **The optimization steps:**



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Shallow geothermal engineering: overview and applications

Lecture 8. Numerical simulations using FEFLOW

Content

Numerical simulation using FEFLOW

- Numerical solutions are applied in geothermal engineering because the analytical solution can only provide approximate information about the heat exchanger behavior.

- There is the need to take into account ground thermal variability, heat transfer at different depth, which is not possible with analytical approximations.

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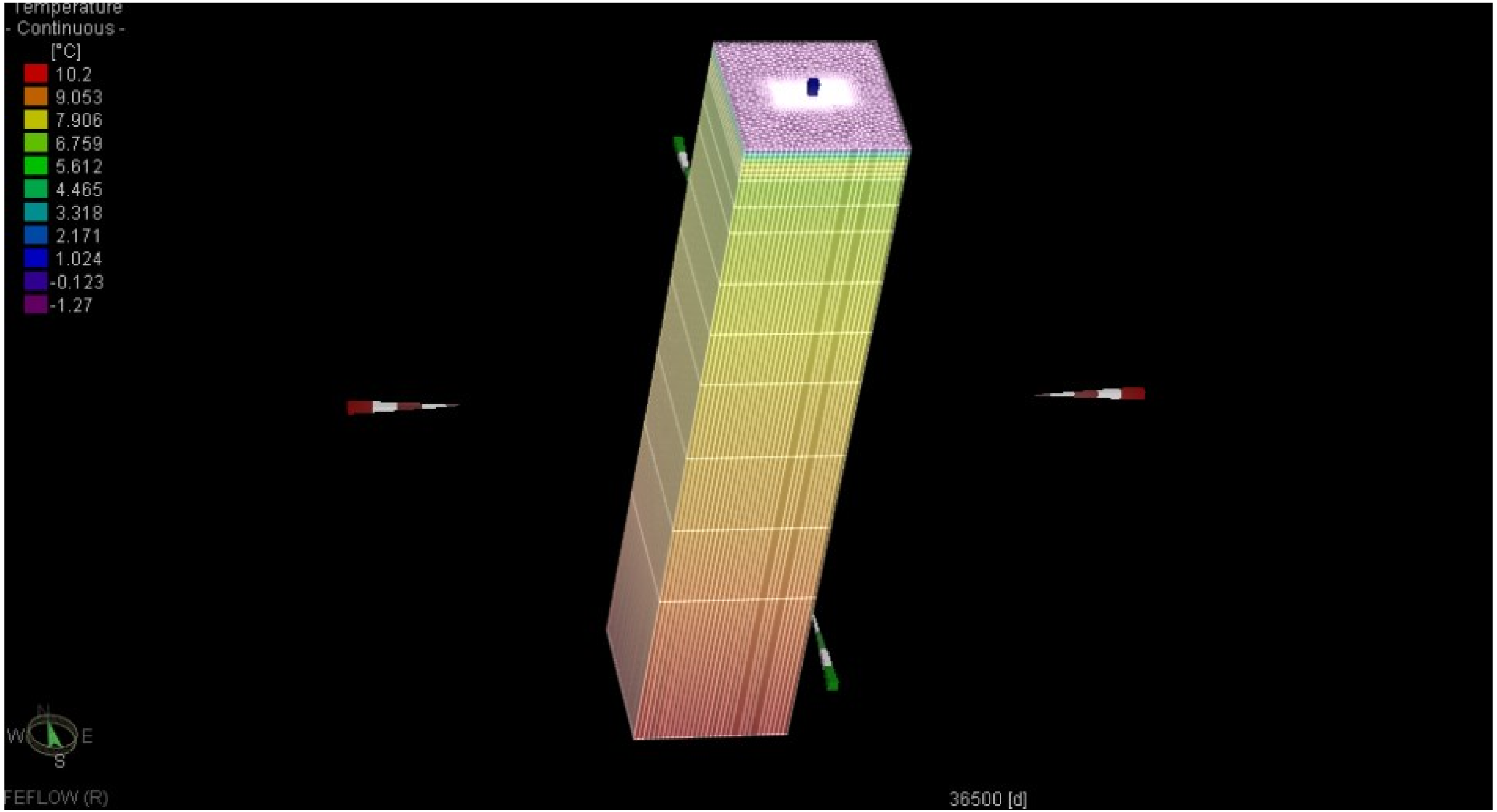
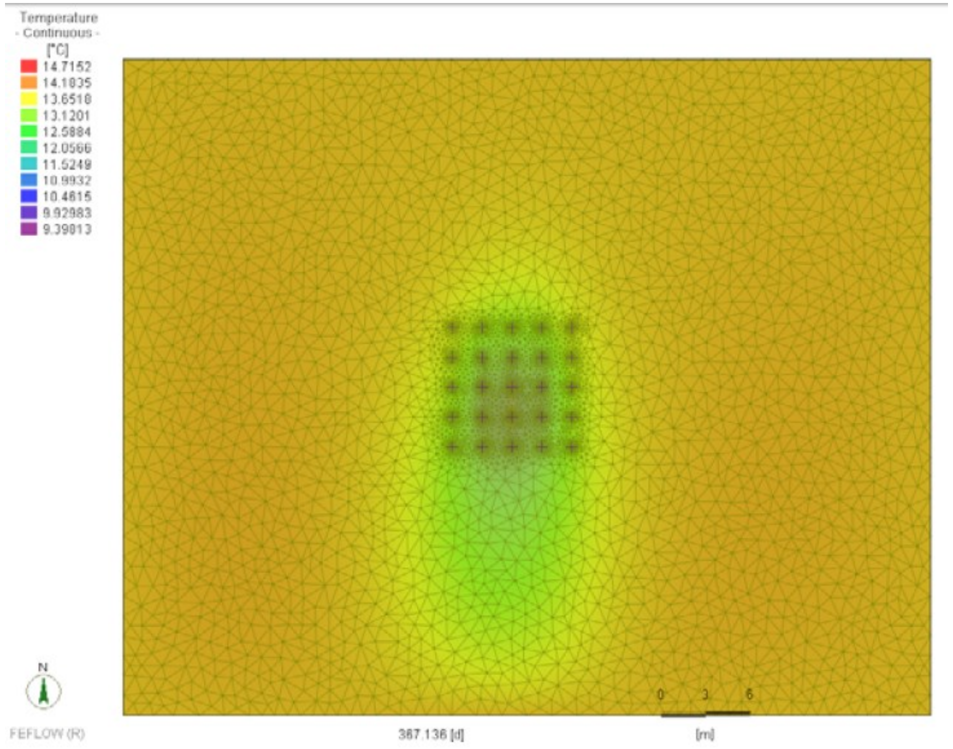
Numerical simulation using FEFLOW



Numerical simulation using FEFLOW

- Finite Element Modeling softwares, such as FEFLOW, have integrated packages of shallow geothermal energy.

- The simulation is not used for the design, but to validate the design specificities.



Numerical simulation using FEFLOW

- In order to perform the simulation, the general components of the geothermal system should already be set up: number of geo-exchangers, types, depth,…

- The model is fed by hypothesized thermal loads or temperature constraints for different time steps and provide a possible simulation of the heat transfer behavior and related temperatures.

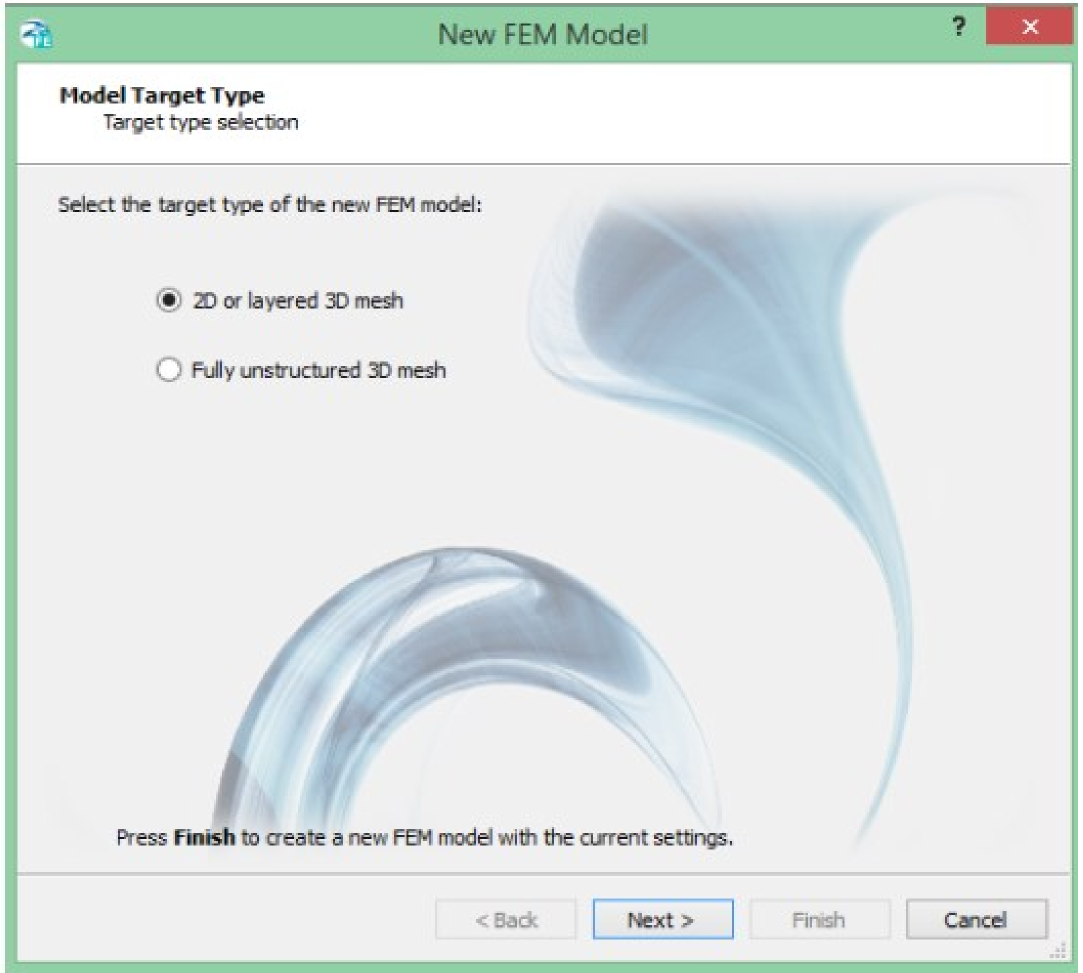
Numerical simulation using FEFLOW

- In order to model a geothermal system using FEFLOW, the following parameters should be known:
  - Involved area, location of buildings and location of geo-exchangers (Autocad, Qgis,..).
  - Climate data
  - Ground thermal and hydraulic properties
  - Groundwater flow movement and direction
  - Heat load to inject and extract from the ground at different time steps.

Numerical simulation using FEFLOW

- The creation of the model is mainly based on «time series» of different variables as boundary conditions:
  - temperature at different depth.
  - Varying groundwater level.
  - target temperature variation in the geo-exchanger.
  - Injected/extracted power to/from the ground, Etc..
- The mesh can be layered or unstructured. In the case of vertical geo-exchangers, the 3D layered version works good.

Numerical simulation using FEFLOW



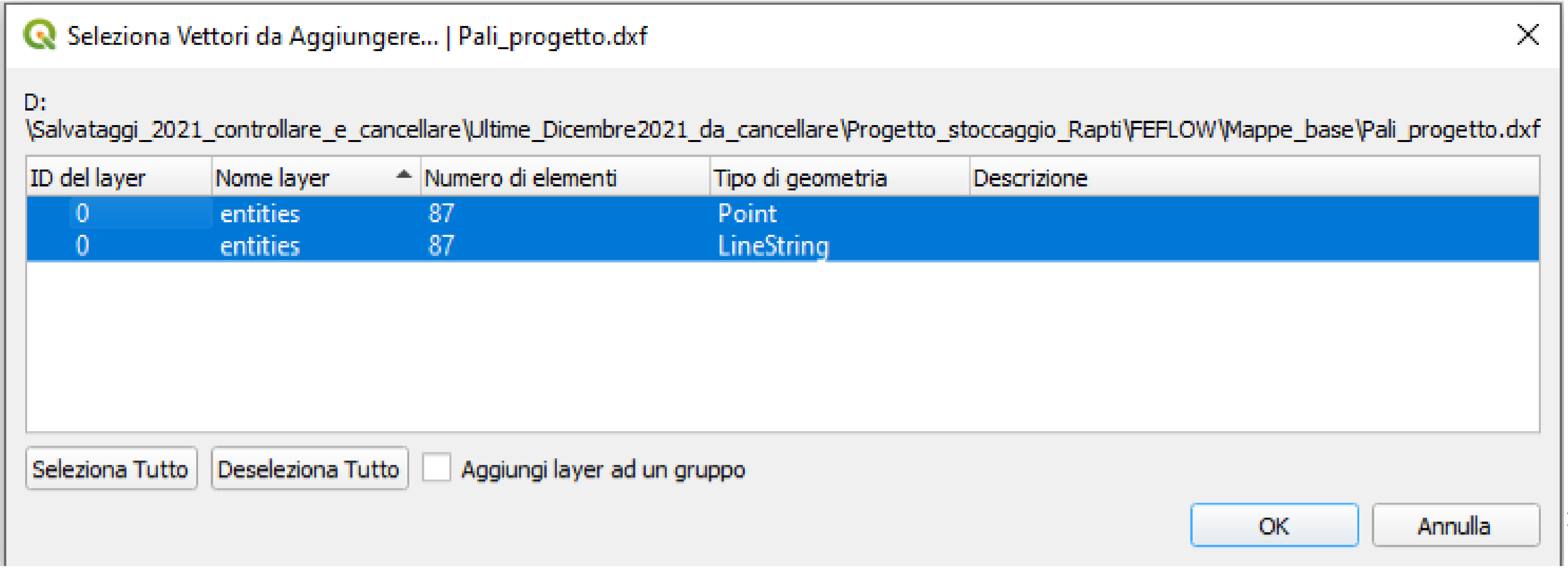
Numerical simulation using FEFLOW

- As an example, the surface layer can be created in Autocad, converted as DXF (ASCI), and then transformed in shapefile SHP in Qgis, to be imported in FEFLOW.

- Since the original drawing is composed by lines, polygons and overall points (the exact geo-exchanger locations), each of them should be imported as a different shapefile, with homogenous local Coordinate Reference System

Numerical simulation using FEFLOW

- Import different shapefiles

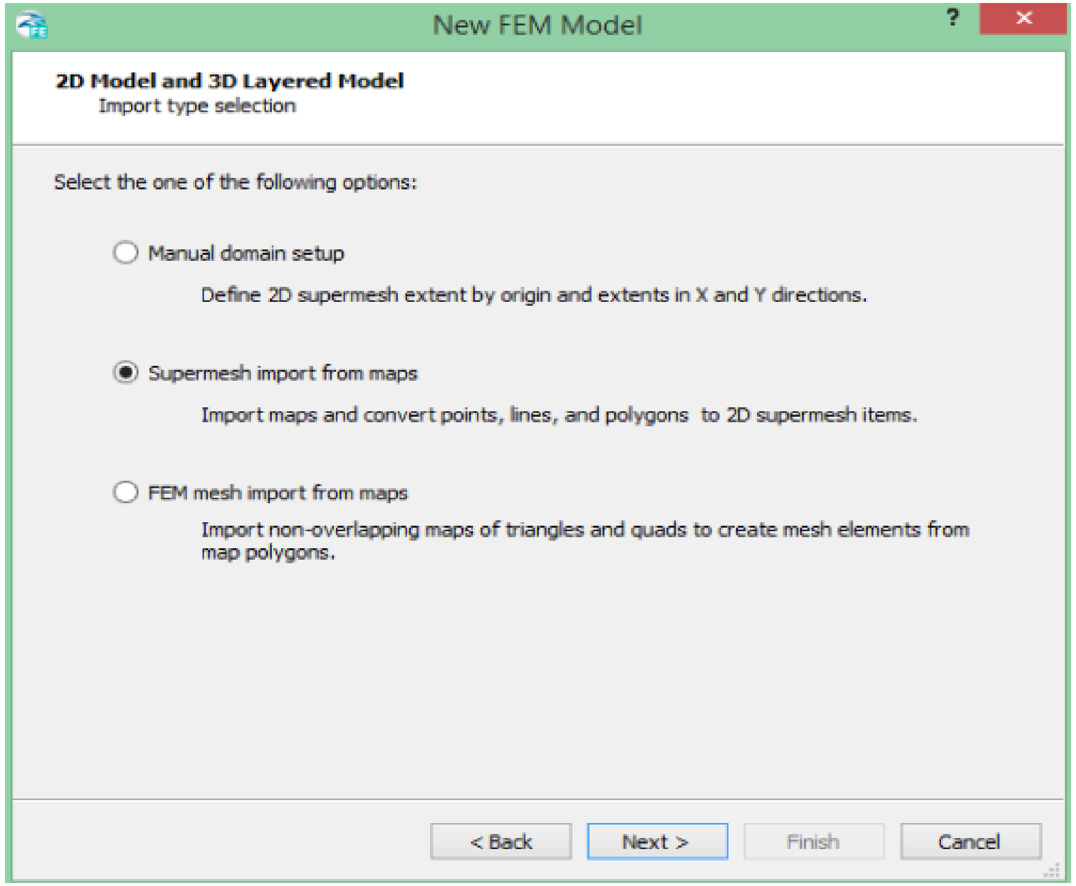


Numerical simulation using FEFLOW

- Important Note: the areas should be identified as polygons, in order to create the mesh later on. Therefore, transformation from lines polygons is necessary (in Autocad or later, in Qgis, as an example).

Numerical simulation using FEFLOW

- The area can be manually created
- or imported.
- It is recommended to import it, after design and transformation in shapefile. In this way, the limits of the buildings and the location of the geo-exchangers are more precise.

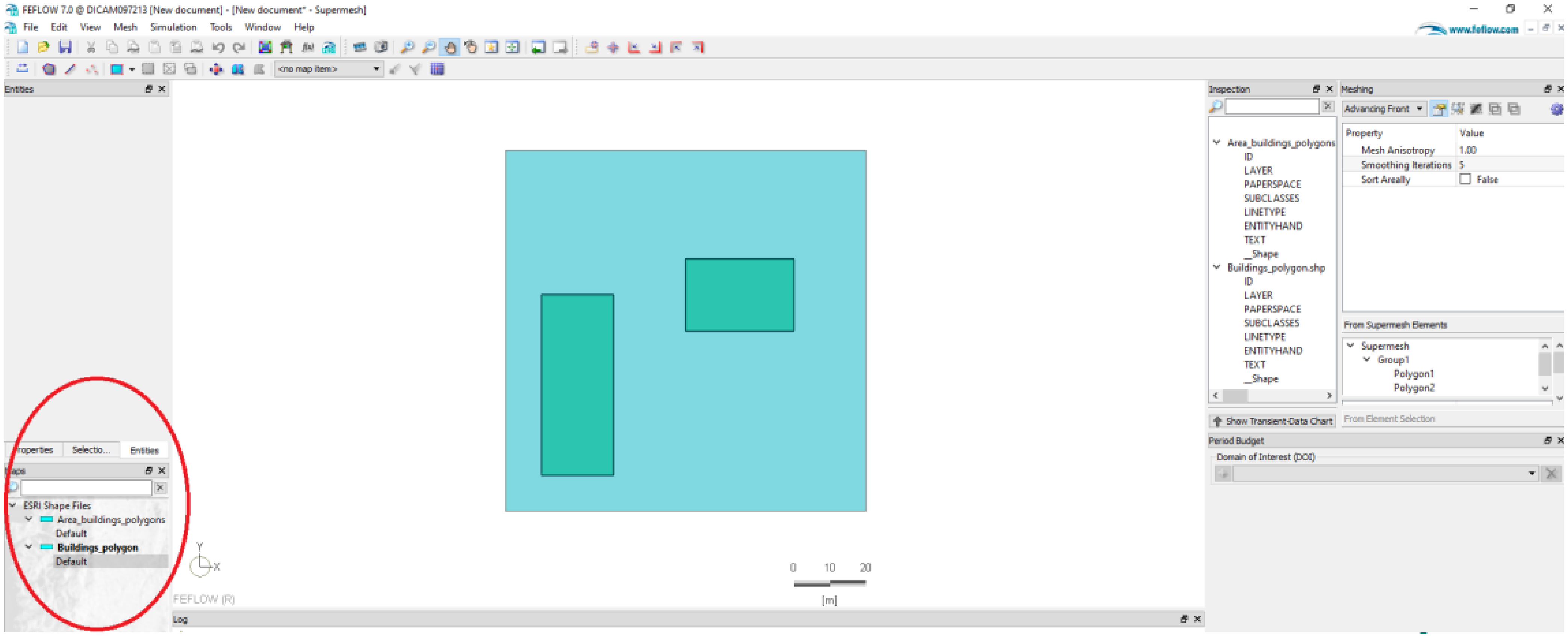


Numerical simulation using FEFLOW

- Once the polygons are imported in Qgis, the mesh can be created.

- Polygons of the area are fundamental, but also small polygons can be inserted (example: buildings), lines (examples: rivers) and overall for geothermal projects points (the locations of the geo-exchangers).

Numerical simulation using FEFLOW

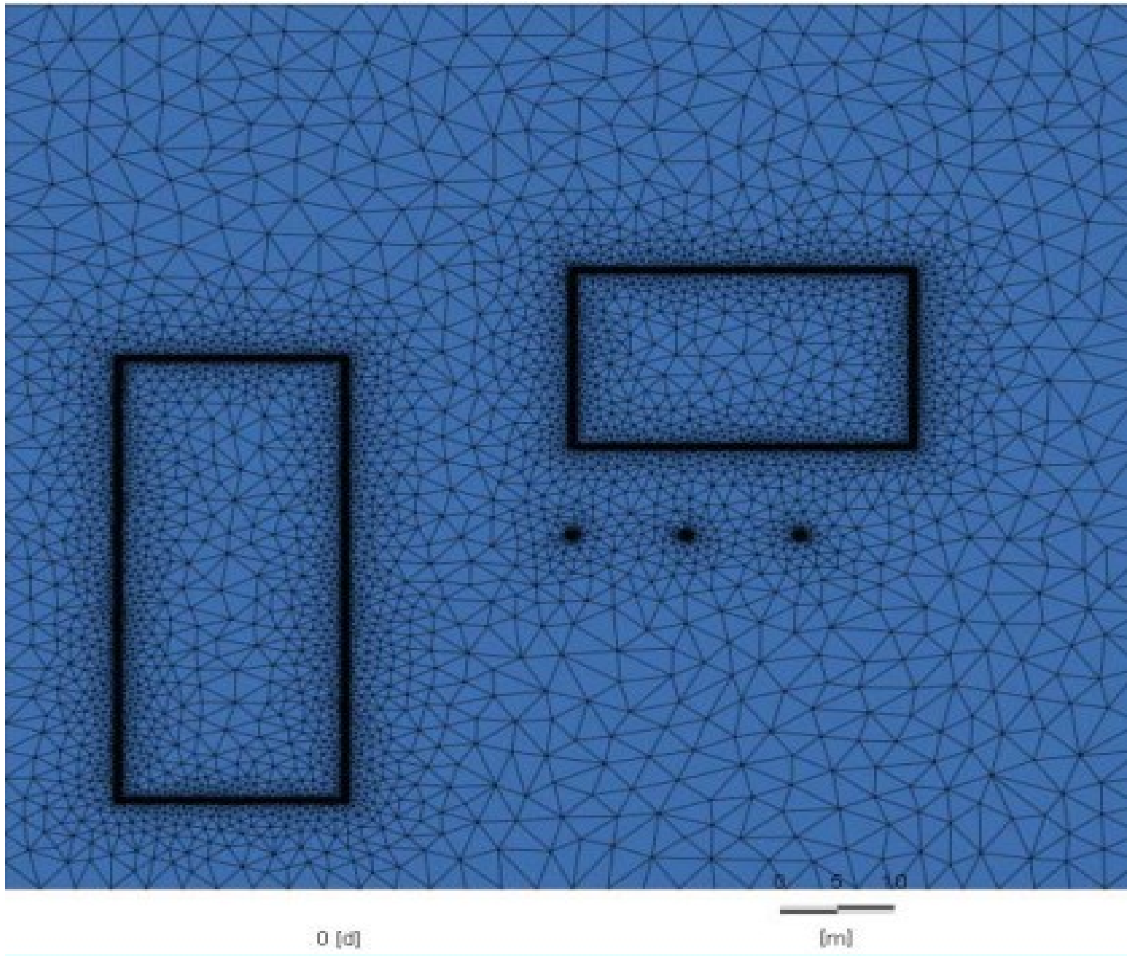


Numerical simulation using FEFLOW

- For geo-exchanger applications, it is useful to refine the mesh around the points (location of geo-exchangers). Select «Triangle» and «Force Delaunay Criterion».

- Refinement must be set up around BHE and can be set up along the lines of buildings.

Numerical simulation using FEFLOW

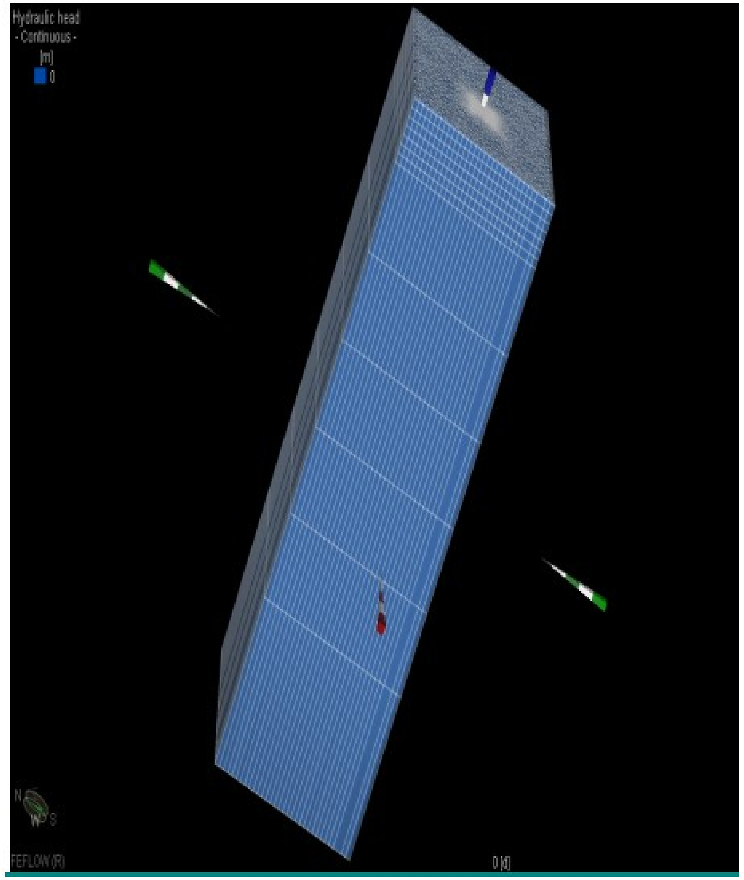


Numerical simulation using FEFLOW

- In a geo-exchanger project, the variability of the thermal and hydraulic properties along depth is fundamental. Therefore, move to the 3D view and increase the number of layers.
- First layer: 1-0 buffer zone with temperature wave data and building data
- Fitted layers at the top, to correctly represent the influence of smoothed weather temperature data underground

Numerical simulation using FEFLOW

- From the «neutral zone», layers coinciding with the different lithology and aquifer conditions
- Last layer of higher thickness, keeping into account the geothermal heat flow coming from the earth crust.



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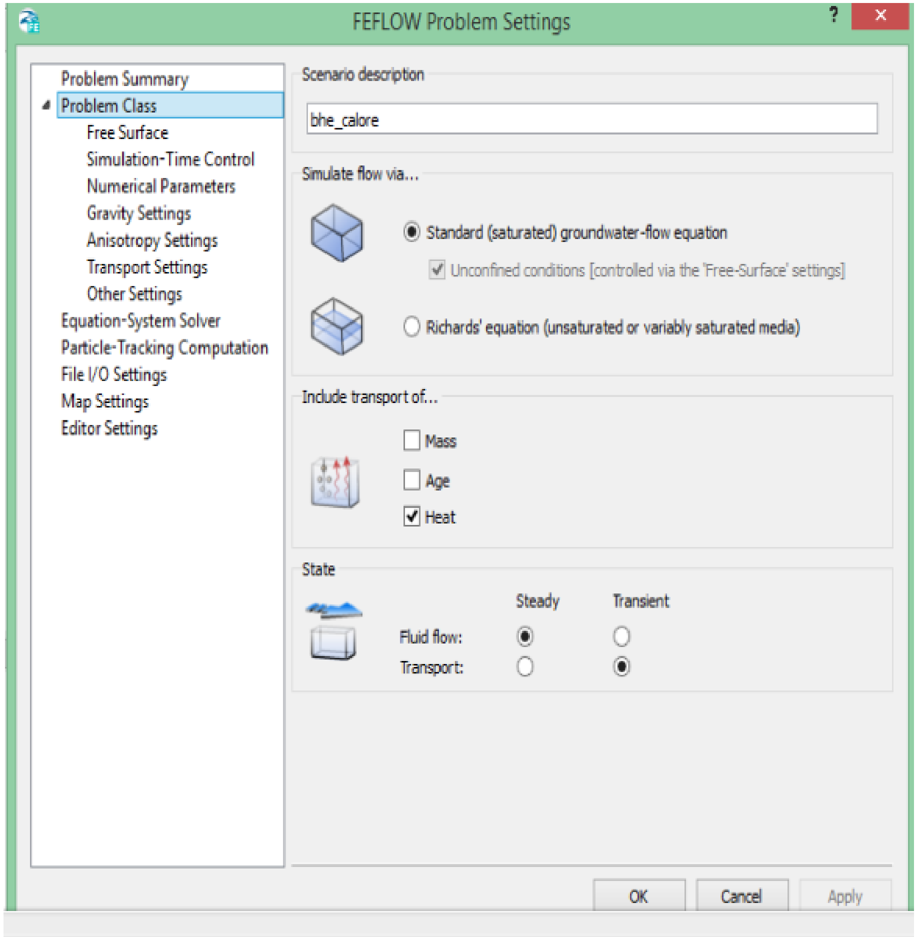
Numerical simulation using FEFLOW

- For geo-exchanger projects, transport of heat must be selected.
- The flow type depends on the aquifer.

- For such type of problems, it is enough to select «first order accurate» predictor-corrector.
- Time length of the simulation must be also decided in the Problem Summary.



Numerical simulation using FEFLOW

- Creation of time series for the boundary conditions, which will influence the heat transfer and groundwater flow movement of «natural state», which means before the heat extraction from geo-exchangers.
- They must be created as .pow files and inserted separately for each layer or line.

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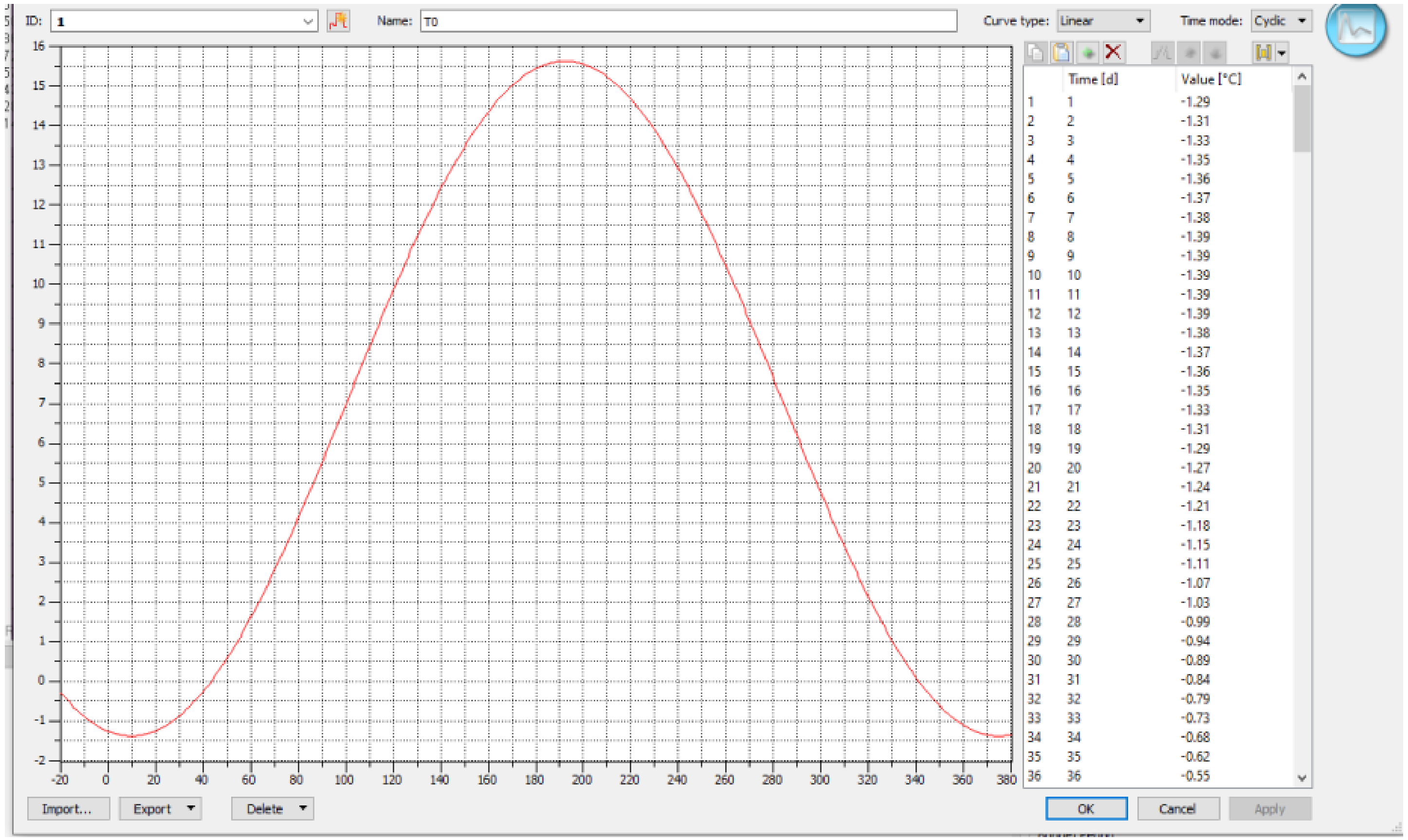
Numerical simulation using FEFLOW

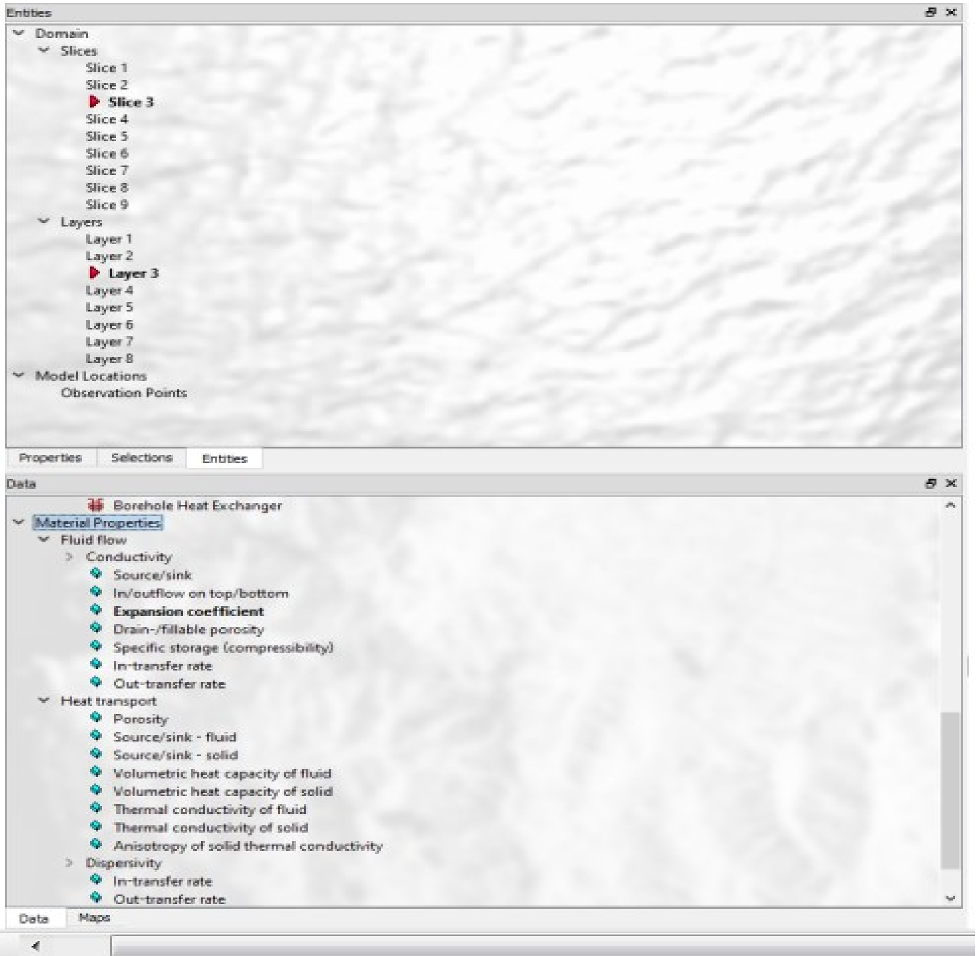


Numerical simulation using FEFLOW

- For each layer, the ground properties can be inserted. They can present a strong variability, therefore high differences in ground properties (because of different geology and hydrogeology) should be considered by separating the layers.

- Ground properties will influence the groundwater flow movement and temperature behavior underground (natural state) and later on, the heat extraction/injection potential of the geo-exchangers.

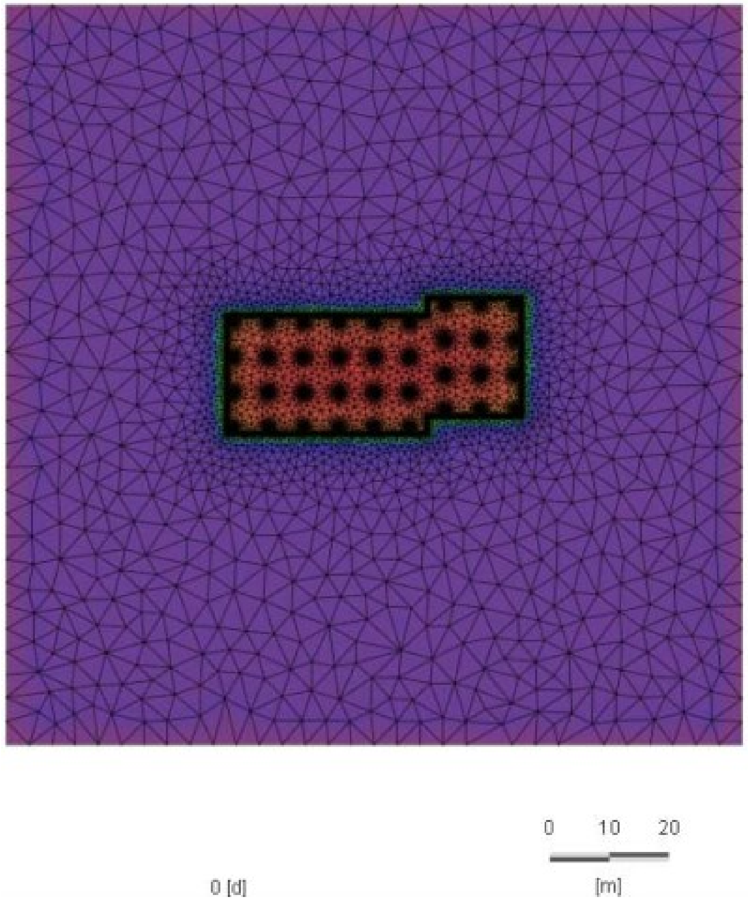
Numerical simulation using FEFLOW

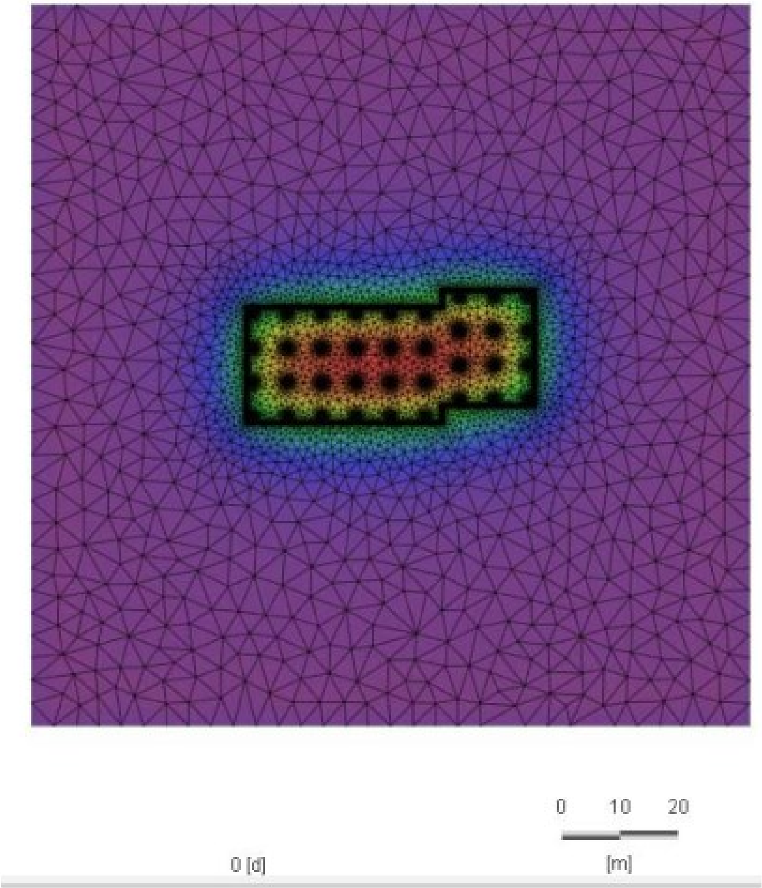


Numerical simulation using FEFLOW

- A continuous heat transfer and groundwater flow movement for the whole area is guaranteed since the time series are set at the boundaries.
- Usually, natural state besides the geo-exchangers is validated by temperature sensors, with the system off.
- Natural state can comprise also building thermal influence.

Numerical simulation using FEFLOW





Numerical simulation using FEFLOW

- In order to validate the natural state, observation points can be inserted, at required depth.
- After many years of operations, the temperature around the geo-exchangers should be stable and similar to the one measured in the field.
- Usually, observation points are inserted at the nodes of the mesh, but it is not mandatory.

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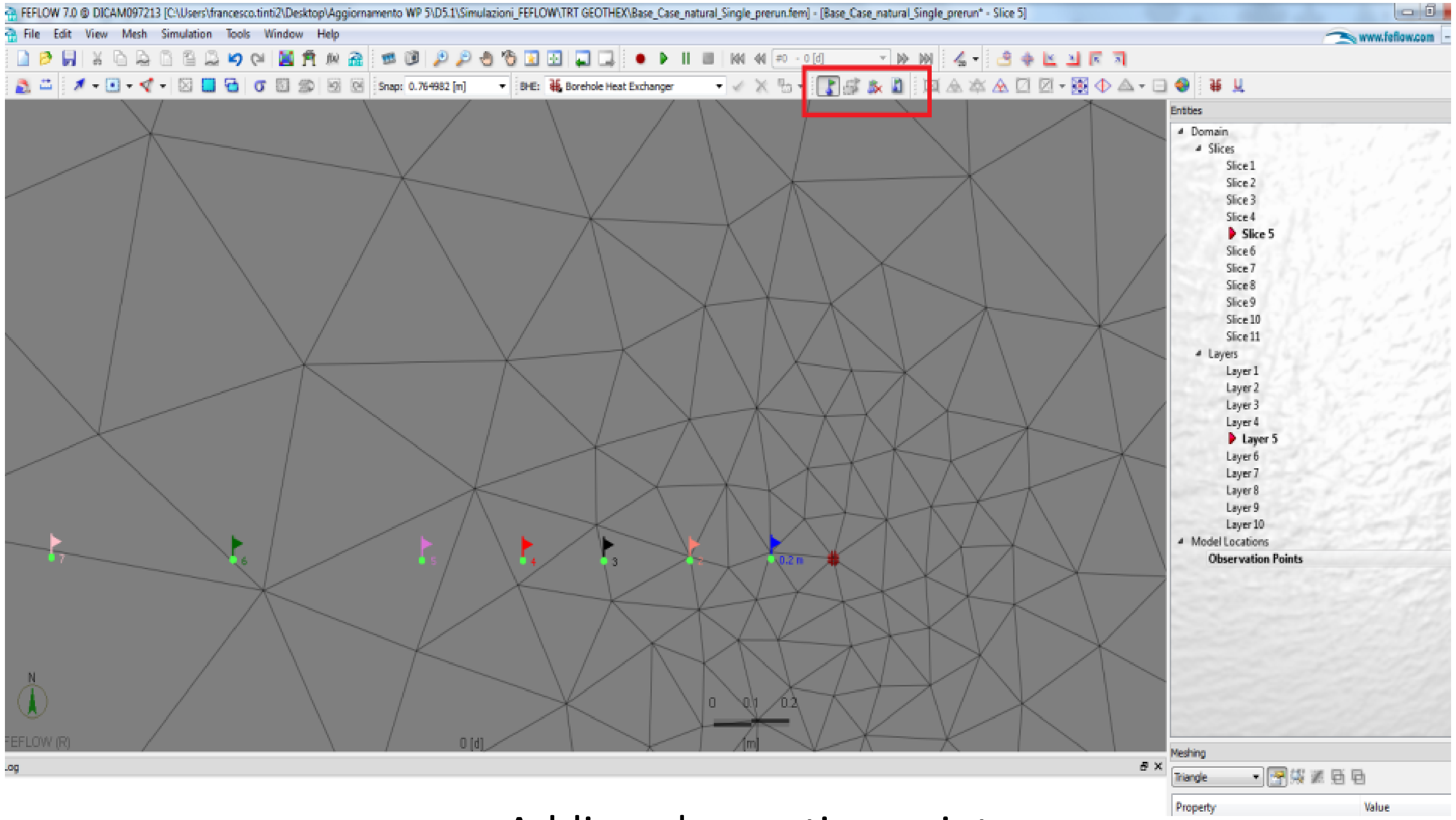
Numerical simulation using FEFLOW



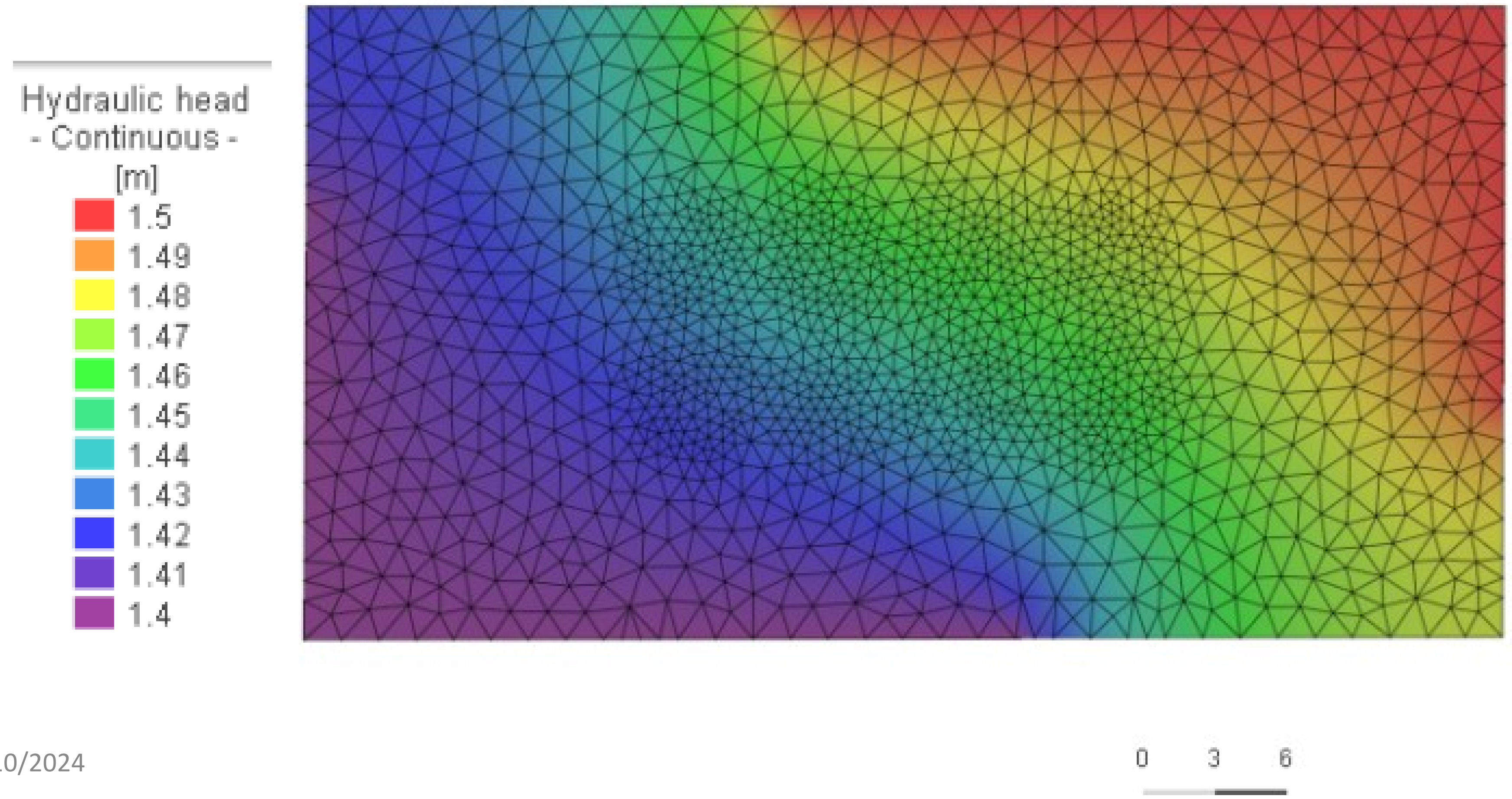
Adding observation points

Numerical simulation using FEFLOW

- The same as temperature, groundwater flow is imposed at the boundaries.
- According to the definition of the hydraulic head differences, the direction and strength of the groundwater flow is set up in the «natural state» phase through piezometers, the «natural state» can be validated as well.

Important: groundwater flow strongly influences the heat transfer behavior, therefore for a proper simulation approaching reality should be carefully taken into account.

Numerical simulation using FEFLOW



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Numerical simulation using FEFLOW

- After confirmation of the natural state, it is possible to set up the geo-exchangers properties: materials, geometry, time series (boundary conditions) and arrays of multiple borehole heat exchangers.

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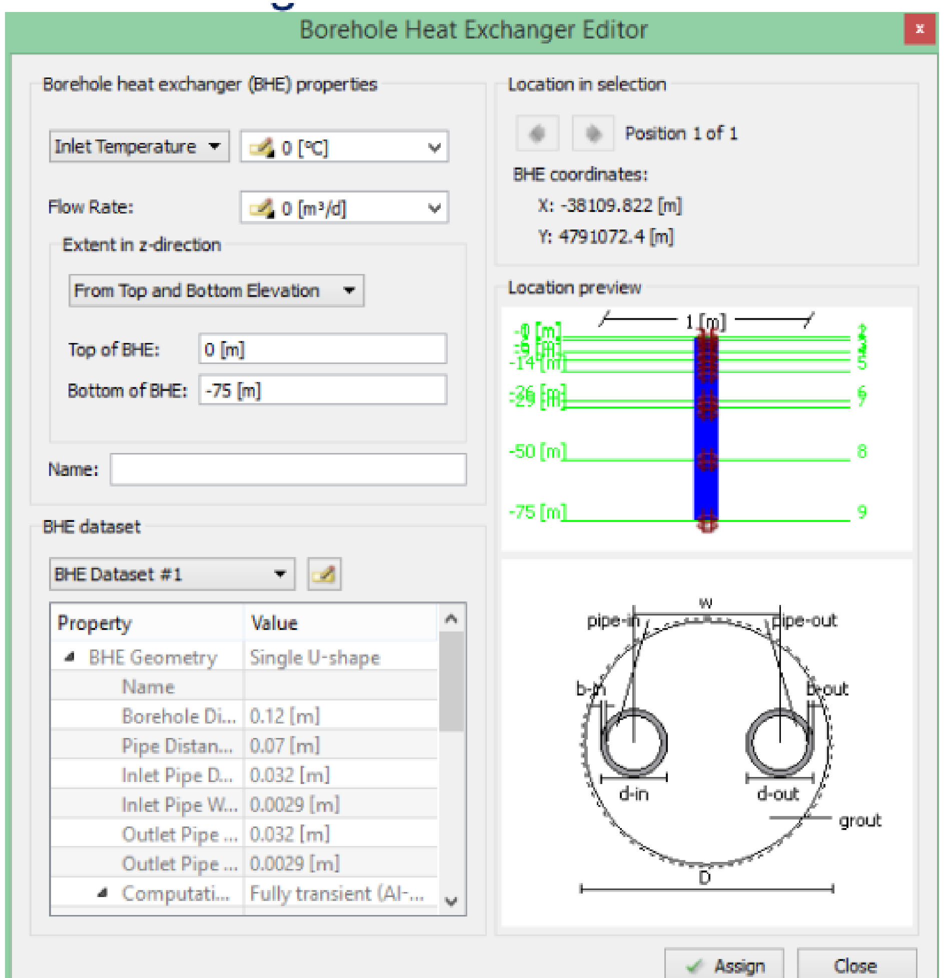
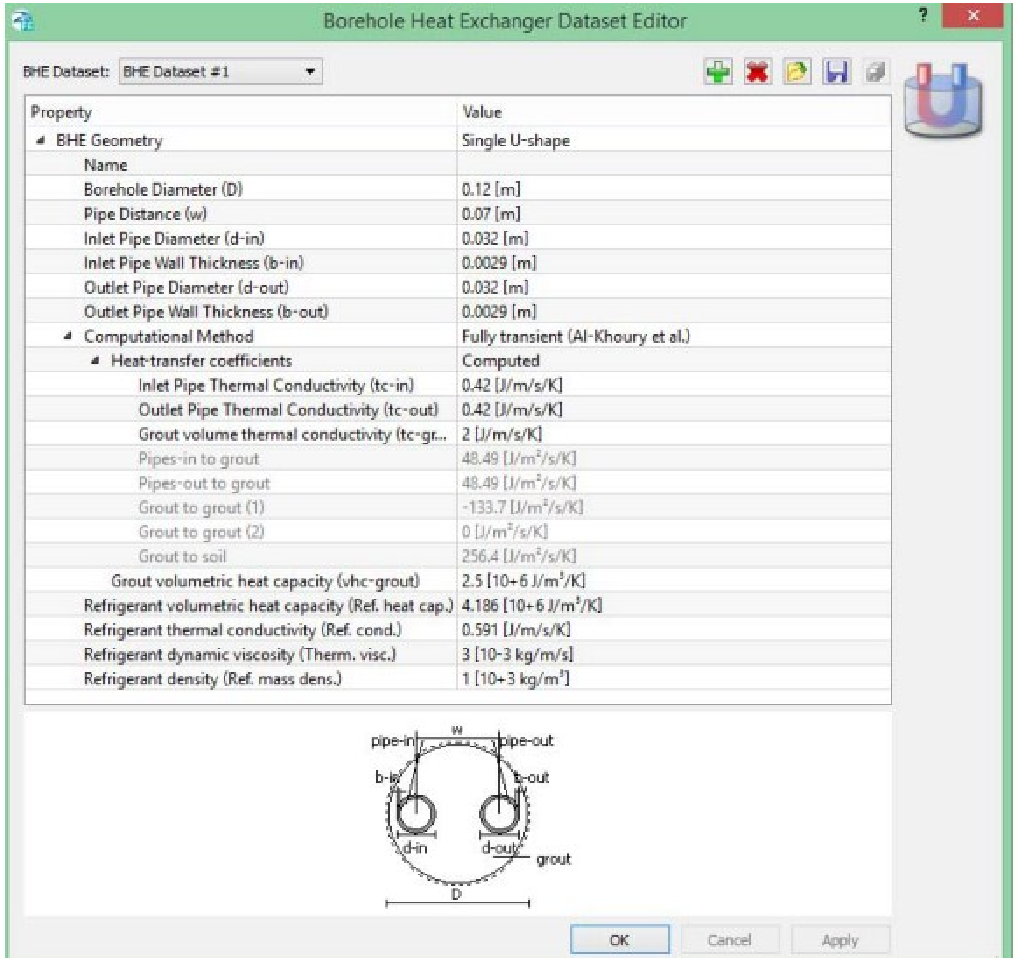
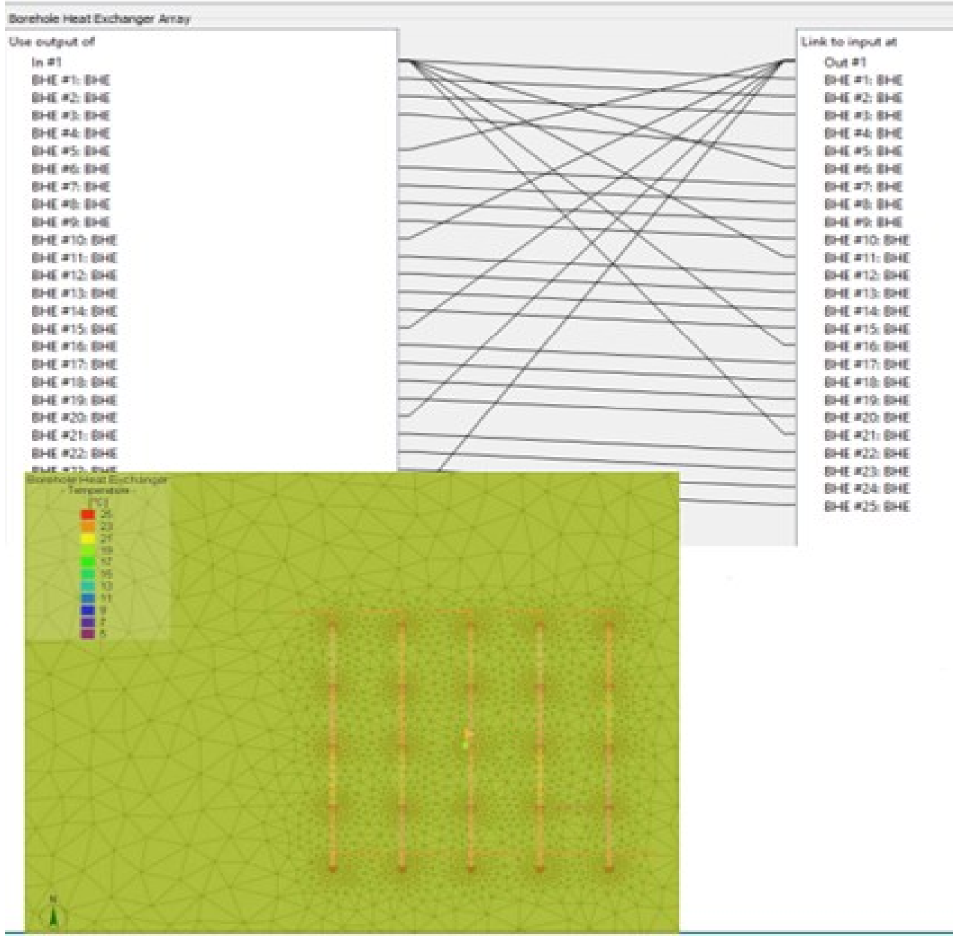
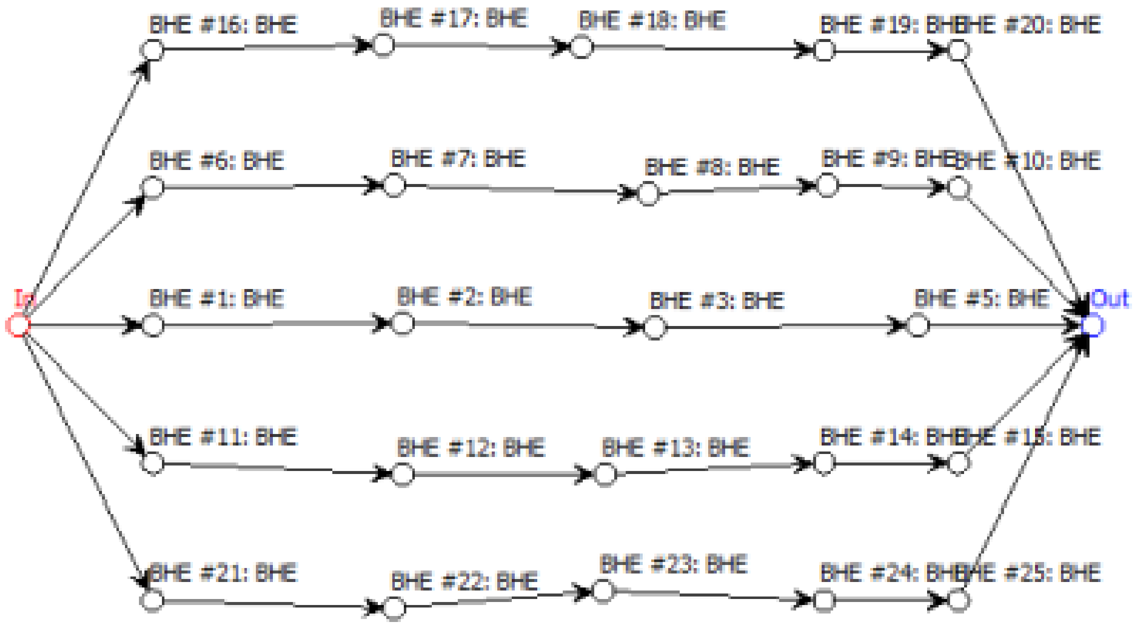
Numerical simulation using FEFLOW





Arrays of BHEs





Time series of BHEs

- This is the most sensitive part. The time series should approximate the real request of the heat pump for each time step.
- The result of the simulation, without validation on-site, to be used for design purposes, will not represent the real behavior of the system, but can provide indications on the minimum requirements of the heat pump.

Minimum requirements of the system

- Minimum inlet temperature in winter.
- Maximum inlet temperature in summer.
- Minimum temperature variation between summer and winter.
- Minimum power provided in the different periods.

All these constraints should be considered and respected.

Simulation result concerns

- Inlet and outlet temperature evolution along depth.
- Inlet and outlet temperature evolution over time.
- Local temperature evolution around the BHE (through observation points).

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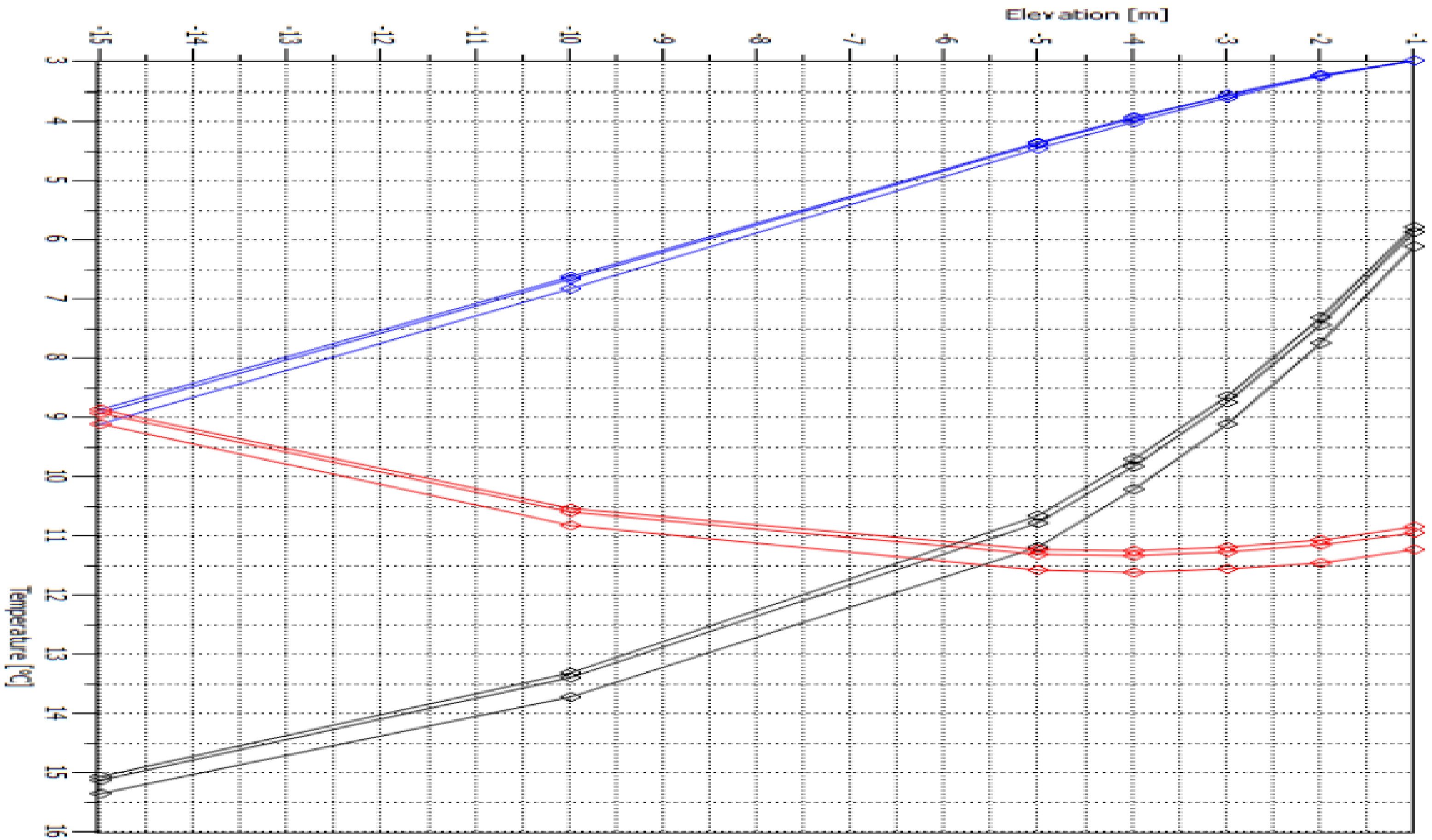
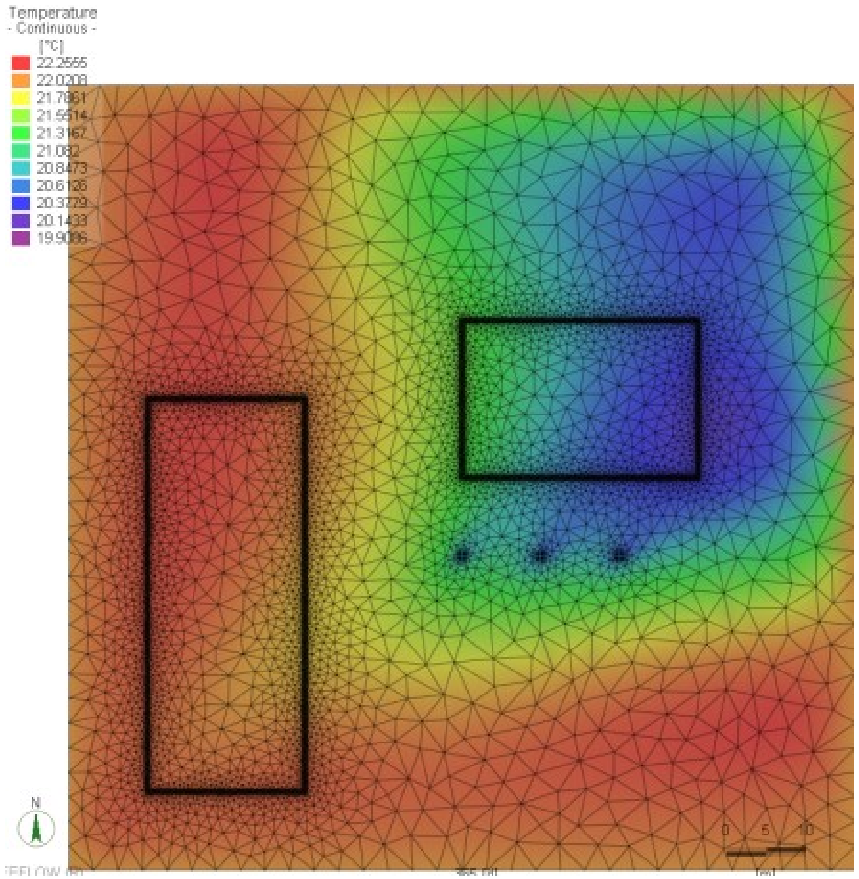
Simulation result concerns



Simulation validation

- Sustainability validation is carried out by comparing the simulation results and the minimum requirements.
- The whole history of the simulation can be recorded as dac file.
- The dac file can be used for coupling simulation with heat pump models.



Thanks for your attention