Geothermal Energy: Heat Flow Quantification

2024 SPE Europe Energy GeoHackathon

Yamal Askoul

Global Subject Matter Expert - Reservoir Engineering
GaffneyCline™ energy advisory
Oilfield Services & Equipment
Baker Hughes

Elkin Santafé

Senior Reservoir Engineer - Geoservices
GaffneyCline™ energy advisory
Europe, North Sea, Caspian & Sub-Sahara Africa
Baker Hughes

Baker Hughes

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1. Heat transfer processes in the well
   - Conduction
   - Convection (free and forced)
   - Radiation

2. Temperature modelling in the well

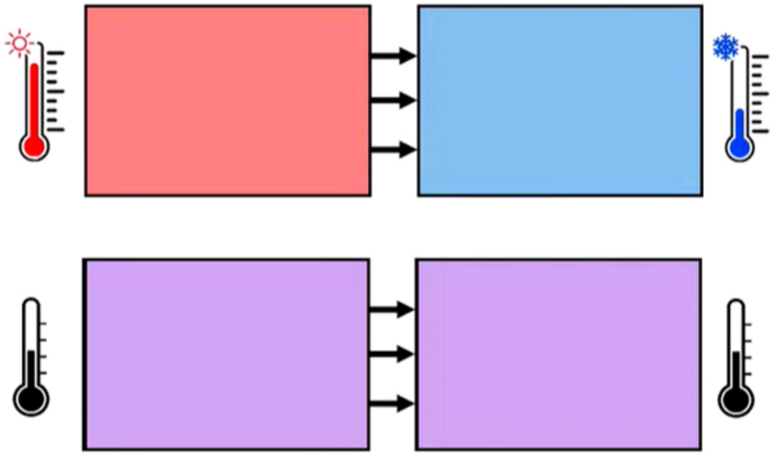
3. Overview of geothermal reservoirs
   - Types of geothermal reservoirs
   - Advanced modeling techniques (simulation)
   - The System Cycle

Heat Transfer Processes in the Well

Heat

Heat → Form of Energy

HEAT can be defined as thermal energy or heat energy that is transmitted from one body to another if their temperatures are different.

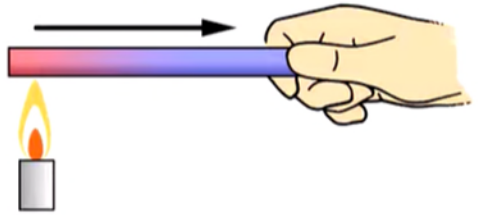


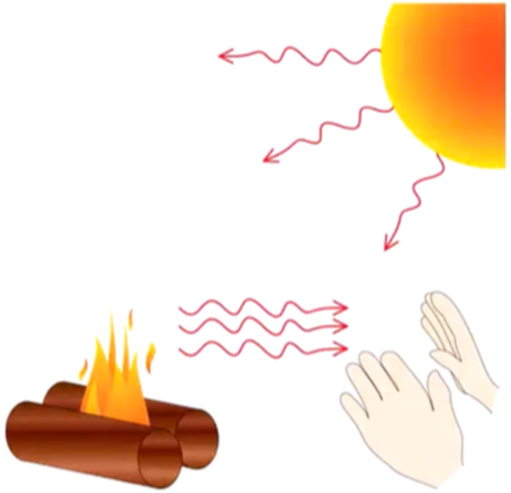
Heat always flows **from the body with the highest temperature to the body with the lowest temperature**.

Heat will be transmitted until **thermal equilibrium** is reached.
(Both substances/objects have the same temperature).

This transfer can occur through different processes...

Heat Transfer Processes





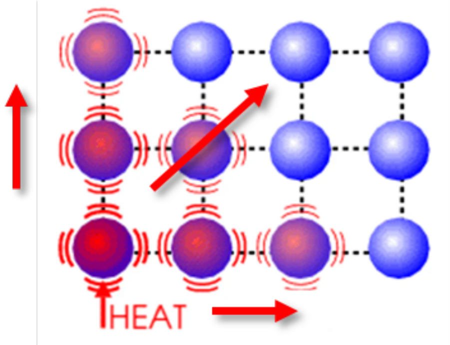
CONDUCTION

CONVECTION

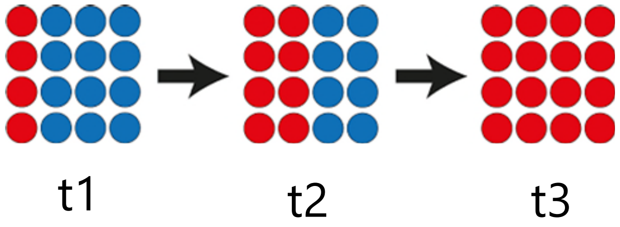
RADIATION

Conduction

The transfer of heat by **direct contact** between the molecules of a body or substance.

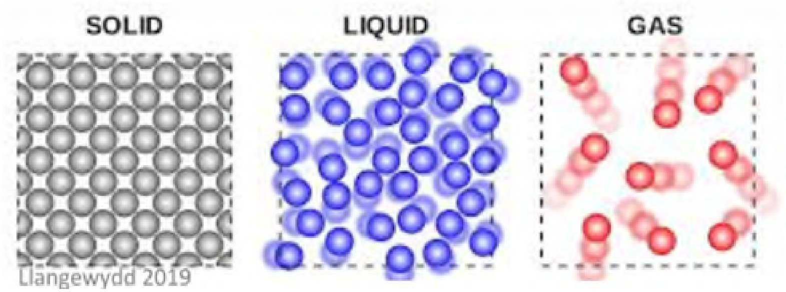


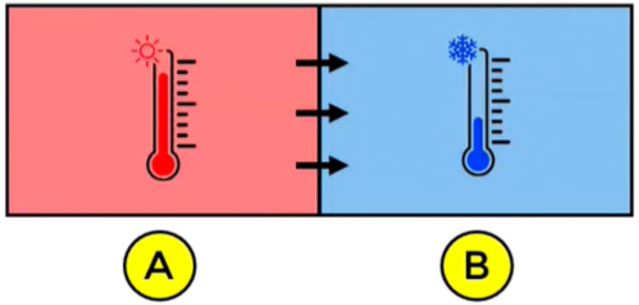
https://scienceready.com.au/pages/conduction-convection-and-radiation



the molecules impact each other, thus transferring heat between them.

Conduction can occur in solids, liquids, and gases – solids conduct most efficiently because the molecules are much closer together than in other states





Thermal Conductivity

Determines the ability of a material or substance to conduct heat.

Material	Thermal Conductivity - *k* - *W/(m K)*
Air, atmosphere (gas)	0.024
Aluminum	205
Balsa wood	0.048
Brass	109
Carbon dioxide (gas)	0.0146
Copper	401
Diamond	1000
Fiberglass	0.04
Glass	1.05
Gold	310
Hardwoods (oak, maple...)	0.16
Iron	80
Lead	35
Mercury, liquid	8.3
Paper	0.05
Silver	429
Softwoods (fir, pine ...)	0.12
Steel, Carbon 1%	43
Stainless Steel	16
Vacuum	0
Water	0.58
Zinc Zn	116

https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

Wood

Thermal Insulator

Silver

Thermal Conductor

Thermal Conductivity

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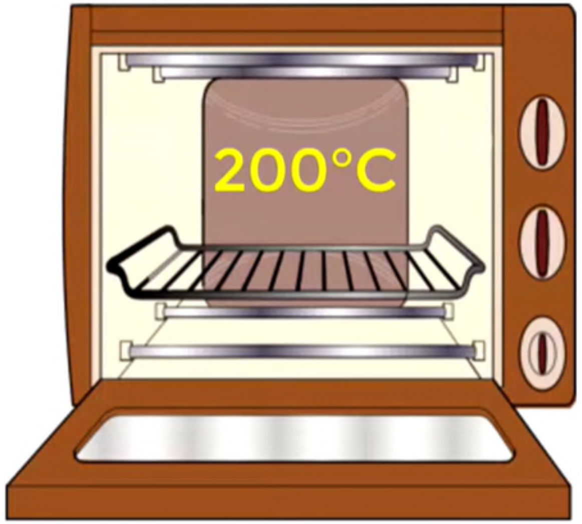


Air is a poor conductor of heat.

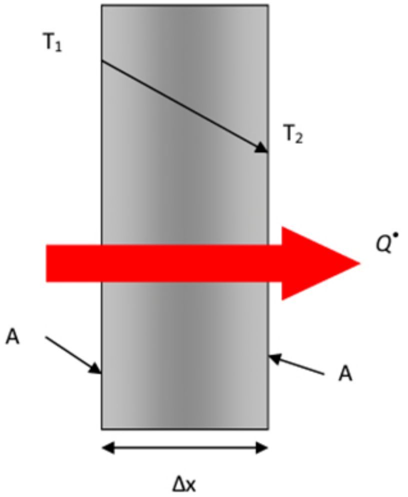
Metal is a good conductor of heat

Conduction

It has been experimentally observed that the rate of heat conduction through a layer is proportional to the temperature difference across the layer and the heat transfer area, but it is inversely proportional to the thickness of the layer

$$\text{rate of heat transfer} \propto \frac{(\text{surface area})(\text{temperature difference})}{\text{thickness}}$$

$$\dot{Q}_{Cond} = kA\frac{\Delta T}{\Delta x} \qquad (W)$$



SFU, Mr. Bahrami – Steady Conduction Heat Tranfer

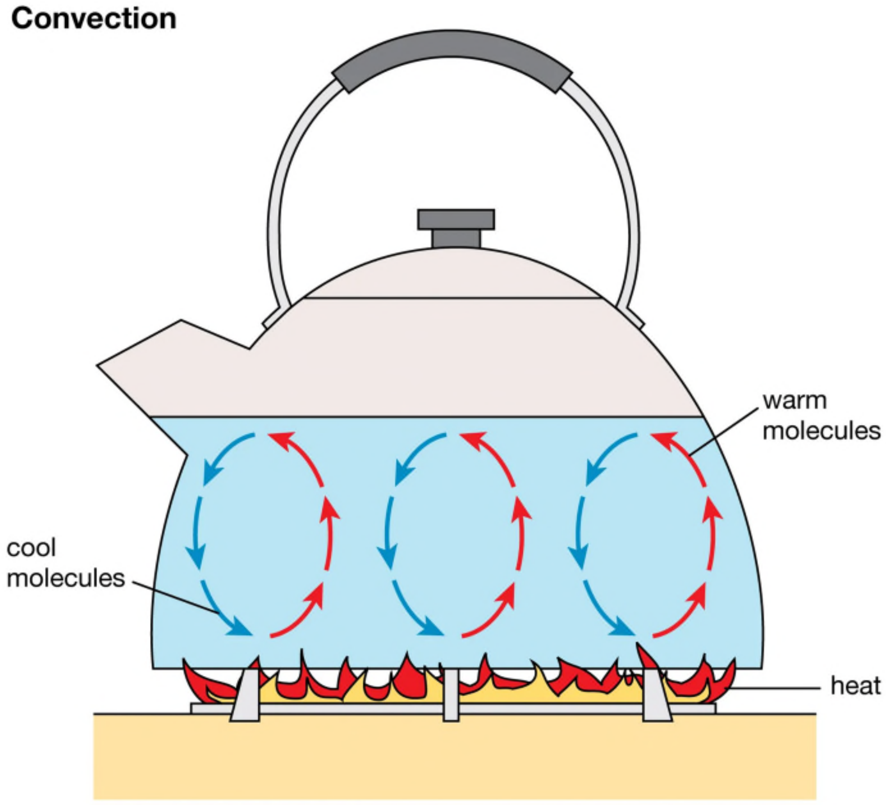
The constant proportionality k is the thermal conductivity of the material. In the limiting case, the equation reduces to the differential form:

$$\dot{Q}_{Cond} = -kA\frac{dT}{dx} \qquad (W)$$

which is called **Fourier's Law of Heat Conduction**.

Convection

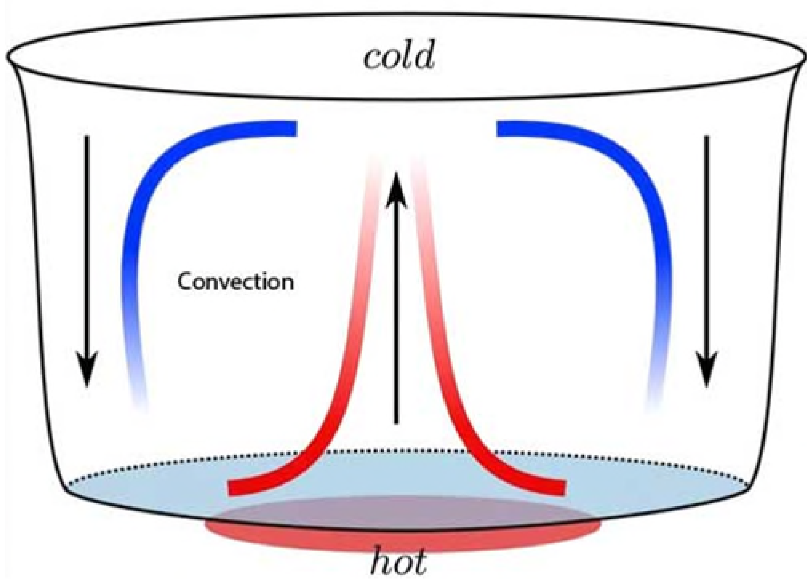
Convective heat transfer is the transfer of heat between two bodies by currents of moving gas or fluid. This convection can be **Natural** or **Forced**.



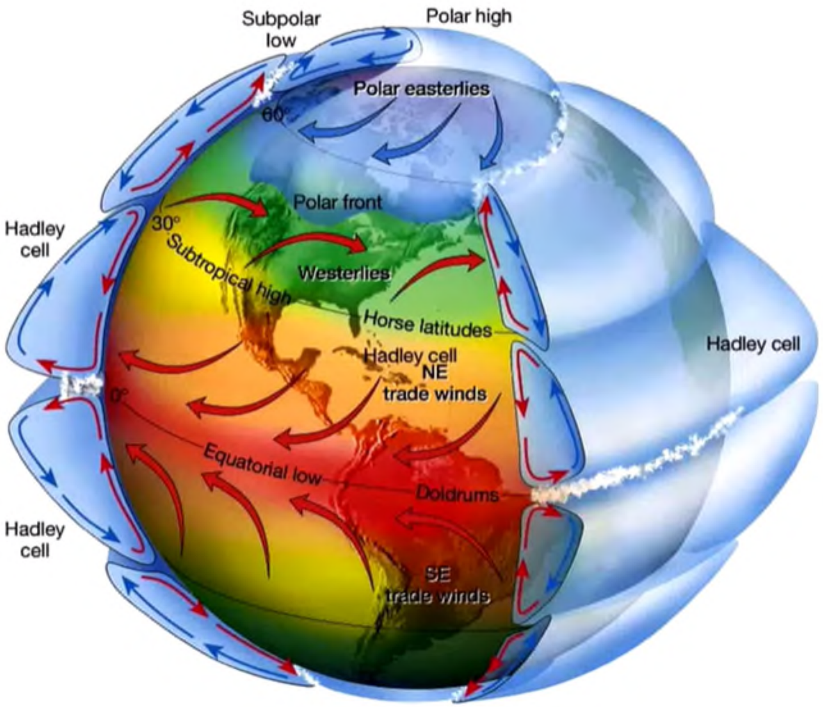
Natural Convection

Natural convection is a mechanism of heat transportation in which the fluid motion is not generated by an external source. Instead, the fluid motion is caused by buoyancy, the difference in fluid density occurring due to temperature gradients.

In summary, the motion of the fluid is caused by **density differences** which in turn are products of **temperature differences**.

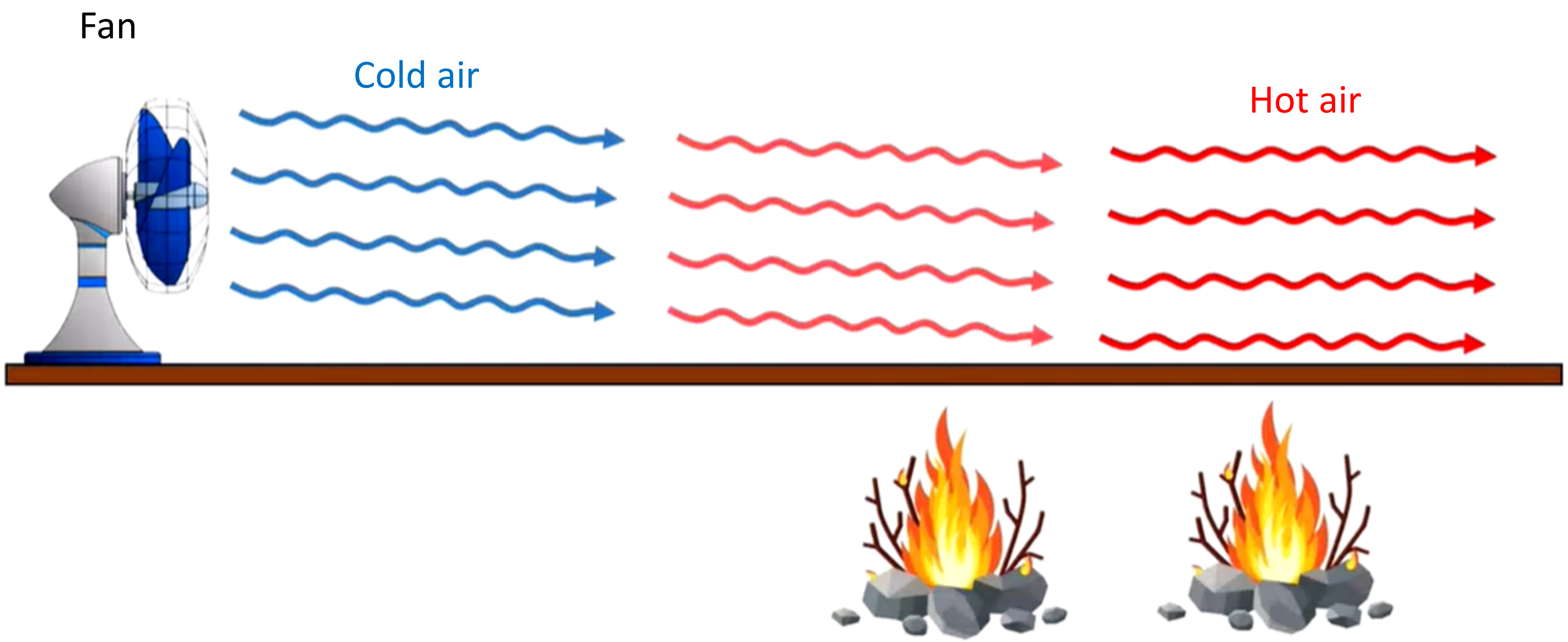


https://science4fun.info/heat-transfer/



Forced Convection

Forced convection is a special type of heat transfer in which fluids are forced to move, in order to increase the heat transfer. This forcing can be done with a ceiling fan, a pump, suction device, or other.



Convection

Convection is a complex heat transfer method, but can be expressed by Newton's Law of Heating and Cooling:

$$q^*_{conv} = h(T_s - T_\infty)$$

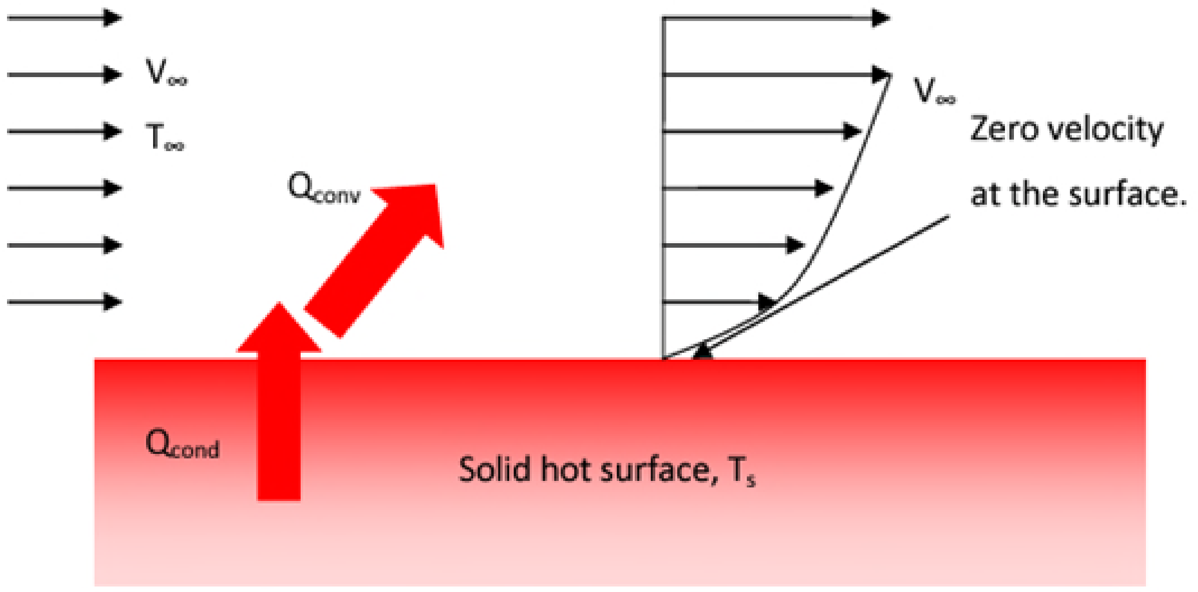
Which simply says that the rate of convection heat transfer (q^*_{conv}), expressed in the units (W/m2) is proportional to the difference between the initial temperature of the material (*Ts*) and the final temperature of the material (*T*∞) through a proportionality constant *h*.

The rate of heat transfer is also strongly dependent on the roughness and shape of the material being heated. **Newton's Law of Heating and Cooling** changes depending on whether or not the convection is forced.

For natural cooling, the *h* value is equal to a certain number. However, by forcing convection and pushing heated or cooled air from one place to another one is able to *change* this proportionality constant and heat or cool an object more quickly.

Convection

Forced Convection



$$\dot{q}_{conv} = h(T_s - T_\infty) \qquad (W/m^2)$$
$$\dot{Q}_{conv} = hA(T_s - T_\infty) \qquad (W)$$

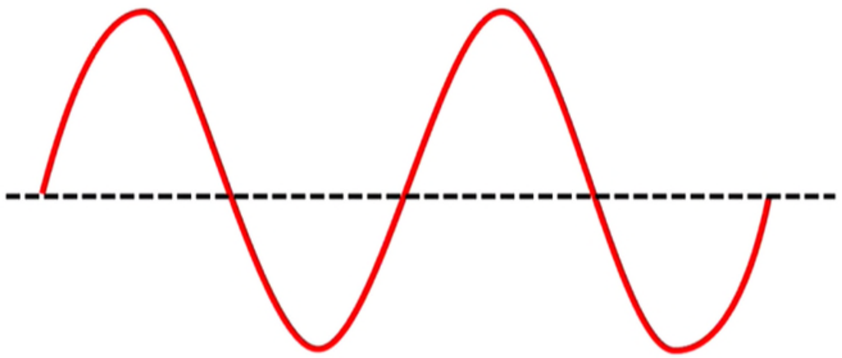
SFU, Mr. Bahrami – Convection Heat Tranfer

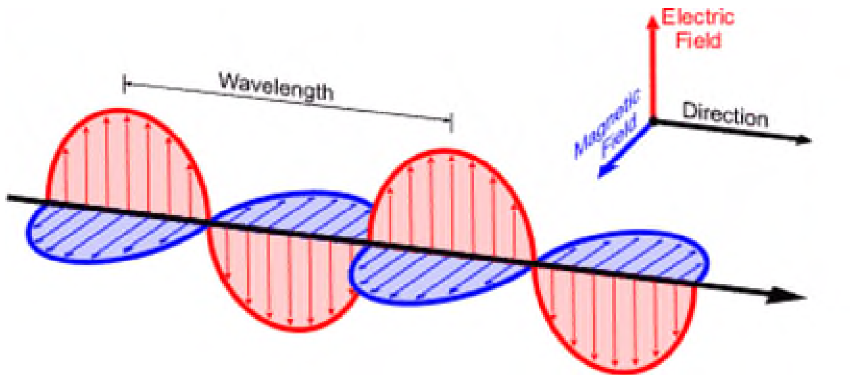
The convective heat transfer coefficient *h* strongly depends on the fluid properties and roughness of the solid surface, and the type of the fluid flow (laminar or turbulent).

Radiation

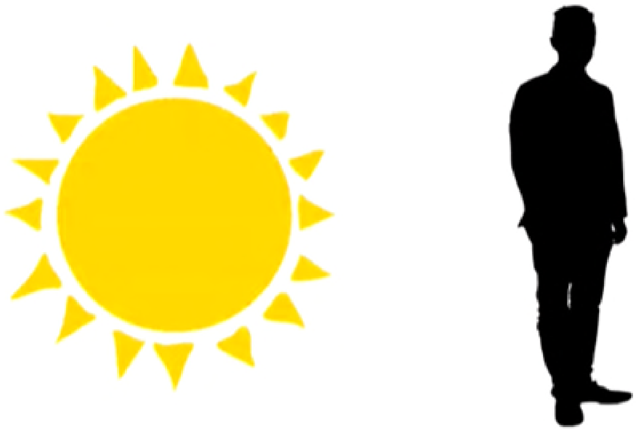
It is heat that is transmitted by means of electromagnetic waves.

Electromagnetic Wave





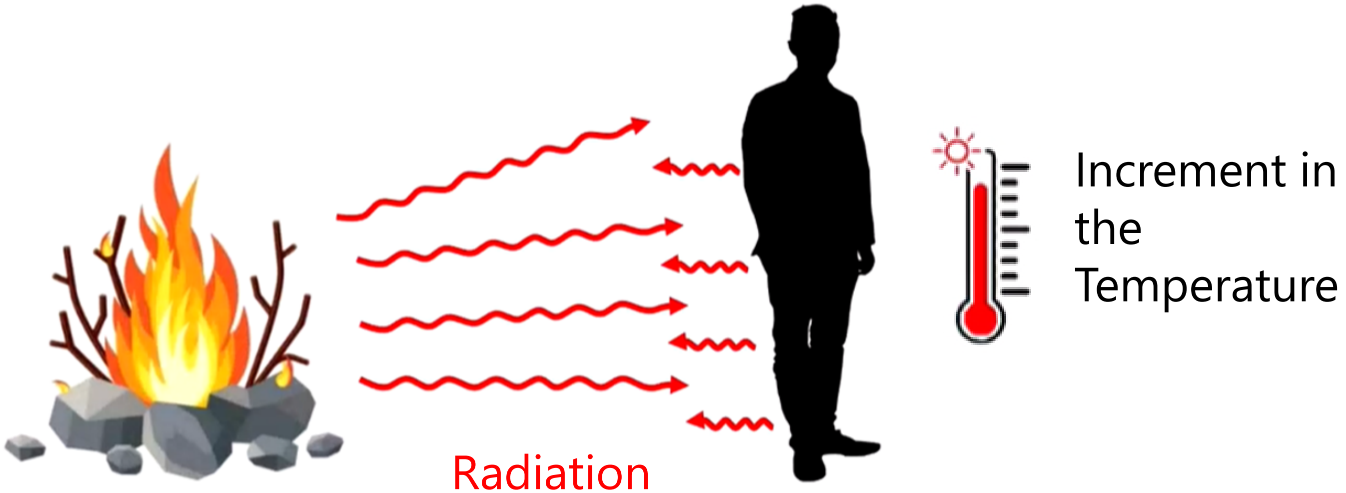
- They do not require a medium to propagate
- They travel at the speed of light



All bodies emit radiation

Radiation

The energy carried by the waves is released when a body absorbs them.



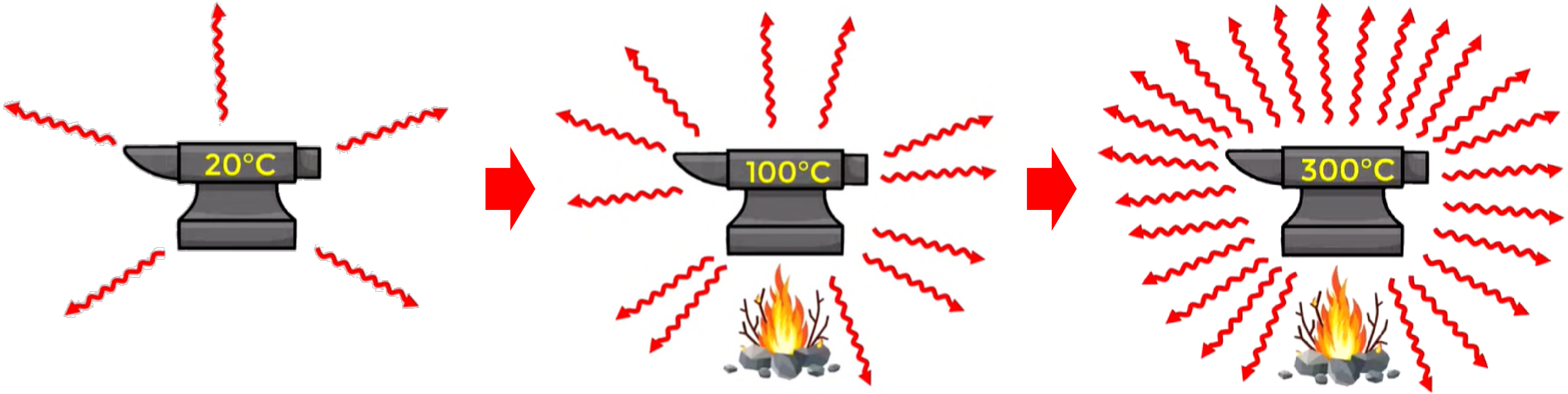
If a body absorbs more radiation than it emits, its temperature will increase.

Radiation

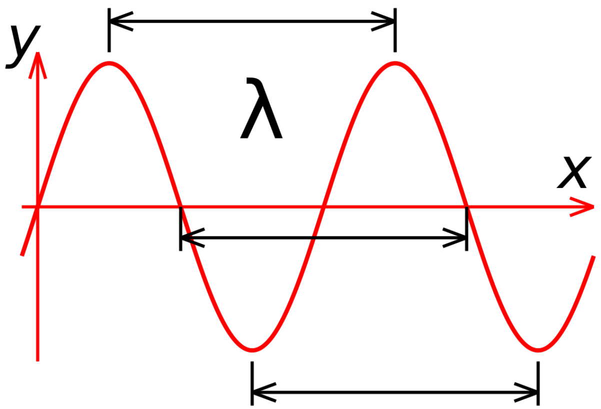
The higher the temperature of the emitting body, the greater the amount of radiation it will emit.

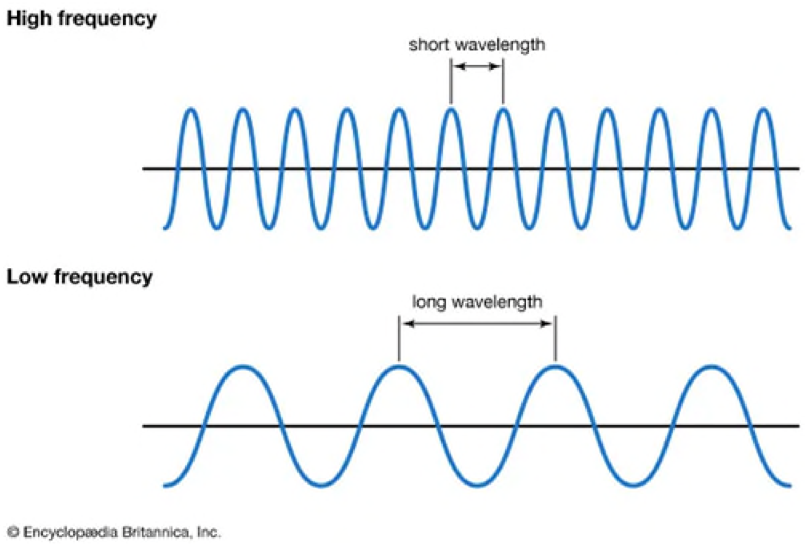
$$R \approx T^4$$

R - amount of radiation emitted
T - temperature



Wavelength - λ





The wavelength is also related to the temperature of the object that emits it. The higher the frequency, the shorter the wavelength. This means that the intensity of the radiation emitted is greater for a hotter body. This is represented by the **Wien's law**:

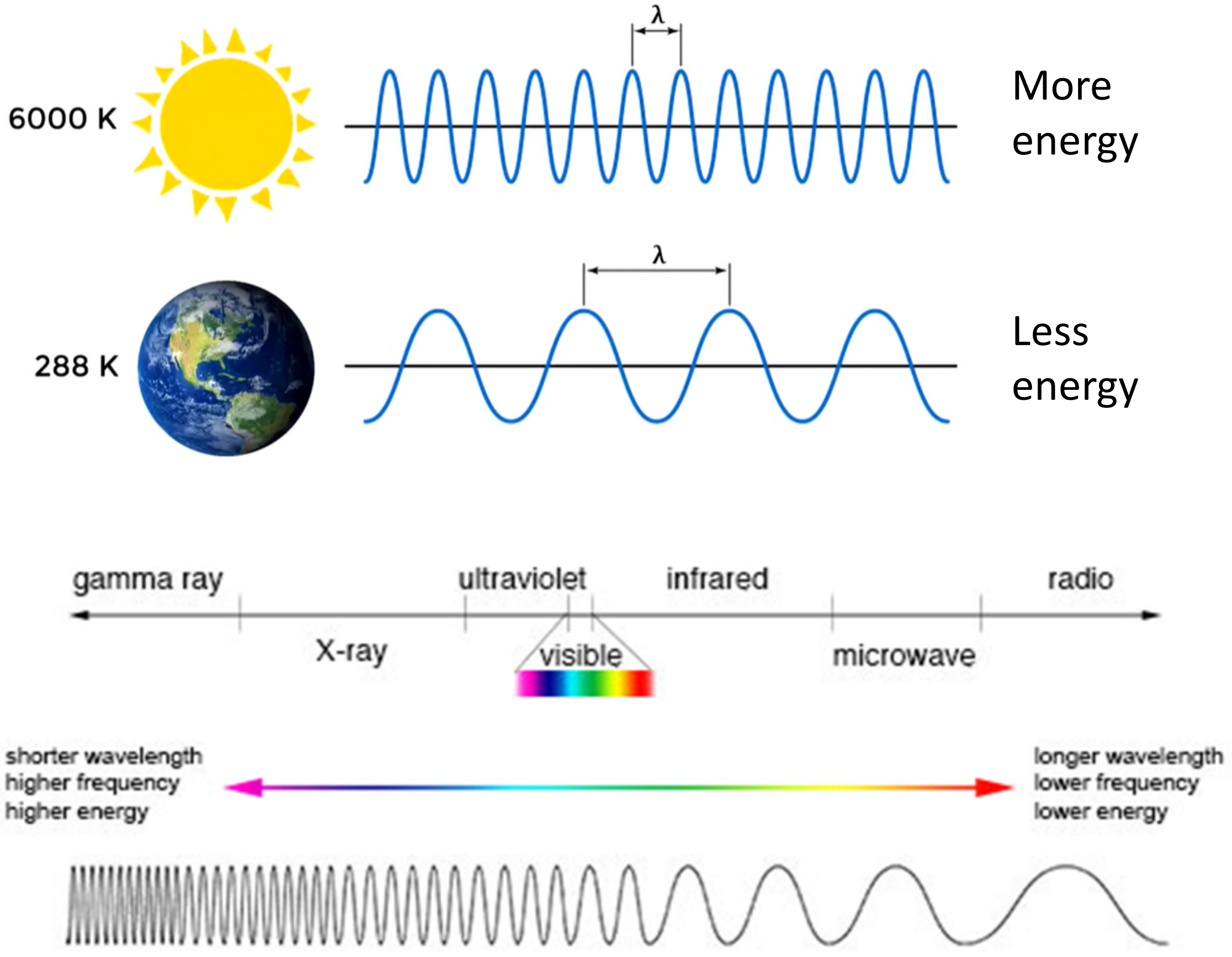
$$\lambda_{max} = \frac{b}{T}$$

λ – wavelength

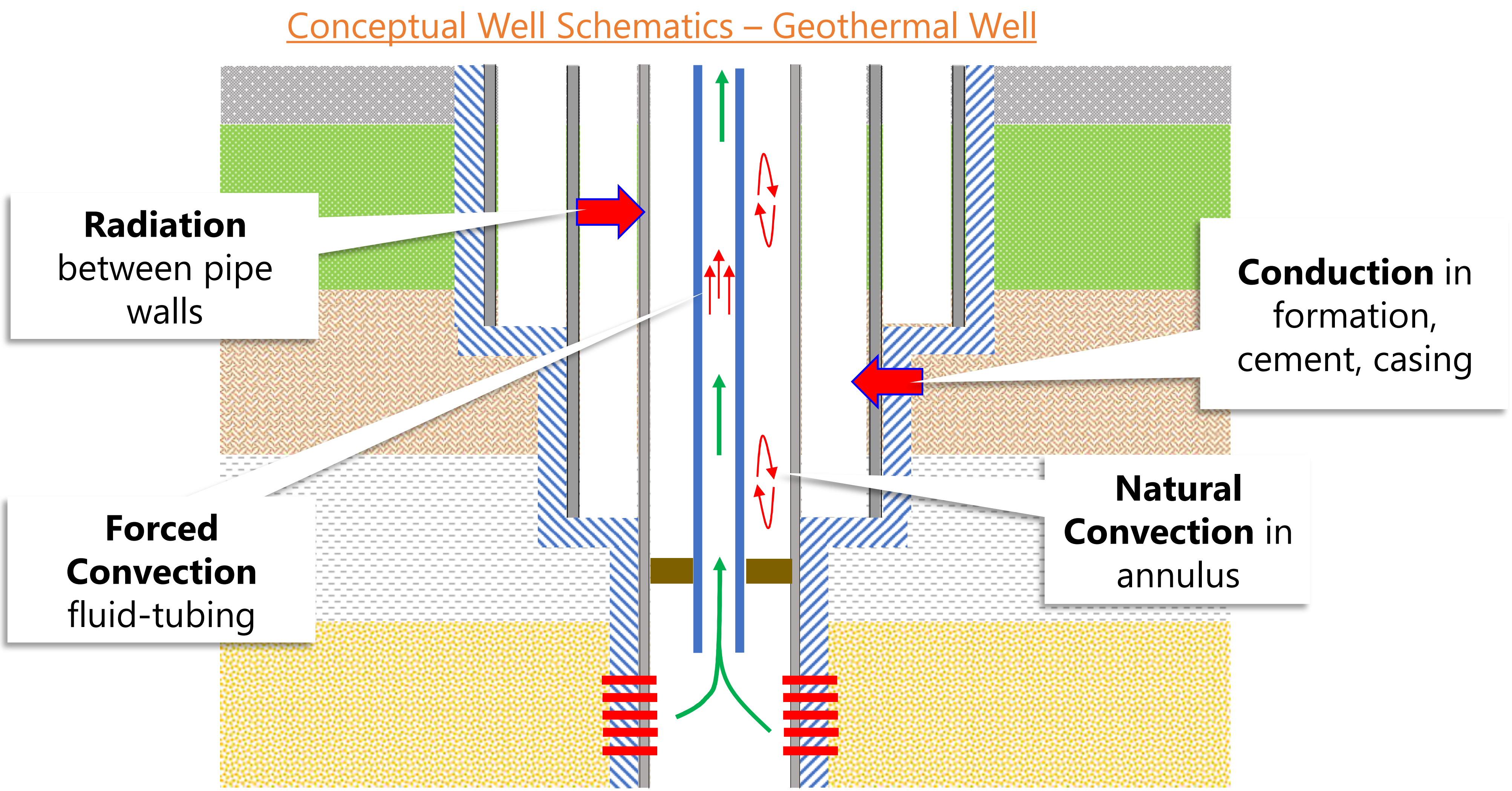
b – Wien's constant

T - temperature

Wavelength and Electromagnetic Spectrum

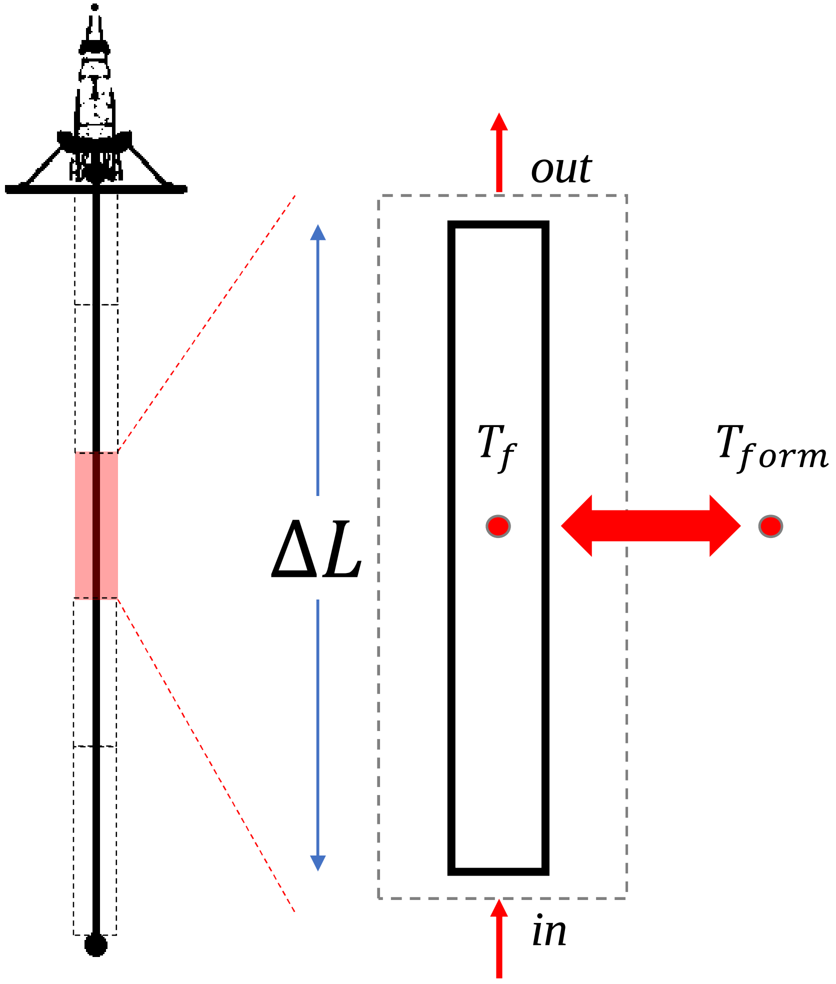


Heat Transfer Mechanisms in a Geothermal Well



Temperature Modelling in the Well

Temperature Modelling in the Well



Conservation equation:

$$\dot{Q} + \dot{W} = \dot{m}(E_{out} - E_{in})$$

This energy (specific) is usually split in:

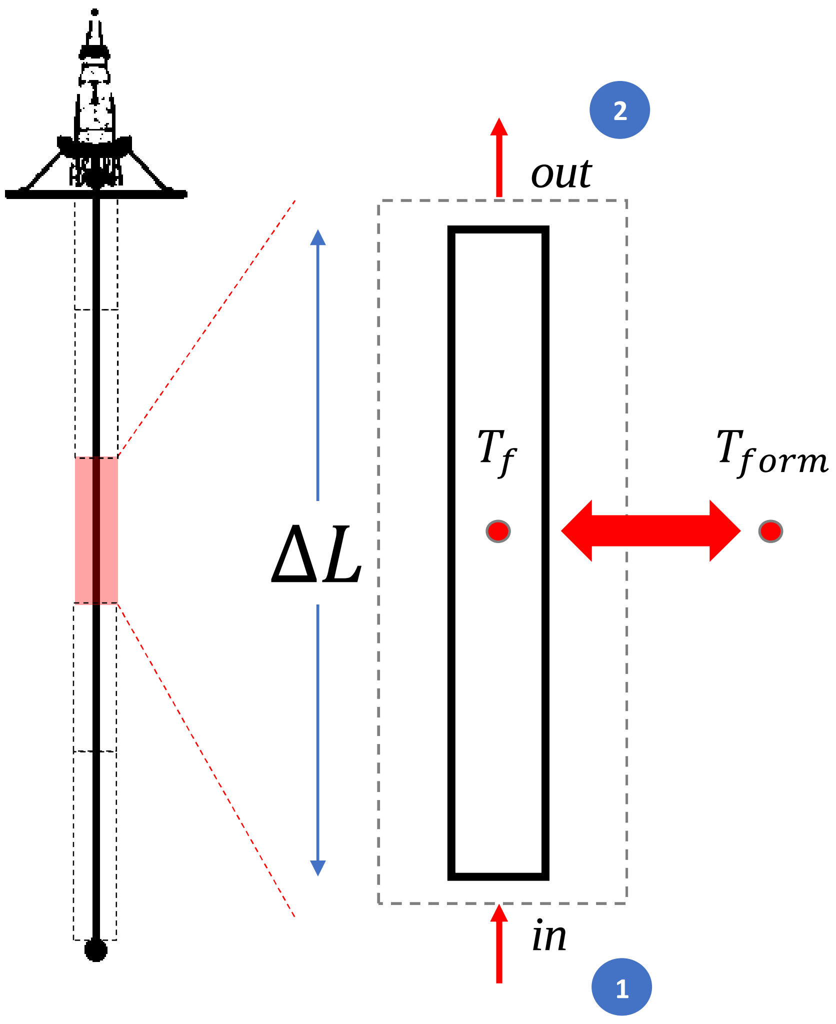
- Internal (u) - enthalpy
- Potential $(z \cdot g)$
- Kinetic $\left({}^{V^2}/_{2}\right)$

There is no work exchange with the surroundings.

$$\dot{Q} = \dot{m}\left(\left(h_{out} + z_{out} \cdot g + \frac{V_{out}^2}{2}\right) - \left(h_{in} + z_{in} \cdot g + \frac{V_{in}^2}{2}\right)\right)$$

$$\dot{Q} = \dot{m}\left(\Delta h + \Delta z \cdot g + \frac{V_{out}^2}{2} - \frac{V_{in}^2}{2}\right)$$

Temperature Modelling in the Well



$$\dot{Q} = \dot{m}\left(\Delta h + \Delta z \cdot g + \frac{V_{out}^2}{2} - \frac{V_{in}^2}{2}\right)$$

$$\Delta L \rightarrow 0$$

$$\frac{d\dot{Q}}{dL} = \dot{m}\left(\frac{dh}{dL} + \frac{dz}{dL} \cdot g + V\frac{dV}{dL}\right)$$

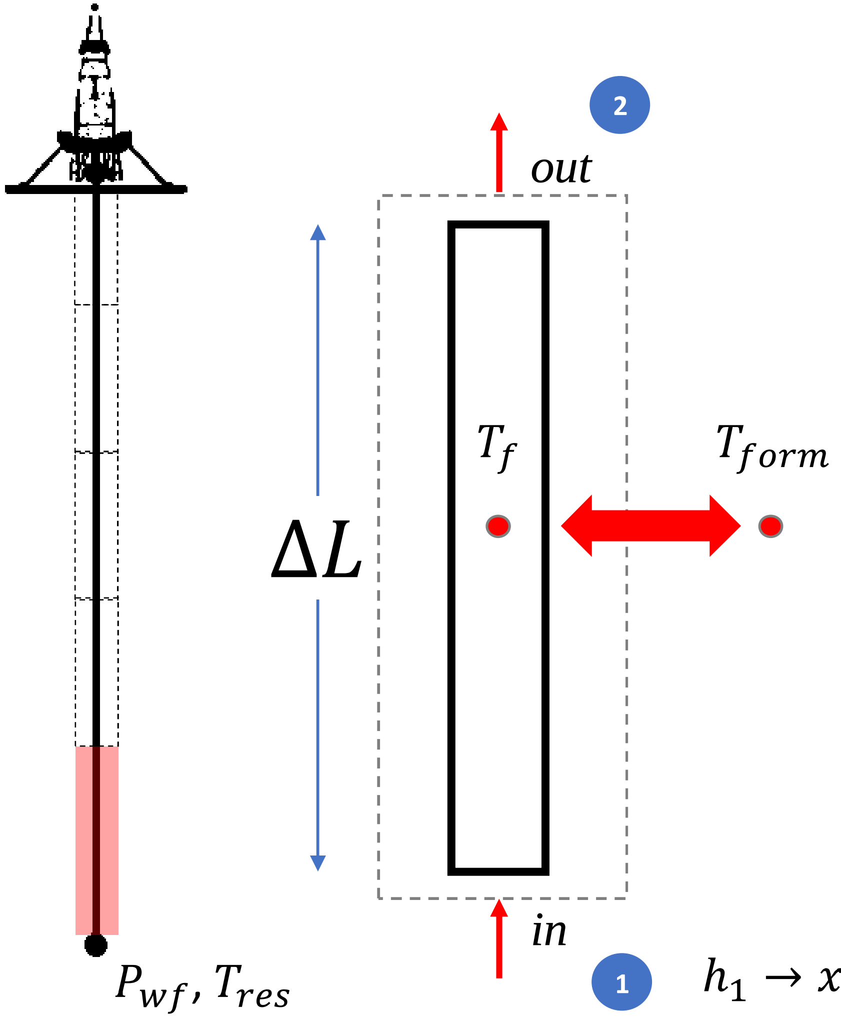
$$V\frac{dV}{dL} \rightarrow 0$$

Non-compressible liquid, the kinetic energy becomes zero

$$\frac{d\dot{Q}}{dL} = \dot{m}\left(\frac{dh}{dL} + \frac{dz}{dL} \cdot g\right)$$

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

Temperature Modelling in the Well



$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

Knows/unknows

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

$h_1 \rightarrow P_{wf}, T_{res}$

$\Delta z \rightarrow \Delta L$

$\dot{m}$ → reservoir model

$P(z)$ → know

$h_1 \rightarrow x_g, x_o, x_w, h_g, h_o, h_w$

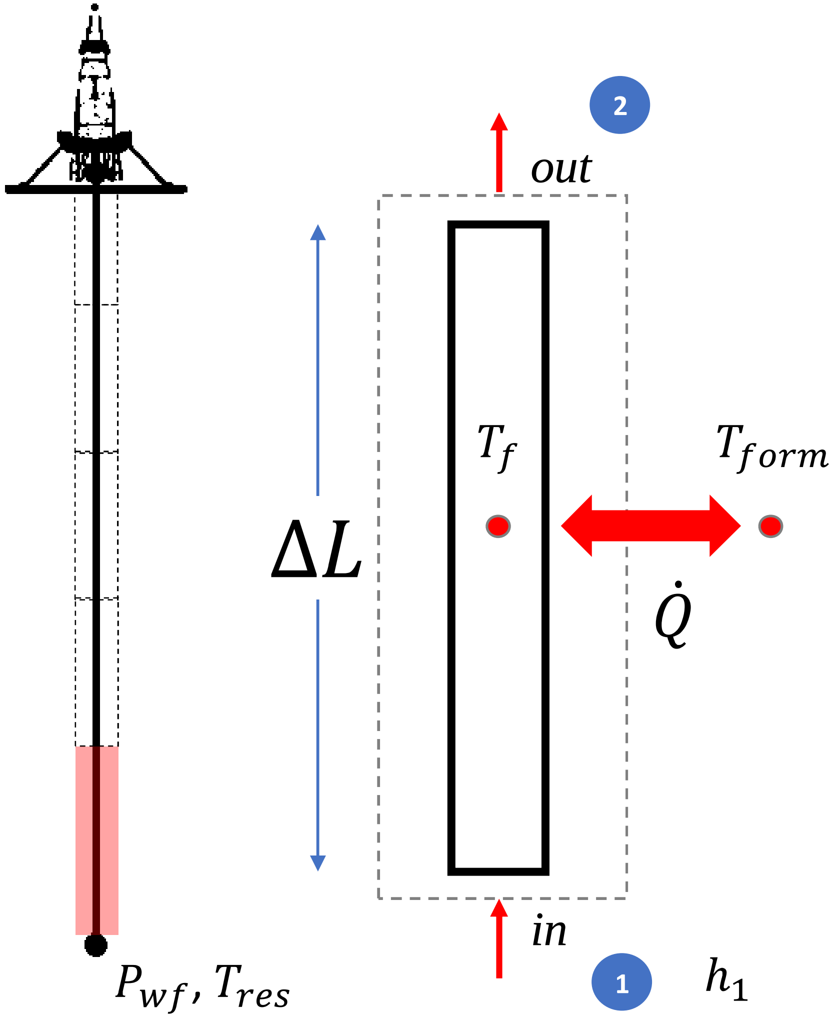
$$h_1 = x_g \cdot h_g + x_o \cdot h_o + x_w \cdot h_w$$

$$x_{phase} = \frac{\dot{m}_{phase}}{\dot{m}_{total}}$$

$$h_1 = \cancel{x_g \cdot h_g} + \cancel{x_o \cdot h_o} + x_w \cdot h_w$$

Water Dominated System

Temperature Modelling in the Well



$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

Knows/unknows

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)$$

$h_1 \rightarrow P_{wf}, T_{res}$
$\Delta z \rightarrow \Delta L$
$\dot{m} \rightarrow$ reservoir model
$P(z) \rightarrow$ know

$\dot{Q} \rightarrow T_f, T_{form} \rightarrow T_f \approx T_1$

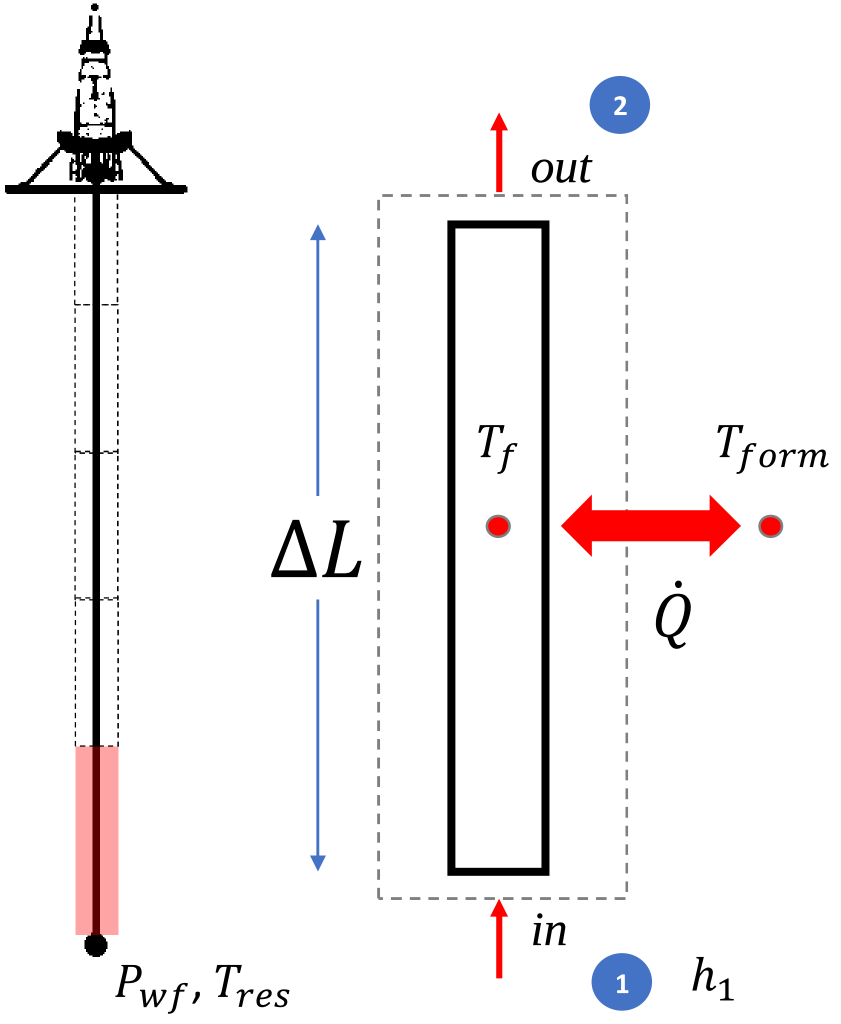
(1): $h_2 = \dfrac{\dot{Q}}{\dot{m}} + h_1 - \Delta z \cdot g$

(2): With P_2 and assuming $T_2 \rightarrow h_2$

Iterative process:

$h_2^{(1)} \approx h_2^{(2)}$

Temperature Modelling in the Well



Water Dominated System

$$\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g) \quad \rightarrow \dot{m}(\Delta h + \Delta z \cdot g)$$

$$\Delta h = C_p \Delta T$$

Liquids

$$C_p = f(P.T)$$

Gases

Knows/unknows

$$\boldsymbol{\dot{Q} = \dot{m}(h_2 - h_1 + \Delta z \cdot g)}$$

$h_1 \rightarrow P_{wf}, T_{res}$

$\Delta z \rightarrow \Delta L$

$\dot{m} \rightarrow$ reservoir model

$P(z) \rightarrow$ know

$\dot{Q} \rightarrow T_f, T_{form} \rightarrow T_f \approx T_1$

(1): $h_2 = \dfrac{\dot{Q}}{\dot{m}} + h_1 - \Delta z \cdot g$

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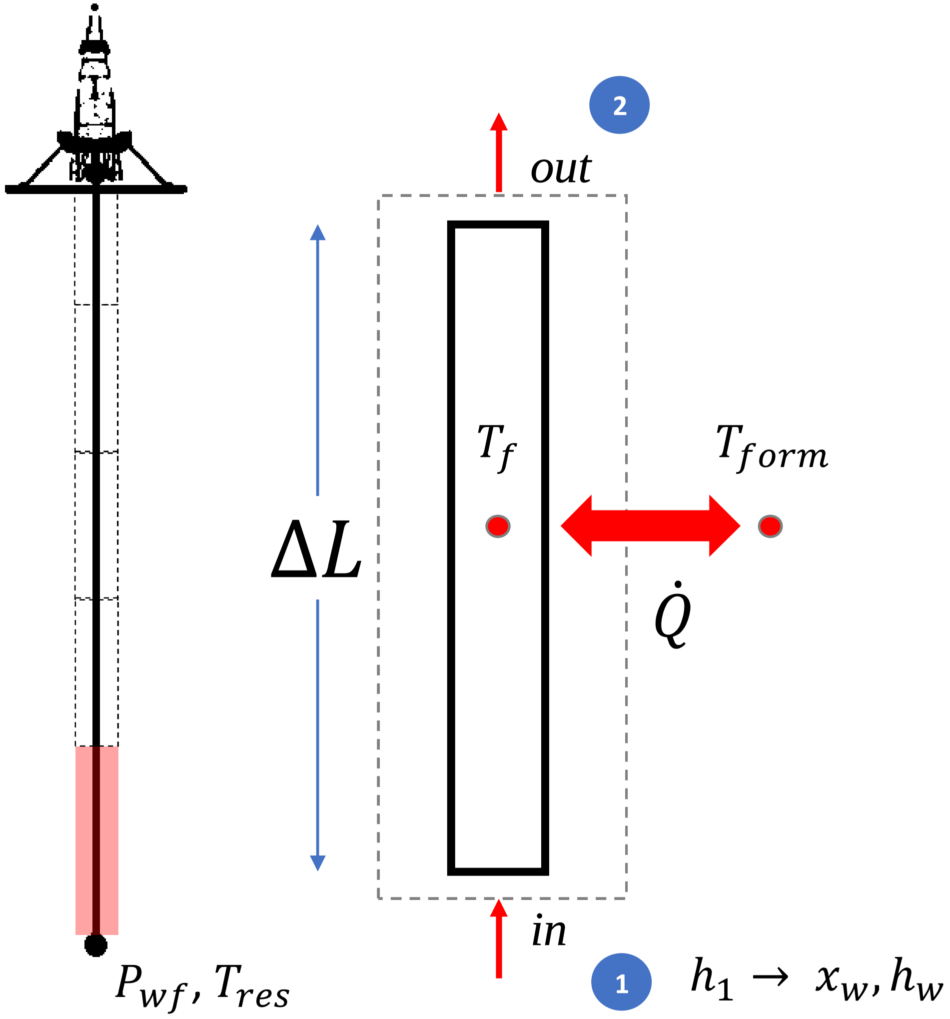
Iterative process:

$h_2^{(1)} \approx h_2^{(2)}$

Temperature Modelling in the Well



Water Dominated System

$$\dot{Q} = \dot{m}(C_p \Delta T + \Delta z \cdot g)$$

Liquid phase

Knows/unknows

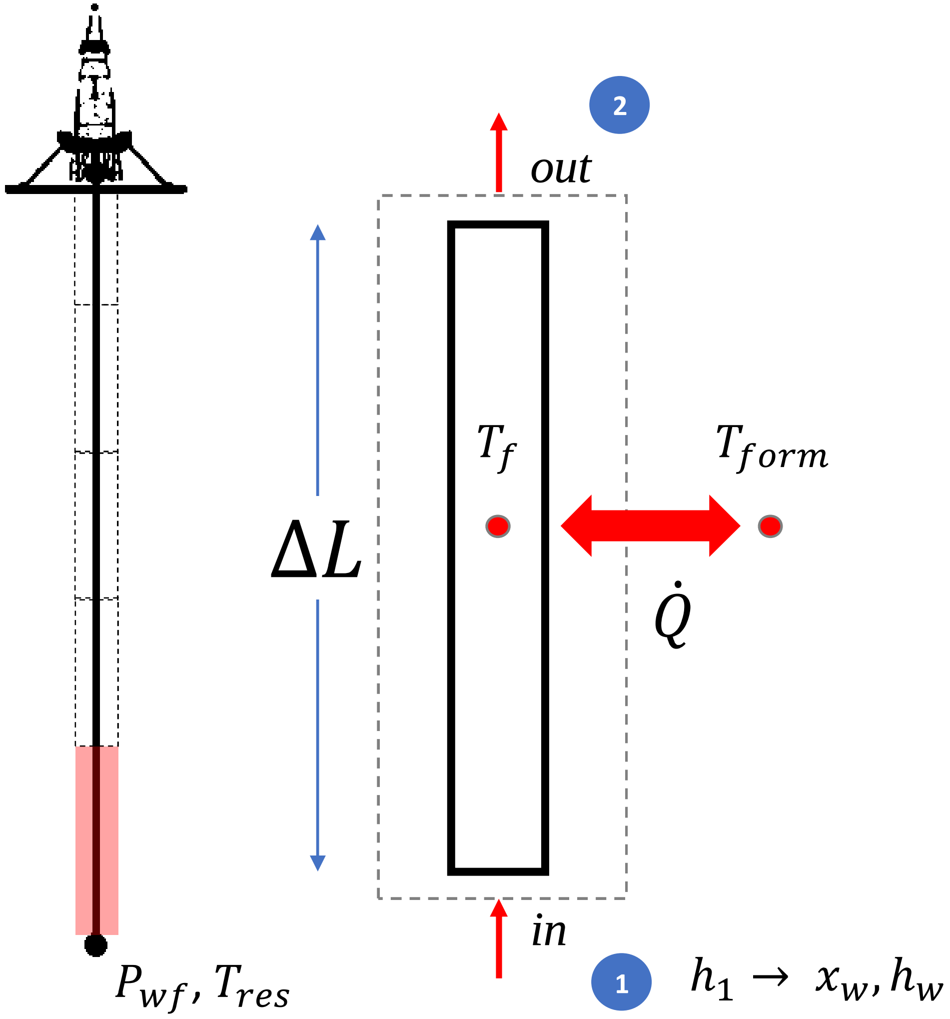
$$\dot{\boldsymbol{Q}} = \dot{\boldsymbol{m}}(C_p \Delta T + \boldsymbol{\Delta z} \cdot \boldsymbol{g})$$

$$\Delta T = T_1 - T_2$$

$$\dot{Q} = UA(T_{surroundings} - T_{fluid,avg})$$

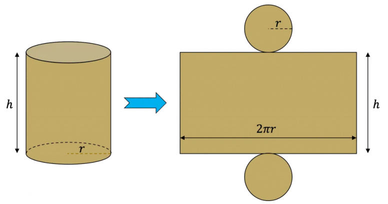
- Conduction
- Forced Convection
- Free Convection
- Radiation

Temperature Modelling in the Well

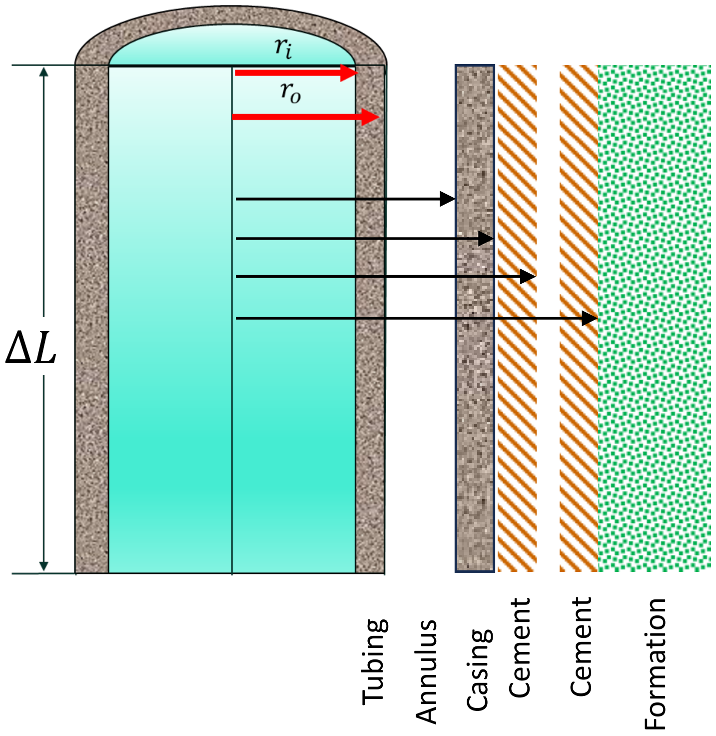


Water Dominated System

$$\dot{Q} = UA\left(T_{surroundings} - T_{f,avg}\right)$$



$$\boldsymbol{A} = 2\pi r = \pi D$$



Overall heat transfer coefficient

$$\boldsymbol{U} = f(r)$$

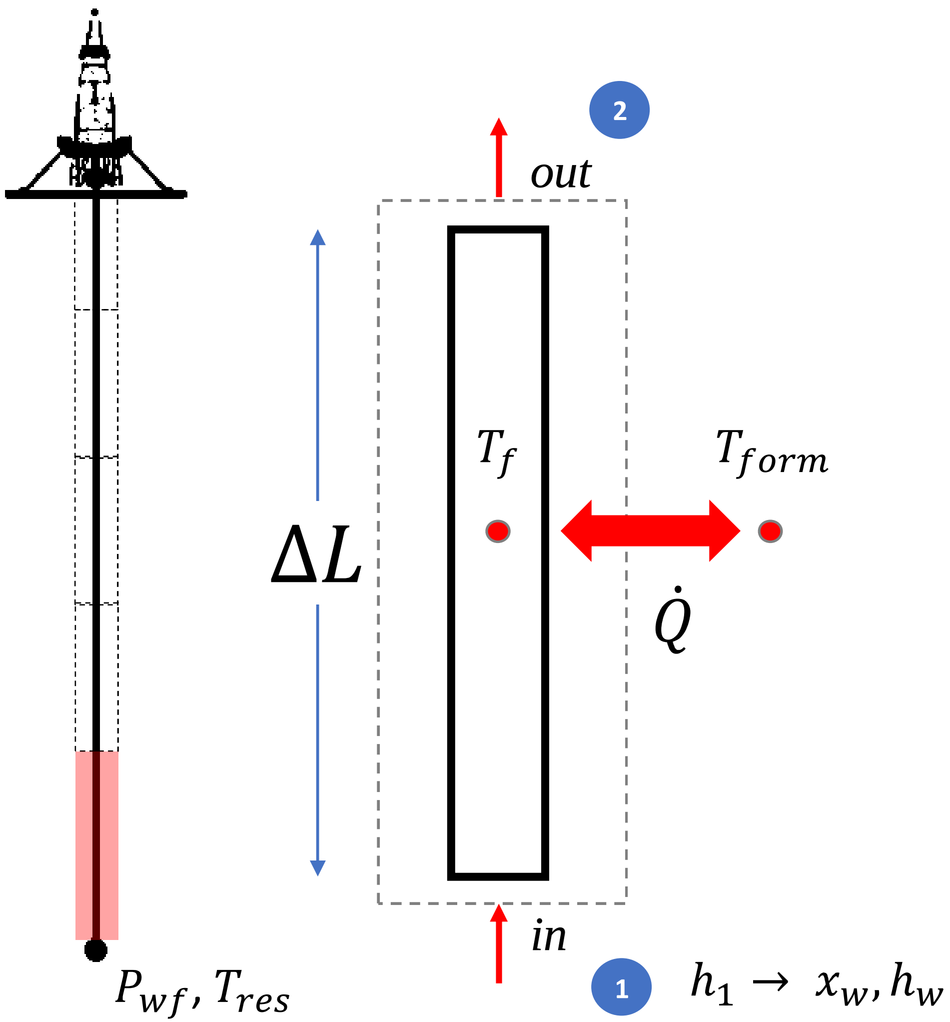
Conduction: k_{av}

Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

Radiation: σ

Temperature Modelling in the Well



Water Dominated System

$$\dot{Q} = UA(T_{surroundings} - T_{f,avg})$$

Conduction:

$$\frac{d\dot{Q}}{dL} = -2\pi \boldsymbol{k_{av}} \frac{(T_i - T_o)}{\ln({}^{r_o}/_{r_i})}$$

Steady State

Convection/Radiation:

$$\frac{d\dot{Q}}{dL} = -2\pi r_i \boldsymbol{h_i}(T_f - T_i)$$

Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

Radiation: σ

Temperature Modelling in the Well

$$\dot{Q} = UA\left(T_{surroundings} - T_{f,avg}\right)$$

Conduction:

$$\frac{d\dot{Q}}{dL} = -2\pi \boldsymbol{k_{av}} \frac{(T_i - T_o)}{\ln\left({}^{r_o}/_{r_i}\right)}$$

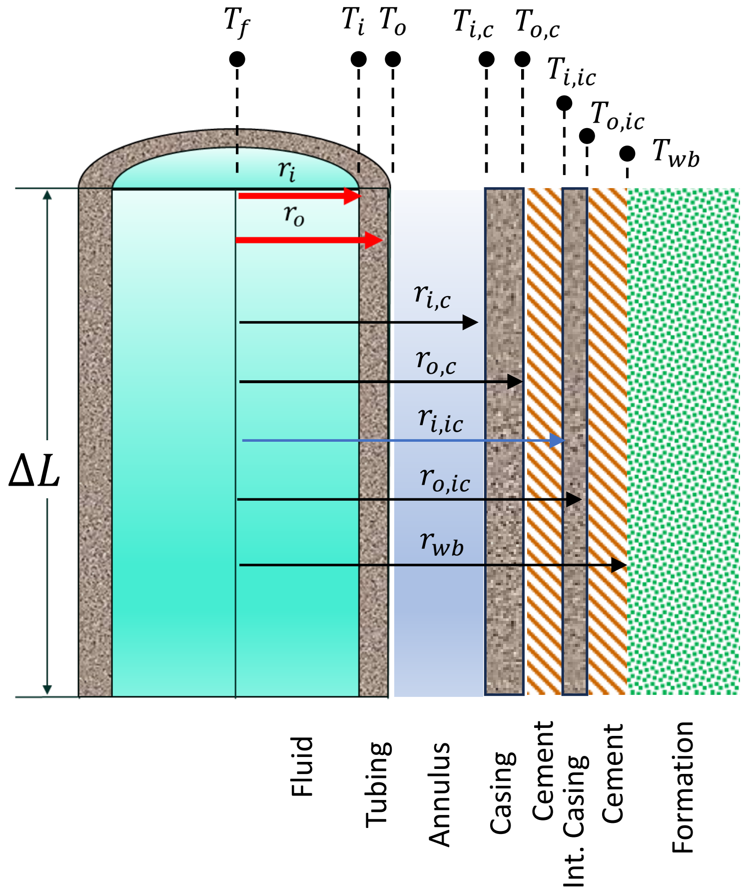
Convection/Radiation:

$$\frac{d\dot{Q}}{dL} = -2\pi r_i \boldsymbol{h_i}\left(T_f - T_i\right)$$

Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

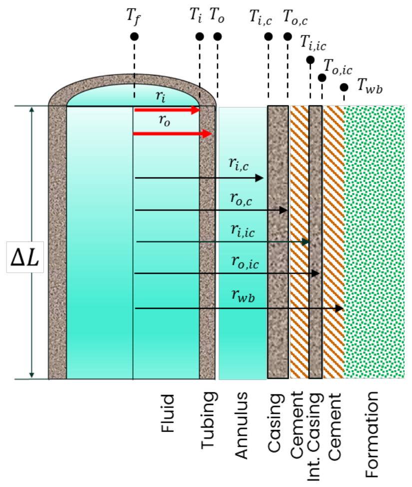
Radiation: σ



$$\frac{d\dot{Q}}{dL} = \left.\frac{d\dot{Q}}{dL}\right|^{conv,tub} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,tub} + \left.\frac{d\dot{Q}}{dL}\right|^{conv,ann} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,cas} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,cem} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,int.cas}$$

Temperature Modelling in the Well

$$\dot{Q} = UA\left(T_{surroundings} - T_{f,avg}\right)$$



Conduction:

$$\frac{d\dot{Q}}{dL} = -2\pi \boldsymbol{k_{av}} \frac{(T_i - T_o)}{\ln\left({}^{r_o}/_{r_i}\right)}$$

Convection/Radiation:

$$\frac{d\dot{Q}}{dL} = -2\pi r_i \boldsymbol{h_i}(T_f - T_i)$$

Forced: $f(Re, Pr)$

Natural: $f(Gr, Pr)$

Radiation: σ

$$\frac{d\dot{Q}}{dL} = \left.\frac{d\dot{Q}}{dL}\right|^{conv,tub} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,tub} + \left.\frac{d\dot{Q}}{dL}\right|^{conv,ann} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,cas} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,cem} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,int.cas}$$

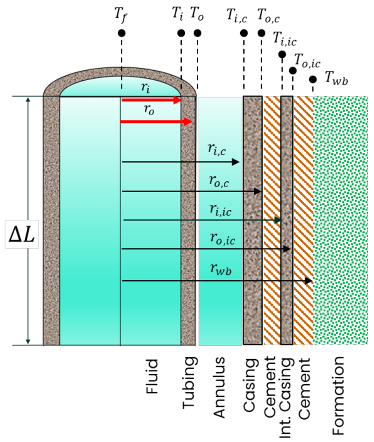
$$= -2\pi r_i h_i(T_f - T_i) - 2\pi k_{tub}\frac{(T_i - T_o)}{\ln\left({}^{r_o}/_{r_i}\right)} - 2\pi r_o h_{ann}(T_o - T_{i,c}) - 2\pi k_{cas}\frac{(T_{i,c} - T_{o,c})}{\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)} - 2\pi k_{cem}\frac{(T_{o,c} - T_{i,ic})}{\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)} - 2\pi k_{int.cas}\frac{(T_{i,ic} - T_{o,ic})}{\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}$$

$$- 2\pi k_{cem}\frac{(T_{o,ic} - T_{wb})}{\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}$$

Temperature Modelling in the Well

$$\left.\frac{d\dot{Q}}{dL}\right|^{conv,tub} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,tub} + \left.\frac{d\dot{Q}}{dL}\right|^{conv,ann} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,cas} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,cem} + \left.\frac{d\dot{Q}}{dL}\right|^{cond,int.cas}$$
$$= -2\pi r_i h_i \left(T_f - T_i\right) - 2\pi k_{tub} \frac{(T_i - T_o)}{\ln\left({}^{r_o}/_{r_i}\right)} - 2\pi r_o h_{ann}\left(T_o - T_{i,c}\right) - 2\pi k_{cas} \frac{\left(T_{i,c} - T_{o,c}\right)}{\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)} - 2\pi k_{cem} \frac{\left(T_{o,c} - T_{i,ic}\right)}{\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}$$
$$- 2\pi k_{int.cas} \frac{\left(T_{i,ic} - T_{o,ic}\right)}{\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)} - 2\pi k_{cem} \frac{\left(T_{o,ic} - T_{wb}\right)}{\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}$$

$$\frac{-\frac{d\dot{Q}}{dL}}{2\pi r_i h_i} + \frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left({}^{r_o}/_{r_i}\right)}{2\pi k_{tub}}} + \frac{-\frac{d\dot{Q}}{dL}}{2\pi r_o h_{ann}} + \frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)}{2\pi k_{cas}}} + \frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}{2\pi k_{cem}}} + \frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}{2\pi k_{int.cas}}} + \frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}{2\pi k_{cem}}}$$
$$= \left(T_f - T_i\right) + \left(T_i - T_o\right) + \left(T_o - T_{i,c}\right) + \left(T_{i,c} - T_{o,c}\right) + \left(T_{o,c} - T_{i,ic}\right) + \left(T_{i,ic} - T_{o,ic}\right)$$
$$+ \left(T_{o,ic} - T_{wb}\right)$$

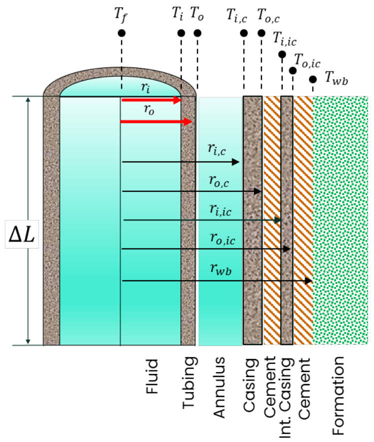


Temperature Modelling in the Well

$$\frac{-\frac{d\dot{Q}}{dL}}{2\pi r_i h_i}+\frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left(r_o/r_i\right)}{2\pi k_{tub}}}+\frac{-\frac{d\dot{Q}}{dL}}{2\pi r_o h_{ann}}+\frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left(r_{o,c}/r_{i,c}\right)}{2\pi k_{cas}}}+\frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left(r_{i,ic}/r_{o,c}\right)}{2\pi k_{cem}}}+\frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left(r_{o,ic}/r_{i,ic}\right)}{2\pi k_{int.cas}}}+\frac{-\frac{d\dot{Q}}{dL}}{\frac{\ln\left(r_{wb}/r_{o,ic}\right)}{2\pi k_{cem}}}$$
$$=\left(T_f-T_i\right)+\left(T_i-T_o\right)+\left(T_o-T_{i,c}\right)+\left(T_{i,c}-T_{o,c}\right)+\left(T_{o,c}-T_{i,ic}\right)+\left(T_{i,ic}-T_{o,ic}\right)$$
$$+\left(T_{o,ic}-T_{wb}\right)$$

Clearing the temperature difference between fluid and wellbore:

$$-\frac{d\dot{Q}}{dL}\left[\frac{1}{2\pi r_i h_i}+\frac{1}{\frac{\ln\left(r_o/r_i\right)}{2\pi k_{tub}}}+\frac{1}{2\pi r_o h_{ann}}+\frac{1}{\frac{\ln\left(r_{o,c}/r_{i,c}\right)}{2\pi k_{cas}}}+\frac{1}{\frac{\ln\left(r_{i,ic}/r_{o,c}\right)}{2\pi k_{cem}}}+\frac{1}{\frac{\ln\left(r_{o,ic}/r_{i,ic}\right)}{2\pi k_{int.cas}}}\right.$$
$$\left.+\frac{1}{\frac{\ln\left(r_{wb}/r_{o,ic}\right)}{2\pi k_{cem}}}\right]=\left(T_f-T_{wb}\right)$$

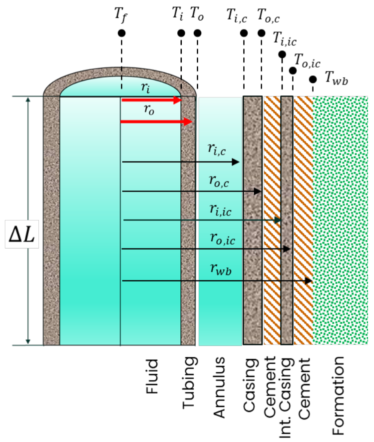


Temperature Modelling in the Well

$$-\frac{d\dot{Q}}{dL}\left[\frac{1}{2\pi r_i h_i}+\frac{1}{\frac{\ln\left({}^{r_o}/_{r_i}\right)}{2\pi k_{tub}}}+\frac{1}{2\pi r_o h_{ann}}+\frac{1}{\frac{\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)}{2\pi k_{cas}}}+\frac{1}{\frac{\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}{2\pi k_{cem}}}+\frac{1}{\frac{\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}{2\pi k_{int.cas}}}\right.$$
$$\left.+\frac{1}{\frac{\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}{2\pi k_{cem}}}\right]=\left(T_f-T_{wb}\right)$$

If the inner radius will be used as reference, we can divide by the inner perimeter of the inner tubing:

$$-\frac{d\dot{Q}}{dL}\frac{1}{2\pi r_i}\left[\frac{1}{h_i}+\frac{r_i\ln\left({}^{r_o}/_{r_i}\right)}{k_{tub}}+\frac{r_i}{r_o h_{ann}}+\frac{r_i\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)}{k_{cas}}+\frac{r_i\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}{k_{cem}}+\frac{r_i\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}{k_{int.cas}}\right.$$
$$\left.+\frac{r_i\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}{k_{cem}}\right]=\left(T_f-T_{wb}\right)$$



Temperature Modelling in the Well

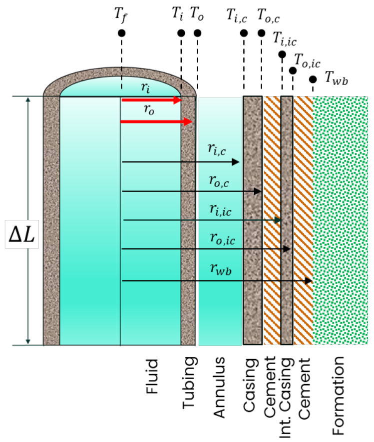
$$-\frac{d\dot{Q}}{dL}\left[\frac{1}{2\pi r_i h_i}+\frac{1}{\frac{\ln\left({}^{r_o}/_{r_i}\right)}{2\pi k_{tub}}}+\frac{1}{2\pi r_o h_{ann}}+\frac{1}{\frac{\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)}{2\pi k_{cas}}}+\frac{1}{\frac{\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}{2\pi k_{cem}}}+\frac{1}{\frac{\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}{2\pi k_{int.cas}}}+\frac{1}{\frac{\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}{2\pi k_{cem}}}\right]=\left(T_f-T_{wb}\right)$$

If the inner radius will be used as reference, we can divide by the inner perimeter of the inner tubing:

$$-\frac{d\dot{Q}}{dL}\frac{1}{2\pi r_i}\left[\frac{1}{h_i}+\frac{r_i\ln\left({}^{r_o}/_{r_i}\right)}{k_{tub}}+\frac{r_i}{r_o h_{ann}}+\frac{r_i\ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)}{k_{cas}}+\frac{r_i\ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}{k_{cem}}+\frac{r_i\ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}{k_{int.cas}}+\frac{r_i\ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}{k_{cem}}\right]=\left(T_f-T_{wb}\right)$$

Overall heat transfer coefficient

W/m 2 -K or BTU/ft2 -h-°F



Temperature Modelling in the Well

Overall heat transfer coefficient:

$$U = \left[\frac{1}{h_i} + \frac{r_i \ln\left({}^{r_o}/_{r_i}\right)}{k_{tub}} + \frac{r_i}{r_o h_{ann}} + \frac{r_i \ln\left({}^{r_{o,c}}/_{r_{i,c}}\right)}{k_{cas}} + \frac{r_i \ln\left({}^{r_{i,ic}}/_{r_{o,c}}\right)}{k_{cem}} + \frac{r_i \ln\left({}^{r_{o,ic}}/_{r_{i,ic}}\right)}{k_{int.cas}} + \frac{r_i \ln\left({}^{r_{wb}}/_{r_{o,ic}}\right)}{k_{cem}}\right]^{-1}$$

Dry Rock Properties

	Cp	Conductivity	Specific Gravity
	BTU/lb/ deg F	BTU/hr/ft/deg F	
Sandstone	0.183	1.06	2.64
Shale	0.224	0.7	2.4
Limestone	0.202	0.54	2.71
Dolomite	0.219	1.0	2.87
Halite	0.219	2.8	2.17
Anhydrite	0.265	0.75	2.96
Gypsum	0.259	0.75	2.32
Lignite	0.3	2.0	1.5
Volcanics	0.2	1.6	2.65

Rock In Situ Fluids

	Cp	Conductivity
	BTU/lb/deg F	BTU/hr/ft/deg F
Water (Low salinity)	1.0	0.35
Water (High Salinity)	1.02	0.345
Heavy Oil	1.04	0.34
Medium Oil	0.49	0.083
Light Oil	0.5	0.0815
Gas	0.26	0.0215

Downhole Equipment

	Conduction Heat Transfer Coefficient	Emmissivity
	BTU/ft/hr/deg F	
Mild Steel Tubing	26	0.65
Plactic Coated Tubing	20	0.65
Stainless Steel (13%)	18	0.4
Stainless Steel (15%)	15	0.3
Line Pipe	27	0.9
Plactic Coated Pipe	20	0.9
Flexible	0.3	0.95
Bitumen	0.6	0.95
Foam	0.02	0.8
Concrete	0.1	0.9

PROSPER thermal properties Database

Temperature Modelling in the Well

$$\underbrace{\dot{Q} = UA\left(T_{surroundings} - T_{f,avg}\right) \qquad \dot{Q} = \dot{m}\left(C_p \Delta T + \Delta z \cdot g\right)}$$

$$\frac{dT}{dx} = \frac{U\pi D}{\dot{m}C_p}\left(T_{surroundings} - T_{f,avg}\right)$$

Ramey's equation:

$$T_f = Az + B - \frac{A}{L_R} + \left(T_o + \frac{A}{L_R} - B\right)e^{zL_R}$$

T_f : Injection Bottomhole temperature

$Az + B$: Linear geothermal gradient

z : true vertical depth

T_o : Injection temperature at surface

L_R : Relaxation coefficient

Temperature Modelling in the Well

$$T_f = Az + B - \frac{A}{L_R} + \left(\boldsymbol{T_o} + \frac{A}{\boldsymbol{L_R}} - B \right) e^{zL_R}$$

T_f : Injection Bottomhole temperature

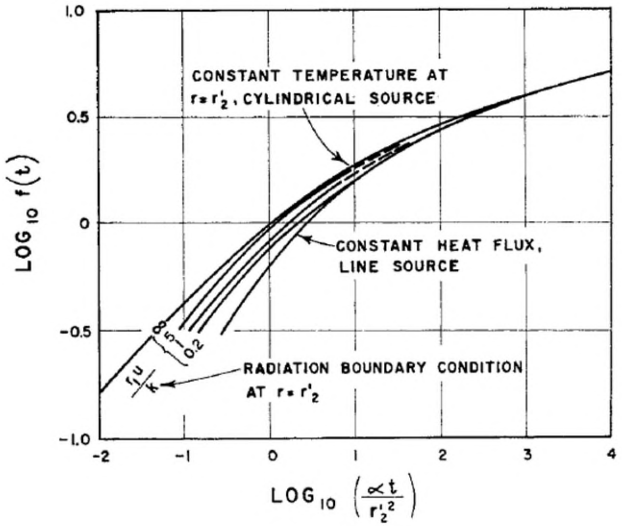
$Az + B$: Linear geothermal gradient

z : true vertical depth

T_o : Injection temperature at surface

L_R : Relaxation coefficient

$$\boldsymbol{L_R} = \frac{2\pi}{C_p \dot{m}} \left(\frac{r_i U k}{k + r_i U T_D} \right)$$



Wellbore Heat Transmission, H.J. Ramey Jr. 1962

Temperature Modelling in the Well

$$T_f = Az + B - \frac{A}{L_R} + \left(\boldsymbol{T_o} + \frac{A}{\boldsymbol{L_R}} - B\right) e^{zL_R}$$

T_f : Injection Bottomhole temperature

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z : true vertical depth

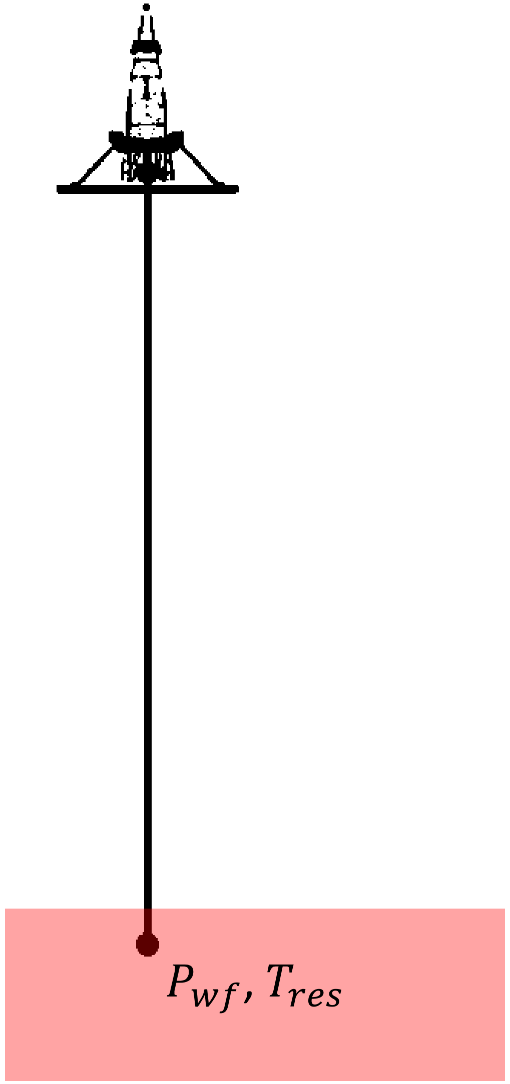
T_o : Injection temperature at surface

L_R : Relaxation coefficient

$$\boldsymbol{L_R} = \frac{2\pi}{C_p \dot{m}} \left(\frac{r_i U k}{k + r_i U T_D}\right)$$

?

Reservoir Model

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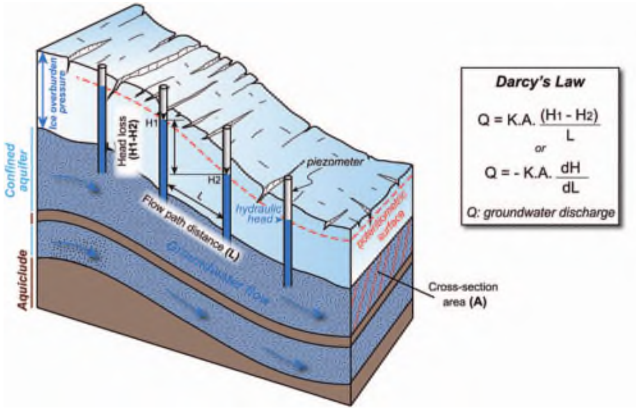
AU FILTRAGE DES EAUX
HENRY DARCY
PARIS
VICTOR DALMONT, ÉDITEUR,
1856

- Porosity
- Permeability
- Fluid properties
- Rock Properties
- Saturations

Darcy's Law:

$$q = -\frac{k}{\mu L}\Delta p$$



Glaciohydrogeology, Past Glacial Environments (pp.431-466), DOI:10.1016/B978-0-08-100524-8.00013-0

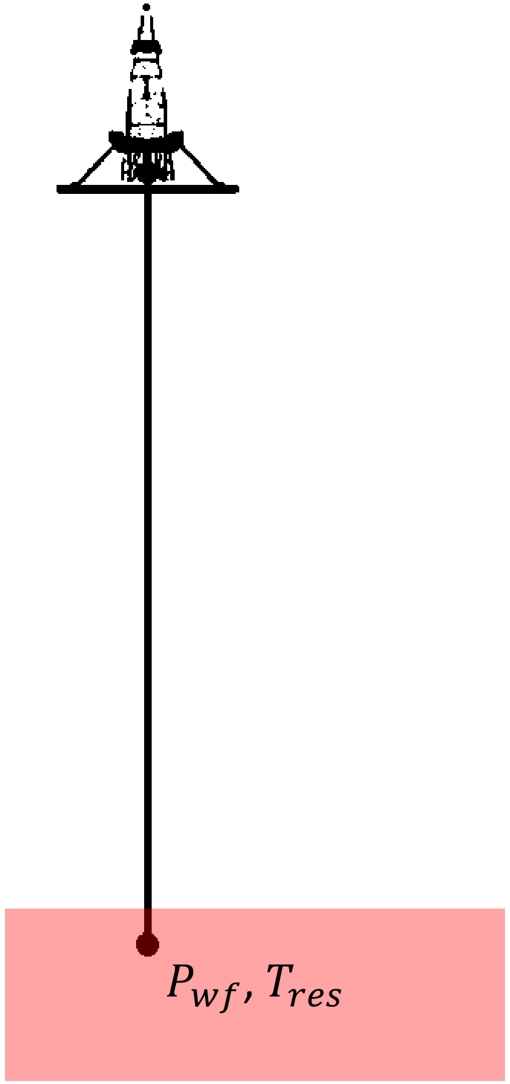
Typical Parameters for Darcy Model

- Reservoir Pressure
- Reservoir Temperature
- Water Cut
- Total GOR
- Permeability
- Thickness
- Drainage Area
- Wellbore Radius

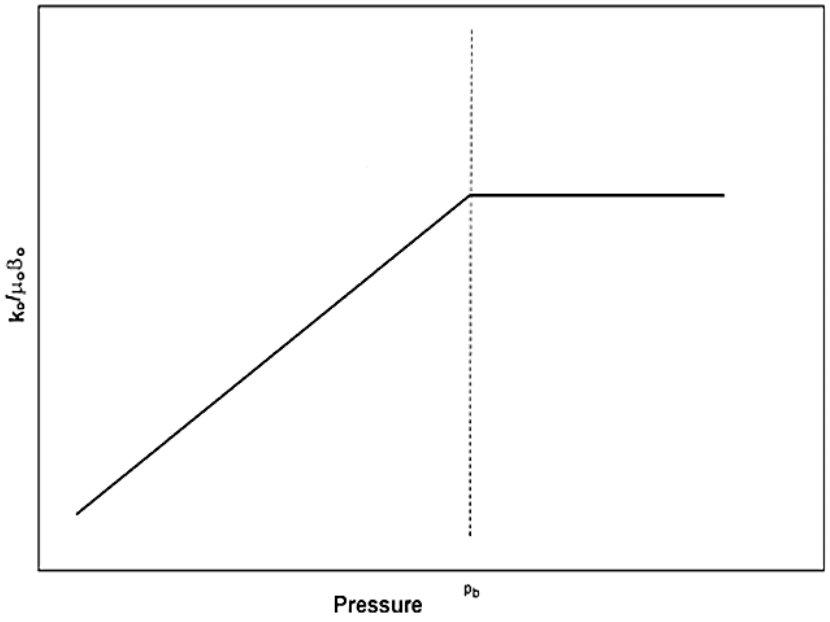
Example of Reservoir Models Available in Commercial Software

PROSPER from PETEX

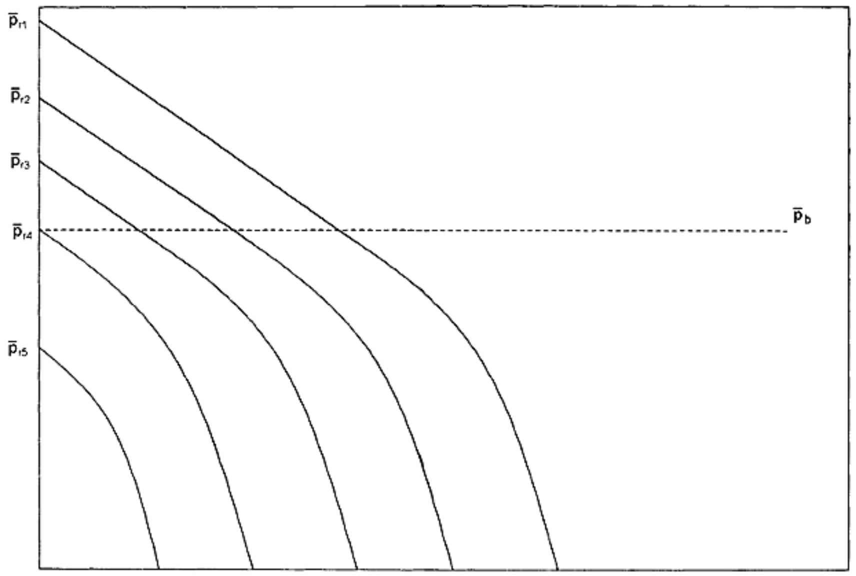
Reservoir Model



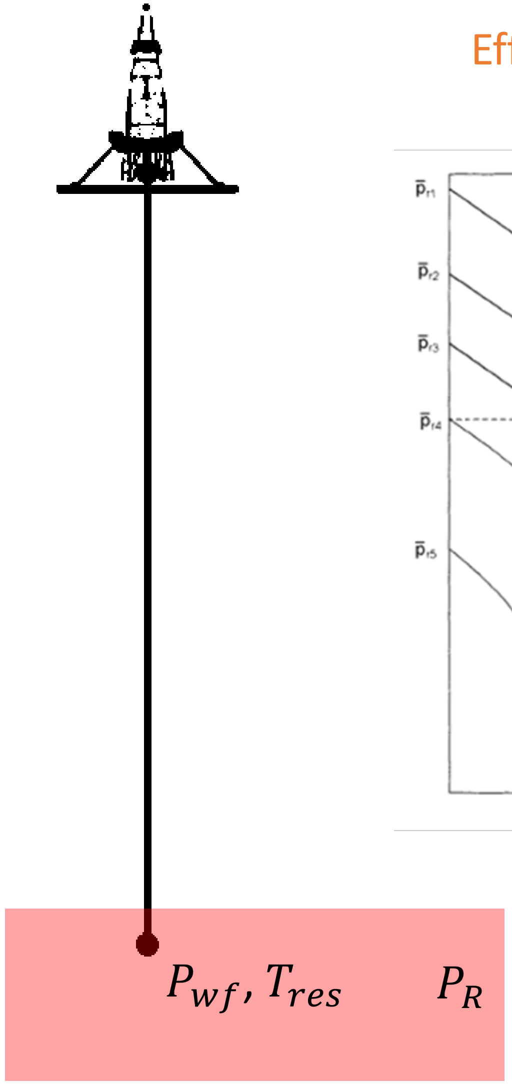
The term ${k_o}/{\mu_o B_o}$ as a function of pressure



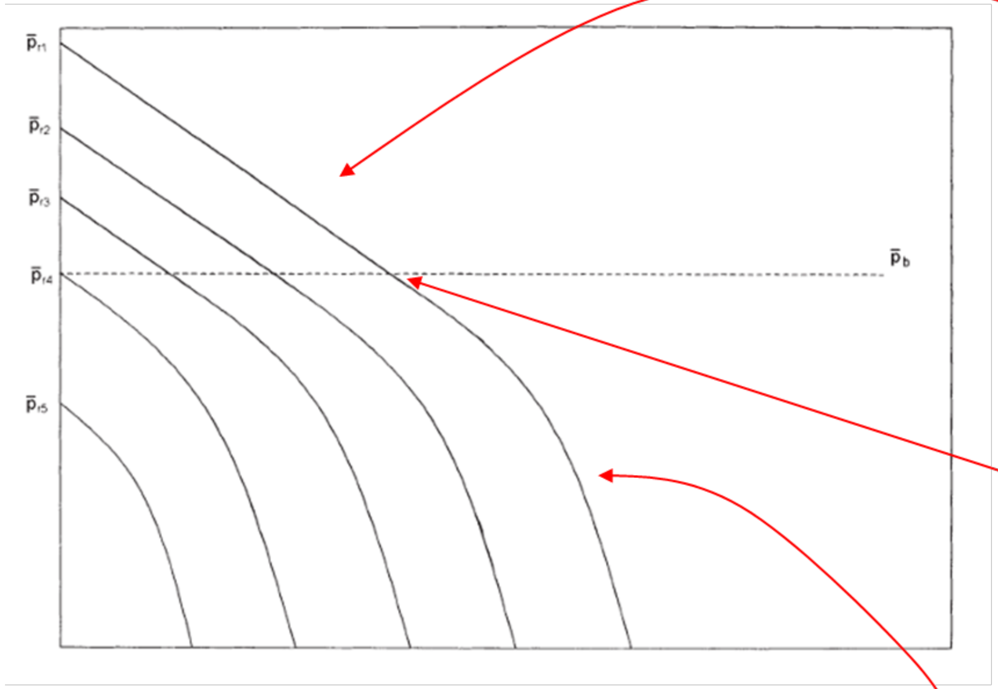
Effect of Reservoir Pressure



Reservoir Model



Effect of Reservoir Pressure



Darcy based on IPR: P_{wf} $(P_{wf} > P_b)$

$$Q = J\left(P_R - P_{wf}\right) = J\Delta p$$

$$J = \frac{2\pi k_o h}{\mu_o . B_o . \ln\left(\frac{r_e}{r_w}\right)}$$

h – thickness (m);

r_e – drainage radius (m);

r_w – wellbore radius (m).

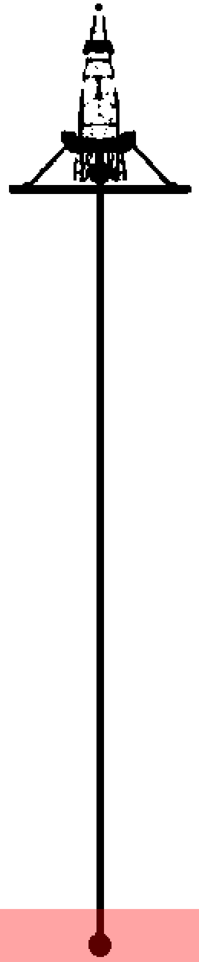
Stabilized test data point (Q and Pwf):

$$Q_{max} = \frac{Q}{1-0{,}2\left(\frac{P_{wf}}{P_R}\right)-0{,}8\left(\frac{P_{wf}}{P_R}\right)^2}$$

Vogel's equation: P_{wf} $(P_{wf} < P_b)$

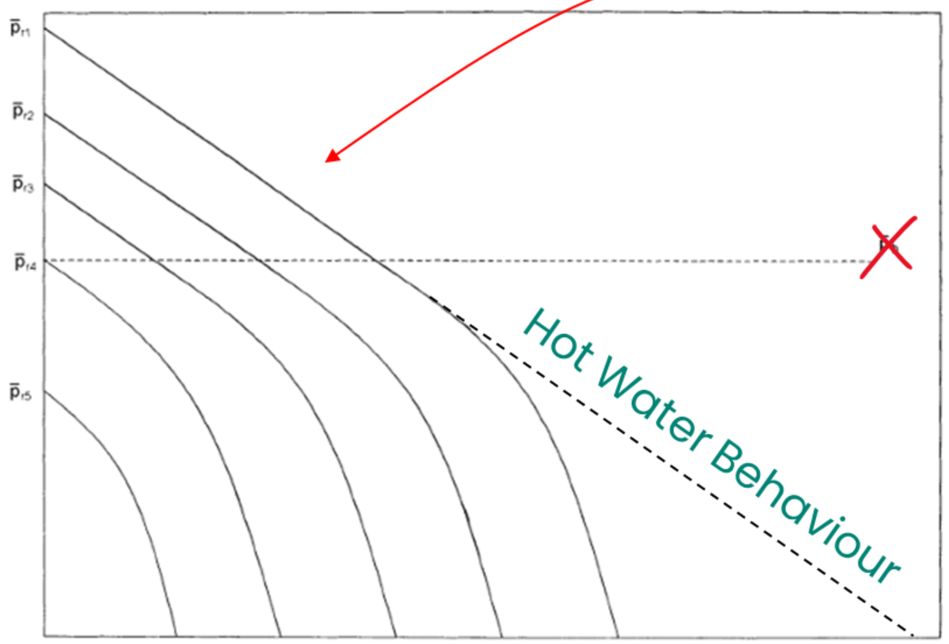
$$Q = Q_{max}\left[1 - 0{,}2\left(\frac{P_{wf}}{P_R}\right) - 0{,}8\left(\frac{P_{wf}}{P_R}\right)^2\right]$$

Reservoir Model



P_{wf}, T_{res}

Effect of Reservoir Pressure



Darcy based on IPR: P_{wf} $(P_{wf} > P_b)$

$$Q = J\left(P_R - P_{wf}\right) = J\Delta p$$

$$J = \frac{2\pi k_o h}{\mu_o . B_o . \ln\left(\frac{r_e}{r_w}\right)}$$

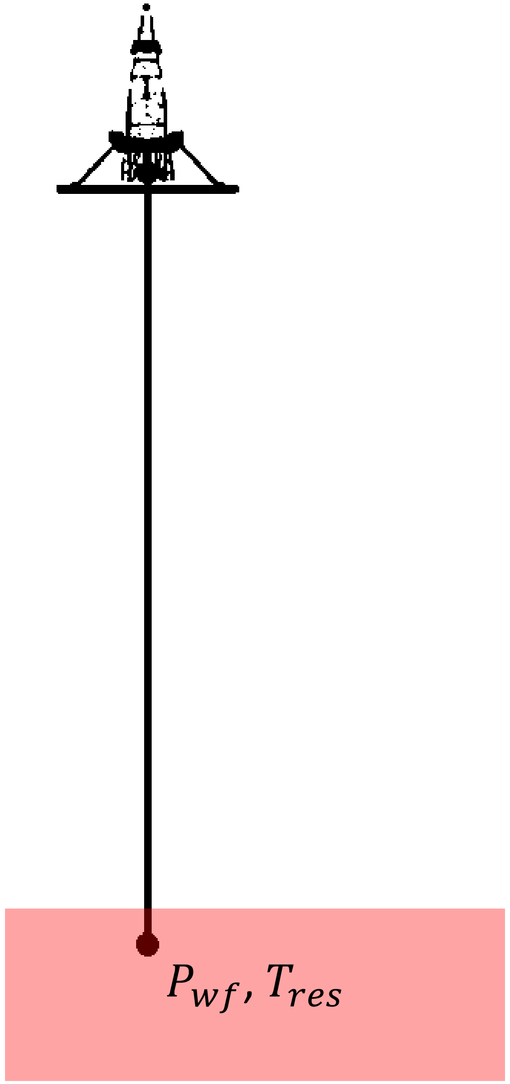
h – thickness (m);

r_e – drainage radius (m);

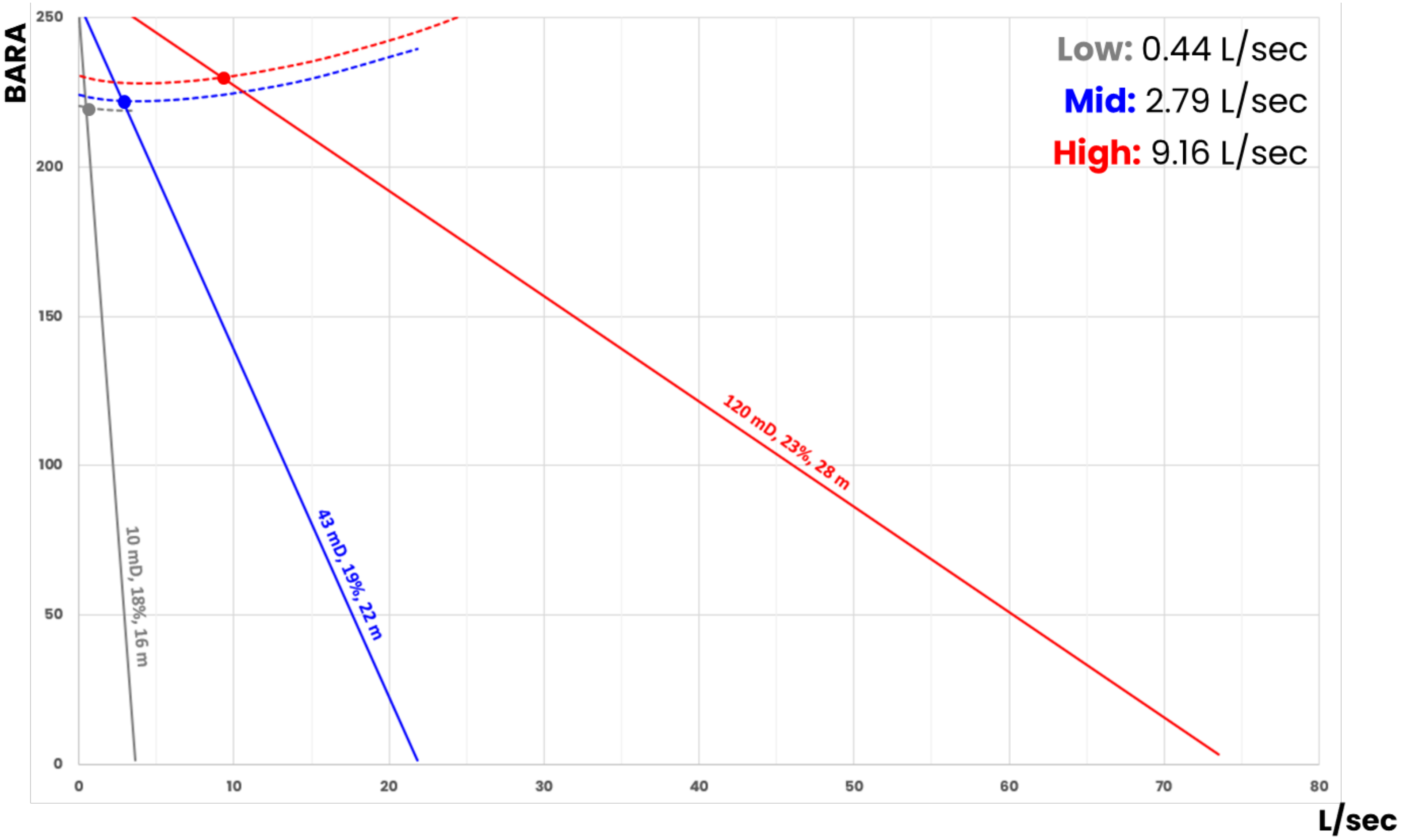
r_w – wellbore radius (m).

In gas phase the behaviour is different

Reservoir Model



Example of incidence of the **reservoir properties in the flow rate**



Simplified Model

- Steady state
- Water Dominated system ($h_1 = x_w \cdot h_w$), single phase (liquid)
- Incompressible fluid
- U assumed
- No phase changes along the tubing
- Reservoir – Darcy Model

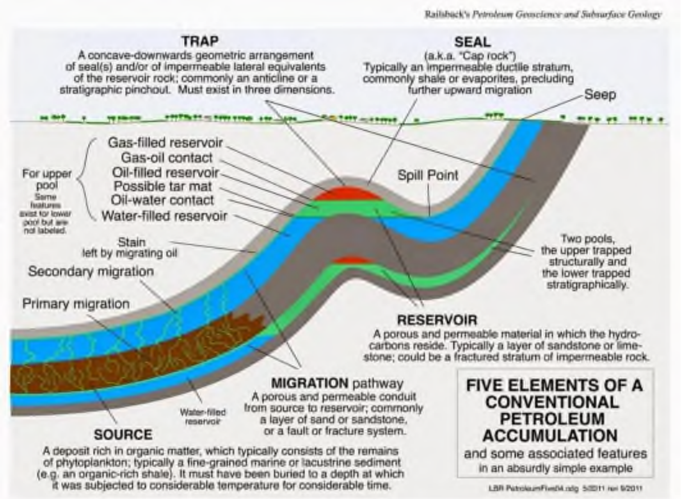
Overview of Geothermal Reservoirs Modelling

Geologic Perspective On Geothermal Play Systems

A geothermal play systems In contrast to the straightforward definition of hydrocarbon play systems, which are clearly defined by their source rock, reservoir and trap, geothermal play systems are lacking such a clear set of geological features. Instead, geothermal play systems appear in diverse geologic environments and theoretically all over the world.

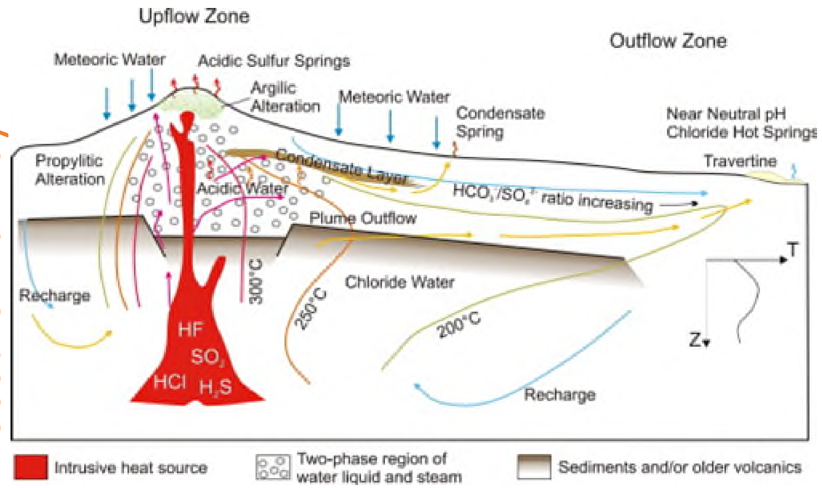
For geothermal resource utilization, important factors are how **<u>much heat is stored</u>** at a drillable depth and if this **<u>heat is producible</u>** at an **<u>economic rate</u>** for a specific project.

Hydrocarbon Play



https://www.geologyin.com/2014/08/petroleum-system.html

Geothermal Play



Inga S. Moeck 2014

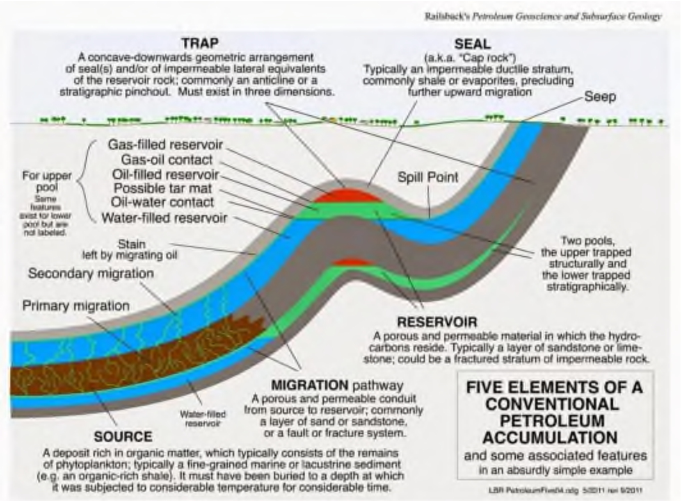
Geologic Perspective On Geothermal Play Systems

A **conceptual model** on how a number of geological factors might generate a recoverable geothermal resource at a specific structural position in a certain geologic setting.

The characteristics of individual geothermal systems are a function of site-specific variables:

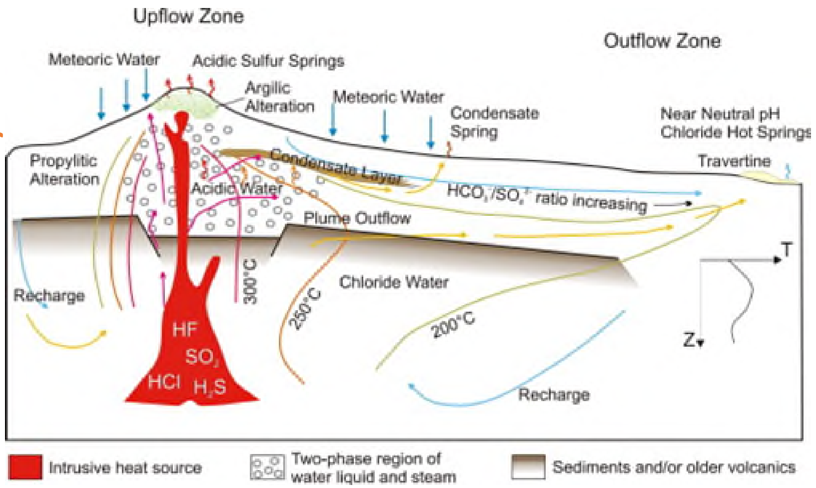
- the nature and depth of the heat source;
- the dominant heat transfer mechanism;
- permeability and porosity distribution;
- rock mechanical properties;
- fluid/rock chemistry;
- fluid recharge rates/sources.
- Identify the play type → focussed exploration strategy

Hydrocarbon Play



https://www.geologyin.com/2014/08/petroleum-system.html

Geothermal Play



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Types of geothermal reservoirs

Type	Subtype	Geologic Setting	Heat Source	Dominant Heat Transport Mechanism
CV-1: Magmatic	CV-1a: Extrusive	Magmatic Arcs, Mid Oceanic Ridges, Hot Spots	Active Volcanism, Shallow Magma Chamber	Magmatic-hydrothermal Circulation
	CV-1b: Intrusive	Magmatic Arcs, Mid Oceanic Ridges, Hot Spots	Active Volcanism, Shallow Magma Chamber	Magmatic-hydrothermal Circulation, Fault Controlled
CV-2: Plutonic	CV-2a: Recent or Active Volcanism	Convergent Margins with Recent Plutonism (<3 Ma), Young Orogens, Post-orogenic Phase	Young Intrusion+Extension, Felsic Pluton	Magmatic-hydrothermal Circulation, Fault Controlled
	CV-2b: Inactive Volcanism	Convergent Margins with Recent Plutonism (<3 Ma), Young Orogens, Post-orogenic Phase	Young Intrusion+Extension, Felsic Pluton, Heat Producing Element in Rock	Hydrothermal Circulation, Fault Controlled
CV-3: Extensional Domain		Metamorphic Core Complexes, Back-arc Extension, Pull-apart Basins, Intracontinental Rifts	Thinned Crust+Elevated Heatflow, Recent Extensional Domains	Fault Controlled, Hydrothermal Circulation
CD-1: Intracratonic Basin		Intracratonic/Rift Basins, Passive Margin Basins	Lithospheric Thinning and Subsidence	Litho/Biofacies Controlled
CD-2: Orogenic Belt		Foreland Basins within Fold-and-thrust Belts	Crustal Loading and Subsidence Adjacent to Thickened Crust	Fault/Fracture Controlled, Litho/Biofacies Controlled
CD-3: Crystalline Rock - Basement		Intrusion in Flat Terrain	Heat Producing Element in Rock, Hot Intrusive Rock	Hot Dry Rock, Fault/Fracture Controlled

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Definition and Classification of Geothermal Resources

The most common classification of geothermal resources is based on the enthalpy of the geothermal fluids. The resources are divided into low, medium and high enthalpy resources, according to criteria that are generally based on the energy content of the fluids and their potential forms of utilization .

	Muffler ºC	Hochstein ºC	Benderitter and Cormy ºC	Haenel et al ºC		
Low Enthalpy	<90	<125	<100	<150		
Moderate Enthalpy	90 -150	125-225	100-200	-		
High Hethalpy	> 150	>255	>200	>150		
Sanyal	Non-Electrical ºC	Very Low ºC	Low ºC	Moderate ºC	High ºC	Ultra-High ºC
	<50-100	100-150	150-180	180-230	230-300	>300

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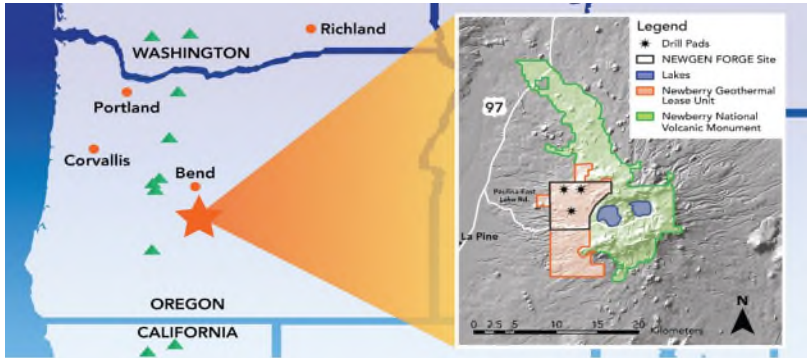
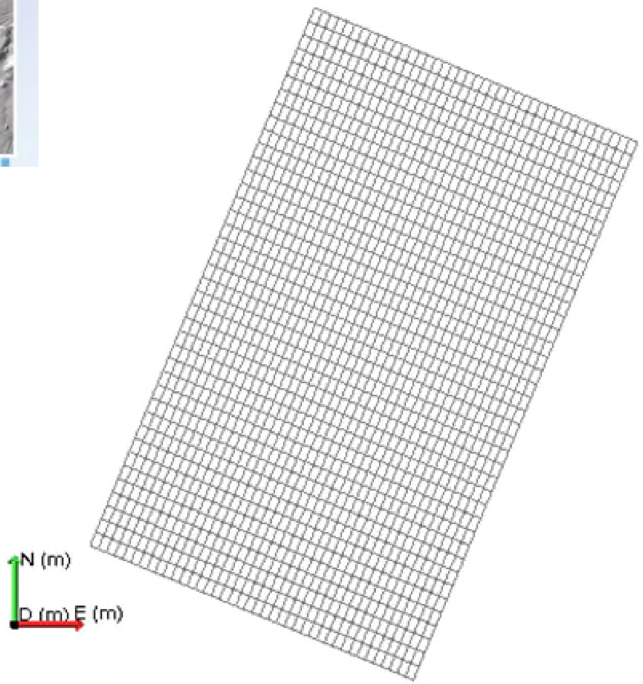
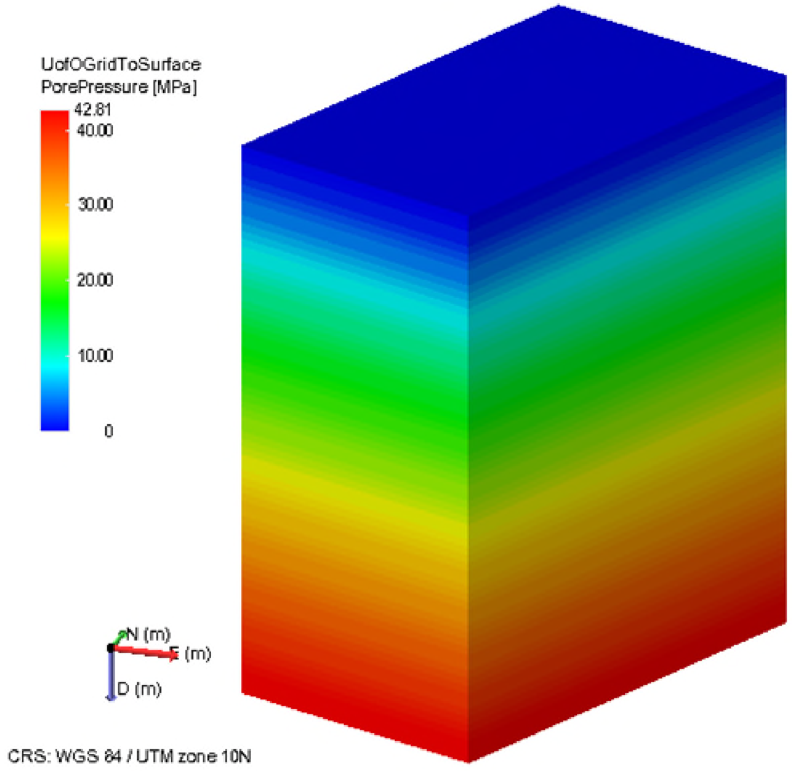
Simplified Geomodel – Case Example



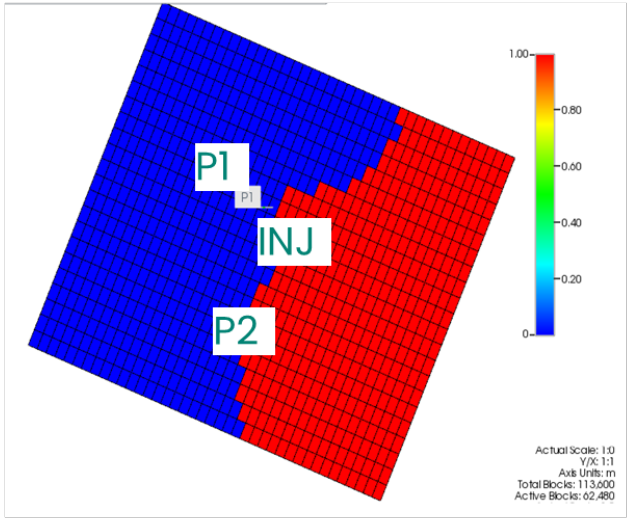
- Modeling area 3000 m x 5000 r
- Vertical extent 5500 m
- Cell size 75x125x75m
- Pressure
- Temperature
- Porosity
- Permeability
- Available information

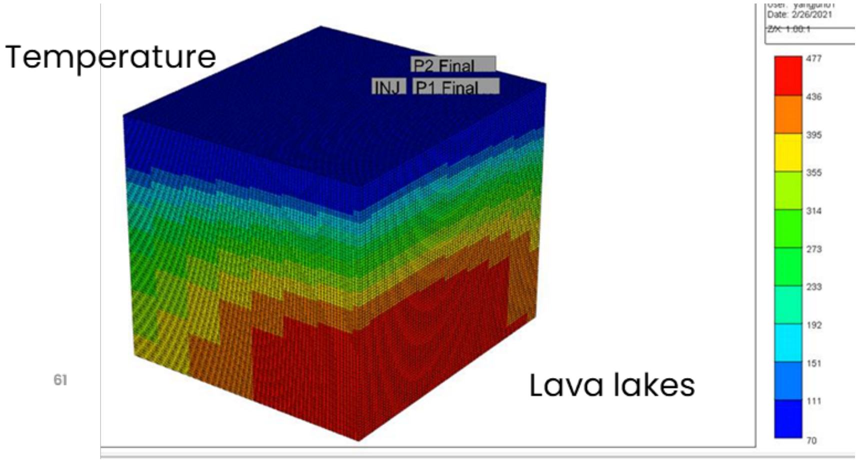




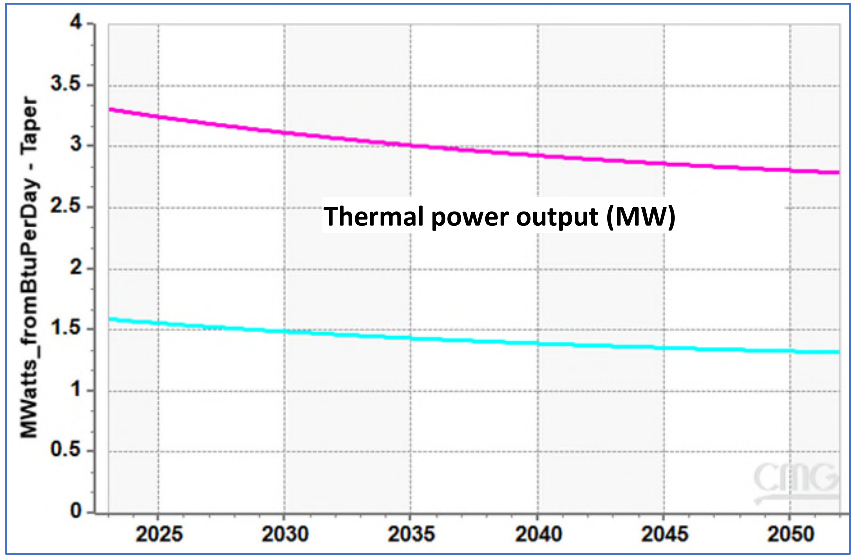
Temperature gradient to create a realistic model

Supercritical Fluid



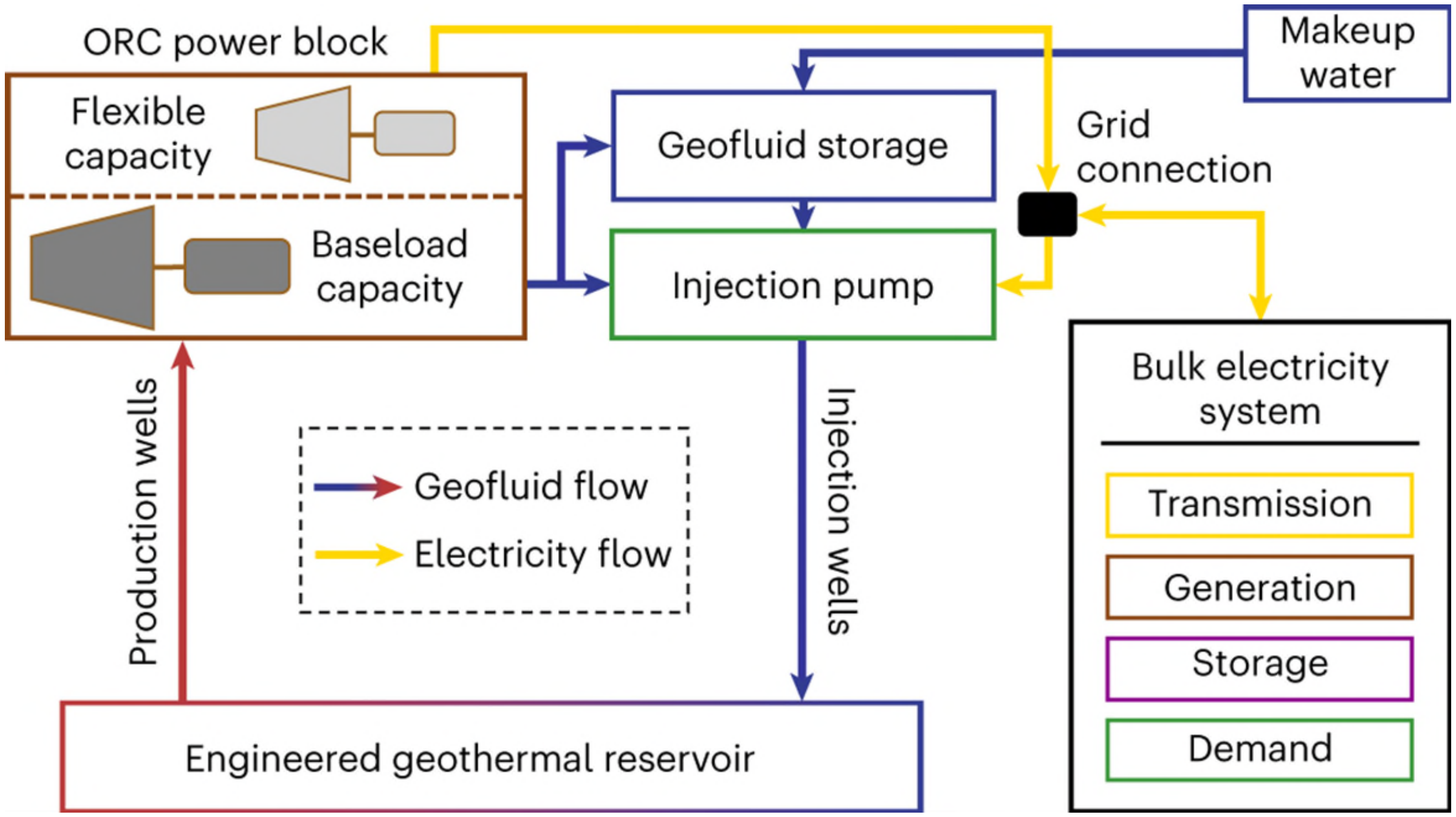


Outcomes & Value Delivery



Initial condition determines the coexistence of superheated water and supercritical water

The System Cycle



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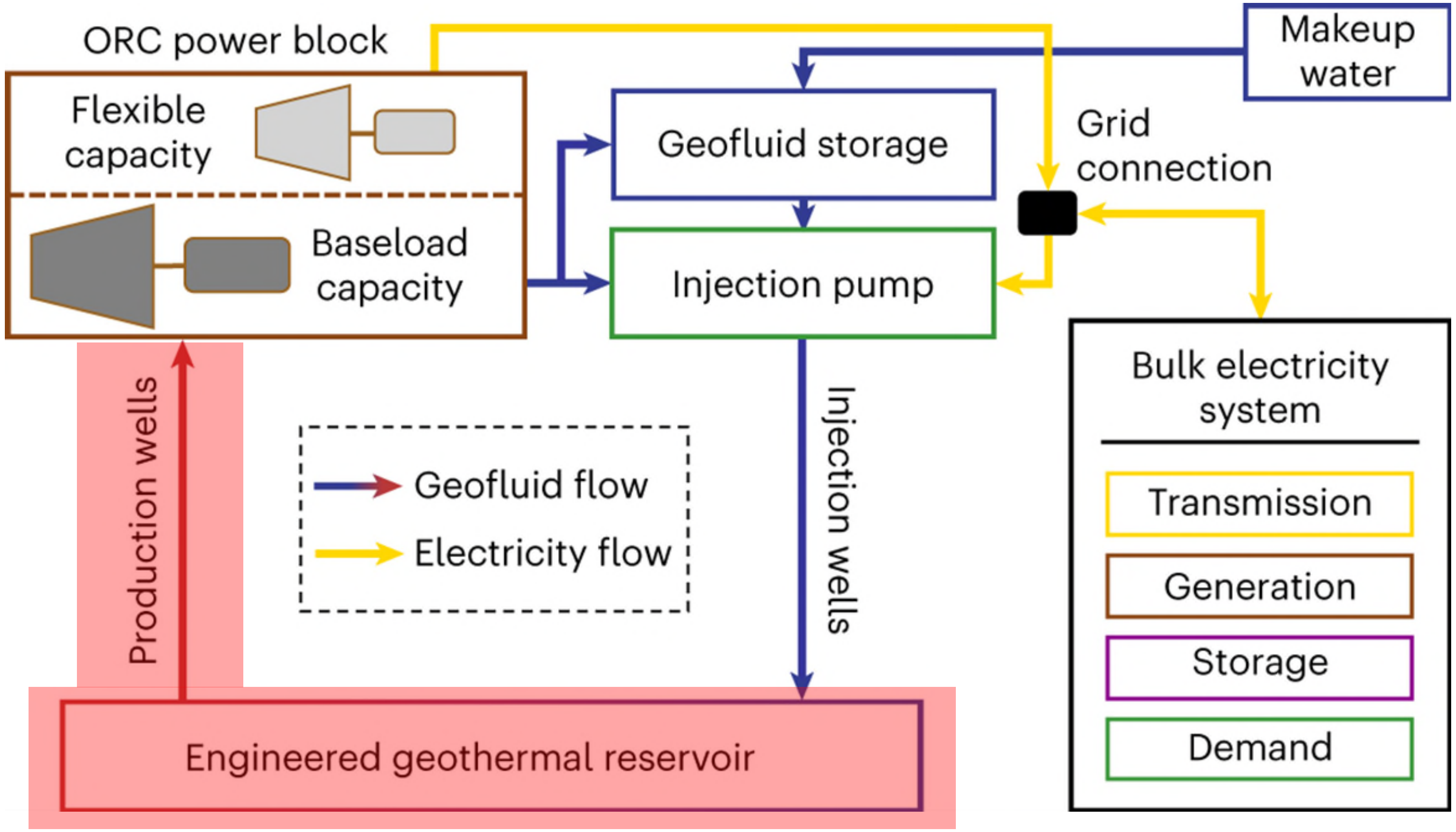
The System Cycle



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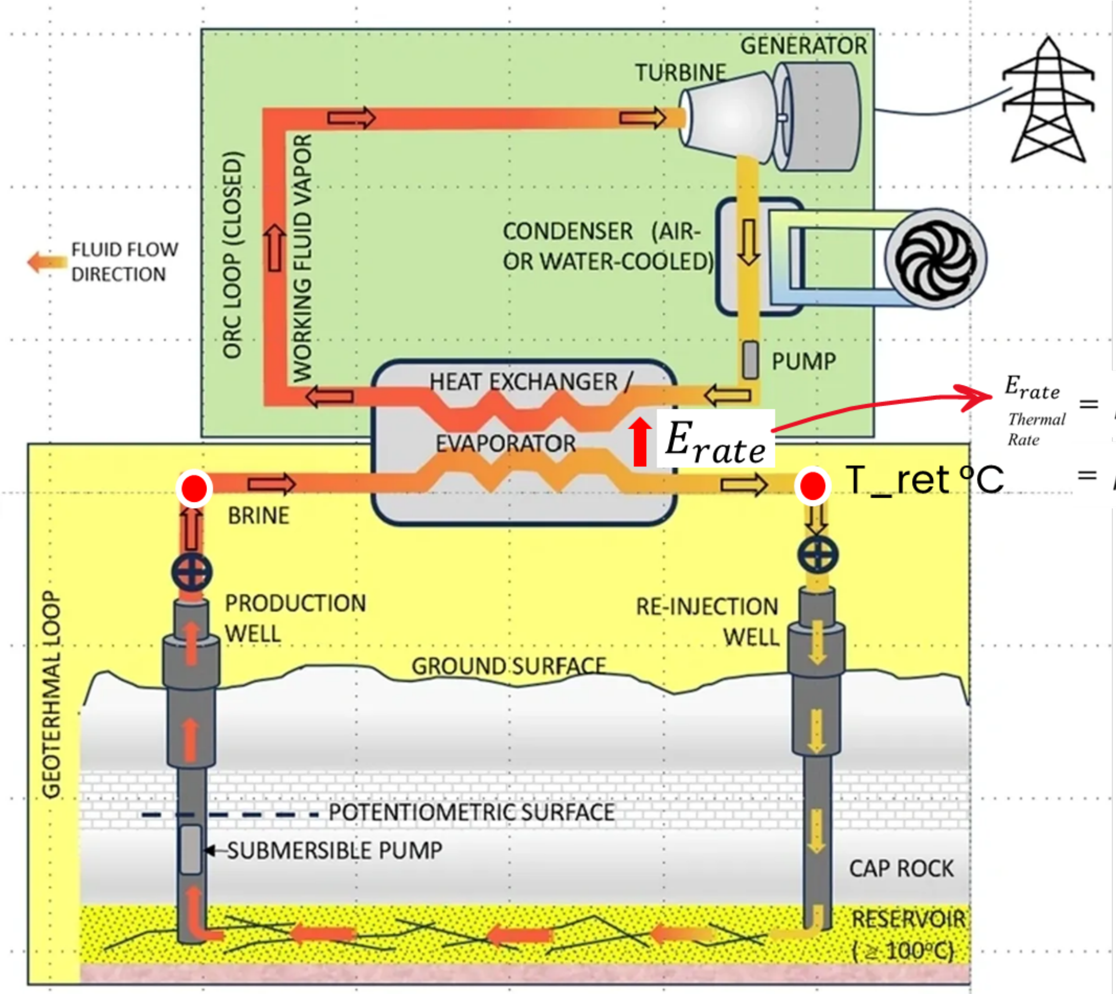
The System Cycle

$$E_{rate}\Big|^{inst}$$

$$E_{rate}\Big|^{inst} = \rho_F * Q * h \quad \textbf{MWt}$$



Modified from https://albertageothermal.ca/the-technology

$$E_{rate\ \mathit{Thermal\ Rate}} = \rho_F * c_F * Q * (T_i - T_o) \ \textbf{MWt}$$

$$= \rho_F * Q * (hi - ho) \quad \textbf{MWt}$$

Q&A