Heat Transfer Modelling For Thermal Stimulation Of Near Wellbore Using COMSOL Multiphysics

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Abstract:
The performance of the oil reservoir is decisively determined by the hydraulic permeability of the rock and the possible flow paths. During the production phase the petrophysical properties of the rock may deteriorate, due to highly viscous oil deposits, especially in the near borehole region. Therefore, it is a challenge to restore the permeability in this area. In order to remove the deposits again and improve the productivity, thermal energy is supplied to underground. The generation of the heat underground using a chemical reaction (Thermite method) represents a new approach for cleaning of the near borehole region.
A numerical simulation was carried out with the simulation software (COMSOL Multiphysics) to support the laboratory tests. Two modules were used to describe the problem; the "non-isothermal flow" module to present the fluid flow and the heat transfer in water inside the wellbore and the "Heat transport in porous media" module to present the temperature distribution in the saturated sand near the wellbore.
Based on the comparison between calculated and measured temperatures the model was modified and then the simulation results showed a good match in comparison to the actual temperatures. A sensitivity analysis was carried out with COMSOL to show the important influencing parameters on the calculation result and the results were presented in a tornado and spinning diagram.

Keywords: COMSOL Multiphysics, heat transfer, thermite, convection, conduction.

Introduction

During the production phase, the permeability in the near borehole area is reduced by deposits of highly viscous oil products. By supplying the thermal energy, the deposits can be mobilized again and transported away. However, due to heat losses, the use of hot steam is limited, to a depth of approximately 1000 m. The generation of the heat underground using a chemical reaction (Thermite method) represents a new approach for cleaning of the near borehole area.

Thermite consists of a mixture of metal oxide (usually iron oxide) and a pure metal powder (usually aluminium powder). A redox reaction takes place with enormous heat development (temperatures up to 2400 ° C).

Due to the high oxygen affinity of aluminium, the oxygen migrates to the aluminium and forms alumina, (1), (2), (3).

$$\mathbf{Fe_2O_3 + 2Al \rightarrow AL_2O_3 + 2Fe + Wärme}$$

Experimental apparatus

1- HD / HT reactor: 200 bar, 300 ° C
2- Capsule (L=180 mm, Ø=80 mm)
3- Tubing pipe (L=1300, Ø =50, δ=3mm)
4- Sealing rings
5- Ceramic and steel plates
6- Thermo- and pressure sensor
7- Computer with LabVIEW

After the construction of mentioned parts of the reactor and the connection of measuring sensors, the reactor looks as shown in Figure (1)

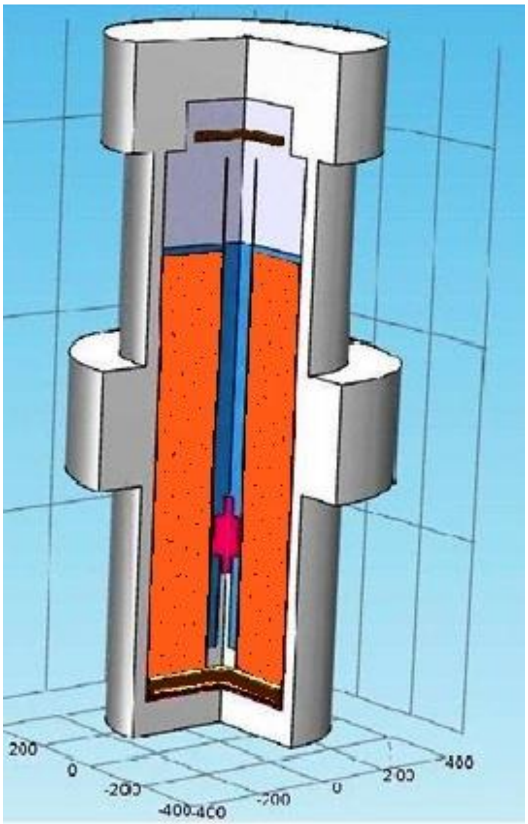

Figure 1. the HT/HP Reactor

Modeling and simulation with COMSOL Multiphysics

Initial values: $P_0 = 30\ bar, T_0 = T_{Lab} = 13\ °C = 286.15\ K, \quad Q = 3\ MJ$

1. Selection of the space dimension: Due to the symmetry of the reactor related to the Z-axis, the modeling and simulation process is carried out in the dimension **2D-axisymmetric**.
2. Creating the geometric model: Figure (2) shows the 2D model geometry. Later, it is presented as a 3D model by rotating around the Z-axis.
3. Materials: Figure (2) shows also the materials required for the model: water saturated-sand (defined by user), water, nitrogen, steel and ceramic (from the material library).

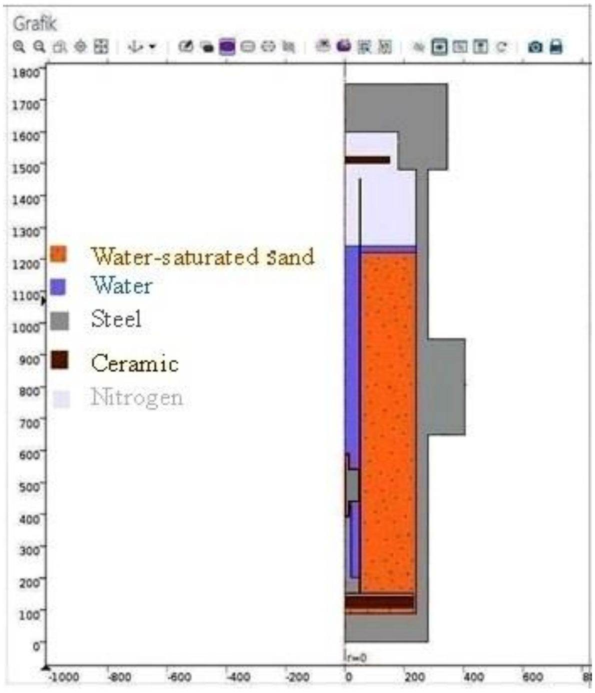

Figure 2. the geometric model and materials

4. Physical processes: when the thermite mixture starts to react, helping an electric charge, an exothermic redox reaction will take place with enormous heat development (3MJ heat in about three minutes).
This heat spreads through the surface of the capsule in all parts of the reactor as follows:

1- **Heat transfer by conduction**: The produced heat during the Thermite reaction transports through all solid parts of the reactor (tubing, steel and ceramic plates, outer body of the reactor,) by conduction.
2- **Heat transfer by convection** (in water or in nitrogen area): As soon as the redox reaction of the thermite mixture starts, the temperature of the capsule increases very rapidly. The surrounding water is heated, and in parallel its density decreases. This creates a difference in density between the surrounding and the upper water. Hot water floats due to the buoyancy forces, while cold water sinks, absorbs some of the heat and then floats again. Therefore, a significant part of the generated heat is transported away by the flowing water. This effect corresponds to the heat transport due to the natural convection caused by the difference in density and is taken into account by COMSOL through the module NIF "non-isothermal flow", (4), (5).
3- **Heat transfer in porous media**: A part of the generated heat reaches the water-saturated sand area; this consists of quartz sand and water in the pores. This part is considered in COMSOL by the module HTPM "heat transport in porous media", (4), (5).
4- **Heat transfer by radiation**: two types of radiation are found (6):
- Surface-to-surface radiation: between the capsule surface and the inner surface of tubing.
  Due to the presence of water between the two mentioned surfaces and due to the high values of the emission level of water (ε = 0.95 - 0.98), almost the total heat radiated from the capsule surface is absorbed by water. Consequently, this effect can be neglected.
- Surface-to-ambient radiation: If a temperature difference occurs between the outer surface of the reactor and the environment, the surface emits a certain amount of heat into the environment.

5- **Heat transport with phase change**: If the boiling temperature were exceeded, the water would boil, the boiling points assuming at different pressures the following values, (7).

Table 1. Boiling temperature of the water at different pressures

Pressure [bar]	Boiling temperature of water Ts [°C]
1	99,63
10	179,88
20	212,37
30	233,84

The boiling temperature of the water increases with increasing pressure which reduces the probability of phase change under similar conditions. Therefore this effect can also be neglected.

Due to the physically complicated model and relatively weak technical data of the computer used, the following procedures are suggested, as shown in figure 3.

- **Step1:** Simplification
- **Step 2:** the NIF "non-isothermal flow" module would be used first to present the fluid flow and the heat transfer in water inside the wellbore. From this, the heat distribution on the edge R of the water-saturated sand is determined.
- **Step 3:** Modeling and simulation by the module HTPM "Heat transport in porous media", with considering the heat distribution on the edge R (from step 2). From this the temperature distribution in the saturated sand is determined.

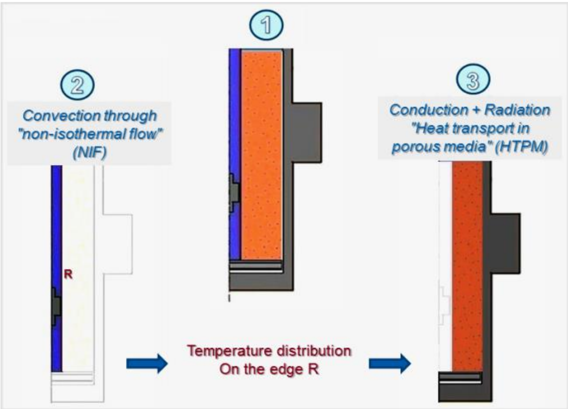

Figure 3. the solution steps

5. Net: a user-defined net was applied.
6. Study: Due to the time dependence of the heat source, a time-dependent study was used.
7. Results:

- **Temperature distribution on the edge R (from step 2) (Figure 4)**

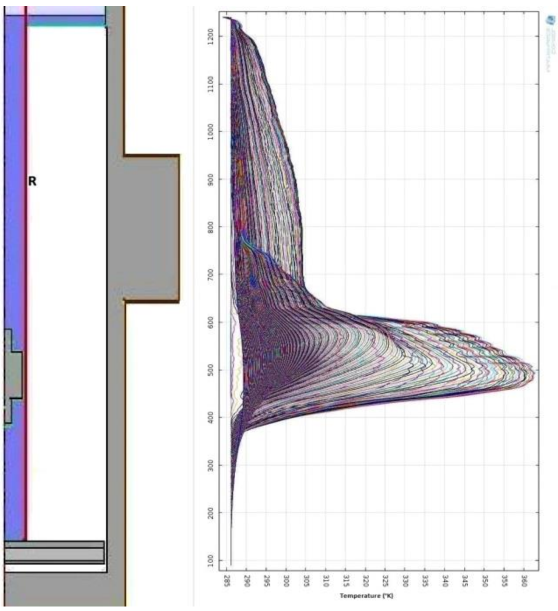

Figure 4. Temperature distribution on the edge R

- **Temperature distribution in water - saturated sand (from step 3) (Figure 5) (Depending on the mean temperature distribution from step 2)**

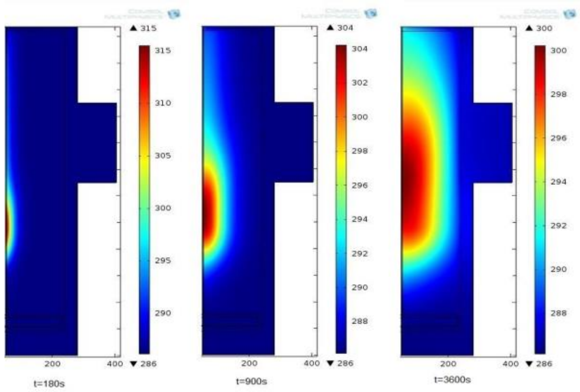

Figure 5. Temperature distribution in water - saturated sand at certain times

For comparison between measured and simulated temperatures, the four points shown in figure (6) were considered.

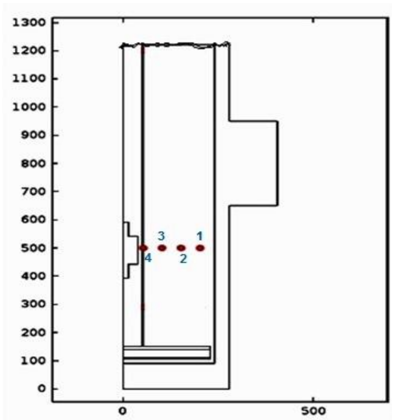

Figure 6. Measuring points

Figure (7) shows the calculated and measured temperature curves in the four measuring points.

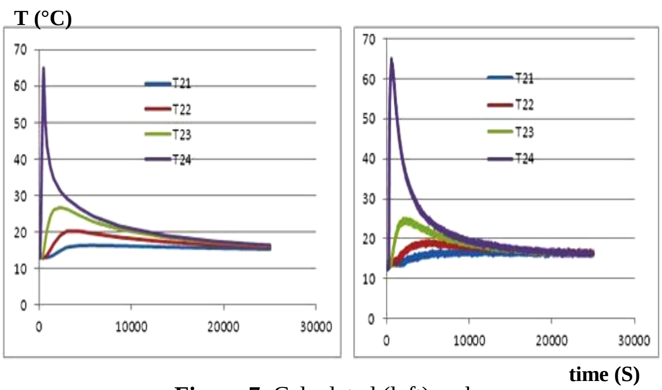

Figure 7. Calculated (left) and measured (right) temperature curve

Table 2: shows a comparison between the maximum temperature difference obtained from the simulation and the measuring at each point.

	max. calculated temperature	max. measured temperature
T4	52.0	52.029
T3	13.740	12.098
T2	7.290	6.462
T1	3.350	4.454

Summary and discussion

- The heat generated by the exothermic redox reaction of the thermite mixture spreads on the edge R, as shown in the figure (3). Most of the heat flows into the area directly opposite the capsule. It decreases upwards to a certain small amount of heat, and downwards quickly to zero. The reason for this is that the water absorbs some of the heat generated and then flows upwards due to the buoyancy force.
- The measured and the calculated temperatures are in general close to each other.

Sensitivity analysis

Here, how strongly the maximum temperature changes at any point when the individual influencing parameters change would be investigated. This can be calculated as following:

1. The individual parameters are changed (increased and decreased) by a certain percentage.
2. The maximum temperatures at any point are calculated and compared each time.

Table 3: the Sensitivity analysis calculations

parameter	Relative changes of the underlying/ baseline value				
	-20%	-10%	basis value	10%	20%
Q	-0.18141361	-0.12057592	0	0.10348458	0.218121
ϴs	-0.0950669	-0.04949389	0	0.05139034	0.10253636
ks	-0.06468877	-0.03308319	0	0.03052938	0.06012798
kw	-0.00681792	-0.00342059	0	0.00309482	0.00621291
Cps	0.053676556	0.025549738	0	-0.02500291	-0.0496102
Cpw	0.057440372	0.0272484	0	-0.026242	-0.0522397
ρs	0.053676556	0.025549738	0	-0.02500291	-0.0496102
ρw	0.057242583	0.027056428	0	-0.02644561	-0.0526585
P0	5.2356E-05	5.2356E-05	0	5.2356E-05	5.2356E-05

A tornado chart is a special type of bar chart, with the data displayed vertically. The data are arranged hierarchically.

As shown in figure (8), the parameters are arranged so that, the parameter which has the greatest influence on the maximum temperature appears at the upper edge of the diagram. The second one is the second from above, etc.

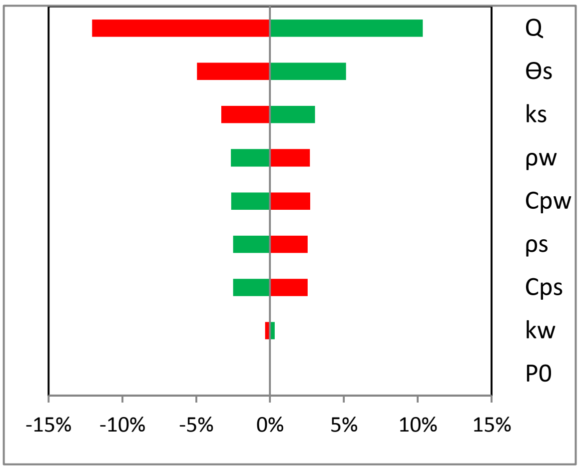

Figure 8. the tornado chart

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Appendix

List of Symbols

Symbol	Unit	meaning
a	m^2/s	Thermal conductivity
a_k	$W/(m^2 \cdot K)$	Heat transfer coefficient
C	J/K	Heat capacity
c	$J/(kg \cdot K)$	Specific heat capacity
k	$W/(m \cdot K)$	Heat conduction
P	N/m^2 - bar	pressure
Q	J	heat
T	K - °C	temperature
t	s	Time
ρ	Kg/m^3	density
δ	m	thickness
ε	-	Emission grade

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Symbol	meaning
cap	capsule
Reak	reactor
Ro	pipe
S	sand
st	steel
W	water
R	edge

List of abbreviations

Symbol	meaning
HD	High pressure
HT	High temperature
NIF	Not isothermal flow
HTPM	Heat transport in porous media