OPM'S LATEST DEVELOPMENTS BY TNO

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TNO innovation for life

SUMMARY

- On-going developments within TNO
  - Outputs (PRT report, summary curves, well potential, etc)
  - Salt precipitation module
  - Radial grid
  - Applications/Testing

TNO PROJECTS CURRENTLY USING OPM-FLOW

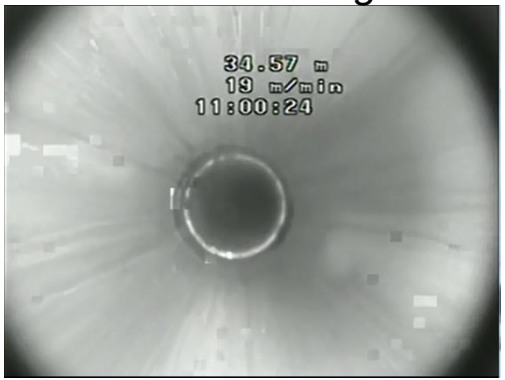
- OPM software development
- Salt Precipitation Modeling
- Geothermal Energy Optimization
- EVEReST (Field Development Optimization), and History matching (ERT)
- Storage integrity tool (CO_2 / H2 Injection)
- Earthquakes Impact Mitigation (as the flow module coupled with MACRIS)
- RoSim (alternative to TNO ‘s in-house DoubletCalc2D/3D)
- Etc…

SALT PRECIPITATION PROBLEM

- Salt precipitation in gas reservoirs can be a huge issue for operators
  - Clogging results in severe production decline
- ~50 of 330 Dutch gas fields suffer from salt precipitation
  - this number is increasing in time
- Precipitation occurs near the wellbore
  - Accumulation in well bore
  - Soaking with small amounts of fresh water restores production

Before washing

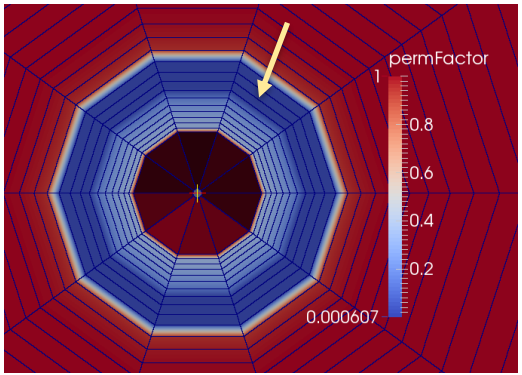
After washing



SALT PROJECTS

- 2013-2016
  - Near well bore modelling using DumuX by Universität Stuttgart
    - Added specific salt related physics:
      - Vapour pressure lowering, Capillary pressure correction, …
- October 2019 (Current JIP Project)
  - Optimization of production
    - Washing strategies (when, how much, for how long)
  - Incorporation of salt precipitation in OPM flow motivated by
    - Performance increasement
    - Usability; larger potential user group
    - Presence of well models. Three-phase flow (gas condensate reservoirs)

Permeability reduced to zero



APPROACH (HIGH-LEVEL)

- Step 1: Incorporate Salt component
  - Salt transport equation + precipitation
    - Primary variable switching
    - Salt concentration depending fluid properties (viscosity, density)
    - Validation using ECLIPSE/Dumux
  - Changing permeability $k = k(\phi)$

Step 1: Adds on black-oil equations

- Step 2: Incorporate water evaporation into gas
  - Modify black-oil equation
  - Relation for vaporized water in gas (pressure and salt dependent)
  - Validate water-gas system with Dumux implementation

Step 2: Changes black-oil equations

SALT TRANSPORT EQUATION

- Transport equation: $$\frac{\partial \varphi_0 m_\varphi (b_w s_w C_w^{NaCl} + s_S \rho^{NaCl})}{\partial t} + \nabla \cdot (C_w^{NaCl} b_w v_w) + C_w^{NaCl} q_w = 0$$
  - C_w^{NaCl}: Salt concentration in water [kg/Sm3].
  - s_s: (volume) saturation of deposited salt, assumed to be immobile.
  - $C_w^{NaCl} q_w$: Source/sink term for wells [kg/s].
  - ρ^{NaCl}: Density of solid salt [kg/m3]
  - Similar equation (but without precipitation) in Eclipse and OPM (very recent, by Trine S. Mykkeltvedt)
- The closure relation for saturations becomes: $s_w + s_o + s_g + s_s = 1$
- Primary variable switching:
  - $C_w^{NaCl} > C_{w,sol}^{NaCl}$ → primary variable becomes s_s
  - $s_s < 0$ → primary variable becomes C_w^{NaCl}
- Remark: Formulation differs from Dumux that use sources and sinks for dissolution/precipitation

$C_{w,sol}^{NaCl}$: solubility limit

BLACK-OIL FORMULATION, WITH WATER VAPORIZATION

Oil: $$\frac{\partial}{\partial t}\left[\varphi_0 m_\varphi \left(b_o s_o + r_{og} b_g s_g\right)\right] + \nabla \cdot \left(b_o v_o + r_{og} b_g \, v_g\right) + q_o = 0$$

Gas: $$\frac{\partial}{\partial t}\left[\varphi_0 m_\varphi \left(b_g s_g + r_{go} b_o \, s_o\right)\right] + \nabla \cdot \left(b_g u_g + \, r_{go} b_o v_o\right) + q_g = 0$$

Water: $$\frac{\partial}{\partial t}\left[\varphi_o m_\varphi (b_w s_w + r_{wg} b_g s_g)\right] + \nabla \cdot \left(b_w v_w + r_{wg} b_g u_g\right) + q_w = 0$$

with r_{wg}: vaporized water in the gas phase

v_α : the velocities of phase α (= gas, oil or water).
$b_\alpha = 1/B_\alpha$ with B_α the formation volume factor of phase α (ratio of reservoir to standard condition volumes [Rm^3/Sm^3])
s_α : the saturation of phase α
r_{og} : vaporized oil in the gas phase (ratio of volumes at standard condition Vo/Vg [Sm3/Sm3] from a volume of gas at reservoir conditions)
r_{go} : solution of gas in oil phase (ratio of volumes at standard Vg/Vo [Sm3/Sm3] from a volume of oil at reservoir conditions)
q_α : source /sink terms for phase α, typically associated to production/injection wells
m_φ: porosity multiplication factor
T: temperature, which we will assume fixed
p_g: pressure in gas phase

PRIMARY VARIABLES

For three-phase case and a grid with n cells, the material balances give us $4n$ equations.
We can define as primary variables:

Phases present	Primary variables
water, gas and oil	$C_w^{NaCl}, p_o, s_g, s_w$
gas and oil	s_s, p_o, s_g, r_{wg}
water and gas	$C_w^{NaCl}, p_g, s_g, r_{og}$
water and oil	$C_w^{NaCl}, p_o, s_w, r_{go}$
water, gas, oil, salt	s_s, p_o, s_g, s_w
gas and oil, salt	s_s, p_o, s_g, r_{wg}
water and gas, salt	s_s, p_g, s_g, r_{og}
water and oil, salt	s_s, p_o, s_w, r_{go}

Possible convergence issues?

INPUT FILE

- Keywords:
  - RUNSPEC:
    - VAPWAT: Activate water vaporization, PROPS should have a RWG table.
    - BRINE: Activate salt transport equation (we assume NaCl only)
    - PRECSALT: Activate Salt Precipitation. PROPS should have SALTSOL
  - PROPS
    - SALTSOL: Solubility limits
    - PERMRED: Defines the permeability multiplier as function of porosity for a reference k
    - PVTWSALT: Defines PVT data for brine
    - PVTGW, PVTGWO: Gas PVT properties with RWG column
    - RWGSALT: Define water vaporization vs. pressure and salt conc.
  - SOLUTION:
    - SALTVD, SALTPVD: Initial salt concentrations in water and rock
  - SCHEDULE:
    - WSALT: Defines the salt concentration in water injectors

New
Exists

PVT TABLES

```
--
-- GAS PVT TABLE FOR WET GAS
--
PVTG
-- PRES      RV         BG      VISC
-- PSIA   STB/MSCF  RB/MSCF  CPOISE
-- ------ --------- -------  ------
    300   0.000132  0.042340 0.01344
          0         0.042310 0.01389 /
    600   0.000124  0.020460 0.01420
          0         0.020430 0.01450 /
    900   0.000126  0.013280 0.01526
          0         0.013250 0.01532 /
    1200  0.000135  0.009770 0.01660
          0         0.009730 0.01634 /
    1500  0.000149  0.007730 0.01818
          0         0.007690 0.01752 /
    1800  0.000163  0.006426 0.01994
          0         0.006405 0.01883 /
    2100  0.000191  0.005541 0.02181
          0         0.005553 0.02021 /
    2400  0.000225  0.004919 0.02370
          0         0.004952 0.02163 /
                                     / TABLE NO. 1
```

```
--
-- GAS PVT TABLE FOR WET GAS
--
PVTGW
-- PRES      RWG        BG      VISC
-- PSIA   STB/MSCF  RB/MSCF  CPOISE
-- ------ --------- -------  ------
    300   0.000132  0.042340 0.01344
          0         0.042310 0.01389 /
    600   0.000124  0.020460 0.01420
          0         0.020430 0.01450 /
    900   0.000126  0.013280 0.01526
          0         0.013250 0.01532 /
    1200  0.000135  0.009770 0.01660
          0         0.009730 0.01634 /
    1500  0.000149  0.007730 0.01818
          0         0.007690 0.01752 /
    1800  0.000163  0.006426 0.01994
          0         0.006405 0.01883 /
    2100  0.000191  0.005541 0.02181
          0         0.005553 0.02021 /
    2400  0.000225  0.004919 0.02370
          0         0.004952 0.02163 /
                                     / TABLE NO. 1
```

PVT TABLES

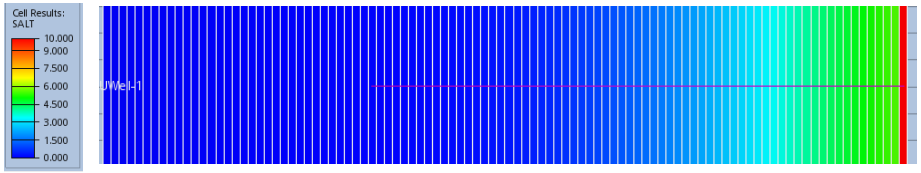
```
--
-- WATER EVAPORATION TABLE FOR BRINE
--
RWGSALT
-- PRES     SALTCON      RWG
-- PSIA      LB/STB    STB/MSCF
-- ------ ---------- ---------

   PRES1    SAL11      RWG11
            SAL21      RWG 21
            ...
            SALN1      RWGN1/
   PRES2    SAL12      RWG12
            SAL22      RWG22
            ...
            SALN2      RWGN2 /
            ...
   ...
   PRESM    SAL1M      RWG1M
            SAL2M      RWG2M
                       ...
            SALNM      RWGNM /
```

```
--
-- GAS PVT TABLE FOR WET GAS
--
PVTGWO
-- PRES      RWG         RV          BG       VISC
-- PSIA    STB/MSCF    STB/MSCF   RB/MSCF    CPOISE
-- ------ ---------- ---------- ---------  ------
    300    0.000132   0.000132   0.042340  0.01344
           0          0          0.042310  0.01389 /
    600    0.000124   0.000124   0.020460  0.01420
           0          0          0.020430  0.01450 /
    900    0.000126   0.000126   0.013280  0.01526
           0          0          0.013250  0.01532 /
    1200   0.000135   0.000135   0.009770  0.01660
           0          0          0.009730  0.01634 /
    1500   0.000149   0.000149   0.007730  0.01818
           0          0          0.007690  0.01752 /
    1800   0.000163   0.000163   0.006426  0.01994
           0          0          0.006405  0.01883 /
    2100   0.000191   0.000191   0.005541  0.02181
           0          0          0.005553  0.02021 /
    2400   0.000225   0.000225   0.004919  0.02370
           0          0          0.004952  0.02163 /
                                          / TABLE NO. 1
```

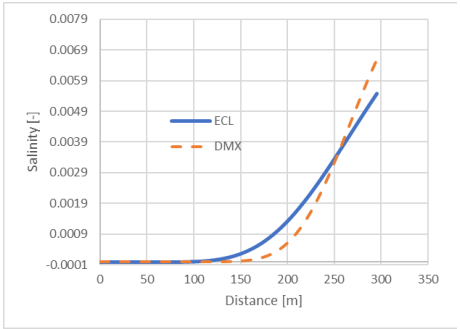
BENCHMARK (DUMU^X)

- Issues to set up an OPM case
  - Two-phase specifying gas-water capillary pressure seems not possible
  - Table SGWFN not working
  - PVTWSALT interpolation

- For now brine tracking compared with ECLIPSE
  - Comparison not good (yet)
  - Difference in PVT properties (Cw)




```
--
-- GAS-WATER RELATIVE PERMEABILITY TABLES (SGWFN)
SGWFN
-- SG KRG KRW PCGW
-- FRAC        PSIA
-- -------- -------- ------- -------
```



PERMEABILITY REDUCTION

- Porosity change is directly related to the change of the (volume) saturation s_s:

$$\varphi = (1 - s_s)\varphi_0$$

- The associated permeability reduction will be calculated using a correlation such as:

Kozeny-Carman (extended)

$$k/k_0 = \left(\frac{\varphi - \varphi_c}{\varphi_0 - \varphi_c}\right)^a \left(\frac{1 - \varphi_0 + \varphi_c}{1 - \varphi + \varphi_c}\right)^b$$

Verma-Pruess

$$\frac{k}{k_0} = \max\left(\frac{1}{(1-\varphi_r)^2}\left(\frac{\varphi}{\varphi_0} - \varphi_r\right)^2, 0\right)$$

Power law

$$\frac{k}{k_0} = \left(\frac{\varphi}{\varphi_0}\right)^\gamma$$

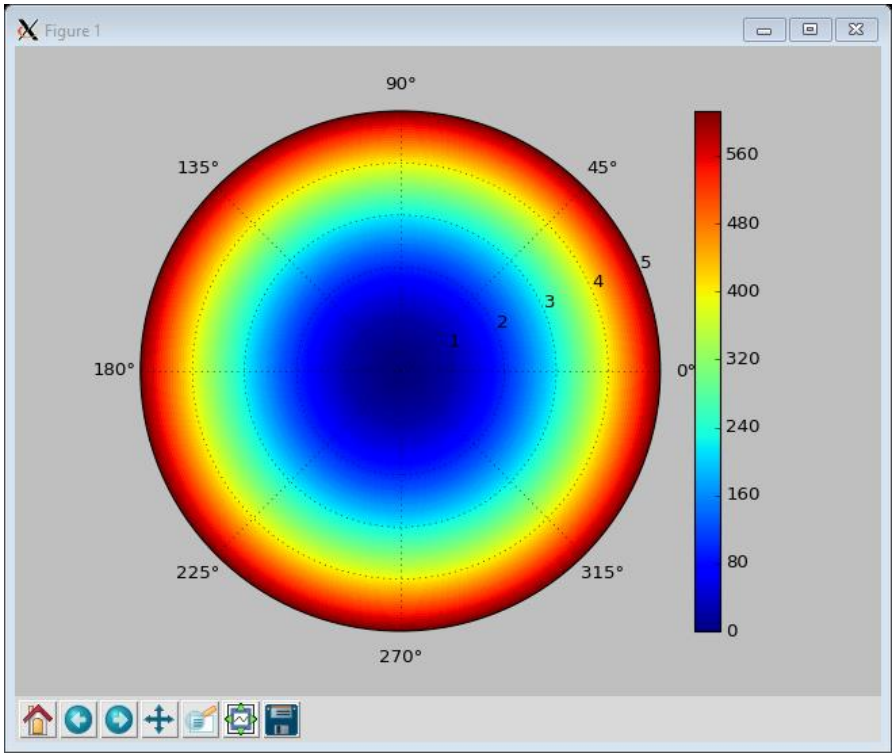
$$k = m_k(\varphi)k_0$$

```
--
-- PERMEABILITY REDUCTION TABLE FOR SALT PRECIPITATION
-- FOR A POROSITY OF REFERENCE
--
PERMRED
--   PHI        M
-- ------ ---------                                  ...
    0          0
    PHI1       M1
    ...
    PHIREF     1
    ...
    PHIMAX     MMAX
```

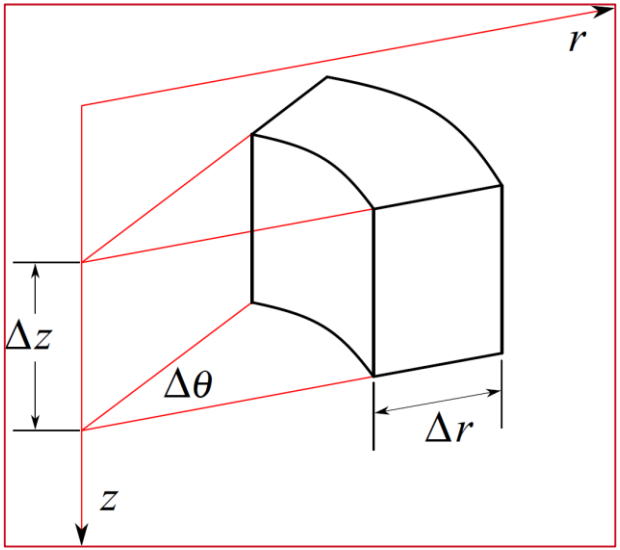
RADIAL GRID

- Motivation:
  - Capture near wellbore effects
  - Local grid refinement

- Keywords:
  - RADIAL
  - COORDSYS
    - COMP/INCOMP
  - INRAD
  - DRV
  - DTHETAV
  - PERMR
  - PERMTHT



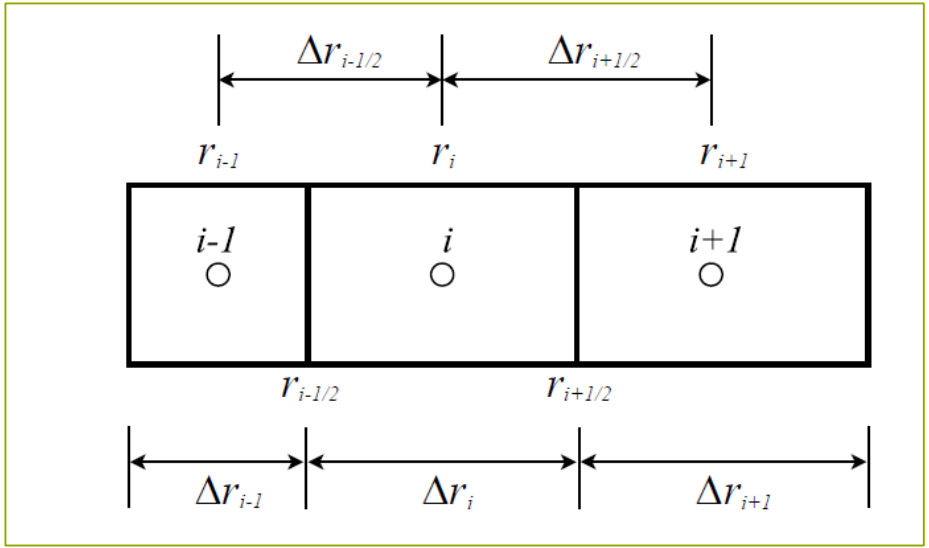
RADIAL DISCRETIZATION



Gridblock volume

$$V_{b_{i,j,k}} = \frac{(r^2_{i+\frac{1}{2},j,k} - r^2_{i-\frac{1}{2},j,k})\Delta\theta_{i,j,k}\Delta z_{i,j,k}}{2}$$

Logarithmic Spacing



$$r_{i+\frac{1}{2},j,k} = \frac{r_{i+1,j,k} - r_{i,j,k}}{\ln\left(\frac{r_{i+1,j,k}}{r_{i,j,k}}\right)}, \qquad r_{i-\frac{1}{2},j,k} = \frac{r_{i,j,k} - r_{i-1,j,k}}{\ln\left(\frac{r_{i,j,k}}{r_{i-1,j,k}}\right)}$$

RADIAL TRANSMISSIBILITIES

$$R_{\alpha,i} = \frac{\phi_{ref,i} V_i}{\Delta t}(A_{\alpha,i} - A^0_{\alpha,i}) + \sum_{j \in C(i)} u_{\alpha,ij} + q_{\alpha,i} = 0$$

$$T_{r_{i\pm\frac{1}{2},j,k}} = \frac{r_{i\pm\frac{1}{2},j,k} k_{r_{i\pm\frac{1}{2},j,k}} \Delta\theta_{i,j,k} \Delta z_{i,j,k}}{\Delta r_{i\pm\frac{1}{2},j,k}} \left(k_r \frac{b}{\mu}\right)_{i\pm\frac{1}{2},j,k}$$

$$T_{\theta_{i,j\pm\frac{1}{2},k}} = \frac{k_{\theta_{i,j\pm\frac{1}{2},k}} \ln\left(\frac{r_{i+\frac{1}{2},j,k}}{r_{i-\frac{1}{2},j,k}}\right) \Delta z_{i,j,k}}{\Delta\theta_{i,j\pm\frac{1}{2},k}} \left(k_r \frac{b}{\mu}\right)_{i,j\pm\frac{1}{2},k}$$

$$T_{z_{i,j,k\pm\frac{1}{2}}} = \frac{(r^2_{i+\frac{1}{2},j,k} - r^2_{i-\frac{1}{2},j,k}) k_{z_{i,j,k\pm\frac{1}{2}}} \Delta\theta_{i,j,k}}{2\Delta z_{i,j,k\pm\frac{1}{2}}} \left(k_r \frac{b}{\mu}\right)_{i,j,k\pm\frac{1}{2}}$$

PERMEABILITIES IN RADIAL DIRECTION

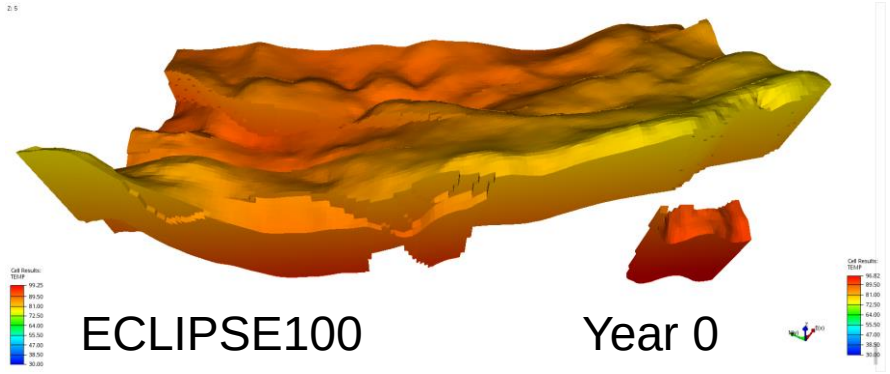
$$k_{r_{i+\frac{1}{2},j,k}} = \frac{k_{i,j,k}\, k_{i+1,j,k} \ln\left(\frac{r_{i+1,j,k}}{r_{i,j,k}}\right)}{k_{i,j,k} \ln\left(\frac{r_{i+1,j,k}}{r_{i+\frac{1}{2},j,k}}\right) + k_{i+1,j,k} \ln\left(\frac{r_{i+\frac{1}{2},j,k}}{r_{i,j,k}}\right)}$$

$$k_{r_{i-\frac{1}{2},j,k}} = \frac{k_{i-1,j,k}\, k_{i,j,k} \ln\left(\frac{r_{i,j,k}}{r_{i-1,j,k}}\right)}{k_{i-1,j,k} \ln\left(\frac{r_{i,j,k}}{r_{i-\frac{1}{2},j,k}}\right) + k_{i,j,k} \ln\left(\frac{r_{i-\frac{1}{2},j,k}}{r_{i-1,j,k}}\right)}$$

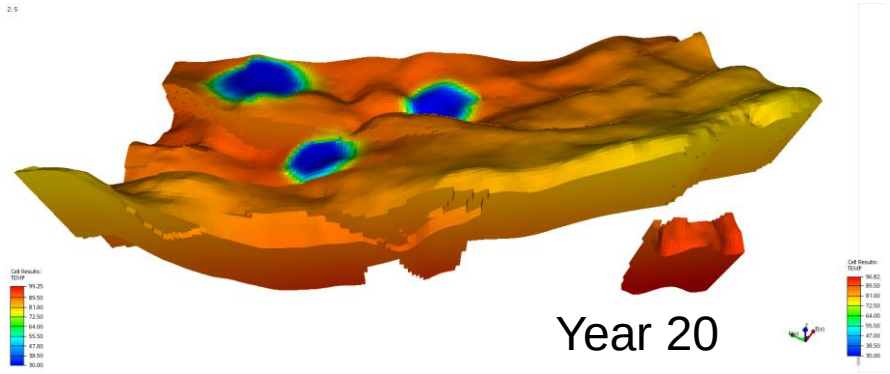
GEOTHERMAL ENERGY

- Needed in short term
  - Working viscosity and density dependency in temperature (fix convergence issues)
  - Well temperature output
- Long term
  - DUALPORO/DUALPERM (Eclipse)
  - MINC (popular in Geothermal, TOUGH2)

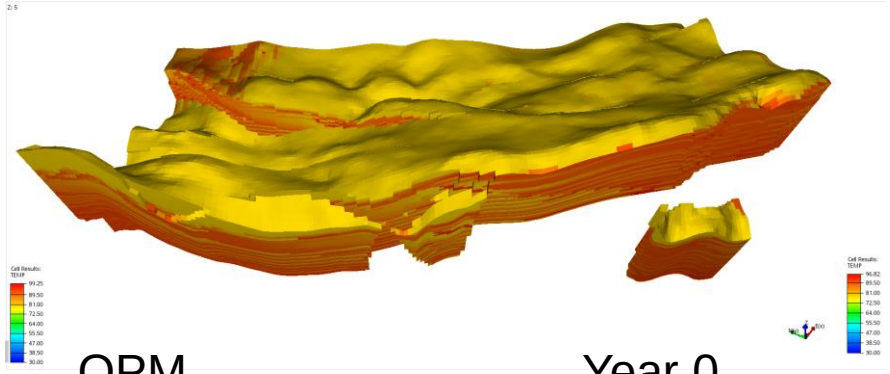
OPM TEMPERATURE INITIALIZATION



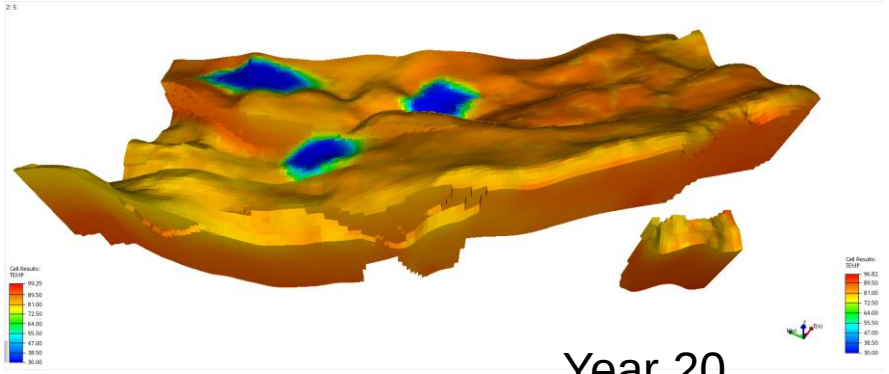
ECLIPSE100 Year 0



Year 20



OPM Year 0



Year 20

PERFORMANCE OF A SINGLE RUN

- OPM Flow 23.10.2019; 30 years run

Model and active cells	ECLIPSE		OPM	OPM with amg and tunning	
	NO VISC	VISC		NO VISC	VISC
NO_TEMP 500 000	1m 40s		7h 30m	26min	
TEMP 400 000	x	7m 45s	x	1h 30m	8h
TEMP 500 000	2m 50s	7m 40s	x	7h	14h
TEMP 1 000 000	x	14m 15s	x	12h	70h

WELLBORE PRODUCED HEAT

To calculate the heat produced (H) over all n well connections:

$$H = \sum_{j=1}^{j=n} q_{w,j} \times \rho_j \times T_j \times C_w \times \Delta t$$

$q_{w,j}$	flow rate per connection [m3/d]
C_w	Heat capacity [kJ/kg/K]
ρ	density [kg/m3]
T	temperature [K]
Δt	time period [d]

(All units in METRIC)

The average temperature T can then be calculated as:

$$\bar{T} = \frac{H}{Q \times \rho \times C_w \times \Delta t}$$

If we assume that heat capacity and density are constant, this reverts to the connection flow averaged temperature.


THANK YOU FOR YOUR ATTENTION
Take a look:
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TNO innovation for life