TNO innovation for life

SALT PRECIPITATION AND WATER EVAPORATION MODELLING IN OPM

OPM SUMMIT – 30-31 AUGUST 2022

› PAUL EGBERTS & CÍNTIA GONÇALVES MACHADO

CONTENTS

- Problem: Salt precipitation in (condensate) gas reservoirs
- Black-oil model extensions in OPM-Flow for
  - Water evaporation
  - Salt precipitation/dissolution
- Implementation aspects
- Overview new keywords
- Test cases
- Wrap up and next steps

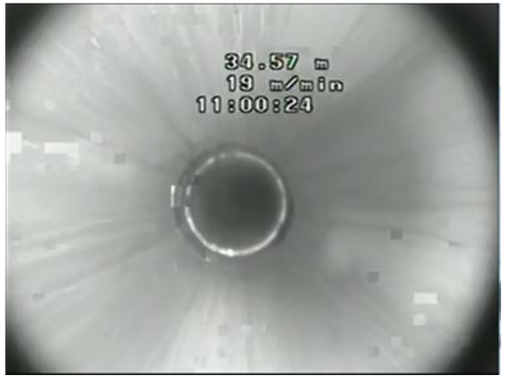
SALT PRECIPITATION PROBLEM

- Salt precipitation in gas reservoirs can be a huge issue for operators
  - Clogging results in severe production decline
  - Clogging may happen on time scale of days
- Precipitation occurs near the wellbore
  - Accumulation in wellbore
  - Soaking with small amounts of fresh water restores production

- TNO has a long history of projects with Dutch gas operators
  - Numerical tools: Tough2 and Dumu^x
- Recent project with Equinor to enable salt precipitation modelling in OPM

Before washing

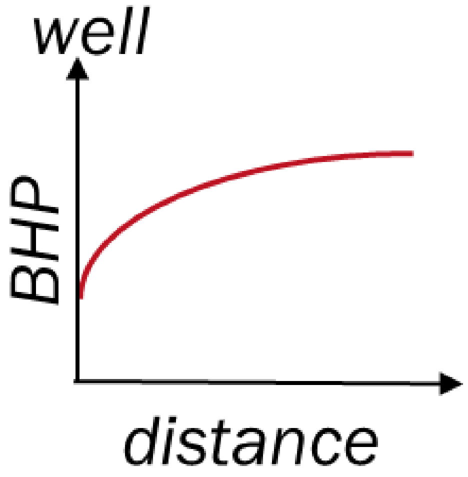
After washing

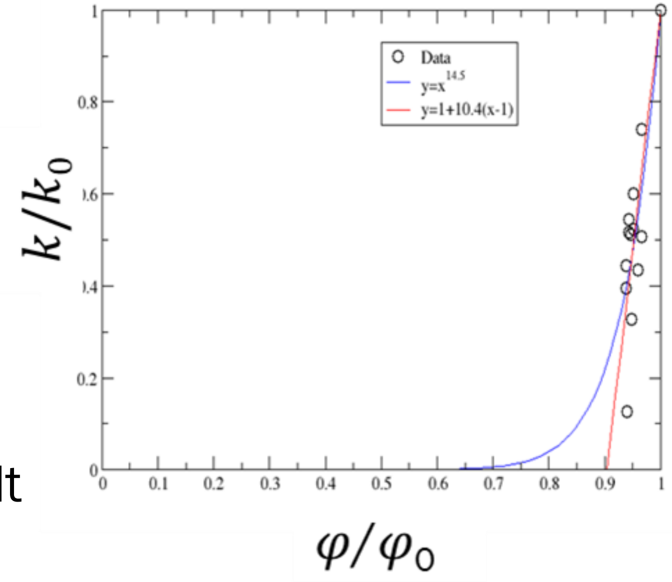


TNO innovation for life

SALT PRECIPITATION MECHANISM

- Gas can contain more water vapor at lower pressures
- Evaporation of brine largest near well (largest pressure decline)
- Evaporation results in increase of salt concentration in brine
- Salt precipitates when solubility limit is reached
- Transport of brine is a source of salt => accumulation of precipitated salt
- Salt precipitation reduces porosity and permeability and eventually clogs pores





TNO innovation for life

IMPLEMENTATION TASKS

Extend OPM-Flow physics to allow for

- Water evaporation into gas phase
- PVT for
  - dry and humid (water vapor) gas
  - combined wet (oil vapor) and humid (water vapor) gas
- Salt precipitation (& dissolution)
- Porosity and permeability reduction

BLACK-OIL MODEL
EXTENDED 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: $$\frac{\partial}{\partial t}\left[\varphi_0 m_\varphi\left(b_g s_g + r_{go} b_o\, s_o\right)\right] + \nabla\cdot\left(b_g v_g + \ r_{go} b_o v_o\right) + q_g = 0$$

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

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

- Requires extension of variable swithing logic and PVT methods for gas

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

BRINE MODULE
EXTENDED WITH SALT PRECIPITATION

Salt transport Eq.: $$\frac{\partial \varphi_0 m_\varphi (b_w s_w c_w^{salt} + s_s \rho^{salt})}{\partial t} + \nabla \cdot \left(c_w^{salt} b_w v_w\right) + c_w^{salt} q_w = 0$$

with

- ρ^{salt}: Density of solid salt [kg/m^3]
- s_s: (volume) saturation of precipitated salt, assumed to be immobile
- c_w^{salt}: Salt concentration in water [kg/Sm3].

- Brine + salt precipitation:
  - Mass split of dissolved and precipitated salt
  - Mobility change due to precipitation (precipitated salt affects absolute permeability)
  - Primary variable switching

IMPLEMENTATION ASPECTS
PRIMARY VARIABLE SWITCHING

- Extension of primary variable switching logic
  - Salt precipitation: c_w^{salt} <-> s_s

  - If c_w^{salt} exceeds solubility limit s_s becomes primary variable

  - If $s_s < 0$ then c_w^{salt} becomes the primary variable

- Water evaporation increases primary variable
  - combinations and
  - switching options

Sw_po_Sg (3-phase)	-> Rvw_po_Sg, Sw_pg_Rv, Rvw_pg_Rv, Sw_po_Rs
Sw_pg_Rv (water-gas)	-> Rvw_pg_Rv, Sw_po_Sg, Rvw_po_Sg
Rvw_po_Sg (gas-oil)	-> Sw_po_Sg, Rvw_pg_Rv,
Rvw_pg_Rv (gas)	-> Sw_pg_Rv, Rvw_po_Sg
Sw_po_Rs (water-oil)	->Sw_po_Sg

R_{vw}: water-gas ratio

IMPLEMENTATION ASPECTS
PVT TABLES

- New PVTGW table for dry & humid gas

  $$B_g = B_g(p, R_{VW})$$

  $$\mu_g = \mu_g(p, R_{VW})$$

  R_{VW}: water gas ratio r_{wg}

  - Analogue to PVTG table for wet gas

```
--
--       GAS PVT TABLE FOR DRY GAS WITH VAPORIZED WATER (OPM FLOW KEYWORD)
--
PVTGW
--       PRES      RW          BG           VISC
--       PSIA      STB/MSCF    RB/MSCF      CPOISE
--       ------    ---------   -------      ------
          300      0.000479     0.042340    0.01344
                   0            0.042310    0.01389      /
          600      0.000469     0.020460    0.01420
                   0            0.020430    0.01450      /
          900      0.000403     0.013280    0.01526
                   0            0.013250    0.01532      /
         1200      0.000354     0.009770    0.01660
                   0            0.009730    0.01634      /
         1500      0.000272     0.007730    0.01818
                   0            0.007690    0.01752      /
         1800      0.000225     0.006426    0.01994
                   0            0.006405    0.01883      /
         2100      0.000191     0.005541    0.02181
                   0            0.005553    0.02021      /
         2400      0.000163     0.004919    0.02370
                   0            0.004952    0.02163      /
                                                         / TABLE NO. 1
```

- PVT for wet & humid gas described by using two tables
  - PVTGW: $B_g = B_g(p, R_V^{sat}, R_{VW})$, similar for μ_g
  - PVTG: $B_g = B_g(p, R_V, R_{VW}^{sat})$, similar for μ_g

INPUT DECK AND DOCUMENTATION (1/2)
KEYWORDS FOR WATER EVAPORATION AND SALT PRECIPITATION

- RUNSPEC:
  - VAPWAT: Activate water vaporization
  - BRINE: Activate salt transport equation
  - PRECSALT: Activate salt precipitation
- SOLUTION:
  - SALTVD, SALT: Initial salt concentration in water
  - SALTPVD, SALTP: Initial salt deposition in the porous medium
  - RVW: Initial water-gas vapor
- SCHEDULE:
  - WSALT: Defines the salt concentration in water injectors

NEW
EXISTING

INPUT DECK AND USER DOCUMENTATION (2/2)
KEYWORDS FOR WATER EVAPORATION AND SALT PRECIPITATION

- PROPS
  - SALTSOL: Solubility limit
  - PERMFACT: Defines the permeability multiplier as function of porosity
  - PVTWSALT: Defines PVT data for brine
  - PVTGW: PVT tables for dry & humid gas
  - PVTGW & PVTG: PVT tables for wet & humid gas
  - RWGSALT: Define water vaporization in gas as function of pressure and salt conc. (*)
- OUTPUTS
  - FSIP, RVW, SALTP, PERMFACT

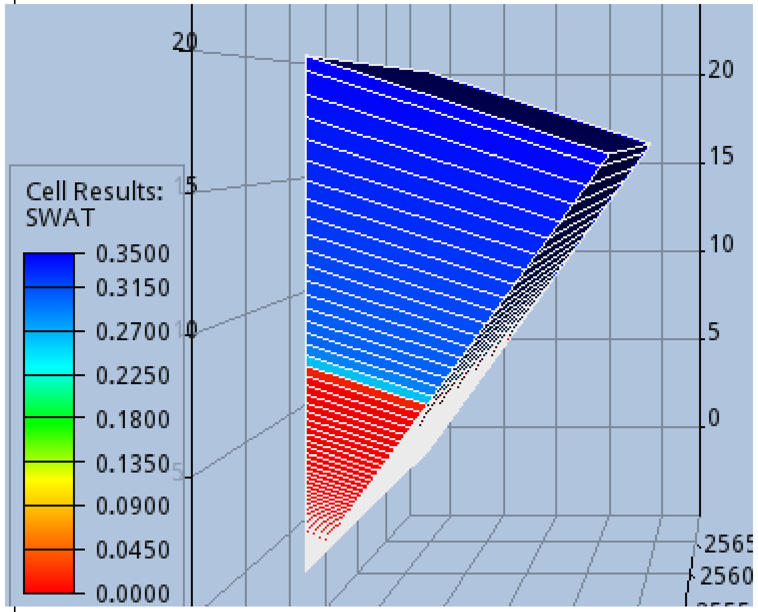
NEW
EXISTING

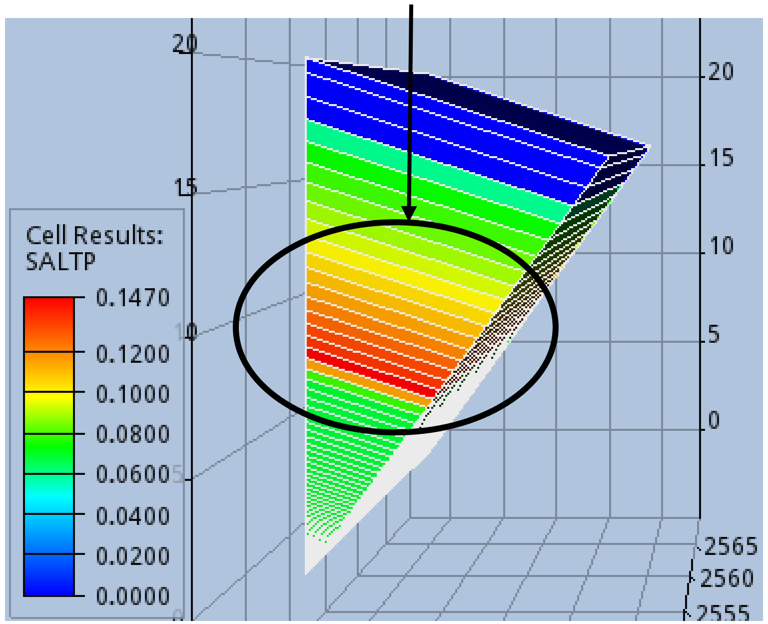
(*) not yet implemented

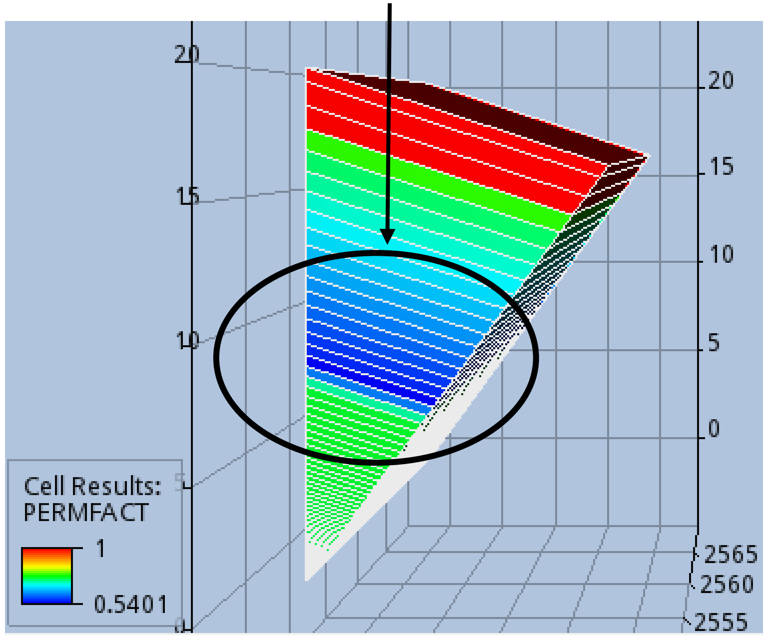
EXAMPLE GAS - WATER SYSTEM
TEST RUN

- Accumulation of salt precipitation at certain distance
  - This behaviour seen in previous work with DuMu^X (SPE-189541)
- Opm-flow takes small times steps

Accumulation of salt *Local permeability reduction*





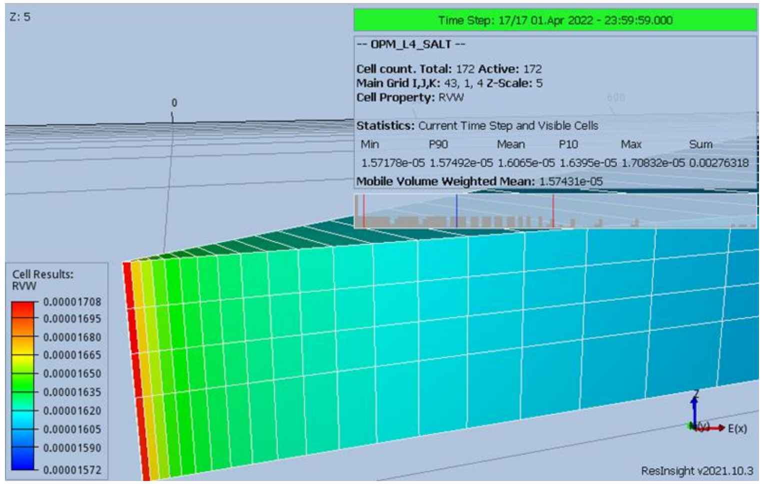


Water Evaporation -> Salt Precipitation -> Permeability Reduction

4-LAYER GAS-CONDENSATE MODEL
TEST RUN (1/3)

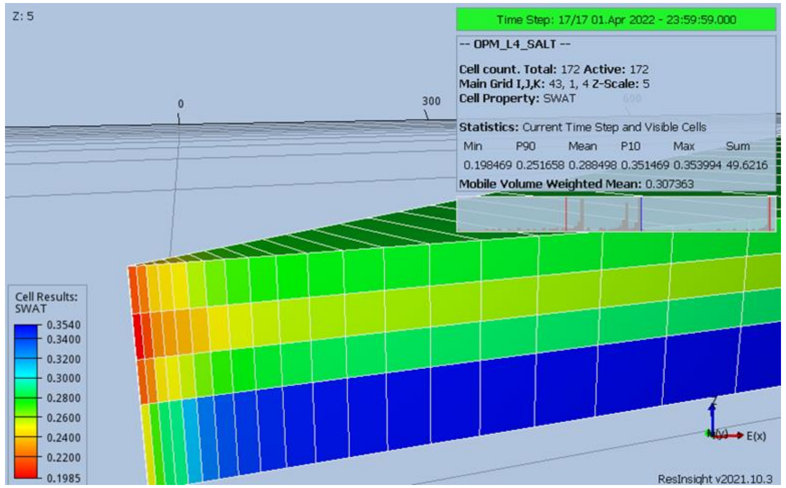
- Snapshots after 9 months of simulation
- Premature ending (convergence issues) of the simulation when permeability is reduced to nearly zero values

Water-gas ratio (r_{wg})



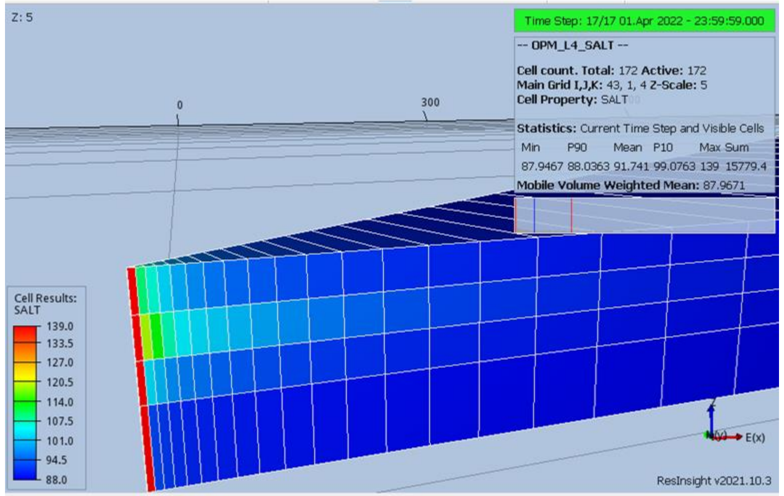
Near the well the water-gas ratio is higher as gas can contain more water vapor for lower pressure

Water saturation (s_w)



Near the well lower water saturation because of water evaporation

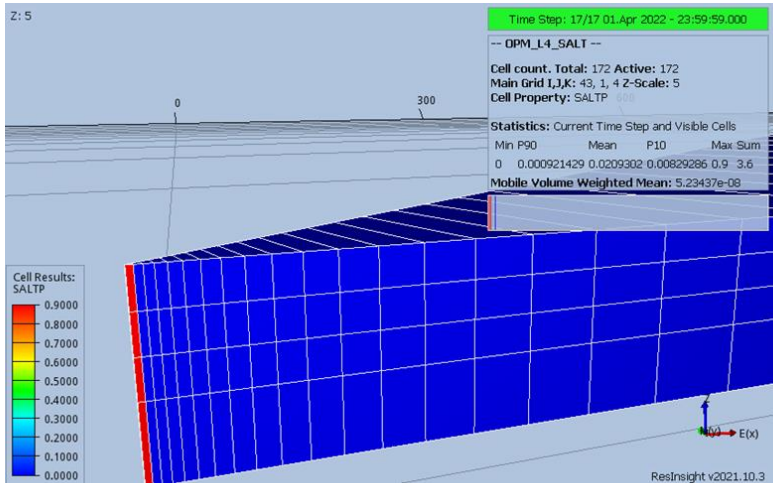
Salt concentration (c_w^{salt})



Due to the water evaporation near the well the salt concentration increases. In the well gridblock it has reached its solubility limit (139 kg/m3)

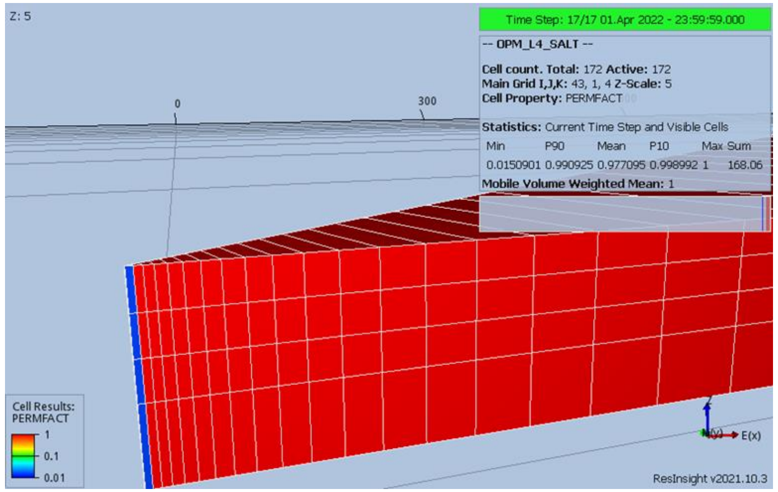
4-LAYER GAS-CONDENSATE MODEL
TEST RUN (2/3)

Precipitated salt saturation (s_s)



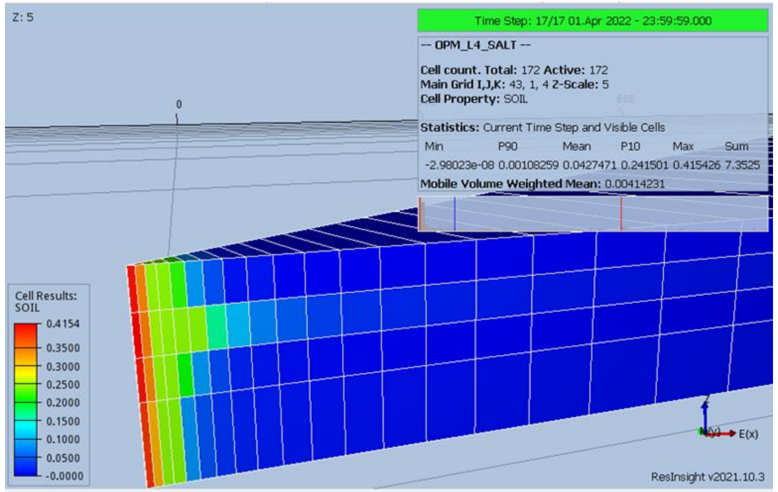
Because in the well gridblock the concentration has reached the solubility limit precipitation takes place

Permeability reduction factor (k/k_0)



Permeability has reduced significantly in the well blocks due to porosity reduction caused by the salt precipitation

Oil saturation (s_o)

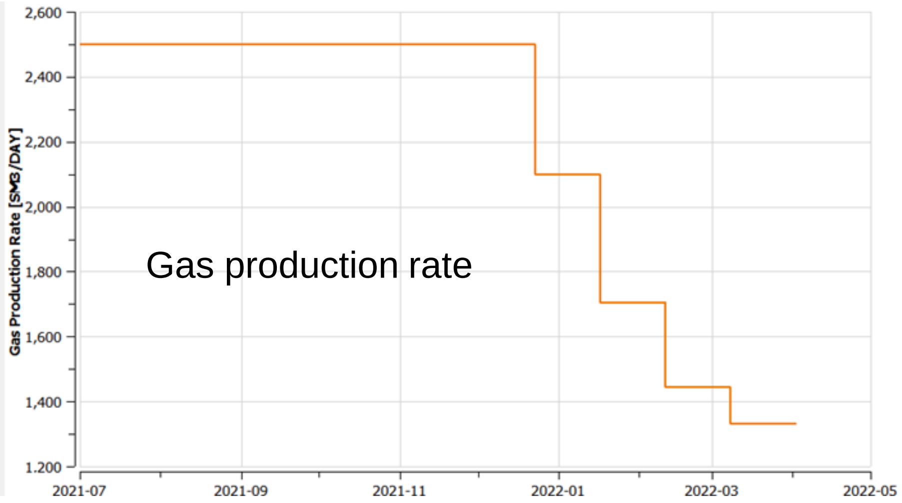


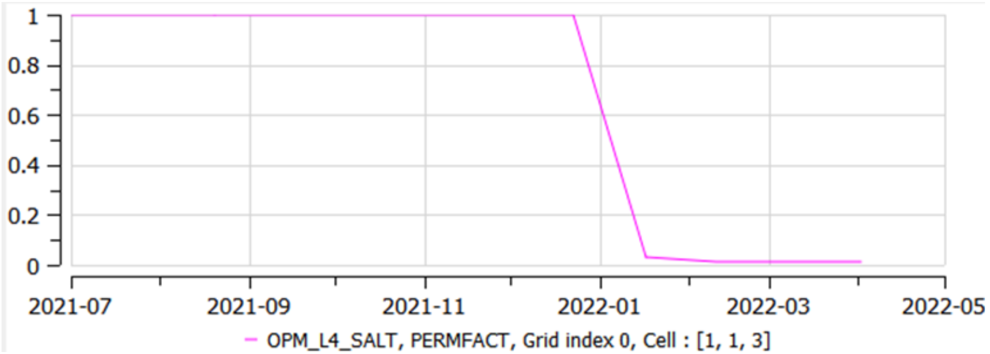
Gas condensation near the well

TNO innovation for life

4-LAYER GAS-CONDENSATE MODEL
TEST RUN (3/3)

- Well runs on gas rate constraint up to moment of precipitation
- The rapid decline in permeability causes the well to run on its BHP constraint of 90 bar afterwards





Permeability reduction factor in well block [1,1,3].

SUMMARY

- Extending black-oil equation to allow for water evaporation into the gas phase. Water evaporation is allowed to take place together with oil vaporization in gas which is essential for modelling salt precipitation occurring in gas condensate reservoirs.
- Extending the salt transport equation to allow for salt precipitation and dissolution.
- Added PVT methods for dry & humid gas and for wet & humid gas. (wet & humid gas is gas that may contain both vaporized oil and vaporized water)
- New input Keywords and tables
- New grid output (for precipitated salt, evaporated water and permeability reduction) that can be visualized with ResInsight.
- All code will be part of the next release (OPM-Flow version 2022-10). The current release (OPM-Flow version 2022-04) contains the water evaporation and salt precipitation for gas-water system.
- Documentation of all input keywords/tables in OPM-Flow Reference Manual (v. 2022-04)
- Salt precipitation and water evaporation modelling is not present in Eclipse (E100) simulator

NEXT STEPS

- Investigate and resolve convergence issues
- Initialization using EQUIL (work in progress PRs)
- RWGSALT table: Define water vaporization in gas as function of pressure and salt concencentration

THANK YOU!

TNO innovation for life