

**IMPERIAL COLLEGE LONDON**

**Department of Earth Science and Engineering**

**Centre for Petroleum Studies**

**Streamline Simulation to Improve Polymer Enhanced Oil Recovery  
for a Mature Oil Field in Austria**

**By**

**Maximilian Busch**

**A report submitted in partial fulfilment of the requirements for  
the MSc and/or the DIC.**

**September 2012**

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**DECLARATION OF OWN WORK**

I declare that this thesis

**Streamline Simulation to Improve Polymer Enhanced Oil Recovery for a Mature Oil Field in Austria**

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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## Abstract

As an increasing number of oil fields mature, active waterflood management and enhanced-oil-recovery (EOR) technologies like polymer flooding will become more important. We show that streamline (SL) simulation is a powerful tool to improve the performance of mature oil reservoirs by making it possible to analyze and assess well patterns for improved waterflood and polymer-flood management.

We show that with the aid of SL simulation, it was possible to improve rate management in both the waterflood and the polymer flood for a mature oil field in Austria. The recovery factor could thus be increased by 2.5 percentage points over a preliminary waterflood strategy with constant well injection rates, which represents a 54% increase of future cumulative oil production over the next 25 years or 1.4 million stb of incremental oil recovery. 0.4 million stb of the incremental oil recovery could be achieved by improving the preliminary waterflood strategy through a dynamic reallocation of the given water field injection rate between the individual wells. The other 1 million stb of incremental oil could be achieved by a polymer-flood strategy in which the focus also was on dynamically reallocating the given water field injection rate between the individual wells. The fieldwide utility factor (UF) of the polymer-flood project was only 1.7 kg of polymer/incremental stb of oil (over the improved waterflood).

For the polymer flood, we introduced a new methodology where we did not optimize polymer concentration and slug size, which are typically considered as the two key design parameters in polymer-flood projects, on a per-pattern basis. Rather, we optimized individual well rates in polymer-flood strategies in which the same concentration and slug size were used for all patterns. Our methodology was based on the pattern-level injection efficiency (IE) metric, which was introduced by Thiele and Batycky (2006) as the volume of offset oil produced per unit of water/polymer injected. Our methodology did not incorporate the economically more meaningful pattern-level UF metric, however, which was defined by Clemens et al. (2011) as the amount of polymer injected per incremental volume of offset oil produced.

Hence, to improve the reservoir performance of the Austrian oil field even further and refine existing methodologies for polymer flooding, it is suggested that a SL-based workflow for improved polymer-flood management be developed that incorporates both the IE and UF metrics and optimizes both individual well rates, and polymer concentration and slug size on a per-pattern basis.

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# Streamline Simulation to Improve Polymer Enhanced Oil Recovery for a Mature Oil Field in Austria

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## Abstract

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We show that with the aid of SL simulation, it was possible to improve rate management in both the waterflood and the polymer flood for a mature oil field in Austria. The recovery factor could thus be increased by 2.5 percentage points over a preliminary waterflood strategy with constant well injection rates, which represents a 54% increase of future cumulative oil production over the next 25 years or 1.4 million stb of incremental oil recovery. 0.4 million stb of the incremental oil recovery could be achieved by improving the preliminary waterflood strategy through a dynamic reallocation of the given water field injection rate between the individual wells. The other 1 million stb of incremental oil could be achieved by a polymer-flood strategy in which the focus also was on dynamically reallocating the given water field injection rate between the individual wells. The fieldwide utility factor (UF) of the polymer-flood project was only 1.7 kg of polymer/incremental stb of oil (over the improved waterflood).

For the polymer flood, we introduced a new methodology where we did not optimize polymer concentration and slug size, which are typically considered as the two key design parameters in polymer-flood projects, on a per-pattern basis. Rather, we optimized individual well rates in polymer-flood strategies in which the same concentration and slug size were used for all patterns. Our methodology was based on the pattern-level injection efficiency (IE) metric, which was introduced by Thiele and Batycky (2006) as the volume of offset oil produced per unit of water/polymer injected. Our methodology did not incorporate the economically more meaningful pattern-level UF metric, however, which was defined by Clemens et al. (2011) as the amount of polymer injected per incremental volume of offset oil produced.

Hence, to improve the reservoir performance of the Austrian oil field even further and refine existing methodologies for polymer flooding, it is suggested that a SL-based workflow for improved polymer-flood management be developed that incorporates both the IE and UF metrics and optimizes both individual well rates, and polymer concentration and slug size on a per-pattern basis.

## Introduction

The Hochleiten field is a mature oil reservoir in Austria that has been in production since 1977. Waterflooding began in 1991. It is a shaly sandstone reservoir with several faults. The oil originally in place (OOIP) was 53 million stb. Because the Hochleiten field is geologically complex, it has not been in the center of OMV's redevelopment plans in the past years. The well-level history match of the simulation model has recently been improved, however, by OMV's E&P Team with the aid of new chloride value measurements, which made it possible to identify flow barriers. In the history matching process, major manipulations were done on the geological model. OMV intend to redirect their focus on the Hochleiten field because of its low current recovery factor of 19% and its high unrecovered potential according to a Buckley-Leverett analysis. An updated waterflood with constant injection rates has recently been tested as a preliminary redevelopment strategy over the next 25 years by OMV's E&P Team. That preliminary strategy would increase the recovery factor from a no-further-action (NFA) forecast by 3 percentage points.

The objective of this paper is to increase the recovery factor of the Hochleiten field even further using SL simulation. To meet the objective, two SL-based steps were carried out. First, OMV's preliminary waterflood strategy was improved by a dynamic reallocation of well injection rates according to the IE metric for a waterflood, where the field injection rate was kept unchanged from the preliminary waterflood strategy. It was possible to increase the recovery factor by 0.7 percentage points

through the improved, more active waterflood management. In the second step, several polymer-injection strategies were tested because the reservoir conditions of a medium oil viscosity, low brine salinity and a mild reservoir temperature seemed favorable to a polymer flood. A polymer-flood strategy could be found that increased the recovery factor by an additional 1.8 percentage points over the improved, more active waterflood at a tolerable fieldwide UF of 1.7 kg/incremental stb. Hence, the SL-based work described in this paper made it possible to increase the recovery factor from OMV's preliminary redevelopment strategy by 2.5 percentage points, which represents a 54% increase of future cumulative oil production over the next 25 years or 1.4 million stb of incremental oil recovery.

Not only did this work find a redevelopment strategy to increase the recovery factor of OMV's Hochleiten field, but it provides a new methodology for improved polymer-flood strategies focusing on active rate management. Both steps carried out in this work, the more active waterflood management and the polymer-flood strategy, are meant to reduce water cycling and increase sweep efficiency for mature oil fields. In the case of the more active waterflood management, that is achieved by a dynamic reallocation of well injection rates. In the case of the polymer-flood strategy, a higher sweep efficiency is achieved by reducing the mobility ratio between the injected water and the resident oil by increasing the viscosity of the injected water through mixing it with water-soluble polymer. The two key design parameters typically considered in polymer-flood projects are polymer concentration and slug size. In the work described in this paper, it became evident that well injection rates can be another crucial design parameter in polymer-flood projects. Based on that observation, the new methodology for improved polymer-flood management is focused on a dynamic reallocation of well injection rates, like in pure waterflooding, according to the IE metric, and is not meant to optimize polymer concentration and slug size on a per-pattern basis. SL simulation is essential for such active rate management because of its ability to analyze individual well patterns and thus obtain the IE metric on a pattern-basis.

### Literature Review

Since Batycky et al. (1997) introduced a comprehensive SL-based reservoir simulator applicable to 3D field-scale flow and discussed the advantages of decoupling a 3D transport problem into multiple 1D problems, a considerable amount of literature has been published on SL-based metrics and workflows. Grinestaff (1999) suggested quantifying injector to producer relationships for a waterflood by using the SL-based concept of dynamic injector-centered patterns, which came to be at the foundation of many SL-based well-by-well metrics and workflows. Thiele and Batycky (2006) established the SL-derived IE metric and based a per-pattern workflow for improved waterflooding through active rate management on it, which is implemented by the floodOPT software tool that was used in the work of this paper. Thiele et al. (2010a) discussed the dual-grid approach of SL simulations in the case of polymer flooding and showed that SL simulation can be efficiently used to model a polymer flood. Clemens et al. (2011) established the SL-derived UF metric and built a per-pattern workflow for improved polymer-flood management on it, which uses an improved waterflood through optimized rate management (as in Thiele and Batycky 2006) as a benchmark against which to assess the polymer flood.

A SL-based workflow has not yet been discussed in the petroleum literature, however, that aims to incorporate optimized rate management (as in Thiele and Batycky 2006) in improved polymer-flood management. Polymer concentration and slug size are treated as the key design parameters in polymer flooding. That injection and production rates are a third key parameter in designing polymer-flood projects is not only intuitive because the injected polymer exclusively resides in the injected water, but will also become evident by the results described in this paper.

### Modern Streamline Simulation

SL simulation has become a powerful complementary tool to conventional finite difference (FD) simulation. (Thiele and Batycky 2006) In SL simulation, the reservoir fluids are transported along SLs rather than across cells. SL simulation involves a dual-grid approach. The traditional ("static") grid contains all the geological and petrophysical data, well locations and rates and initial conditions, and it is used to solve for the spatial pressure distributions in the reservoir by using an implicit pressure explicit saturation (IMPES) formulation. The dynamic grid, which is represented by the SLs and thus updated at every timestep, is used to solve for the spatial and temporal transport of the fluids in the reservoir. (Batycky et al. 1997)

Hence, SL simulation transforms a 3D transport problem into multiple (independent) 1D problems that can be solved more efficiently. SL simulation can be aptly framed using the concept of the overall displacement efficiency  $E$ , which is:

$$E = E_D \times E_V \dots\dots\dots (1)$$

where  $E_D$  is the local displacement efficiency and  $E_V$  is the volumetric displacement efficiency. In modern SL simulation it is no longer required to further separate the volumetric displacement efficiency  $E_V$  into an areal and a vertical component because modern SLs span the reservoir in 3D. Thus, the volumetric displacement efficiency can be fully captured by the geometry of the SLs. The local displacement efficiency is entirely decoupled from the volumetric displacement efficiency and represented by the transport equation physics along the SLs (Clemens et al. 2011). As discussed in Thiele et al. (2010a), the transport of water along a SL is parameterized in terms of the time of flight (TOF)  $\tau$  and is expressed as:

$$\frac{\partial S_W}{\partial t} + \frac{\partial f_W}{\partial \tau} = 0; \quad f_W = \frac{\lambda_W}{\lambda_W + \lambda_O}; \quad \lambda_i = \frac{k_{ri}}{\mu_i} \dots\dots\dots (2)$$

where  $S_W$  is the water saturation;  $f_W$  is the water fractional flow;  $\lambda_i$  is the mobility of phase  $i$ , where  $w$  is water and  $o$  is oil;  $k_{ri}$  is the relative permeability of phase  $i$ ; and  $\mu_i$  is the viscosity of phase  $i$ . Analogously, the transport of polymer dissolved in the water along a SL is expressed as:

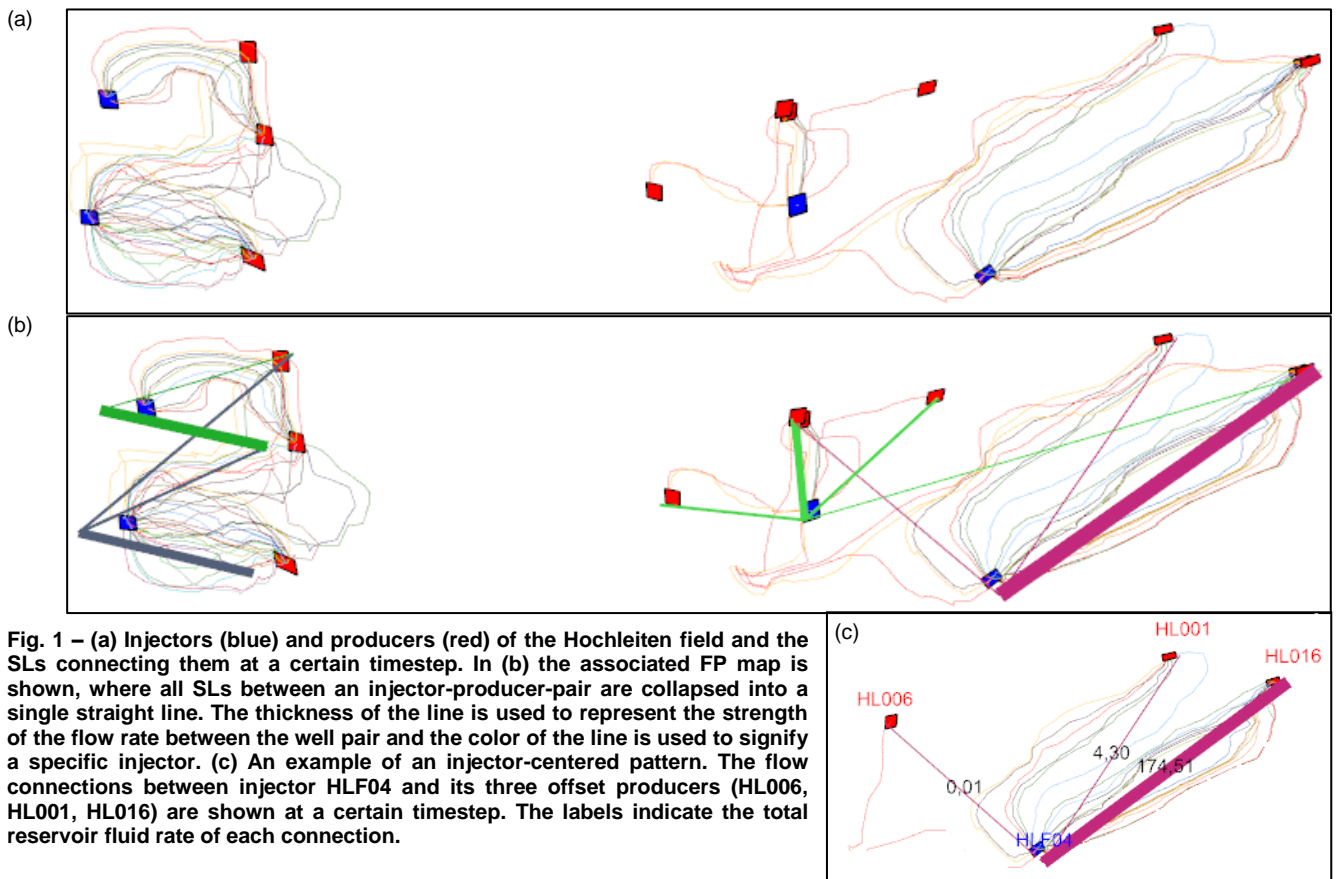


$$\frac{\partial}{\partial t}(S_w C_p) + \frac{\partial}{\partial \tau}(f_w C_p) = 0 \quad \dots\dots\dots (3)$$

where  $C_p$  is the concentration of the polymer p in the aqueous phase. The extension of the polymer transport equation to incorporate adsorption and an approach to model the polymer shear-rate dependence are discussed in Thiele et al. (2010a). Because, as will be explained later,  $\mu_w$  is a function of  $C_p$ , equations 2 and 3 are interlinked. The numerical solution of that system of equations is beyond the scope of this paper.

There are two major benefits of SL over FD simulation. SL simulation is more computationally efficient because larger timesteps can be taken because due to the dual-grid approach, there is no global grid Courant-Friedrichs-Lewy constraint. (Batycky et al. 1997) The faster speed of SL simulation proved essential throughout the workflow of this paper to perform all the simulations within a reasonable amount of time. The other major benefit of SL simulation is its unique ability to quantify (and visualize) the reservoir flow rates between injectors and producers at every timestep. The flow rates between the wells, or well allocation factors (WAFs), are directly derived from SLs and thus reflect all the data that affect the behavior of the dynamic grid, including porosity, permeability and pressure distributions, relative permeabilities, fault structure and historical well rates. (Thiele and Batycky 2006) Based on this crucial SL-feature to obtain WAFs, an injector-centered pattern can be defined as an injector and its offset producers. The concept of injector-centered patterns is very powerful and at the foundation of the work described in this paper.

Flux-pattern (FP) maps schematically depict the SL-derived WAFs used for pattern performance plots and concepts, such as the IE and the UF. (Thiele and Batycky 2006) **Fig. 1** shows the SLs and FP map of the Hochleiten field and gives an example of an injector-centered pattern.



## Reservoir Characterization and Production History

The Hochleiten oil field is north of Vienna along the Hochleiten-Pirawarth fault system. It covers an area of about 2.5 km<sup>2</sup> and extends in a southwest/northeast direction. There are several sealing and non-sealing faults, which could not be accurately resolved by seismic data. The reservoir is Sarmation sandstone and is interbedded with shale layers. Three of the shale layers are thick, sealing barriers that divide the field into four reservoirs. The fluid contact levels vary across the field because of the sealing shale layers and faults.

The oil density is 913kg/m<sup>3</sup> and the oil viscosity is 39.2cp. The formation water viscosity is 0.69cp and its salinity is 16,500ppm. The reservoir temperature is 36°C and the initial pressure was 92bar.

The history match was difficult from the geological model. The fault structure and permeabilities were substantially manipulated in the simulation grid to match the observed rate, pressure and chloride value behavior on a well-by-well basis to a reasonable degree of satisfaction. It is unlikely that the current geological model can be improved because of scarce log data

for initial wells and the complex structure of the reservoir.

OOIP is 53 million stb. Oil production started in 1977 and waterflooding began in 1991. There are 45 wells, 30 producers and 4 injectors are currently active. The current oil rate of the field is 600stb/day at a watercut of 90%. 10 million stb of oil and 21.5 million stb of water have been produced until today. 12 million stb of water have been injected, which is 19% of pore volume. Hence, the voidage replacement ratio (VRR) is 38% and the current recovery factor is only 19%. The NFA recovery factor forecast is 20.5%. A preliminary redevelopment strategy done by OMV's E&P Team with updated constant water injection rates for all four injectors yielded a recovery factor forecast of 23.5%. According to a Buckley-Leverett analysis the maximum technical recovery factor is 42% under a perfect sweep efficiency, which suggests that further reservoir management options should be explored.

### Improved Waterflood

As suggested in Clemens et al. (2011), to accurately assess the benefit of polymer injection it is reasonable to look at the incremental oil production over an improved waterflood. Hence, the first step was to improve the waterflood, which could then be used as a benchmark against which to evaluate different polymer-flood strategies. It is shown in this section that the waterflood from OMV's preliminary redevelopment strategy with the constant injection rates could be substantially improved by dynamically reallocating the given water field injection rate between the individual injectors.

**Methodology.** The SL-based workflow established by Thiele and Batycky (2006) was used to improve the waterflood from OMV's preliminary redevelopment strategy. floodOPT is a software tool to implement that workflow for improved waterflood management, either by increasing oil production at a given water field injection rate or by maintaining oil production at a lower amount of injected water. The way how floodOPT improves the waterflood is by varying injection and production rates for individual wells over time; rate ranges and BHP constraints can be chosen for each well to take into account operational constraints. In dynamically varying well injection and production rates, floodOPT uses the SL-based concept of the IE for a waterflood, which for each injector-centered pattern/well-pair connection is defined as:

$$\text{IE (waterflood)} = \frac{\text{offset oil production}}{\text{water injection}} \dots\dots\dots (4)$$

If IE (waterflood) is expressed as an instantaneous ratio of rates, it is a metric to assess the efficiency with which water is injected at a given time; if IE (waterflood) is expressed as a ratio of cumulative volumes, it shows the average efficiency with which water is injected over a given time period. The water injection is known and the offset oil production can be calculated by the SL-derived WAFs, so floodOPT can obtain IE (waterflood) for each injector-centered pattern/well-pair connection at every timestep. This SL-based approach to obtain dynamic IEs (waterflood) for every pattern/well pair allows the reservoir engineer to improve the waterflood by dynamically reallocating injection water from less to more efficient patterns/well pairs and thus increasing the volumetric displacement efficiency.

**Fig. 2, Table 1, and Table 2** illustrate how floodOPT works in more detail. Fig. 2 depicts the FP map of the Hochleiten field at two consecutive timesteps with a 6-months interval, Table 1 shows the associated IE values for the first of the two timesteps, and Table 2 compares the well injection rates for the two timesteps. It can be seen from Table 1 that at the first of the two timesteps, the pattern with injector HL033 has a higher IE (waterflood) than patterns HL019 and HLF04 (4% compared to 2%). It can also be seen that for the pattern with injector HL019, the connections to producers HL020 and HL027 are more efficient than the connections to producers HL007 and HL045 (5% compared to 1% and 2%), and for the pattern with injector HLF04 the connection to producer HL016 is more efficient than the connection to producer HL001 (6% compared to 2%). Hence, as can be seen from Table 2, at the subsequent timestep, part of the injected water into injectors HL019 and HLF04 is reallocated to injector HL033, while the field injection water rate is maintained. Furthermore, a greater proportion of the injected water into HL019 travels toward producers HL020 and HL027 and a greater proportion of the injected water into HLF04 travels toward producer HL016. For the pattern with injector HLF04, for instance, that is achieved by increasing the production (target) rate of producer HL016 and decreasing the one of producer HL001, so that producer HL016 “pulls” a greater proportion of the “pushing” water injected into HLF04 than in the first timestep. (Thiele and Batycky 2006)

For the case of the Hochleiten field it was not planned to maintain current oil production with a more efficient use of injection water because there is no shortage of injection water supply, rather it was planned to increase oil production at the current water field injection rate of 3,300stb/d. Operational constraints were set at a maximum production rate of 1,000stb/d and a maximum injection rate of 3,150stb/d for individual wells and the BHP constraints were set to be 10bar for producers and 100bar for injectors. As already stated, a reasonable well-level history match has recently been achieved by OMV's E&P team. This makes the per-pattern analyses performed throughout the work described in this paper practicably meaningful for reservoir management purposes because it affords reasonable confidence that the simulation model is representative of the field.

**Results.** Fig. 3 shows the pattern performance plot for the four injector-centered patterns of the Hochleiten field for both the waterflood with the constant injection rates of OMV's preliminary redevelopment strategy and for the waterflood with the dynamic rates obtained from floodOPT. In the waterflood with the constant injection rates, the pattern with injector HL031 is the least efficient pattern. It has the lowest instantaneous IEs (waterflood) in the beginning of the forecast (i.e. the slope of its pattern performance curve is the smallest for low cumulative amounts of injected water) and its instantaneous IEs (waterflood)

quickly converge to negligibly small numbers. That means that pattern HL031 has the lowest average IE (waterflood) (i.e. the slope to the endpoint of its pattern performance curve is the smallest). The pattern with injector HL033, on the other hand, is the most efficient pattern in the waterflood with the constant injection rates, with its average IE (waterflood) approximately 6 (=180/30) times higher than the average IE (waterflood) for the pattern with injector HL031. In the floodOPT-based waterflood, in which the given field injection rate is reallocated according to the IE (waterflood) metric, the least efficient injector HL031 is shut and the amount of injection water used for injector HL031 in the waterflood with the constant rates (approximately 5.5 million stb) is reallocated to the most efficient pattern HL033.

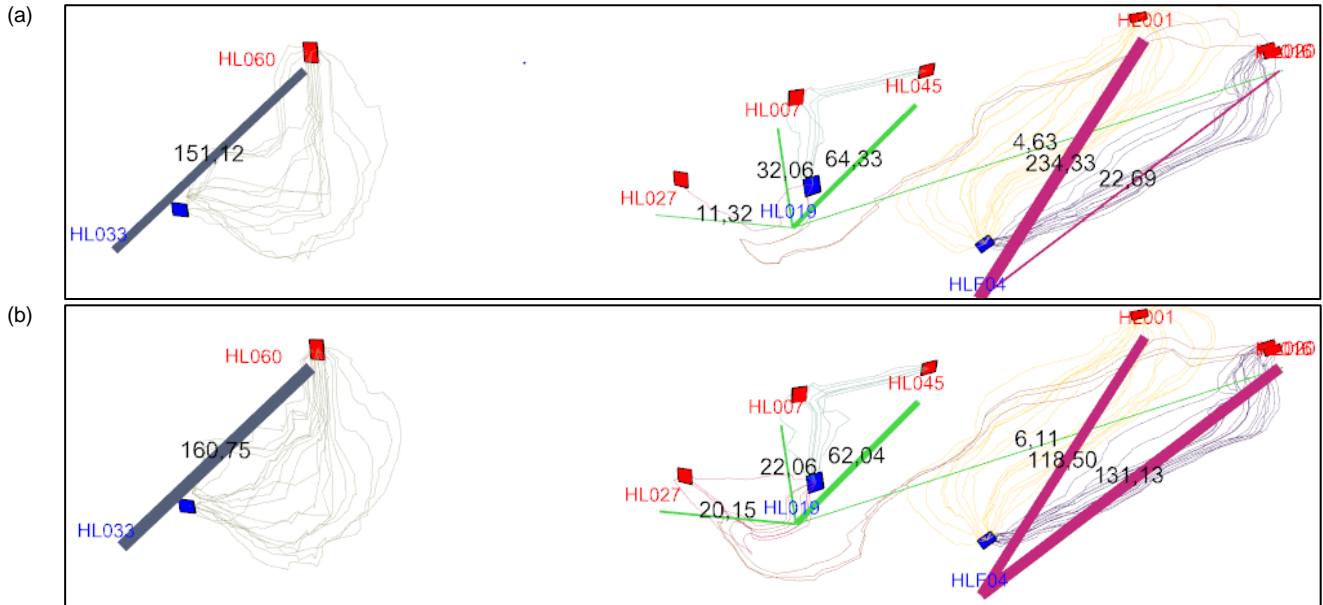


Fig. 2 (a) and (b) – FP map of the Hochleiten field at two consecutive timesteps with a 6-months interval. Injectors (blue) and producers (red) and the flux connections between them, represented by the straight lines, are shown. The color of the line signifies the injector from which the flux originates and the label indicates the injected water rate of the well-pair connection. [Note: It was not possible to remove the blur about the two producers in the top right of (a) and (b). The flux from injector HL019 (green line) leads to producer HL020 and the flux from injector HLF04 (pink line) leads to producer HL016.] Since it is not possible with the software used to show the IE (waterflood) value for the well-pair connection as a label on the FP map, the IE (waterflood) values for each connection and for the three injector-centered patterns are shown in Table 1 for the first of the two timesteps. Given the IE (waterflood) values shown in Table 1, the injected water rate of flow connections HL033-HL060, HL019-HL020, HL019-HL027, and HLF04-HL016 is increased in the subsequent timestep (b) at the expense of the injected water rate of the other well-pair connections. Those changes in the well-pair fluxes are shown in Table 2.

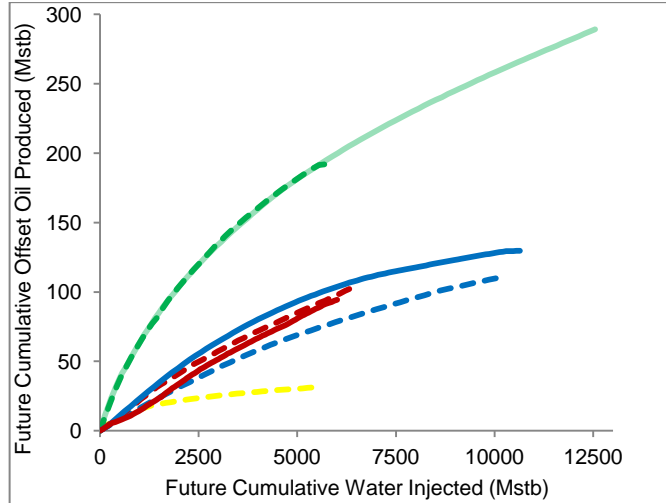
**TABLE 1 – WAF DATA USED TO CALCULATE IE (WATERFLOOD) FOR EACH WELL-PAIR CONNECTION AND INJECTOR-CENTERED PATTERN OF THE FPmap FOR THE FIRST OF THE TWO TIMESTEPS [Fig. 2(a)]**

Injector	HL033	HL019					HLF04		
Offset producer	HL060	HL007	HL020	HL027	HL045	All offset producers	HL001	HL016	All offset producers
Rate of water injected ( $\text{rm}^3/\text{d}$ )	151.1	32.1	4.6	11.3	64.3	112.3	234.3	22.7	257.0
Rate of offset oil produced ( $\text{rm}^3/\text{d}$ )	6.6	0.4	0.2	0.5	1.1	2.2	3.9	1.4	5.3
IE (well-pair connection, %)	4.3	1.3	5.1	4.6	1.7		1.7	6.0	
IE (injector-centered pattern, %)	4.3					2.0			2.0

**TABLE 2 – INJECTION RATES FOR EACH WELL-PAIR CONNECTION AND INJECTOR-CENTERED PATTERN FOR THE TWO CONSECUTIVE TIMESTEPS [Fig. 2(a) and (b)]**

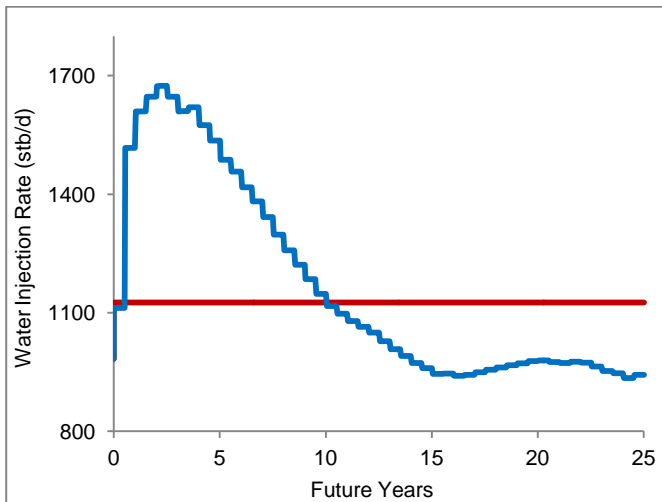
Injector	HL033	HL019					HLF04			All injectors, i.e. field
Offset producer	HL060	HL007	HL020	HL027	HL045	All offset producers	HL001	HL016	All offset producers	
1 <sup>st</sup> timestep: Rate of water injected ( $\text{rm}^3/\text{d}$ )	151.1	32.1	4.6	11.3	64.3	112.3	234.3	22.7	257.0	520.5
2 <sup>nd</sup> timestep: Rate of water injected ( $\text{rm}^3/\text{d}$ )	160.8	22.1	6.1	20.2	62.0	110.4	118.5	131.1	249.6	520.8

Another interesting result from Fig. 3 is that by dynamically varying the injection rate of injector HLF04, it is possible to increase the average IE (waterflood) of pattern HLF04 without significantly increasing the cumulative amount of injected water in HLF04 (i.e. the endpoint of the blue solid line is above but not significantly to the right of the endpoint of the blue dotted

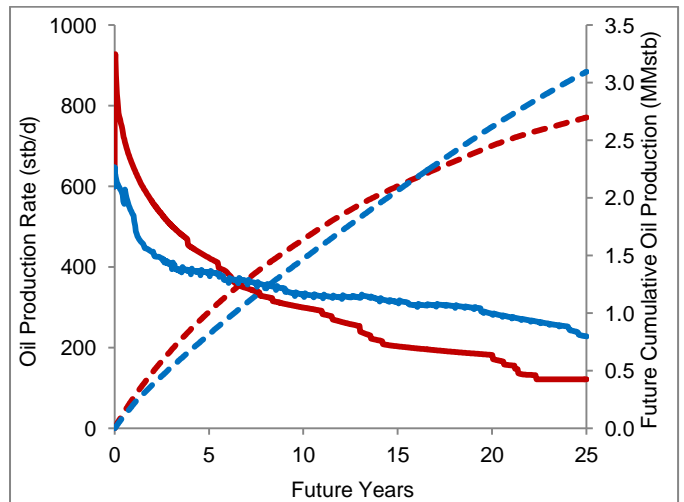


**Fig. 3 - Pattern performance plot for the four injector-centered patterns of the Hochleiten field.** The dotted lines show the pattern performance curves for the waterflood with the constant injection rates of OMV's preliminary redevelopment strategy and the solid lines show the waterflood with the dynamic rates obtained from floodOPT. Pattern performance curves for injector HL031 are yellow, for injector HLF04 they are blue, for injector HL019 they are red, and for injector HL033 they are green. For every pattern, the offset oil production is plotted against the amount of injected water. Thus, the pattern performance plot visualizes the IE (waterflood) of individual patterns. The slope of a pattern performance curve indicates the instantaneous IE (waterflood) of a pattern at a given point of time (represented by the cumulative water injection until that point, shown on the x-axis). The slope of the pattern performance curves decreases over time because IE (waterflood) necessarily decreases as the waterflood matures and water cycling issues arise. The slope to the endpoint of a pattern performance curve indicates the average IE (waterflood) of a pattern over the 25-years forecast period.

found to be economical, which made a good case for going one step further in the hierarchy of reservoir development strategies and testing whether polymer flooding could improve the performance of the Hochleiten field.



**Fig. 4 - Water injection rate for injector HLF04 over the 25-years forecast for both the waterflood with the constant injection rates of OMV's preliminary redevelopment strategy (red) and for the waterflood with the dynamic injection rates obtained from floodOPT (blue).**



**Fig. 5 - Oil production rate (solid lines) and cumulative oil production (dotted lines) for the Hochleiten field over the 25-years forecast for both the waterflood with the constant injection rates of OMV's preliminary redevelopment strategy (red) and for the waterflood with the dynamic injection rates obtained from floodOPT (blue).**

### Polymer-Flood Design

Polymer flooding is one of the most mature EOR technologies. (AISofi and Blunt 2010) The Daqing oil field in China is the most prominent example that polymer flooding can lead to a substantial increase in oil recovery under favorable conditions. In

line). **Fig. 4** shows that the way how injector HLF04 is made more efficient over the 25-years forecast is by increasing the water injection rate relative to the constant injection rate of 1,130stb/d from OMV's preliminary waterflood strategy over the first half of the forecast period and decreasing it over the second half.

**Fig. 5** shows that the preliminary waterflood with the constant injection rates done by OMV's E&P team yielded a future cumulative oil production of 2.7 million stb for the 25-years forecast. Using floodOPT to allocate the current water field injection rate of 3,300stb/d more efficiently between the injectors, it was possible to increase the future cumulative oil production for the 25-years forecast from 2.7 million stb to 3.1 million stb. Hence, a more active waterflood management made it possible to increase the future cumulative oil production from waterflooding by 15% or 0.4 million stb, which represents 0.7% of OOIP. The drawback of dynamically reallocating the water field injection rate with floodOPT is that the incremental cumulative oil production of 0.4 million stb does not fully materialize in net present value (NPV) terms because in the first 6 years the oil production rate is higher for OMV's preliminary waterflood strategy with the constant injection rates. That observation does not significantly reduce the advantage of the dynamic reallocation strategy based on floodOPT, however, because at the point of time where the project is carried out discount rates should not be set high because opportunity costs are low in the present macroeconomic environment.

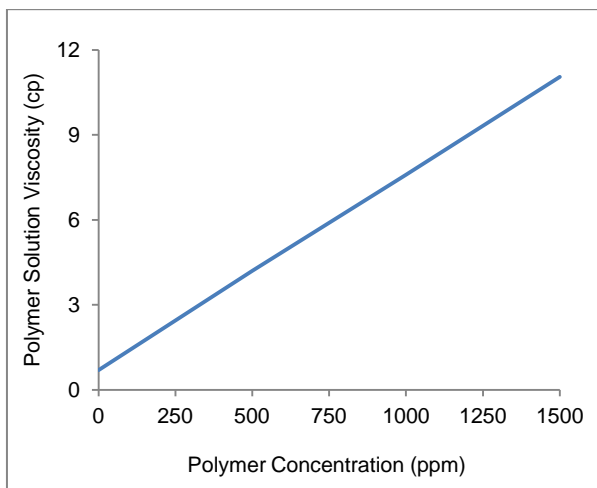
A higher water field injection rate and various locations for additional wells were tested. Neither a greater amount of injected water nor infill drilling was

Daqing the incremental oil recovery of a polymer flood over a waterflood is 10% of OOIP. (Yupu et al. 2006) Apart from a medium oil viscosity, favorable conditions for polymer flooding are low brine salinity and a mild reservoir temperature, both of which make polymer degradation less likely. Hence, the Hochleiten field is a good polymer-flood candidate with its oil viscosity of 39.2cp, its brine salinity of 16,500ppm and its reservoir temperature of 36°C.

The main rationale behind polymer flooding is to increase the viscosity of the injected water to decrease the mobility ratio between the displacing water and the displaced oil. This results in a better sweep efficiency and thus a higher oil recovery (within a forecast period that is not unreasonably long). The following five physical phenomena are important in a polymer-flood design (Thiele et al. 2010a):

1. Water viscosity as an increasing function of polymer concentration.
2. Polymer adsorption on the rock, which removes polymer from the flowing fluid and slows down the advancement of the polymer front.
3. Polymer shear-rate dependence: the polymer commonly used in practice is shear-thinning, which means that the effect of polymer concentration on water viscosity decreases with an increasing injection rate.
4. Inaccessible pore volume (IPV): a fraction of the pore volume is inaccessible to the polymer because of the size of polymer molecules.
5. Residual resistance factor (RRF): the relative rock permeability to water is reduced through polymer adsorption.

All of the above physical phenomena except the polymer shear-rate dependence were incorporated in the field-scale model. AlSofi and Blunt (2010) demonstrated that the shear-thinning behavior of the polymers commonly used in practice impairs the sweep and oil recovery in polymer-flood projects; non-Newtonian polymer rheology was not considered in the field-scale simulation, however, because no shear-rate data for the different reservoir rock classes were available. The rheology of the polymer solution obtained from laboratory experiments is shown in **Fig. 6**. Due to injectivity concerns, fractures with a half length of 45m were made on the simulation model around the wells where polymer was injected.



**Fig. 6 – Rheology of the polymer solution. The viscosity of the pure water is 0.7cp. The higher the polymer concentration of the solution, the higher its viscosity.**

Polymer concentration and slug size are typically considered as the two key design parameters in a polymer flood. For the case of the Hochleiten field, the polymer concentrations tested were 500, 1,000 and 1,500ppm, which increased the pure water viscosity of 0.7cp to solution viscosities of 4.2, 7.6 and 11cp, thereby decreasing the endpoint mobility ratio from 28 to 4.7, 2.6 and 1.8. The slug sizes tested were 3, 5, 7 and 10 years, which represented 6%, 10%, 14%, and 19% of pore volume. Polymer injection was begun at the same date at the outset of the forecast for each pattern in every simulation and polymer injection was made continuous with no pure water injection in between; the polymer slug was succeeded by pure waterflooding until the end of the 25-years forecast in each case. It will be shown in this paper that injection rates can be a third essential parameter in designing a polymer flood.

While for a waterflood, IE is defined as the offset oil production per unit of injected water, for polymer injection IE can be defined as the offset oil production per unit of injected polymer (this definition was implicitly used, though not explicitly stated in Clemens et al. 2011):

$$IE (\text{polymer injection}) = \frac{\text{offset oil production (stb)}}{\text{mass of polymer injected (kg)}} \quad (5)$$

The major cost driver in polymer-flood projects is not capital expenditure (CAPEX) but operating costs (OPEX) because expenditure for polymer mixing and other required facilities is considerably less than the costs for the required amount of injected polymer. Since OPEX is crucial in polymer flooding, care should be taken not to overdesign slug concentration and slug size in pursuit of maximizing oil recovery. For that reason Clemens et al. (2011) established the concept of the UF, which denotes the average mass of polymer injected per incremental stb of offset oil produced in a polymer-flood project:

$$UF = \frac{\text{mass of polymer injected (kg)}}{\text{incremental offset oil production (stb)}} \quad (6)$$

The UF is a useful metric for polymer-flood designs to indicate the incremental operating costs per incremental unit of revenue. The UF concept is similar to IE. The UF is essentially an efficiency metric. However, as opposed to the IE, which simply considers oil production, the UF takes into account the incremental oil production relative to a base case (i.e. the oil production from the base case is subtracted from the oil production of the polymer-flood project). Since only the incremental oil production is economically meaningful, the UF is an economically more useful efficiency metric for polymer-flood designs than IE.

Because it had a better performance than OMV's preliminary waterflood with the constant injection rates, the floodOPT-driven waterflood in which the current water field injection rate was dynamically reallocated between the injectors was used as a base case to calculate the incremental oil from polymer flooding.



Two different methodologies for finding an economical polymer-flood strategy are discussed in the subsequent sections of this paper. In the first methodology, the constant injection rates of OMV's preliminary waterflood strategy were retained, which made it possible to do a per-pattern analysis of polymer-injection strategies because patterns did not change significantly over the forecast period. The second methodology is new. floodOPT was used for the different polymer-flood strategies, which essentially introduced injection and production rates as a third control parameter in designing polymer floods, besides polymer concentration and slug size. That second methodology did not allow for a per-pattern analysis because patterns changed over time due to the dynamic rate behavior. It will be shown that only with the second approach, where injection rates were dynamically varied, was it possible to find polymer-injection strategies that performed better than the base-case floodOPT-driven pure waterflood. It was not possible to find a polymer-injection strategy with the constant injection rates that was economical relative to the floodOPT-driven pure waterflood with the dynamic injection rates.

### Pattern-Level Polymer-Flood Strategies with Constant Injection Rates

**Methodology.** The SL-based workflow used in this section of the paper to design a polymer flood was established by Clemens et al. (2011). It is a promising workflow aimed to improve polymer injection on a per-pattern basis, which for the Romanian field to which it was applied in the paper of Clemens et al. led to an increase in the recovery factor of 5.3 percentage points at a fieldwide UF of 2 kg/incremental stb. The workflow is based on the ability of SL simulation to obtain WAFs and analyze well patterns, which was illustrated in Fig. 1. The UF metric can thus be individually applied to each pattern to assess its economically meaningful efficiency, which is different from conventional FD simulation, where pattern analysis is not possible and the UF can only be obtained for the entire field. Hence, the purpose of the SL-based workflow is to carry out economically efficient polymer-flood designs in a much more granular fashion than with FD simulation.

It should be emphasized that the workflow is not a mathematically rigorous but an intuitive engineering approach because it does not formally minimize the UF and/or maximize incremental oil recovery. The workflow rather provides the engineer with guidelines that relate to individual well patterns and are thus readily actionable. Since the workflow is not based on a mathematical and thus universal foundation but is meant to be a practicable engineering approach, it is important to apply it to another than the Romanian field to which it was originally applied to get a better idea of the scope of its usefulness and possible limits. It will be shown that in the case of the Hochleiten field, the granular per-pattern workflow yielded fieldwide results that were only insignificantly better than the results from crude field-level approaches.

The five steps of the workflow are:

1. The current waterflood is improved to serve as a benchmark against which to assess the economic benefit of polymer injection. This step was already discussed.
2. A single crude field-level polymer SL simulation is performed using the same slug concentration and slug size for all injectors. The outcome of that simulation is used to identify poor patterns using a pattern performance plot. Patterns that perform below a certain IE (polymer injection) threshold are not used for polymer injection but kept on a simple waterflood.
3. Sensitivity analyses of the remaining patterns are performed by varying the polymer injection control parameters of slug size and concentration. Owing to the speed of SL simulation, it is possible to test a considerable number of polymer concentration/slug size combinations for each pattern within a reasonable amount of time. The incremental cumulative oil recovery and UF are recorded for each polymer concentration/slug size combination for each pattern.
4. A maximum UF value that is decided to be economically acceptable under the prevalent price relationship of polymer and oil is used as a constraint to choose the polymer concentration/slug size combination yielding the highest amount of incremental oil recovery for each pattern. Thus, an optimal polymer concentration/slug size strategy can be obtained for each injection pattern under a predetermined UF constraint.
5. A field-scale simulation is performed with the optimal polymer concentration/slug size strategy for each pattern to obtain the incremental oil recovery for the entire field at the predetermined UF. Since the system contained in the workflow is nonlinear, several iterations of Steps 2 through 5 might be needed.

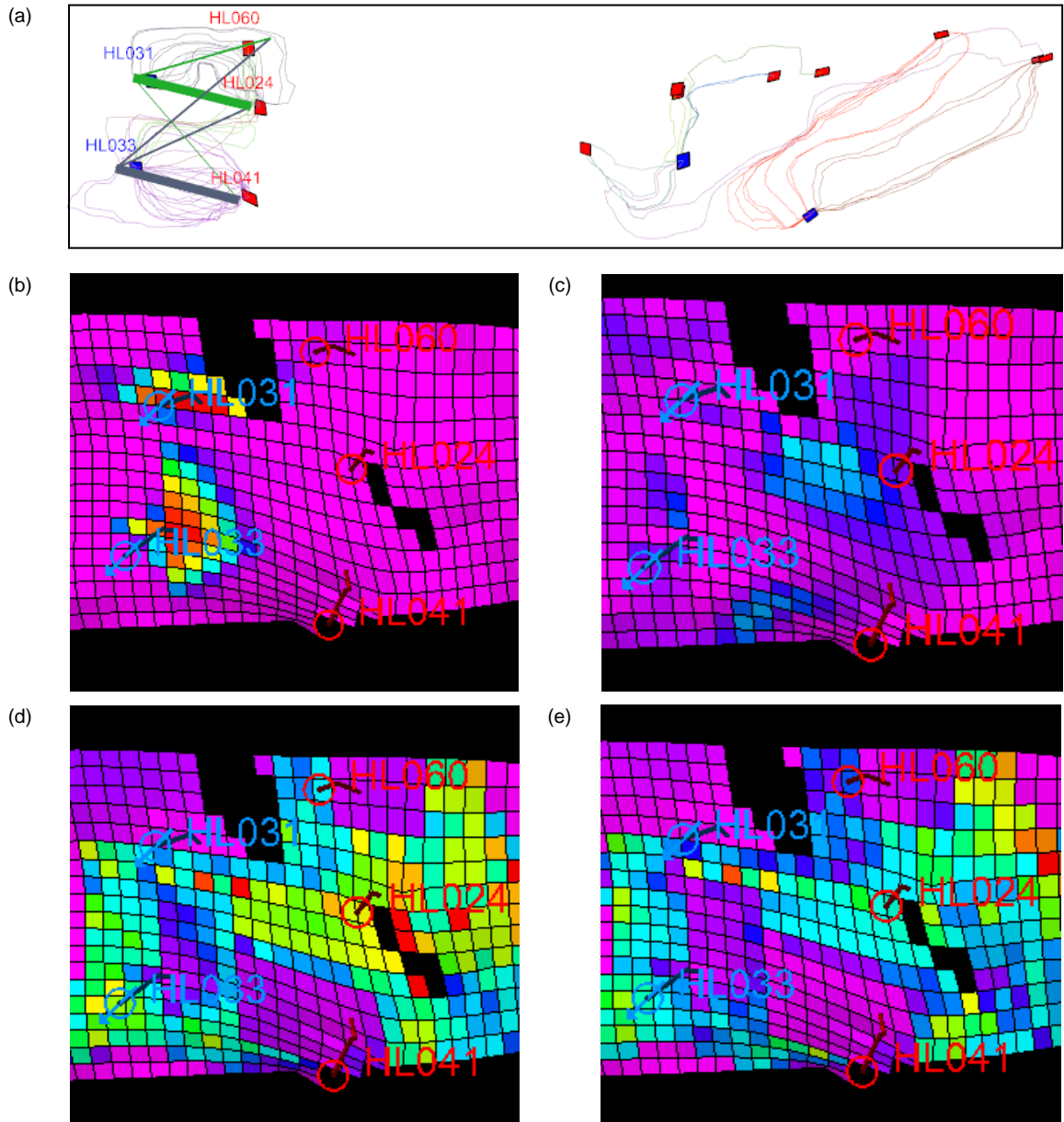
Throughout this section, the constant injection rates, which are required for the pattern-level workflow for improved polymer-flood management by Clemens et al., were chosen to be the ones from OMV's preliminary waterflood strategy.

**Results. Step 2.** Fig. 7 illustrates polymer injection for the western two patterns of the Hochleiten field for a crude field-level polymer-flood strategy, where the same polymer concentration of 1,000ppm and slug size of 3 years were used for every injector. The injected polymer travels along the SLs from the injectors to the offset producers together with the injected water in which it resides. The thus viscosified water fluxes between injectors and offset producers move more in unity with the viscous oil and thus help to achieve a better sweep efficiency, leading to a higher oil recovery.

In Fig. 8 the oil saturation over time for a simulation grid cell between injector HL031 and producer HL024 is compared between the polymer-flood strategy from above and OMV's preliminary waterflood strategy. Both strategies have the same well injection rates; the difference is the 3-years polymer injection at the outset of the forecast. In the case of the polymer injection, an oil bank builds up in the grid cell because the viscosified water has swept oil from previous grid cells along its way into the grid cell shown. Since the oil bank is pushed ahead by the polymer front, the oil bank has already moved to the next grid cell, when the polymer front reaches the grid cell shown. There is a better sweep due to polymer injection because compared to the pure waterflood, more oil entered the cell in the shape of the oil bank and less oil remains in the cell at the end of the forecast.

Fig. 9 shows the pattern performance plot for the four injector-centered patterns of the Hochleiten field for the polymer-

flood strategy where the same polymer concentration of 1,000ppm and slug size of 3 years were used for every injector. The pattern with injector HL033 is significantly more efficient than the other three patterns. As shown in **Table 3**, all four patterns have an average IE (polymer injection) of below 1.6kg of polymer injected per stb of offset oil produced, so the efficiency is reasonably high for all patterns and no patterns were discarded for polymer injection at this stage of the workflow.



**Fig. 7 - (a)** Injectors (blue), producers (red), and the SLs connecting them for the Hochleiten field, and the associated FPmap for the western two patterns (centered on injectors HL031 and HL033). **(b)** Polymer concentration in the western part of the field at the point where the polymer injection ends in this polymer-flood strategy, i.e. three years after it started at the outset of the simulation. The color scale ranges from pink (0 ppm) to red (1000ppm). **(c)** Polymer concentration in the western part of the field 15 years after the polymer injection ended. The polymer has moved from the injectors to the offset producers over the 15 years. **(d)** Oil saturation in the western part of the field at the point where the polymer injection ends in this polymer-flood strategy, i.e. at the time of (b). The color scale ranges from pink (20%) to red (70%). **(e)** Oil saturation in the western part of the field 15 years after the polymer injection ended, i.e. at the time of (c). The oil saturation has decreased in the region of the two western flux patterns over the 15 years. As the injected polymer solution has moved toward the offset producers, it has swept the resident oil along ahead of its way. Because of the good displacement efficiency in polymer flooding, the oil saturation has substantially decreased in the area around the two injectors and it has also decreased in the area around the offset producers, with some oil still to be produced over the remaining forecast period as the polymer front pushes on.

**Step 3.** Sensitivity analyses were done for each pattern of the Hochleiten field, varying polymer concentration and slug size. **Fig. 10** shows the pattern performance plot for injector HL033 at a fixed polymer concentration for the slug sizes of 3, 5, 7 and 10 years. **Fig. 11** shows the pattern performance plot for injector HL033 at a fixed slug size for the polymer concentrations of 500, 1,000 and 1,500ppm. The sensitivities were analyzed and the cumulative amounts of polymer injection and offset oil production were obtained for the 12 polymer injection strategies (i.e. all combinations of the 3 concentrations and 4 slug sizes) for each of the four patterns.

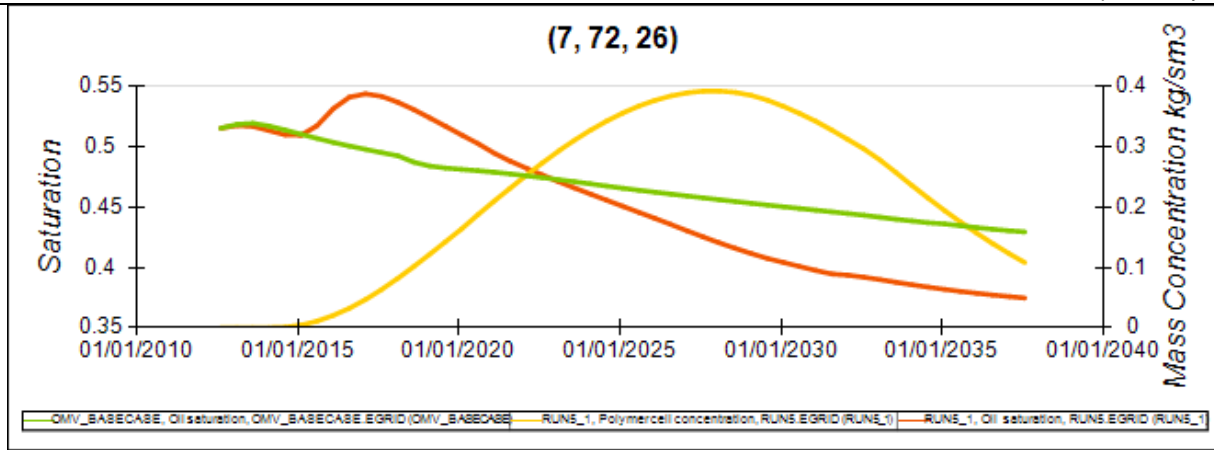


Fig. 8 – Multi-value probe of a simulation grid cell between injector HL031 and producer HL024. For this grid cell, the oil saturation (red) and the polymer concentration (yellow) of a polymer-flood strategy, in which the same polymer concentration of 1000ppm and slug size of 3 years were used for each injector, and the oil saturation (green) of OMV's preliminary waterflood strategy are plotted against the 25-years forecast period. The better sweep efficiency of the polymer-injection strategy can be seen from the oil bank that reaches the grid cell ahead of the polymer front and from the lower oil saturation at the end of the forecast period than in the pure waterflood strategy.

The next step was to calculate the UF of the 12 polymer-injection strategies for each pattern. As discussed above, the floodOPT-driven waterflood with the dynamic injection rates was used as a base case to calculate the incremental offset oil recovery. At that point of the workflow it became obvious that polymer injection with the constant injection rates of OMV's preliminary development strategy is not economical. For every pattern, the UF of almost every of the 12 polymer-flood strategies was either intolerably high or even negative (meaning that the floodOPT-driven pure waterflood strategy yielded a higher offset oil production than the polymer-injection strategy).

That observation meant two important things. First, it demonstrated the substantial benefit of dynamically reallocating the well rates according to the IE (waterflood) metric in the pure waterflood of the Hochleiten field and thus it demonstrated the need for active rate management. Second, the usefulness of the UF metric and its important difference from the IE (polymer injection) metric became apparent. That point is further illustrated in Table 3, where the IE (polymer injection) and UF metrics are juxtaposed for a polymer strategy for the Hochleiten field with a concentration of 1,000ppm and a slug size of 3 years for each injector. It can be seen that even though all patterns have an IE (polymer injection) of below 1.6kg/offset stb, their UFs are bad; pattern HL033, which has the best IE (polymer injection), even has a negative incremental offset oil recovery.

Observing those stark differences between the values of IE (polymer injection) and UF for the same polymer-flood strategy and considering that UF is the economically more useful metric for polymer-flood designs, it is obvious that those two metrics are different indeed and care should be taken to calculate UF.

**Step 4.** At this stage of the workflow it was already obvious that there is no economical polymer-flood strategy with the constant injection rates from OMV's preliminary development strategy. The workflow of Clemens et al. (2011) was resumed, however, to test whether its aim to improve the performance of a polymer flood by a granular per-pattern relative to a crude field-level approach can be achieved

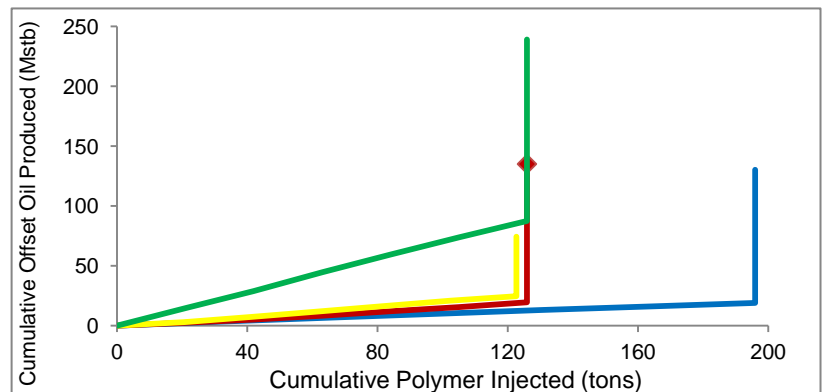


Fig. 9 - Pattern performance plot for the four injector-centered patterns of the Hochleiten field for a polymer-flood strategy where a concentration of 1,000ppm and a slug size of 3 years were used for every injector. Pattern performance curves for injector HLF04 are blue, for injector HL019 they are red, for injector HL031 they are yellow, and for injector HL033 they are green. (Note: The red mark indicates where the pattern performance curve for injector HL019 ends.) For every pattern, the offset oil production is plotted against the amount of polymer injected. Hence, the pattern performance plot depicts the IE (polymer injection) metric. The straight vertical line in each pattern performance curve indicates the period of chase-water recovery, where polymer injection has stopped but offset oil production still continues because of the continued waterflooding and the remaining polymer in the reservoir. As for the pattern performance plot for a waterflood, the slope to the endpoint of an individual pattern performance curve indicates the average IE (polymer injection) of a pattern. The reason why the patterns with injectors HL019 and HL033 have the same ultimate amount of polymer injection is that they have the same constant water injection rate, so they have the same cumulative amount of injection water at any point of time. Since injectors HL019 and HL033 have the same slug size and polymer concentration in this scenario for step 2 of the workflow of Clemens et al. (2011), they have the same ultimate amount of polymer injection.



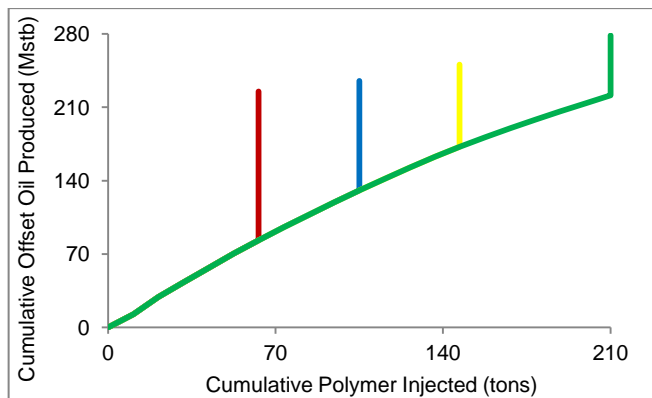
for the case of the Hochleiten field and thus to get a better idea of the scope of the workflow.

To test whether the pattern-level workflow helps to find a polymer-injection strategy that delivers better results (in the shape of a higher incremental oil recovery and/or a lower UF) than a crude field-level approach, OMV's preliminary waterflood was used as a benchmark instead of the floodOPT-driven waterflood. It should be emphasized that using OMV's preliminary waterflood strategy instead of the floodOPT-driven waterflood as the base case is a legitimate way to test whether the workflow of Clemens et al. (2011) works in the case of the Hochleiten field, which is the purpose of the subsequent section. It would not be legitimate, however, to use OMV's preliminary waterflood strategy as the base case to assess whether a polymer strategy is economical; that no polymer strategy with the constant injection rates is economical, however, was already discussed in the previous section and is thus not the subject of the subsequent section.

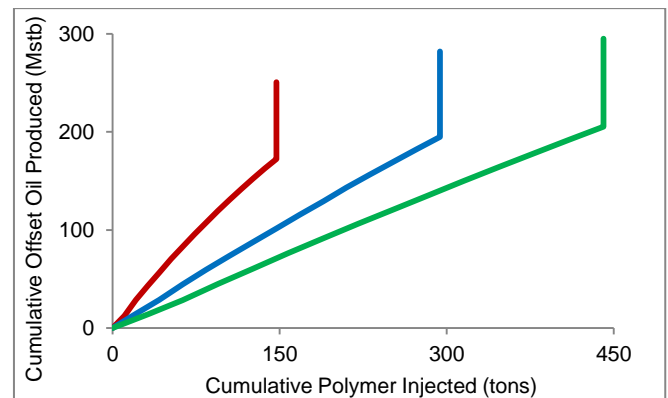
**TABLE 3 – COMPARISON OF THE IE (POLYMER INJECTION) AND UF METRICS FOR A POLYMER-FLOOD STRATEGY WITH A CONCENTRATION OF 1,000PPM AND A SLUG SIZE OF 3 YEARS FOR EACH INJECTOR**

injector-centered pattern	Cumulative polymer injected (tons)	Cumulative offset oil produced (Mstb)	floodOPT - driven waterflood: cumulative offset oil produced (Mstb)	Inverse of IE (polymer injection) (kg/offset stb)	UF (kg/incremental offset stb)
HLF04	196	130	130	1.5	392.2
HL019	126	135	94	0.9	3.1
HL031	123	74	*	1.6	*
HL033	126	239	289	0.5	-2.5

\* Unavailable because the injector HL031 is shut in floodOPT-driven waterflood.



**Fig. 10 – Sensitivity analysis for the pattern with injector HL033 with respect to different slug sizes at a fixed polymer concentration.** The pattern performance plot of injector HL033, in which the offset oil production is plotted against the amount of polymer injected, is shown for the slug sizes of 3 (red), 5 (blue), 7 (yellow), and 10 (green) years at a fixed polymer concentration of 500ppm. The straight vertical line in each pattern performance curve is due to the period of chase-water recovery. For a fixed polymer concentration and a variable slug size, the differences in the pattern performance curves of a given pattern are the ultimate amount of polymer injected (i.e. the x-axis value where the vertical line branches off) and the magnitude of the chase-water recovery (i.e. the length of the vertical line). The slug size yielding the highest IE (polymer injection) for pattern HL033 at a fixed polymer concentration of 500ppm is 3 years. The reason is that the significant increase in the cumulative amount of polymer injection due to a greater slug size cannot be compensated for by the negligible increase in offset oil production (i.e. as the slug size of the polymer-flood strategy is increased, the slope to its endpoint decreases).

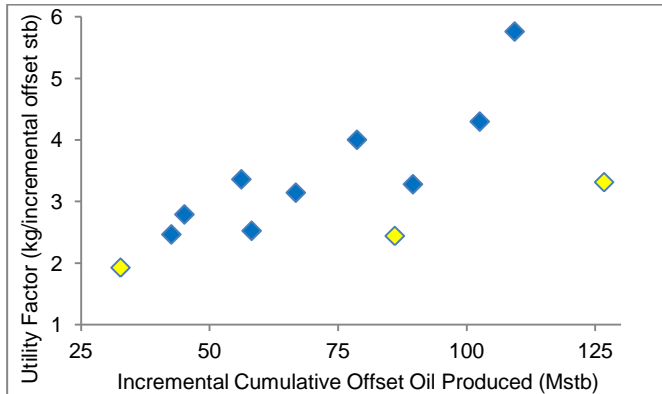


**Fig. 11 – Sensitivity analysis for the pattern with injector HL033 with respect to different polymer concentrations at a fixed slug size.** The pattern performance plot of injector HL033 is shown for the polymer concentrations of 500 (red), 1,000 (blue), and 1,500ppm (green) at a fixed slug size of 7 years. The reason why in the case of a fixed slug size and variable polymer concentrations, pattern performance curves do not overlap during the period of polymer injection (i.e. until the vertical line branches off) is that any value of the cumulative polymer injection on the x-axis represents different points of time for different polymer concentrations (where the lowest-concentration strategy is the furthest in time at any x-value) and hence the offset oil production on the y-axis is not the same for any x-value.

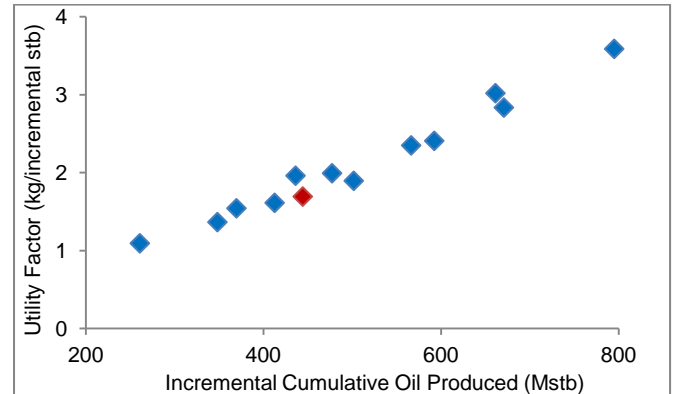
**Fig. 12** shows a pattern-level UF performance plot for the 12 polymer-injection strategies for the pattern with injector HL033. The polymer-injection strategy with a concentration of 1,000ppm and a slug size of 10 years (represented by one of the yellow marks) was selected for injector HL033. Analogous to the analysis for pattern HL033 shown in Fig. 12, the pattern-level UF performance plots for the other three patterns were analyzed to obtain for each pattern the polymer concentration/slug size strategy yielding the highest incremental offset oil recovery at a predetermined UF maximum.

**Step 5.** To see whether the SL-based workflow of Clemens et al. (2011) for improved polymer-flood management worked in the case of the Hochleiten field, a simulation was performed with the optimal polymer concentration/slug size strategy for each pattern, as obtained from the pattern-level analyses done in Step 4. The results of that simulation, in which individual patterns did not have the same polymer concentration/slug size strategy, were assessed against the results from the crude field-

level polymer-flood strategies, in which the same concentration and slug size were used for all four patterns in every simulation (i.e. 500ppm and 3years for all four injectors, then 500ppm and 5years for all four injectors, and so on; i.e. there are 12 crude field-level polymer-flood strategies). That assessment was done in **Fig. 13**, which shows a field-level UF performance plot for the pattern-level polymer strategy based on the workflow of Clemens et al. (2011) and the 12 crude field-level polymer strategies.



**Fig. 12 – Pattern-level UF performance plot for the pattern with injector HL033 of the Hochleiten field.** For each of the 12 polymer-injection strategies for injector HL033, the pattern-level UF is plotted against the pattern-level incremental (relative to OMV's preliminary waterflood strategy with the constant injection strategies) offset oil recovery. Hence, every mark represents a different polymer-injection strategy for injector HL033. A lot of polymer-injection strategies (represented by the blue marks) are dominated because there are other strategies (represented by the yellow marks) that deliver a higher incremental oil recovery without a higher UF or a lower UF without decreasing the incremental oil recovery. Depending on the predetermined maximum for UF, one of the polymer-injection strategies represented by the yellow marks should be chosen as an optimal polymer concentration/slug size strategy for the pattern with injector HL033.



**Fig. 13 - Field-level UF performance plot for the Hochleiten field for the per-pattern polymer strategy obtained from the workflow of Clemens et al. (represented by the red mark) and for the 12 crude field-level polymer-flood strategies (represented by the blue marks).** For each field-level polymer strategy, the fieldwide UF is plotted against the fieldwide incremental (relative to OMV's preliminary waterflood strategy with the constant injection strategies) oil recovery. The per-pattern polymer strategy dominates one crude field-level polymer strategy and is not dominated by any of the other 11 crude field-level polymer strategies. In general, there is a positive linear trend in the plot, which means that there is a trade-off between a high incremental oil recovery over the base-case waterflood and a low UF. Hence, the greater the tolerance of a high UF, the greater the incremental oil recovery that can be achieved from polymer injection. Tolerance of a high UF is a function of the price relationship between a stb of oil and a kg of polymer; the greater the price of a stb of oil relative to the price of a kg of polymer, the greater the tolerance of a high UF.

It can be inferred from Fig. 13 that the SL-based workflow of Clemens et al. (2011) worked because its per-pattern polymer strategy dominates one crude field-level polymer strategy and is not dominated by any other crude field-level strategy. The benefit of the workflow is not significant in the case of the Hochleiten field, however, because the crude field-level strategy that the per-pattern polymer strategy dominates is also dominated by two other crude field-level strategies and because the per-pattern polymer strategy does not deviate from the positive linear trend in the field-level UF performance plot of Fig.13.

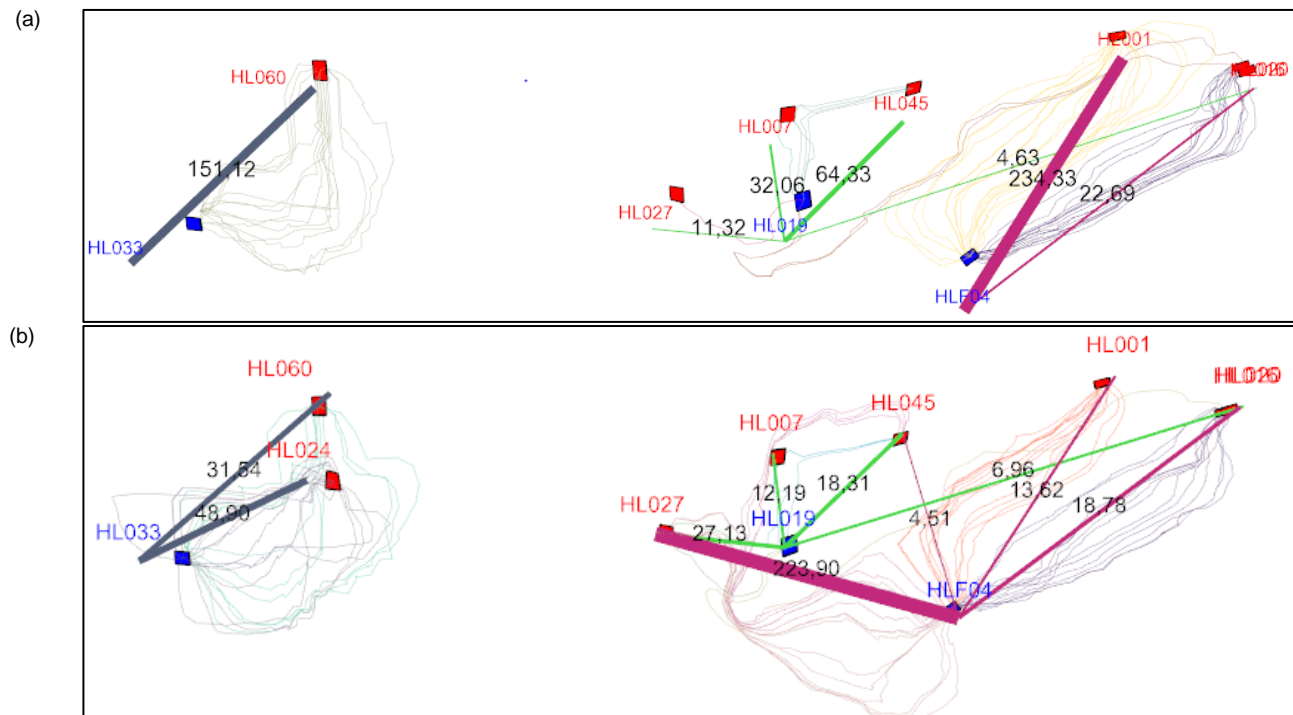
One reason why the granular pattern-level approach did not significantly outperform the crude field-level approaches in the case of the Hochleiten field might be that four patterns are not enough to substantially benefit from the individual analysis of each pattern suggested by the workflow. Another reason might be the nonlinearity contained in the workflow. The simulations in Step 3 were done for each injector for a scenario, where a polymer concentration of 1,000ppm and a slug size of 5 years were used for the other three injectors. Because that scenario did not significantly deviate from the per-pattern polymer-flood strategy obtained from the pattern-level analysis in Step 4 (a polymer concentration of 1,000ppm for injectors HL033, HL031 and HL019 with a slug size of 10, 3 and 5 years respectively), nonlinearity was not expected to be a major issue in the analysis. There was no time to investigate the issue of nonlinearity in depth, however.

### Field-Level Polymer-Flood Strategies with Dynamic Injection Rates

**Methodology.** In this new methodology, the floodOPT software tool was used to test crude field-level polymer-flood strategies with dynamic well injection rates. As already discussed, floodOPT is designed to optimize the rate management in waterflood projects by using the metric of IE (waterflood). floodOPT is not programmed to know polymer injection and thus, it does not use the polymer-flood-related metrics of the IE (polymer injection) or the UF. There is no reason, however, why the underlying logic of floodOPT cannot be applied to polymer flooding.

floodOPT calculates the IE (waterflood) for each pattern/well-pair connection at every timestep and dynamically reallocates the given water field injection rate accordingly from less to more efficient injection patterns/well pairs. Since floodOPT is based on the IE (waterflood) metric, it essentially relies on the reservoir fluxes between the wells. Hence, because the fluxes in the reservoir change due to polymer injection, which is illustrated in **Fig. 14**, floodOPT indirectly incorporates polymer injection even though it is not programmed to know it. If applied to a polymer-flood project, floodOPT indirectly

IE (waterflood) denotes the offset oil production per unit of injected water for a certain pattern. IE (polymer injection) denotes the offset oil production per unit of injected polymer for a certain pattern. In cases where the same polymer concentration and slug size are used for each pattern, the metrics of IE (waterflood) and IE (polymer injection) essentially have the same meaning because the polymer injected into a certain pattern [i.e. the denominator of IE (polymer injection)] is simply a factor of the water injected into that pattern [i.e. the denominator of IE (waterflood)]; if in a polymer-flood project where the same polymer concentration and slug size are used for each pattern, a certain pattern has a higher IE (polymer injection) than another pattern, that pattern also has the higher IE (waterflood) than that other pattern. Hence, by reallocating the injected water according to the IE (waterflood) metric, floodOPT indirectly reallocates the injected polymer according to the IE (polymer injection) metric in polymer-flood projects with the same polymer concentration and slug size for each injector.



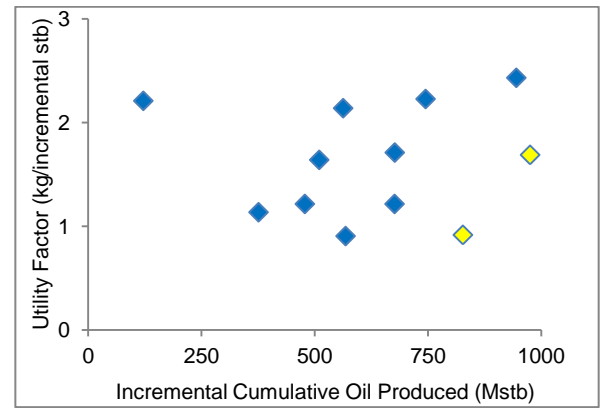
Based on that reasoning, floodOPT was applied to polymer-flood projects with the same polymer concentration and slug size for each pattern to investigate the importance of dynamic well injection rates as a control parameter in designing polymer floods. The UF metric, which is an economically more meaningful metric in polymer-flood projects than IE (polymer injection), could not be incorporated into this methodology. It was thus essential to calculate the fieldwide UF for each crude polymer concentration/slug size strategy at the end of this methodology and discard any polymer-injection strategy of which the fieldwide UF is intolerably high.

The polymer-injection strategy with a concentration of 1,500ppm and a slug size of 7 years for all injectors (represented by one of the yellow marks) was selected, which delivered an incremental oil recovery of 1 million stb over the floodOPT-driven waterflood at a fieldwide UF of 1.7kg/incremental stb. For that polymer-flood strategy, **Fig. 16** illustrates that even though floodOPT is not programmed to know polymer flooding, it incorporates polymer injection in its optimization process. It can be seen how compared to the pure waterflood case, floodOPT decreases and dynamically varies the water field injection rate before and during the breakthrough of the oil bank due to the polymer injection.

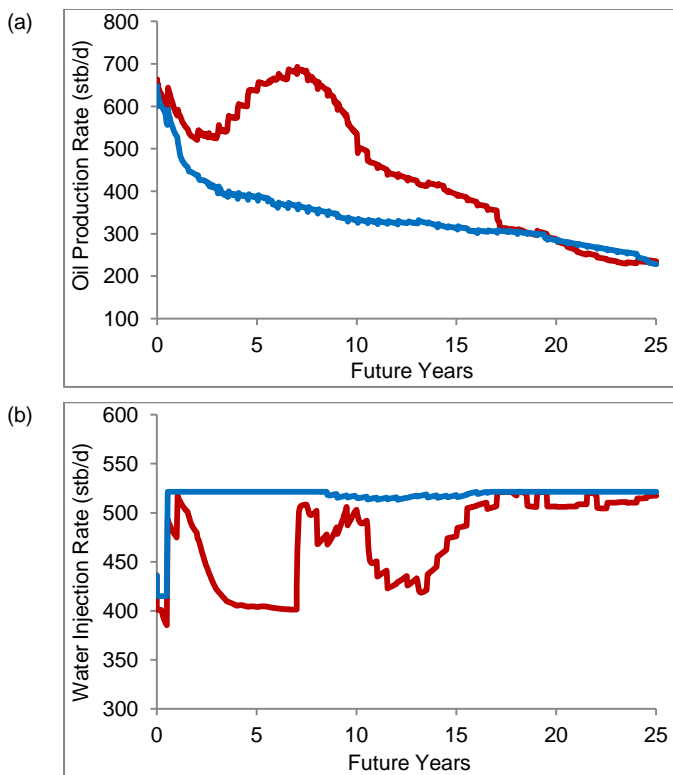
The significant benefit of using floodOPT for crude field-level polymer-injection strategies is demonstrated in **Fig. 17**, which compares the performance of the same crude field-level polymer strategy for the case in which floodOPT was used to dynamically reallocate well injection rates to the case in which the constant injection rates from OMV's preliminary strategy were used. Using floodOPT and its active rate management, it was possible to inject a smaller amount of polymer and obtain a higher cumulative oil recovery for the same crude field-level polymer-injection strategy.

## Discussion

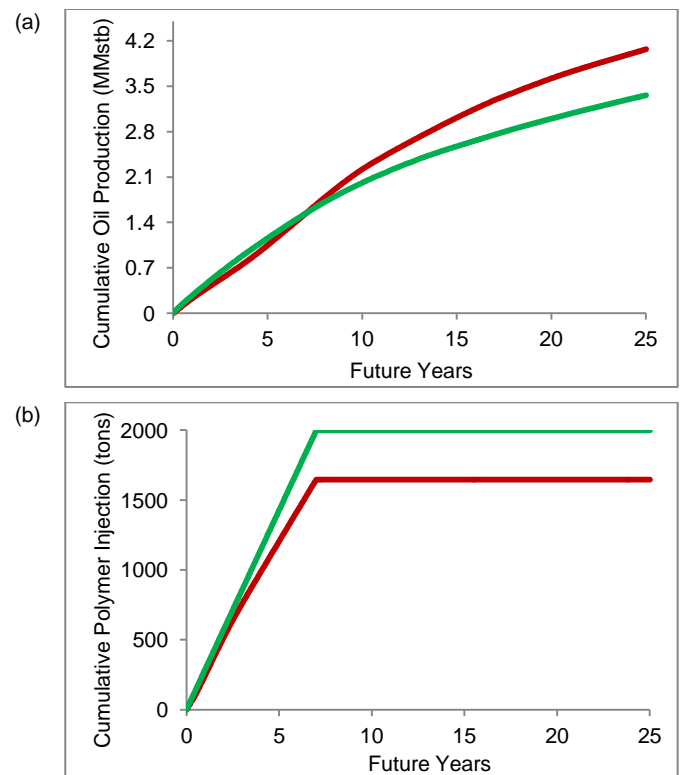
With the aid of SL simulation in both the improved waterflood management and the floodOPT-driven polymer-flood strategy, it was possible to increase the recovery factor of the Hochleiten field by 2.5 percentage points over a preliminary waterflood strategy with constant well injection rates, which, as shown in **Fig. 18**, represents 1.4 million stb of incremental oil recovery. 0.7 of the 2.5 percentage points, or 0.4 million stb of incremental oil recovery, could be achieved by an improved waterflood, in which the given field injection rate was dynamically reallocated between the individual injectors according to the SL-based IE (waterflood) metric. The other 1.8 percentage points, or 1 million stb of incremental oil, could be achieved by a floodOPT-driven polymer-injection strategy at a tolerable fieldwide UF of 1.7 kg/incremental stb (over the improved waterflood).



**Fig. 15 – Field-level UF performance plot for the Hochleiten field for the floodOPT-driven crude field-level polymer strategies.** For each of the 12 crude field-level polymer strategies, the fieldwide UF is plotted against the fieldwide incremental (relative to the floodOPT-driven waterflood base case) oil recovery. Two polymer-injection strategies (represented by the yellow marks) dominate the other 10 strategies (represented by the blue marks). There is no longer a positive linear trend because of the active rate management in this methodology.



**Fig. 16 (a) and (b) – Oil production rate (a) and water injection rate (b) over the 25-years forecast for the floodOPT-based crude field-level polymer-injection strategy with a concentration of 1,500ppm and a slug size of 7 years for all injectors (red) and for the floodOPT-based pure waterflood (blue).** There is a clear match between the period of the oil bank breakthrough due to the polymer injection and the period in which the water field injection rate is dynamically varied by floodOPT.



**Fig. 17 (a) and (b) – Cumulative oil production (a) and cumulative polymer injection (b) over the 25-years forecast for the crude field-level polymer-injection strategy with a concentration of 1,500ppm and a slug size of 7 years for all injectors for the case where the dynamic well injection rate behavior from floodOPT was used (red) and for the case where the constant well injection rates from OMV's preliminary strategy were used (green).** In the case where floodOPT was used, the cumulative oil production could be increased from 3.4 to 4.1 million stb, which represents a 21% increase, while 350 tons less of polymer were injected.

In the case of the Hochleiten field, the granular per-pattern workflow for improved polymer-flood management with constant injection rates by Clemens et al. (2011) only delivered insignificantly better results than crude field-level polymer-injection strategies with the same constant injection rates. No economical polymer-flood strategy could be found by following the per-pattern workflow at constant well injection rates, in which polymer concentration and slug size were individually optimized for each injector. Economical polymer-flood strategies could rather be found by focusing on a dynamic reallocation of the given water field injection rate between the individual injectors according to the IE (waterflood) metric, while the same polymer concentration and slug size were used for each injector. That observation suggests that as in pure waterflooding, active rate management is crucial in polymer-flood projects.

### Summary and Suggestion for Further Work

Using SL simulation for improved waterflood and polymer-flood management, it was possible to increase the recovery factor of the Hochleiten field relative to OMV's preliminary redevelopment strategy by 2.5 percentage points, which represents 1.4 million stb of incremental oil recovery, at a tolerable fieldwide UF of 1.7 kg/incremental stb.

The following recommendation for a new SL-based workflow is made. The workflow for improved polymer-flood management suggested by Clemens et al. (2011) focuses on optimizing polymer concentration and slug size on a per-pattern basis by using the SL-based UF metric, while not considering a dynamic reallocation of well injection rates. The new methodology for improved polymer-flood management introduced in this paper, which proved more beneficial in the case of the Hochleiten field, on the other hand, focuses on optimizing well injection rates on a per-pattern basis by using the SL-based IE metric, while not considering different polymer concentration and slug size strategies for each pattern. Considering the stark difference between the IE and UF metric in polymer-flood projects illustrated above and considering that the second methodology did not incorporate the economically more meaningful UF metric, it can be expected that there is still room for further improvement of polymer-flood management for the Hochleiten field.

It is thus suggested that a SL-based workflow for improved polymer-flood management be developed that optimizes both individual well injection rates (using the IE metric) and polymer concentration and slug size (using the UF metric) on a per-pattern basis. Such a workflow promises to be useful in polymer-flood projects, which are likely to gain in importance as an increasing number of oil fields mature.

### Nomenclature

$C_p$	=	flowing polymer concentration
$E$	=	overall displacement efficiency
$E_D$	=	local displacement efficiency
$E_v$	=	volumetric displacement efficiency
$f_w$	=	water fractional flow
$k_{ri}$	=	relative permeability of phase i
$S_w$	=	water saturation
$\mu_i$	=	viscosity of phase i
$\lambda_i$	=	mobility of phase i
$\tau$	=	time of flight (TOF)

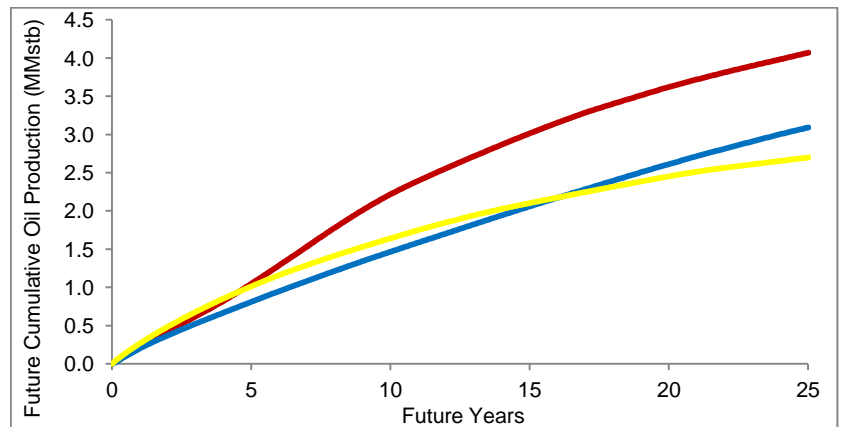


Fig. 18 – Future cumulative oil production over the 25-years forecast for OMV's preliminary waterflood strategy (yellow), the floodOPT-driven improved waterflood strategy (blue), and the floodOPT-driven crude field-level polymer-injection strategy with a concentration of 1,500ppm and a slug size of 7 years for all injectors (red). OMV's preliminary waterflood strategy yielded a future cumulative oil production of 2.7 million stb. Using floodOPT to improve the waterflood, it was possible to obtain another 0.4 million stb; using floodOPT to improve the polymer-flood strategy, the cumulative oil production could be further increased by 1 million stb.

### Acknowledgements

I would like to thank my supervisors Prof. Martin Blunt and Torsten Clemens for their advice. I am also grateful to Marco Thiele for his help. Thank you to Matteo Di Giovinnazzo from Streamsim Technologies for his software support and to OMV for providing the infrastructure.

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**Appendix: Critical Literature Review****Milestones in the study of Polymer EOR using SL Simulation**

Table of content

<b>SPE Paper n°</b>	<b>Year</b>	<b>Title</b>	<b>Authors</b>	<b>Contribution</b>
36726-PA	1997	“A 3D Field-Scale Streamline-Based Reservoir Simulator”	R.P. Batycky, M.J. Blunt, M.R. Thiele	<ol style="list-style-type: none"> <li>1. First to develop and test a SL-based reservoir simulator applicable to 3D field-scale flow, which takes changing well conditions and gravity into account.</li> <li>2. Discussed advantages of decoupling a 3D transport problem into multiple 1D problems.</li> </ol>
54616-MS	1999	“Waterflood Pattern Allocations: Quantifying the Injector to Producer Relationship with Streamline Simulation”	G. H. Grinestaff	First to suggest quantification of injector to producer relationships for a waterflood using SL-based ‘Dynamic Injection Pattern Allocations’.
84080-PA	2006	“Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management”	M.R. Thiele, R.P. Batycky	<ol style="list-style-type: none"> <li>1. First to heuristically improve waterflood management on a well-by-well basis using SL-derived dynamic WAFs.</li> <li>2. Established SL-derived IE metric.</li> </ol>
115545-PA	2010	“Polymer-Flood Modeling Using Streamlines”	M.R. Thiele, R.P. Batycky, S. Pöllitzer, T. Clemens	<ol style="list-style-type: none"> <li>1. First to demonstrate that SL simulation can be efficiently used to model polymer flooding.</li> <li>2. Discussed dual-grid approach of SL simulation for polymer flooding.</li> </ol>
123971-PA	2010	“Streamline-Based Simulation of Non-Newtonian Polymer Flooding”	A.M. AlSofi, M.J. Blunt	<ol style="list-style-type: none"> <li>1. First to investigate the effects of non-Newtonian polymer rheology on oil recovery.</li> <li>2. Demonstrated that neglecting the shear-thinning nature of polymers typically used in polymer flooding leads to overly optimistic recovery predictions.</li> </ol>
132774-PA	2011	“Improved Polymer-Flood Management Using Streamlines”	T. Clemens, J. Abdev, M.R. Thiele	<ol style="list-style-type: none"> <li>1. First to present a detailed SL-based workflow to improve polymer-flood management on a well-by-well basis and test it on a Romanian oil field. Improved waterflood management (see SPE 84080-PA) is used as benchmark case in the workflow.</li> <li>2. Established SL-derived UF metric.</li> </ol>

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**Brief summary of each paper relevant to the study of Polymer EOR using SL Simulation**

*SPE 123971-PA (2010)*: SPE Journal 15(4), December, p. 895-905

“Streamline-Based Simulation of Non-Newtonian Polymer Flooding”

Authors: AlSofi, Abdulkareem M.; Blunt, Martin J.

Contribution to the understanding of polymer EOR using SL simulation:

Showed that Non-Newtonian effects of polymers are commonly neglected in SL-based polymer-flood simulations.

Objective of the paper:

To demonstrate that the Non-Newtonian nature of many polymers should not be neglected in polymer-flood SL simulations to avoid overly optimistic recovery predictions for shear-thinning polymers and to avoid ignoring the potential benefits from using viscoelastic polymers or reducing flow rates for shear-thinning polymers.

Methodology used:

Incorporated the interdependence between Non-Newtonian viscosities and pressure into the SL simulation model through an iterative viscosity/pressure solver.

Conclusion reached:

The Non-Newtonian effects of polymers should not be neglected in a SL-based polymer-flood model and flow rates should be adjusted accordingly.



“A 3D Field-Scale Streamline-Based Reservoir Simulator”

Authors: Batycky, R.P.; Blunt, M.J.; Thiele, M.R.

Contribution to the understanding of polymer EOR using SL simulation:

Developed and tested a SL-based reservoir simulator applicable to 3D field-scale flow, which takes changing well conditions and gravity into account

Objective of the paper:

To present a new SL-based reservoir simulator applicable to 3D field-scale flow and discuss its advantages over traditional FD models.

Methodology used:

Applied the SL-based reservoir simulator to tracer, first-contact miscible (FCM) and waterflood 2D and 3D displacements and compared results with conventional FD methods. Also used a history matching field example.

Conclusion reached:

By decoupling 3D transport problems into multiple 1D problems, SL simulation can accommodate greater timesteps, thus increasing computational efficiency and reducing numerical diffusion.

Comments:

SL simulation is ideal for convectively-dominated, large, heterogeneous, multi-well reservoirs, where conventional FD simulation may not be able to solve the problem at all.

*SPE 108701-MS (2007)*: SPE Annual Technical Conference and Exhibition, 11-14 November, Anaheim, California, U.S.A.

“Assisted History Matching of a 1.4-Million-Cell Simulation Model for Judy Creek ‘A’ Pool Waterflood/HCMF Using a Streamline-Based Workflow”

Authors: Batycky, R.P.; Seto, A.C.; Fenwick, D.H.

Contribution to the understanding of polymer EOR using SL simulation:

None, but helped improve understanding of SL concept.

Objective of the paper:

To test a SL-based assisted history matching workflow on a large and complex field with a large amount of production data.

Methodology used:

Used SLs for well-level history matching: mapped obtained gridblock multipliers directly to the 3D grid along associated SLs after each timestep, thus gradually updating the geology.

Conclusion reached:

SLs are a useful means to assist well-level history matching (and thus improve the overall field-level history match).

Comments:

1. The field-level match even improved for phase signatures, timesteps and wells not considered in the history-matching process.
2. (Time-consuming) checks for geological consistency at every timestep were not needed as the initial geological model was reasonable.

“Revisiting Reservoir Flood-Surveillance Methods Using Streamlines”

Authors: Batycky, Rod P.; Thiele, Marco R.; Baker, Richard O.; Chugh, Shelin H.

Contribution to the understanding of polymer EOR using SL simulation:

Introduced SL-based dynamic injector-centered patterns as a more convenient concept for flood surveillance than fixed patterns (with geometric or flow-based WAFs). Contribution not that much because central concept of dynamic injector-centered patterns with offset producers being those to which the injector is connected at a given timestep was already used (though not explicitly defined) in SPE 54616-MS (1999).

Objective of the paper:

To use SLs to efficiently build a flood-surveillance model without resorting to time-consuming history-matched (SL or FD) simulations.

Methodology used:

Used SL-based dynamic injector-centered patterns to build a surveillance model and compared the well-pair fluxes obtained to the well-pair fluxes from a fully history-matched SL simulation with the same well rates and locations.

Conclusion reached:

For reservoir surveillance purposes, a model that only incorporates gross geological features, historical well rates and well locations is a good proxy for the more sophisticated history-matched SL simulation model.

Comments:

1. It was assumed that a detailed geological description is not needed for surveillance purposes because the geology and reservoir connectivity is already implied in the historical well rates.
2. The correlation of the surveillance model with the history-matched SL simulation model was found to be better for: high-rate rather than low-rate well pairs, offset oil production rather than individual well-pair fluxes (because of the summation effect), and late rather than early timesteps

*SPE 89175-MS (2006)*: Journal of Petroleum Technology 58(2), February, p. 84-89

“Advances in Polymer Flooding and Alkaline/Surfactant/Polymer Processes as Developed and Applied in the People’s Republic of China”

Authors: Chang, H.L.; Zhang, Z.Q.; Wang, Q.M.; Xu, Z.S.; Guo, Z.D.; Sun, H.Q.; Cao, X.L.; Qiao, Q.

Contribution to the understanding of polymer EOR using SL simulation:

None, but demonstrated that field-scale polymer flooding can be very successful.

Objective of the paper:

To present the success and future potential of polymer flooding, colloidal-dispersion gels (CDGs) and alkaline/surfactant/polymer (ASP) flooding in China.

Methodology used:

None.

Conclusion reached:

Significant progress has been made in polymer flooding in China since the 1990s. Further conclusions for CDGs and ASP flooding, which are beyond the scope of this paper.

Comments:

In Daqing, incremental oil recoveries due to polymer flooding are about 10% of OOIP.

“Improved Polymer-Flood Management Using Streamlines”

Authors: Clemens, Torsten; Abdev, Joseph; Thiele, Marco R.

Contribution to the understanding of polymer EOR using SL simulation:

Established the SL-derived metric of the UF (cumulative mass of polymer injected [kg] / cumulative volume of incremental oil produced [stb]) and developed a pattern-level workflow for improved polymer-flood management based on SL simulation and the UF metric.

Objective of the paper:

To introduce a SL-based workflow for improved polymer-flood management on an individual-well-pattern basis and demonstrate its usefulness on a Romanian oil field.

Methodology used:

Used SL simulation and the UF metric to identify over- and underperforming injectors and to assess the impact of varying polymer concentration and slug size for individual injectors.

Conclusion reached:

Using the right per-pattern polymer-injection strategy, it is possible to increase oil recovery (relative to a base-case improved waterflood strategy) at a tolerable UF.

Comments:

The paper established the per-pattern workflow for improved polymer-flood management at constant injection rates used (and tested) in the work described in this paper.

*SPE 54616-MS (1999)*: SPE Western Regional Meeting, 26-27 May, Anchorage, Alaska

“Waterflood Pattern Allocations: Quantifying the Injector to Producer Relationship with Streamline Simulation”

Authors: Grinestaff, G. H.

Contribution to the understanding of polymer EOR using SL simulation:

Quantified injector to producer relationships for a waterflood using SL-based ‘Dynamic Injection Pattern Allocations’.

Objective of the paper:

To show how Dynamic Injection Pattern Allocations can be used for proactive waterflood management.

Methodology used:

Used a well-level history-matched SL model to dynamically capture Injection Pattern Allocations at every timestep that the production changed (and/or the geology was adjusted).

Conclusion reached:

SL simulation is a useful way to quantify injector to producer relationships and thus it is useful for proactive waterflood management.

Comments:

Observed that little time should be spent on a detailed geological description, but focus should be on history matching production data for each well instead.

“Revitalising a Medium Viscous Oil Field by Polymer Injection, Pirawarth Field, Austria”

Authors: Poellitzer, Stefan; Florian, Thomas; Clemens, Torsten

Contribution to the understanding of polymer EOR using SL simulation:

None, but helped improve understanding of polymer EOR.

Objective of the paper:

To assess whether a medium viscous oil field in Austria can be revitalized by polymer EOR.

Methodology used:

A very applied paper that was not peer-reviewed. Hence, a workflow typical in industry: geological description, core flood experiments, reservoir simulation.

Conclusion reached:

Results of pilot simulation favored polymer injection. A pilot test is planned.

Comments:

1. Water chloride concentration data were used as an additional matching parameter besides conventional production data.
2. Fluid and reservoir conditions favorable to polymer injection were outlined: medium viscous oil, low brine salinity, moderate reservoir temperature, high reservoir permeability.
3. Key physical phenomena to be taken care of in polymer EOR simulations: polymer rheology, polymer adsorption, RRF, IPV.

***SPE 84080-PA (2006):*** SPE Res Eval & Eng 9(2), April, p. 187-196

“Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management”

Authors: Thiele, Marco R.; Batycky, Rod P.

Contribution to the understanding of polymer EOR using SL simulation:

Established the SL-derived metric of the IE (offset oil production/water injection) to heuristically improve waterflood management on a well-by-well basis.

Objective of the paper:

To improve waterflood management by using the IE metric to reallocate injection water from less to more efficient injectors/well-pair connections.

Methodology used:

Used SL simulation to obtain dynamic WAFs and calculate IE for all injectors/well pairs at all timesteps.

Conclusion reached:

The SL-derived IE metric is a powerful means to increase oil production without increasing water injection (or to decrease water injection without decreasing oil production).

Comments:

There can be no mathematical proof that the dynamic (target) injection rates are optimal due to the heuristic nature of the workflow. At the same time, however, the heuristic nature makes it an intuitive and visually powerful reservoir-management workflow.



“Polymer-Flood Modeling Using Streamlines”

Authors: Thiele, M.R.; Batycky, R.P.; Pöllitzer, S.; Clemens, T.

Contribution to the understanding of polymer EOR using SL simulation:

Showed that SL simulation can be efficiently used to model polymer flooding.

Objective of the paper:

To use SL simulation to model the total displacement efficiency of polymer flooding.

Methodology used:

Used SL simulation to decouple local displacement physics along the SLs from the volumetric displacement in the 3D grid, the latter being taken care of by the geometry of the SLs, which change at every timestep due to varying well rates and the dynamic total mobility field.

Conclusion reached:

Polymer flooding can be modeled more efficiently with SL simulation than with FD simulation without a significant loss of accuracy.

Comments:

The physical phenomena important in polymer flooding: water viscosity as a function of polymer concentration, the adsorption of polymer on the rock, the shear-rate dependence of polymer, IPV, the reduction of water relative permeability (RRF).

*SPE 118608-MS (2010)*: Journal of Petroleum Technology 62(1), January, p. 64-70

“Streamline Simulation for Modern Reservoir-Engineering Workflows”

Authors: Thiele, M.R.; Batycky R.P.; Fenwick, D.H.

Contribution to the understanding of polymer EOR using SL simulation:

None, but good SL overview.

Objective of the paper:

To give a general overview of the SL concept, its advantages and limitations and its applications

Methodology used:

None because it is no research paper.

Conclusion reached:

SLs are a useful and versatile reservoir engineering tool.

Comments:

1. Besides its higher speed (than FD simulation), another reason for SL simulation being useful in flood management is its ability to quantify injector-producer-relationships.
2. As it is easier to quantify uncertainty with SL simulation because of its higher speed, SL simulation is a potential catalyst for moving away from incorporating ever more detailed physics in a single representation of the subsurface and focusing on subsurface uncertainties instead.
3. SLs help interdisciplinary teams make timely reservoir-management decisions because SLs are visually powerful and intuitive to comprehend.

*SPE 100855-MS (2006)*: SPE Asia Pacific Oil & Gas Conference and Exhibition, 11-13 September, Adelaide, Australia

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“Commercial Success of Polymer Flooding in Daqing Oilfield – Lessons Learned”

Authors: Yupu, Wang; He, Liu

Contribution to the understanding of polymer EOR using SL simulation:

None, but demonstrated commercial success of polymer flooding in the Daqing field.

Objective of the paper:

To show the commercial success and technological improvements made in Daqing since 1996.

Methodology used:

None.

Conclusion reached:

Polymer flooding in Daqing has been commercially successful and technological improvements have been made.