A Study of the Grid Orientation Effect in the Gullfaks Brent Reservoir Simulation model.

By

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A report submitted in partial fulfillment of the requirements for the MSc and/or DIC

September 2011
Declaration of own work

I declare that this thesis

“A study of the Grid Orientation Effect in the Gullfaks Brent Reservoir Simulation Model”

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

Grid orientation effect on reservoir simulations has been studied many times since the 70’s and several SPE (Society of Petroleum Engineers) papers have been written in order to explain it and to suggest some ways to correct it. One of the main improvements is to use a multi-point flux approximation method. However when running a big model where some grid orientation effects can be suspected but not impacting dramatically, how to avoid using complex simulation methods in order to save Central Processing Unit time? Can the grid orientation be quantified and reduced in other ways so that the model can be simulated using simpler methods?

The Gullfaks Brent reservoir simulation model has been implemented and compared to history data; some grid effect was suspected due to difficulties in matching a well-oriented 45 degrees from the injector. This paper presents a study of the grid orientation effect on the water production in a segment of the model, where these wells are located. In this field case study, the grid orientation effect quantification can be complex. Results also depend on more practical facts that must be taken into account. Although reference will be done to the fine geological grid in a first stage, production data exist since 1986 and will be used in the process of real field case history match simulation. An investigation process will be proposed to detect existing grid effects. Demonstrations will be given, warning the users that grid orientation effects can change depending on the adjustments done in the process of history matching. In this field case, it will be shown that the adjustments contribute to reducing or vanishing the difference seen in simulating with different grid orientation, depending on wells. Finally a more general discussion will be open to suggest some ideas of future work to reduce these effects.
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The Gullfaks Brent reservoir simulation model has been implemented and compared to history data; some grid effect was suspected because of experiencing difficulties in matching a well oriented 45 degrees from the injector. This paper presents a study of the grid orientation effect on the water production in a segment of the model, where these wells are located. In this field case study, the grid orientation effect quantification can be complex. Results also depend on more practical facts that must be taken into account. Although reference will be done to the fine geological grid in a first stage, production data exist since 1986 and will be used in the process of real field case history match simulation. An investigation process will be proposed to detect existing grid effects. Demonstrations will be given, warning the users that grid orientation effects can change depending on the adjustments done in the process of history matching. In this field case, it will be shown that the adjustments contribute to reducing or vanishing the difference seen in simulating with different grid orientation, depending on wells. Finally a more general discussion will be open to suggest some ideas of future work to reduce these effects.

Introduction

The Gullfaks field lies in the northern part of the Norwegian North Sea. Production began in 1986 (Figure 1). The main recovery mechanism is water injection. In the segment model where the issue has been raised, the grid is oriented approximately 45 degrees relative to the injector I3 and the producer P1 (Figure 1). It is uncertain how this influences the history match of P1. Even with quite strong history match adjustments, the producer P1 does not predict as much water
production as observed in the historical data. A grid orientation effect was suspected but how will it influence the other producer P2 directly opposed grid wise to the injector I3?

A first step will be to define the grid orientation effect, review the literature and correlate our case to the former studies to state possibilities of grid orientation effect existence. Then the study will focus on creating a 45 degrees oriented grid versus the base coarse grid, called the diagonal grid. One step is to compare these base and diagonal grids, in order to observe the initial grid effect. Then a comparison will be done versus refined grids in order to see some expected convergence. Next step will be, in the process of history match, to run sensitivities on both orientations and observe the evolution of the grid orientation effect. Practical assumptions will be listed former to the analysis of the results to get a better understanding of the field case study. Finally, using these results and by opening a discussion, it will be attempted to answer to three objectives:

- If a grid orientation effect exists, which grid is closest to the “right answer”?
- While adjusting the model for history match, will the amplitude of the grid orientation effect be changed and in which ways?
- What factors can reduce the grid effect to get closer to a realistic model without changing the understanding of the geology?

**Literature Review**

When different grid orientations give different answers, under certain conditions, this has been termed as the grid orientation phenomenon. The saturation contours will have a diamond shape although it should be radial in the case of a five-spot pattern. That was first pointed out by Todd et al. (1972). The reason for this is that injected fluid, in a numerical model, will tend to flow along the grid lines. If the mobility ratio is favourable (below or equal to 1), refining can help decreasing the effect. In other cases, refining will not solve the problem, which shows that it is not only due to truncation errors. In a five point finite approximation, the issue comes from the fact that water mobility for a grid cell (i, j) can result in mobility at the grid cell (i+1, j) and (i, j+1) but not at (i+1, j+1) in the following step. Todd et al. (1972) first enounce the use of two-point upstream weighting of relative permeability that reduces the effect but not solve it. Holloway et al. (1975) proposed a method in which flow terms are corrected by accounting for diagonal flow. A finite-difference method using nine point approximations was developed by Yanosik and McCracken (1976) and is nowadays implemented in more complex simulators. An important observation was done by C.W. Brand et al. (1991): when the mobility ratio is greater than 1, the grid orientation effect can be understood as the numerical manifestation of a physical instability in addition to numerical dispersion. As long as numerical dispersion dominates the physical instability, refining will not be a solution and instead can grow exponentially. Therefore C.W Brand et al. (1991) suggests a method to determine a reasonable block size for a given displacement problem, depending on the mobility ratio. Correlating to the Gullfaks study case, where mobility ratio is approximately 1.6, it can be expected to see some grid orientation effect and some kind of convergence when refining since the case is not too unfavourable. The experiments will be oriented toward these assumptions, keeping in mind the last observation quoted.

Since history data exists, it is interesting to use these ones to study the grid orientation effect in addition to testing the consequences of refining. History data, in the process of history match, will be used to evaluate better the properties of the reservoir; it can also be useful to observe and monitor how the grid orientation effect is changed with the adjustments done. An interesting paper written by D. Eydninov et al. (2006) demonstrates the use of history matching procedure to estimate rock properties. It attempts using the chemical composition of the production to reduce the uncertainties on these ones with the history match procedure. It is shown that using simulators based on a multipoint flux approximation approach adopted in the permeability estimation problem is required if one wishes to perform history matching on distorted grids. This example suggests being careful with the history matching procedure while looking at numerical distortions such as grid orientation effect. It may lead to misinterpretation of the data in the parameter estimation, when using the traditional two-point flux approximation method. Therefore in this study, it is attempted to look also at the grid orientation effect on the parameter adjustments while history matching and advising on the history dependence of this effect.

**The Gullfaks Brent model**

The Gullfaks field lies in block 34/10 in the northern part of the Norwegian North Sea. It is a structural complex reservoir modelled with approximately 200 faults. It is subdivided into a domino system, an accommodation zone and a horst complex.

The structural complexity was a challenge during modelling and history matching. The simulation grid is constructed 100x115x47. Vertical layering is defined by proportional gridding and horizontal resolution is defined by control lines along the major faults. Faults are implemented by stair case to achieve right volumes in compartments and less distortion of grid cell shapes. The geological grid is a refinement of the simulation grid to get a good correspondence when upsampling from geological grid to simulation grid. Arithmetic upsampling method was used for porosity (weighting with bulk volume) and water saturation (weighting with pore volume); a diagonal tensor was used for permeability.

![Figure 2 : Gullfaks Lower Brent reservoir zonation](image)
Extensively faulted, the field comprises three major sandstone reservoir formations: Statfjord, Cook and the Brent group. It has been developed with three platforms - Gullfaks A, B and C. Statoil moved straight up among the subsea technology front-runners in 1986 by installing the most advanced seabed system of its day on Gullfaks. Based on diverless completion, six of these subsea wells were tied back to the A platform during 1986-87. Gullfaks is among the most significant oil fields in the North Sea. Peak production, reached in 1994, was more than 600 000 barrels per day (average 530 000 barrels per day). Average production in 1996 reached 440 000 barrels per day. The way forward during the first decade has been demanding and challenging, particularly because the field geology is very complex. The Gullfaks group has established ambitious goals beyond 2000. Recoverable reserves have been upgraded from the original estimate of 1.3 billion barrels to 1.9 billion barrels. The Lower Brent reservoir in which the wells are completed consists of 5 sequences, which will be referred to in the study (Figure 2).

Outline of the experiments

This study has been carried out on two geological realizations of the properties, in order to take into account the differences that could exist from one realization to another one. One realization among all 30 realizations has quite a different behaviour for the wells in question since it can match better the production history for the well P1. In order to look in a neutral way at the problem, grid orientation effect has been investigated on one random realization (R1) and then compared to realization R24 that is the one closest to the history, after adjustments on the model. The main difference observed in R24 is the permeability distribution that shows more of a higher permeable layer in sequence 3 between the I3 and P1 wells and a lower vertical permeability, which create a “channel” allowing a quicker lateral flow of the water (see appendix B). This last observation will drive the main actions taken to adjust for history match, as to “force” some kind of lateral flow to enable water to reach P1. Some completion details are given in a section below in order to explain why this preferential flow channel can help P1 to get more water, inversely less water for P2. The aim will be to analyse the initial grid orientation effect and its evolution for the two realisations in the adjustments done. Refined grids and history data will be used as references.

The main grids created and used for the study are:

- Base coarse grid (100x100m) called "Base" with 47 layers
- 45 deg oriented coarse grid (100x100m) called "Diagonal" with 47 layers
- Base grid refined laterally (50x50m) keeping 47 layers called “Refined base” using same upscaled properties in order to focus on the grid orientation effect
- 45 deg oriented grid refined laterally (50x50m) keeping 47 layers called “Refined diagonal” using same upscaled properties in order to focus on the grid orientation effect
- The Base and Diagonal grids with upscaled properties from realisation 24 on a coarse resolution similar to the two first grids stated above
- Geological grid with only the concerned segment model (50x50m with 394 layers) called “Fine”

The main adjustments done in the process of history match (that force a lateral flux between P1 and I3) and used here to run sensitivities for the study were:

- Adding lateral calcite barriers around the wells P1 and I3 on six to nine grid cells that have been observed on some wireline logs. The extent of these barriers will remain an uncertainty but the idea is to create this low permeable area at the right depth in the model, located in sequence 2, in order to help creating a preferential flow channel between these wells.
- Creating a permeability contrast between sequence 2 and 3 by putting maximum values and multipliers in the layers permeabilities in order to stress on what was observed in R24 and suspected to be present between these two wells. This understanding of the geology remains uncertain as the type of heterogeneity might vary. This illustrates a way to understand better the geology by using data available and the production history. It will be used here as an example to observe the evolution of the grid orientation effect to understand why P1 produces too little water. Another observation is that the coarse model has 47 layers whereas the fine has 394 layers, which can also explain that the vertical resolution in properties could have been “averaged” in an unfavourable way depending on the realisation.

Approach of quantification

A very important step is to set the way the grid orientation effect will be quantified to perform the analysis of the results. Note that the differences observed in the two orientated grid simulations will depend on the model but also the historical events and volumes as these are history simulations.

Here is a suggestion of a method based on the type of differences observed in the results (Figure 3):
• **Difference in percentage of the total water volume produced** at a time $t$. On a model point of view, it will depend on the difference in rates and in breakthrough. On a history point of view, it will depend on the volumes or rates produced in history and set in Eclipse. This set up, that is the same for the two grids, might influence differently the total volume produced: although the rates and breakthrough will occur at a different time depending on the model, an interruption of production will occur at the same time for the two grids.

• **Difference in time of breakthrough**: this depends on the velocity of the fluid injected and the fact that in a numerical model, it will tend to flow along the grid lines (see literature review section). This will consequently change the volume produced at a time $t$ in history. For example, if a well produces water for 10 years and the two grids orientations have a 1-year difference of breakthrough; it can be expected to see 10% difference in the volume of water produced. However this can vary due to the fact that history simulations are run in this study as stated in the first point. But also it can vary due to **difference in rates**. There might not be a “clear time translation” between the two simulations. If the rates remain quite similar but shifted in time like the breakthrough and if production interruptions or events in history do not occur too often, the total volumes produced curves will then be parallel.

• **Difference in rates**: it depends on velocities that depend on the rock and fluid properties, used in the mobility calculated on each grid cell crossed. From one grid to another, the number and type of grids cells followed by the fluid in its path (diagonal or direct/ lateral or vertical for example) to reach a point will affect these calculations. The difference in the number of grid cell crossed, their shapes and the additional pressure drops that can exist too, will affect the velocities. In this study, this concept will be stated as “Difference in rates”, either variable or stable. If stable, the acceleration of the fluid is the same; if variable, the simulations either converge or diverge. For water rate, it can be easier to look at water cut differences, as the difference in rates depend also on the difference in oil rates. Oil volumes are set by reservoir volumes and depend on surface volume factors. The grid orientation effect have therefore a little impact on the oil production, this is hidden by the fact that water breakthrough happens after an oil production of 80%. The difference in rates can be an important concept as it can be used to discuss how to reduce the effect later on: it is easier to treat a time-shifted problem with little difference in velocities.

![Figure 3: Illustration of the three criterias](image)

These criterias will be stated for each case in a table as part of the results section to analyse the grid orientation effect.

### Useful information for the study

Some assumptions related to the field case must be stated in order to start analysing the results of the study. These ones can help understanding the behaviours of the model.

• The Gullfaks Brent model is large. In order to shorten the simulation time, the segment where the wells are located has been isolated. Simulation has been run and compared to the full field model. Since the segment is nearly isolated due to the surrounding extended faults, production results do not differ much but the difference in pressure is around 50 bars, keeping the pressure above the bubble point. Due to this, the isolated segment model will be used for looking at production volumes but not pressure.

• P1 is completed in sequence 1 to 4 whereas P2 is completed only in sequence 1 and 2. I3 is completed in sequences 1 to 3. Due to this, creating a high permeable lateral channel in the sequence 3 will help P1 to produce more water, and inversely to reduce water produced by P2. This also helps understanding why the realization 24 is favourable to P1 water production as the vertical permeability is lower (needed for the water to travel from the channel to the perforated sequence in P2).
The water production on the two wells seems to be very dependent on each other. P2 is closer to I3. The grid effect, if existent, is expected to be smaller. Pseudo relative permeability functions are used and calibrated for the actual model. This is a property that might be interesting to test when investigating for reducing the grid orientation effect and will be discussed later in the paper.

Results of simulations

Water fronts on Base, Diagonal, Refined base and diagonal grids

As seen previously in the literature review, it can be expected to see some grid orientation effect in this case (Figure 4). The difference in shapes of water front between the two grids in the two resolutions exists and it is more contrasted in the coarser grids. The next step is to attempt observing some type of convergence when refining laterally as observed in the literature review when the mobility ratio is not too unfavourable.

An important observation is that the direct path for each well, on a coarse resolution, sees an earlier breakthrough and seems to be faster (Figure 5 and Figure 6): it is the diagonal grid for P1 and the base grid for P2. If there is a tendency to converge, then a reference to the Fine simulation can be done in order to see which model is closer to geological grid (Figure 7 and Figure 8). Another objective is to see how the grid orientation effect changes when adjusting the model in the process of history match. As stated earlier in the outline section, work has been done on two realisations and will also be presented from Figure 9 to Figure 20. Finally a comparison to history production data will be presented (Figure 21 and Figure 22).
Comparisons of Diagonal and Base coarse grids to Refined grids to see an eventual convergence

Producer P1: Initial model without any history adjustments

Figure 5: Simulation results for P1 for Diagonal and Base grids on two lateral resolutions: a tendency of convergence for some models although the direct path represented in the 100x100m diagonal grid for P1 stands out from the other cases.

Producer P2: Initial model without any history adjustments

Figure 6: Simulation results for P2 for Diagonal and Base grids on two lateral resolutions: Convergence between refined laterally and diagonal coarse. The direct path represented in the 100x100 base grid for P2 stands out from the other cases.
Comparisons of Diagonal and Base coarse grids referencing to Fine

Figure 7: Comparison of simulation results for P1 between the Diagonal and Base referencing to Fine grid

Figure 8: Comparison of simulation results for P2 between the Diagonal and Base referencing to Fine grid
Comparison of Base and Diagonal grids in the process of history matching in realization 1

Figure 9: Water cut, water and oil production for P1 in initial model in R1

Figure 10: Water cut, water and oil production for P1 after adding calcite barriers for R1

Figure 11: Water cut, water and oil production for P1 after creating a permeability contrast between sequence 2&3 in R1
Figure 12: Water cut, water and oil production for P2 in initial model in R1

Figure 13: Water cut, water and oil production for P2 after adding calcite barriers for R1

Figure 14: Water cut, water and oil production for P2 after creating a permeability contrast between sequence 2&3 in R1
Comparison of Base and Diagonal grids in the process of history matching in realization 24

Figure 15: Water cut, water and oil production for P1 in initial model in R24

Figure 16: Water cut, water and oil production for P1 after adding calcite barriers for R24

Figure 17: Water cut, water and oil production for P1 after creating a permeability contrast between sequence 2&3 in R24
Figure 18: Water cut, water and oil production for P2 in initial model in R24

Figure 19: Water cut, water and oil production for P2 after adding calcite barriers for R24

Figure 20: Water cut, water and oil production for P2 after creating a permeability contrast between sequence 2&3 in R24
### REALIZATION 1

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<th>Difference in rates</th>
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<td></td>
<td>P2</td>
<td>1 month</td>
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<td>12%</td>
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<tr>
<td>Permeability contrast</td>
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<td>2 years</td>
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### REALIZATION 24

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<td>3 months</td>
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<td>&lt;5%</td>
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<td></td>
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<td>Permeability contrast</td>
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<td>13%</td>
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<tr>
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<td>P2</td>
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<td>~0</td>
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</table>

Table 1: Summary of the results of simulations on the coarse grids upscaled from realization 1 and 24 using the two grid orientations (Base and Diagonal) and adjustments

Referencing the two grids to production history

![Figure 21: Water cut, water and oil production for P1 in Realization 24 compared to history data](image-url)
Figure 22: Water cut, water and oil production for P2 in Realization 24 compared to history data

This is not the final history matched simulation model because other wells exist in the segment and must be taken into account. However this illustrates the changes overtaken in the adjustments for history match and the evidence of some unfavourable effects for P1 water production in the base grids.

Water fronts on Base and Diagonal on the two realisations

Figure 23: Grid orientation effect observed on 2D graphs plots of water saturation front on Base and Diagonal grids on the two realizations
Analysis

Comparison of the Base and Diagonal coarse grids to the Refined base and diagonal grids: effect of lateral refinement

After observing the existence of some grid orientation effects (Figure 4), the first step was to compare the two simulations results to laterally refined grids in the two orientations (Figure 5 and Figure 6). For each well, three simulations, that are the diagonal path for the concerned well (Base for P1 and Diagonal for P2) and the two lateral refined grids (Refined base and Refined Diagonal) tend to converge. The shorter path (Diagonal for P1 and Base for P2), that is included in the grid that gives the well a direct path to the injector, will stand out and have higher fluid velocities then the other simulations. But if we look closely to the rates, the refined cases tend to converge with the shorter path on late times. This can suggest that the total volumes produced could have a late behaviour close to the shorter path although their early behaviour is close to the longer path. The issue is that the two wells have inverse behaviours due to their position and are not independent, which make the concept of a “good model” quite complex. It is difficult to use one model for an early behaviour and another one for a late behaviour.

Comparison of the Base and Diagonal coarse grids to the Fine grid: effect of the vertical heterogeneities

To verify the observation done formerly, a comparison to the Fine grid has been done (Figure 7 and Figure 8). It can be observed and confirmed that the Fine grid behaviour is close to the longest path at early time and to the shortest path at late time. There is a clear transition of the Fine grid in between the two other grids, both on the total volumes and on the rates. It might be analysed from these results that the early behaviour for the coarse grids is too fast and the late behaviour too slow. As mentioned earlier in the outline of the experiments, the coarse model has 47 layers whereas the fine has 394 layers, which could induce a lost in the vertical resolution of the properties while upscaling.

Quantification of the grid orientation effect using the three criterias

Therefore the grid orientation effect quantification has been carried out on two realisations (Figure 9 to Figure 20) with different permeability profiles (see appendix B), one more favourable to history match. On the three criterias of quantification, the grid orientation effect is lower in realisation 24 than in realization 1 (Figure 14 for R24). It is suspected that a channelled flow exist more in the favourable realization. “Forcing fluids to flow laterally” shortens the paths. Grid orientation effect is a result of more or less longer paths depending on the grid. The longer the path, the bigger the difference will be between the Base and the Diagonal grids. As a consequence, wells closer to the injector can be expected to have less grid orientation effect, which is the case for P2.

Looking at Table 1, different behaviours can be noticed on the sensitivities done on the two realisations to adjust for history match, aiming to increase the water production:

- When creating calcite barriers around P1 and I3 in sequence 2 (Figure 10 and Figure 13 for R1; Figure 16 and Figure 19 for R24), which are not exactly the same in each grid due to the size and placement of the blocks, the difference in the rates vary a lot although the difference in breakthrough time is the same, when comparing to the initial model without adjustments (Figure 9 and Figure 12 for R1; Figure 15 and Figure 18 for R24). The difference in total volume of water produced is consequently increased for P1 in this adjustment, especially in the diagonal grid. The velocities difference between the diagonal and base grids is also due to the permeability contrast existing between a block set in the calcite barrier zone and the one that are not: depending on how much fluid flows through these layers, different in the two grids, the front will be slowed down compared to fluid flowing above in sequence 3.

- When creating some permeability contrast between sequence 2 and 3 in order to “force lateral flow” (Figure 11 and Figure 14 for R1; Figure 17 and Figure 20 for R24), it was also expected to see the difference in breakthrough time reduced in both realizations compared to the initial model without adjustments (Figure 9 and Figure 12 for R1; Figure 15 and Figure 18 for R24). Although the quantities produced are increased due to the adjustment, the difference in total volume of water produced should be reduced too. The difference in rates is quite stable in this case due to the uniform channel that allows a lateral flow. For realization 24, the difference in breakthrough is decreased compared to the initial case without adjustments. The difference in rates is quite stable and therefore the 13% difference in total water produced corresponds approximately to the difference in breakthrough. For realization 1, the difference in breakthrough is actually increased compared to the initial case. However the difference in rates is quite stable whereas in the initial case it was not, which explains that the two cases can not be compared to each other. It might be that if the accelerations of the fluid were similar and at the highest value in the initial model, the difference in breakthrough would have then been higher.

- The difference in rates remains quite stable in the sensitivities run in realization 24 whereas it isn’t in realization 1. This is due again to the permeability distribution in realization 24 that helps fluids to flow laterally. Two main comments can be raised concerning the difference in rates:
Comparing to history data

There is clearly a better match for the diagonal grid in the case of P1 well whereas the grid orientation effect is inexistent for P2 well (Figure 21 and Figure 22) after adjustments. But, as seen formerly, the fine grid will not necessarily match the diagonal grid completely although it might be close on a late behaviour. The grid orientation effect is however quite reduced when adjusting which confirms that it is not the main issue in this case.

Summary

After a comparison of the Base and Diagonal coarse grid to refined grids, it is observed that a grid orientation effect exists and that P1 and P2 have an inverse behaviour. When simulating on the two grid orientations, the choice of a grid was difficult since one coarse grid (Base or Diagonal) would match the refined grids on either the early or late behaviour inversely between the producers P1 and P2. To summarize this observation, the shorter path for the two wells would match better on late behaviour whereas the longer path would match on early behaviour. That is due to the vertical resolution lost in upsampling from 394 layers to 47 layers: the two grids, where the flow path will be different, will produce water differently, depending on how “vertical is the fluid path”.

Therefore the grid orientation effect has been quantified on two realisations of the properties from the geological grid in order to observe the difference between the Base and Diagonal grids while adjusting in the history match process. One realization and the adjustments done contribute in reducing a lot the grid orientation effect when getting closer to the history data: the difference in breakthrough time, in volumes produced and in rates between the Base and Diagonal grids are reduced comparing to other realizations without adjustments. When comparing to history data, the Diagonal grid match better but the difference for P1 between the Base and Diagonal grid is low while it has disappeared for P2. Fortunately the grid orientation effect is decreased with this adjustments and realization, which shows that the grid orientation impact is finally low in this case.

On a more general point of view, it is quite complex to quantify the grid orientation effect on a field case when history matching, due to time dependent events and well dependent characteristics. Although differences exist between several oriented grids, it might not be necessary or possible to apply solutions given in former papers due to the implementation of the model and its complexity. A mistake could be done in trying to adjust for history match on grids that might be too optimistic or not enough on later behaviours. Although grid orientation effects exist at a time t when comparing to history, it might converge or diverge; an important point is to choose the appropriate model for prediction.

Finally it was noticed that many actions or factors such as constructing pseudo relative permeability, upscaling methods or adjusting on wells controls could influence on the grid orientation effect. Therefore it could be interesting to run sensitivities, test and quantify on real cases their impact to reduce these effects, keeping in mind to use reasonable actions in the field context for future use of the model.

Discussion and suggestions for further work

It is easy to be mistaken on the grid orientation effect while running history simulation as the model sometimes do not have time to converge or stabilize, if it happens later in time. Separating the quantification in different criterias similarly to this study can help explaining some unexpected behaviour. Being aware of this issue, it is important to adjust to the right model, which can be used later as a prediction model.

If a grid orientation effect is suspected and detected in a field case model, it can be a good practise to try quantifying it the same way as it was done in this study: correlate to literature cases and check that the mobility ratios range is not too unfavourable (in that case consider solutions given in former papers), if not run laterally refined and geological grids on a sector model to find a tendency of convergence, and finally evaluate the changes in grid orientation effects while adjusting the model. In the case of this study, the results analysis showed that “forcing lateral flow” while adjusting for history match would decrease the grid orientation effect. If after adjustments the grid orientation has increased, it might be good to use the analysis done while comparing to finer grids to understand which model can fit best in future work. A suggestion would be investigating on several orientations to find a reasonable fit for all wells for instance.

More generally, which factors could be investigated to reduce the existing grid orientation effect on a field case? Several ideas have been raised in this study that can be discussed and tested in future work:

- When constructing pseudo relative permeability, the grid orientation effect can be considered as a factor. The relative permeability impacts the ability of the fluids to flow in presence of other fluids; the mobilities calculation differ, difference in volumes, rates and breakthrough time will be different (Appendix C)
- When several wells are subject inversely to an important grid orientation effect, a good practise is to create and test several grid orientations in order to find a reasonable fit to all wells (Appendix D)
• When the difference in rates is quite stable (running a prediction simulation can help seeing this), the problem can be assimilated to a shifted case with a lag time equivalent to the difference in breakthrough. It can be interesting to test some adjustments on well controls in order to force breakthrough time. However a special care must be taken in order to respect the history events. The advantage of this action is that it is well dependent and not global model dependent.

• Finally upscaling methods can also influence the grid orientation effect. Compensating for or reducing the effect can be tested but keeping a good understanding of the geology has to be a priority.

References

## Literature review

Appendix A: Literature review

<table>
<thead>
<tr>
<th>SPE Paper №</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>3516</td>
<td>1972</td>
<td>Methods for Increased Accuracy in Numerical Reservoir Simulators</td>
<td>M.R. Todd, P.M. O’Dell, G.J. Hirasaki</td>
<td>This paper proposes first the use of two point upstream weighting of fluid mobility to reduce grid orientation effect.</td>
</tr>
<tr>
<td>5522</td>
<td>1975</td>
<td>“Reduction of Grid orientation effect in reservoir simulation”</td>
<td>Carl C. Holloway, L. Kent Thomas, Ray G Pierson</td>
<td>This paper presents a method for reducing grid orientation effects, inherent in Finite difference simulators, by modification of the interblock phase transmissibilities to account for diagonal flow.</td>
</tr>
<tr>
<td>5734</td>
<td>1979</td>
<td>“A Nine-Point, Finite-Difference Reservoir Simulator for Realistic Prediction of Adverse Mobility Ratio Displacements”</td>
<td>J. L. Yanosik, T.A. McCracken</td>
<td>First to discuss the development and testing of a nine-point, finite-difference reservoir simulator.</td>
</tr>
<tr>
<td>6100</td>
<td>1979</td>
<td>“Grid orientation effects and the use of orthogonal Curvilinear coordinates in Reservoir simulation”</td>
<td>G.E. Robertson, P.T Woo</td>
<td>Proposal to reduce grid orientation effects by using an areal orthogonal curvilinear grid, solution that does not require any programming change.</td>
</tr>
<tr>
<td>8248</td>
<td>1979</td>
<td>“A weighted nine-point–finite-difference scheme for eliminating the grid orientation effect in numerical reservoir simulation.”</td>
<td>C.M Stephen Ko, D.K Anthony Au</td>
<td>It is an extension of the previous nine-point finite-difference formulation where the weighting factors involved in the linear combination are made variable.</td>
</tr>
<tr>
<td>12248</td>
<td>1983</td>
<td>“Interpretation of Results From Well Testing Gas-Condensate Reservoirs: Comparison of Theory and Field Cases”</td>
<td>K.H. Coats, A.D Modine</td>
<td>This paper presents a method for calculating nine-point transmissibilities for a general heterogeneous system with unequal grid spacing.</td>
</tr>
<tr>
<td>12250</td>
<td>1983</td>
<td>“Finite Difference Solutions to Grid Orientation Problems Using IMPES”</td>
<td>W.J.Bertiger, L.Padmanabhan</td>
<td>New nine point finite difference method based on interpolation of fluid velocities across the cell boundary. Reduces the effect of grid orientation with both uniform and non-uniform grids. It is also easily incorporated into any conventional finite difference code.</td>
</tr>
<tr>
<td>12251</td>
<td>1983</td>
<td>“A Nine-Point Finite Difference Operator for Reduction of the Grid Orientation Effect”</td>
<td>P.C. Shah</td>
<td>Developed a new nine-point difference operator especially suited to the block centered grid; this new scheme maintains symmetry of the coefficients since it is derived from the physical considerations. This scheme is applicable to an inhomogeneous permeability distribution and to non uniform rectangular grids.</td>
</tr>
<tr>
<td>21228</td>
<td>1991</td>
<td>“The Grid Orientation Effect in Reservoir Simulation”</td>
<td>C.W. Brand, J.E. Heinemann, Leoben; K. Aziz</td>
<td>The purpose of this paper is to provide for immiscible displacement a detailed analysis of the interplay of numerical and physical instability in finite difference methods. The results show that in general the GOE cannot be overcome with grid refinement. For a certain range of parameters, however, first the GOE decreases under grid refinement, reaching a minimum, and then increases again on finer grids. A technique is provided for estimating reasonable block size for a given displacement problem.</td>
</tr>
<tr>
<td>88617</td>
<td>2004</td>
<td>“A unique Grid-Block System for Improved grid orientation”</td>
<td>E.Chong, Z.Siyah, E.Putra, D.Schechter</td>
<td>Propose using hybrid grid blocks (Rectangular grid blocks are interspersed with orthogonal grid blocks. Boundaries are populated with triangular grid blocks) to reduce the computational work involved in solving a linear equation of finite difference equations and therefore the grid orientation effect.</td>
</tr>
</tbody>
</table>
Authors: M.R. Todd, P.M. O’Dell, G.J. Hirasaki

Contribution to the grid orientation effect: First paper that proposes the use of two point upstream weighting of fluid mobility.

Objective: Two methods to increase the computing efficiency of reservoir simulators: the use of upstream weighting of fluid mobility and an automatic time step selector for control of solution oscillations.

Methodology used: Upstream weighting of fluid mobility and Stability analysis on confined five spot waterflood pattern for different mobility ratios using parallel and diagonal grids.

Conclusion reached:
Total cost of reservoir simulation can be reduced thanks to the two methods described:
- The computing time can be reduced until 40 time using a two point scheme instead of a single point scheme.
- A practical base for automatic selection of time step provided in the paper save engineering and computing time.
SPE 5522: Reduction of Grid orientation effect in reservoir simulation (1975)

Authors: Carl C. Holloway, L. Kent Thomas and Ray G Pierson

Contribution to the grid orientation effect: This paper presents a method for reducing grid orientation effects, inherent in Finite difference simulators, by modification of the interblock phase transmissibilities to account for diagonal flow, using also the two point weighting scheme in calculating mobilities.

Objective: Reducing grid orientation effect by modification of the interblock phase transmissibilities to account for Diagonal flow.

Methodology used: Derivation and modification of the transmissibilities in IMPES and simulation on cases such as with different mobilities and on a five spot pattern waterflood system.

Conclusion reached: With the two point upstream mobility weighting and the modified transmissibilities, the grid orientation can be eliminated but not for all problems with high mobility ratios. More accurate description if the saturation surface is necessary to eliminate completely the grid orientation effect.

Comments: the effect of this method is nevertheless smaller compared to the effect of the two point upstream weighting scheme for calculating mobilities, introduced by Todd et al. (1972).
SPE 5734: A Nine-Point, Finite-Difference Reservoir Simulator for Realistic Prediction of Adverse Mobility Ratio Displacements (1979)

Authors: J. L. Yanosik, T.A. McCracken

Contribution to the grid orientation effect: First to discuss the development and testing of a nine-point, finite-difference reservoir simulator.

Objective: Because reservoir simulators based on a five point finite difference techniques do not predict the correct performance for unfavourable mobility ratio, the objective is to test a nine point finite difference reservoir simulator and show that it help reducing the grid orientation effect.

Methodology used: Simulate the technique on a five spot pattern system for mobility ratio ranging from 0.5 to 50.

Conclusion reached:
- For unfavourable mobility ratio immiscible displacement, the nine point finite simulator gives similar results as a five-point simulator with two-point upstream mobility weighting.
- For unfavourable mobility ratio piston like displacement, the nine point finite simulator gives better results then a five-point simulator with two-point upstream mobility weighting that gives unrealistic results.
SPE 6100: Grid orientation effects and the use of orthogonal Curvilinear coordinates in Reservoir simulation (1979)

Authors: G.E. Robertson, P.T Woo

Contribution to the grid orientation effect: Proposal to reduce grid orientation effects even in the case of unfavourable mobilities by using an areal orthogonal curvilinear grid, solution that does not require any programming change.

Objective: Reduce grid orientation effects by using an areal orthogonal curvilinear grid, solution that does not require any programming change.

Methodology used: Implement in IMPES an areal orthogonal curvilinear grid and test on five spot pattern waterflood and steam injected system. Comparison with former work presented in a literature review.

Conclusion reached: Grid orientation has a more pronounced effect:
- On saturation front than on oil recovery.
- On a nine spot steamflood than on five-spot steamflood

The curvilinear grid can be easily used to estimate flood performance without programming modification.

Comments: Only the orthogonal curvilinear coordinates in areal “one layer” simulation are discussed here. In layered or 3D systems, the technique should be similar but tested.
SPE 8248: A weighted nine-point-finite-difference scheme for eliminating the grid orientation effect in numerical reservoir simulation (1979)

Authors: C.M Stephen Ko, D.K Anthony Au

Contribution to the grid orientation effect: It is an extension of the previous nine-point finite-difference formulation where the weighting factors involved in the linear combination are made variable.

Objective: Develop and test a weighted nine-point finite difference scheme.

Methodology used: numerical experiments for shock mobility ranging from 1 to 50.

Conclusion reached:
- The developed nine-point scheme is independent of grid orientation for quarter five spot patterns.
- The weighting factors are a function of shock mobility ratio and independent of grid block size and treatment of interblock mobility.
- For adverse shock mobility ratio (greater than 10) piston like displacements, a refined areal grid is required to predict accurately the areal sweep for the flood pattern.
Contribution to the grid orientation effect: This paper presents a method for calculating nine-point transmissibilities for a general heterogeneous system with unequal grid spacing.

Objective: Provide a method for calculating nine-point transmissibilities for a general heterogeneous system with unequal grid spacing.

Methodology used: Derivation of the transmissibilities calculations and test by simulating on heterogeneous reservoirs, nonuniform or variable grid spacings.

Conclusion reached: This method for calculating transmissibilities coefficients for inclusion of a nine-point finite difference scheme is more adapted to heterogeneous reservoirs.

Comments: This paper is the continuity of Yanosik and McCracken, except that the transmissibilities calculation is adapted.
Contribution to the grid orientation effect: New nine point finite difference method based on interpolation of fluid velocities across the cell boundary. Reduces the effect of grid orientation with both uniform and non-uniform grids. It is also easily incorporated into any conventional finite difference code.

Objective: Provide a nine-point finite difference scheme that works for uniform and non-uniform grid spacing.

Methodology used: Derivation of the nine point finite scheme based on the interpolation of fluid velocities across the cell boundary and numerical tests.

Conclusion reached:
The velocity interpolation method had a good performance in reducing the grid orientation effect when applying in both five-point finite or nine-point finite difference schemes.

Authors: P.C. Shah

Contribution to the grid orientation effect: Developed a new nine-point difference operator especially suited to the block-centered grid; this new scheme maintains symmetry of the coefficients since it is derived from the physical considerations. This scheme is applicable to an in a homogeneous permeability distribution and to non-uniform rectangular grids.

Objective: Developed a new nine-point difference operator especially suited to the block-centered grid

Methodology used: numerical study on steam flood five spot pattern system

Conclusion reached: The new scheme, specifically derived for block centered grids and based on physical considerations, reduce the grid orientation effect when tested on a thermal simulator for non-uniform rectangular grids and anisotropic rock permeabilities.

Comments: It is an extension again of the nine-point finite difference scheme introduced by Yanosik and McCracken
Contributions to the grid orientation effect:
- Differentiate the effect due to anisotropic numerical diffusion and physical instability of the displacement front by applying a linear stability analysis to the finite difference equations.
- Confirms that the Grid orientation effect cannot always overcome by refining but that it can also become worst.
- Provides a technique for estimating reasonable block size for a given displacement problem.

Objective:
Provides a technique for estimating reasonable block size for a given displacement problem in a case of adverse mobility ratio displacement.

Methodology used: Use of linear stability analysis of the finite difference equations for immiscible, incompressible, two phase flow.

Conclusion reached:
The grid orientation effect can be understood as the numerical manifestation of a physical instability. As long as the numerical dispersion dominates this physical instability, “numerical fingering” occurs and has an exponential growth in the case of mobility ratio greater than one. The linear growth rate can be used to predict the grid size for which the error remains small.

Comments: This paper gives for the first time the two reasons of the difference observed in simulating different grid orientation: numerical dispersion and physical instability.

Authors: W.H. Chen, L.J. Durlofsky, B.Engquist, S.Osher

Contribution to the grid orientation effect: Tested and proved the efficiency in reducing grid orientation effect by using higher order finite difference methods.

Objective: Second order TVD and third order ENO schemes are applied to minimize numerical dispersion, allowing for the accurate resolution of stabilizing terms and the subsequent minimization of grid orientation effects.

Methodology used: Apply higher order, shock capturing, and finite difference methods on miscible and immiscible displacement processes. Two higher order methods are investigated: Second order TVD (total variation diminishing) scheme and a third order ENO (essentially non oscillatory) scheme.

Conclusion reached: The ENO scheme is able to resolve the stabilizing effects of physically dispersive terms. The ENO and TVD scheme can reduce substantially the grid orientation effect relative to the first order method, even on heterogeneous reservoirs. When using higher order numerical methods, it does not only reduce the grid orientation effect but also allow using coarser grids and saving CPU time keeping the same accuracy.
Contribution to the grid orientation effect: The method provides improved accuracy for simulating infill drilling, pattern realignment, horizontal well, reducing grid orientation and numerical dispersion.

Objective: Provide a practical method for minimizing grid orientation effect and numerical dispersion: a nine-point formulation of the pressure and saturation equations with a third order accurate total variation diminishing scheme (TVD).

Methodology used: Derivation of the method then coded in the simulator. Test on immiscible and miscible floods, on anisotropic systems and finally on heterogeneous reservoirs.

Conclusion reached: The technique developed in the paper outperforms previous techniques in minimizing the grid orientation effect and the numerical dispersion if five nodes between well pairs us is respected (less than 1% recovery).
Authors: E.Chong, Z. Syihab, E.Putra, D.Schechter

Contribution to the grid orientation effect: Provide a grid block type to reduce the grid orientation effect.

Objective: Develop a grid system that can improve the representation of the configuration and minimize the grid orientation effect: rectangular grid blocks interspersed with octagonal grid blocks. Boundaries are populated with triangular grids blocks.

Methodology used: Comparison of simulations of a quarter five spot waterflood using parallel and diagonal grids with different mobility ratios: 0.5, 1 and 10.

Conclusion reached:
- Grid orientation is always observed in general even with favourable mobility ratios
- Refinement can help reducing the effect but not vanishing it for favourable mobility ratio (equal or lower than 1).
- The hybrid grid implemented in this study is able to minimize the grid orientation effect even for unfavourable mobility ratio (greater than 1) with relative difference of about 6% for all cases run.

Comments: There is a good literature review on the work done on the grid orientation effect in this paper, summarizing thematically and not historically. The hybrid grid block proposed might not be easy to implement for complex structural reservoir, where distorted cells might occurs a lot.
Appendix B: Realization 24 characteristics

The above figures demonstrate that realisation 24 has properties definition that allows a preferential flow of the water in sequence 3 compared to realisation 1. For that reason, as seen in the results of the study, the grid orientation effect is lower in realisation 24 than in realisation 1 as the fluid flows mainly along the same path, either in diagonal or base grids.
Appendix C: Example of relative permeability effect on the two-grid orientations

A large difference in breakthrough shift between the two sets of relative permeabilities can be observed. This must be taken into account when creating the pseudo functions.
Appendix D: Example of testing different orientated grids

These figures demonstrate that testing several grid orientations gives unexpected results. Indeed the volumes produced and the rates observed are to be questioned, as the results do not show any logical order. The analysis of these is not obvious and might require more investigation and further work.