IMPERIAL COLLEGE LONDON

Department of Earth Science and Engineering

Centre for Petroleum Studies

Reservoir Heterogeneity: Should It Be Modelled as Conformance or Dispersion?

By

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

September 2010

DECLARATION OF OWN WORK

I declare that this thesis "**Reservoir Heterogeneity: Should It Be Modelled as Conformance or Dispersion?**" 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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Name of student: Adnan Khalid

Name of supervisor: Dr. Ann H. Muggeridge

Abstract

Displacement efficiency in any Enhanced Oil Recovery (EOR) process is affected by how we model reservoir heterogeneity, particularly in contrasting permeability layered reservoirs. Vertical sweep efficiency is adversely affected if flow is dominated by advection or channelling of the oil-displacing agent. The displacing agent would flow preferentially through the high permeability layer and would leave the low permeability layer partially swept. On the other hand, flow dominated by dispersion would increase the vertical sweep efficiency. While this might not ensure better microscopic displacement efficiency, either way, correct identification of flow regime has a significant effect on overall oil recovery and project economics.

This paper investigates whether conformance or dispersion is the dominant process during 1st contact miscible displacement in a layered reservoir and to determine the relevant importance of both the mechanisms on recovery during single well tracer tests (SWTT) and well to well tracer tests (WTWTT). We have used diffusion coefficient as an input and calculated Taylor's 'effective diffusion' using method presented by Brigham et al. (1961) for both SWTT and WTWTT over same distance and pore volumes. Using Lake and Hirasaki's (1981) transverse dispersion number N_{TD}, we have attempted to segregate conformance from dispersion. The impact of variations like reservoir height, vertical permeability and permeability contrast ratios were investigated to see their impact on mixing in the reservoir.

For high values of N_{TD} used in this study, diffusion driven dispersion dominates convection dominated conformance as predicted by Lake and Hirasaki (1981) & Tungdumrongsub and Muggeridge (2010). As the N_{TD} decreases and approaches unity, convection appears in a more pronounced manner. Due to software limitations, we have not been able to establish the exact value of N_{TD} where transition from diffusion dominated flow to convection dominated flow takes place. For higher values of N_{TD}, when dispersion is dominating conformance, recovery is the quickest. The recovery time increases as N_{TD} decreases, as in convection dominated conformance. This work gives a comparative extent of mixing in a layered reservoir through SWTT and WTWTT.

Acknowledgements

I would like to thank Dr. Ann H. Muggeridge for her support, guidance and patience during this study, without which getting this done would have been very difficult.

I would like to dedicate this work to my mother who made it possible for me to join this MSc Program; whose love, encouragement, prayers and belief in me continues to strengthen my spirits; to the loving memory of my father who instilled the virtues of patience, hard work and perseverance in me and made me the person that I am today and last but certainly not the least, to my loving wife for bearing with me, so patiently.

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Reservoir Heterogeneity: Should It Be Modelled as Conformance or Dispersion?

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For high values of N_{TD} used in this study, diffusion driven dispersion dominates convection dominated conformance as predicted by Lake and Hirasaki (1981) & Tungdumrongsub and Muggeridge (2010). As the N_{TD} decreases and approaches unity, convection appears in a more pronounced manner. Due to software limitations, we have not been able to establish the exact value of N_{TD} where transition from diffusion dominated flow to convection dominated flow takes place. For higher values of N_{TD}, when dispersion is dominating conformance, recovery is the quickest. The recovery time increases as N_{TD} decreases, as in convection dominated conformance. This work gives a comparative extent of mixing in a layered reservoir through SWTT and WTWTT.

Introduction

Recovery of oil through Enhanced Oil Recovery (EOR) processes is dependent on displacement efficiency. Recovery efficiency is a function of volumetric sweep efficiency and microscopic displacement efficiency. Volumetric sweep efficiency quantifies the degree to which the oil in a reservoir is contacted by the displacing agent; both in the areal extent (areal sweep efficiency) and vertical extent (vertical sweep efficiency). Microscopic displacement efficiency quantifies the effectiveness of the displacing agent in displacing the oil at the pore level.

Reservoir heterogeneity, particularly contrasting permeability layers, can have an unfavourable impact on the vertical sweep efficiency during a displacement process. In such a reservoir with vertically completed injector and producer wells, advection or channelling of the oil-displacing agent would result in reduced vertical sweep efficiency. The displacing agent tends to have a preference for the high permeability layer and would only partially sweep the low permeability layer leaving sizeable quantity of oil unrecovered.

However, dispersion due to genuine mixing would significantly improve the vertical sweep efficiency of the displacement process. Lake and Hirasaki (1981) showed that due to transverse dispersion during first contact miscible displacements in a layered system could cause cross flow of displacing agent from high permeability layer into the low permeability layer. If this transverse mixing is big enough then the vertical sweep efficiency can approach 100%. This, however, might not ensure improved oil recovery since dispersion may adversely affect the microscopic displacement efficiency (Sehbi et al. 2001). Dispersion may require a larger slug of displacing agent. Nonetheless, either treatment of flow regime would have an impact on overall oil recovery and reservoir economics. Hence during design of any EOR process, correct identification of the effect of heterogeneity either as conformance or dispersion is important for optimum reservoir management.

In order to model either of the processes requires an accurate estimation of the extent of mixing in the reservoir over a range of length scales. For a heterogeneous media, although there have been plenty of research both through simulations and field tracer tests, there is still confusion in reaching a common conclusion on how to do this. Dispersivities, which are a function of particle size and local heterogeneity, calculated through core analysis, single well tracer test (SWTT) or commonly known as echo tests and well to well tracer tests (WTWTT) or transmission test appear to be scale-dependent. Single well tracer tests & well to well tracer test conducted at the field level and on laboratory cores by Pickens and Grisak (1981) support this. Many researchers have reported similar observations (Rigford et al. 1990; Mahadevan et al. 2002; Kulkar et al. 1988). However, in a recent paper, Coats et al. (2004) differentiates between apparent dispersivity and physical dispersivity. He observes that apparent dispersivity is due to conformance whereas physical dispersivity is a rock property and typically has values equal to the ones found at the core level. Furthermore, he opines that scale dependence of dispersivity is devoid of meaning and exists as a consequence of using the non-applicable one dimension convection-dispersion equation to analyse effluent profiles which in fact reflect conformance. Another explanation for difference between SWTT and WTWTT dispersivities is given by Jha et al. (2009) who says that the difference exists because the WTWTT test includes the effects of the diffusion and velocity dependent mixing or what he refers in his paper as convective spreading lumped together. Convective spreading, being reversible, is cancelled on flow reversal and therefore, the dispersivity calculated through echo tests only includes the effects of diffusion (which is irreversible).

It is the purpose of this paper to investigate simulations of tracer propagation in a 2-dimensional layered heterogeneous media using physical diffusion in single well tracer tests and well to well tracer tests and comment on the following:

- How does macroscopic dispersion estimated by Single Well tracer Tests (SWTT) compare with Well to Well Tracer Test (WTWTT) in a layered reservoir and
- Whether it is possible to distinguish between complete transverse mixing in the reservoir and channelling from tracer tests

Concepts and Definitions

Taylor (1953) suggested that displacement of a solute in a solvent flowing through a capillary tube will be governed by the Diffusion equation:

$$\frac{\partial C_m}{\partial t} = K\frac{\partial^2 C_m}{\partial {x_1}^2} \quad \text{.......(1)}$$

however, he showed, the only difference in this case was that the rate of mixing is governed by a dispersion coefficient, *K*, instead of the usual Fickian diffusion coefficient, *D*. He developed a relationship between *K* and *D* and showed that *K*, in this case, is far larger than *D*. The dispersion coefficient quantifies mixing over an averaged section. Dispersion is characterised as having contributions from (i) convection and (ii) molecular diffusion. Convection is the movement of fluids caused due to the presence of pressure gradient whereas molecular diffusion is true mixing between the fluids driven by concentration variations.

In any displacement process, dispersion has two components; longitudinal dispersion and transverse dispersion. Longitudinal dispersion is the dispersion along the direction of the bulk velocity and is given by the expression:

$$K_l = \frac{D_o}{F\phi} + \alpha_l v \quad \text{.......(2)}$$

where α_l is the longitudinal dispersivity and is dependent on particle size and heterogeneity of the porous media (Perkins & Johnston 1981). The values of longitudinal dispersivities have been reported as scale dependent (Pickens and Grisak 1981). This has been a rather debatable issue, as discussed in the earlier section. Anyway, typical values reported range from sizes comparable to particle size in a porous media to 10 or 1000 times higher on a bigger scale length (Pickens & Grisak (1981)). The first term is the molecular diffusion component and the second term is the convective contribution to dispersion coefficient. At velocities above 1 ft/day the convective term dominates the diffusive contribution, whereas for velocities less than 0.1 ft/day, the diffusive contribution dominates. Similarly, transverse dispersion is given by the expression:

$$K_t = \frac{D_o}{F\phi} + \alpha_t v \quad \text{.......(3)}$$

where α_t is the transverse dispersivity which has a value roughly 30 times less than α_l (Lake & Hirasaki (1981)).
Taylor (1953) had shown that, if certain conditions are satisfied, transverse diffusion will combine with longitudinal velocity and would be evident as longitudinal dispersion. Lake and Hirasaki (1981) applied the derivation presented by Taylor (1953) to flow in stratified media and proved that in a 2-layered reservoir with contrasting permeability, transverse dispersion’s effect

combines with longitudinal velocity and appears as a much larger longitudinal diffusion or ‘effective diffusion’. Similar observations were made by Rigford et al. (1990). If this transverse dispersion is large enough, the two layered reservoir would behave as a single layer reservoir with averaged properties.

This implies that the magnitude of transverse dispersion determines whether we have channelling that may look like apparent dispersion of the front based on effluent profile plot versus time (Coats et al. 2004) or what would be true mixing in the reservoir indicated as dispersion of front. Lake and Hirasaki (1981) defined a dimensionless number, transverse dispersion number (N_{TD}), which is useful to differentiate channelling, which is convection dominated flow, from true mixing or dispersion, which is dominated by velocity dependent diffusion. Transverse dispersion number is given by the expression:

$$N_{TD} = 14\left(\frac{L}{H}\right)\left(\frac{K_t \bar{k} \phi_1}{H \bar{v} k_1 \bar{\phi}}\right) \qquad (4)$$

In this expression, L (m) and H (m) are length and height of the layered reservoir, K_t (m^2) is transverse dispersion, $\bar{v}$ is the arithmetic mean velocity (m/s), ϕ_1 is the porosity in layer 1 (fraction), $\bar{\phi}$ is the mean reservoir porosity (fraction), k_1 is the permeability in layer 1 (m^2) and $\bar{k}$ is the arithmetic mean permeability (m^2).

They suggested that if N_{TD} is less than 0.2, the flow is dominated by channelling and when N_{TD} is greater than five, the flow is purely dispersion dominated. Tungdumrongsub & Muggeridge (2010) suggested that dispersion dominates when N_{TD} is greater than one. It should be noted that in using equation 4, all the units should be in SI.

Assumptions

Throughout this work we have assumed that the fluids are incompressible and miscible, have equal density, viscosity, unit formation volume factor and linear relative permeability. The injection and production wells are fully penetrated and perforated throughout the width of the reservoir. The intention of doing this was to allow flow in both the layers parallel to layers. Whatever cross flow that would exist in the simulation would be due to transverse dispersion as described by Lake & Hirasaki (1981). The reservoir is perfectly layered with permeability variation only along the vertical dimension except in the base case which is a homogeneous reservoir. The porosity throughout the work is taken as constant. The initial concentration of tracer in the reservoir at t=0 is zero and the reservoir is subjected to unit step tracer input at t=0.

Methodology

The simulator used for the study was Eclipse 100. The simulations used grid size of 322×1×10 and 197x1x10 to simulate 2-D single well tracer test and well to well tracer test respectively for flow through a two layered reservoir as shown in Figure 1.

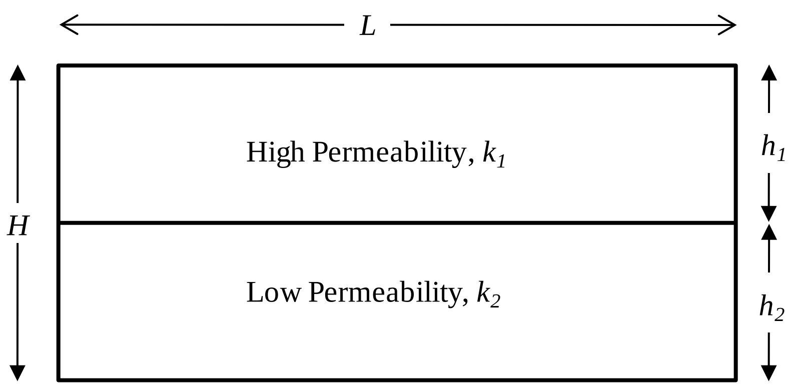

Figure 1: Schematic of the reservoir model used in the study. This two layered system is similar to the one used by Lake and Hirasaki (1981). Miscible gas or tracer was injected into the left side and produced from the same side for Single Well Tracer Tests.

We used the Flux Limiting Scheme in Eclipse. The physical dispersion in the simulation was set to zero. The diffusion coefficient was set in the simulations as an input parameter. For the SWTT, we tried to replicate the work done by Abraham et al. (2008) to study the effect of different values of D on mixing in a homogeneous case. Grid refinement was performed with the intention to ensure that physical diffusion dominated numerical diffusion or the truncation error during the simulations. However, doing this proved to be particularly hard in Eclipse 100 using low or rather realistic diffusion coefficient values. Despite extensive grid refinement exercise (presented as Attachment B) it proved impossible to calculate the same value of diffusion coefficient from the effluent profiles from a homogeneous reservoir as was input. This was despite using a fine grid that showed the solution was converged i.e. there was no change upon grid refinement. As a result in further simulations of layered reservoirs we assumed that the molecular diffusivity was the value calculated from the effluent profiles of the tracer floods in homogeneous models. The dimensions of the system are given in Table 1.

For the SWTT, we injected 0.3 Pore Volumes of water based tracer into the reservoir full of water and back produced it to analyse the tracer or effluent concentration in order to measure the extent of mixing in the reservoir. The tracer velocity in the reservoir was maintained at 1ft/day throughout all the simulations. The simulations were set up in a way (using reservoir voidage control) that the average pressure of the reservoir remained constant throughout the time so that there was no variation in the velocity of the frontal advance. We analysed the distance travelled by the tracer in the SWTT and the WTWTT were set up in a way that the pore volume injected in the latter was same as in the SWTT with the same velocity. Further, the distance travelled by the tracer in the SWTT (back and forth) was set as the inter-well distance in the WTWTT without changing the size of the grid blocks. According to equation 1, the concentration of the tracer depended on the distance and time, so, the amount of mixing in SWTT and WTWTT would be same for homogeneous cases. The system dimensions and parameters used for WTWTT are given in Table 1 along with the parameter variations to study their sensitivity on mixing during simulations on layered systems in both, SWTT and WTWTT.

In order to calculate the effective diffusion, K, we used the method presented by Brigham et al. (1961). Brigham et al. (1961) used the work presented by Taylor (1953) and modified the parameters in the Taylor's equation which related K to the length of the transition zone between any two specified compositions. Brigham et al. (1961) introduced an error function parameter U which accounted for the predicted growth of the mixing zone as it passed by an observer. They suggested that any displacement which followed equation 1 would have a concentration versus time plot on Arithmetic Probability Co-ordinate paper as a straight line. This straight line would prove that the displacement is strictly following the equation 1. Brigham presented their equation as:

$$K = \frac{1}{V_p T}\left[\frac{L(U_{80} - U_{20})}{2.38}\right]^2 \qquad (5)$$

Table 1: Properties of homogeneous system for SWTT and WTWTT & Parameter Variations used in Simulations

Properties for Homogeneous Case in SWTT		
Grid Size		322x1x10
Permeability (i,j,k), md		40
Porosity		0.1
Length of System (L), ft		3280.8
Height of System (H), ft		98.4
Thickness of System (Y), ft		172
Properties for Homogeneous Case in WTWTT		
Grid Size		197x1x10
Permeability (i,j,k), md		40
Porosity		0.1
Length of System (L), ft		1998.6
Height of System (H), ft		98.4
Thickness of System (Y), ft		172
Parameter Variation		
Permeability Contrast, A	k_1/k_2	2, 5, 10, 20, 50
Vertical Permeability	K_v/k_h	1, 0.5, 0.1, 0.01, 0.00000001, 0
Height, H		1, 0.75H, 0.6H, 0.5H

Furthermore, N_{TD} was also calculated using equation 4 to verify Lake and Hirasaki (1981) conclusion on the condition of discriminating conformance due to heterogeneity and true mixing due to diffusion.

Results and Discussion

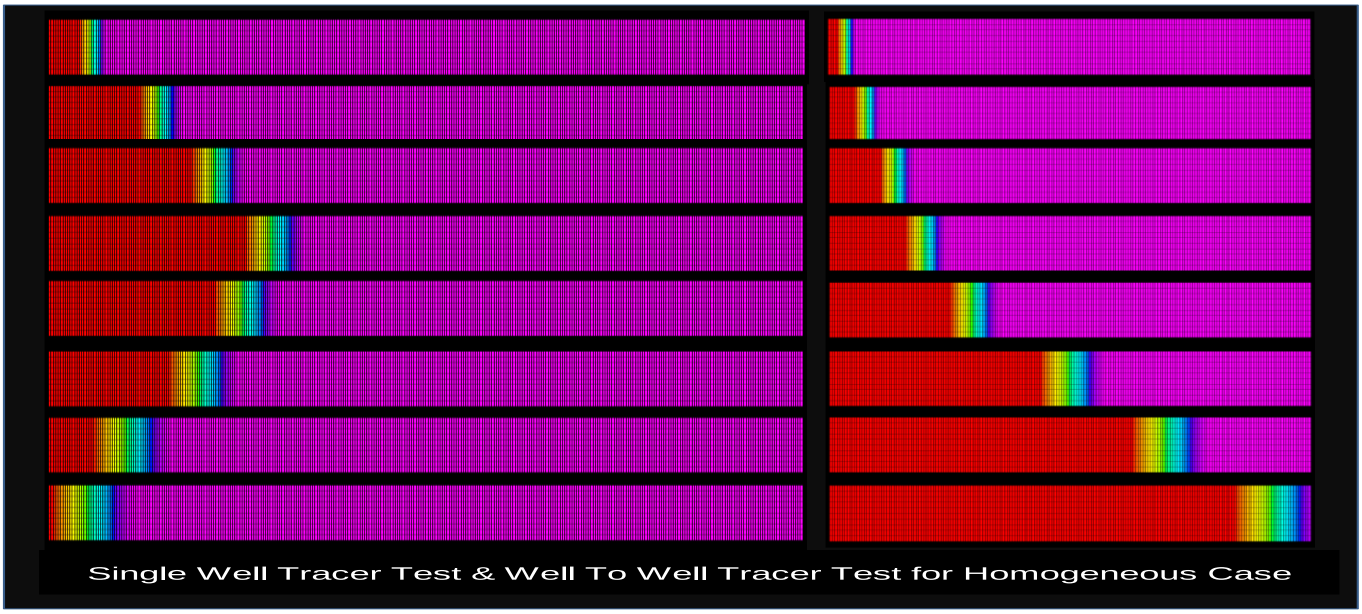

Figure 2: Tracer concentration distribution for SWTT and WTWTT in a homogeneous medium

Figure 2 shows the tracer concentration propagation during the SWTT and WTWTT (on the right) in homogeneous medium. The only mixing taking place in the above cases is due to diffusion, evident from the shape of the frontal advance and dilution of the front. For the SWTT, the mixing zone (concentration 0.1-0.9 shown between scarlet and pink colour) keeps increasing till the tracer traces its backward motion completely. Same observation can be made for WTWTT. In both the cases, the mixing zone's width is the same. The values of effective diffusion calculated using Brigham et al. (1961) were in close conformity to each other as shown in Figure 3. From this we can infer, that effective diffusion is not dependent on direction of flow and is dependent on distance and time for homogeneous case.

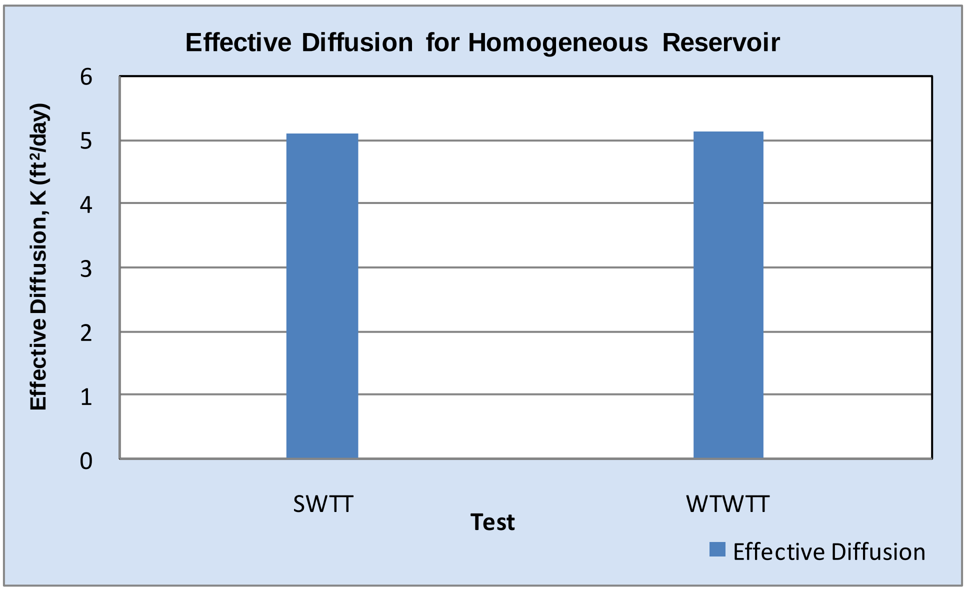

Figure 3: Values of effective diffusion for homogeneous reservoir from single well tracer test and well to well tracer test.

Figure 4 shows the mixing during the SWTT and WTWTT for same N_{TD} and permeability contrast ratio. Similar behaviour of mixing zone can be seen in

Figure 4 as was observed for homogeneous case. It can be seen that due to the heterogeneity the tracer tends to travel faster in the top layer than the bottom layer. Hence we see a bigger spread of the mixing zone for same

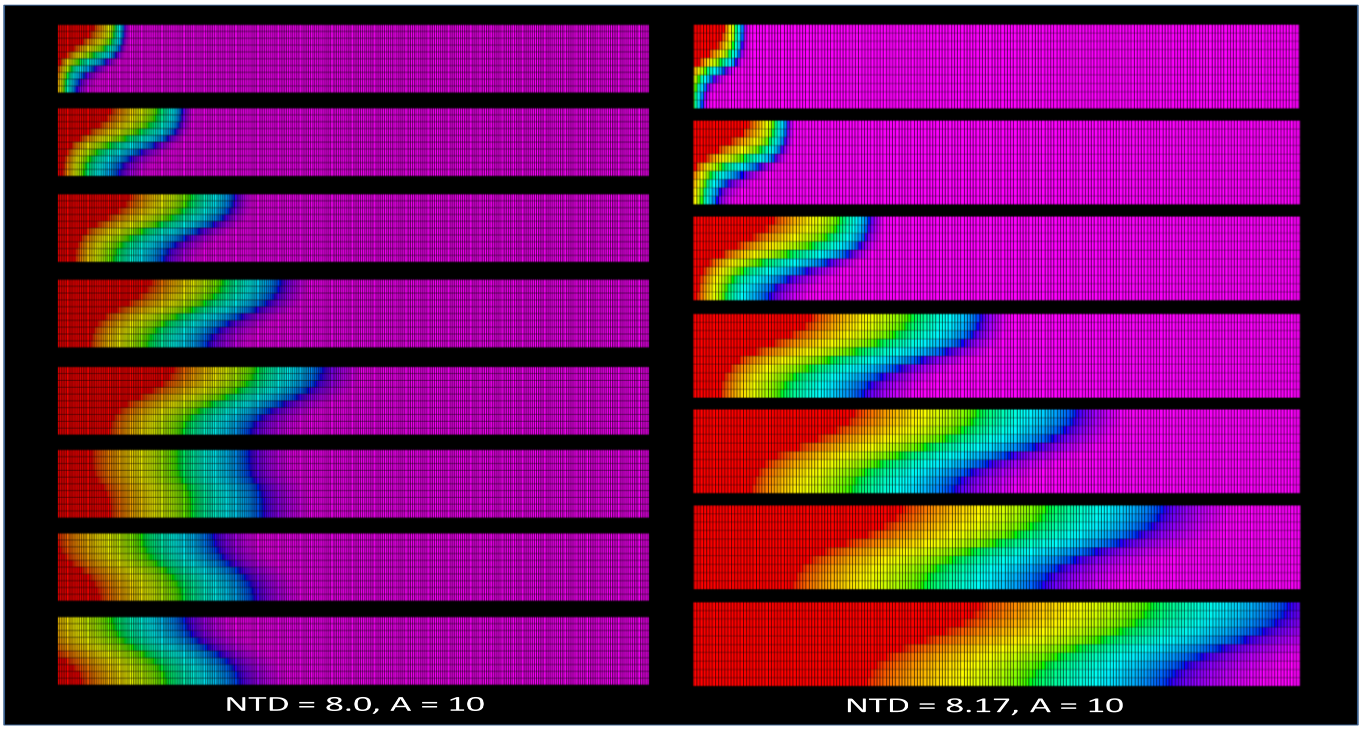

Figure 4: Mixing in SWTT and WTWTT for same N_{TD} & permeability contrasts

concentration band as before, indicating a higher degree of mixing. This higher degree of mixing or 'effective diffusion' is the same as mentioned by Lake and Hirasaki (1981) and is velocity and concentration dependent in nature. From different simulations, it was observed that this extent of mixing increases as the permeability contrast increases. The rapid frontal advance creates a concentration gradient across the transverse section of the reservoir. Diffusion tends to equalise the concentration gradient across the mixing zone. Looking at the shape of the frontal advance, we can notice that, for this particular permeability contrast and N_{TD}, diffusion is dominating the flow although there is an advective component.

The simulation runs made in this study resulted in high values of N_{TD} and in fact, for all cases, diffusion is dominating over the frontal advance created because of permeability contrast. These high values of N_{TD} are consequence of the limitation of Eclipse in generating correct diffusive behaviour and in order to overcome this, the value of diffusion coefficient used was particularly high, as mentioned earlier. Therefore, we were unable to see frontal advance shape for lower N_{TD} values, particular below 1 which would have produced convective dominated mixing i.e. a scenario where diffusion fails to equalise the concentration gradient caused by the rapid frontal advance. None the less, from the simulation runs carried out in the study, we observed that the frontal advance becomes more and more pronounced as the N_{TD} of the system moves closer to unity and can say that as N_{TD} decreases, the convection dominated flow appears to be more pronounced. However, more work is required to establish the accurate value of N_{TD}, where transition from diffusion dominated flow to convective dominated flow takes place using realistic values of D.

The values of effective diffusion calculated for the case above and others can be seen from Figure 5 . It can be observed that the value of effective diffusion is higher for the case of WTWTT than SWTT. Further, as the permeability contrast increases or as the N_{TD} decreases, the gap between the effective diffusion values of SWTT and WTWTT increases. In both cases, however, the effective diffusion for heterogeneous system shows a marked increase in comparison to the values from homogeneous case. The gap in the values of effective diffusion in SWTT and WTWTT, for same permeability contrast, would lead to higher dispersivity value in case of WTWTT. Since the value of dispersivity are measured over the same scale and is still higher in case of WTWTT, highlights non-dependency of dispersivity on scale length. There is some other mechanism which masks the mixing effect in SWTT. A possible reason for this could be the fact that in SWTT, due to flow direction reversal, the concentration of the tracer is rearranged while tracer reverses its direction which affects the extent of mixing of tracer, therefore, resulting in a lower value of effective diffusion. Since there is no flow reversal in WTWTT, there is no change in the concentration gradients within the advancing front and mixing continues to progress without any concentration gradient alterations.

Further to this, since we are using a very high diffusion coefficient the resultant effective diffusion is also very high. This has made the dispersivity look bigger in comparison to the ones which would be normally seen at core or laboratory scale, but in reality, this is could be down to the higher diffusion coefficient. Further work is required using realistic diffusion coefficients on a simulator which models diffusive behaviour correctly to establish whether the dispersivities found from such analysis compare well with the ones found at core and laboratory scale. This would conclusively prove whether dispersivity is scale dependent or not. One thing is for sure that as the permeability contrast grows the value of dispersivity would increase.

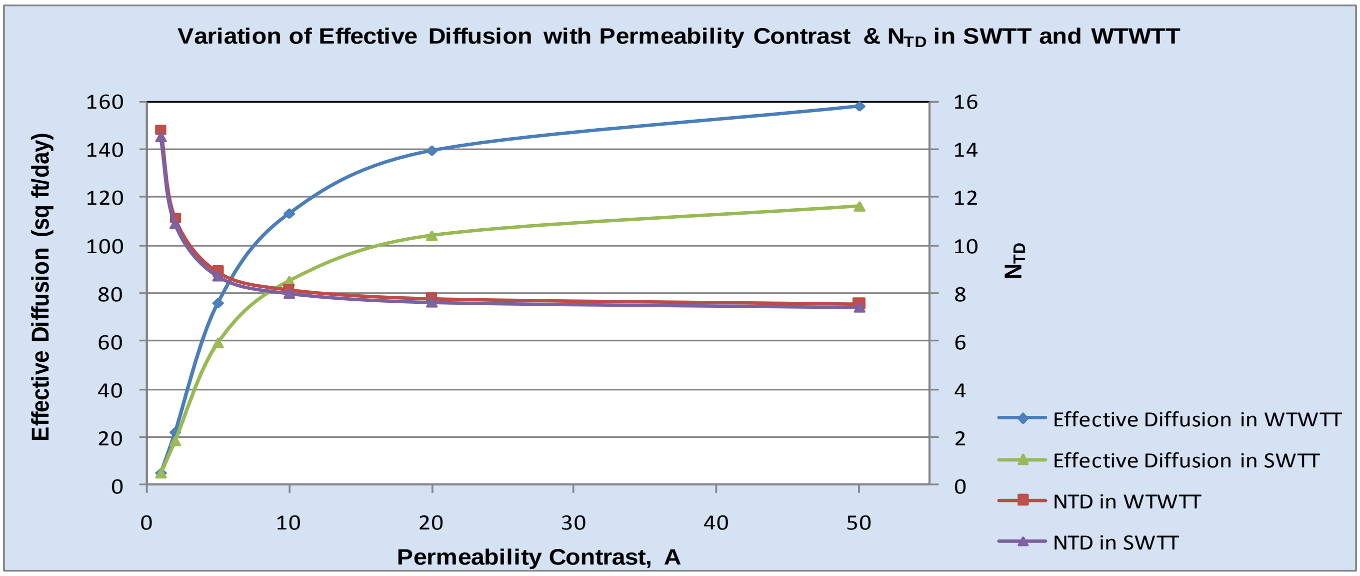

Figure 5: Effective diffusion in single well tracer tests and well to well tracer tests for different N_{TD} and permeability contrasts, A.

Figure 6 shows the tracer concentration distribution observed for mixing concentration zone 0.1 to 0.9 at the end of injection (0.30 Pore Volumes Injected (*PVI*)) for different permeability contrast ratio and transverse dispersion numbers. As the permeability contrast between the layers increases the width of mixing zone increases which indicates a greater extent of mixing in the reservoir. This is in line with the findings of Lake and Hirasaki (1981) and Rigford et al. (1990). As iterated earlier, it is evident that diffusion is dominating in all the cases shown.

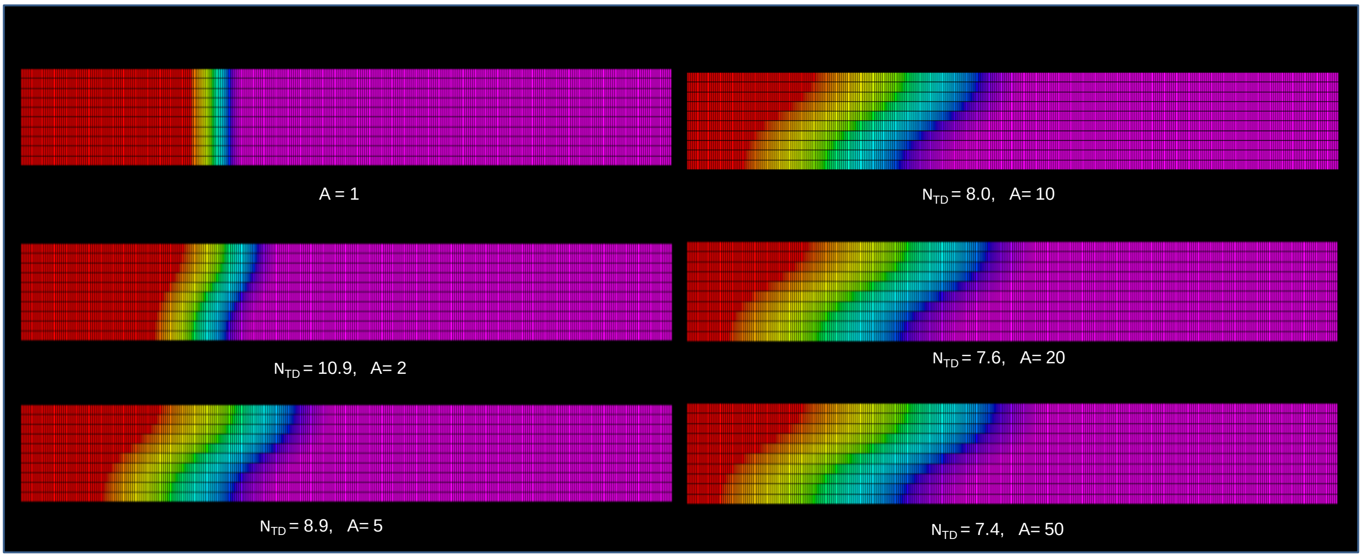

Figure 6: Tracer concentration distribution observed for mixing concentration band 0.1 to 0.9 at the end of injection (0.3 pore volume injected) for different permeability contrast ratios, A and transverse dispersion number. We can see the mixing zone increases in size as the permeability contrast increases indicating an increase in transverse mixing as the velocity difference between the two layer increases.

Figure 7 shows the recovery of tracer against pore volumes produced in SWTT. For the homogeneous case the recovery of tracer is the quickest. The time required to produce all of the tracer increases as the permeability contrast increases or as the N_{TD} decreases. This can be explained by Lake and Hirasaki's (1981) work. As the permeability contrast increases, more transverse mixing is taking place which is pushing the tracer into the low permeability layer. It is this tracer in the low permeability layer, which has moved from high permeability layer, which is taking more and more time to produce (as also predicted by Tungdumrongsub & Muggeridge (2010)). From the shape of the profiles, we can conclude that diffusion is still dominating the flow. There is no evidence of heterogeneity driven convective flow as such. Following the trend of increasing permeability contrast ratio A, which takes us closer to the convection dominated flow, we can conclude that as the permeability contrast increases, the time required to recover the entire tracer would increase. Therefore in case of conformance, the recovery time would be greater as compared to diffusion dominated dispersive flow.

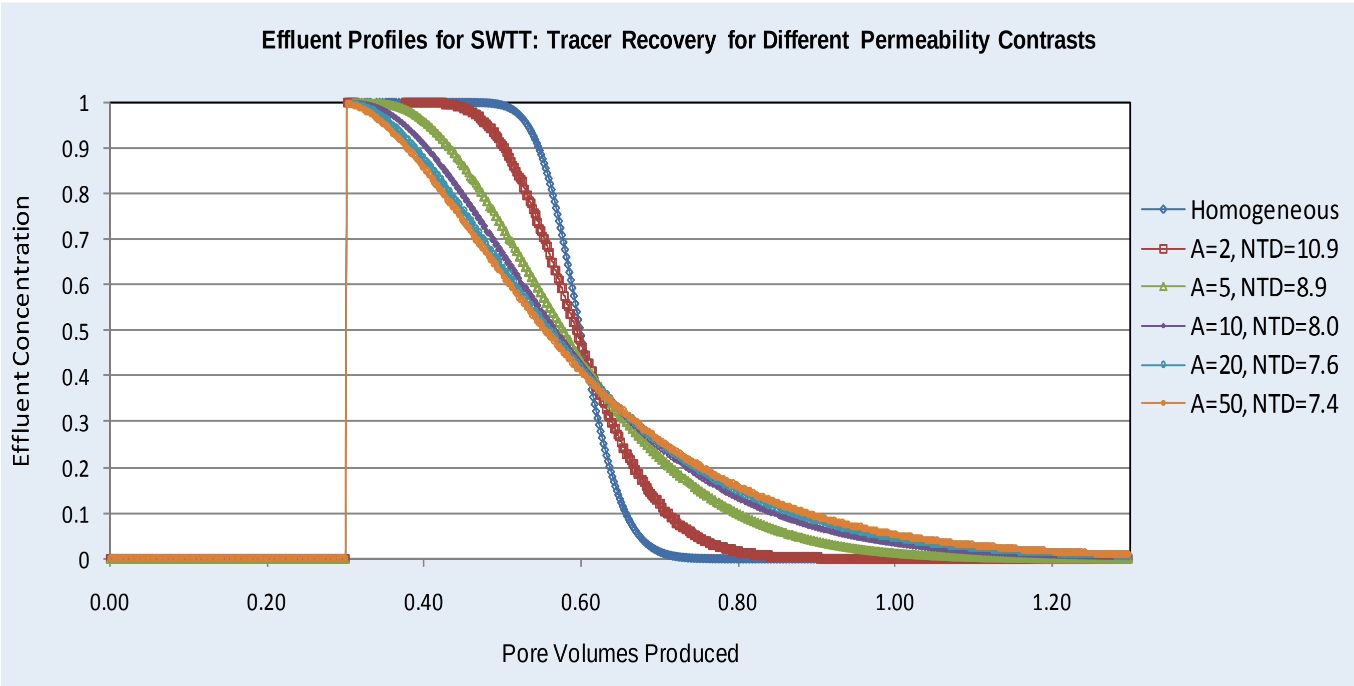

Figure 7: Shows the recovery of tracer with respect to pore volumes produced. The tracer is recovered the quickest in the case of homogeneous case. As the permeability contrast increases the recovery of tracer becomes more and more slow. It is the slowest for the case of highest permeability contrast.

Similar behaviour can be seen from the effluent profiles of WTWTT in Figure 8. As the N_{TD} moves closer to unity and convection becomes more and more dominant, the recovery time increases more and more. Further the breakthrough of tracer in the producing well occurs earlier and earlier as permeability contrasts increase.

Figure 9 shows how the mixing is effected by decreasing the height of the reservoir in SWTT. There is a decrease in the thickness of the mixing zone indicating a decrease in value of effective diffusion calculated from effluent profiles, as predicted by Lake and Hirasaki (1981). It can be observed that for A=2 and $\boldsymbol{N_{TD}}$=43.6, the two layers are almost behaving like one as predicted by Lake and Hirasaki (1981). The diffusion is very strong in this case and is dominating the frontal advance. **Figure 10** shows the values of effective diffusion with variation of height of the reservoir. For A=2, a decrease in value of height by half corresponds to a proportional decrease in value of K. However, that is not the case for A=10. A decrease of half in height of the reservoir results in 65% decrease in the value of the effective diffusion. A similar trend can be observed, more or less, for the WTWTT, as shown in **Figure 11**.

Figure 12 shows mixing zone's sensitivity to k_v/k_h for same permeability contrast. There is no change in the spread of the mixing zone for all practical values of k_v/k_h. The diffusion dominated dispersive behaviour is dominant in all the cases. Even when the k_v/k_h is set zero, still the separate frontal advance sans any transverse mixing is depicting diffusive behaviour, although separately. This is the case where we have no cross-flow between the layers and hence there is no transverse mixing between the layers. The effective diffusion decreases in this case and is lower than the values seen for homogeneous cases. Figure 13 shows the effluent profiles for the variation of k_v/k_h for SWTT. There is no change evident from the effluent profiles for all the cases except for k_v/k_h=0 case, where the effect of permeability contrast can be seen. It is interesting to note that the recovery of tracer in this particular case is quicker than the cases where transverse mixing is taking place.

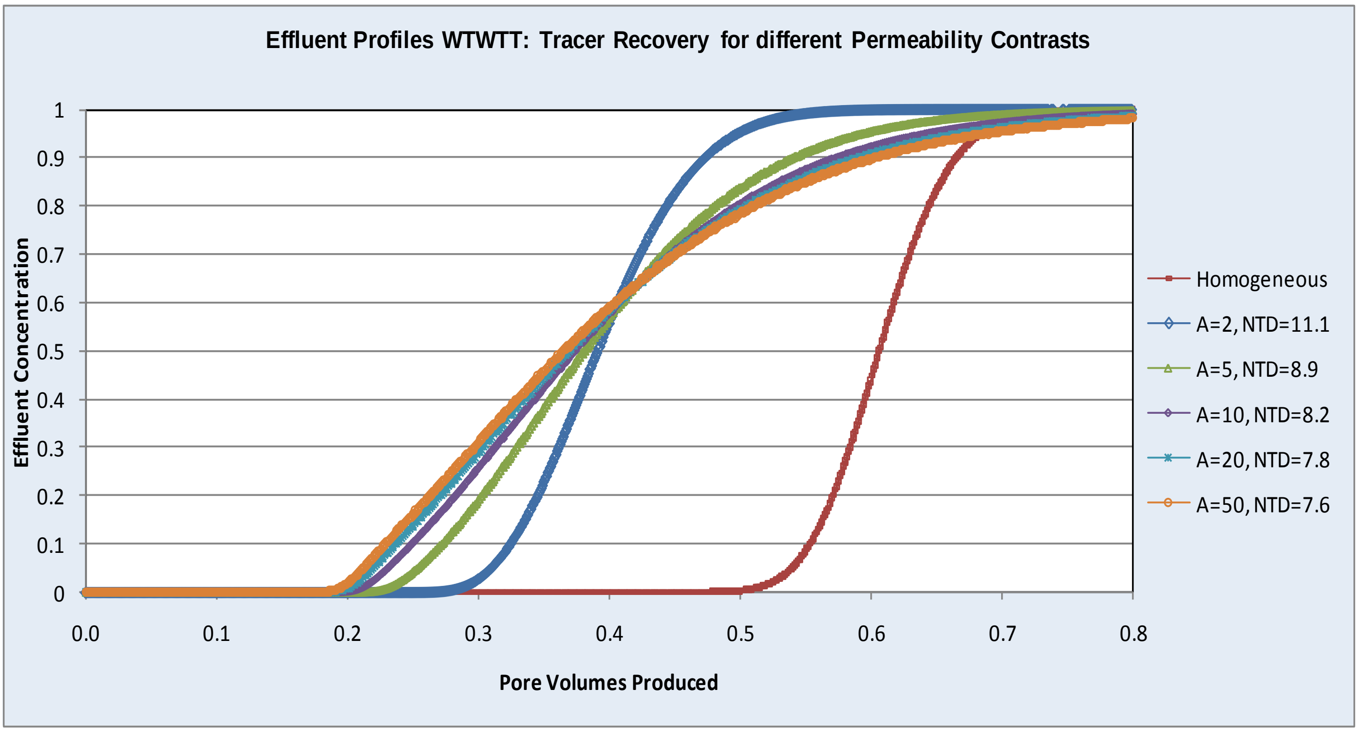

Figure 8: Effluent profiles for WTWTT: tracer recovery for different permeability contrasts & N_{TD}

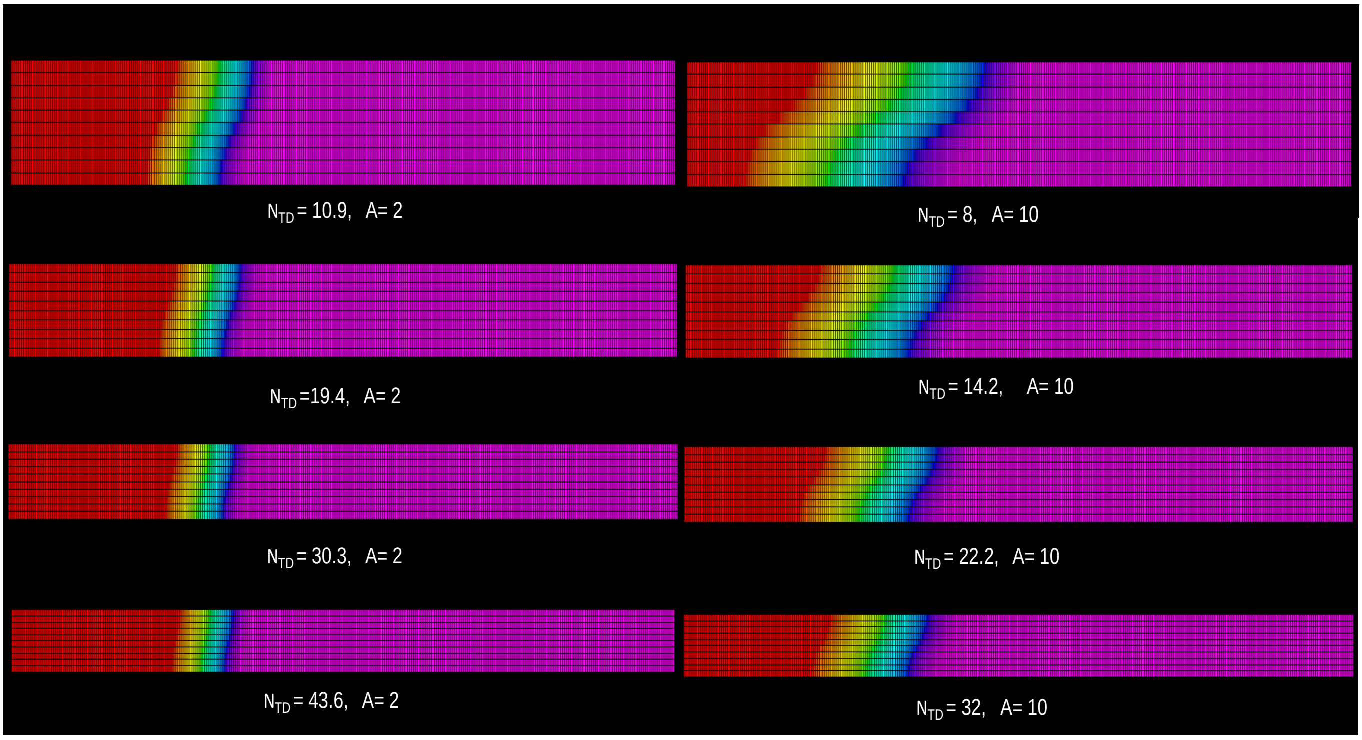

Figure 9: Shows the effect of reducing height of the reservoir for two different permeability ratios. In both the cases, we can notice a decrease in the thickness of mixing zone indicating a decerase in the value of *K*.

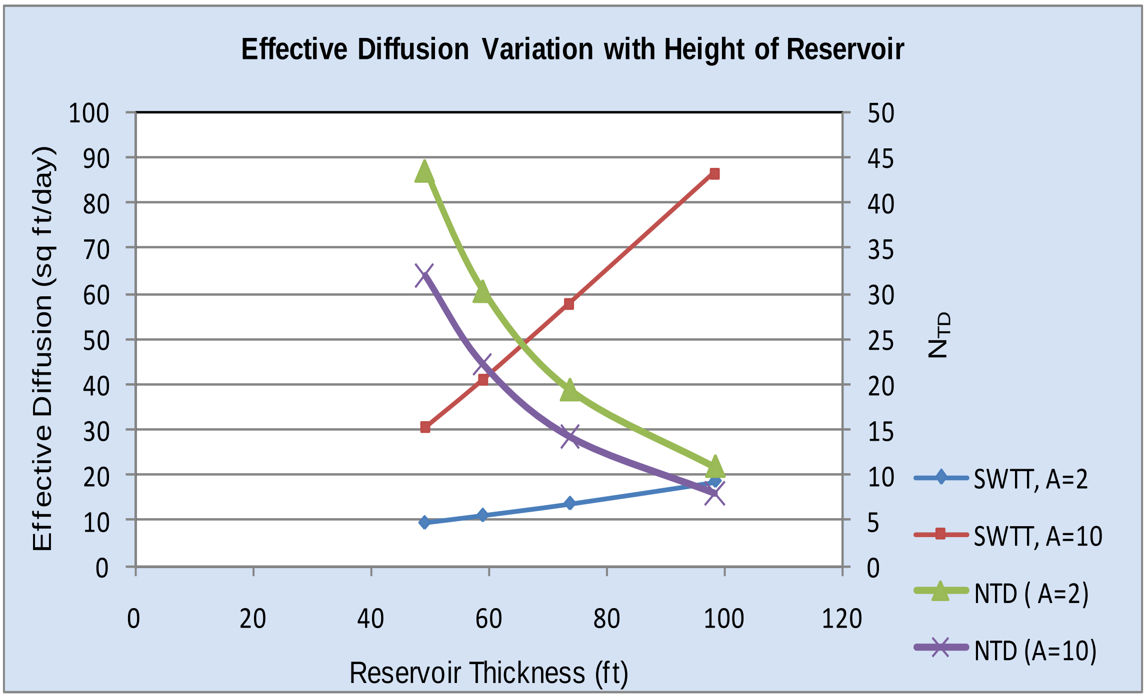

Figure 10: Effective diffusion variation with height of reservoir In SWTT for different permeability contrasts

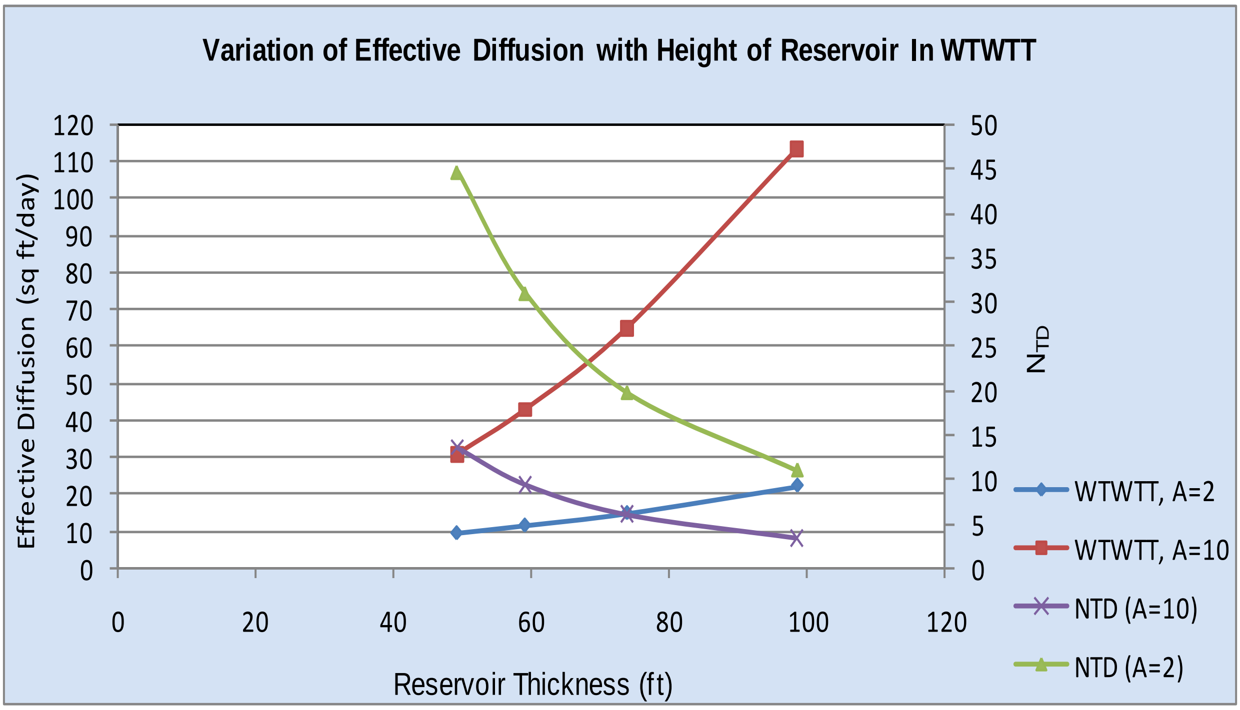

Figure 11: Effective diffusion variation with height of the reservoir in WTWTT for different permeability contrasts

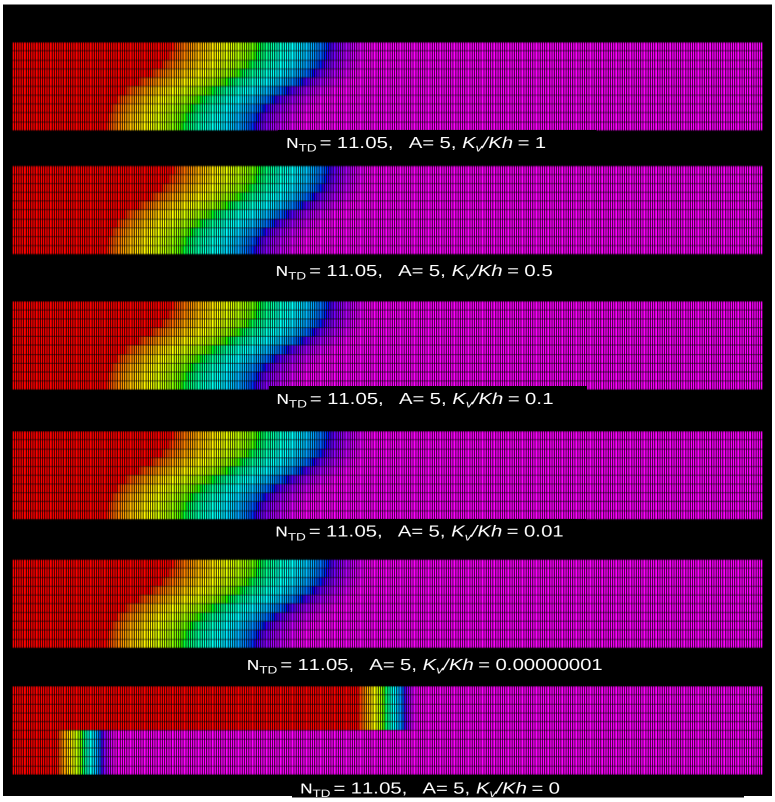

Figure 12: Shows mixing zone's sensitivity to k_v/k_h for permeability contrast 5:1 in SWTT. For all practical values there is no change in the thickness of mixing zone.

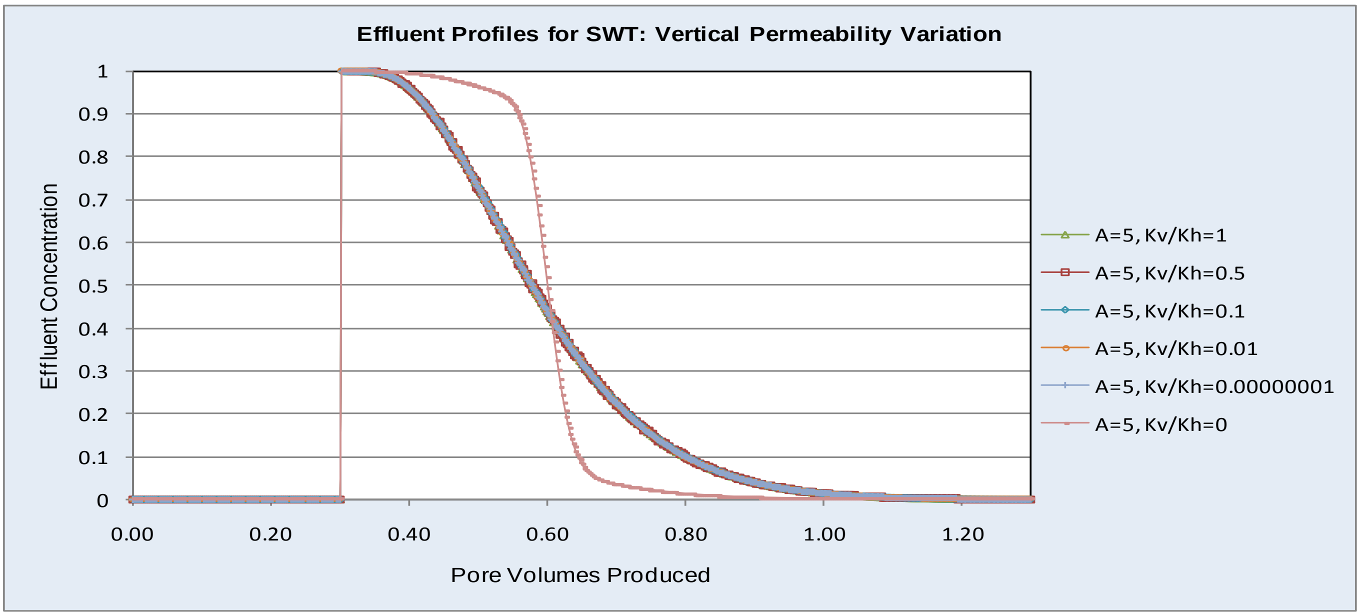

Figure 13: Shows effluent profiles from SWTT for k_v/k_h Variation (permeability contrast 5:1). For the case of k_v/k_h = 0, there is a change in effluent profile which is similar to the one corresponding to heterogeneity difference.

Similar trend can be seen for the WTWTT in the Figure 14 but rather interestingly, the recovery time for tracer in k_v/k_h=0 case is the poorest, unlike the SWTT. The reason for this shape of the tracer concentration profile in this case is because of the slow movement of the front in the lower permeability layer, which up till 0.8 *PV*s hasn't still made it to the producing well.

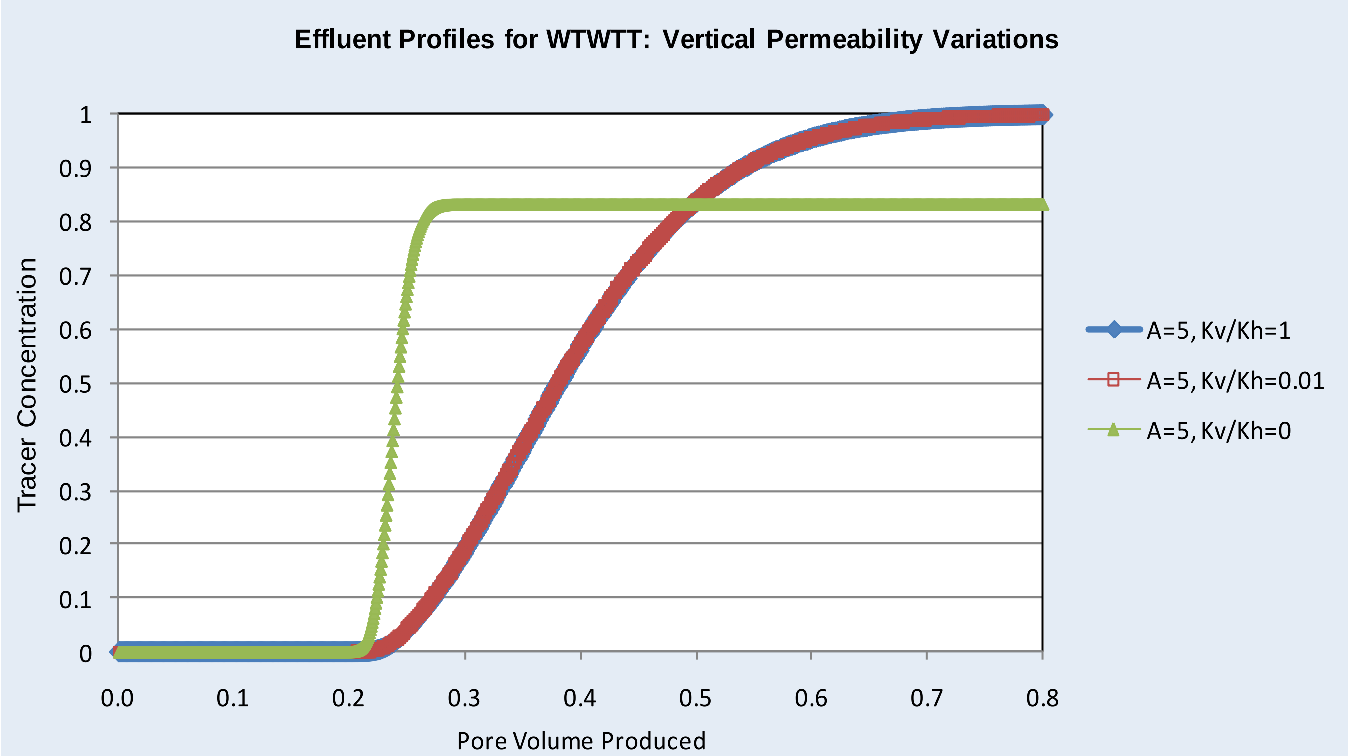

Figure 14: Effluent profile for WTWTT for vertical permeability variation.

Conclusions and Recommendations

We have extended the work of Lake & Hirasaki (1981) on stratified media to get a quantitative extent of mixing during displacement process using Brigham et al. (1961). We have used diffusion coefficient as input to analyse the resultant mixing in a layered system. Due to software limitations, we have used diffusion coefficients higher than the realistic ones. This has resulted in higher values of effective diffusion which gave rise to high dispersivity values compared to the ones calculated at core or laboratory scale. More work is required using alternate software and low diffusion coefficient to investigate the scale dependency of dispersivity. The dispersion calculated from SWTT and WTWTT shows that the dispersion from WTWTT is slightly higher than SWTT, despite being calculated over the same distance and flow rate. This could be attributed to the change in flow direction in case of SWTT which alters the concentration distribution of tracer during reversal, reducing the extent of mixing in SWTT. From the observed trends, dispersivity would increase with increasing permeability contrast, highlighting its dependence on the level of heterogeneity of the system.

We have used Lake and Hirasaki's (1981) N_{TD} to show that frontal advance due to heterogeneity, during 1st contact miscible displacement, would be dominated by diffusion driven dispersion for all values of N_{TD} in this study (greater than 7.4). It can be concluded that as the N_{TD} decreases and moves closer to unity, convection begins to dominate more and more. More work is required to establish the value of N_{TD} where the transition from diffusion driven dispersion to convection dominated channelling takes place. Based on the sensitivity analysis for different parameters, we can conclude that:

- A decrease in the height of the reservoir reduces the effective diffusion as predicted by Taylor and Hirasaki (1981).
- Effective diffusion tends to increase with increasing permeability contrast.
- There is no effect on effective diffusion by varying the vertical permeability of the system for all practical values of vertical permeability.

We have showed for SWTT that for a convection dominated frontal advance, the recovery of tracer takes more time. For higher values of N_{TD} where diffusion dominates the frontal advance, the recovery is quicker. Similar trend is observed for WTWTT although effective diffusion is slightly higher in WTWTT than SWTT. Regardless, whether the dispersion is scale dependent or not, the effluent concentration profiles in all the cases undertaken in our study indicate the s-shaped dispersion. Further work is required to model convection dominated frontal advance to say for sure whether the wiggly concentration profile for conformance of heterogeneity would appear in the effluent concentration. Based on what we have seen, it will.

Nomenclature

A	=	Permeability Contrast, k_1/k_2
B	=	Anisotropy factor, k_v/k_h
C_m	=	Averaged concentration
D_o	=	Molecular diffusion coefficient, L^2/t, ft^2/day [m^2/sec]
F	=	Formation electrical resistivity factor
H	=	Height of the system, L, ft [m]
h	=	Thickness of Layer, L, ft [m]
K	=	Dispersion coefficient, L^2/t, ft^2/day [m^2/sec]
K_l	=	Longitudinal dispersion coefficient, L^2/t, ft^2/day [m^2/sec]
K_t	=	Transverse dispersion coefficient, L^2/t, ft^2/day [m^2/sec]
k	=	Permeability, L^2, md [m^2]
k_v	=	Vertical Permeability, L^2, md [m^2]
k_h	=	Horizontal Permeability, L^2, md [m^2]
k_1	=	High permeability, L^2, md [m^2]
k_2	=	Low permeability, L^2, md [m^2]
$\bar{k}$	=	Arithmetic mean permeability, L^2, md [m^2]
L	=	Length of the system, L, ft [m]
N_{TD}	=	Transverse Dispersion Number, fraction
PVI	=	Pore volumes Injected
T	=	Time required to inject or produce one pore volume of porous medium, t, days
t	=	Time, t, day [sec]
U	=	error function parameter $(V_P-V)/\sqrt{V}$
U_{80}	=	Error function parameter at 80% concentration of tracer
U_{20}	=	Error function parameter at 20% concentration of tracer
V	=	Volume of fluid recovered at time of sample, L^3, STB [m^3]
V_P	=	Pore volume of porous medium, L^3, STB [m^3]
$\bar{v}$	=	Mean frontal advance velocity, L/t, ft/day [m/s]
v	=	Interstitial longitudinal velocity, L/t, ft/day [m/s]
x_1	=	Distance, L, ft [m]
∂	=	Partial differential
α_l	=	Longitudinal dispersivity, L, ft [m]
α_t	=	Transverse dispersivity, L, ft [m]
Φ	=	Porosity of the system, fraction
$\bar{\phi}$	=	Arithmetic mean porosity, fraction

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Appendix A

CRITICAL LITERATURE REVIEW

MILESTONES IN RESERVOIR HETEROGENEITY: SHOULD IT BE MODELLED AS CONFORMANCE OR DISPERSION

Paper No.	Year	Title	Authors	Contribution
Royal Society London A219: 186-203	1953	Dispersion of Soluble Matter in Solvent Flowing Slowly Through a Tube	Taylor, G. I.	First to apply Fick's law to displacement in capillary tubes and showed that instead of Diffusion coefficient (D) in Fick's law, the rate of mixing of the front is governed by a much higher dispersion coefficient (K). He derived a relationship which related dispersion coefficient with diffusion coefficient.
Royal Society London 225: 473-477	1954	Conditions Under Which Dispersion of a Solute in a Stream of Solvent Can be Used to measure Molecular Diffusion	Taylor, G. I.	First to give conditions under which the relationship between K and D can be used for a valid representation of dispersion in a tube.
SPE-1430-G	1961	Experiments on Mixing During Miscible Displacement in Porous Media	Brigham, W. E., Reed, P. W. and Dew, J. N.	Brigham et al. developed a relationship, using Taylor's work, to calculate dispersion coefficient (K) using a error function parameter and effluent profiles.
SPE-2811-PA	1971	Quantitative Evaluation of Numerical Diffusion (Truncation Error)	Lantz, R. B.	Developed relationships which quantify the numerical diffusion or truncation error in simulations making use of convective-diffusive equations These relationships could be used for choosing the right grid blocks and time steps in order to reduce the effects of truncation error.
Water Resources Research 16 (5): 901-917	1980	Is Transport in Porous Media Always Diffusive? A Counterexample	Matheron, G. and Marsily, G. De.	First to show that stratified heterogeneity can sometimes obtain a non-Fickian type of transport, even asymptotically i.e. which doesn't conforms to the usual convection-diffusion equation. They give conditions under which must be satisfied in order to convection-diffusion equation to be valid asymptotically for flow parallel and non-parallel to the stratification.

Water Resources Research 17 (4): 1191-1211	1981	Scale-Dependent Dispersion in a Stratified Granular Aquifer	Pickens, J. F. and Grisak, G. E.	First to develop theoretical basis for quantification of scale dependent dispersion in stratified media. Conducted scale dependent field tracer and laboratory tests to establish that longitudinal dispersivity is scale dependent.
SPE-8436-PA	1981	Taylor's Dispersion in Stratified Porous Media	Lake, L. W. and Hirasaki, G. J.	First to apply Taylor's concept to stratified heterogeneous media. Developed relationships to study the factors affective Taylor's 'effective dispersion'.
Water Resources Research 21 (5): 676-684	1985	Analysis and Interpretation of Single-Well Tracer Tests in Stratified Aquifers	Güven, O., Falta, R. W., Molz, F. J. and Melville, J. G.	Used the concept of local longitudinal and vertical dispersion and effects of stratification, ditching the previous microscopic or full aquifer dispersivity concepts which gave rise to scale dependency of dispersivity, to measure dispersive properties. They showed that if flow fields and local dispersion coefficients are known in sufficient detail, we can simulate the movement of injected tracer in a stratified media accurately.
SPE-14364	1988	Dispersion and Reservoir Heterogeneity	Arya, A., Hewett, T. A., Larson, R. G. and Lake, L. W	Investigated the effect of heterogeneity, aspect ratio, diffusion coefficient and autocorrelation on megascopic and macroscopic dispersion.
SPE-17339	1998	The Effects of Small-Scale Heterogeneities on the Effective Dispersivity of Porous Medium	Kelkar, B. G. and Gupta, S. P.	Investigated the effect of small scale heterogeneities on effective dispersivities running sensitivities on length of the system, heterogeneities spatial distribution, degree of heterogeneity and average length of heterogeneity.
SPE-90390	2004	Modelling Conformance as Dispersion	Coats, K. H., Whitson, C.H. and Thomas, L.K	Using data from previous experiments made observations that large dispersivities from field tracer tests are result of applying effluent profiles to match the inapplicable 1D-convection dispersion equation. They asserted that scale dependency of dispersivity is devoid of meaning.
SPE 113429	2008	Investigation of Field Scale Dispersion.	John, A. K., Lake, L.W., Bryant, S.L. and Jennings, J.W.	Using dispersivity values as input in particle tracking simulator showed that dispersive mixing is significant in field scale miscible displacement in heterogeneous formation.
SPE-103054	2009	Flow Reversal and Mixing	Jha, R. K., John, A. K., Bryant, S. L. and Lake, L. W.	Investigated mixing mechanisms in Echo tests and based on observations, explained why the dispersivities obtained are scale-dependent.

SPE 8436-PA (1981)
Taylor's Dispersion in Stratified Porous Media

Authors: Larry W. Lake & George J. Hirasaki

Contribution:

- The paper defines Transverse Dispersion number which helps discriminate between apparent dispersion due to heterogeneity from real mixing due to dispersion.
- Helps explain the increase in effective longitudinal dispersion in stratified medium.
- Explains the characteristics of effective longitudinal dispersion in stratified medium though derivation of an equation for effective longitudinal dispersion. The equation is useful to explain the different values of effective dispersion obtained through various simulation results in our study when parameters like permeability contrast, reservoir thickness etc are changed.
- The paper gives a good introduction on longitudinal and transverse dispersion, their constituents, typical values of longitudinal and transverse dispersivity and gives the cut-off velocity at which convection dominates molecular mixing.

Objective of the paper: The purpose of this paper is to present a criterion under which Taylor's dispersion or effective longitudinal dispersion will apply to layered systems and to describe the resulting effective dispersion. One of the purpose of this paper is also to use stratification to explain large field-measured values of longitudinal dispersivity.

Methodology used: The approach is to explore the very close analogy between transverse dispersion in a two-layer medium and molecular diffusion in a capillary tube (the latter presented in a set of papers by Sir Geoffrey I. Taylor in 1953-54). An expression for Transverse dispersion number is developed analytically and the continuity equation corresponding to the assumption of authors is solved numerically to verify transverse dispersion number. The authors then proceed to extend the results to Multilayered Media.

Conclusion reached:

- For Transverse dispersion in a two-layer medium, the displacement behaviour is bounded by that of a two-layer medium with dispersion only occurring longitudinally within each layer and that of a single-layer medium having an augmented longitudinal dispersion coefficient. In the latter case, the behaviour is directly analogous to Taylor's dispersion in a capillary tube.
- A transverse dispersion number, NTD, indicates where (between he above limits) a displacement in a two-layer medium will lie. When NTD is less than 0.2, the medium behaves with heterogeneous character; when NTD is greater than five, the medium behaves as if it were single-layered.

SPE 103054 (2009)
Flow Reversal and Mixing

Authors: Raman K. Jha, Abraham K. John, Steven L. Bryant, and Larry W. Lake

Contribution: The paper was very useful for developing understanding of

- the mechanism of mixing in porous media,
- how differentiate between convective spreading and diffusion,
- how mixing is influenced in single well tests (velocity, penetration depth, heterogeneity)
- how velocity variation can influence diffusion and convective mixing.
- Comparison of dispersion in single well test and two well tests.

Objective of the paper: Is to explain the mechanism of mixing and the origin of the irreversibility of dispersion in flow through porous media.

Methodology used: The authors simulate the effect of flow reversal on mixing in 2D porous media using two different approaches,

- In the first approach, they perform direct numerical simulation of a solute-slug transport (by solving Navier-stokes and convection/diffusion equations) in a surrogate pore space. This approach gives a direct visualization of mixing in simple flow geometries. The effect of flow reversal on mixing is investigated for several diffusion coefficients, penetration depths and flow geometries.
- In the second approach, they use particle tracking to simulate the effect of flow reversal at larger length scales. This approach is free from numerical dispersion, can be used in absence of diffusion and has no limits on the size of the simulation.

Conclusion reached: Following are the conclusions from their study which relate to our study:

- The dispersion coefficients obtained from transmission-dispersion experiments have effects of convective spreading and diffusion lumped together. Flow-reversal tests discriminate between convective spreading and local mixing (true mixing). Echo dispersion for the former case approaches 0 and in the latter case equals the transmission dispersion. The fraction of irreversibility of dispersion indicates the degree of local mixing.
- Pore-scale simulations show that mixing caused by diffusion is enhanced by the local velocity gradients induced by the grain arrangement and because of the splitting of the solute front along sand grains.
- Purely convective spreading in the absence of diffusion is reversible. It is the local mixing caused by diffusion that makes dispersion in porous media irreversible. Diffusion is the fundamental mechanism of local (true) mixing at pore scale.

SPE 113429 (2008)
Investigation of Field Scale Dispersion

Authors: Abraham K. John, Larry W. Lake, Steven L. Bryant and James W. Jennings

Contribution:

- The paper provided with the basic idea of setting up the simulation.
- Concepts and definitions provided in the paper were quite useful.

Objective of the paper: To resolve the ambiguity between convective spreading and mixing in a reservoir during miscible flooding.

Methodology used:
Flow reversal tests (Echo Test) and transmission test for tracer transport using particle tracking simulations on 3D high resolution models at field scale.

Conclusion reached:

1. Flow reversal (echo) tests can be used to distinguish between convective spreading and dispersive mixing. Echo dispersivities estimated from simulations are comparable in magnitude with the corresponding transmission values.
2. Purely convective transport, in certain cases, can also appear to have a dispersion-like behaviour. It would be incorrect to model this using a dispersive flux term.

Comments:
The work does not answer the question on how mixing takes place at the field scale in a heterogeneous medium and how to model it.

J. Phys.: Condens. Matter 2 (1990) SA437-SA-442
Reversible and irreversible tracer dispersion in porous media

Authors: P Rigford, C Leroy, E Charlaix, C Baudet, E Guyon and J P Hulin

Contribution:

The paper discusses tracer dispersion in porous media.

Echo Tracer Dispersion

- It discusses echo tracer dispersion and analyses the ‘dispersion length’ or ‘dispersivity’ obtained through echo and transmission tests over a wide range of Peclet number. The authors observe that for Gaussian samples where the transmission data follows the ‘convection-diffusion’ equation, echo and transmission dispersivity are equal for whole range of Peclet numbers investigated.
- However, for heterogeneous cases, echo dispersivity is lesser than transmission dispersivity by a factor of 2-3 and the difference tends to increase with increasing Peclet Number.
- Furthermore, the echo dispersion curves are Gaussian while transmission curve does not follow the convection-diffusion equation.

Dispersion in Stratified Media

- It discusses dispersion in stratified media and observes that at high Peclet numbers, the there are two distinct fronts in the transmission curves corresponding to two flow velocities and transverse mixing is weak in this case. The echo curve is much sharper. Further, echo dispersivity reaches tends towards a value corresponding to dispersion in a single layer while transmission dispersivity tends towards an upper limit determined by the permeability contrast and the path length.
- For low Peclet Number, echo and transmission dispersivity are same and their value is determined by a compromise between longitudinal convective dispersion and transverse dispersion.

Transition to Irreversibility in Homogeneous Samples

- The authors investigate the reversibility of tracer for different depths of penetration during echo test.

Objective of the paper: To present experimental studies of heterogeneities of porous media by tracer dispersion.

Methodology used:
The authors analyse tracer dispersion using the classical transmission or echo techniques on homogenous and stratified systems (made from glass beads). Further an electrochemical technique is applied to dispersion measurements with a resolution better than one grain size.

Conclusion reached:

None in particular, since the bits related to our work, were already covered in what Lake and Hirasaki had done.

SPE 2811 (1971)
Quantitative Evaluation of Numerical Diffusion (Truncation Error)

Authors: R. B. Lantz

Contribution: This paper helped in understanding the cause of Numerical diffusion or truncation error and how to reduce it while using the simulator. This was particularly useful in grid sizing optimization so that physical diffusion/dispersion is dominant to numerical diffusion/dispersion.

Objective of the paper: Is to give the user more than just a qualitative feel for the importance of truncation error. Further, analytical expressions for quantifying the truncation error have been developed which could be used for choosing block sizes and time steps to keep the numerical diffusivity small.

Methodology used: Analytical expressions for truncation error are compared by experiment to computed values for numerical diffusivity.

Conclusion reached: In order to reduce numerical diffusion in the simulations choose a smaller size of the grid block and time steps.

Water Resources Research, Vol 16, No. 5, Pages 901-917, Paper Number 80W0366 (1980)
Is Transport in Porous media Always Diffusive? A counterexample

Authors: G. Matheron and G. De Marsily

Contribution: Not much

Objective of the paper: Is to investigate whether macro-dispersivity is always a Fickian process or whether it can be represented by the convection-diffusion equation?

Methodology used: The authors use extensive mathematical formulation to investigate the objective of this paper.

Conclusion reached:

- When the flow is strictly parallel to the stratification, Fickian behaviour will not occur and that the usual convection diffusion equation should not be used. This stems from the fact that the group of pure convection does not cause mixing in this case. If transverse local dispersion takes place, Fickian behaviour could eventually be reached asymptotically for large time or large displacement of the dissolved species. This, however, would only happen under the unrealistic requirement that the covariance function of the velocity exhibits a hole effect, so that its integral is zero and has a Laplace transform behaving linearly in the Laplace variable near the origin.
- If the flow is not strictly parallel to the stratification, then the group of pure convection causes mixing and Fickian behaviour will take place asymptotically near very reasonable assumption that the integral of the covariance of the parallel velocity component is finite.
- It was possible to show that the asymptotic directional macro-dispersion coefficient, parallel to the layering, depends more on the lateral mixing generated by the vertical velocity component than on the local transverse dispersion coefficient.
- Even if an asymptotic Fickian behaviour can be obtained as a result of the above mentioned mechanisms, it may not be applicable to real life situations: the time needed to obtain asymptotic behaviour may be too large and may allow the tracer to encounter other aquifer heterogeneities, which can be viewed as a nonstationarity of the medium.
- Making dispersion coefficient D a function of time is only an artefact, valid approximately for a point source with a pulse injection in time and giving only an approximate picture of the concentration at a given time t but not for all time between zero and t. A new simulation with another constant d is necessary for any new prediction at a different time, which makes the problem intractable. In any case, distributed sources would be very difficult to represent this way.
- The study of macro-dispersion also provides an answer to the question why the usual convection-diffusion model predicts upstream migration of a solute from its injection point, when large dispersivities are used. This is due to the inapplicability of the dispersion equation for early time, especially if a single dispersion coefficient is used at all times.
- A better mathematical formulation of the transport process in porous media, valid for all time, seems necessary. In the meantime, a possible way is to include many more details in the description of the aquifer when modelling dispersion. Instead of assuming the existence of an equivalent homogenous medium, one should try to represent in three dimensions the position and properties of each of the layers of the medium that can be identified. In each of these layers the appearance of asymptotic behaviour will be faster and thus the dispersion equation will be valid much earlier.

Comments: The results assume that the aquifer is of infinite thickness; however, they may be too restrictive if the aquifer is very thin. The authors opine that further work is required to include the effect of aquifer thickness in the analysis.

SPE 1430-G (1961)
Experiments on Mixing During Miscible Displacement in Porous Media

Authors: William E. Brigham, Philip W. Reed & John N. Dew

Contribution:

The biggest contribution from this paper was the use of the formula and methodology for calculating the effective diffusion from our simulations by analysing effluent profiles.

Objective of the paper: The paper describes experiments on miscible displacements in various porous media and the results of these experiments. The authors examine the effect on change in the amount of mixing by varying velocity, length of travel, bead size, viscosity ratio and pack diameter.

Methodology used: The authors used glass bead packs and natural cores as porous media. Bead diameters varied from 0.044 to 0.47 mm and pack lengths varied from 83 to 678 cm. Data was collected on the amount of mixing between two miscible fluids during the displacement of one fluid by another using various systems of porous media and various fluids. By taking samples as small as 0.5 cc and using refractive index for analysis, the data on breakthrough curves was plotted. To plot the data correctly on APP, a parameter $(Vp\text{-}V)/\sqrt{V}$, was used which allowed for the predicted growth of the front as it moved past the observer.

Conclusion reached: For displacements at a favourable viscosity ratio (ratio ≤ 1.0):

- The ‘square root law’, which concludes that the amount of mixing is proportional to the square root of the distance travelled, is valid.
- The length of the mixed zone is a function of velocity. The zone length increases at very low flow rates and very high flow rates, and there exists a velocity at which the zone length is a minimum. At this velocity, diffusion contributes only a small fraction of the total dispersion coefficient.

Water Resources Research, Vol. 21, No. 5, Pages 676-684, Paper Number 5W0113 (1985)
Analysis and Interpretation of Single-Well Tracer Tests in Stratified Aquifers

Authors: O. Guven, R. W. Falta, F. J. Moltz, and J. G. Melville

Contribution: The paper was useful in setting up, analysing and interpreting the results of the Single-well tracer tests.

Objective of the paper: Is to apply a view point consistent with the practical implications of author's earlier research to the analysis and interpretation of single well tracer tests performed in a stratified aquifer.

Methodology used: The authors have used the concept of local longitudinal and vertical dispersion and the effects of stratification instead of the earlier 'macroscopic' or 'full aquifer' dispersivity concepts, which have given rise to the scale dependency of dispersivity in the past. The actual analysis is based on the Eulerian-Langrangian numerical model which assumes perfect stratification implying that the horizontal permeability is a function of the vertical coordinate only and other parameters are either constant or depend only on the vertical coordinate. The local seepage velocity varies with the vertical coordinate and hence advection rates of the racer only depend on the vertical coordinate. The Single Well model takes into account the depth dependent advection in the radial direction and local hydrodynamic dispersion in the vertical and radial directions. This model was verified in part by comparison with available analytical solutions valid for homogeneous aquifers and in part by comparisons with the results of the Pickens and Grisak (1981) which were performed on stratified aquifer.
After verification of the model, several cases with assumed values of the relevant parameters are studied to determine the effects of various factors on the results of single-well tracer tests.

Conclusion reached:

- The movement of an injected tracer in a stratified aquifer may be accurately simulated without resorting to the use of a scale-dependent dispersivity if the flow field and local dispersion coefficients are known in sufficient detail. When the advection process is simulated accurately, the values of the local dispersivity will be small, constant and on the order of those measured at individual levels in the aquifer.
- The relative concentration versus time data recorded at the injection-withdrawal well is primarily a measure of the local dispersion which has taken place during the experiment.
- The effects of local dispersion will depend in part on the hydraulic conductivity distribution in the aquifer and in part on the size of the experiment.
    - As the size of the experiment increases, the effects of local vertical dispersion will become larger compared to the effects of local radial dispersion.
    - Local vertical dispersion will cause a solute travelling in a high permeability layer in an aquifer to migrate into adjacent low permeability layers where its movement will be relatively slow in comparison.
    - In case of alternating layers of high and low permeability, a large amount of tracer could become relatively immobile after migrating into the low permeability layers, perhaps largely by diffusion.

Comments: The authors idea is quite appealing. They have a different perspective to handing the issue of dispersivity measured in the laboratory being non-consistent with the ones measured in the field. In reality, it is quite difficult or rather impractical to have a complete picture of the spatial permeability distribution, flow fields and advection pattern in the reservoir, mainly because of cost. This is acknowledged by the authors themselves as well in the paper.

SPE 14364 (1988)
Dispersion and Reservoir Heterogeneity

Authors: Atul Arya, Tom A. Hewett, Ronald G. Larson, Larry w. Lake

Contribution:
None in particular.

Objectives of the paper:
1. To examine the interrelationship between heterogeneity and diffusion.
2. To examine the mixing resulting from macroscopic variations in the permeability of the medium.
3. To investigate the behaviour of longitudinal dispersivity in field scale miscible displacements, with special emphasis on analysing systems with large heterogeneity (using Dykstra-Parsons coefficient values which are higher than the values investigated in the past).

Methodology used:
The investigative tool is numerical simulation of first-contact-miscible, equal-density, constant mobility displacements in two Dimensional, randomly heterogeneous flow fields.

Conclusion reached:
1. Megascopic dispersivity increases with system aspect ratio. At high aspect ratio, it increases with time. This is true even for small correlation lengths. Macroscopic dispersivity, however, is invariant with time at all aspect ratios.
2. Diffusion does not influence megascopic dispersivity because of the long length scales. At the macroscopic scale, diffusion promotes transverse mixing, resulting in time-invariant dispersivities. Macroscopic dispersivity is constant for both correlated and uncorrelated media. For large diffusion, the effects of heterogeneity are less important.

Water Resources Research, Vol. 17, No. 4, Pages 1191-1211, Paper Number 1W0532 (1981)
Scale-Dependent Dispersion in a Stratified Granular Aquifer

Authors: John G. Pickens and Gerald E. Grisak

Contribution: Understanding of the possibility that the dispersivities obtained at different scale lengths are different.

Objective of the paper: is to develop a theoretical basis for the quantification of scale-dependent dispersion in stratified granular media and to show from detailed monitoring and analysis of several field tracer tests that longitudinal dispersivity is dependent on the scale of groundwater sampling.

Methodology used: The authors have used extensive 2 single well tracer tests and 1 well to well tracer tests to establish the scale dependence of dispersivity in a stratified aquifer. Further they have developed relationships to relate the magnitude of longitudinal dispersivity to the statistical properties of the stratified medium and travel distance of the solute. Authors have also conducted laboratory tracer tests on sand columns obtained from the field site along with obtaining statistical properties of permeability distribution for stratified aquifer and calculating the corresponding scale-dependent dispersivity expression for the aquifer.

Conclusion reached:

- The mean longitudinal dispersivity obtained from analysis of transport at the scale of individual levels in the aquifer for the single-well tests is 0.7cm. Although the aquifer is known to exhibit laminations of the order of 0.1-0.5 cm, there was no evidence of scale dependence with different travel distances, possibly because a constant or asymptotic dispersivity had been reached at a travel distance closer than the nearest sampling point.
- The full-aquifer dispersivity obtained from analysis of the withdrawal-phase concentration history for the injection-withdrawal well of a single-well test is dependent largely on the effect and extent of transverse migration between layers in response to hydraulic and concentration gradients.
- The full-aquifer longitudinal dispersivity obtained from analysis of the withdrawal-well breakthrough curve of a two well test is also scale dependent. This dispersivity is dependent on the aquifer hydraulic conductivity distribution and distance between wells.
- The average dispersivity value of 0.035 cm, obtained in three laboratory tracer test on repacked column of sand, is considered to be a representative laboratory-scale value for sand from field site. Again a scale effect is observed between the laboratory dispersivity and dispersivity obtained at individual level (0.7cm). This is result of greater non-homogeneity of the aquifer and the averaging cause by the groundwater sampling system.

SPE 75247 (2002)
Estimation of True Dispersivity in Field scale Permeable Media

Authors: Jagannathan Mahadevan, Larry W. Lake, and Russell T. Johns.

Contribution:

1. The single well tracer test dispersivities agree with field-measured dispersivities. Although, the SWTT values taken by the authors are over a much narrower range of travel distance, the agreement in values according to the authors, suggests that the echo dispersivities would grow with travel distance if they were measured over a larger distance. This was supported by numerical simulations results. However, the authors are at a loss to explain satisfactorily the agreement between SWTT and field-dispersivities.

Objective of the paper:

Objective of this paper is to investigate the three types of dispersion in permeable media to obtain realistic estimates of dispersive mixing at the field scale.

Methodology used:

The authors use numerical simulations (UTCHEM reservoir simulator) to generate a transmission history by performing an injection and production on a two dimension, layered permeable medium with a range of permeability values. Apart from this, they have used analytical model for the flow of particles in reservoir media.

Conclusion reached:

1. All dispersivities—echo, local and transmission—are the same in homogenous media.
2. For layered media which is heterogeneous, echo and transmission are very different.

Comments: All numerical simulations in this paper assume the following:

1. 1-D radial (or Cartersian) and homogenous system (Single layer) with constant porosity
2. Single phase flow

SPE 90390 (2004)
Modelling Conformance as Dispersion

Authors: Coats, K.H., Whitson, C.H., Thomas, L.K.

Contribution: The paper differentiates between the rock property physical dispersivity, associated with dispersion and apparent dispersivity associated with conformance. Numerical studies on effect of dispersion often use large input dispersivity values which stem from large apparent dispersivities determined by matching 1D CD equation to production well effluent tracer concentration profiles. The authors opine, that these large apparent dispersivities reflect conformance or other behaviour not governed by the 1D CD equation and should not be used to justify large physical dispersivity as input to numerical studies. Scale dependency of dispersivity is devoid of meaning.

Objective of the paper:
The objective of the paper is to prove that the large apparent dispersivities are basically conformance and not due to in-situ mixing or dispersion.

Methodology used:
Inferences are made in this paper using analytically models previously generated by researchers modified to reach the conclusions given by the authors.

Conclusion reached:

1. Heterogeneity alone causes no in-situ mixing in the reservoir.
2. Apparent dispersivity is obtained by matching observed or numerically calculated effluent concentration curves with the one dimensional convection dispersion equation. That equation does not physically describe field tracer test behaviour. That behaviour largely reflects areal and vertical conformance, which in turn depend upon well pattern and completion intervals, heterogeneity and drift.
3. The observed scale dependence of apparent dispersivity is empty of meaning. When it exists then it is a necessary consequence of apply the non-applicable 1D CD equation with its single parameter, the Peclet number, to match effluent profiles reflecting conformance.

Appendix B

GRID REFINEMENT STUDY

The intention of grid refinement was to ensure that physical diffusion dominates numerical diffusion during the simulations. Lantz (1971) had mathematically shown that in order to reduce numerical diffusion in any simulation, the size of the grid blocks and time steps for calculations should be kept as small as practically possible. Therefore, an extensive attempt was made to reduce the size of the grid blocks so that the effects of physical diffusion could be explicitly seen. Table B.1 highlights the values of numerical diffusion using different grid sizes and D=0.00093sqft/day.

Table B. 1: Values of Numerical Diffusion for Different Grid Sizes & D=0.00093 sqft/day

Cases (Grid Sizes)	Values of Numerical Diffusion K (sqft/day) for Different Grid Sizes with D = 0.00093 sqft/day			
	U90-10	U80-20	U70-30	U60-40
22×1×10	74.2	52.5	45.7	42.3
42×1×10	32.5	26.2	23.7	22.5
82×1×10	19.9	16.8	15.7	14.9
162×1×10	14.8	13.0	12.1	11.7
322×1×10	12.7	11.1	10.6	10.2
642×1×10	11.8	10.2	9.9	9.5
1282×1×10	11.3	9.9	9.5	9.1
2562×1×10	11.1	9.7	9.3	8.9
5122×1×10	11.0	9.6	9.2	8.8
10242×1×10	10.9	9.5	9.2	8.8

Figure B.1 shows plots of effluent profiles versus pore volumes produced for the cases in Table B.1. The table above shows that there is little difference in the values of diffusion for sizes below the grid size 322×1×10. Therefore this grid size was chosen as our base case grid. But the simulations were still not dominated by physical dispersion as can be seen from Table B.1 and Figure B.1. The simulator in use had the explicit Flux Limiting Scheme which greatly reduced numerical dispersion. However, it should be noted that it does not remove numerical dispersion completely. Table B.2 highlights the values of calculated diffusion using the grid size of 322×1×10, flux limiting scheme for different values of diffusion coefficient.

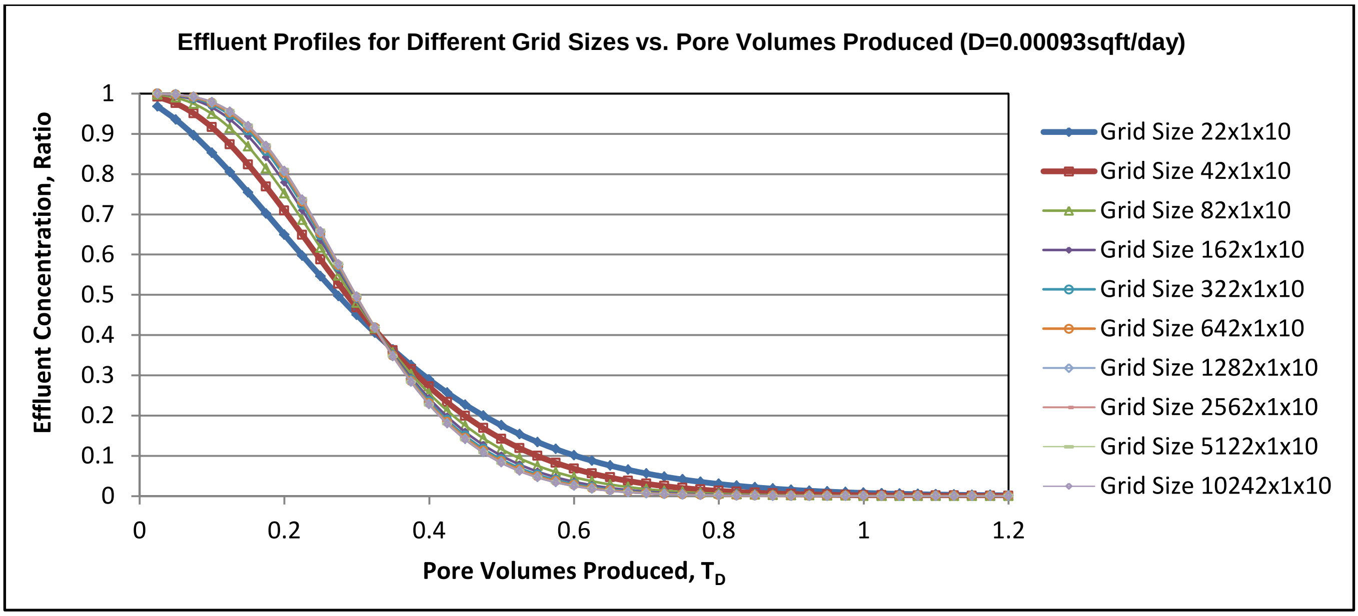

Figure B. 1: Effluent Profiles for Different Grid Sizes versus Pore Volumes Produced. Diffusion Coefficient Used is 0.00093sqft/day. There is little or no difference between effluent profiles for grid sizes finer than 162×1×10.

Table B. 2: Values of Numerical Diffusion K (sqft/day) for Base Grid Size using Flux Limiting

Cases	Values of Numerical Diffusion K (sqft/day) for Same Grid Size but different Physical Diffusion Coefficients			
	U90-10	U80-20	U70-30	U60-40
D=0 sqft/day	0.07	0.08	0.08	0.08
D=0.0093 sqft/day	0.09	0.09	0.10	0.10
D=0.093 sqft/day	0.43	0.44	0.46	0.45
D=0.93 sqft/day	6.71	6.48	6.39	6.26

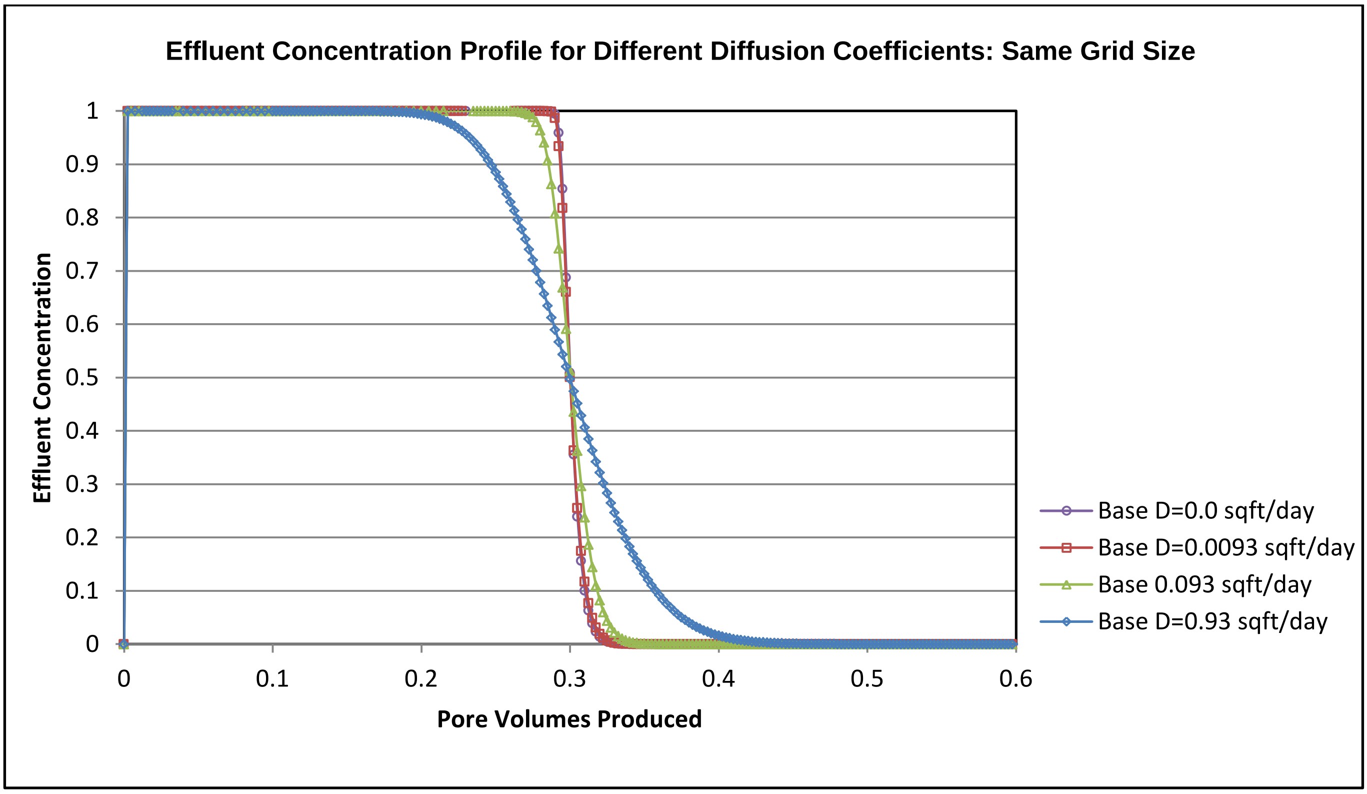

Figure B. 2: Plot for D=0 sqft/day shows minute numerical diffusion or mixing. In such case, effluent profile should have been a unit step shape without smooth edges in response to a unit step input concentration. It can also be seen from D=0.93 sqft/day plot that the effluent profile is a typical Gaussian shape.

From the values of K corresponding D=0.093, D=0.0093 & D=0.0 sqft/day in Table B.2, we can see that flux limiting scheme has significantly reduced numerical diffusion. However, for the case of D=0 sqft/day, it is still showing small numerical diffusion. This can be seen from the effluent profiles in Figure B.2. However, this reduced numerical diffusion gave us confidence that physical diffusion is now dominating numerical diffusion and giving us a good qualitative match. In order to ensure that was the case, the value of diffusion coefficient was increased by another order of magnitude to see the change. The curve for that, as shown in figure B.2, is perfectly Gaussian and shows a greater degree of mixing. Quantitatively, looking at Table B.2, we can see that for every order of magnitude increment in the value of input diffusion coefficient, we have a corresponding increment in the order of magnitude of numerical diffusion.

Table B.3 highlights the values of numerical diffusion for different grid sizes using a diffusion coefficient D=0.93 sqft/day. The need for doing this was simply to check whether after using flux limiting scheme we have the same response as was seen in Table B.1.

Table B. 3: Values of Numerical Diffusion for Different Grid Sizes & D=0.93 sqft/day

Cases (Grid Sizes)	Values of Numerical Diffusion K (sqft/day) for Different Grid Sizes			
	U90-10	U80-20	U70-30	U60-40
66 x 1 x 10	9.1	8.7	8.6	8.4
162 x 1 x 10	6.9	6.7	6.6	6.4
322 x 1 x 5	6.8	6.6	6.5	6.4
322 x 1 x 10	6.7	6.5	6.4	6.3
422 x 1 x 10	6.7	6.5	6.4	6.3

It is clear from above table that there is no difference between values of calculated diffusion for the last two cases. Hence as a result of this grid refinement study, it was decided to use Grid size 322×1×10 with an input diffusion of 0.93sqft/day in our simulations. Figure B.3 gives the effluent profiles for above cases and indicates minute differences between the effluent profiles, thus confirming the grid refinement is dominated by physical diffusion and can be used for a fairly reasonable level of accuracy in our simulations.

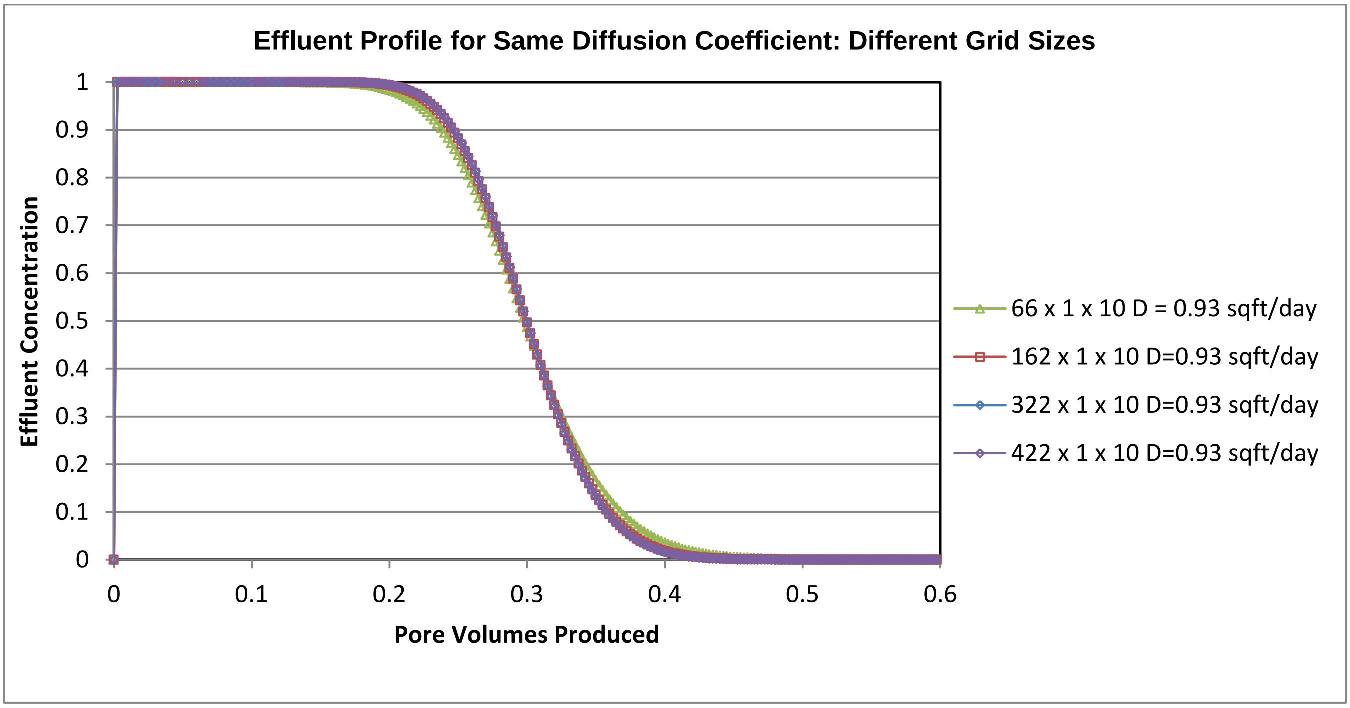

Figure B. 3: Effluent profiles for D=0.93sqft/day for different grid sizes.

APPENDIX C

Eclipse Code For Single Well Tracer Test (Homogonous Case)

```
-- ECHO ECLIPSE
RUNSPEC
DIMENS
322 1 10 /
OIL
WATER
FIELD
TRACERS
0 1 0 0 DIFF/
DISPDIMS
2 7 2/
EQLDIMS
-- using default values
1 100 20 1 20/
TABDIMS
1 2 50 50 1* 1* /
WELLDIMS
4 10 2 4 /
REGDIMS
10 10/
NSTACK
24 /
START
1 JAN 2008 /
UNIFOUT
UNIFIN
GRID
DX
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
1*3 320*10.23375 1*3
/
DY
3220*172 /
DZ
3220*9.84 /
TOPS
322*5000 /
INIT
PORO
3220*0.10 /
PERMX
3220*40 /
COPY
PERMX PERMY /
PERMX PERMZ /
/
EDIT
```

```
PROPS
TRACER
ANK WAT 'STB'/
/
TRACTVD
TRDIFANK
0.93 /
0 /
TRDISANK
1 1 1 1 1 1 1 1 1 1/
1 1 1 1 1 1 1 1 1 1/
/
PVTW
-- PREF FVF              WATERCOMP   VISC            VISCOSIBILITY
2500.0 1.00000001 1.8E-11 .40000 .00E+00 /
//
ROCK
-- PREF          ROCK COMP
 4000.00 .3500E-05 /
/
PVDO
2500 1.00000001000 0.4
3000 1.00000000100 0.4
3500 1.00000000010 0.4
4000 1.00000000001 0.4
4500 1.000000000001 0.4 /
//
DENSITY
45 45 0//
/
SWFN
   0          0        0
   0.05    0.05      0
   0.1000  0.1000    0
   0.15    0.15      0
   0.20    0.2000    0
   0.30    0.3000    0
   0.35    0.35        0
   0.40    0.4000    0
   0.45   0.45         0
   0.50    0.5000    0
   0.55   0.55         0
   0.60    0.6000    0
   0.65   0.65         0
   0.70    0.7000    0
   0.75   0.75         0
   0.80    0.8000    0
   0.85   0.85         0
   0.90    0.9000    0
   0.95   0.95         0
   1.0000  1.0000    0 /
/
SOF2
    0       0
   0.05  0.05
   0.1   0.1
   0.15  0.15
   0.2   0.2
   0.3   0.3
   0.35  0.35
```

```
   0.4   0.4000
   0.45  0.45
   0.5   0.5000
   0.55  0.55
   0.6   0.600
   0.65  0.65
   0.700 0.700
   0.75  0.75
   0.8   0.8000
   0.85  0.85
   0.9   0.900
   0.95  0.95
   1.0   1.0/
/
DISPERSE
0        0        0.000
         1        0.000 /
90       0        0.000
         1        0.000 /
150      0        0.000
         1        0.000 /
210      0        0.000
         1        0.000 /
270      0        0.000
         1.0      0.000 /
330      0        0.000
         1        0.000 /
/
RPTPROPS
TRACER /
/
REGIONS
SOLUTION
EQUIL
 4000 2500 3000 /  .00000  .00000  .00000    0     0     1*
TBLKFANK
3220*0.0 /
RPTSOL
  -- Initialisation Print Output
  --
'SWAT' 'RESTART=2' 'FIP=1' 'EQUIL' /
RPTRST
'BASIC=2' 'ALLPROPS' 'TRAS' /
SUMMARY
FWCT
WWCT/
WWPT/
FWIR
WWIR/
WOIR/
WWIT/
FTPTANK
WTPTANK/
FTITANK
WTITANK/
FTPCANK
WTPCANK/
FTICANK
WTICANK/
FVPR/
```

```
FVIR/
FTIRANK/
FTPRANK/
WTPCANK/
WTICANK/
FPR
BPR/
WBHP/
FOIR
WOIR/
FWPV/
FOPV/
FRPV
/
RUNSUM
SEPARATE
SCHEDULE
RPTSCHED
  'RESTART=2' 'FIP=1' 'WELLS=2' 'WELSPECS'/
WELSPECS
'P1' 'G' 322 1 1* 'WAT'  /
'I20' 'G' 1 1 1* 'WAT'  /
/
COMPDAT
'P1'  322 1 1 10 'OPEN' 1* 1* .3048 /
'I20' 1 1 1 10 'OPEN' 1* 1* .3048 /
/
WCONPROD
'P1' 'OPEN' 'RESV' 3* 1* 301.4212 275 /
WCONINJE
'I20' 'WATER' 'OPEN' 'RESV' 1* 301.4212 /
WTRACER
'I20'  'ANK' 1 /
TSTEP
100*9.84313
WTRACER
'I20' 'ANK' 0.0 /
WELSPECS
'I1' 'G' 322 1 1* 'wat' /
'P20' 'G' 1 1 1* 'WAT'/
COMPDAT
'I1'  322 1 1 10 'OPEN' 1* 1* .3048 /
'P20' 1 1 1 10 'OPEN' 1* 1* .3048 /
'P1'  322 1 1 10 'SHUT' 1* 1* .3048 /
'I20' 1 1 1 10 'SHUT' 1* 1* .3048 /
WCONPROD
'P20' 'OPEN' 'RESV' 3* 1* 301.4212 275 /
WCONINJE
'I1' 'wat' 'OPEN' 'RESV' 1* 301.4212 /
TSTEP
1000*6.202/
END
```

APPENDIX D

Eclipse Code For Well To Well Tracer Tests (Homogonous Case)

```
-- ECHO ECLIPSE
RUNSPEC
DIMENS
197 1 10 /
OIL
WATER
FIELD
TRACERS
0 1 0 0 DIFF/
DISPDIMS
2 7 2/
EQLDIMS
1 100 20 1 20/
TABDIMS
1 2 50 50 1* 1* /
WELLDIMS
2 10 2 4 /
REGDIMS
10 10/
NSTACK
24 /
START
1 JAN 2008 /
UNIFOUT
UNIFIN
GRID
DX
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
1*3 195*10.23375 1*3
/
DY
1970*172 /
DZ
1970*9.84 /
TOPS
197*5000 /
INIT
PORO
1970*0.10 /
PERMX
1970*40 /
COPY
PERMX PERMY /
PERMX PERMZ /
EDIT
PROPS
TRACER
ANK WAT 'STB'/
```

```
TRACTVD
TRDIFANK
0.93 /
0 /
TRDISANK
1 1 1 1 1 1 1 1 1 1/
1 1 1 1 1 1 1 1 1 1/
/
PVTW
-- PREF FVF                   WATERCOMP   VISC                 VISCOSIBILITY
2500.0 1.00000001 1.8E-11 .40000 .00E+00 /
//
ROCK
-- PREF              ROCK COMP
 4000.00 .3500E-05 /
/
PVDO
2500 1.00000001000 0.4
3000 1.00000000100 0.4
3500 1.00000000010 0.4
4000 1.00000000001 0.4
4500 1.000000000001 0.4 /
//
DENSITY
45 45 0//
SWFN
-- WATER SATURATION           WATER RELPERM         WATEROIL CAPILLARY PRESSURE
    0             0          0
    0.05    0.05      0
    0.1000  0.1000    0
    0.15    0.15      0
    0.20    0.2000    0
    0.30    0.3000    0
    0.35    0.35          0
    0.40    0.4000    0
    0.45   0.45          0
    0.50    0.5000    0
    0.55   0.55          0
    0.60    0.6000    0
    0.65   0.65          0
    0.70    0.7000    0
    0.75   0.75          0
    0.80    0.8000    0
    0.85   0.85          0
    0.90    0.9000    0
    0.95   0.95          0
    1.0000  1.0000    0 /
/
SOF2
     0         0
    0.05  0.05
    0.1   0.1
    0.15  0.15
    0.2   0.2
    0.3   0.3
    0.35  0.35
    0.4   0.4000
    0.45  0.45
    0.5   0.5000
    0.55  0.55
```

```
   0.6   0.600
   0.65  0.65
   0.700 0.700
   0.75  0.75
   0.8   0.8000
   0.85  0.85
   0.9   0.900
   0.95  0.95
   1.0   1.0/
/
DISPERSE
0       0       0.000
        1       0.000 /
90      0       0.000
        1       0.000 /
150     0       0.000
        1       0.000 /
210     0       0.000
        1       0.000 /
270     0       0.000
        1.0     0.000 /
330     0       0.000
        1       0.000 /
/
RPTPROPS
TRACER /
REGIONS
SOLUTION
EQUIL
 4000 2500 3000 /  .00000  .00000  .00000    0    0    1*
TBLKFANK
1970*0.0 /
RPTSOL
'SWAT' 'RESTART=2' 'FIP=1' 'EQUIL' /
RPTRST
'BASIC=2' 'ALLPROPS' 'TRAS' /
SUMMARY
FWCT
WWCT/
WWPT/
FWIR
WWIR/
 WOIR/
 WWIT/
FTPTANK
WTPTANK/
FTITANK
WTITANK/
FTPCANK
WTPCANK/
FTICANK
WTICANK/
FVPR/
FVIR/
FTIRANK/
FTPRANK/
WTPCANK/
WTICANK/
FPR
BPR/
```

```
WBHP/
FOIR
WOIR/
FWPV/
FOPV/
FRPV
/
RUNSUM
SEPARATE
SCHEDULE
RPTSCHED
  'RESTART=2' 'FIP=1' 'WELLS=2' 'WELSPECS' /
WELSPECS
'P1' 'G'  197 1 1* 'WAT'  /
'I20' 'G' 1 1 1* 'WAT'  /
COMPDAT
'P1'  197 1 1 10 'OPEN' 1* 1* .3048 /
'I20' 1 1 1 10 'OPEN' 1* 1* .3048 /
WCONPROD
'P1' 'OPEN' 'RESV' 3* 1* 301.4212 275 /
WCONINJE
'I20' 'WATER' 'OPEN' 'RESV' 1* 301.4212 /
WTRACER
'I20'  'ANK' 1 /
TSTEP
1000*4.036669/
END
```