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A Pseudo-TOF Based Streamline Tracing For Streamline Simulation Method In Heterogeneous Hydrocarbon Reservoirs

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ABSTRACT: *In this study, a modified model to trace streamlines in two-dimensional incompressible fluid flows through porous media is proposed. This modification improves the speed of the standard streamline method using a self-consistent approach, where a combination of backward and forward tracing algorithms is applied based on a pseudo-time-of-flight mapping calculated on corresponding underlying grids. This model covers all the Eulerian (background) grid-blocks with an optimized number of streamlines while meeting a given accuracy criterion. Compared to the conventional streamline methods, it is also shown that the efficiency (i.e. overall speed of the simulation) of the modified streamline method enhances as the domain complexity and heterogeneities increase.*

KEYWORDS- *Reservoir simulation, Streamline method, Backward and Forward Streamline tracing, Pseudo time-of-flight, Missed Grid Block*

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I. INTRODUCTION

Streamline simulations have been extensively used in oil & gas reservoir modeling as a viable alternative to traditional methods (e.g. finite difference and finite-volume methods), especially for large and heterogeneous media where multi-well and multiphase flow modeling is required (Batycky et al.[1, 2, 3], Blunt et al. [4]). Streamline method is free of numerical dispersion, and requires lower computational efforts (Batycky et al. [1]). It is shown that streamline-based transport modeling is typically one or two orders of magnitude faster than grid-based approaches, while provides essentially identical results (Batycky et al. [1], Huang et al. [5]). The streamline method and its application to transport equation simulations have been developing over the course of several studies (e.g. see the work of Muskat [6], Muskat and Wyckoff [7], Fay and Prats [8], and Higgins and Leighton [9], Higgins et al. [10], Parsons [11], Martin and Wegner [12], Bommer and Schechter [13], Lake et al. [14], Emanuel et al. [15], and Hewett and Behrens [16]). Streamline-based simulation acquires a fundamentally different approach to solve the transport equations. Instead of using a cell-by-cell scheme, the streamline method breaks up the two or three dimensional transport equations into multiple one-dimensional (1D) equations along streamlines, and approximates the fluid flow calculations by the sum of these 1D solutions (Datta-Gupta and King [17], Pollock [18]). There are two immediate advantages for this approach; (i) solving multiple 1D problems is computationally faster than solving the original 2D or 3D problems with the same number of unknowns at once, and (ii) the stability constraint of the underlying Eulerian gird-blocks can be effectively relieved by solving 1D equations along streamlines (Batycky et al. [1, 2], Blunt et al. [4], Thiele et al. [19]). The speed and efficiency of the streamline simulation make it more feasible to simulate reservoirs of multi-million cells, where one needs to entirely integrate a detailed geologic and geophysical data into the simulation (Datta–Gupta and King [20], King and Datta-Gupta [21]).

There are some drawbacks within standard streamline method (SSM). For example, the results of simulations depend highly on the number of streamlines that are launched from injector to producer cells (Batycky et al. [1], Thiele [22], Thiele et al. [23]). When a large number of streamlines are traced in the model the number of missed grid-blocks (i.e. not covered by any streamlines) are fewer, however it comes to the cost of a high computational time Datta-Gupta and King [17]. In a highly heterogeneous media, the situation becomes more challenging where a very large number of streamlines might be needed to cover all the grid-blocks. Several studies (e.g. Batycky et al. [3], Crane and Blunt [24], Siavashi et al. [25]) have shown that tracing a large number of streamlines is not a practical solution to cover all the grid-blocks, and thus, they proposed several compensative methods to resolve this issue. For instance, a streamline from a missed grid-block can be traced backward to the nearest grid-block containing a streamline (Batycky et al. [2], Crane and Blunt [24]). In another but similar method described by Batycky et al. [2], and Siavashi et al. [25], a streamline can be assigned to a missed grid-block, which is then traced backward in the velocity field towards an injector (Datta-Gupta and King [17]). These compensative methods while performing well with respect to the standard streamline method, do not follow a prescribed optimum pattern to assign streamlines to the missed grid-blocks. For this reason, an approach that provides a desirable accuracy of the fluid flow with an optimum number of streamlines is of interest. Mallison et al. [26], and Matringe et al. [27] tackled this problem, where they introduced a new mapping and optimizing streamline coverage. In the model presented by Matringe et al. [27], streamlines are considered to form a flow-aligned unstructured grid for the transport equation. This point of view, with the mapping formulation proposed by Mallison et al. [26] (to link streamline grid to background grids) allow the local adaptation of the streamline density. It means that in order to increase streamlines density (number of streamline (SL)/grid) where it is necessary partial streamlines (streamlines that do not start and end at wells) are allowed to be used (Matringe et al. [27]).

In the present study, a straight forward approach is introduced that simply improves the efficiency of streamline method in comparison with conventional methods (especially those proposed by Batycky et al. [3], Crane and Blunt [24], Siavashi et al. [25]) for a given accuracy criterion. This approach introduces a new mapping to trace streamlines that acquires minimized intervention, and uses the minimum possible number of streamlines while covering all grid-blocks.

II. STANDARD STREAMLINE METHOD (SSM)

To make this paper self-contained, the concept of the standard streamline method has been summarized here. For more detailed descriptions, refer to Batycky et al. [1, 2] and Faroughi et al. [28].

2.1 GOVERNING IMPES FORMULATION

The streamline method is based on the IMPES approach. The IMPES method includes a coupling of an implicit pressure solution with an explicit solution for the transport equation (e.g. concentration and saturation) (Abou-Kassem et al. [29]). Ignoring gravity, capillary and dispersion effects leads to the following equation, in term of total pressure P, for an incompressible multi-phase flow in a porous medium(Batycky et al. [1], Faroughi et al. [28]),

$$\nabla.(\lambda_t \nabla P) = 0, \tag{1}$$

Where(λ_t) denotes the total mobility defined as

$$\lambda_t = \sum_{j=1}^{n_P} \boldsymbol{K} \frac{k_{rj}}{\mu_j}. \tag{2}$$

In Eq. (2), $\boldsymbol{K}$ denotes the absolute permeability tensor, k_{rj} is the relative permeability and μ_j is the shear dynamic viscosity of phase j(Batycky [30]). To calculate the flow of individual phases, material balance equation for each phase is required such as (Batycky [30]),

$$\emptyset \frac{\partial S_j}{\partial t} + \vec{u}_t . \nabla f_j = 0, \tag{3}$$

Where $\emptyset$ is the porosity of the medium, and $\vec{u}_t$ is the total velocity derived from the solution of the pressure field and Darcy's Law. The term of phase fractional flow, f_j, in Eq. (3) is obtained by (Batycky [30]),

$$f_j = \frac{k_{ri}/\mu_j}{\sum_{i=1}^{n_P} \frac{k_{ri}}{\mu_i}}. \tag{4}$$

In a conventional simulation, Eq. (3) is solved in its full two-dimensional (2D) form, while the streamline method decouples these 2D equations for all phases into multiple 1D equation along individual streamlines (Batycky [30]).

3.2 COORDINATE TRANSFORM IN STANDARD STREAMLINE METHOD (SSM)

Once the pressure equation (Eq. (1)) is solved on the Eulerian grid-blocks, Darcy’s Law is applied to determine the total velocity at grid-block faces. Based on the velocity field, streamlines are traced from the grid-block faces containing injectors to that of producers. As streamlines are traced cell-by-cell, the Time-of-Flight (TOF) (Batycky et al. [1], Datta–Gupta and King [20], Thiele [22], Thiele et al. [23], Faroughi et al. [28], Batycky [30]) is determined along each individual streamline defined as,

$$\tau(s) = \int_0^s \frac{\emptyset}{u_t(\zeta)} d\zeta, \tag{5}$$

where ζ denotes a coordinate along the streamline. Equation (5), based on the total velocity, $u_t(\zeta)$, determines the time required to reach a point s on the streamline along the streamline. To obtain the coordinate transform (from Eulerian to TOF), we rewrite Eq. (5) as (Thiele [22]),

$$\frac{\partial \tau}{\partial s} = \frac{\emptyset}{|u_t|}, \tag{6}$$

That can be approximated as (Batycky et al. [1], Thiele [22], Batycky [30]),

$$|u_t| \frac{\partial}{\partial s} \equiv \vec{u}_t . \nabla = \emptyset \frac{\partial}{\partial \tau}. \tag{7}$$

Substituting Eq. (7) into Eq. (3) leads to

$$\frac{\partial S_j}{\partial t} + \frac{\partial f_j}{\partial \tau} = 0, \tag{8}$$

which is the governing pseudo one-dimensional material balance equation for phase j transported along the streamline coordinate, TOF (Batycky et al. [1], Thiele [22], Batycky [30]).

III. MODIFIED STREAMLINE METHOD (MSM)

In the standard streamline method, as can be outlined from Eq. (8), each grid-block must at least contain one streamline to be able to approximate the flow physical characterizes (Batycky et al. [1], Faroughi et al. [28], Batycky [30])). Ref. 26 and 27 (Mallison et al., Matringe et al.) have applied a different solution mapping method between TOF and Eulerian mesh, and showed that it is not always necessary to pass streamlines from all grid blocks, which ultimately increase the efficiency of the streamline method. However, the modified streamline method is defined based on the following two facts; (i) the number of streamlines launched in the model must not affect the calculation of transport equations, and (ii) each grid-block must at least contain one streamline passing through.

In the SSM, streamlines are normally launched from the faces of the injectors toward the producers, or vice versa, while, in the MSM, streamlines tracing starts from the center of a grid-block with the longest pseudo-TOF which can be approximated based on the velocity gradient, $|\Delta u|$ for each grid-black. The grid-block possessing the longest pseudo-TOF is mostly located far from the injector and producer, or possibly possesses the lowest absolute permeability. In the second step within the MSM, the streamline is traced forward and backward using Pollack's method (Pollock [18], Thiele [22], Thiele et al. [23], Batycky [30]) from the center of the grid-block to its faces (see Fig.1(a)). Applying this approach leads to the determination of the inlet and outlet points as well as the real TOF of the streamline passing through the concerned grid-block. Next, as depicted in Fig.1(b), Pollack's method is utilized to complete the streamline tracing forward and backward to the producer and injector grid-block faces, respectively.

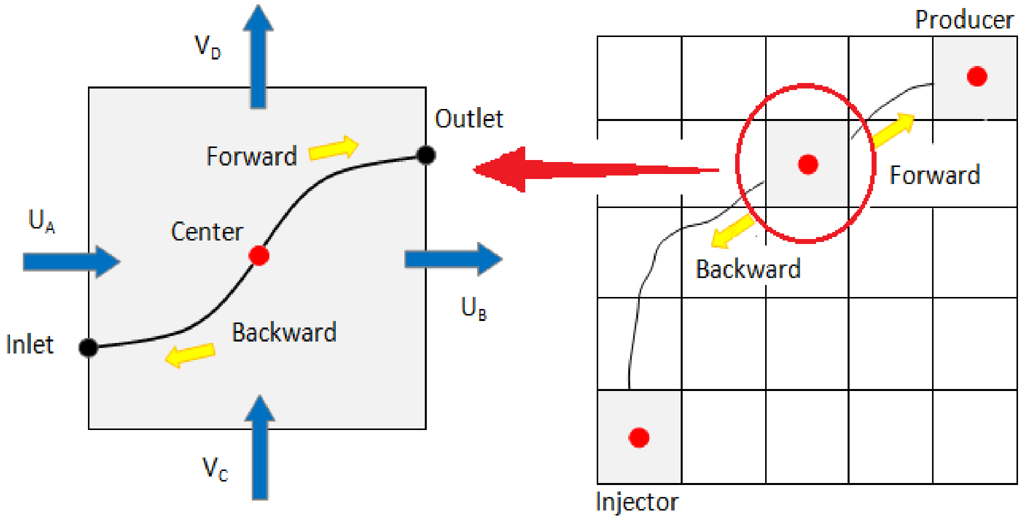

Figure.1. (a) Tracing streamline forward and backward from the center of the grid-block to its faces, and (b) from grid-block faces to injector and producer using Pollack's method.

The aforementioned processes continue until all grid-blocks contains at least one streamline, i.e. the MSM finds a gird-block with the second, third, fourth, and so on longest pseudo-TOF, and lunches a streamline from their center to the injector and producer. It should be noted that the MSM skips a grid-block to start tracing from its center, if one of the former traced streamlines has already passed through it. Fig. 2 schematically shows the sequence by which five streamlines are traced using the MSM to cover all grid-blocks in a quarter of a 5 spot problem. Grid number 1 is the one where the first streamline is launched (as it acquires the longest pseudo-TOF), and grid number 5 having the shortest pseudo-TOF is a grid where the final streamline is traced for this specific problem. Other blocks are skipped, because they contain a streamline already. It should be noted that, in a real problem with fine mesh, the majority of grid-blocks may contain multiple streamlines.

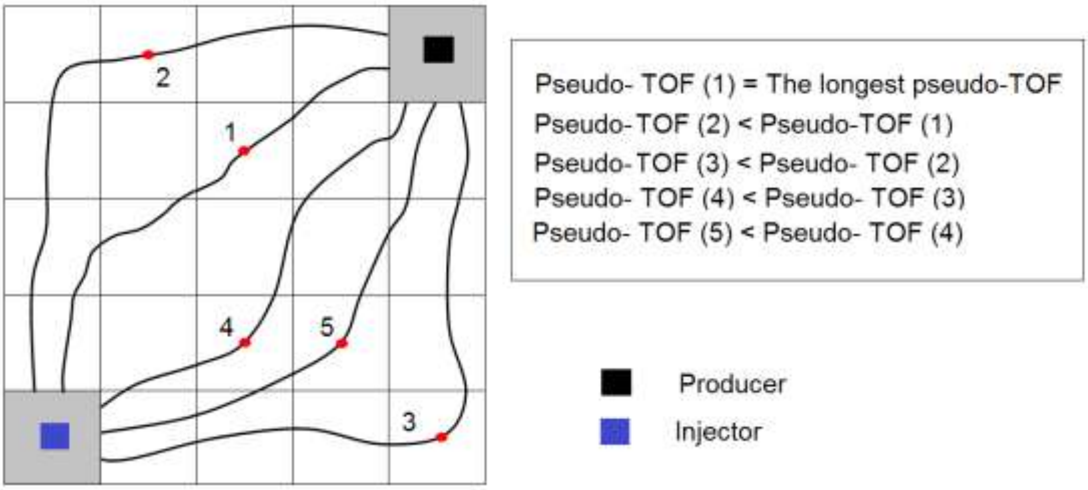

Figure.2. the sequence over which streamlines are traced using MSM; the pseudo-TOF for grid-blocks defined by the magnitude of the velocity gradient is the parameter upon which the tracing is performed until all grid-blocks contain at least one streamlines.

3.1 CALCULATION OF THE GRID-BLOCK PROPERTIES

Once all streamline are traced as described in section 3 and 1D solutions are obtained along streamlines, one must convert the streamlines properties on the TOF grid to the Eulerian grid-blocks, and approximate the physical properties on individual grids. To this end, one may employ a weighted averaging approach, i.e. the phasic concentration/saturation associated with a grid-block is calculated using the weighted average of the concentration/saturation of streamlines passing through the grid-block (Thiele et al. [19], Crane and Blunt, [24]). The averaged grid-block saturation for each phase, $\bar{S}_{gb}$, is thus calculated by (Batycky [30], Thiele [31]),

$$\bar{S}_{gb} = \sum_{i=1}^{n_{gb}^{sl}} w_i \bar{S}_i^{sl}, \tag{9}$$

Where $\bar{S}_i^{sl}$ is the average saturation for the i^{th} streamline, and w_i is a weighting factor associated with the i^{th}streamline; note that for each grid-block $\sum_{i=1}^{n_{gb}^{sl}} w_i = 1$ (Batycky [30]).

The flux across each face of the injection grid-block is considered to be uniform that is consistent with the underlying velocity field. In the SSM, streamlines are usually distributed in a uniform manner on each face; consequently, streamlines convey an equal flux throughout the model. With this assumption, the weighting factor for individual streamlines is simply related to their time-of-flight in the grid-block, and is calculated by (Batycky [30]),

$$w_i = \frac{\Delta\tau_i}{\sum_{i=1}^{n_{gb}^{sl}} \Delta\tau_i}. \tag{10}$$

The MSM applies another approach to distribute the flux among the traced streamlines. The flux is different for each streamline because of the non-uniform spacing between streamlines traced backwards meeting the faces of an injector grid-black. Fig. 3 illustrates the difference between the forms by which streamlines are connected to the face of an injector in both SSM and MSM. In Standard method (SSM), Fig. 3(a), streamlines are launched from the injector faces in a uniform manner, however in the modified method (MSM), Fig. 3(b), streamline spacing at the connections is not uniform. Therefore, to ensure continuity condition, streamtubes of different sizes around each streamline are constructed that convey different fluxes. The weighting factor for the MSM must updated to,

$$w_i = \frac{q_i \Delta\tau_i}{\sum_{i=1}^{n_{gb}^{sl}} q_i \Delta\tau_i}, \tag{11}$$

where, q_i is the flux of the streamtube associated to i^{th} streamline. The flux for streamtubes is assigned based on their cross-sectional area, i.e. the boundaries of streamtubes are considered to be located at the mid-distance between two consecutive streamlines. With this assumption, as shown in Fig. 4, streamlines are not necessarily located at the center of their associated streamtubes, whose fluxes, q_i, are determined by

$$q_i = \frac{(a+b)}{2L} q, \tag{12}$$

where q is the total flux at the edge, and a and b are the distances between the contact points of sl_i with closest streamlines from each side on the edge, see Fig. 4. For the streamlines lacking one of the adjacent streamlines (e.g. first and final streamlines on each edge), Eq. (12) is replaced by

$$q_i = \frac{\left(a + \frac{1}{2} b\right)}{L} q, \tag{13}$$

where, a is the distance of the contact point of sl_i with the nearest vertex of the injector edge, and b holds its aforementioned definition in Eq. (12). Fig. 4 shows the schematic representation of streamtubes associated to streamlines and the way with which a and b in Eqs. (12), and (13) are determined.

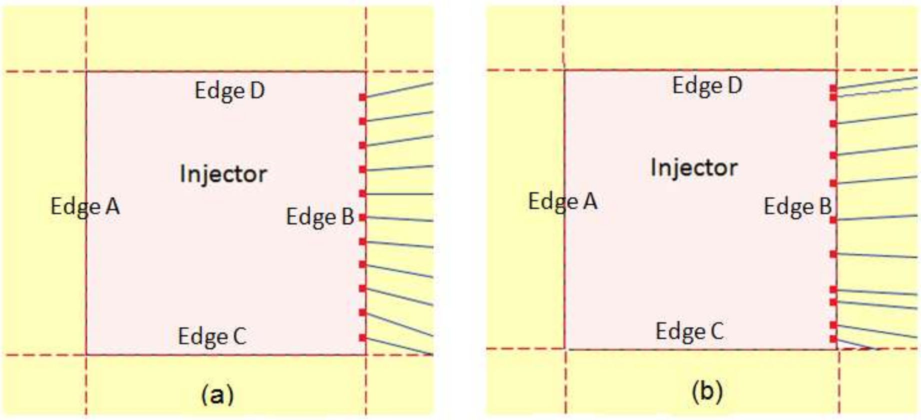

Figure.3. Streamline and injector face connection in (a) SSM and (b) MSM. Squares show a place where streamlines connect to the face of the injector grid. This connection is uniform in SSM, while non-uniform for the MSM.

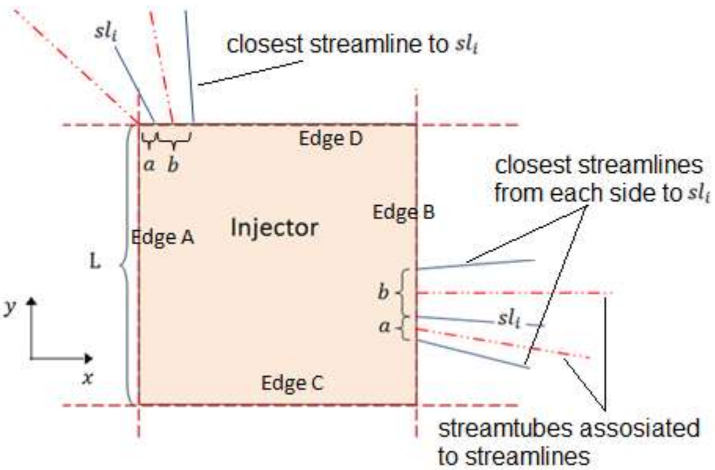

Figure.4. a schematic representation of the streamlines and2D streamtubes considered around them to determine the associated flux for each streamline.

IV. RESULTS

We test the efficiency of the proposed modified streamline method against the standard streamline method for a given accuracy criterion in three different numerical examples. Note that the pressure equation for both methods is solved using the conventional Finite difference approach.

The first example concerns a 100×100 homogenous medium. The traced streamline for this problem using the MSM and SSM (with no backward streamlines from missed grid block) are demonstrated in Fig. 5. One observes that the density of streamline for both methods is comparable close to wells (injector and producer). The MSM requires 196 streamlines to cover all grid-blocks, while it can be seen that the top-left and bottom-right corners are left without streamlines in the SSM (using 196 streamlines). To overcome this issue, several streamlines must be traced backward from those grid-blocks to cover all missed grid blocks, see Ref. 2, 24, and 25, and this explicitly increases the overall simulation time.

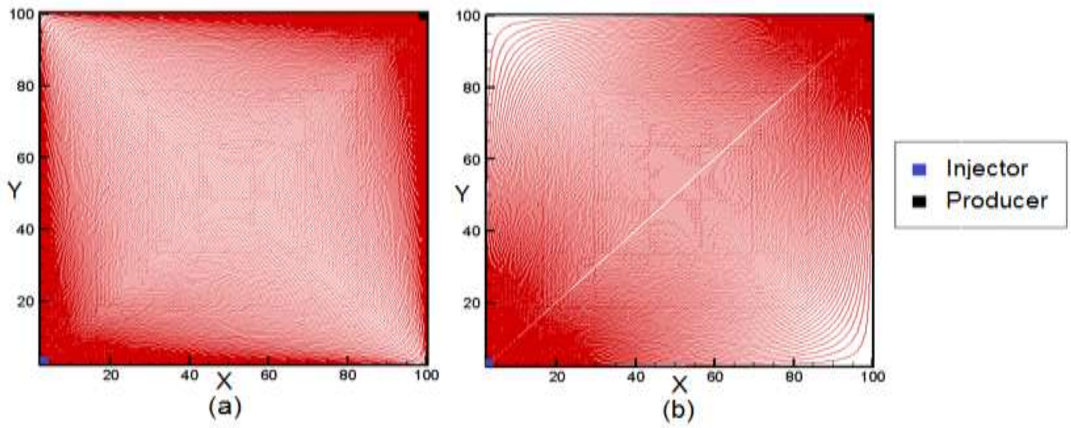

Figure.5. Shows the difference in tracing streamlines in (a) MSM with 196 (SL), and (b) SSM with 196 (SL)

In the SSM, the selection of the initial number of streamlines is vital in order to reach the optimum CPU time, and it directly increases the CPU time. On the other hand, since the number of streamlines to be traced backward implicitly depends on the initial number of streamlines, using fewer initial streamlines leads to a larger number of missed cells. In fact, an increase in number of backward streamlines results in an increase in the CPU time (Siavashi et al. [25]).

Fig. 6 shows a comparison between the performance (CPU-time) of the MSM and SSM for the modeling of a 100×100 quarter five spot homogenous medium. Vertical axis in Fig.6 displays the normalized simulation time, and the horizontal axis shows the number of required streamlines in MSM, and the number of initially traced streamlines (with no backward streamlines from missed grid block) in the SSM. The dashed line represents the performance of the SSM with different initial number of streamlines. The gray point on the dashed line shows the number of initial streamlines required to reach an optimum CPU time while using the SSM. The optimum CPU time with SSM simulation and using 190 streamlines is about 57.5 (sec) in this problem. The red Point in Fig.6 shows that the MSM requires at least 196 streamlines to simulate the considered 100×100 homogeneous problem in 60.5 (sec). For this example, as shown in Fig.6, the simulation time for MSM is higher than the optimum solution using SSM, but it is important to note that the MSM reaches at the final result with only one try, and that the probability of choosing the optimum number of streamlines for the SSM at the first try is almost impossible.

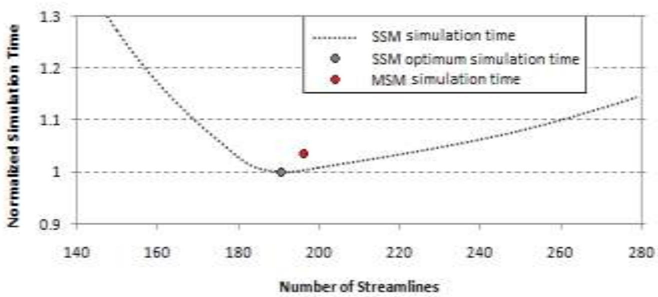

Figure.6. shows the Normalized Simulation time for SSM with different number of streamlines (190 streamlines in optimum point) and MSM with 196 streamlines for a homogeneous quarter five spot model.

Next, two different heterogeneous models are considered to better highlight the differences between the MSM and SSM results. We show that the heterogeneity of the medium greatly affects the density of streamlines at areas where either possess lower flux or lower absolute permeability. This problem most likely occurs in the SSM, while can be avoided using the proposed tracing method in this study. Fig. 7(a) shows the absolute permeability field for problem 1, which is a 100×100 heterogeneous quarter five spot model. The variation of the permeability in this problem is relatively low (i.e. about one order of magnitude). Fig. 7(b) depicts the result of the traced streamlines using the MSM that requires only 203 streamlines, and Fig.7(c) shows the same but for the SSM with 224 streamlines without considering the backward streamlines from the missed grid blocks. In the MSM, streamlines cover the entire grid-blocks with the minimum number of streamlines (203), but SSM needs a compensative method to cover missed grid-blocks.

Fig. 8 compares the performance (CPU-time) of MSM and SSM for the pre-described problem 1 with a given accuracy criterion. According to Fig. 8, it can be found that the solution time for problem 1 using the MSM is around 71 (sec), however it is about 76 (sec) for the SSM only when the optimum number of 224 initial streamlines is used; otherwise the CPU-time will be higher than 76 (sec).

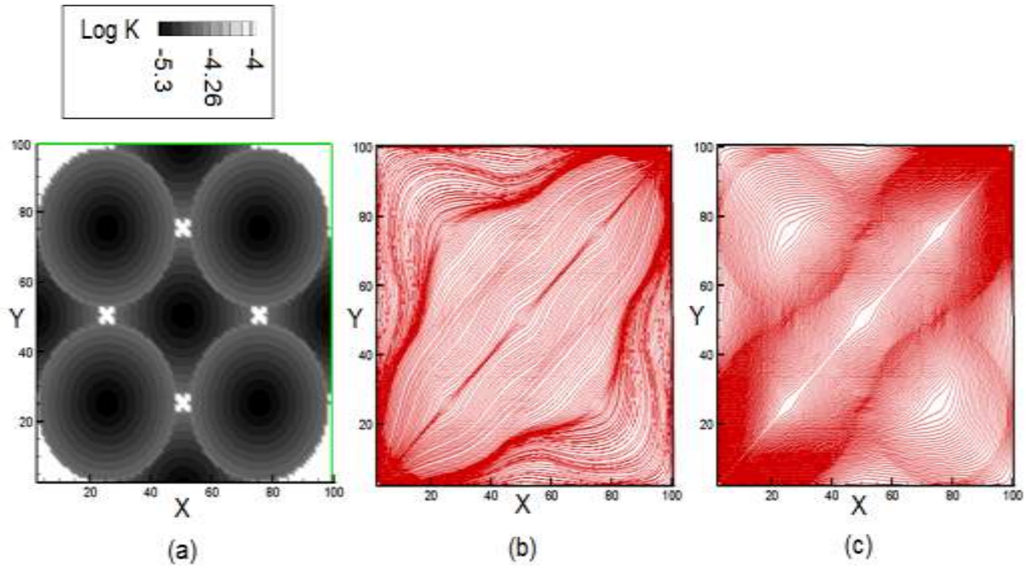

Figure.7. A heterogeneous (100 ×100) problem 1; Panel (a) shows the permeability field and panel (b) and (c) show the streamlines traced by the MSM (203 SL) and SSM (224 SL).

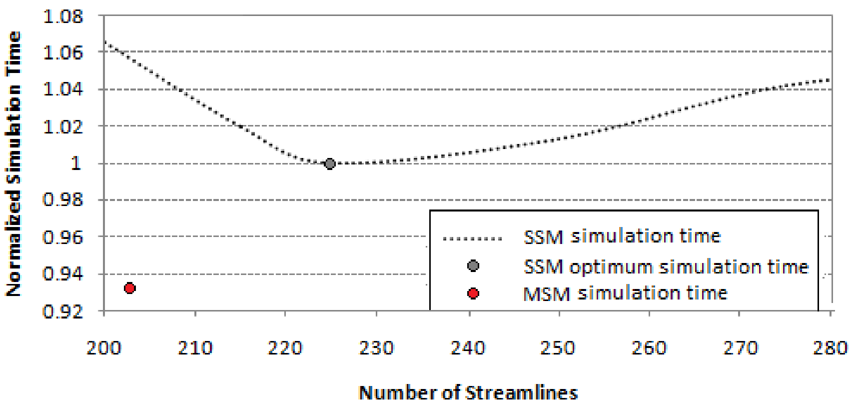

Figure.8.shows the Normalized Simulation time for SSM with different number of streamlines (224 streamlines in optimum point) and MSM with 203 streamlines for a heterogeneous quarter five spot problem 1.

The last numerical attempt in this work considers a 100×100 quarter five spot medium with a wider range of absolute permeability as depicted in Fig. 9(a). The heterogeneity in this problem (problem 2) varies by three orders of magnitude. Fig. 9(b), and 9(c) show the streamlines traced using the MSM with 249 streamlines, and the SSM with optimum 380 streamlines. It could easily be found that in the SSM most of the streamlines are concentrated in the center of domain, and many grid-block are missed. This issue increases the need for a higher number of backward tracing streamlines, and thus increases the CPU-time.

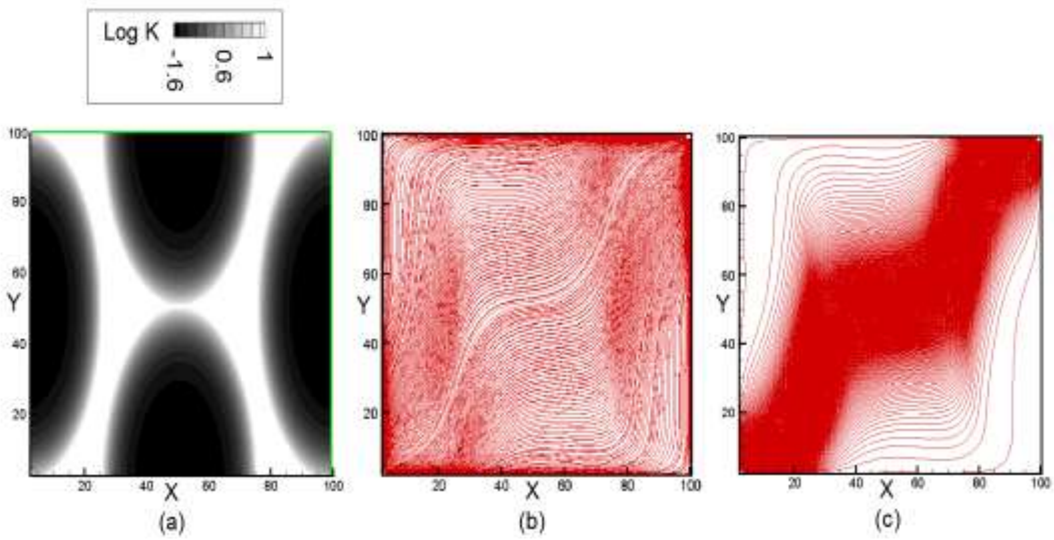

Figure.9. a quarter five spot model with a 100×100 grid-blocks, (a)Permeability field for problem 2; (b) and (c) show the streamlines traced by the MSM (249 SL) and SSM (380 SL).

For problem 2, we use different number of streamlines for the SSM to find the optimum initial streamlines and simulation time, which are 380 and 142 (sec), respectively. The simulation takes only 103 (sec) using the MSM with 249 streamlines.

These presented results show that the MSM guarantees the solution of the problem with a lower computational cost in heterogeneous media. Note that, for all examples, FORTRAN 90 codes are run on a desktop with a 3.4GHz Core i7-2600 CPU and 16 GB of RAM, and problems were run 10 times to ensure the compatibility.

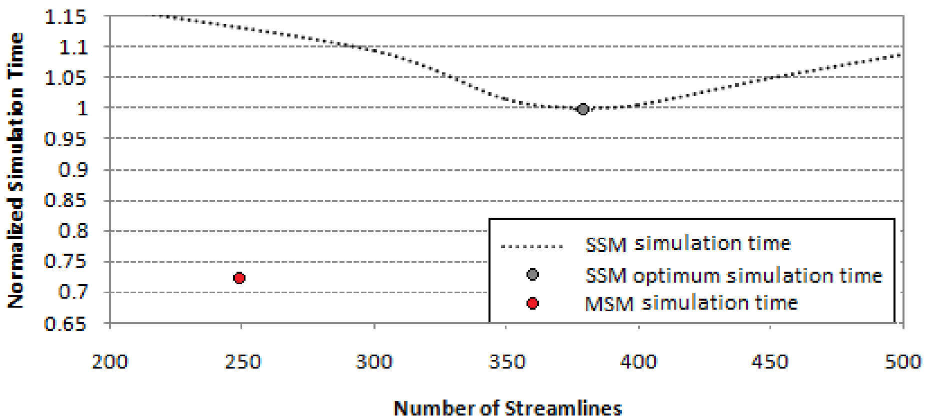

Figure.10.shows the Normalized Simulation time for SSM with different number of streamlines (380 streamlines in optimum point) and MSM with 249 streamlines for a heterogeneous quarter five spot problem 2.

V. CONCLUSION

In this study, a modified approach to trace streamlines used in the streamline-based simulation methods is introduced. The modified streamline method improves the speed of the standard streamline method by providing an approach that covers all Eulerian grid-blocks with the minimum possible number of streamlines while meeting the same accuracy criterion. This aim is achieved by starting the backward and forward streamline tracing from the centers of grid-blocks that possess the longest pseudo-TOF (i.e. lowest magnitude of the velocity gradient) in order. This approach automatically ensures that at least one streamline is passed through each grid-block. Results show that the modified streamline method requires less number of streamlines with respect to the standard methods, and consequently decreases the computational costs. Note that this reduction in computational cost increases as heterogeneities in the medium increases. Another interesting feature of the proposed method is that there is no need to adjust the number of streamlines during the simulation to obtain the optimum number of streamlines and thus simulation time in different problems.

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