Pressure-driven permeability simulation

$f_a(x + \vec{e}_a \Delta t, t + \Delta t) =$
$f_a(x,t) + \tau^{-1}\left(f_a^{eq}(x,t) - f_a(x,t)\right) + \Delta t F_a$

Here τ denotes the fluid relaxation time and $f_a^{eq}(x,t)$ represents the Maxwell Boltzmann distribution function given by:

$f_a^{eq}(x,t) = w_a \rho(x)\left[1 + \frac{\vec{e_a}\cdot\vec{u}}{c_s{}^2} + \frac{1}{2}\frac{(\vec{e_a}\cdot\vec{u})^2}{c_s{}^4} - \frac{1}{2}\frac{(\vec{u})^2}{c_s{}^2}\right],$

with the weights $w_a = \frac{1}{3}$ for $a = 0$, $w_a = \frac{1}{18}$ for $a = 1,\dots,6$ and $w_a = \frac{1}{36}$ for $a = 7,\dots,18$; c_s here represents the sound speed.

The following equation gives the relation with the force applied:

$$F_a(x,t) = w_a\left(1 - \frac{1}{2\tau}\right)\left[3\frac{\vec{e_a} - \vec{u}}{c^2} + 9\frac{\vec{e_a}(\vec{e_a}\cdot\vec{u})}{c^4}\right]\vec{F}$$

The fluid properties of interest like velocity ($\vec{u}$) and density (ρ) can be determined using equations:

$\rho = \sum_{a=0}^{18} f_a$ and $\vec{u} = \frac{1}{\rho}\sum_{a=0}^{18} f_a \vec{e_a} + \frac{\vec{F}\Delta t}{2\rho}$.

LBM Formulation of Darcy Flow: Lattice Boltzmann (LB) method was used to compute permeability (k) of each axis. A ($D3Q19$) model with multiple relaxation time was implemented in the opensource LBM package Palabos (Chopard, 2009). This is the preferred approach to single-relaxation time when using for complex geometries (Hilpert 2011). For the inlet and outlet, a fixed pressure boundary condition was imposed. No slip boundary condition was imposed on the four sides perpendicular to the main flow direction and a simple bounce back boundary condition was imposed on solid boundaries obtained from the segmented imaging results. Darcy law falls within the laminar flow regime and all simulations were carried out to honor that. Each directional permeability was evaluated by using the total flux to the pressure gradient using the equation:

$$U = -\frac{k}{\mu}\frac{dP}{dx}$$

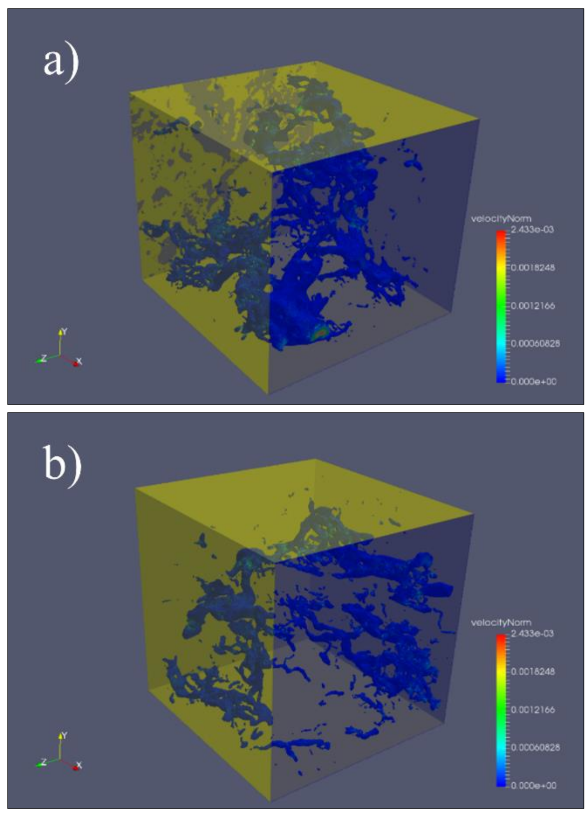
where U is the average velocity, μ is the fluid viscosity, $-dP/dx$ is the pressure gradient ($= dP/L$ where L is the length in the main flow direction), with x being the flow direction.

Permeability Simulation on core

Mentioned are the boundary conditions and modelling strategies used for the cores. Pressure difference between inlet and outlet was kept as $1.5 \times 10^{-5} lu$. A bounce-back boundary condition was applied at the walls.

$$Lattice\ units: Physical\ units = 1\ lu : 10\ um$$

The whole domain was binarized such that the voxel held a True value where the fluid was supposed to flow and a False value at the matrix region. For each of the three axes the inlet and outlet were designated along the flow direction such that they were perpendicular to the path. The simulations were then run until convergence. Number of iterations were fixed at 10000.



Pressure-driven permeability simulation

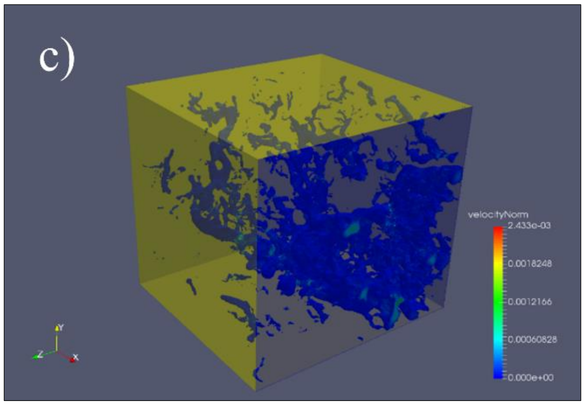


Figure 6. The Darcy Flow along x-axis (a), y-axis (b) and z-axis (c)

Results

A comparison table of experimentally derived permeability and numerically derived permeability is shown in Table 1. Reported are the directional permeabilities along the x, y and z axes. The calibration table for porosity is shown in Table 2.

Table 1: Simulated and experimental permeability value

Permeability	**Sample#105**
K experimental	k = 58.10 mD
K simulation	kx = 63.30 mD
	ky = 49.59 mD
	kz = 11.58 mD

Table 2: Porosity determined from experiment and those calibrated from experiment

Porosity	**Sample#105**
Φ experimental	24.50 %
Φ after calibration from experimental	23.49 %

Conclusions

The LBM was used to perform fluid flow on 3D µCT data obtained from carbonate sample of the Mumbai offshore field. The stages of processing comprise of digital image processing and fluid flow modelling.
The following can be concluded from the study:

1) Image processing is an essential step for quality check of the data. It is difficult to set a global thresholding parameter, which honor the porosity and permeability at the same time.
2) The LBM method is a simple yet sophisticated fluid flow solver as far as its application is concerned. The boundary conditions can be easily applied by merely changing the reference-id of the boundary lattice points, such as integer 1 for boundaries and integer 0 for the domain where the fluid needs to flow.
3) The porosity and permeability predicted from LBM simulation agree well with those obtained from laboratory measurement of these parameters.

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Acknowledgments

The authors acknowledge GEOPIC, ONGC for kindly providing the log data and core samples through PAN-IIT research program.