Mesoscopic Computational Haemodynamics

Artoli, A.M.M.

Citation for published version (APA):
List of Figures

1.1 Evolution of lattice Boltzmann models in terms of applications (text) and annual number of publications (columns). The graph is generated using the ISI Web of Science and Science Direct digital databases. ... 9

4.1 Shear stress computed from the distribution functions (Eq. (3.22)) compared to that computed from the Navier-Stokes solution (Eq. 4.9) and the derived lattice BGK analytical solutions (Eq. 4.13), using VBC and equilibrium distributions, for Re = 10, in the Couette flow benchmark. Values at y = 0 are zoomed inside the figure. ... 39

4.2 Relative errors in \( v_x \) and \( \sigma_{xy} \), using the LBM with the velocity boundary conditions for Re = 10, in the channel and the Couette flows. ... 41

4.3 Relative errors in \( \sigma_{xy} \), using the LBM with the velocity boundary conditions, for Re = 6.30 and 60, in the Couette flow benchmark. ... 42

4.4 Temporal error behaviour in the Couette flow problem. ... 43

4.5 Geometry of the simulated symmetric bifurcation ... 44

4.6 Contours of velocity magnitudes and shear stress in Lattice Units for Re = 1\((dx/dt = 0.0091 \text{ m/sec})\), Re = 200\((dx/dt = 0.0912 \text{ m/sec})\) and Re = 1250\((dx/dt = 0.5706 \text{ m/sec})\). ... 46

4.7 Comparison of LBM velocity profiles (upper four graphs) and shear stresses (lower left) with the FVM solution along the line CD of the symmetric bifurcation for Re = 1, 200 and 1250 with different grid resolutions. The lower right graph shows the pressure drop along the centerline AB. ... 48

5.1 Velocity profile (in Lattice Units) at \( t = 0.75T \) with \( \tau = 1, \alpha = 4.34 \), Re = 10 and St = 0.6 in a 2D oscillatory channel flow using the BBN. The dots are the lattice BGK results. The dashed line is the analytical solution and the solid line is the analytical solution with a shift of 0.5 time step. 55

5.2 Obtained velocity profiles (in Lattice Units) over a complete period (dots) compared to the shifted theory (lines) with \( \tau = 1, \alpha = 4.34 \), Re = 10 and St = 0.6. The measurements are taken at the middle of the channel, at each \( t = 0.05nT \) where \( n = 0,1,\ldots,20 \). ... 56
5.3 Error behaviour over a half cycle for different values of $\delta$, as a function of the fractional time $t/T$ without (lines) and with (points) time-shift correction for $\alpha = 4.34$, $Re = 10$ and $St = 0.6$ in a 2D oscillatory tube flow using the BBN boundary condition. .................................................. 57

5.4 Relative Error in velocity, averaged over the whole period, versus the time step for $\alpha = 15.53$, $Re = 10$ and $St = 7.68$ in a 2D oscillatory channel flow. The slope of the straight line is 0.90. The dashed line is the error with reference to the shifted in time analytical solution. A second order BBN boundary condition is used here. .................................................. 58

5.5 Velocity profiles (in Lattice Units) obtained from lattice BGK simulations (dots) for $\alpha = 15.53$, $Re = 200$ and $St = 0.38$ in a 2D oscillatory channel flow, showing excellent agreement with the analytical solutions (lines). The effect of time shift is not observable. .................................................. 58

5.6 Velocity profiles obtained from lattice BGK simulations (dots) for $\alpha = 4.00017$, $Re = 10$ and $St = 0.51$ in a 2D oscillatory channel flow when inflow and outflow boundary conditions are used. Selected simulation times are shown. The shift in time has little effect but is still there. . 59

5.7 Obtained velocity profiles (dots) compared to the analytical Womersley solutions (lines), for $\alpha = 8.4661$ and $Re = 10$ in a 3D oscillatory tube flow using the bounce-back on the links. The overall average error is about 15%. .................................................. 61

5.8 Obtained velocity profiles (dots) compared to the analytical Womersley solutions (lines), for $\alpha = 8.4661$, $Re = 10$ and $St = 2.2815$ in a 3D oscillatory tube flow using the BBC. The overall average error is about 7%. . 61

5.9 First order error behaviour as a function of $T$ at $\alpha = 8.4661$, $Re = 10$ and $2.2815$ for a 3D oscillatory tube flow with the curved bounce back and linear interpolation. .................................................. 62

5.10 Velocity profiles with $\tau = 0.6, T = 1200, d = 39$, $\alpha = 7.7284$, $Re = 1250$ and $St = 0.0152$ in a 3D oscillatory tube flow. The dots are the lattice BGK results with BBC boundary condition. The lines are the analytical solutions .................................................. 62

5.11 Shear stress (in Lattice Units) obtained from lattice BGK simulations (dots) for $\alpha = 4.34$, $Re = 10$ and $St = 0.6$ in a 2D oscillatory channel flow, showing excellent agreement with the analytical solutions (lines). The effect of time shift is not observable. .................................................. 63

5.12 Shear stress (in Lattice Units) obtained from lattice BGK simulations (dots) for $\alpha = 7.7284$, $Re = 1250$ and $St = 0.0152$ in a 3D oscillatory tube flow, showing excellent agreement with the analytical solutions (lines). The measurements are taken at each $t = 0.1$ nT where $\alpha = 0, 1, 20$. . 64

6.1 Obtained samples of velocity profiles (dots) in lattice units during the systolic cycle in a 3D tube, compared to the analytical Womersley solution (lines) with: (a) BBL and (b) BBC2 wall boundary conditions. .................................................. 70
6.2 Velocity profiles at $M = 0.50$ using the BBC1 boundary condition with overall average error of about 0.07, still less than the BBL results at a 10 times lower Mach number. The system is instable with the BBL at this Mach number. ........................................ 73

6.3 Average error behaviour as a function of Mach and Knudsen numbers, for the systolic tube flow using the BBL, BBC and BBC2 boundary conditions. ........................................ 73

6.4 Convergence behaviour as a function of Mach number at fixed $\delta$, obtained by using 8 processors and applying the BBC1 boundary condition. ........................................ 75

6.5 Convergence behaviour obtained by reducing the grid spacing n times, time-step $n^2$ times and increasing the period $n^2$ times, for the BBL, BBC and BBC2 boundary conditions as a function of grid points representing the diameter of the tube. The relaxation parameter is kept constant and the body force is reduced $n^3$ times to return the same Reynolds and Womersley parameters at $R_e = 1250$ and $\alpha = 16$. ........................................ 77

6.6 Local deviations from Analytical solutions, $\delta E$, computed for the velocity field at $t = 20T$ (top Curve), $30T$, $40T$ and $50T$ (bottom curve). The diameter of the tube is represented by 65 nodes and the period is $T = 360$ sampling points. The average errors are tabulated in Table 6.3. ........ 78

7.1 Error in velocity as a function of Mach number and boundary conditions for systolic flow in a rigid tube with $\alpha = 16$ and $R_e = 1150$. ............... 80

7.2 Obtained (dots) velocity profiles (left) and shear stress (middle) in lattice units during the systolic cycle (right), compared to the analytical Womersley solution (lines) for the 3D tube benchmark. The dots in the right column indicate times at which the profiles are shown. For this simulation $\alpha = 16$, $R_e = 270$, and $M_d = 0.1$ ............... 83

7.3 Comparison in mass- (left) and momentum (right) tolerance as a function of the number of time-steps , between non-annealed (upper row), 4 levels annealed (middle row) and directly annealed (bottom) simulations. The Mach number is reduced 5 times in the annealed simulations (from 0.5 to 0.1). ............... 85

7.4 A lattice Boltzmann Comparison between interactive simulations and restarted simulations in terms of simulation time for a symmetric bifurcation benchmark. ........................................ 86

8.1 An MRA reconstructed model of the aortic bifurcation with left and right iliacs. The right iliac is more bent than the left one. The computational grid size is $37 \times 61 \times 73$ nodes. ........................................ 92

8.2 Change in Womersley parameter(left) and Reynolds number (right) along the segmented aorta during resting and exercise conditions. ........................................ 93

8.3 Steady flow in the aortic bifurcation. The maximum Reynolds number is 1500. ........................................ 94
8.4 Velocity profiles in the aortic bifurcation computed at every 36° of the cardiac cycle, at 120 heart beats/min and a flow rate of 90 cm$^3$/sec ........ 95

8.5 Negative velocity profiles during the systole are frequently observed close to the aortic bifurcation. The figure shows two snapshots of velocity 2.0 cm proximal to the bifurcation. .............................. 97

8.6 Velocity streamlines showing (a): Vortex formation during diastole (at $t = 0.4T$) and (b) flow mixing (at $t = 0.5T$). ............................... 98

8.7 Effective stress on the walls of the aortic bifurcation computed at every 36° of the cardiac cycle. The posterior wall has low values throughout the whole systolic cycle, while relatively high values of the stress near the curved exits are observed. ........................................ 101