

# FAQS

**DUE TO THE REVOLUTIONARY NATURE OF OUR PRODUCT AND TECHNOLOGY, WE ARE FREQUENTLY ASKED QUESTIONS (FAQ) ABOUT EXA. WE HOPE THESE QUESTIONS AND ANSWERS WILL HELP YOU TO UNDERSTAND OUR TECHNOLOGY, ITS SIGNIFICANT CAPABILITIES AND USES.**

## **Q Briefly describe pros and cons of the lattice Boltzmann method compared to the Navier-Stokes method?**

**A** The lattice Boltzmann method [LBM] is based on a discrete equation derived from the well known in kinetic theory Boltzmann equation. The basic quantity in LBM is the single-point distribution function whose evolution is governed by the corresponding equation. The discretization in LBM is chosen in such a way that the resulting relevant hydrodynamics does not suffer any discrete lattice effects. The Navier-Stokes [NS] equation system is shown to be a result of this kinetic description of a fluid at the so called hydrodynamic regime, with sufficiently long spatial and temporal variations. Once this quantity is solved, the familiar hydrodynamic quantities (such as the fluid velocity, density, and pressure) can be obtained via simple post-processing. This method can couple with the turbulence dynamics straightforwardly via a relaxation process and boundary condition modeling.

The advantages of the Exa lattice Boltzmann methods over the Navier-Stokes-based ones are:

1. Robust simulations in which numerical stability can be guaranteed even for highly nonlinear flows;
2. Far smaller numerical diffusion at the same resolution due to a simple advection process;
3. Simplicity of the algorithm and ability to include many physical extensions naturally;
4. Complete scalability for doing massively parallel computations;
5. More fundamental treatment of the boundary conditions, and a precise determination of the hydrodynamic fluxes;
6. Ability to handle arbitrarily complex geometry via fully automated grid generation;
7. No need for explicitly solving pressure dynamics.

The existing well developed lattice Boltzmann algorithms are for finite but low Mach number values (as opposed to fully incompressible or transonic/super-sonic flows). Hence, there are limits in the range of applications so far. Also, the existing algorithms are fully explicit. As far as the method for fluid physics, it is as fundamental as the Navier-Stokes approach, and is argued to be more suitable for large scale turbulent flow simulations.

## **Q How does one describe the differences between LES and VLES turbulence models?**

**A** There are three essential scale ranges of turbulence: the *dissipative*, *inertial range*, and *anisotropic eddies*. The dissipative eddies and inertial range eddies are universal in nature and thus lend themselves to theoretical modeling. Anisotropic eddies are non-universal and well founded turbulence models for this scale have not been (and may never be) developed.

For fluids simulations there are two choices for handling turbulence: simulate it, or model it. Simulation of turbulence requires 3D transient solvers with low numerical dissipation. It also requires resolution on the order of the Reynolds Number [Re] cubed. Thus for engineering Re, some amount of turbulence modeling is required to account for the macroscopic effects of the turbulent flow structures that are not resolved directly by the simulation.

The major difference in turbulence models depends on what scales of turbulence the model is attempting to account for. Reynolds Averaged Navier-Stokes [RANS]-based approaches attempt to model all scales of turbulence. However, theoretical models for anisotropic eddies do not exist and thus RANS methods attempt to adapt turbulence models developed from the theory of the universal scales.

Large Eddy Simulation [LES] conversely attempts to simulate directly (via resolution) all of the *large eddies* which

requires resolving the flow structures all the way down to the small scale end of the inertial range, and most often the dissipative eddy range near-wall. As a result, only the sub-grid scale physics is modeled, which is dependent on the local resolution scale. The main disadvantage of this approach is that the computational cost of this resolution is not feasible for high enough Reynolds number values that are needed for engineering applications. Another issue is that, despite many years of research, LES is so far still at a relatively primitive stage which has shown success only on a few simple flow benchmark cases.

Very Large Eddy Simulation [VLES] however, keeps with the philosophy of LES in that the anisotropic eddies can not be modeled and thus need to be directly and time-accurately resolved. Where VLES differs from LES is in the inertial range of turbulence. Since these scales are universal in nature, turbulence modeling still applies here. Turbulent time and length scales are not explicitly determined by the local resolution scales, but are functions of the resolved flow and turbulent properties. Unlike typical LES, there are additional turbulent variables, other than the mean resolved flow being dynamically simulated simultaneously. Also, wall models must be employed in order to reduce the requirement of resolving all the way to the wall.

**Q Please explain simply why LBM is more compatible with VLES than Navier-Stokes?**

**A** There are just a few points:

1. VLES/LES requires a 3D transient solver, a VLES model can not be applied to a steady-state solver to give physically correct results for intrinsically time-dependent flows. NS solvers

are notoriously more expensive and difficult to solve in transient mode. LBM is naturally a transient solver.

2. VLES/LES requires the direct simulation of turbulent eddies. However, this is only possible with a fluids solver that generates little to no numerical dissipation. Numerical dissipation acts as a viscosity that works to dissipate the turbulent eddies you are trying to capture. LBM naturally has ultra low numerical dissipation despite being extremely stable. NS solvers require very significant numerical dissipation to be numerically stable.

3. LBM employed by Exa PowerFLOW is able to precisely and directly control local wall fluxes on surfaces of arbitrary shapes and orientations. In NS, one often requires to use fine body-fitted grids and higher order schemes for such a purpose of getting accurate near-wall properties.

**Q Which paper best describes the VLES model adopted by PowerFLOW? Is it the paper by Victor Yakhot and Exa's Physics Group "A New Approach to Modeling Strongly Non-Equilibrium, Time-Dependent Turbulent Flows"?**

**A** This is an excellent paper for understanding the fundamental benefits (from the physics, rather than algorithmic, point of view) of using the LBM-based approach for turbulent flow simulations compared to the NS-based CFD. As far as the turbulent VLES modeling is concerned, the paper by Victor et al (Phys. Fluids A, vol.4, p.1510, [1992]) is the best representative paper in the published domain. The main Exa-proprietary pieces not included in published papers are 1) extended wall model for both the flow field and for the turbulent properties; and 2) the swirl effects.

**Q LBM is known to become unstable at higher Reynolds number regions, but PowerFLOW does not have this problem. How does PowerFLOW take care of it?**

**A** Exa has made significant advances in PowerFLOW that go well beyond the generally available LBM implementations. Exa recognizes the importance of algorithm stability and has incorporated a number of features into PowerFLOW to ensure stability for the entire operating range of industrial applications. Exa initially developed its software based on Lattice Gas [LGA] instead of LBM. One of the reasons for this was the unconditional stability of the Lattice Gas system. Due to this LGA history, coupled with Exa's leading research in the field of lattice Boltzmann, Exa has been able to extract the stability from the LGA approach and couple it into the lattice Boltzmann approach.

Technically, among many other features, the key differences between the stability of the PowerFLOW algorithm and existing standard lattice Boltzmann algorithms are:

1. ensured positivity of the particle distribution functions;
2. existence of a generalized H-theorem for both isothermal and thermal flows;
3. a fully physically realizable boundary condition process; and
4. extended collision process and refined particle distribution functions.