Real-time Thermal Flow Predictions for Data Centers

Using the Lattice Boltzmann Method on Graphics Processing Units for Predicting Thermal Flow in Data Centers

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Data Centers

- A facility used to host computer server and networking equipment.
- Servers are mounted in racks.
- Computer Room Air Conditioners (CRACs) cool equipment using heat exchangers.

Figure 1: Server racks in data center module POD 2 at RISE SICS North.

Data Centers

Figure 2: Dell R430 blade server with six internal fans.

Figure 3: Computer Room Air Conditioner, SEE Cooler HDZ-3.

Data Centers

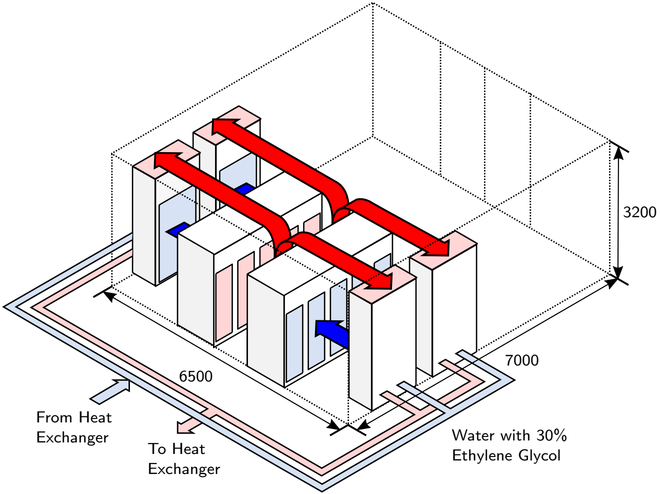


Figure 4: Theoretical heat flow in the data center POD 2 at RISE SICS North. Hot aisle configuration.

Data Centers

- The full Information Communication Technology (ICT) electrical energy footprint was estimated to be 900TWh in 2012, corresponding to 4.6% of the total global electricity consumption[1].
- In a 2017 study of 100 data centers, air conditioning systems were often found ineffective using between 21 to 61% of the total facility energy, averaging at 38%[2].
- How to achieve the most energy efficient cooling while meeting thermal specifications?
- Computational Fluid Dynamics (CFD) make it possible to test different cooling control systems and configurations.

[1] W. Van Heddeghem, S. Lambert, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Trends in worldwide ICT electricity consumption from 2007 to 2012," Comput. Commun., vol. 50, pp. 6476, Sep. 2014.

[2] J. Ni and X. Bai, "A review of air conditioning energy performance in data centers," Renew. Sustain. Energy Rev., vol. 67, pp. 625640, Jan. 2017.

Fluid Dynamics

The most common equation in fluid dynamics is the Navier-Stokes equation. For compressible fluids

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+(\vec{u}\cdot\nabla)\vec{u}\right)=-\nabla\vec{p}+\rho g+\mu\nabla^2\vec{u}, \tag{1}$$

which represent the conservation of linear momentum and pressure. It is most often used with the continuity equation

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{u})=0. \tag{2}$$

representing the conservation of mass.

Computational Fluid Dynamics (CFD)

A physical fluid flow problem is stated using general sets of partial differential equations constrained by boundary conditions and initial conditions.

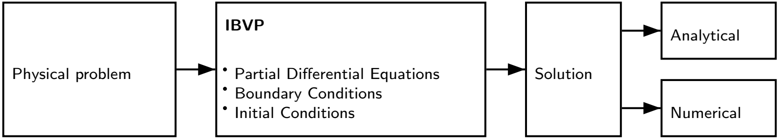


Figure 5: The Initial Boundary Value Problem.

Commercial and Open Source CFD toolkits

FEM and FVM methods are based on the Navier-Stokes equations and the continuity equation.
Models fluid behavior as a continuum, but discretizes domain into finite volumes/elements.
Examples:

- ANSYS CFX (FVM & FEM)
- COMSOL Multiphysics (FEM)
- OpenFOAM (FVM)

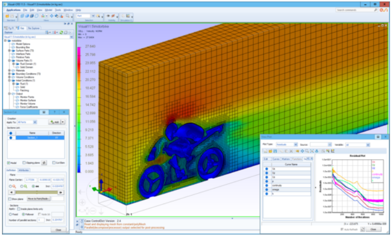


Figure 6: GUI for OpenFOAM called Visual-CFD.

The Lattice Boltzmann Method (LBM)

The LBM models the behavior of a group of particles as distribution functions in a uniform grid.

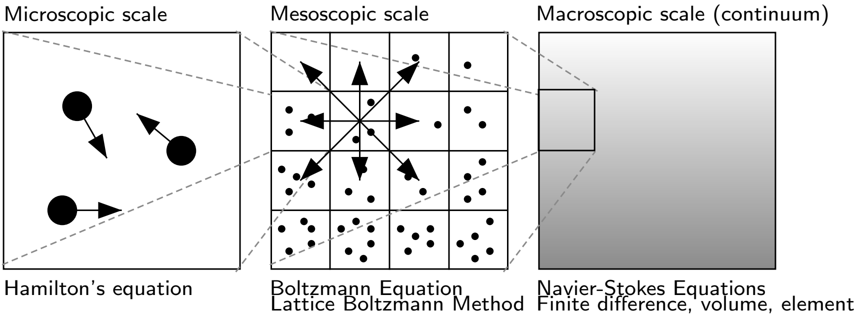


Figure 7: Techniques of simulations for different scales of fluid representations.

LBM: Space Discretization

LBM discretizes the domain into a uniform grid of cells called lattice sites.

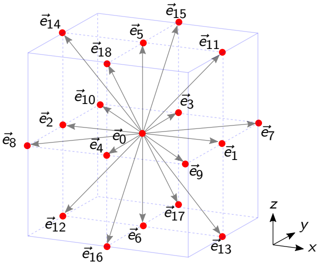
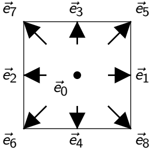


Figure 8: D3Q19 lattice site.



$$
\begin{aligned}
\vec{e}_0 &= (\ \ 0,\ \ 0) & w_0 &= 4/9\\
\vec{e}_1 &= (\ \ 1,\ \ 0) & w_1 &= 1/9\\
\vec{e}_2 &= (-1,\ \ 0) & w_2 &= 1/9\\
\vec{e}_3 &= (\ \ 0,\ \ 1) & w_3 &= 1/9\\
\vec{e}_4 &= (\ \ 0,-1) & w_4 &= 1/9\\
\vec{e}_5 &= (\ \ 1,\ \ 1) & w_5 &= 1/36\\
\vec{e}_6 &= (-1,-1) & w_6 &= 1/36\\
\vec{e}_7 &= (-1,\ \ 1) & w_7 &= 1/36\\
\vec{e}_8 &= (\ \ 1,-1) & w_8 &= 1/36
\end{aligned}
$$

Figure 9: D2Q9 lattice site. Direction vectors $\vec{e}_i$ are lattice velocities, with their corresponding weight w_i.

The Boltzmann Equation

The Boltzmann equation is based on a concept called *kinetic theory*. Velocity distribution function

$$f^{(N)}(\vec{x}^{(N)}, \vec{p}^{(N)}, t) \tag{3}$$

gives the probability of finding N number of particles with the displacements $\vec{x}$ and momentums $\vec{p}$ at the time t. For non-dilute gases $f^{(1)}$ is sufficient.
If disturbed by external force future positions and momentums are

$$f^{(1)}(\vec{x} + \Delta\vec{x}, \vec{p} + \Delta\vec{p}, t + \Delta t), \tag{4}$$

if no particle collisions take place.

The Boltzmann Equation

When taking particle collisions into account however,

$$\left(\vec{u} \cdot \nabla_{\vec{x}} + F \cdot \nabla_{\vec{p}} + \frac{\partial}{\partial t}\right) f^{(1)}(\vec{x}, \vec{p}, t) = \Gamma^{(+)} - \Gamma^{(-)}. \tag{5}$$

$\Gamma^{(-)}$ represents the number of particles starting at $(\vec{x},\ \vec{p})$ and not arriving at $(\vec{x} + \Delta\vec{x},\ \vec{p} + \Delta\vec{p})$ due to particle collisions. Vice versa for $\Gamma^{(+)}$.

LBM: The Discrete Lattice Boltzmann Equation

The evolution of the system is described by the Discrete Lattice Boltzmann Equation

$$f_i(\vec{x} + \vec{e_i}\Delta t, t + \Delta t) = f_i(\vec{x}, t) + \Gamma(f_i(\vec{x}, t)). \tag{6}$$

Each distribution function f_i is associated with a direction. Γ is called a collision operator and can be implemented in different ways. RAFSINE uses the Bhatnagar–Gross–Krook (BGK) method.

LBM: Bhatnagar, Gross and Krook (BGK)

The BGK implements the collision operator $\Gamma(f_i(\vec{x}, t))$ for velocity distribution functions

$$f_i(\vec{x} + \vec{e}_i \Delta t, t + \Delta t) = f_i(\vec{x}, t) - \frac{1}{\tau} \left(f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t) \right) \quad (7)$$

and temperature distribution functions

$$T_i(\vec{x} + \vec{e}_i \Delta t, t + \Delta t) = T_i(\vec{x}, t) - \frac{1}{\tau_T} \left(T_i(\vec{x}, t) - T_i^{eq}(\vec{x}, t) \right). \quad (8)$$

LBM: Natural Convection

Buoyancy by Boussinesq approximation ignores density differences

$$\vec{F}_B = -\vec{g}\beta(T - T_0), \qquad (9)$$

$\vec{g}$ gravity vector,
$(T - T_0)$ thermal gradient,
β thermal expansion coefficient at reference temperature T_0.

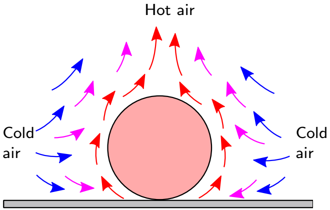


Figure 10: Flow due to natural convection.

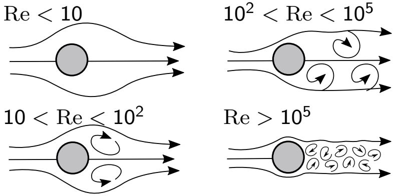


Figure 11: Flow conditions for different Reynolds numbers.

Large Eddy Simulation (LES) ignores dynamics of small scale swirling motion of fluids (eddies) since large scale eddies carry more energy. Based on applying a low-pass filter on the Navier-Stokes equations.

LBM: Initialization Step

At time $t = 0$ the distribution functions are initialized

$$f_i(\vec{x}, 0) = f_i^{eq}(\rho(\vec{x}), \vec{u}(\vec{x})), \tag{10}$$

where ρ is the initial pressure and $\vec{u}$ is initial velocity.

LBM: Streaming Step

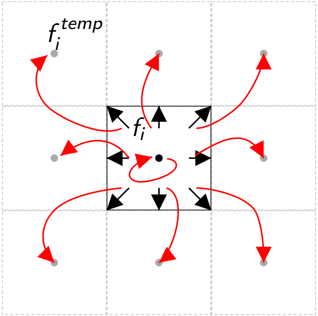


Figure 12: Lattice streaming step, representing advection in a fluid. All functions f_i are copied to the neighboring f_i^{temp} in parallel.

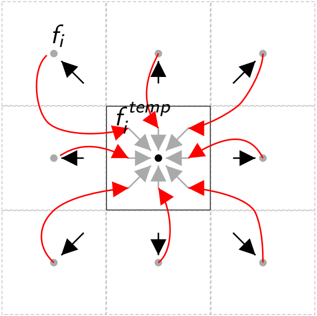


Figure 13: Also in the streaming step, the current site is filled with new distributions from the neighboring sites.

LBM: Collision Step

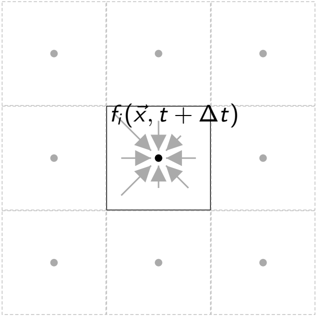


Figure 14: Collision step, representing diffusion in a fluid. Particles from adjacent sites collide locally in the current site (see BGK).

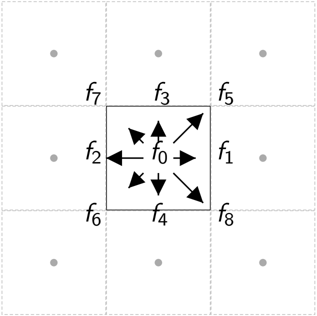


Figure 15: During the collide step the particle populations are redistributed. Both mass and momentum is conserved.

LBM: Boundary Step

Boundary conditions define what happens at the edges of the domain.
Dirichlet specifies solution by value, e.g.

- Periodic (infinity)
- No-slip condition (walls)

Von Neumann specifies the derivative of a solution, e.g.

- Zero-gradient (fan intake)
- Node-to-node velocity increase (fan exhaust)

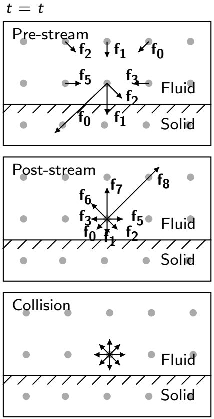


Figure 16: Half-way bounce-back boundary condition on a D2Q9 lattice.

RAFSINE

- Written by Nicolas Delbosc during his Ph.D study in the School of Mechanical Engineering at the University of Leeds, England.
- Implements LBM (BGK model) in C++ with streaming-, collision- and boundary-steps accelerated by Nvidia CUDA.
- Simulates fluid behavior in real time or faster depending on domain size.
- OpenGL visualization of system evolution.

Figure 17: Nvidia GTX 1080 Ti.

RAFSINE

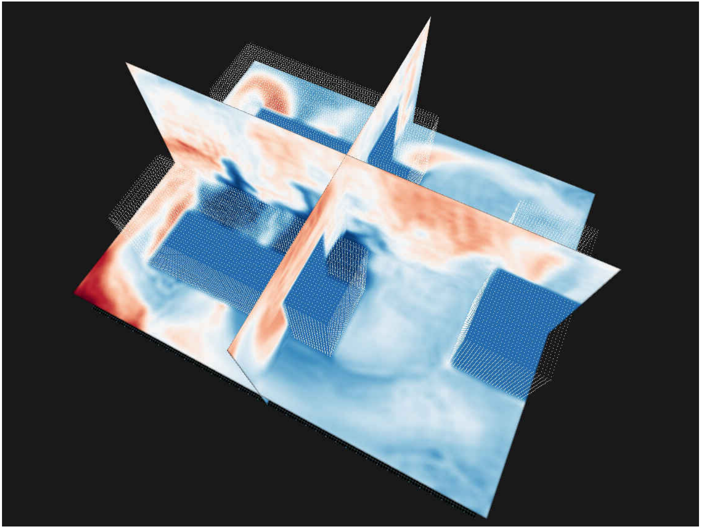


Figure 18: Visualization of heat flow in a data center with cold aisle.

RAFSINE

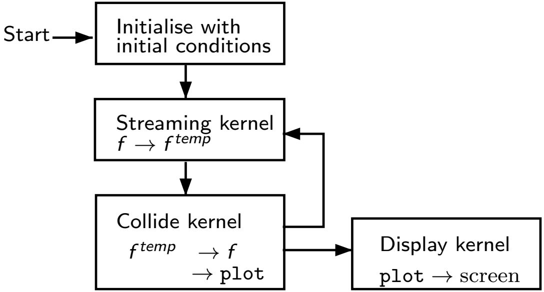


Figure 19: Structure of the LBM program.

How to use the OpenGL visualization of a headless server on a local workstation?

VirtualGL: OpenGL over VNC

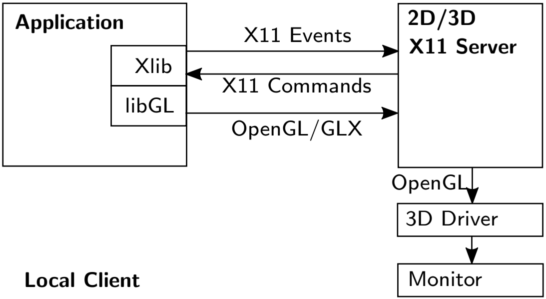


Figure 20: Direct OpenGL rendering using GLX on a local GPU with a monitor attached.

VirtualGL: OpenGL over VNC

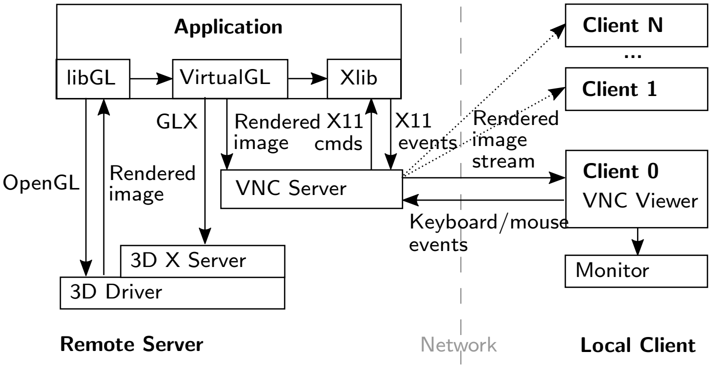


Figure 21: In-Process GLX Forking with an X11 proxy over a network, in the form of a VNC server and client.

Improving performance

Original code was mostly sequential, rendering the simulation blocked execution. Problematic with VirtualGL.

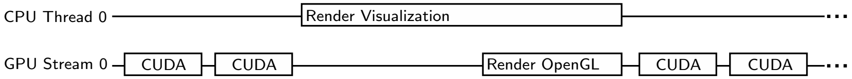


Figure 22: Single threading in the original RAFSINE application.

Improving performance

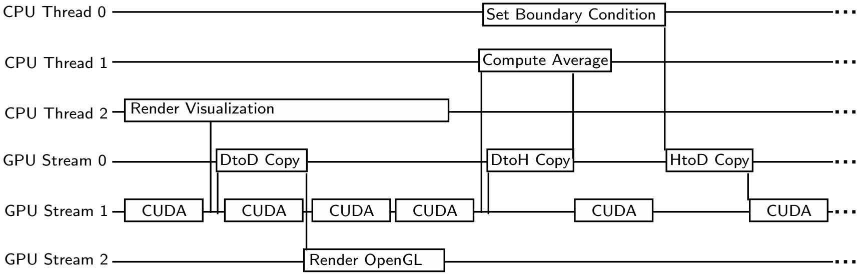
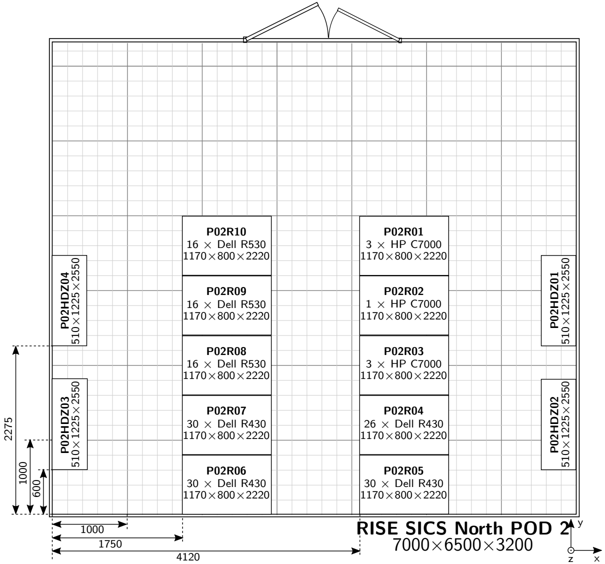


Figure 23: Multithreading and multistreaming.

Data Center Model: Schematic



Data Center Model: CRACs

Computer Room Air Conditioner (CRAC) with air inlet on top and exhaust on the front. Sloped surfaces were simplified.

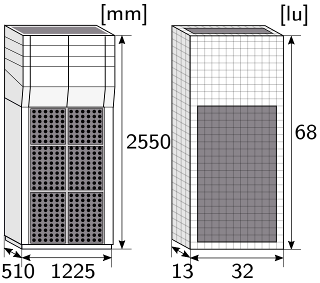


Figure 24: Heat exchange cooler SEE Cooler HDZ-2.

Exhaust boundary condition sets constant static pressure and temperature.

Inlet zero-gradient, so no change in velocity along plane normal.

Data Center Model: Server Racks

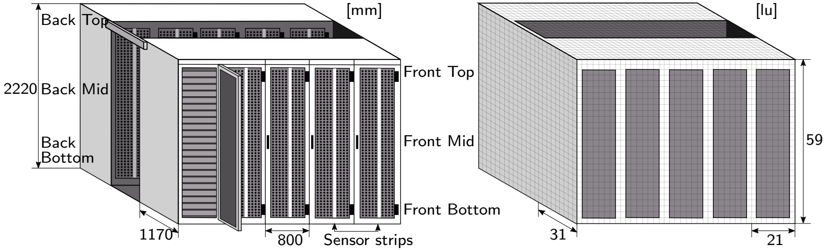


Figure 25: Two rows of five Minkels server racks positioned in hot aisle configuration. The entrance is separated by a curtain of flexible plastic sheets.

Data Center Model: Server Racks

Exhausts emit variable flow Q_{out} and temperature T_{out},

$$\vec{u}_{out} = \frac{Q_{out}}{\int dA} \vec{n}, \tag{11}$$

$$T_{out} = \frac{\int T_{in} dA}{\int dA} + \Delta T, \tag{12}$$

$$\Delta T = \frac{P \cdot \nu}{Q_{out} \cdot k \cdot Pr}. \tag{13}$$

Kinematic viscosity, $\nu = 1.568 \cdot 10^{-5}$ m^2/s.
Thermal conductivity, $k = 2.624 \cdot 10^{-5}$ kW/m K.
Prandtl number of air at 30°C, $Pr = 0.707$.
Power consumption, P kW was directly measured for each rack.
Volumetric flow rate Q_{out} must be calculated from fan speed.

Data Center Model: Server Racks

Approximate Q_{out} for each rack using the affinity laws

$$\frac{P_{max}}{P_{op}} = \left(\frac{\omega_{max}}{\omega_{op}}\right)^3, \qquad (14)$$

$$\frac{P_{max}}{P_{op}} = \frac{Q_{max}}{Q_{op}}. \qquad (15)$$

Solve for Q_{op}, then

$$Q_{out} = \omega_{rack} \cdot n_{servers} \cdot n_{fans} \cdot Q_{max} \frac{(\omega_{op})^2}{(\omega_{max})^3}. \qquad (16)$$

ω_{rack} average fan speed for all servers in rack.

Equipment	**Fan type**	**Amount** n_{fans}	**Max power** P_{max} **[W]**	**Max speed** ω_{max} **[RPM]**	**Max flow** Q_{max} **[CFM]**
Dell R430	Delta Electronics GFB0412SHS-DF00	6	13.2	14300	30.23
Dell R530	Delta Electronics PFR0612DHE-SP00	6	19.2	14500	65.95
HP C7000	Unknown				
Voltaire 4700	Unknown				

Data Center Model: Overview

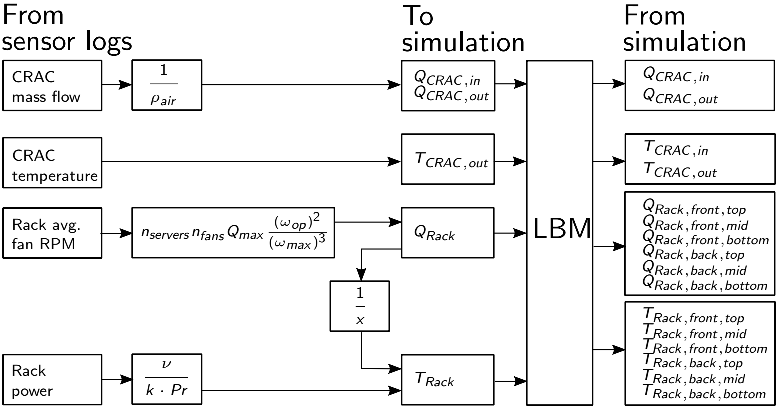


Figure 26: Overview of simulation inputs and outputs.

Data Center Model: Geometry

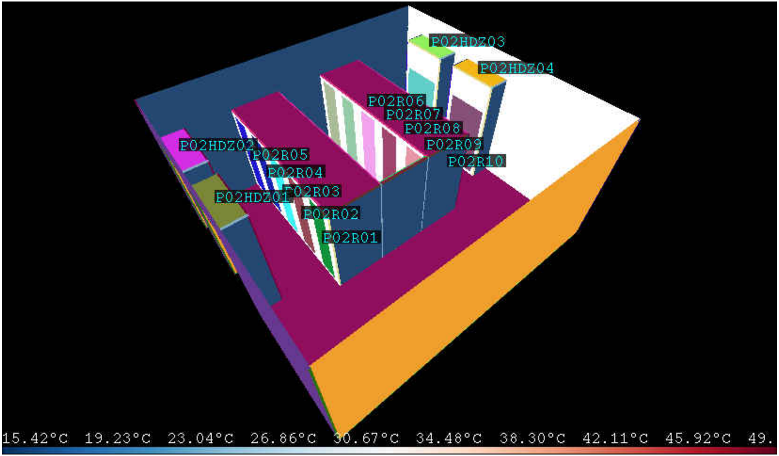


Figure 27: Geometry of data center module POD 2.

Data Center Model: Simulation

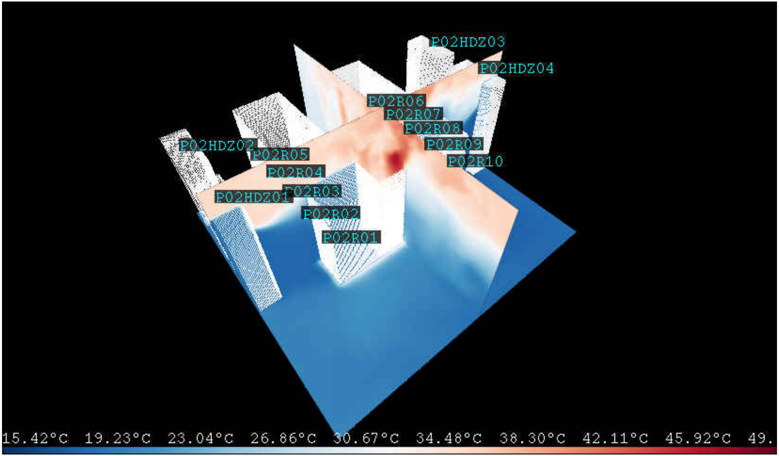
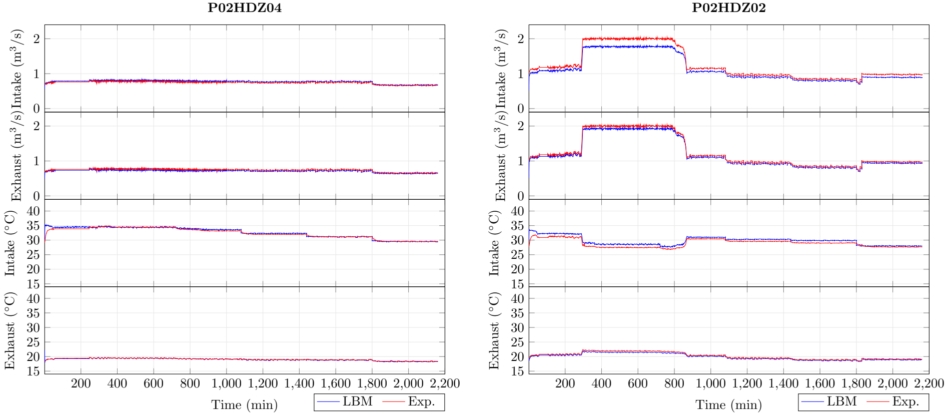


Figure 28: Simulating data center module POD 2.

Model Validation: CRACs

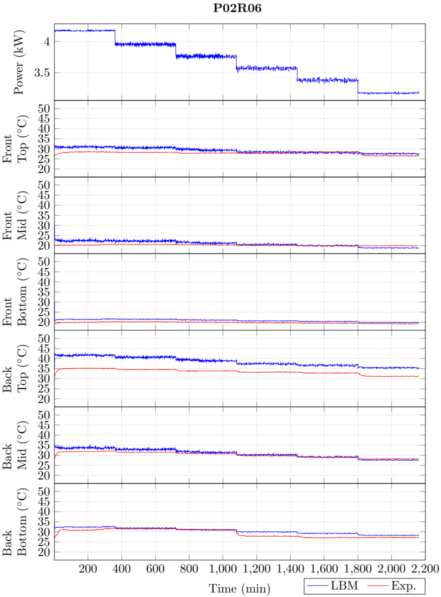


Model Validation: Server Racks

Table 1: The RMS of the difference between simulated and experimental temperatures in $^\circ$C, and volumetric flow rate in m^3/s at the inlets of the four CRAC units.

CRAC	**Inlet temp.**	**Exhaust temp.**	**Inlet flow**	**Exhaust flow**
1	0.709	0.479	0.194	0.0705
2	0.836	0.331	0.132	0.0543
3	1.91	0.0759	0.0233	0.0322
4	0.302	0.0909	0.0298	0.0338

Model Validation: Server Racks



Model Validation: Server Racks

Table 2: The RMS of the difference between simulated and experimental temperatures in $^{\circ}$C at different positions on the server racks.

Rack	Front Bottom	Front Mid	Front Top	Back Bottom	Back Mid	Back Top
1	0.316	3.06	3.19	2.25	2.55	7.4
2	0.812	1.78	4.36	3.51	2.83	3.42
3	1.09	1.47	4.13	6.04	3.26	2.69
4	0.599	1.97	5.29	2.21	1.4	1.04
5	0.761	2.2	2.95	0.85	2.43	1.85
6	1.08	1.24	1.6	1.42	1.04	5.06
7	0.221	1.32	1.17	2.53	1.94	5.66
8	1.14	1.2	4.47	1.45	2.45	0.719
9	0.64	1.66	4.75	0.969	1.55	0.728
10	0.653	3.11	4.48	2.45	3.84	1.87

Model Validation: Sources of Error

- Too coarse lattice resolution
- Very simplified server rack geometry, server positioning
- Temp sensor positions might be slightly off
- Server fan speed and power consumption averaged for entire rack
- Racks 1, 2, 3 missing fan speed data
- Air flow rate could not be verified
- Improve turbulence model

Future Work

- Model improvements
- Better GUI, 3D CAD capability
- Support MRT and Cascaded LBM
- Multiple GPUs

Thanks for listening!