Fire Simulation using FDS (Fire Dynamics Simulator)

FDS Simulation

- **Fire Dynamics Simulator (FDS)**
  - Widely used system for the simulation of fires in different human structures, developed in National Institute of Standards and Technology (NIST), USA (fire.nist.gov/fds)

FDS simulates:

- Pyrolysis
- Low-speed heat and smoke transfer
- Thermal radiation
- Flame spread
- Fire suppression by sprinklers

FDS Simulation

- **FDS Physical Principles: Conservation of Mass, Species, Momentum and Energy**

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \mathbf{u} = \dot{m}_b'''$$

$$\frac{\partial}{\partial t}(\rho Y_\alpha) + \nabla . \rho Y_\alpha \mathbf{u} = \nabla . \rho D_\alpha \nabla Y_\alpha + \dot{m}_\alpha''' + \dot{m}_{b,\alpha}'''$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla . \rho \mathbf{u}\mathbf{u} + \nabla p = \rho \mathbf{g} + \mathbf{f}_b + \nabla . \tau_{ij}$$

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla . \rho h_s \mathbf{u} = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla . \dot{\mathbf{q}}'' + \epsilon$$

Here $\dot{m}_b''' = \sum_\alpha \dot{m}_{b,\alpha}'''$ is the production rate of species by evaporating droplets or particles, ρ is the density, $\mathbf{u} = (u, v, w)$ is the velocity vector, Y_α, D_α, and $m_{b,\alpha}'''$ are the mass fraction, diffusion coefficient and mass production rate of α-th species per unit volume, respectively. p is the pressure, $\mathbf{f}_b$ the external force vector, τ the viscous stress tensor, and h_s is the sensible enthalpy. The term $\dot{q}'''$ is the heat release rate per unit volume from a chemical reaction, and $\dot{q}_b'''$ is the energy transferred to the evaporating droplets. The term $\dot{\mathbf{q}}''$ represents the conductive and radiative heat fluxes.

FDS Simulation

- **FDS Physical Principles**
  - System of PDE and equation of the state for these unknowns: density, velocity temperature, pressure and mass fractions
  - Divergence of the momentum equations gives Poisson equation for H(u,p)

$$\nabla^2 H = -\frac{\partial \nabla . \mathbf{u}}{\partial t} - \nabla . \mathbf{f}$$

  - Inputs : geometry of the problem, material properties and other parameters. FDS reads input parameters from a single text file which provides all the necessary information to describe the fire scenario.

FDS Simulation

- **FDS Numerical method**
  - Explicit predictor-corrector finite difference scheme, which is second order accurate in space and time
  - Poisson equation for modified pressure is solved in every time step by a direct FFT-based solver that is part of a library CRAYFISHPAK

FDS Simulation

- **FDS Compiling and Building**
  - FDS version 5.3.3. is used
  - Compilers used
    - GNU 4.1.2 and 4.4.0 (gcc, gfortran, OpenMP)
    - Open MPI 1.4
  - 4 programming models are build
    - sequential, MPI, OpenMP, and hybrid MPI+OpenMP

FDS Simulation

- **FDS Support**
  - To automate the process of simulation runs, for each configuration an **fds-manager** script was created which provides for the following actions:
    - it accepts and checks input arguments specifying the FDS input file and cluster configuration (the number of nodes, cores, and eventually the number of MPI processes and OpenMP threads)
    - it produces an **fds-submission** script which serves as an input to the Portable Batch System (PBS)
    - it realizes the execution of the FDS simulation using the previously generated job-submission script

FDS Simulation

- **FDS Running**
  - Experiments are carried out on the HP blade cluster of the configuration:
    - 16 blade nodes, each comprising of 2 quad-core CPU Intel Xeon X5570@ 2.9GHz, 24-48GB RAM, 500GB hard disk
    - 6 nodes are interconnected by the Infiniband network (40Gb/s)
    - 10 nodes are interconnected by the Ethernet network (4Gb/s)
    - Disk storage: 48 TB disk array

FDS Simulation

- **FDS Input**
  - FDS reads input parameters from a single text file which provides all the necessary information to describe the fire scenario.
  - The computational domain representing the given fire scenario included 12-25 millions rectangular mesh cells dependent on the resolution.
  - Simulations with the given fire scenario consumed 8-48GB RAM.

FDS Simulation

- **FDS Output**
  - The numerical solution to the governing equations is written to various types of files. All output quantities must be explicitly declared (in the input file) at the start of the calculation.
  - Simulations with the given fire scenario produced output data files of amount 7-20GB.
  - The simulation result can be visualized using the Smokeview program that reads FDS output files and produces animations on the computer screen.

FDS Simulation

- **Requirements for running FDS simulations on Cluster/Grid**
  - FDS simulations with the real scenario represent long-time, computational intensive and memory consuming jobs
  - Hardware requirements
    - HP, reliable, and failure-free computing resources involving a sufficient amount of memory
  - Software requirements
    - Fortran 90 and C compilers including OpenMP library, MPI, MPI-Start

FDS Simulation

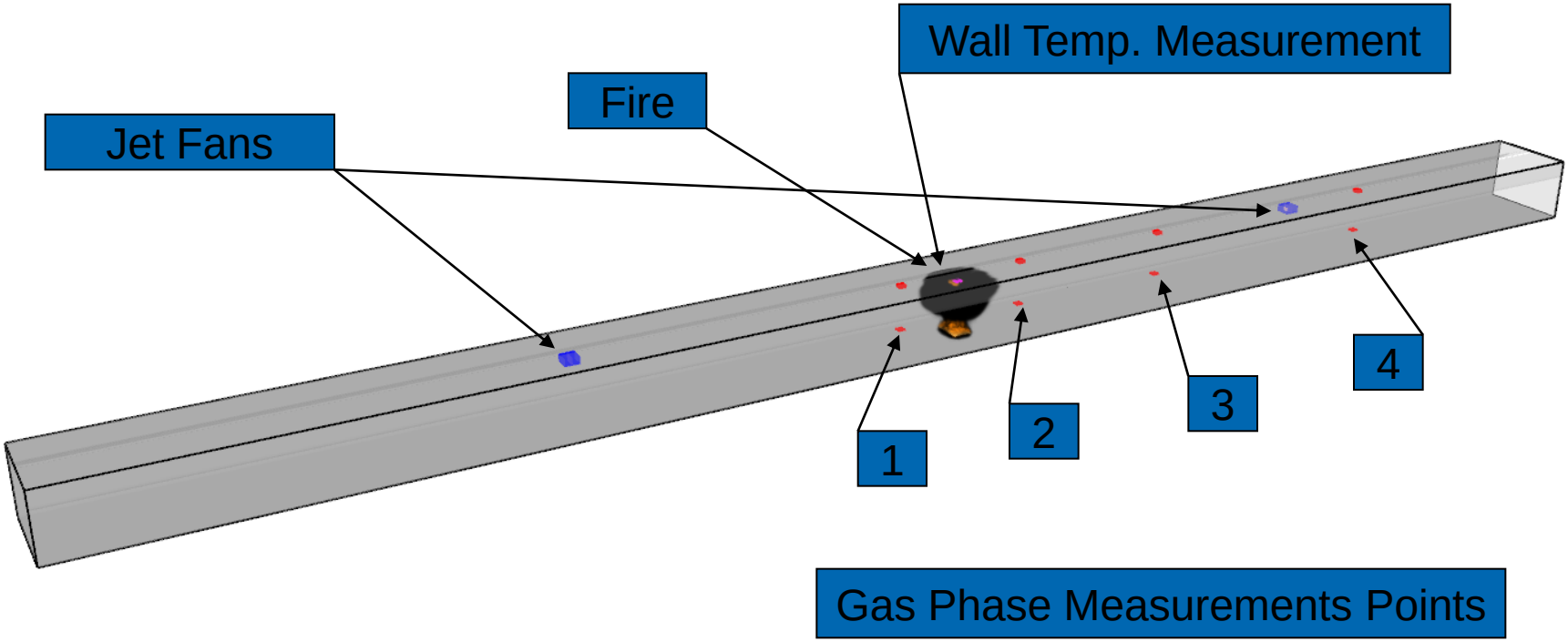
- **Requirements for running FDS simulations on Grid**
  - Grid middleware functionalities
    - the proxy credential delegation and renewal
    - the submission of parallel MPI and OpenMP jobs
    - monitoring the status of submitted jobs
    - the job output retrieval
    - optionally, the job perusal (the real time output retrieval) enabling the inspection of the job output in real time
    - the basic data management services

FDS Simulation

- **Fire Scenario**
  - We have constructed a model of a two-lane road tunnel with dimensions 10x180x7m with 2 fans located on the tunnel ceiling at the distance 50m and 140m from the left entrance.
  - The fire source was represented by burning of a flammable liquid in a pool with dimensions 2x3m placed in the distance 92m from the left entrance of the tunnel, 1.1m above the floor level.
  - The initial air temperature in the whole tunnel was set to 20°C.
  - The total duration of the simulation was 150s.

FDS Simulation

- **Scheme of the Tunnel**



FDS Simulation

- **Computational Requirements**

Resolution	20 cm	10 cm	5 cm
Cells Number	1,62 mil.	12,96 mil.	103,68 mil.

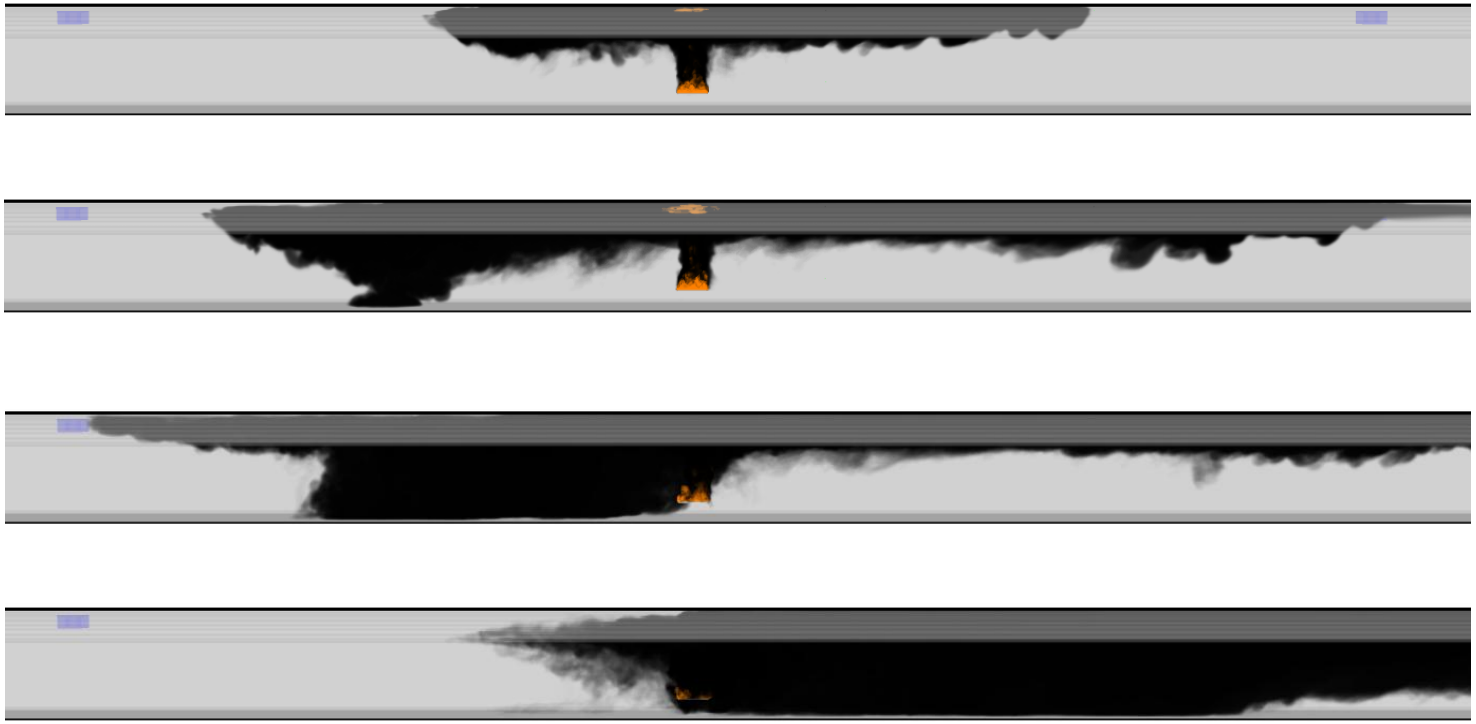
- Simulation time for 10 cm resolution is 377 hours. It increases approximately with the fourth power of increasing resolution.

FDS Simulation

- **Parallel Processing and the Domain Decomposition**
  - Computational domain is decomposed into meshes
  - Each mesh can be assigned to specific MPI process
  - Velocity values at the mesh boundaries are then averaged in order to maintain stability

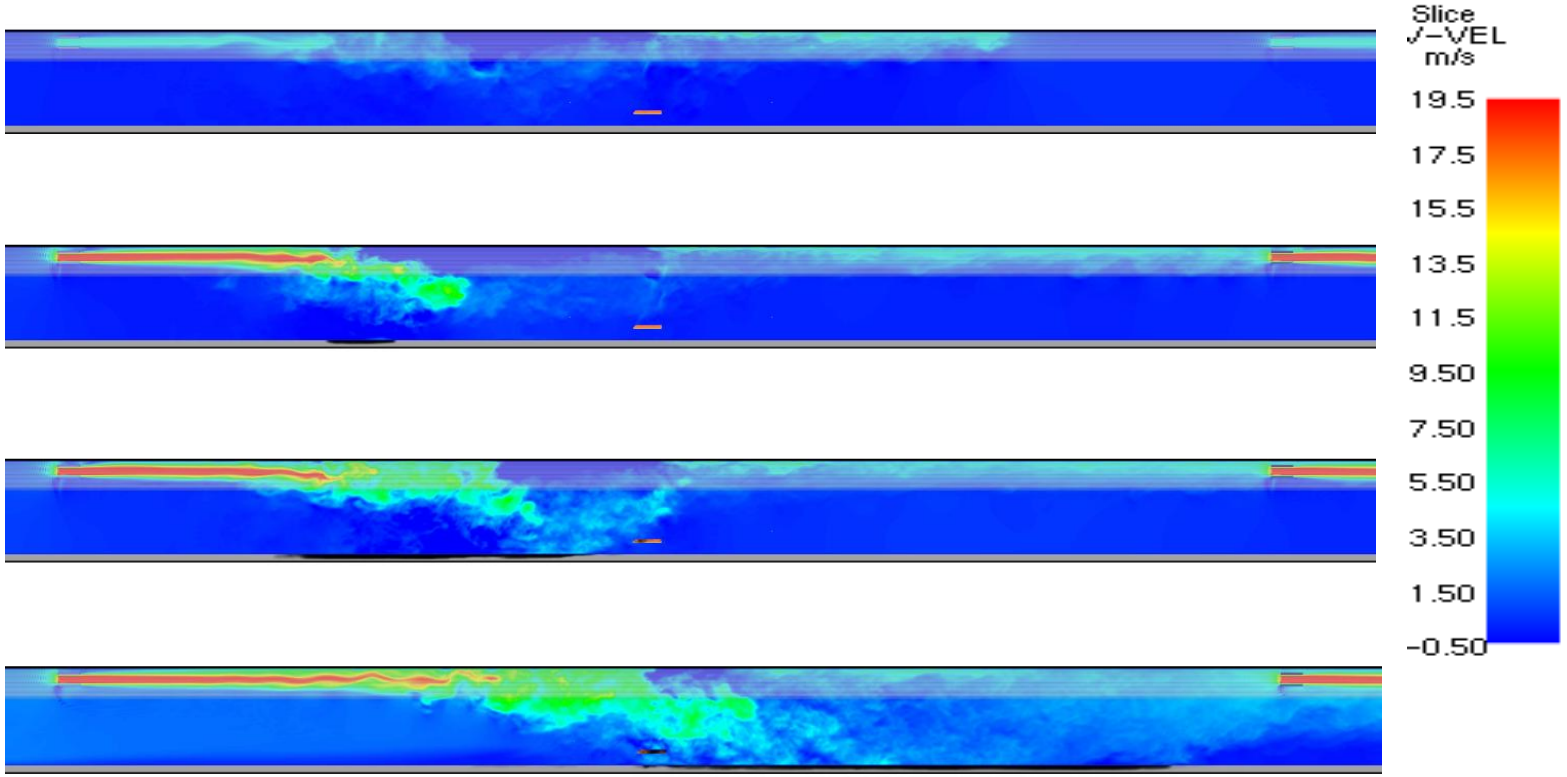
FDS Simulation

- **Simulation Results – Smoke Density at the 50th, 57th, 63th, 150th s**



FDS Simulation

- **Simulation Results – Velocity at the 50th, 57th, 63th, 150th s**



FDS Simulation

- **Simulation Variants and their Performance**

Sim.	Mesh Division Description	MPI process	Cells [mil.]	Max Cells Per Mesh [mil.]	Time Steps	Wall Clock Time [hrs]	Max/ Min Mesh CPU [hrs]	$c_{(1M)}/c$
1M	1M: 180m, 10cm	Seq.	12.96	12.96	33041	377.2	375.8 375.8	1.00
3M	3M: 60m, 10cm	3	12.96	4.32	31905	172.4	169.5 165.6	0.73
10M	1M: 60m, 10cm 8M: 7.5m, 5cm 1M: 60m, 10cm	10	43.20	4.32	60727	313.6	309.6 289.4	0.80
24M	24M: 7.5m, 10cm	24	12.96	0.54	31206	32.6	32.0 26.9	0.48
48M	48M: 3.75m, 10x 5x10cm	48	25.92	0.54	68759	63.2	61.5 53.8	0.50

Thank you for your attention!