Fire Plume Modeling

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Short Course on Introduction to Air Pollution Modeling, Wessex Institute

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Industrial Plumes vs. Large Fires

Gaussian Models

Fire Models

Talk Outline

- Part 1: Background
  - Fires: Photos & Diagrams
  - Fire Modeling: Basic Inputs & Parameters
  - Modeling Goals and Strategies
- Part 2: CFD Modeling of Fires using FDS
  - Model Description, Setup, I/O
  - Pool Fire Test Case (Neutral Atmospheric Stability)
  - Pool Fire Test Case (Stable Atmospheric Stability)
- Part 3: Modeling with BUOYANT
  - Non-CFD: Steady-State Plume Model with fire plume rise model
  - Test Cases: How much of fire plume resides in ABL?

Part 1: Background

Large Industrial Fires

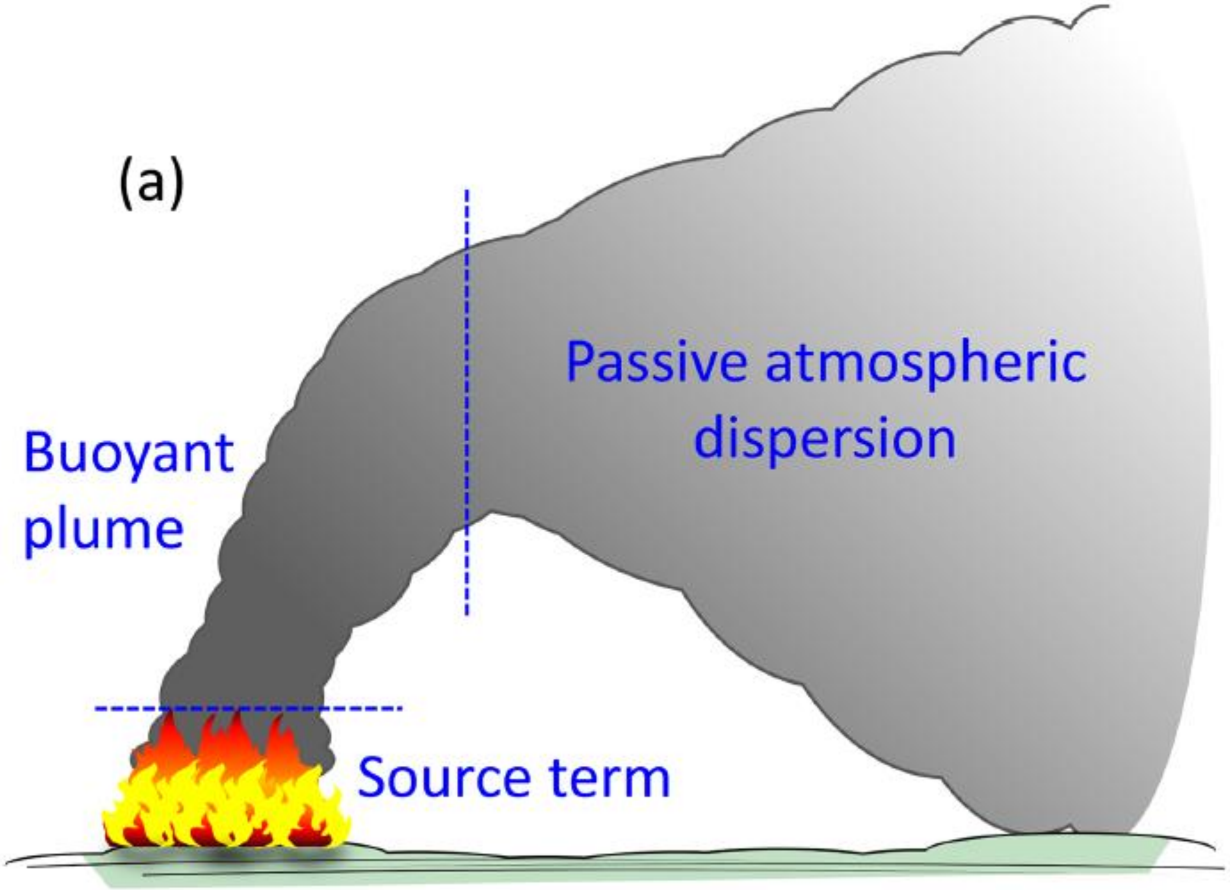
- Heat and Mass Fluxes
- Buoyancy Flux ~ (Heat Release Rate Per Unit Area) x (Area of Release)

- Plume Rise, Plume Buoyancy, Clean Air Entrainment
- Constituents: Carbon Dioxide, Smoke, Trace Metals, others

Large Industrial Fires

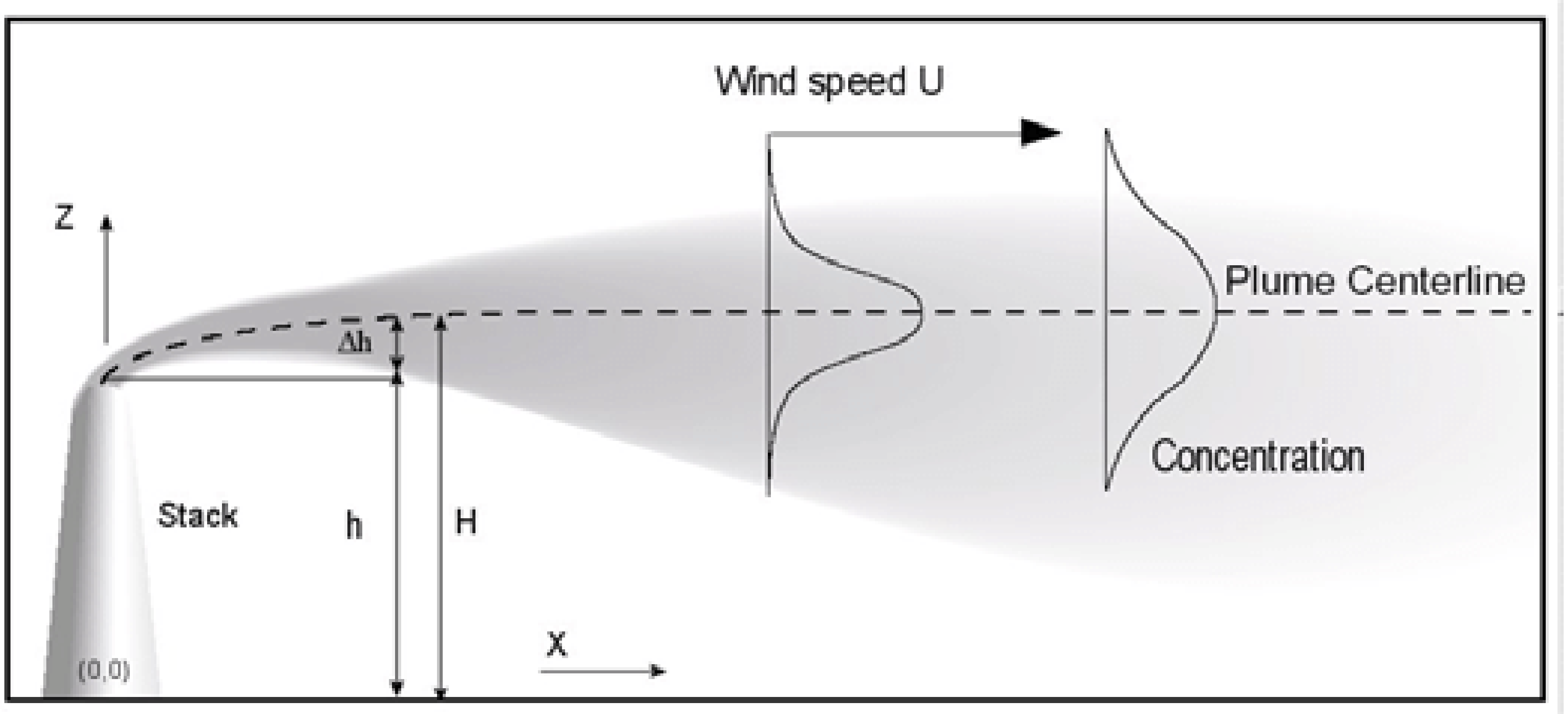
- Plume Rise through the Atmospheric Boundary Layer?
- Penetration into the inversion capping the ABL

Fire Dispersion: Physics & Modeling (1)



Kukkonen et al (2022); https://gmd.copernicus.org/articles/15/4027/2022/

Steady-State Gaussian Plume Model



- Dispersion in weak to modestly strong ambient ABL turbulence
- Weak to modest plume rise (Δh)
- Calculated relatively accurately by standard Briggs plume rise equations

Guassian Plume Modeling: Briggs Plume Rise

Buoyancy Flux (F)

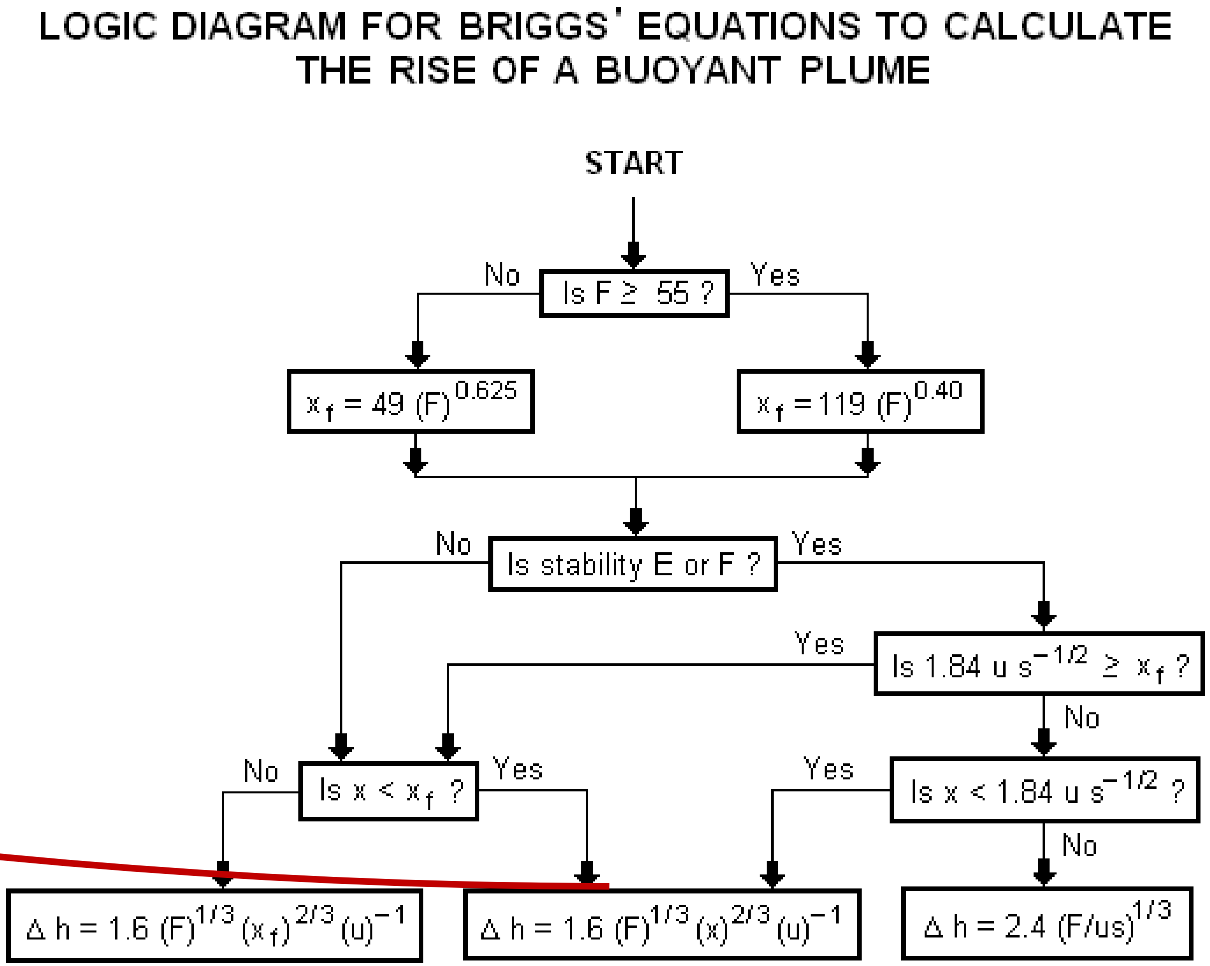
F = Stack Heat Release x $(1/\rho c_p)(g/T)$

-> Units m^4/s^3

$$\Delta h = 1.6F^{1/3}x^{2/3}u^{-1}$$

u - wind speed

x – distance downwind



https://en.wikipedia.org/wiki/Atmospheric_dispersion_modeling#Briggs_plume_rise_equations

Fire Modeling: Basic Inputs & Parameters (Emissions)

Heat & Mass Release Rate

qHc = ΔHc x mfuel,

where …

qHc = heat release rate (kJ/s = kW)

ΔHc = heat of combustion (MJ/kg)

mfuel = mass flow rate of the fuel (g/s)

Buoyancy Flux = F = Heat Release x $(1/\rho c_p)(g/T)$ -> Units m^4/s^3

Fire Modeling: Basic Inputs & Parameters (Emissions)

Example: Pool Fires

Material	H_c kJ kg^{-1}	$q_{m,\infty}$ kg (m^2 s)$^{-1}$	$k\beta$ m^{-1}	y_{CO_2} g g^{-1}	y_{CO} g g^{-1}	y_{hc} g g^{-1}	y_s g g^{-1}
Acetone (C_3H_6O)	25 800	0.041	1.9	2.14	0.003	0.001	0.014
Benzene (C_6H_6)	40 100	0.085	2.7	2.33	0.067	0.018	0.181
Butane (C_4H_{10})	45 700	0.078	2.7	2.85	0.007	0.003	0.029
Heptane (C_7H_{16})	44 600	0.101	1.1	2.85	0.01	0.004	0.037
Kerosene	43 200	0.039	3.5	2.83	0.012	0.004	0.042
LNG (mostly CH_4)	50 000	0.078	1.1	2.72	–	–	–
LPG (mostly C_3H_8)	46 000	0.099	1.4	2.85	0.005	0.001	0.024

Heat of Combustion

Mass Release Rate (Infinite-diameter pool)

Yields (mass released per mass fuel burned)

Kukkonen et al (2022); https://gmd.copernicus.org/articles/15/4027/2022/

Fire Modeling: Basic Inputs & Parameters (Meteorological)

Dispersion

- Wind Speed
- Atmospheric Stability
- Boundary Layer Depth, Height of Inversion Base
- Atmospheric Lapse Rate above Boundary Layer

Particle Formation, Chemistry, Deposition

- Humidity
- Precipitation

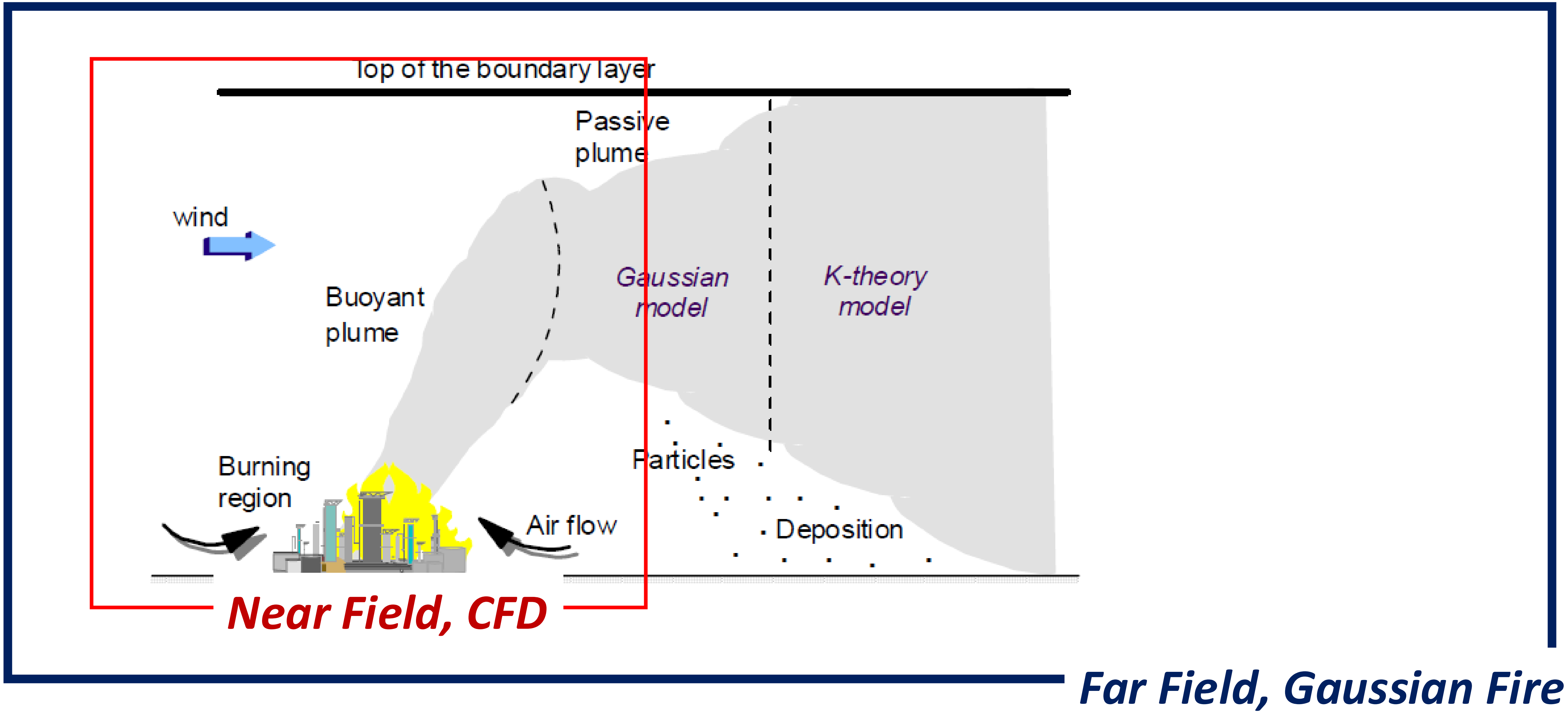
Desired Features in Fire Dispersion Model

- Simple but effective inputs to characterize source characteristics
  - ➢ Mass and heat release
  - ➢ Constituents
- Proper handling of plume rise
  - ➢ Enhanced buoyancy
  - ➢ Entrainment of ambient air into rising fire plume
  - ➢ CFD directly simulates, plume models must parameterize
- Capturing induced circulations
  - ➢ Fire-driven circulations due to strong buoyant convection
  - ➢ Need CFD for this

Fire Dispersion Models: Options

- Computational Fluid Dynamics (CFD)
  - Fire Dynamics Simulator (FDS, https://www.nist.gov/services-resources/software/fds-and-smokeview
  - Full 3-D solutions for Navier-Stokes equations
  - Full suite of embedded models for fire physical processes (pyrolysis, combustion, phase change, chemistry, etc …)
  - Near-Field (within 1-km from source)
- Gaussian Dispersion Models designed for fires
  - BUOYANT (https://gmd.copernicus.org/articles/15/4027/2022/)
  - Steady-state w/ Embedded fire plume rise model
  - Far-Field (beyond 1-km from source)

Highlight: Near vs. Far-Field Modeling



Part 2: CFD Modeling using FDS (near-field dispersion)

Fire Dynamics Simulator (FDS): Basics

- U.S. National Institute of Standards and Technology (NIST)
- https://www.nist.gov/services-resources/software/fds-and-smokeview
- Computational Fluids Dynamics (CFD)
- Full Physics: Various physical processes, sub-models and configurations
- Indoor and outdoor capabilities
- Simulates fire generation/spread **and** dispersion of reactants/smoke
- Rectangular grid (relatively simple mesh generation …)

Fire Dynamics Simulator (FDS) Installation & Execution

- Windows executable (no compilation necessary)
- Command line interface (no GUI)
- Enter inputs into text file
- Smokeview graphics to view output

FDS Test Runs: Grid & Fire Inputs

- **Grid**
  - 25 x 25 x 25 m resolution over 2000 x 1000 x 1000 m domain (80 x 40 x 40)
  - Surface “pool” fire of 150 x 150 m centered at (x, y, z) = (1000,500,25)
- **Fire Inputs**
  - Single-step mixing controlled combustion
  - Fuel is propane
  - Heat Release Rate = 250 kW/m2
  - Corresponds to a fuel consumption rate of about 0.005 kg/m2/s
  - Set 10% of reactants to be smoke (by mass)

FDS Test Runs: Meteorological Inputs

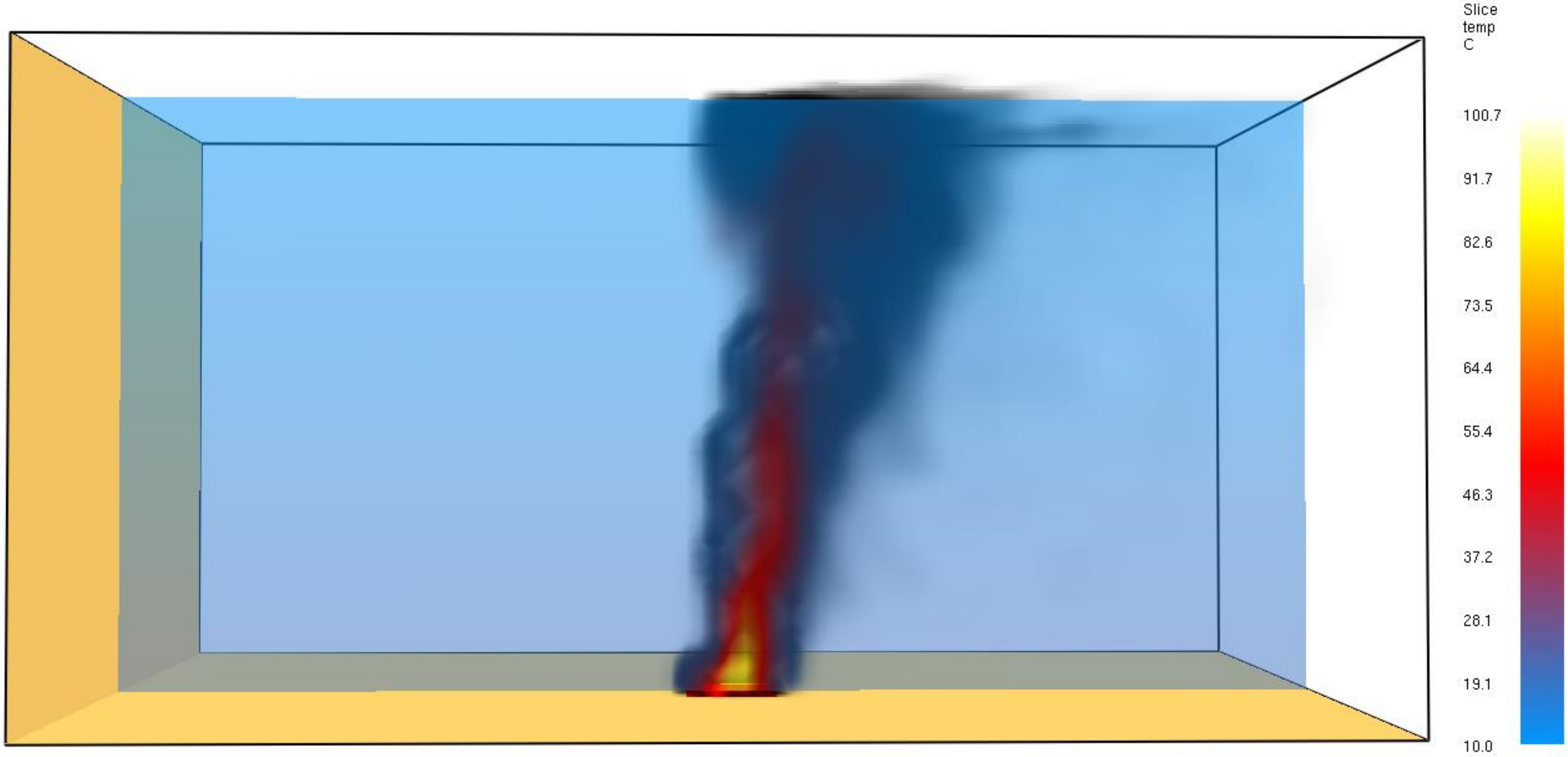
- **Wind**: Boundary layer background flow of about 2 m/s
- **Neutral Case**: Set lapse rate to adiabatic (stability class D)
- **Stable Case**: Set lapse rate to isothermal (stability class E or F)

Compare output for neutral vs. stable

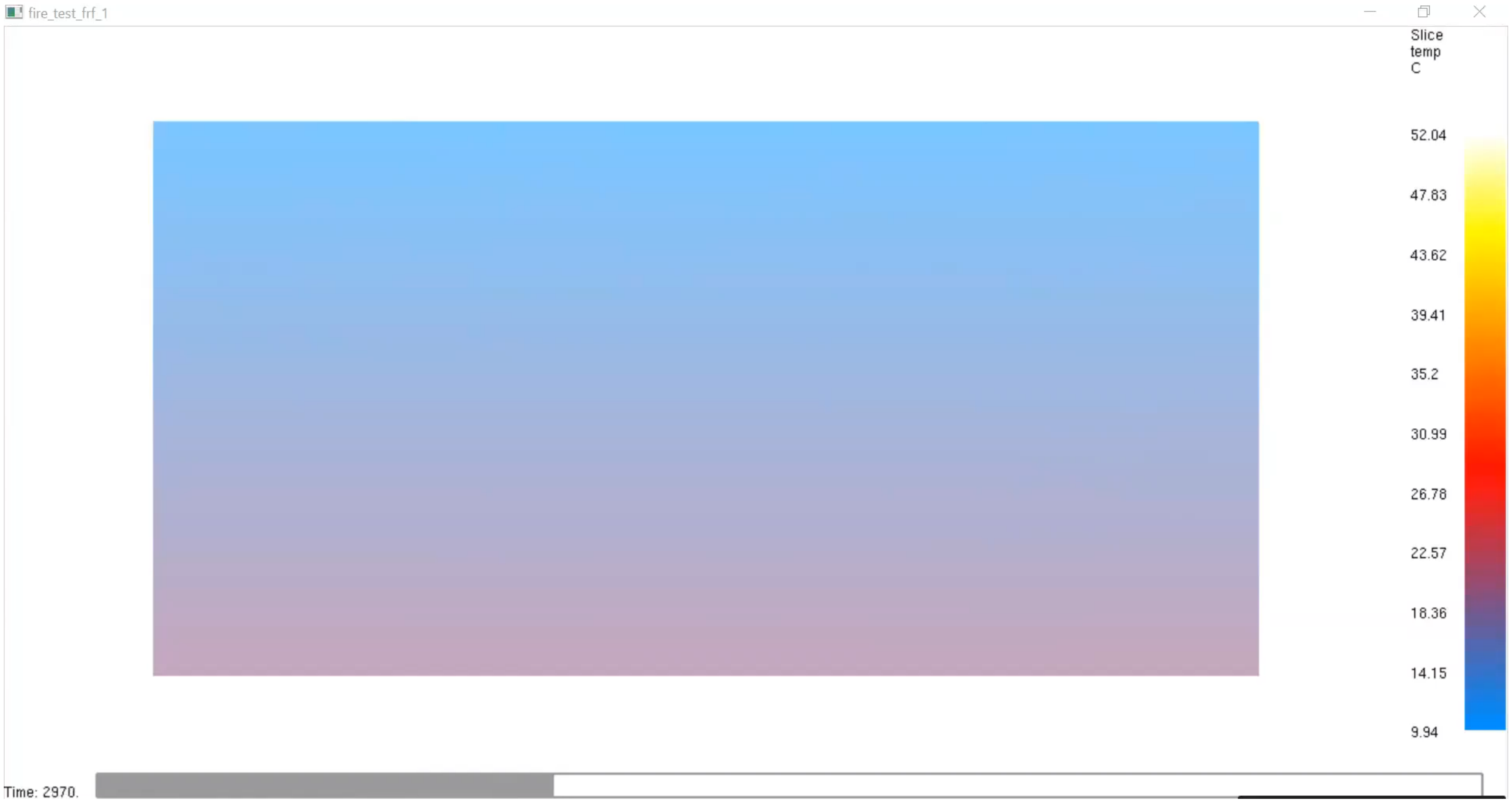
FDS Test Runs: Procedure

- 14400 seconds integration time (= 4 hours)
- "Turn on" fire @ t = 7200
  - 0 < t < 7200: "spin up" period to bring background wind to quasi steady-state
  - 7200 < t < 14400: "fire period"
- After period of build-up of fire @ t = 7200, new "fire-affected" quasi steady-state is reached by around t = 8400.
- Plots to be shown are @ t = 14400 (final time)

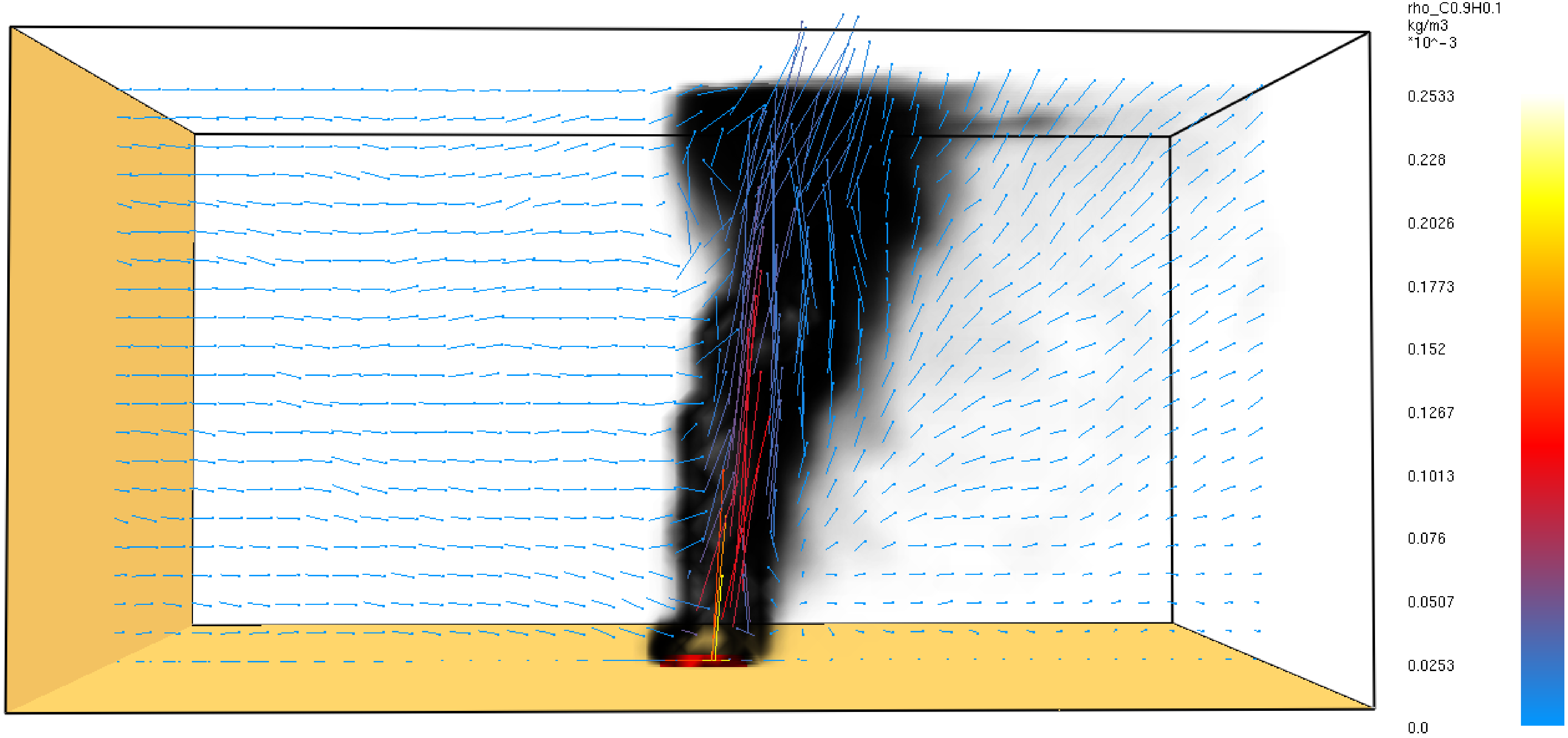
Neutral: Smoke & Temperature (image)



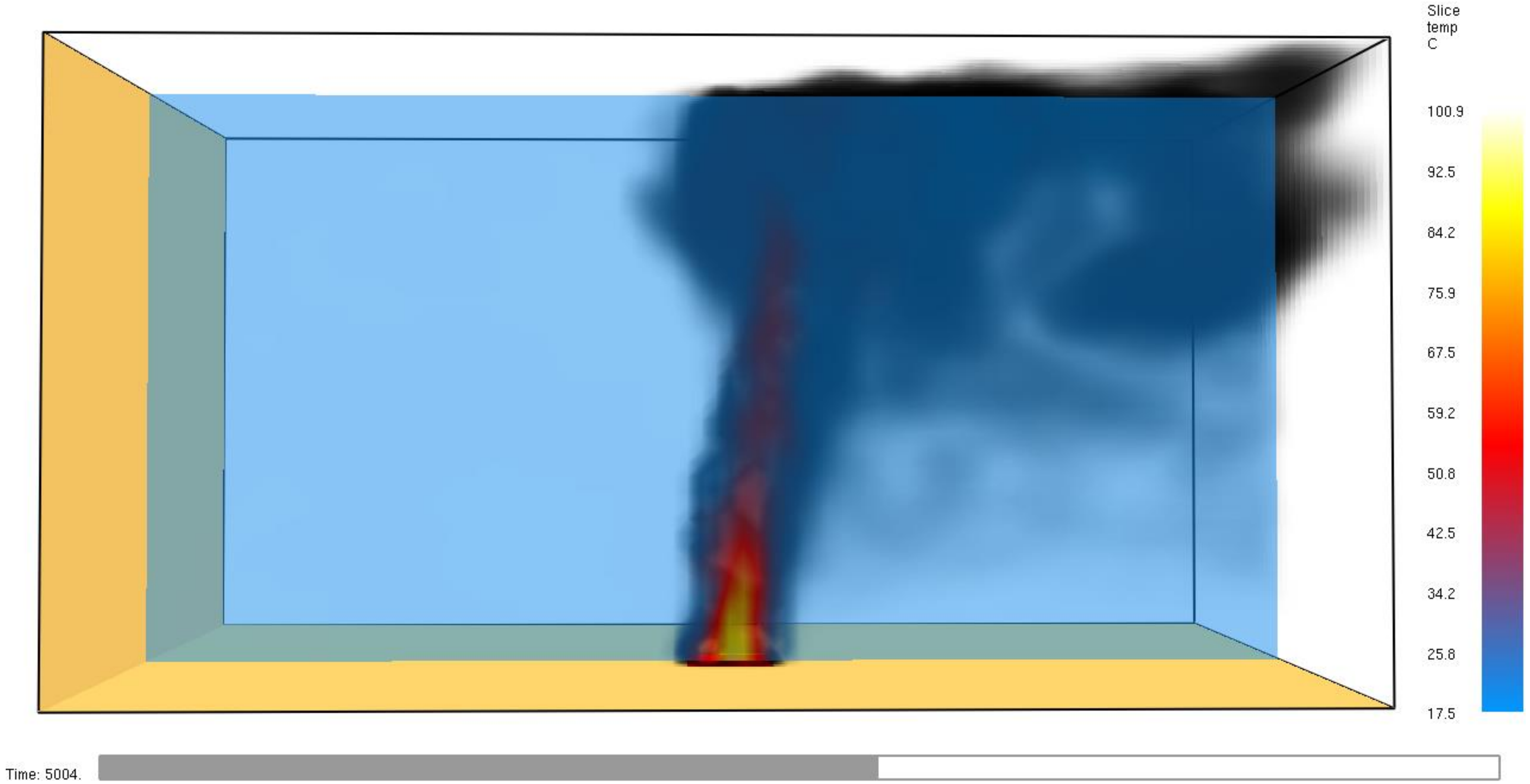
Neutral: Smoke and Temperature (video)



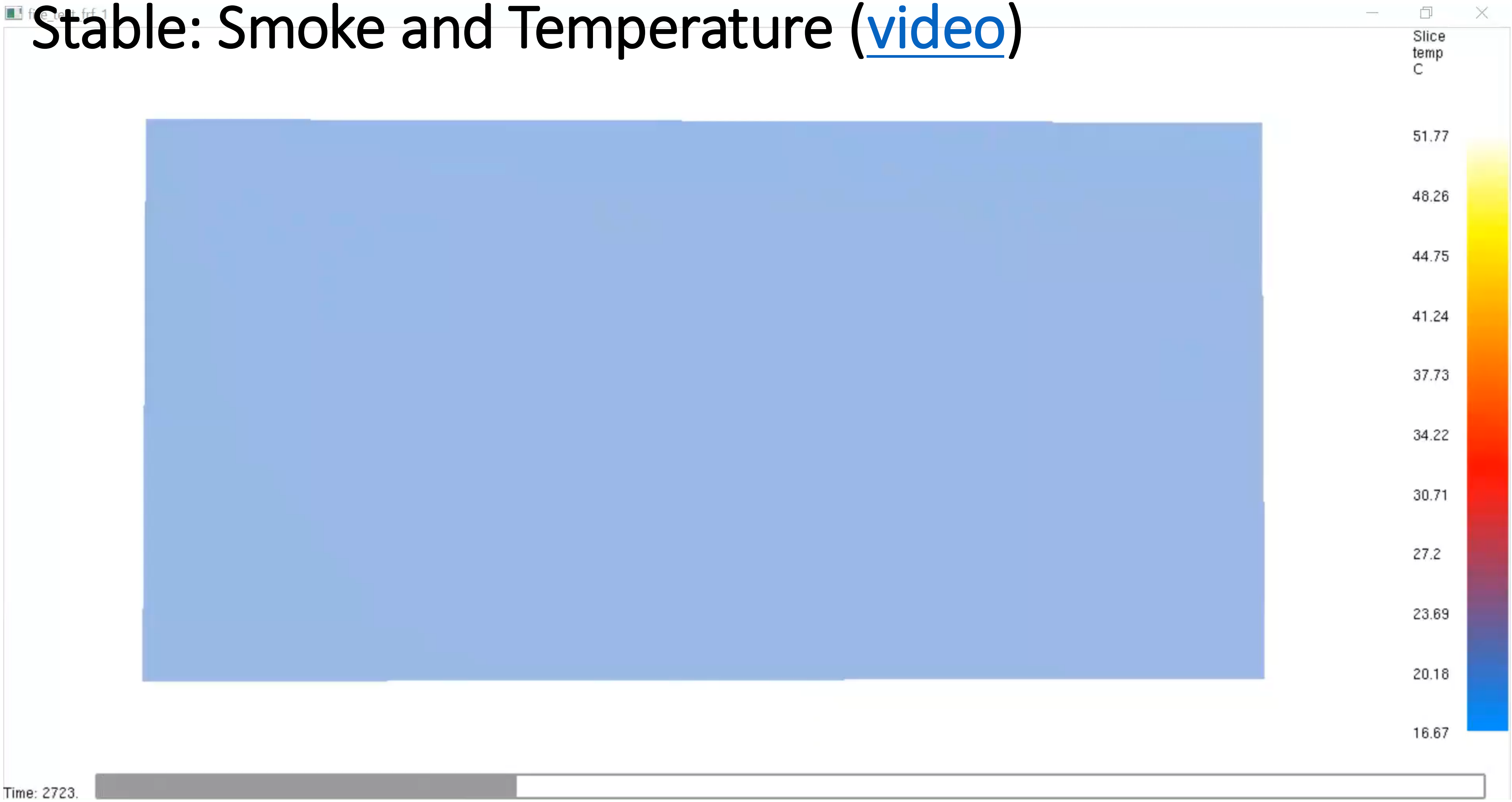
Neutral: Smoke & Winds (image)



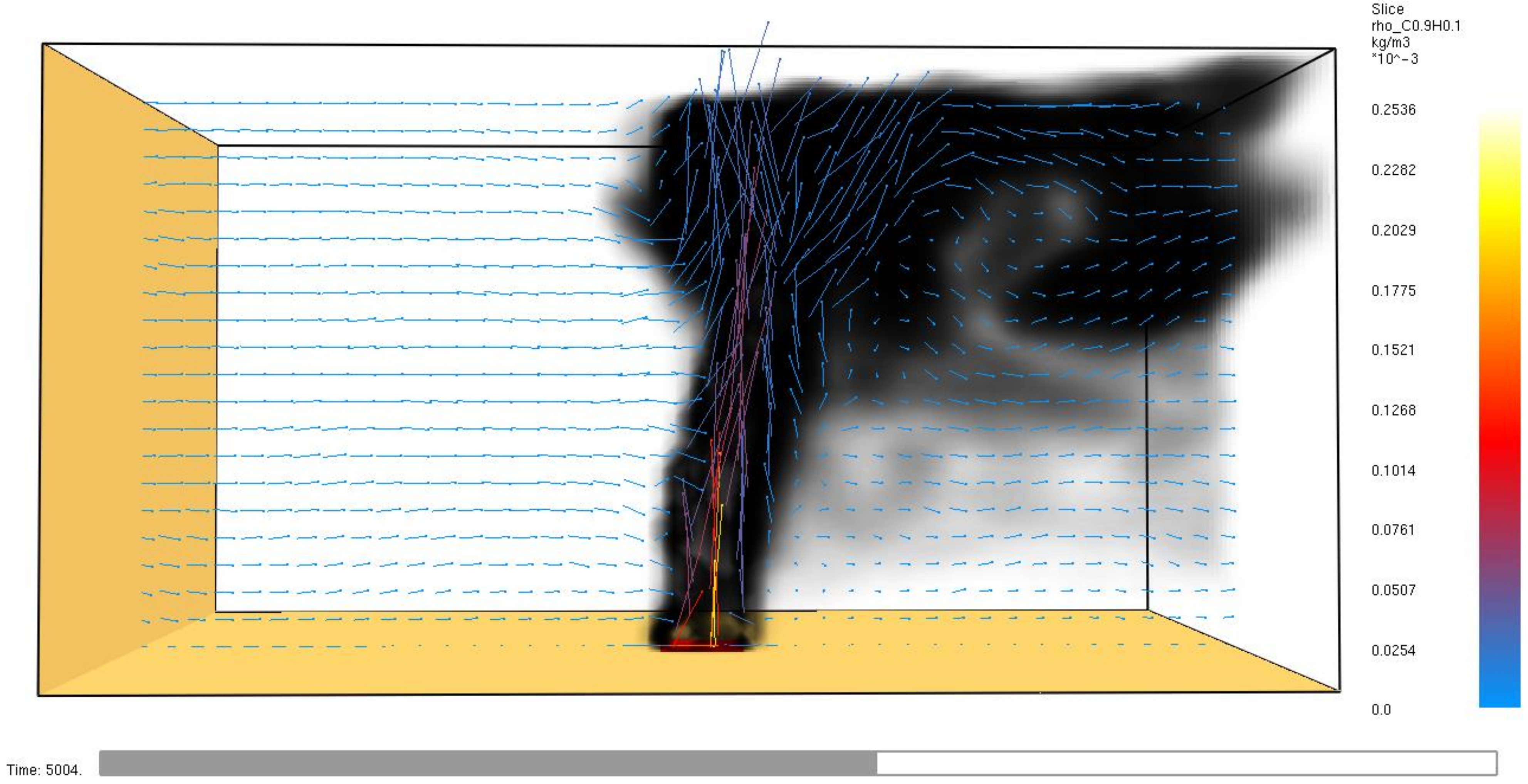
Stable: Smoke & Temperature (image)



Stable: Smoke and Temperature (video)

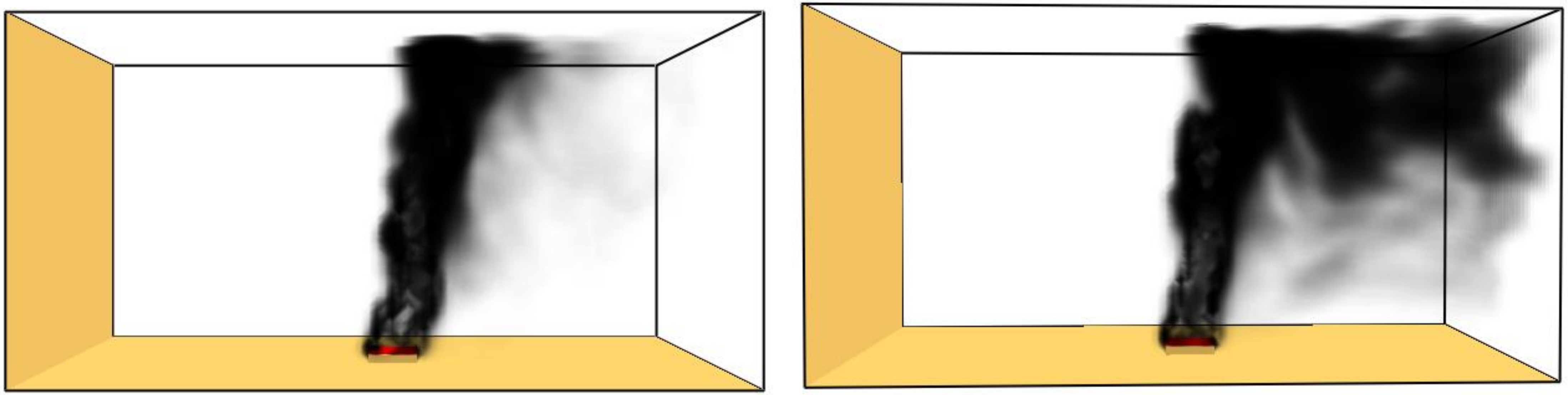


Stable: Smoke & Winds (image)



Smoke visuals @ t = 2 hours after fire start

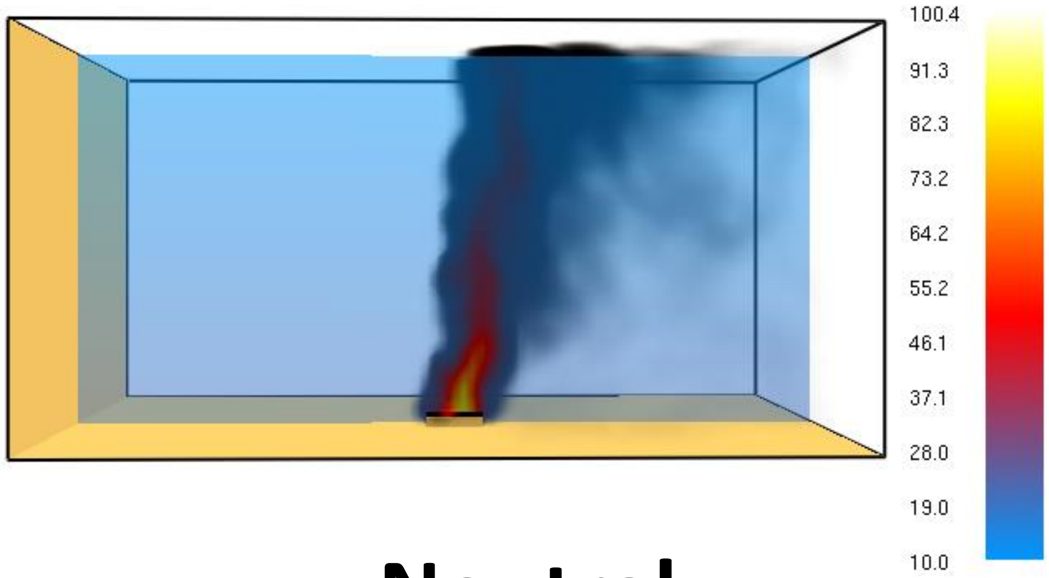
z = 1000 m



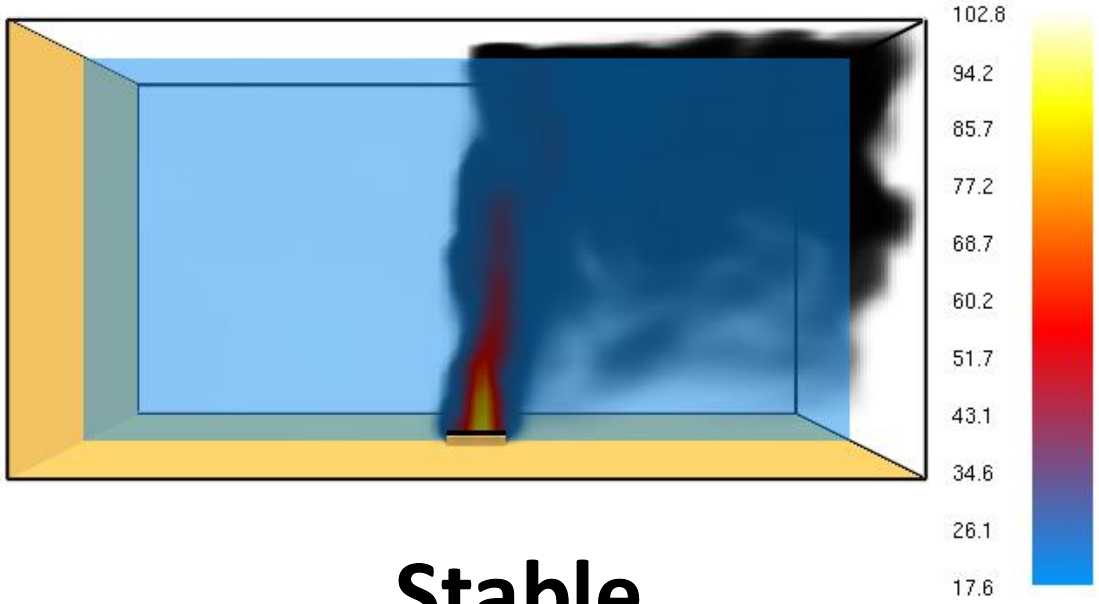
Neutral

Stable

Smoke visuals overlaid w temperature (deg C) @ t = 2 hours after fire start



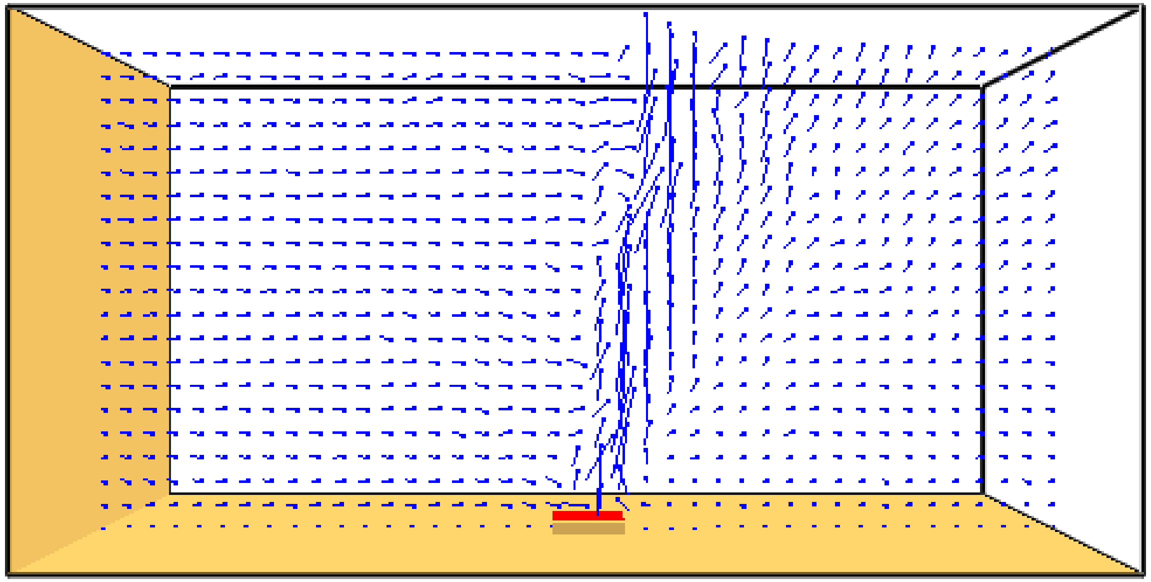
Neutral



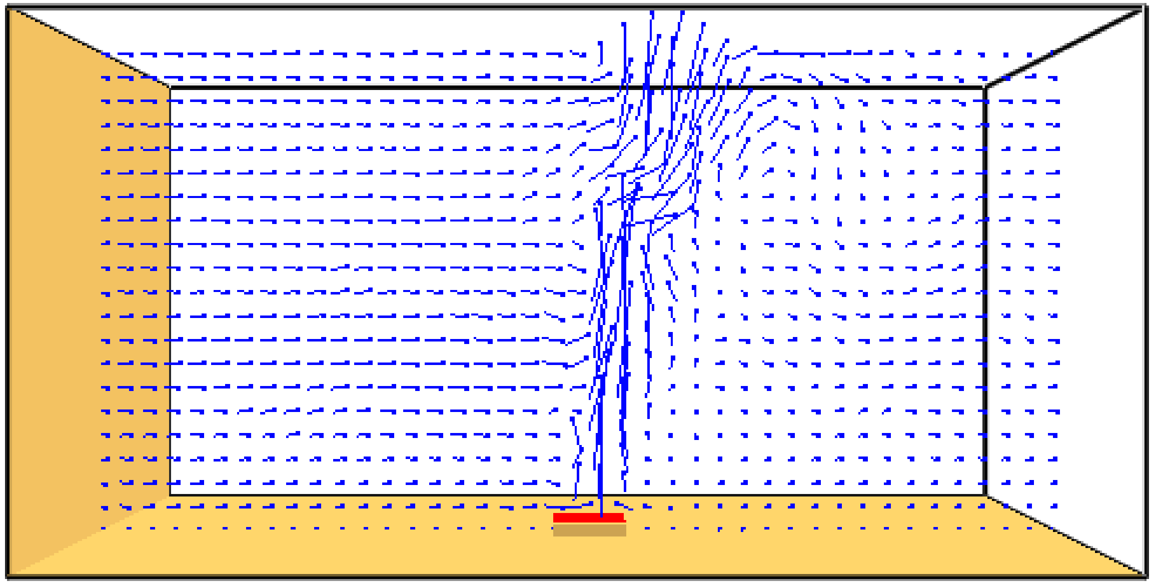
Stable

Flow vectors @ t = 2 hours after fire start

Stable

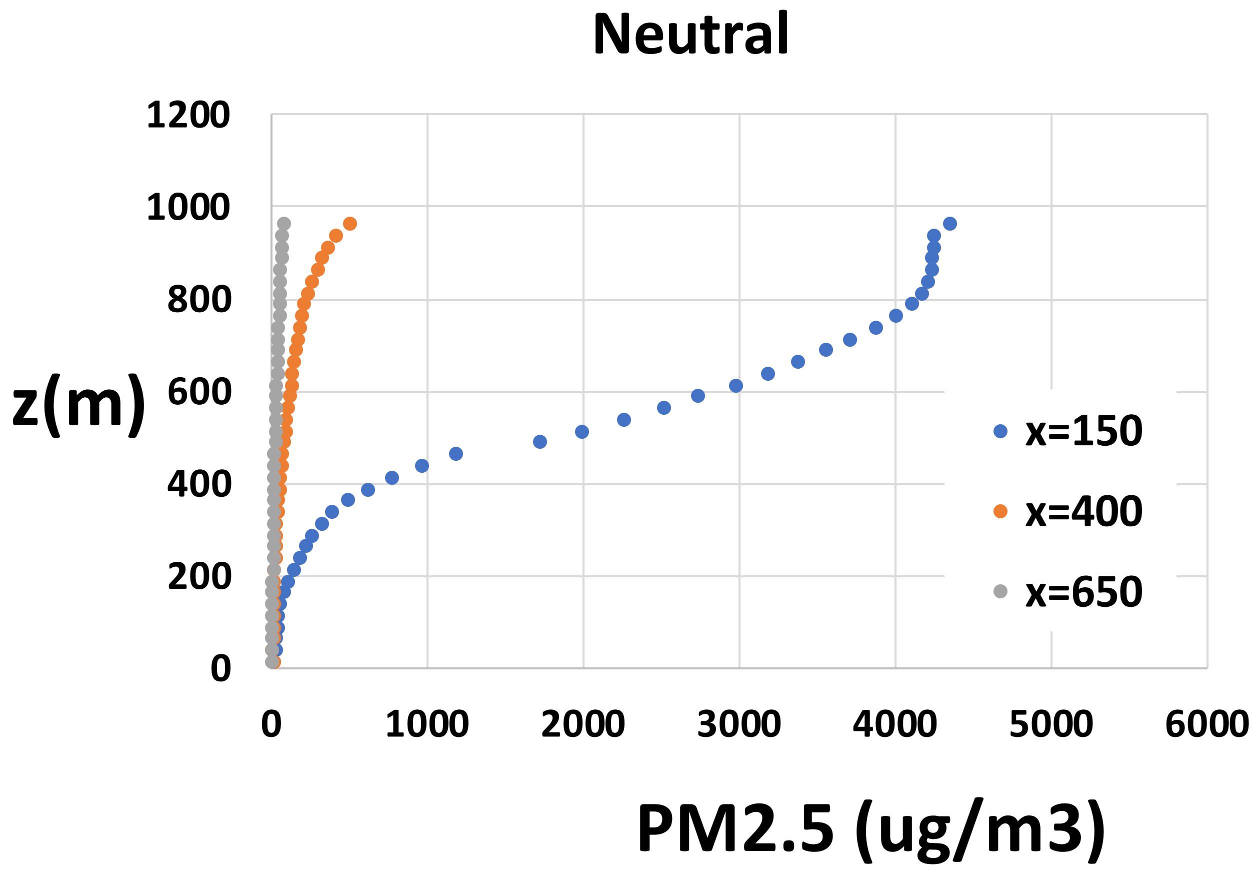


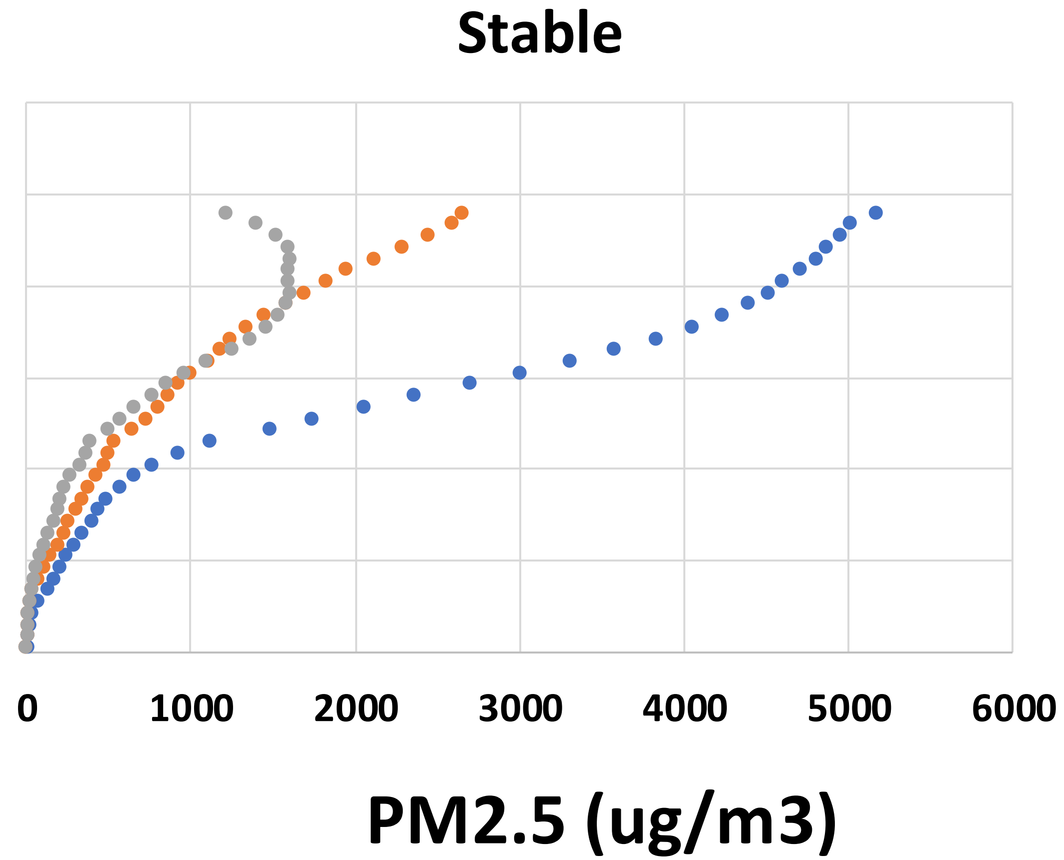
Neutral

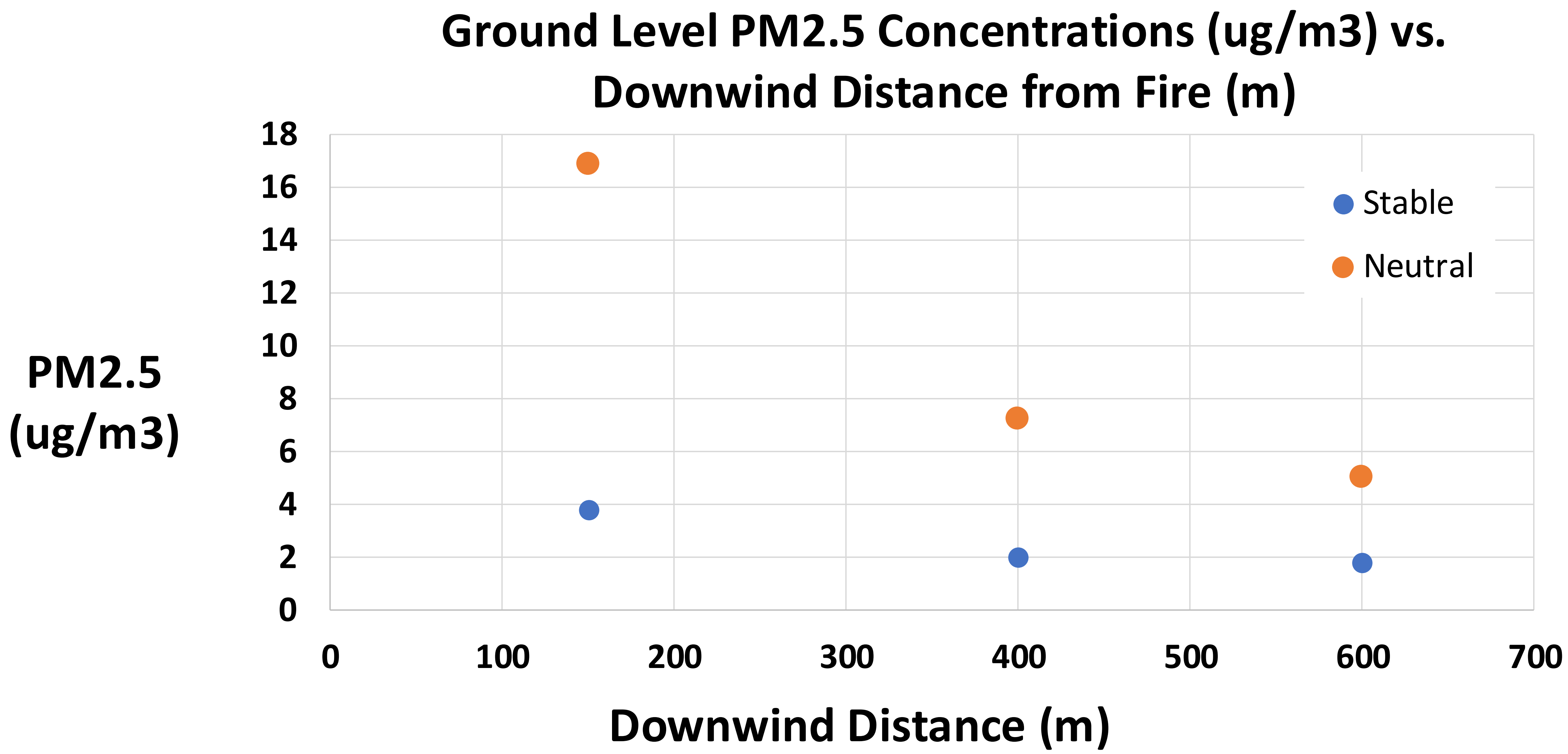


Stable

PM2.5 (ug/m3) vs. Height (meters) @ different downwind distances from fire



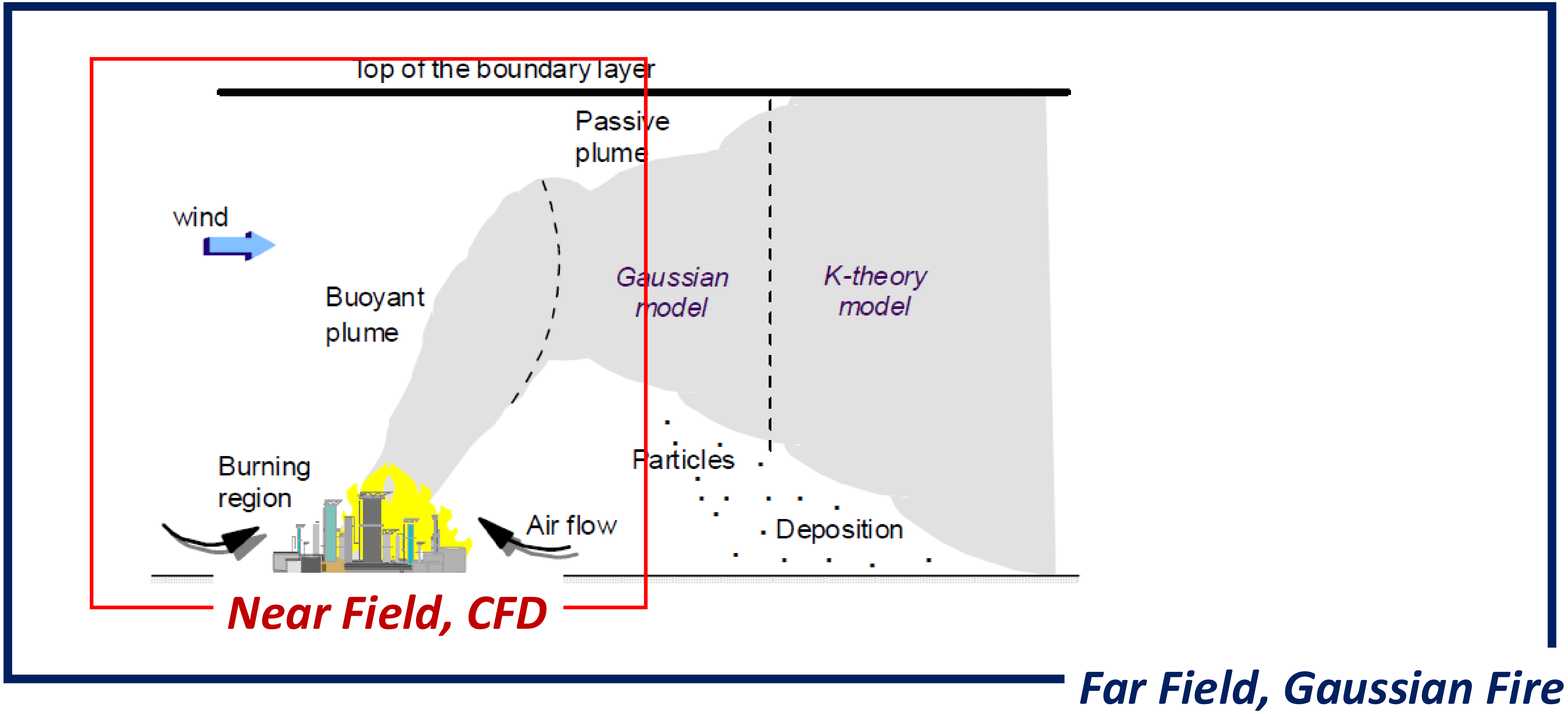




Ground Level PM2.5 Concentrations (ug/m3) vs.
Downwind Distance from Fire (m)
PM2.5
(ug/m3)
18
16
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600
700
Downwind Distance (m)
Stable
Neutral

Part 3: Gaussian Plume Modeling using BUOYANT

Reminder: Near vs. Far-Field Modeling



BUOYANT: Basics

- Finnish Meteorological Institute
- https://gmd.copernicus.org/articles/15/4027/2022/
- Steady-State Gaussian plume model
- Embedded fire plume rise model
- Far-field dispersion (> 1 km)

BUOYANT: Installation & Execution

- FORTRAN code (compilation necessary)
- Need to install FORTRAN compiler
- MSYS2 virtual LINUX required on WINDOWS, has ‘gfortran’ as a package
- Command line interface (no GUI)
- Enter inputs into text file
- Text file outputs

Large Industrial Fires

- Question … how much of the plume stays within the ABL?
- Run cases to check how model predicts this quantity.

BUOYANT: Test Runs

- **Meteorological Inputs**
  - Wind Speed = 3.22 m/s
  - Neutral ABL w depth = 1000 m
- **Pool Fire: Case 1 ("low' heat release)**
  - Heat Release Rate = 20 kW/m2
- **Pool Fire: Case 2 ("medium" heat release)**
  - Heat Release Rate = 700 kW/m2
- **Pool Fire: Case 3 ("high" heat release)**
  - Heat Release Rate = 1800 kW/m2

Reminder: FDS Test Runs

- **Grid**
  - 25 x 25 x 25 m resolution over 2000 x 1000 x 1000 m domain (80 x 40 x 40)
  - Surface “pool” fire of 150 x 150 m centered at (x, y, z) = (1000,500,25)
- **Fire Inputs**
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  - Fuel is propane
  - Heat Release Rate = 250 kW/m2
  - Corresponds to a fuel consumption rate of about 0.005 kg/m2/s
  - Set 10% of reactants to be smoke (by mass)

BUOYANT Test Runs: Results
(Fraction of plume that stays in the ABL)

Modeling Run	Heat Release Rate (kW/m2)	Fraction of Plume in ABL
Case 1 (Low Heat Release)	20	0.5597
Case 2 (Medium Heat Release)	700	0.1874
Case 3 (High Heat Release)	1800	0.05533

- Fraction in ABL highly sensitive to fire strength (via heat release)
- More plume in ABL → High surface concentration
- Appears to capture an observable feature of strong fires … that most plume mass can stay aloft above ABL

Conclusions

Dispersion Modeling for Fires

- Two approaches demonstrated as alternatives to typical Gaussian models
- Initial test results of both appear promising

1. Computational Fluid Dynamics, CFD)

Fire Dynamics Simulator (FDS)

2. Steady-Steady Gaussian Modeling with Fire Plume Rise

BUOYANT