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Evaluation of the Air-Demand, Flame Height, and Radiation Flux from a Low-Profile Flare

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OUTLINE

- Introduction to ISIS-3D and Flare Modeling
- ISIS Model Setup and Methodology
- Low Profile Flare Tests
- Model Validation
- Burner Predictions
  - Air Demand
  - Radiation Load
- Observations and Conclusions

ISIS-3D General Comments

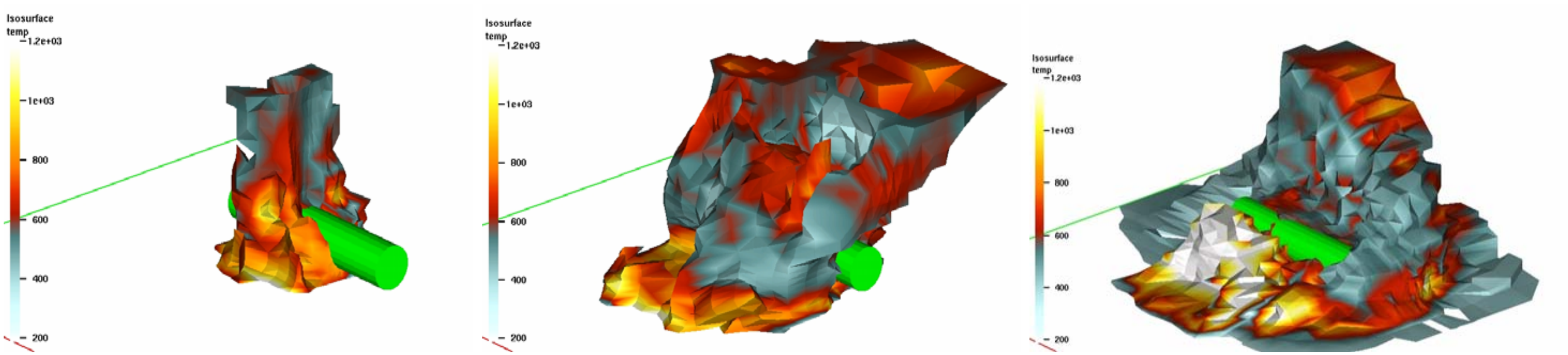
- Based on Computational Fluid Dynamics with radiative heat transfer and combustion chemistry
- Linked model is capable of simulating *complex*, three-dimensional objects engulfed in fires
- Provides *reasonably* accurate estimates of the total heat transfer to objects from large fires
- Predicts *general* characteristics of temperature distribution in object
- Accurately assess impact of variety of risk scenarios (wind, % flame coverage, thermal fatigue for given geometry, etc.)
- Reasonable CPU time requirements on “standard” desktop LINUX workstation

ISIS-3D Trade-Offs

- Sacrifice *generality* (large fires only) in favor of *quick turnaround* time and quantitative *accuracy*
- Re*action rate* and *radiation heat transfer* models apply only to large fires
- Models intended to make ISIS-3D predictions "good-enough" for industrial use

Radiation Inside Large Fires

- High soot volume fractions make large fires non-transparent (optically thick) which causes flame to radiate as a cloud (radiatively diffuse)
- Fire volume defined as where soot volume fraction is greater than a minimum volume fraction ($f_{Soot} > f_{min}$)
- Flame edge ($f_{FlameEdge}$) defined where soot volume fraction is 0.05 ppm - based on comparisons with large fire experiments



Calculated flame surfaces for 3 time steps from ISIS-3D simulation of validation experiment

Radiation Outside of Large Fires

- When $f_{Soot} < f_{FlameEdge}$ => outside "flame" (participating medium considered)
- View factors from fire to un-engulfed surfaces calculated at each time step (include attenuation by flames)
- Radiation view factor from object surface to surroundings calculated at each time step
- $\varepsilon_{FireSurface} = 1$ (fire is black body radiator)
- Radiation from fire surface to surroundings based on $T_{surround}$ = Constant

Diffuse Radiation Within Fire

- Calculated indirectly using a Rossland effective thermal conductivity

$$k_R = \frac{16\sigma T^3}{3\beta_R} >> k_{Air}$$

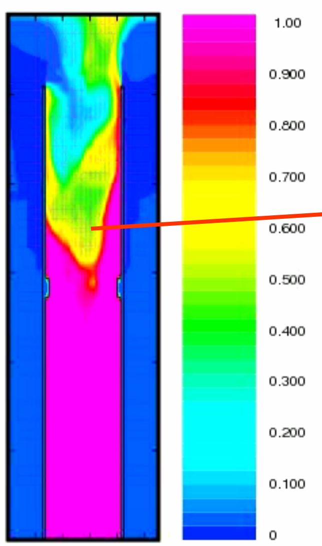
- σ = Stefan-Boltzman Constant
- T = Local temperature
- β_R= Local extinction coefficient (dependent on local species concentrations)

Combustion Model

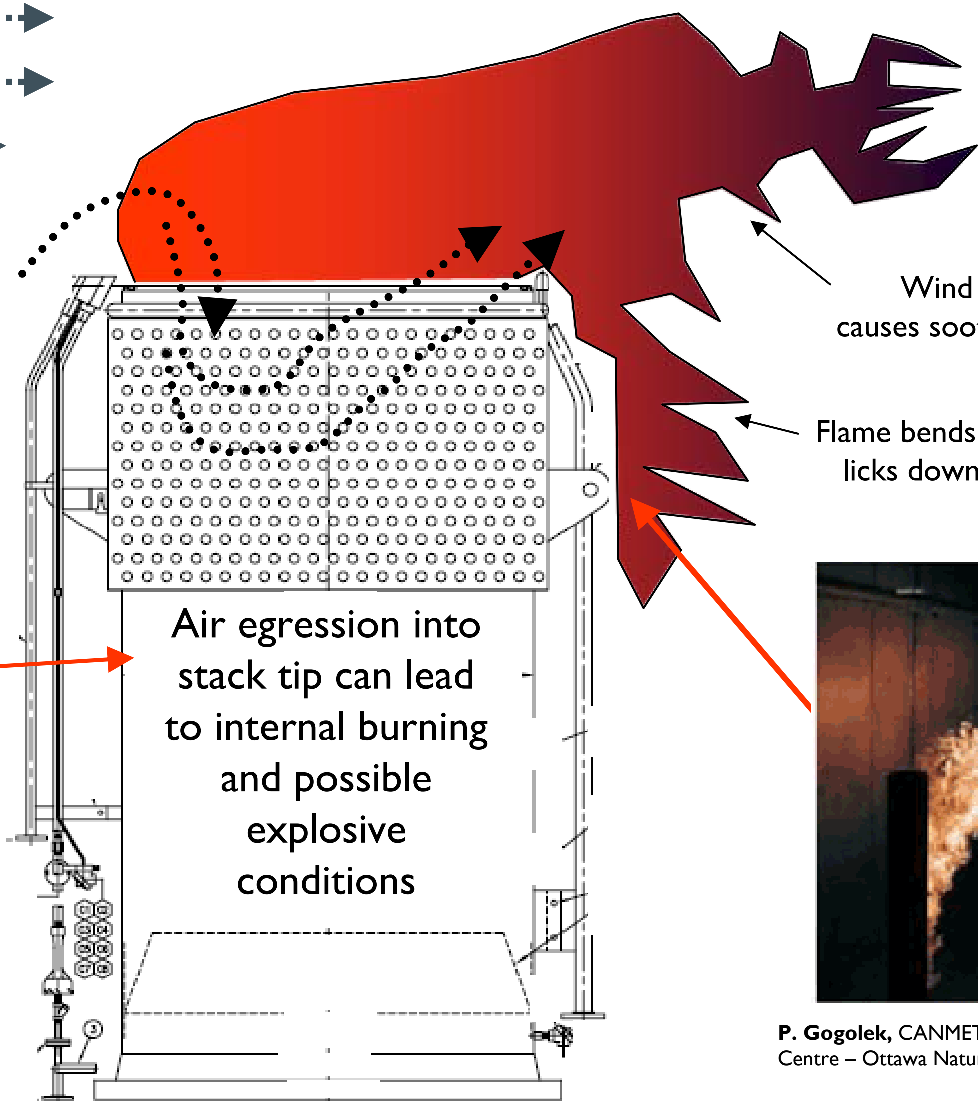
- Variant of Said et al. (1997) turbulent flame model
- Relevant Species (model includes relevant reactions)
  - F = Fuel Vapor (from evaporation or flare tip)
  - O_2 = Oxygen
  - PC = $H_20(v) + CO_2$
  - C = Radiating Carbon Soot
  - IS = Non-radiating Intermediate Species
- Eddy dissipation effects and local equivalence ratio effects
- Reactions based on Arrhenius kinetics
- C and T_A determined for all reactions

Flares in Cross Winds - Modeling Issues

Mass Fraction CH4



Cross winds cause air egression into flare stack



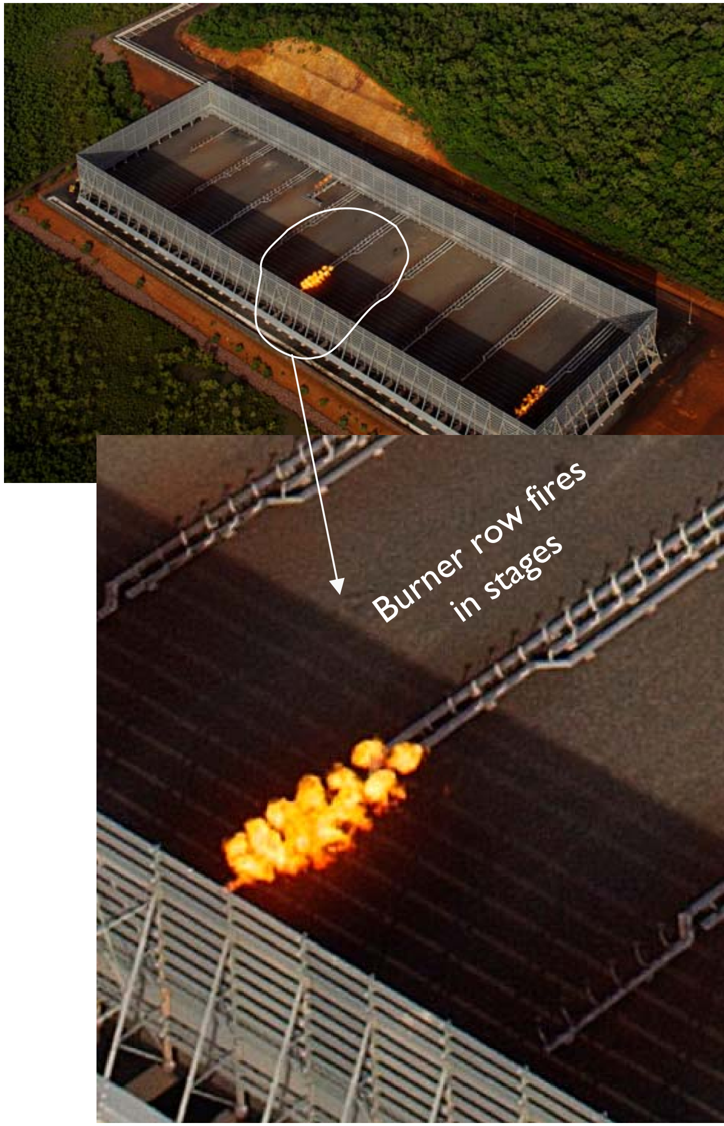
Wind shortens Flame and causes soot formation on back side of flame

Flame bends over in wind and licks downwind side of flare stack

P. Gogolek, CANMET Energy Technology Centre – Ottawa Natural Resources Canada

Low Profile Flares - Modeling Issues

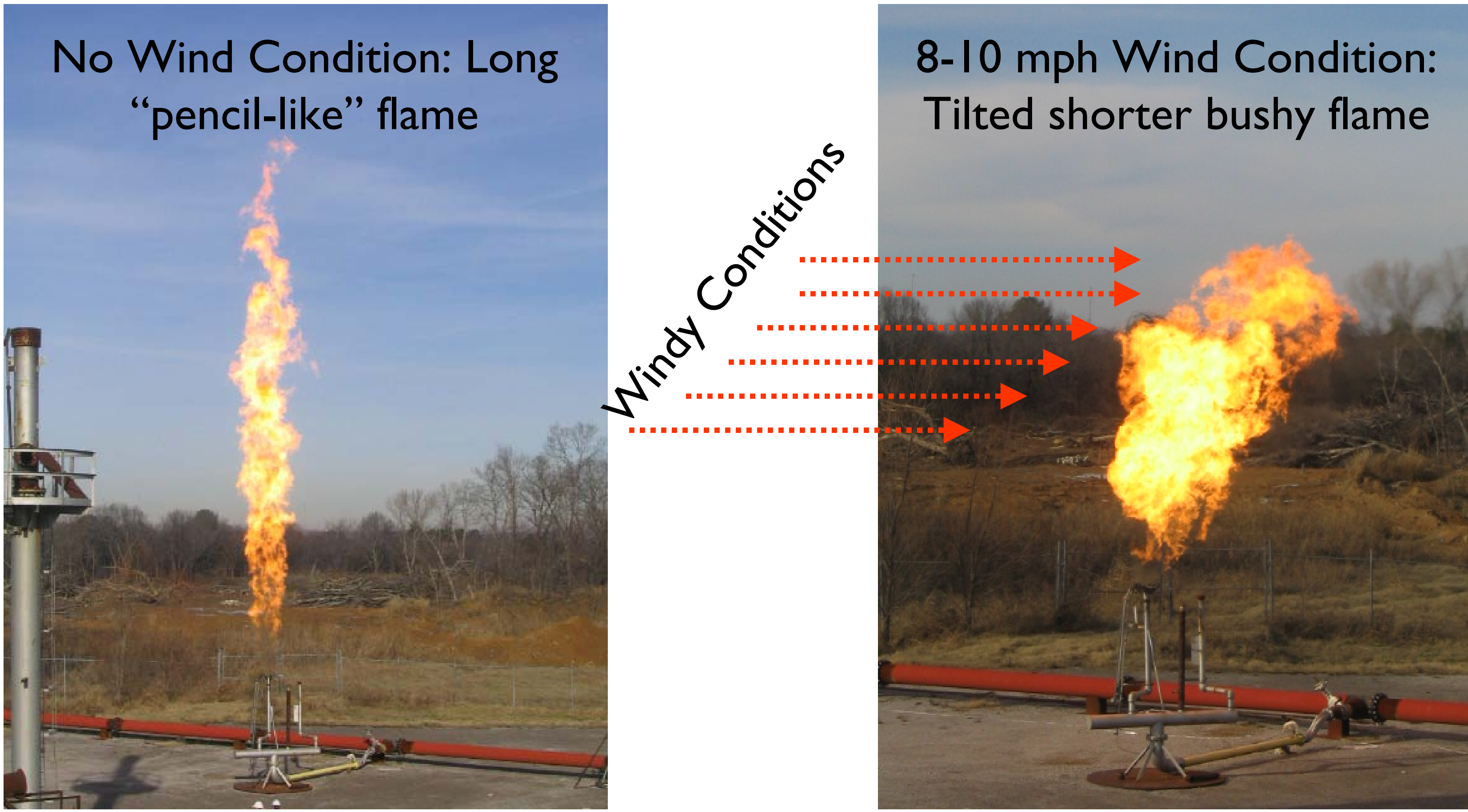
- High tip velocity increases air entrainment
  - Tip design critical to air entrainment
  - Local high velocity can translate into high sound levels
- Assist media not available to increase combustion air
  - smoke below certain tip pressure (D-stage pressure)
- Tip spacing critical
  - Flares must cross light
  - Possible Flame merge lengthens flames
  - Adjacent rows compete for air (longer flames, poor performance)



Approach to Modeling Full Flare Fields

- Model Single Burner Test
  - Perform Calibration Tests
  - Calibrate Soot Yield and Reaction Parameters for Test Fuel
  - Predict flame shape and size
- Model Multi-Burner Test
  - Perform Radiation Calibration Tests
  - Check Tip/Row Spacing
  - Predict flame shape and size
- Model Full Flare Field
  - Use Calibrated Soot Yield and Radiation Models
  - Predict Flare Performance (Smoke Production/Air Demand)
  - Predict Radiation Load on Wind Fence

Single Tip Burning Propane: wind vs. no-wind



Modeling Low Profile Flare Test

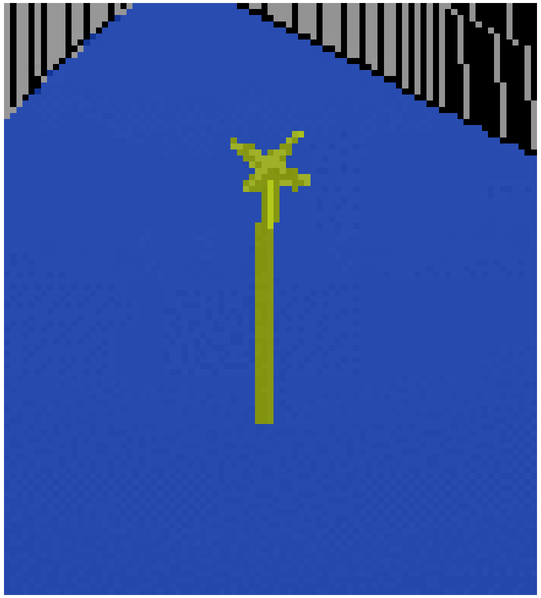
- Propane injected as mass, momentum and species sources
- Fuel Mol wt – 44 (C_3H_8)
- Tip elevation – 2.0 m (6.5 ft)
- Tip Geometry Provided by Client
- Test Conditions for Propane Mass Flow = 0.46 kg/s (3,651 #/hr)
- Flame height determined by fuel and soot burnout
- Air inflow calculated implicitly from pressure boundary conditions
- Radiation Flux calibrated from measured data at two locations

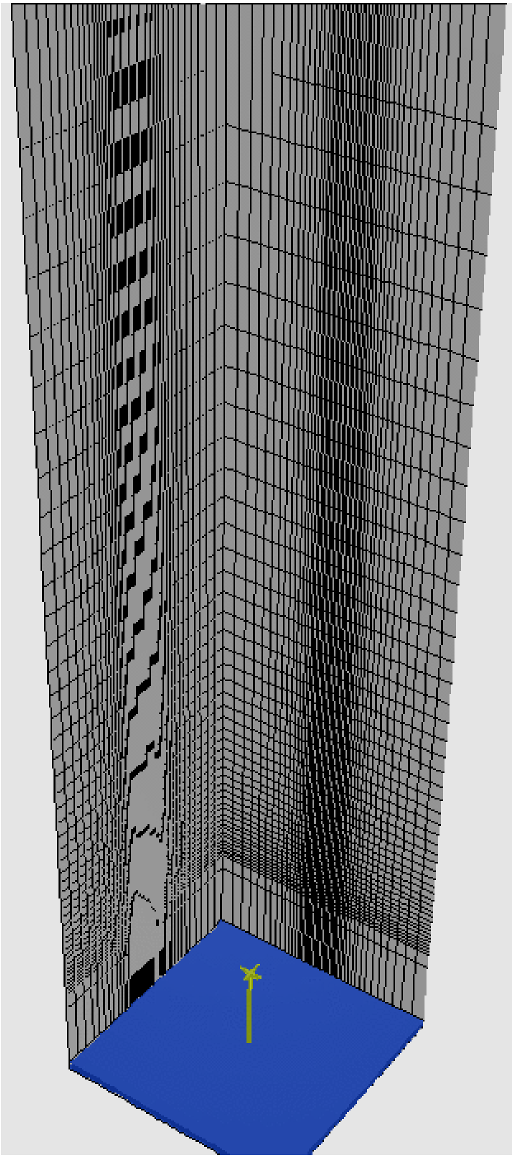
Single Burner Flare Model

- 6 x 6 x 26 m physical domain
- Flare tip located 2 m above ground level
- Turbulence and Arrhenius kinetics Included for fuel gas
  - Reaction Parameters adjusted to match observed flame characteristics
  - Soot Yield matched flame height (i.e., soot burnout)
- Flare Movies for no wind, 3m/s (7mph) wind conditions
- Predicted results for Air demand and Radiation loss from flame determined

Single-burner Mesh

- Rectangular cells
- Local refinement near burner tip
- 110,000 computational cells





Combustion Models

Propane:

$C_3H_8 + 3.6\ O_2 \rightarrow 3\ CO_2 + 1.6\ H_2O + 0.024\ \text{Soot} + 46\ \text{MJ/kg propane}$

$\text{Soot} + 2.66\ O_2 \rightarrow 3.66\ CO_2 + 32\ \text{MJ/kg Soot}$

Ethylene:

$C_2H_4 + 0.57\ O_2 \rightarrow 0.93\ C_2H_2 + 0.64\ H_2O + 9.4\ \text{MJ/kg ethylene}$

$C_2H_2 + 2.58\ O_2 \rightarrow 2.7\ CO_2 + 0.7\ H_2O + 0.2\ \text{Soot} + 34.1\ \text{MJ/kg intermediate}$

$\text{Soot} + 2.66\ O_2 \rightarrow 3.66\ CO_2 + 32\text{MJ/kg Soot}$

Mixed Gas:

$0.572\ C_2H_4 + 0.383\ C_2H_6 + 0.043\ H_2 + 0.982\ O_2 \rightarrow$

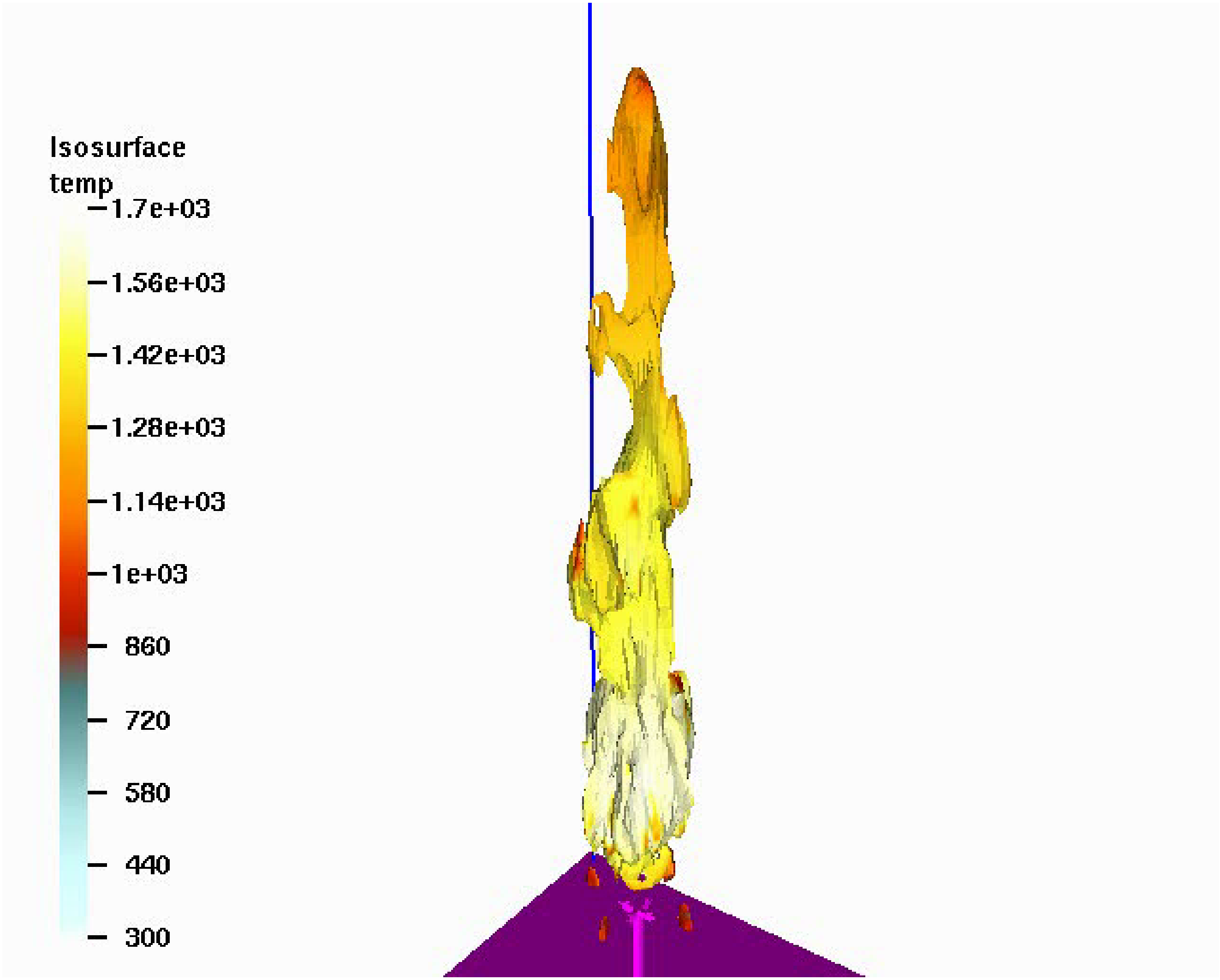
$0.53\ C_2H_2 + 0.34\ C_2H_3 + 1.1\ H_2O + 14.2\ \text{MJ/kg}$

$0.61\ C_2H_2 + 0.39\ C_2H_3 + 2.66\ O_2 \rightarrow$

$2.66\ CO_2 + 0.813\ H_2O + 0.181\ \text{Soot} + 34.4\ \text{MJ/kg}$

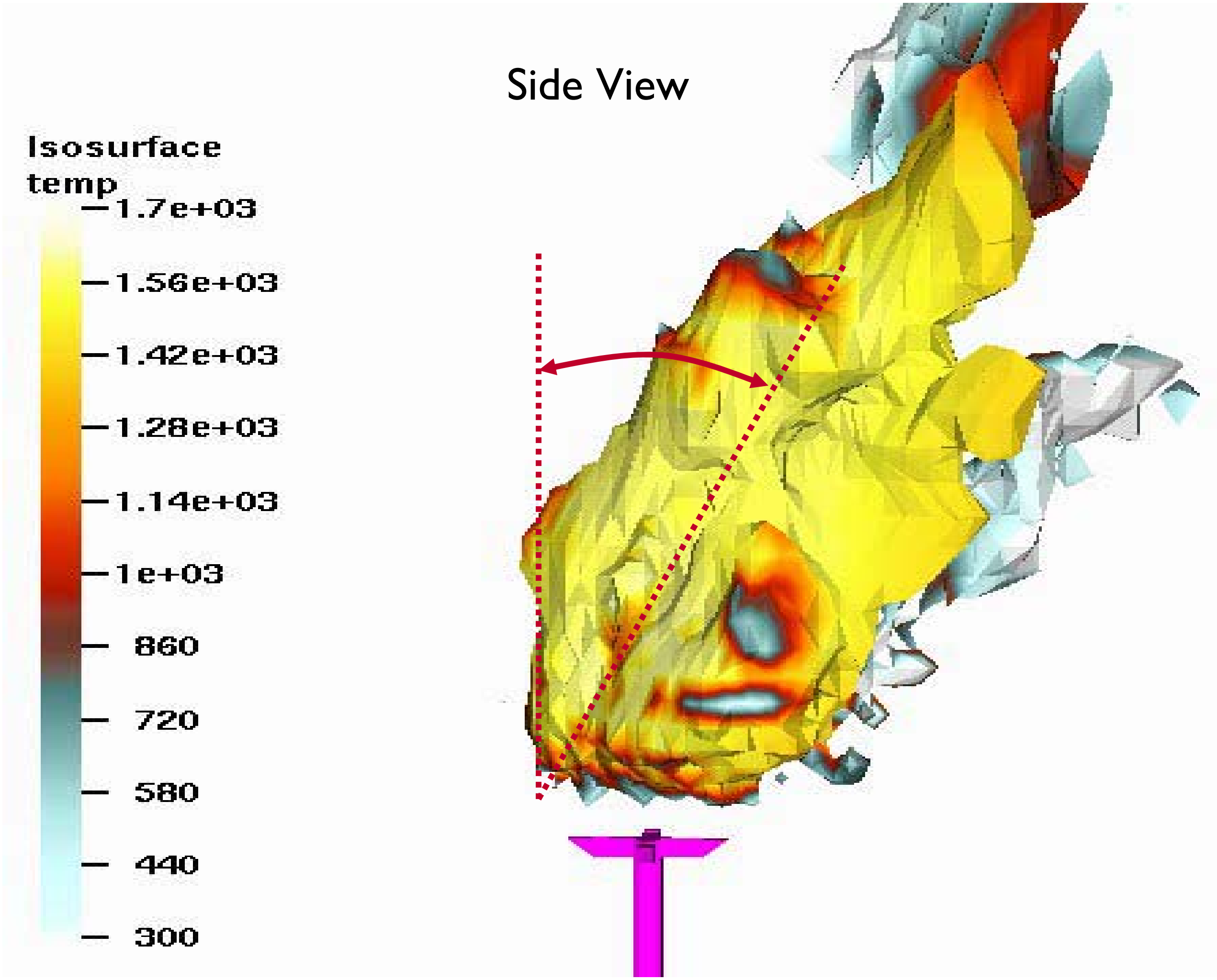
$\text{Soot} + 2.66\ O_2 \rightarrow 3.66\ CO_2 + 32\ \text{MJ/kg}$

Flame in No Wind



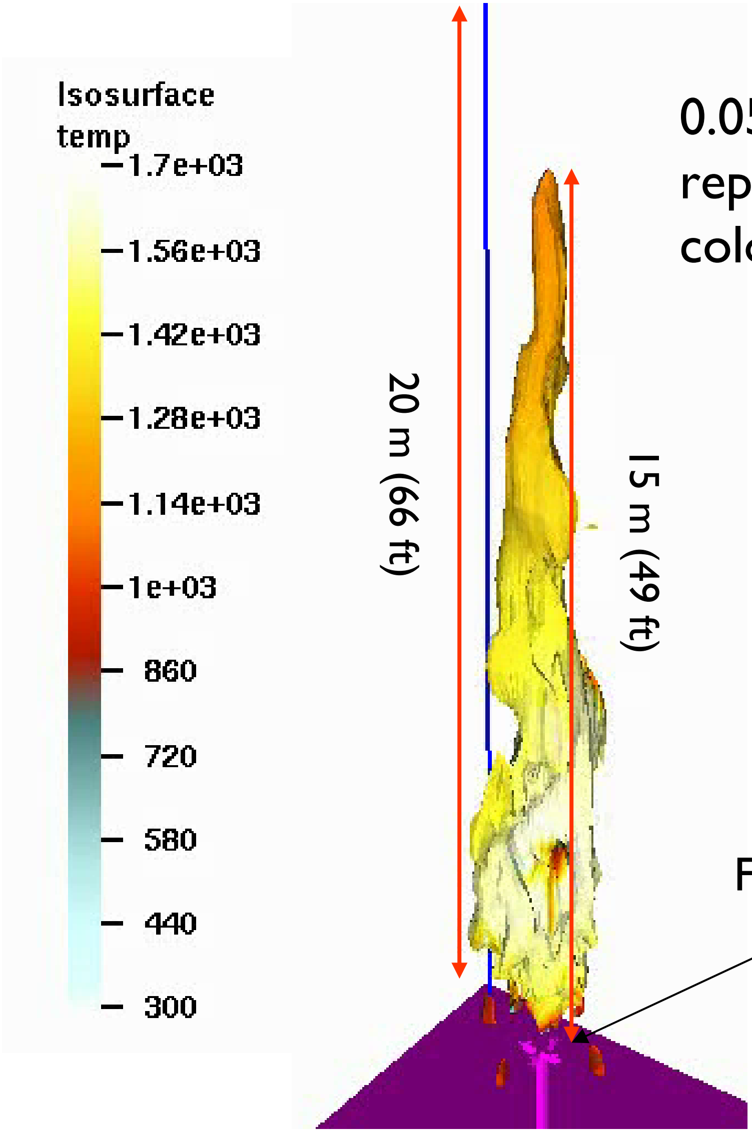
No wind produces tight "pencil-like" flame

Flame in 3.0 m/s Wind



Wind produces tilted bushy, shortened flame

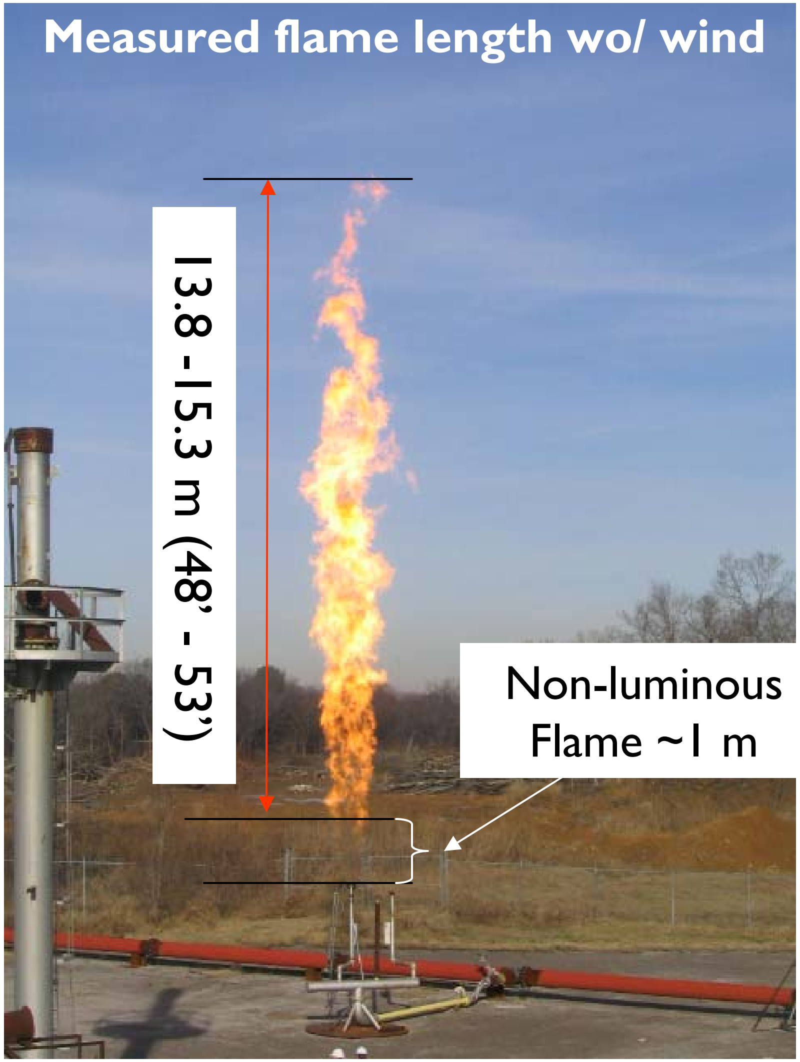
Predicted flame length for no-wind condition



0.05 ppm Soot Iso-surface used to represent Flame volume – surface colored by gas temperature

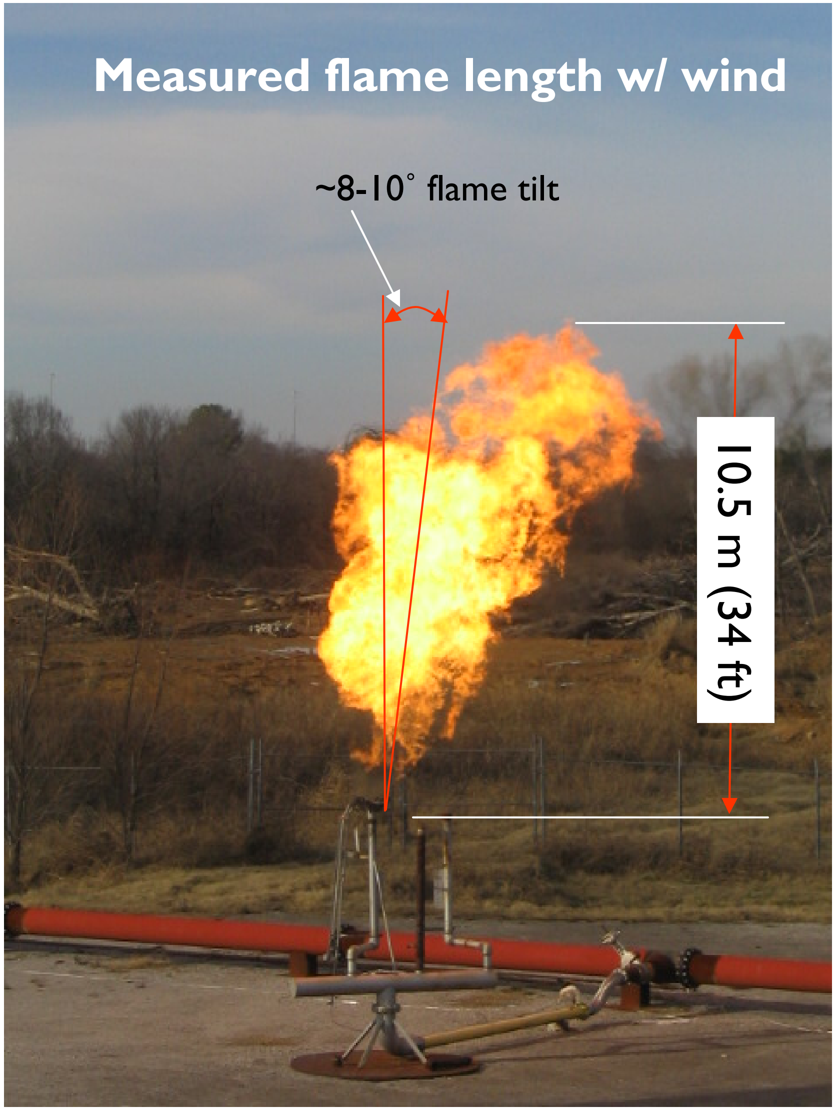
Flare tip located 2 m (~7 ft) above grade

Single-Tip Ground Flare Test Results



- No Wind Condition (<1 mph wind)
- Ave Flame Length = 14.8 - 16.3 m (48 - 53 ft)
- "Pencil-like" tight flame
- Small non-luminous flame at base
- Propane Flow rate: measured 1.4" WC @ 57 ˚F across orifice plate => 7.3 psig tip back pressure (measured on 18 inch pipe run)

Single-Tip Ground Flare Test Results

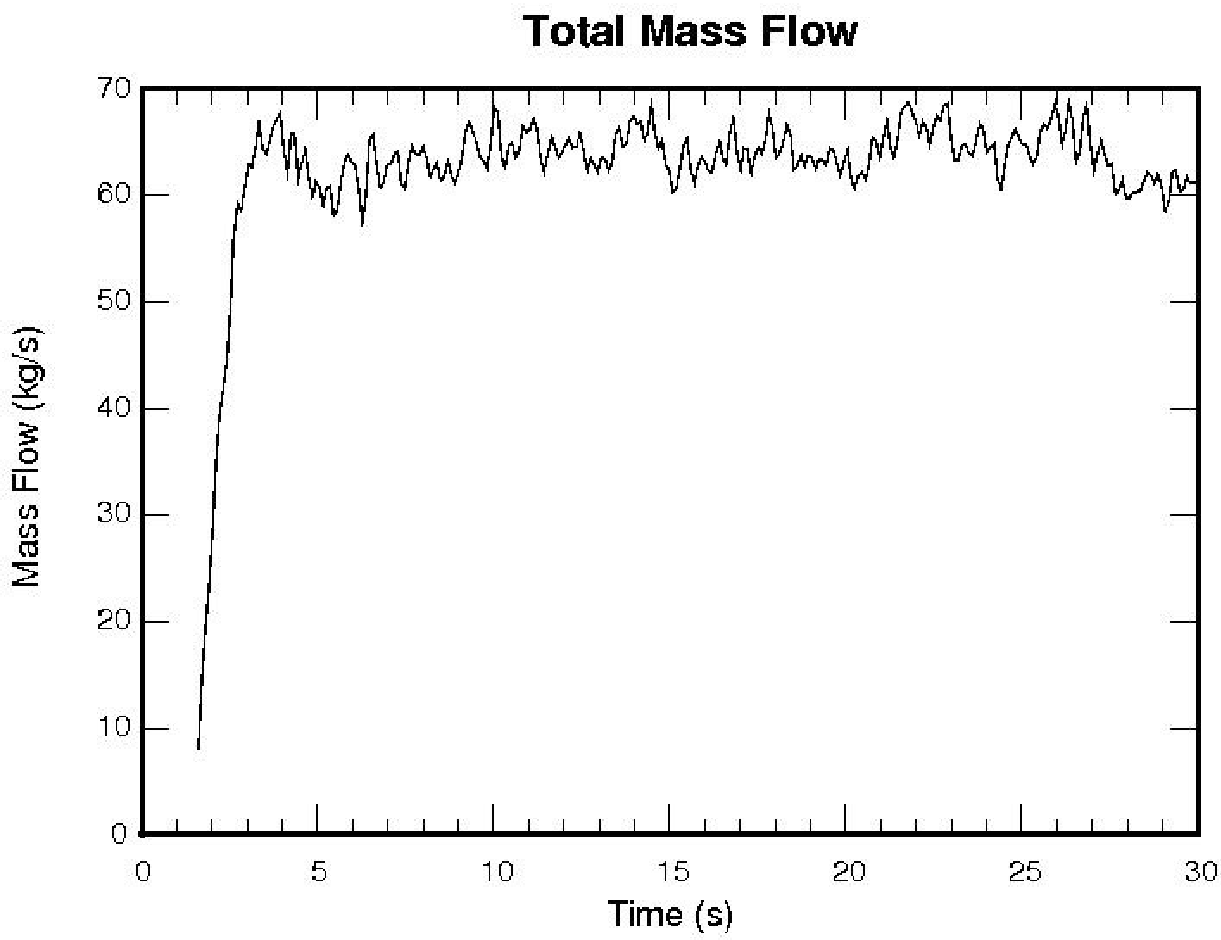


- 1.4" WC @ 57 ˚F => 7.3 psig tip pressure
- 12-16 Km/hr (8-10 mph) crosswind
- ~30% flame height reduction
- Minimum flame tilt (~8°)

Model Used to Predict Flare Air Demand

- Based upon total mass flow through a 3.6 m square plane located 20 m height above flare
- Predicted flame height is 17 m above ground (15 m flame length)
- Predicted 60 kg/sec air demand by flame
- Total air inflow through all walls around computational domain is 100 kg/sec

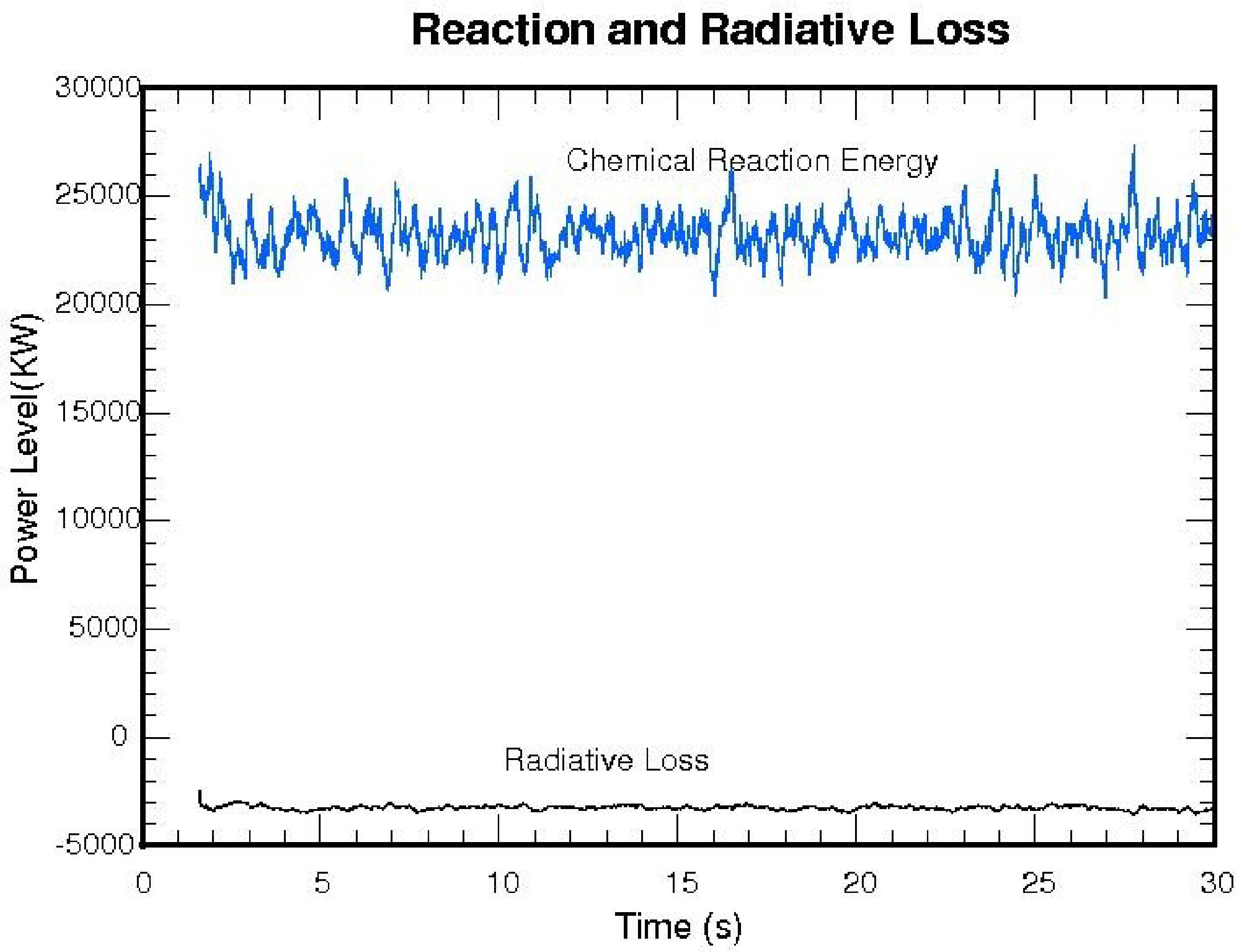
Predicted Air Demand vs. Time



Model Used to Predict Flame Radiation Loss

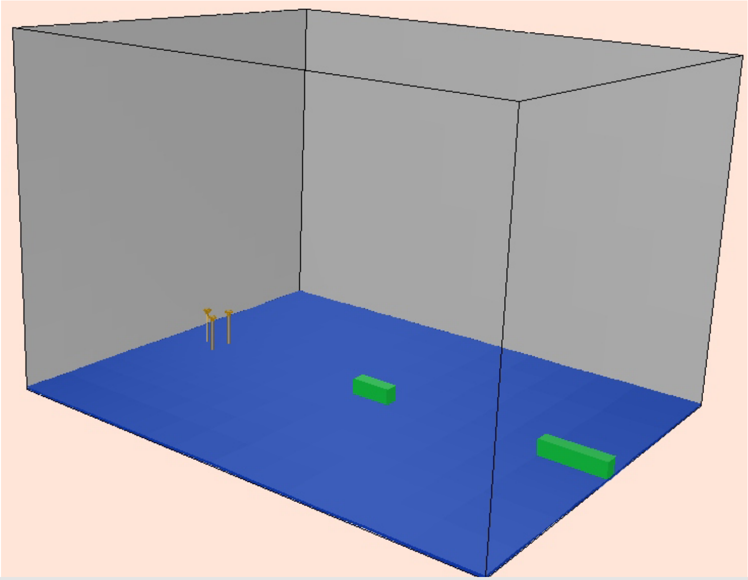
- Radiation Depends upon Soot, CO_2, H_2O Concentration in Flame and Flame Size
- Soot yield from hydrocarbon assumed constant for propane
- Predicted approx 3 MW radiation loss from 22 MW Flame or 13.6% heat loss

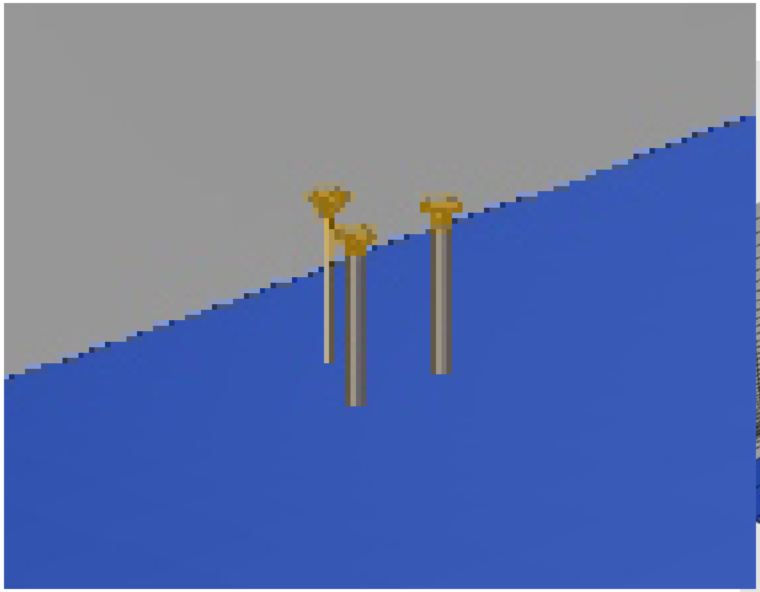
Predicted Flame Energy Balance

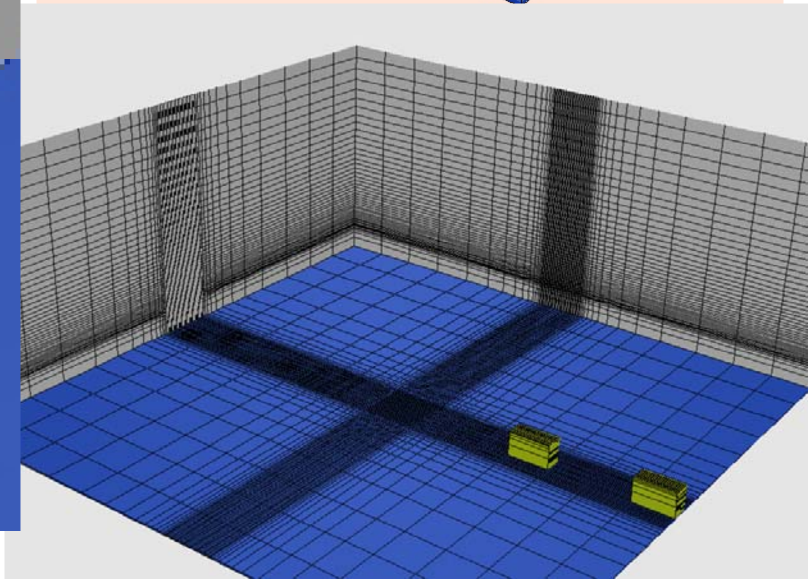


Three-burner Mesh

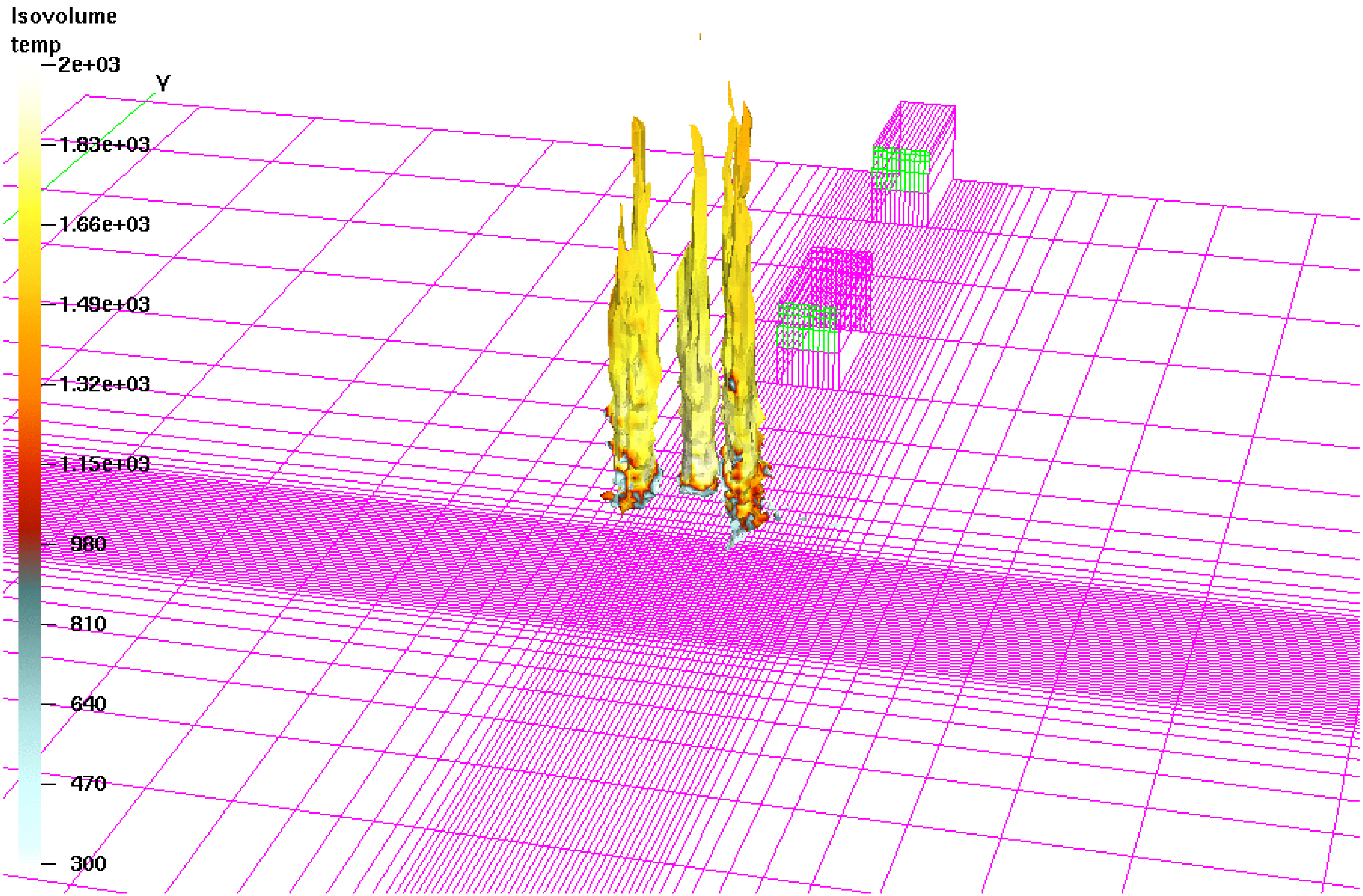
- Rectangular cells
- Domain size is 30 m X 35 m X 25 m
- Local refinement near burner tips and radiation meters
- 188,000 computational cells







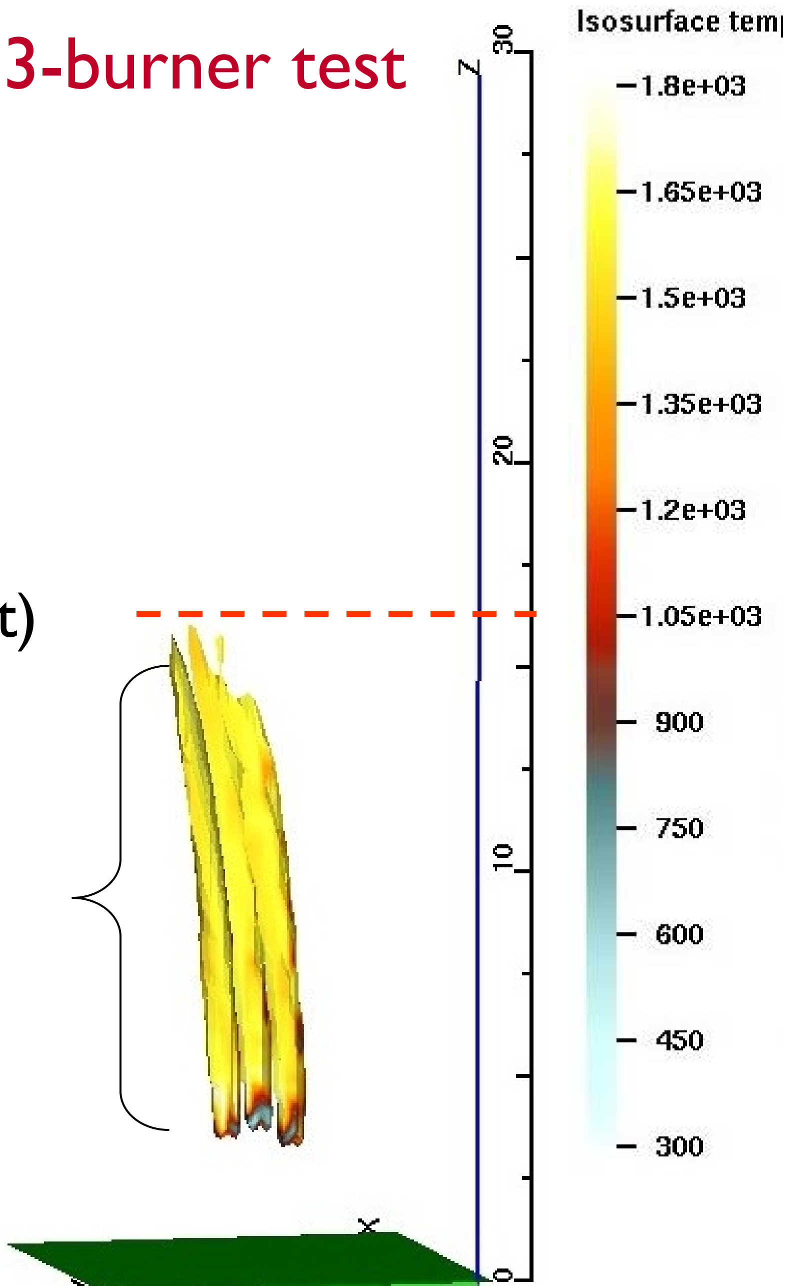
Predicted 3-burner flare with radiation monitors



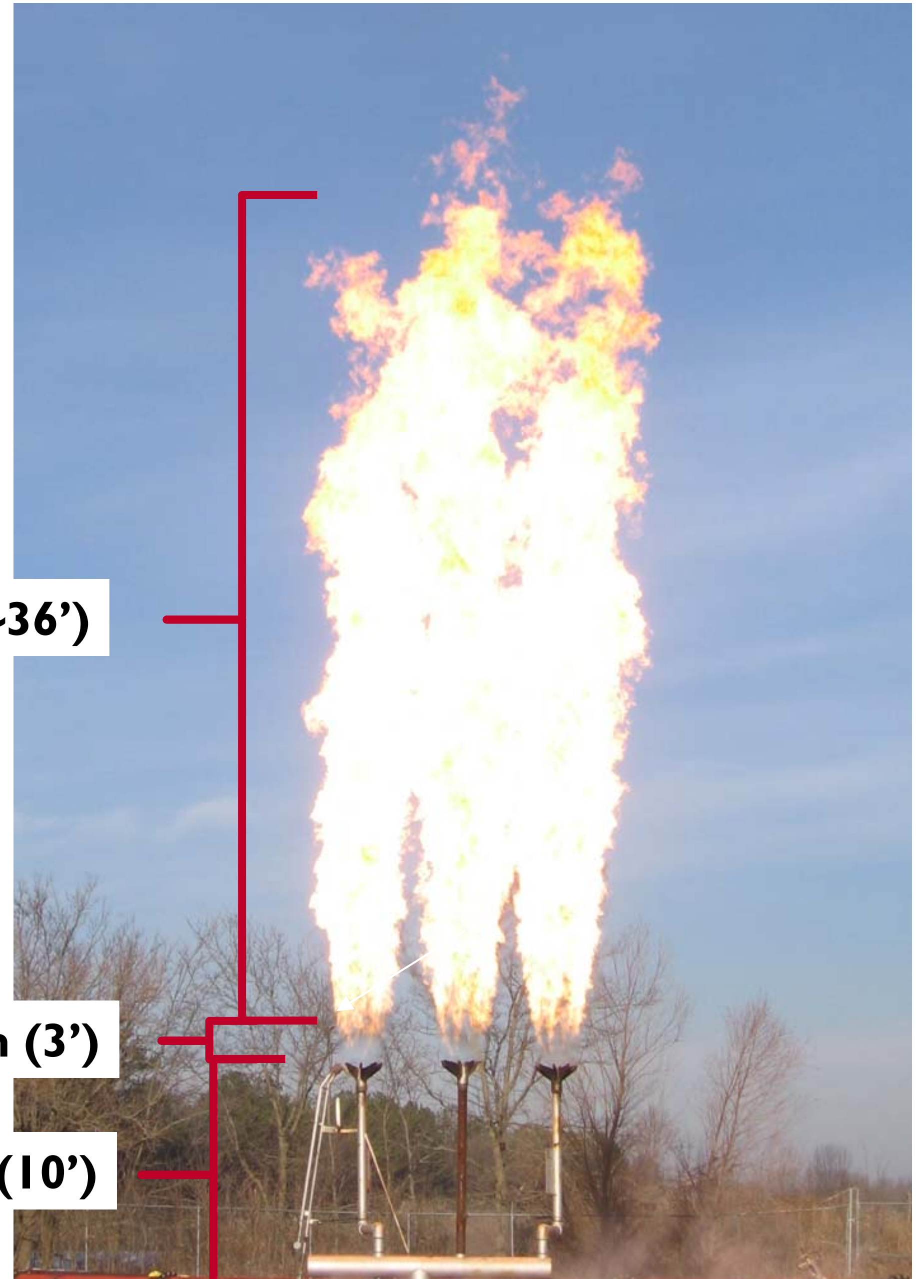
Predicted Flame Height for 3-burner test

~16 m (52 ft)

12 m (39 ft)



3-burner Flare Test with Ethylene (no wind)



Flame height ~11 m (~36')

Non-luminous region ~1 m (3')

Tip Height~3 m (10')

Predicted Radiation from 3-Burner Flare after Modifications to Account for Ground and Atmospheric Attenuation Effects

Radiation Issues Accounted for in Prediction:

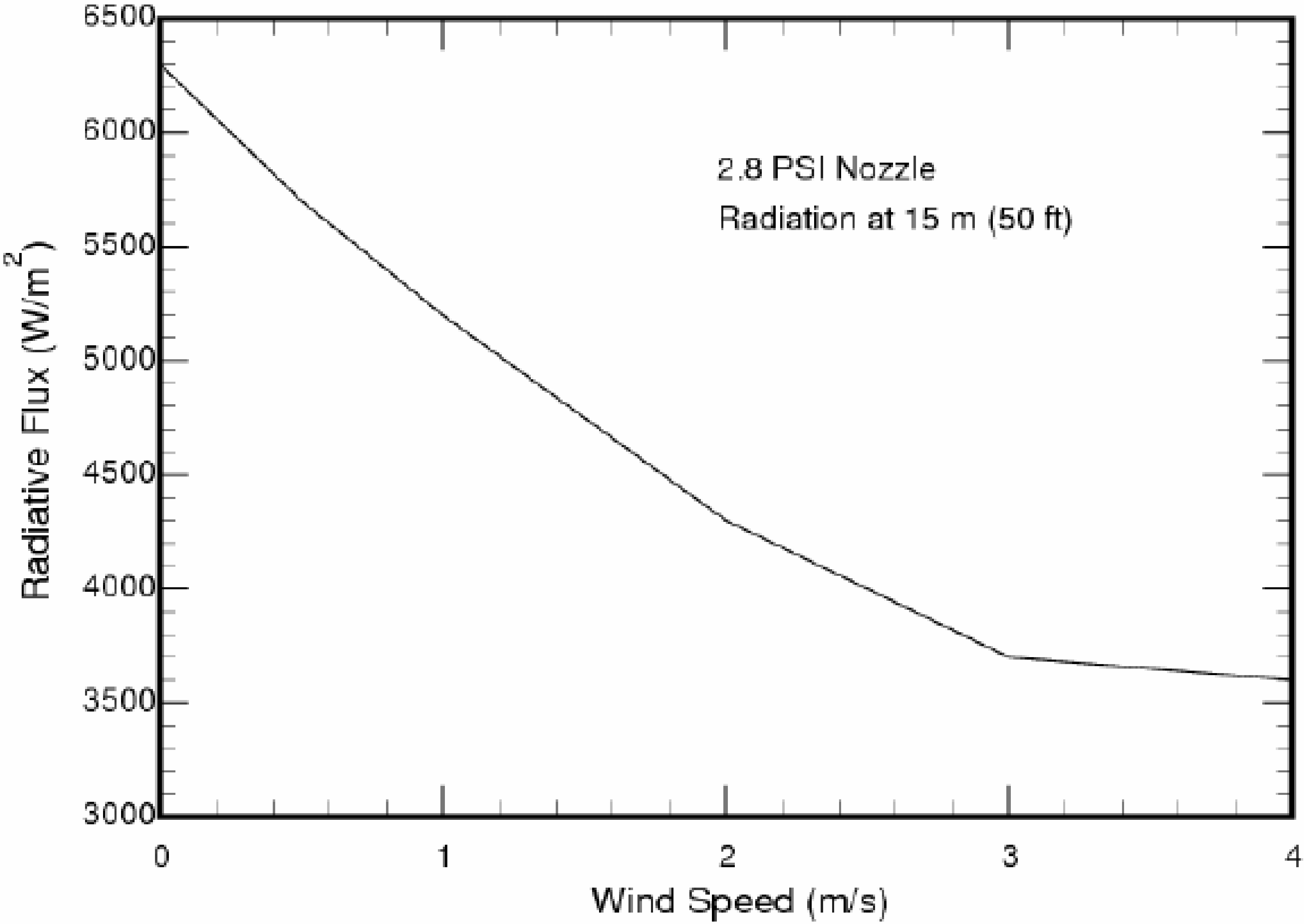
1. Ground re-radiating and reflecting incident radiation from flame to flux meters
   - Assumed ground $\varepsilon = \alpha = 1$; allow ground to heat to steady state temperature
2. Atmospheric attenuation of radiation from flame to flux meters
   - Model uses ambient/source temperatures with H_2O/ CO_2 absorption

WALL (from plan view perspective)	Left Wall ISIS-3D Output" W/m^2	Right Wall ISIS-3D Output W/m^2	Bottom Wall ISIS-3D Output W/m^2	Flame Optical Thickness
PEAK FLOW				
Initial Radiation	78,000	63,000	108,000	0.275
Radiation Modification	61,000	35,000	NA	
SUSTAINED FLOW				
Initial Radiation	15,000	15,000	35,000	0.28
Radiation Modification	6,600	6,600	NA	

3-Burner Flare Radiation Predictions Compared to Experimental Data

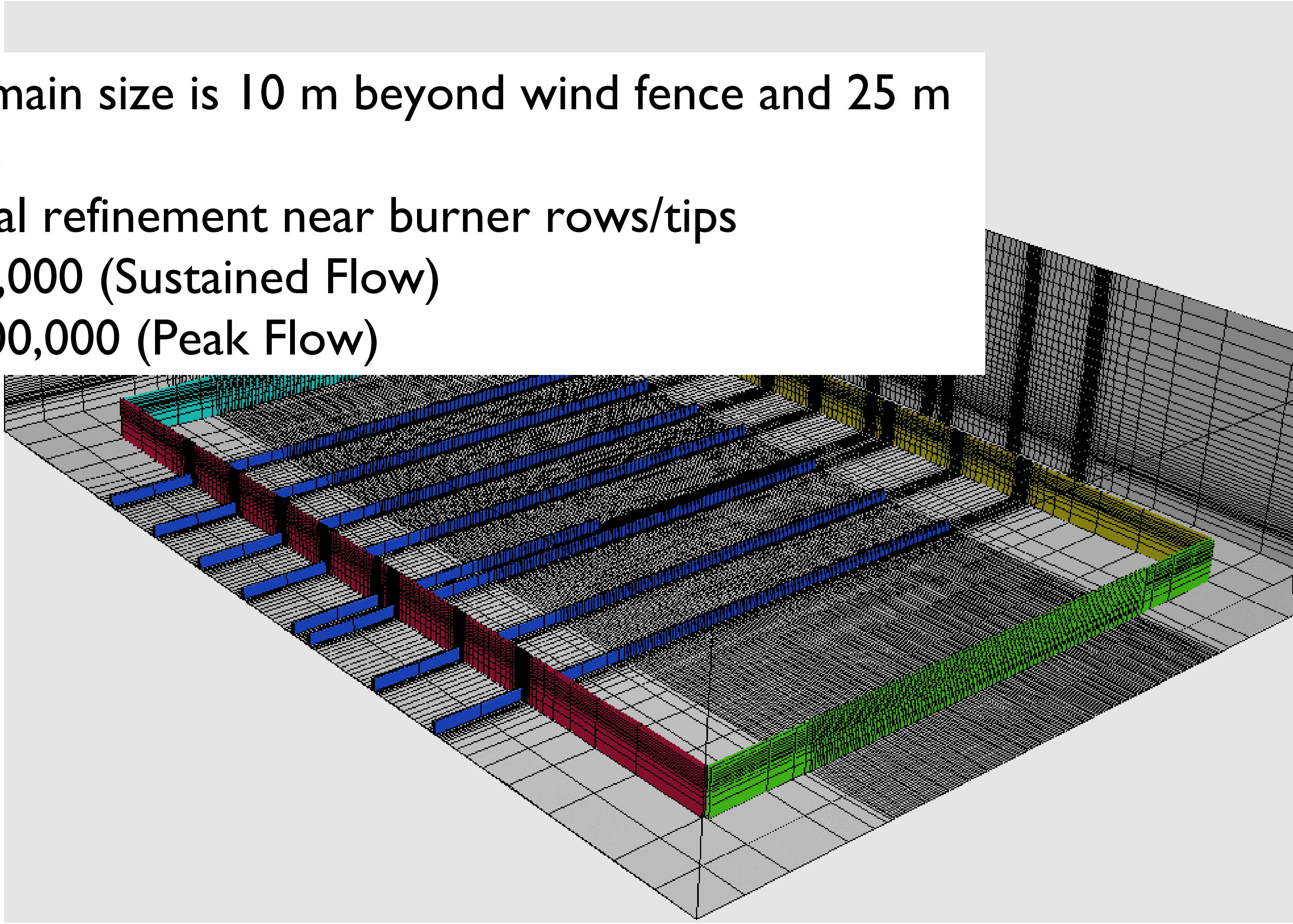
Tip Size	Position (m)	Burner Pressure (psi)	Total Predicted Radiation (W/m^2)	Measured Radiation (W/m^2)	Difference (%)
3	15	2.8	2700	3344	-20.0 %
3	15	7.3	4750	4803	-1.0 %
3	15	11.4	6150	6192	-0.7 %
3	30	2.8	650	671	-3.0 %
3	30	7.3	1350	1184	+14.0 %
3	30	11.4	1650	1532	+8.0 %
4	15	2.8	4325	6371	-32.0 %
4	15	7.3	8050	8192	-2.0 %
4	15	11.4	10000	9536	+5.0 %
4	30	2.8	1150	1513	-23.0 %
4	30	7.3	2580	2464	+5.0 %
4	30	11.4	3250	2747	+18.0 %

Wind Effect on Radiative Flux from 3-burner C_2H_4 flare at 15 m

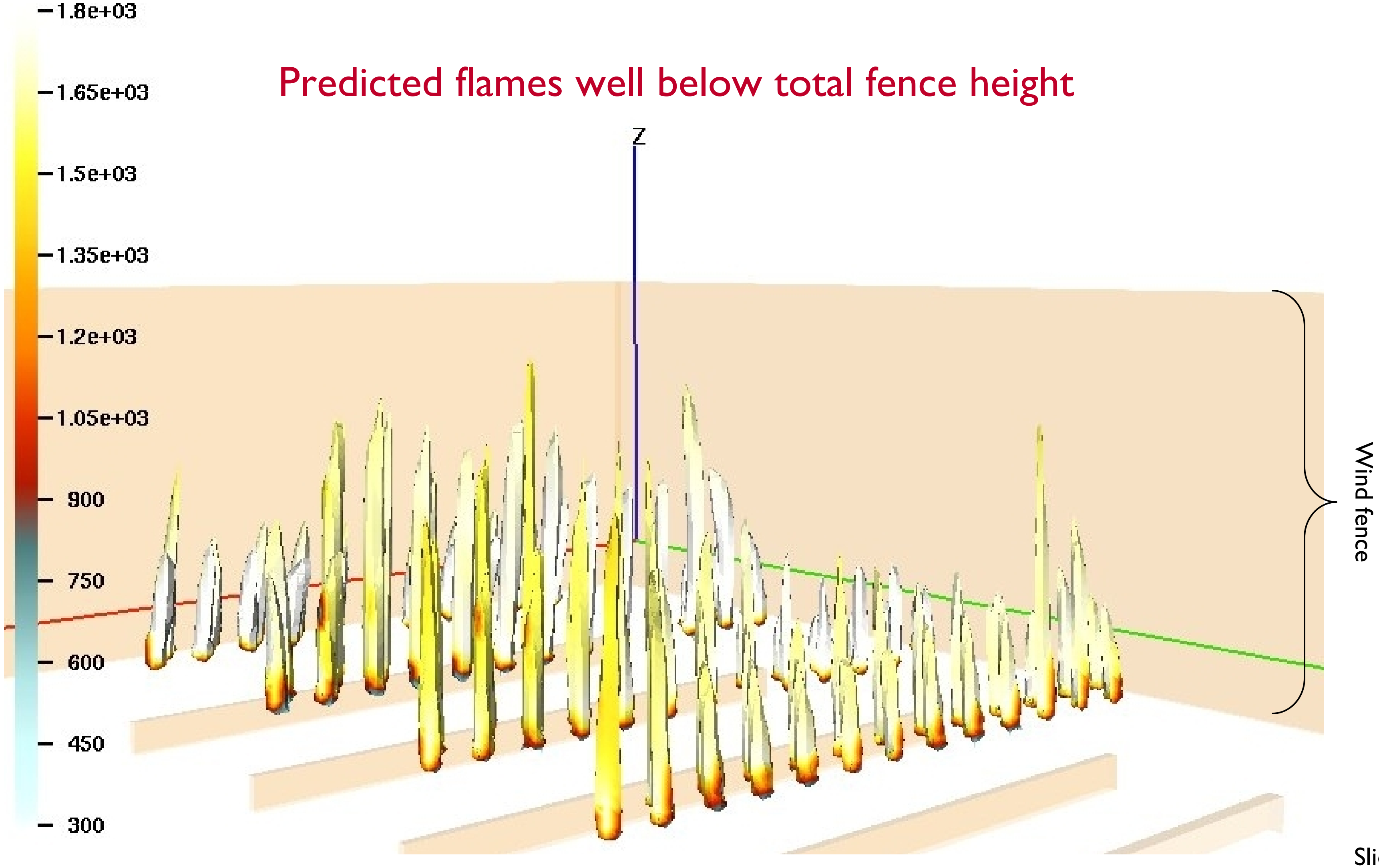


Full Field Flare Grid

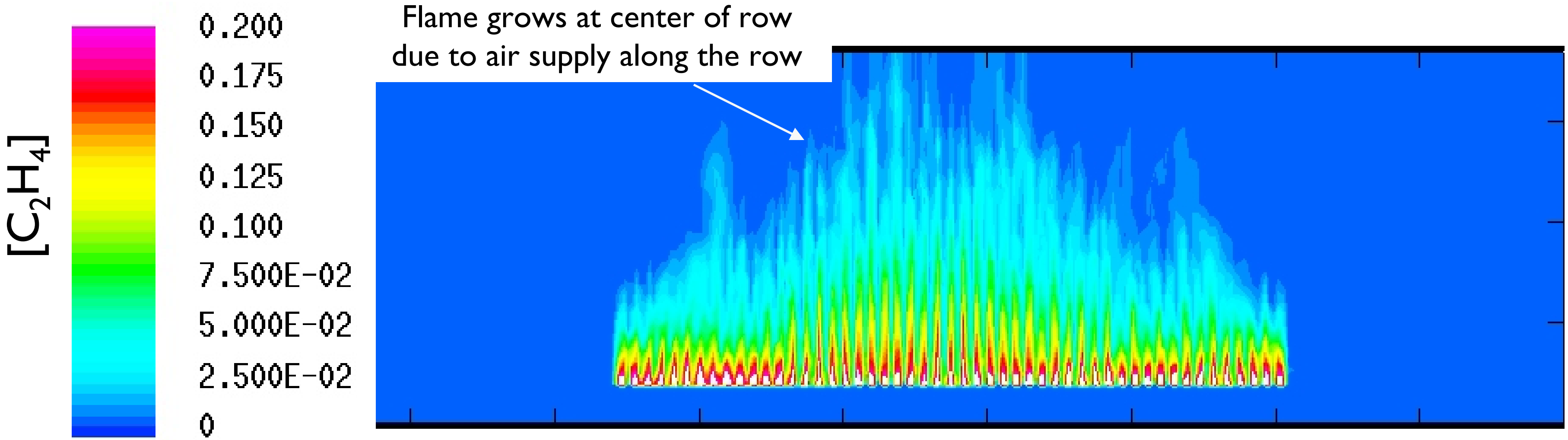
- Domain size is 10 m beyond wind fence and 25 m high
- Local refinement near burner rows/tips
- 700,000 (Sustained Flow)
- 1,200,000 (Peak Flow)



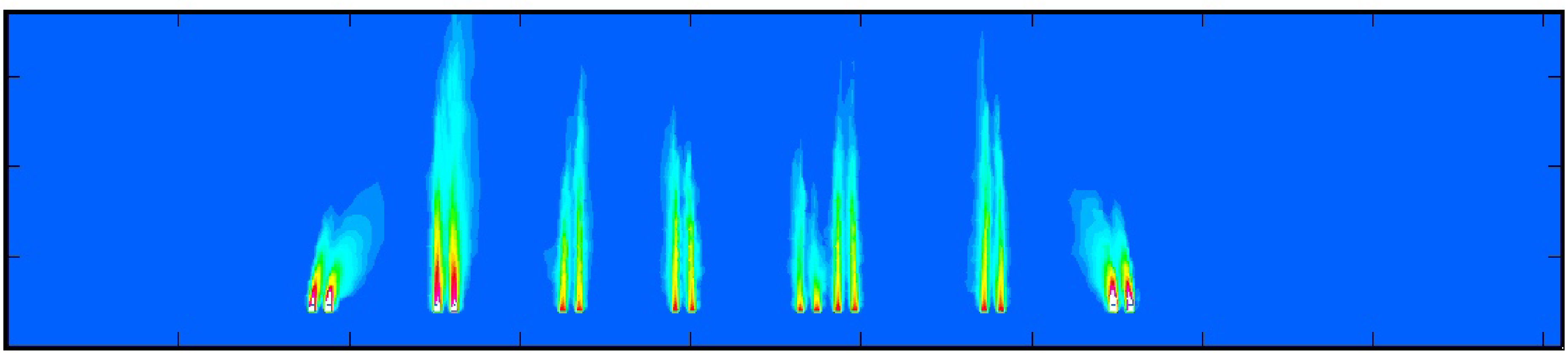
[C_2H_4] Iso-surface for 1/4 Symmetry Peak Flow-no wind condition



Max [C_2H_4] along line of sight for peak flow case



Side view along row showing flame elongation toward center of row



End view of flame height for each row and impact of inflow on outer rows

Summary of all Air/Fuel Requirements for "no-wind" conditions

Case Description	Evaluation Plane Area (m^2)	Total Air Flow (kg/s)	Fuel Flow (kg/s)	Air/Fuel Mass Ratio
1 Burner Propane	14.63	60	0.46	130
1 Burner (Tip 3) Ethylene	13.26	52	0.94	55
3 Burner (Tip 3 - 7.3PSI) Ethylene	36	134	2.88	47
3 Burner (Tip 3 - 11.4PSI) Ethylene	36	144	3.84	38
3 Burner (Tip 4 - 7.3PSI) Ethylene	36	150	4.26	35
3 Burner (Tip 4 - 11.4PSI) Ethylene	36	160	5.79	28
Full Field Peak Flow Ethylene	3226	9700	262.3	37
Full Field Sustained Flow Mixed Gas	1843	4800	93.6	51.3

Conclusions

- ISIS-3D Model:
  > Single-burner model used 110,000 cells
  > Three-burner model used 188,000 cells
  > Full-field model used 700,000 cells (Sustained Flow);
  > 1,200,000 cell (Peak Flow)
  > Combustion chemistry for propane, ethylene, mixed gas
- Modeled flame shape/size for 3 fuels for single and three burner tests
- Predictions compared to data from 12 tests (2 tip sizes, 3 operating pressures, 2 radiation sample locations)
- Predicted "*reasonable*" estimates of radiation heat transfer and air demand for low profile flare
  > Air/fuel ratios range from 28 to 47 for 3-burner test and from 37 (Peak Flow Case) to 51 (Sustained Flow Case)
- Calibrated flare model applied to full-flare field to estimate:
  > Air demand for specified tip/row spacing
  > Radiation load on wind fence for nominal and peak flow cases
  > Expected flame height and smoke production for nominal and peak flow cases