THREE DIMENSIONAL FLAME PROPAGATION ABOVE LIQUID FUEL POOLS

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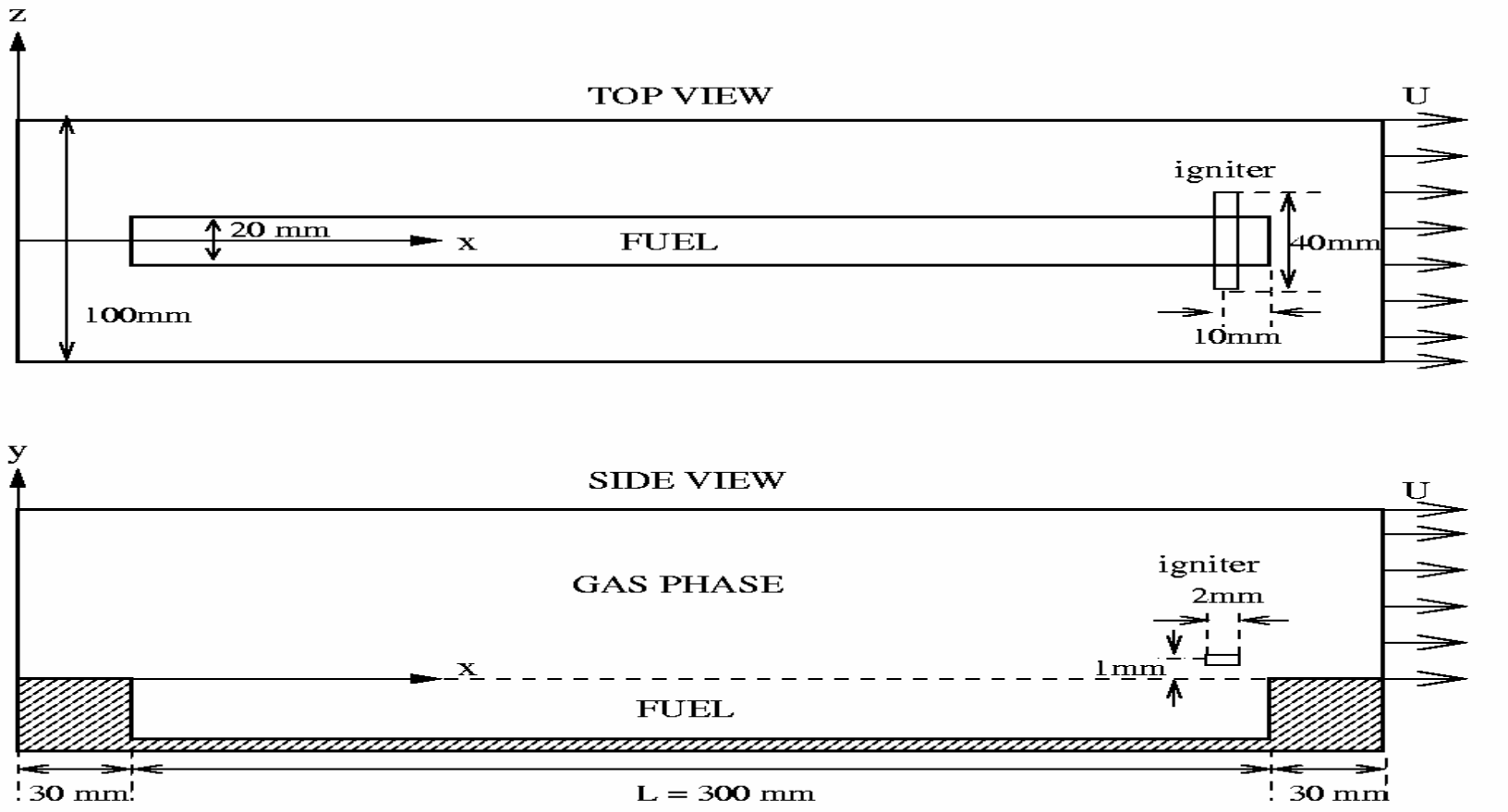
OBJECTIVES

- Examine 3-D effects for ignition and flame spread above a finite-width liquid-fuel pool. Determine pool-edge effects, flame curvature, lateral air and liquid motion.
- Determine flame speed, domains and frequency of pulsation, domains of uniform spread, flammability limits, and nature and size of recirculation zone.
- Analyze the influences of initial pool temperature, opposed-flow forced velocity, temperature-dependent surface tension, gas buoyancy, and liquid buoyancy.
- Guide and interpret drop-tower and sounding-rocket experiments of H. Ross and F. Miller of NASA Glenn.

CONFIGURATION



3-D Liquid Fuel Pool in wind tunnel floor. Igniter modelled as a hot gas pocket with a linear temperature increase to 1700 K in 0.01s.

ASSUMPTIONS & CONDITIONS

- Unsteady, three-dimensional Newtonian flow.
- Laminar, viscous, multicomponent, reacting gas flow.
- Laminar, viscous, single-component, incompressible, vaporizing-liquid flow.
- Fourier heat conduction and Fickian mass diffusion.
- Variable properties.
- One-step chemical kinetics for alcohol fuel.
- Linear relationship between surface tension coefficient and surface temperature.
- Symmetry about the central vertical plane.
- Controlled air mass flow.
- A vaporized fuel layer develops over the fuel before the igniter is activated. The layer extends over the pool edge.

DIFFUSION MODELS

- **Old Diffusion Model**

$$D_j = \frac{\mu}{\rho Sc} \qquad j = 1, ..., N$$

where μ viscosity, ρ density, Sc Schmidt number, N number of species.

- **New Diffusion Model**

$$D_j = \frac{1 - Y_j}{\sum_{i \neq j}^{N} X_i / D_{ij}}$$

where D_{ij} is the binary diffusion coefficients

$$D_{ij} = \frac{0.00266 T^{3/2}}{P M^{1/2} \sigma_{i,j} \Omega_D}$$

$$M_{ij} = \frac{2 M_i M_j}{M_i + M_j} \qquad \sigma_{ij} = \frac{\sigma_i + \sigma_j}{2}$$

Ω_D is a function of kT/ε, M is molecular mass of species. ε and σ as the characteristic Lennard-Jones energy and length, respectively.

NUMERICAL METHOD

- The numerical method uses the SIMPLE algorithm modified for second-order accuracy and to include an approximate factorization method to perform sub-iterations within each implicit time step.
- Only half of the wind tunnel is considered due to symmetry.
- A non-uniform mesh clustered grid points in the flame region is used.
- The grid lines are redistributed to concentrate in the flame region every time the flame front has moved 1 mm.
- Linear interpolation is used to map each dependent variable from the old to the new grid.

CASES INVESTIGATED

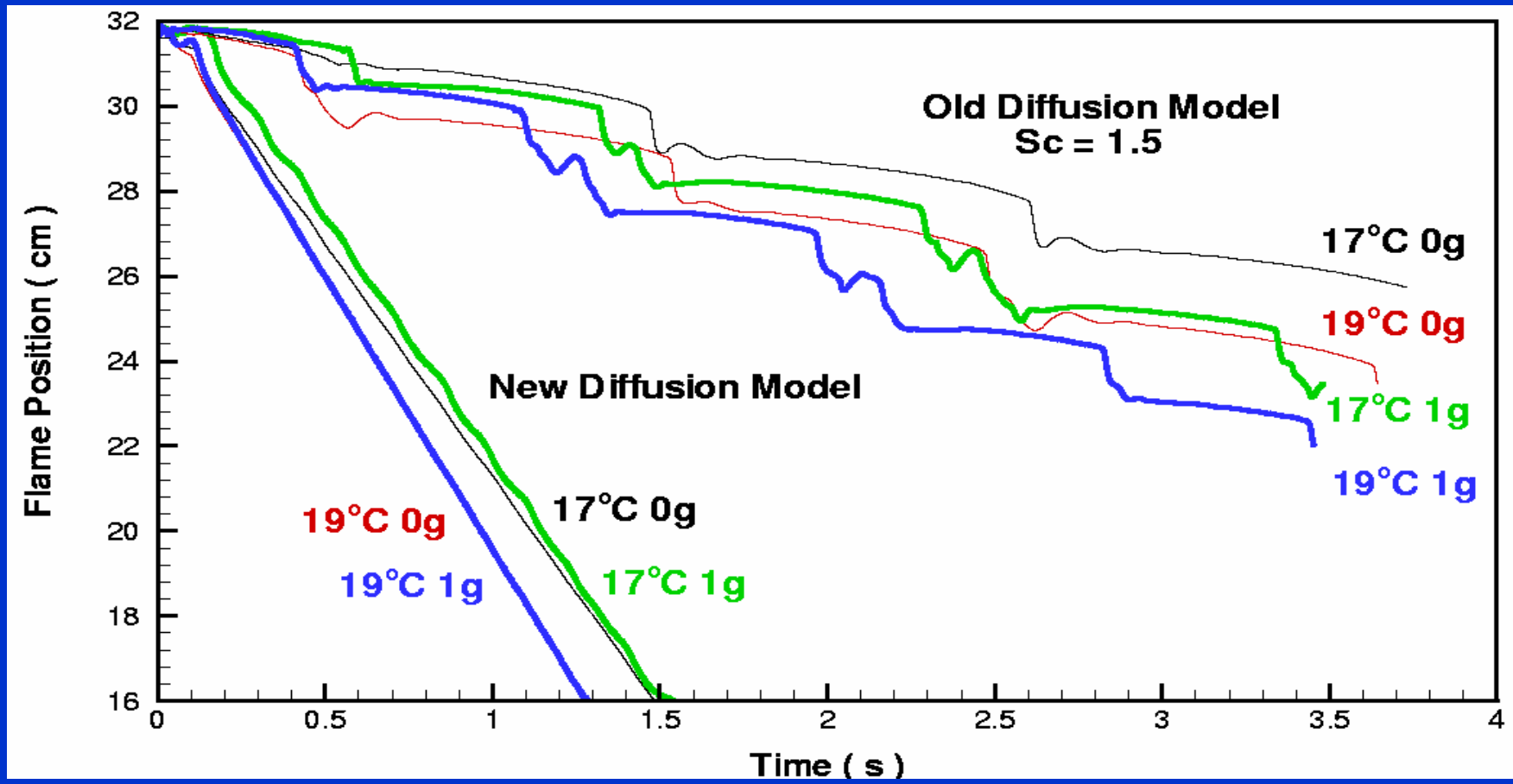
3D, 0-g, Hot Tunnel Floor (Insulated)
3D, 1-g, Hot Tunnel Floor (Insulated)

3D, 0-g, Cold Tunnel Floor (Heat Sink)
3D, 1-g, Cold Tunnel Floor (Heat Sink)

2D , 0-g
2D, 1-g

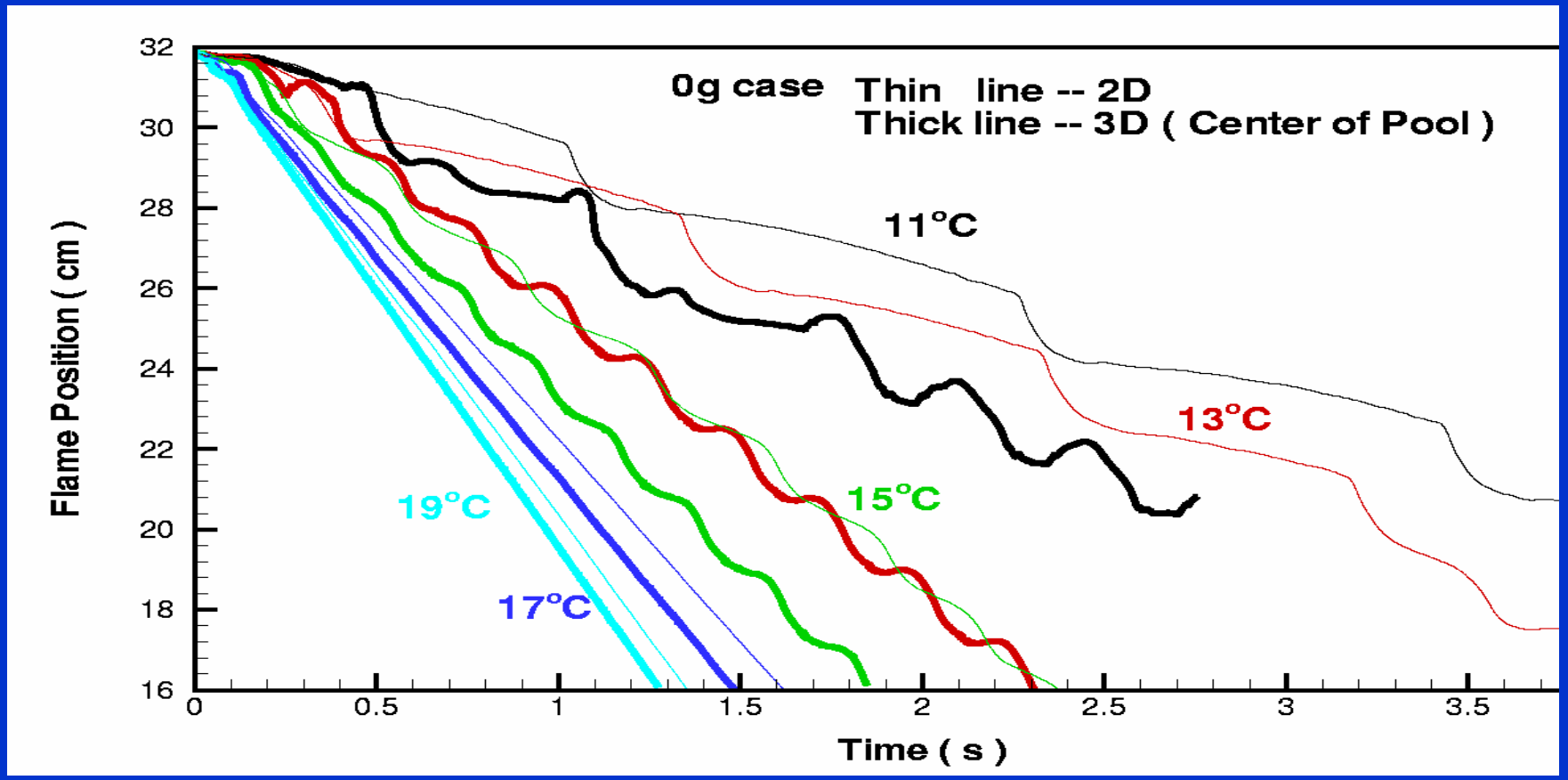
Other Parameters: Propanol Fuel, Opposed air velocity = 30cm/s; Pool depth = 2mm; Initial Fuel Temperature = 11 to 19^{o}C.

EFFECT OF DIFFUSION MODEL



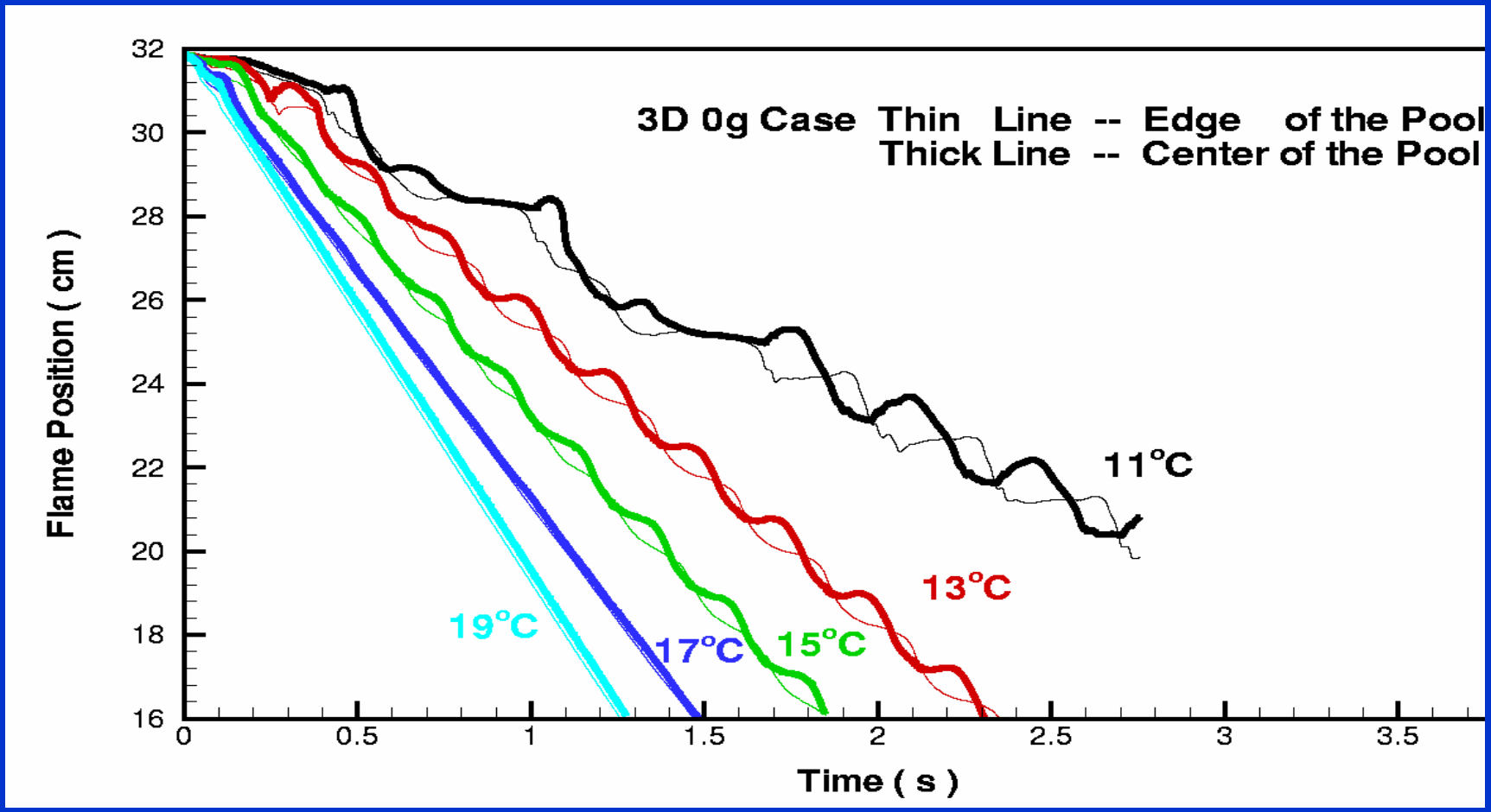
30 cm/s opposed flow. Flame speed and frequency increase with pool temperature. Pulsations occur at both 1-g and 0-g. Fast oxygen diffusion accounts for increased flame speed.

3D VS. 2D COMPARISON
Hot Tunnel Floor , 0-g, 30cm/s



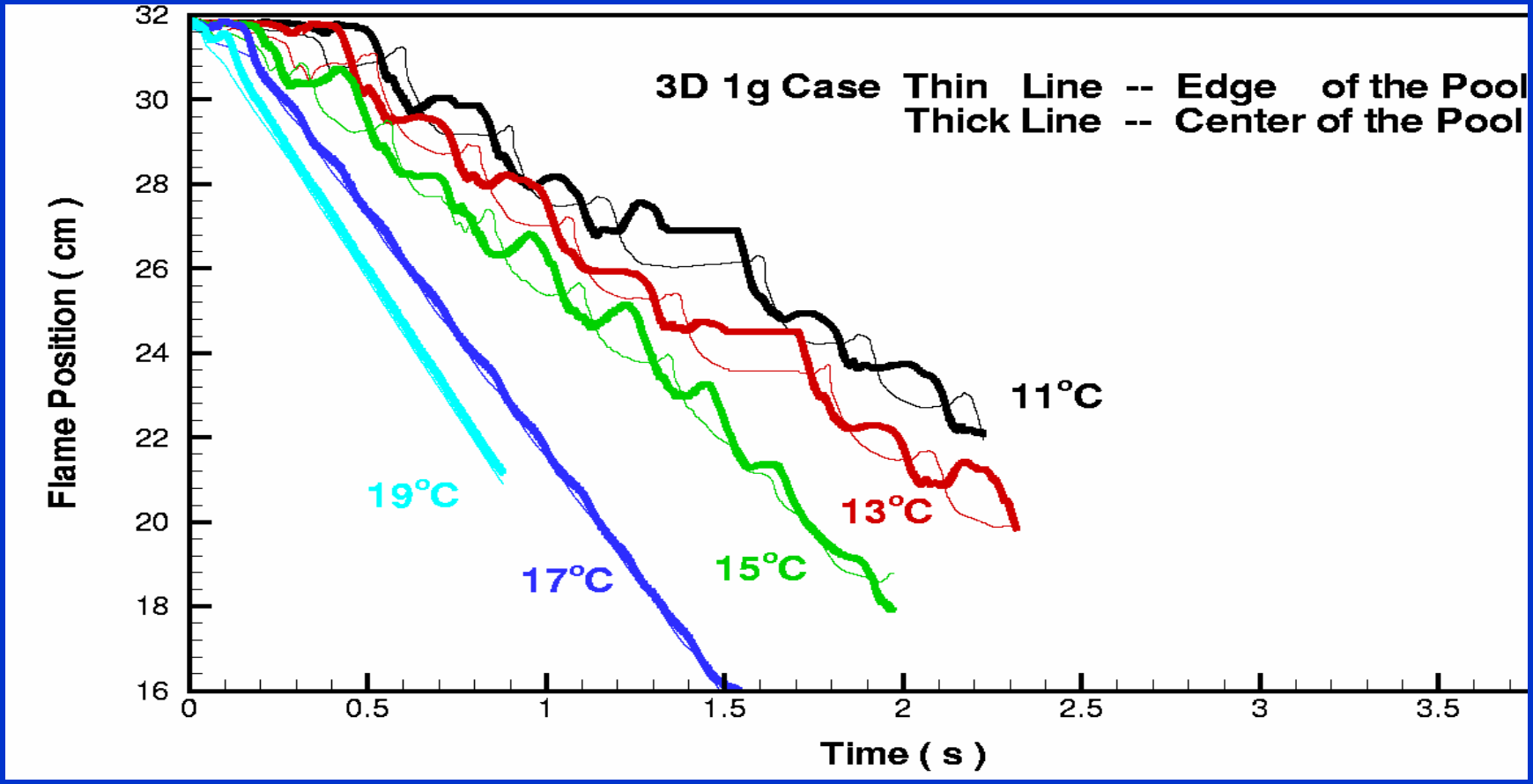
Flame speed and frequency increase with pool temperature.

FLAME POSITION VS. TIME
Hot Tunnel Floor, 0-g, 30cm/s



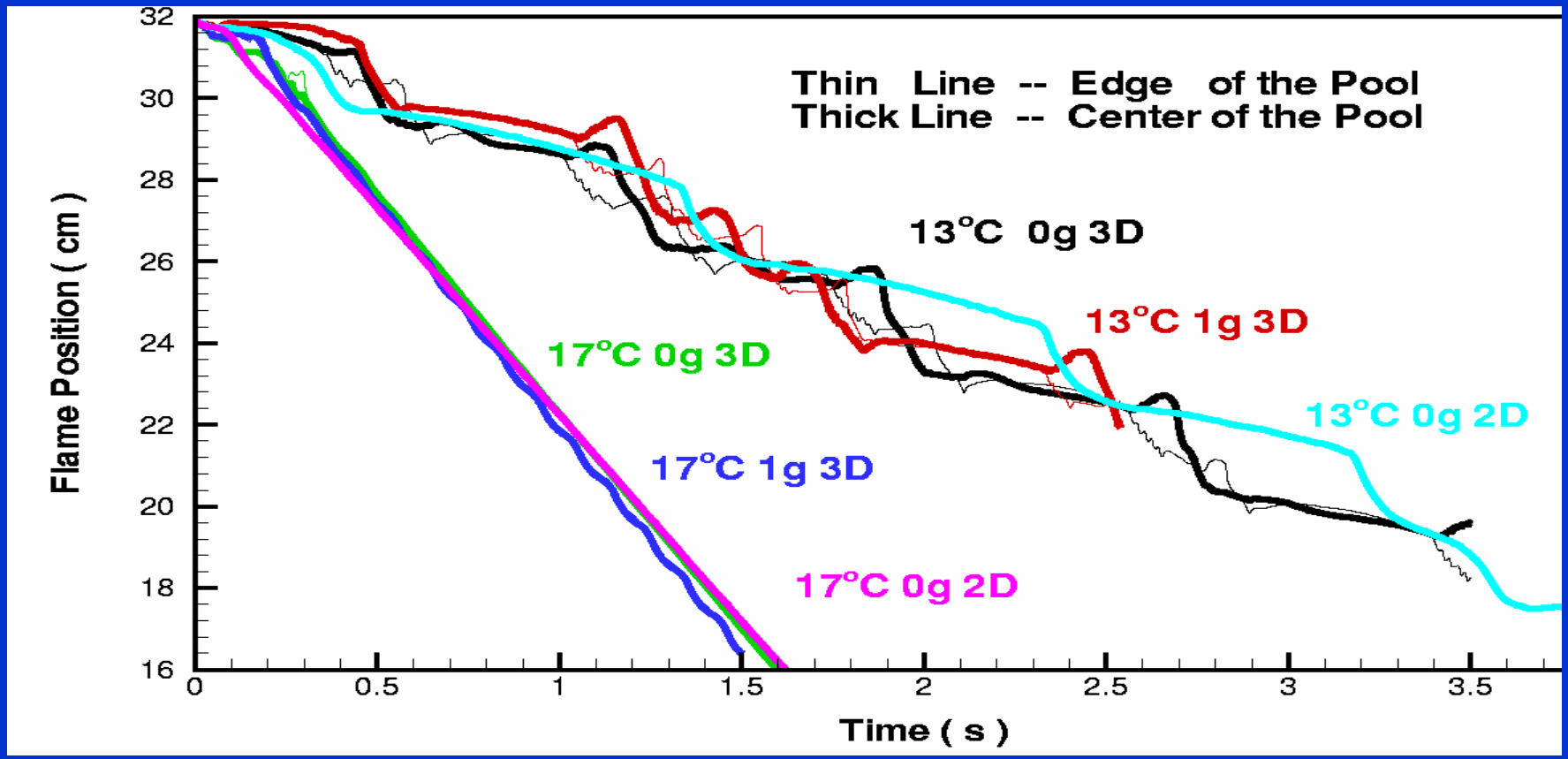
Flame speed and frequency increase with pool temperature.

FLAME POSITION VS. TIME
Hot Tunnel Floor, 1-g, 30cm/s



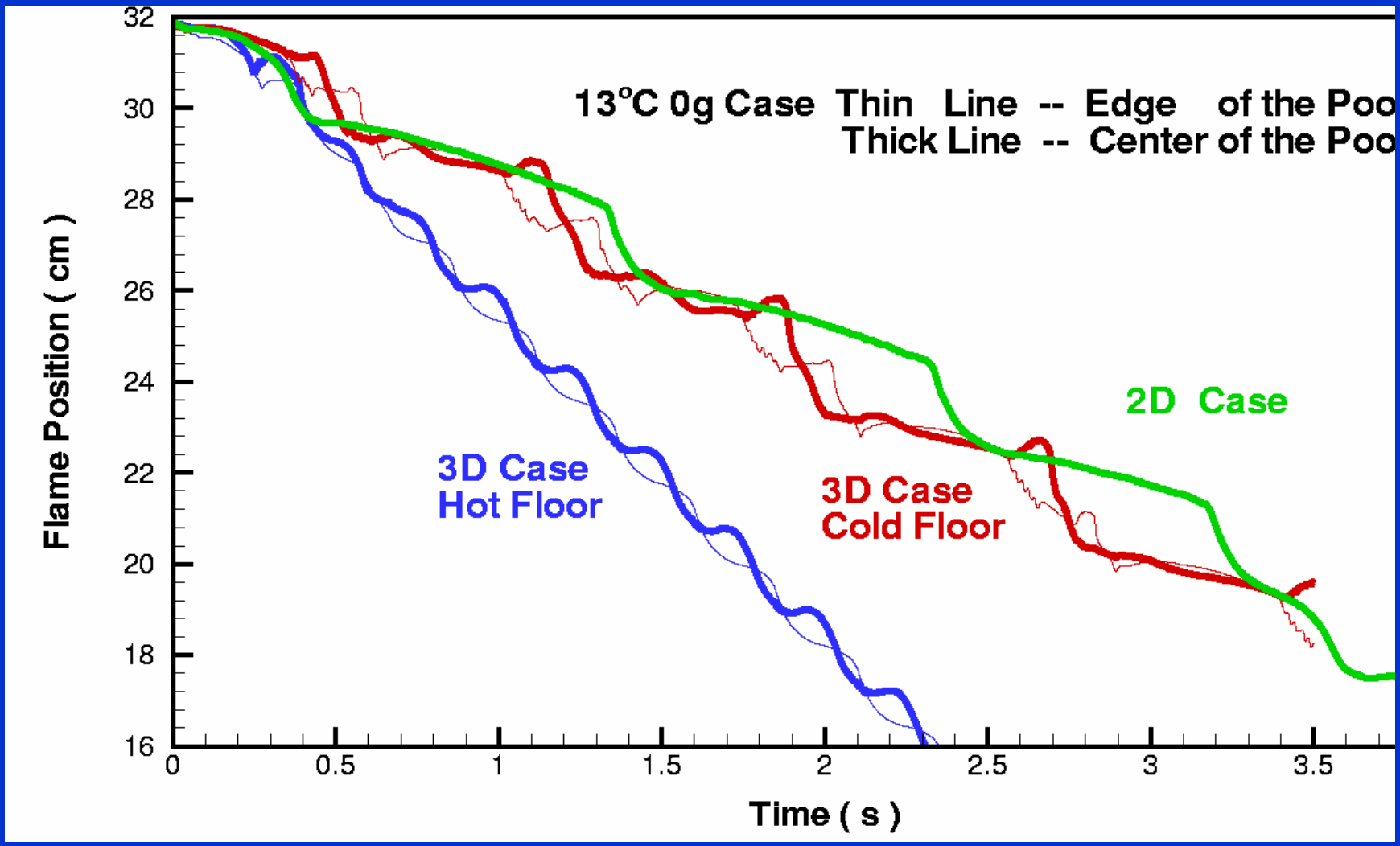
Flame speed and frequency increase with pool temperature. Pulsations occur at both 1-g and 0-g.

FLAME POSITION VS. TIME
Cold Tunnel Floor, 0-g and 1-g



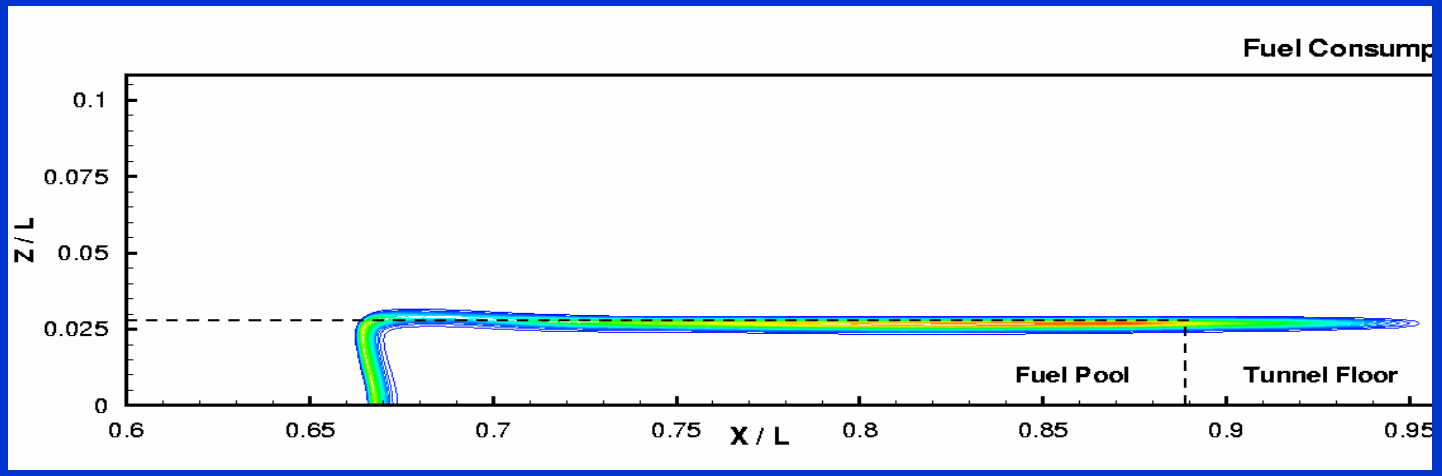
30 cm/s opposed flow. Flame speed and frequency increase with pool temperature. Pulsations occur at both 1-g and 0-g.

FLAME POSITION VS. TIME
Hot Floor, Cold Floor, and 2D

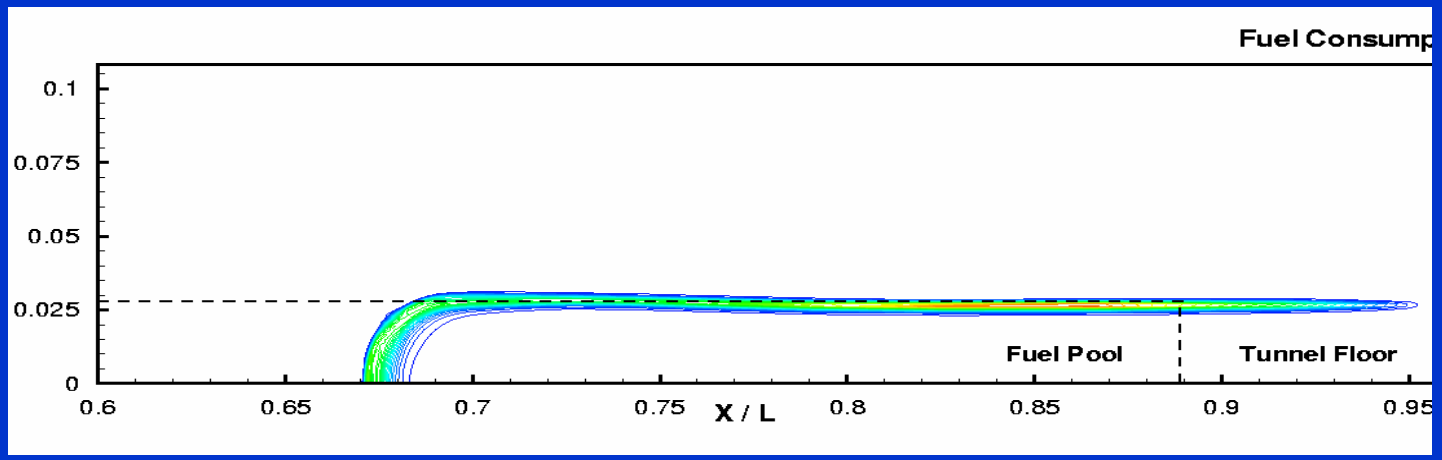


Top View – Fuel Consumption Rate

Slow phase, t=2s



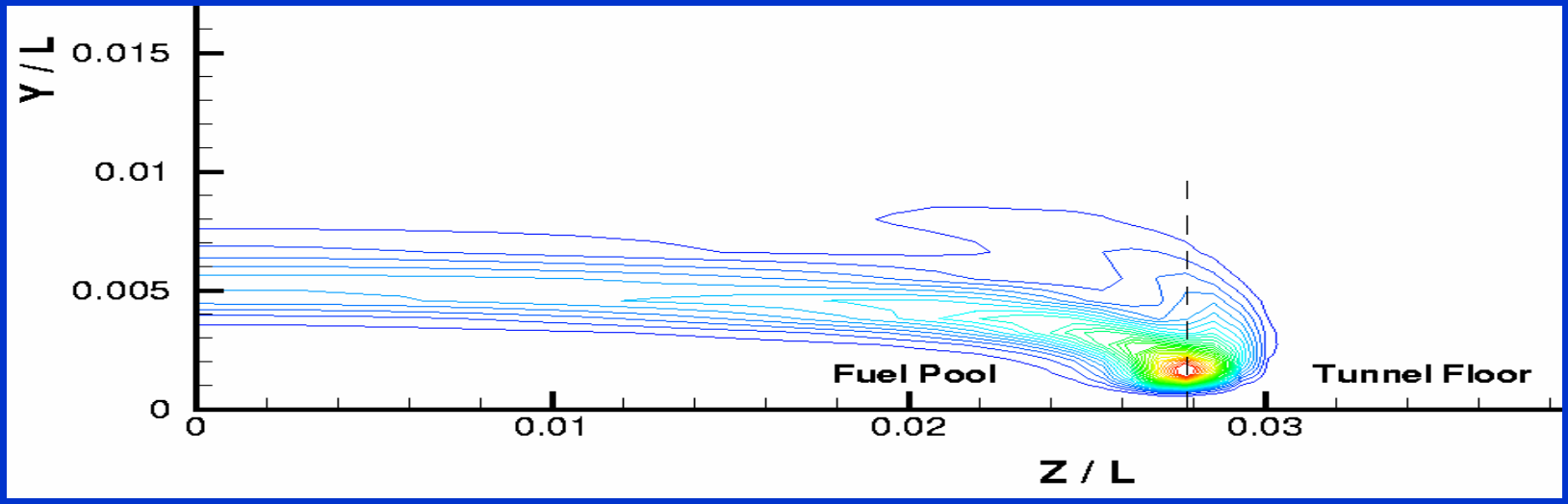
Fast phase, t=1.8s



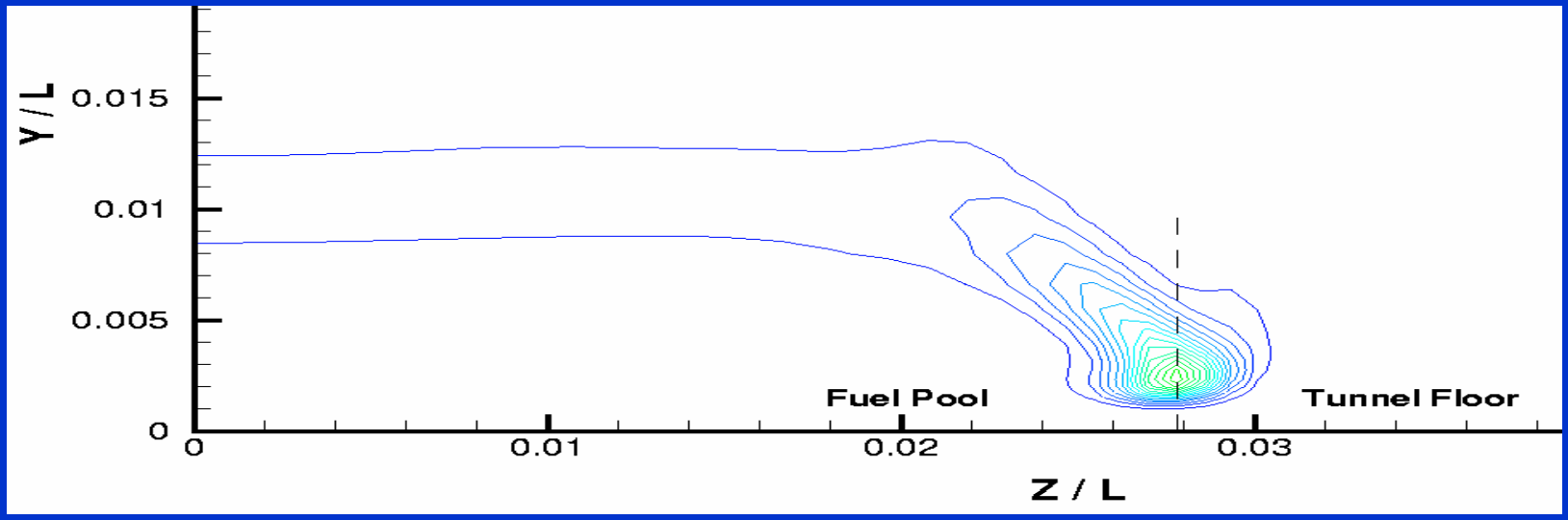
13 °C, pulsating case, 1-g, y=1mm. Cold Tunnel Floor. Flame tails lie along pool edge.

Cross View – Fuel Consumption Rate

x/L =.69

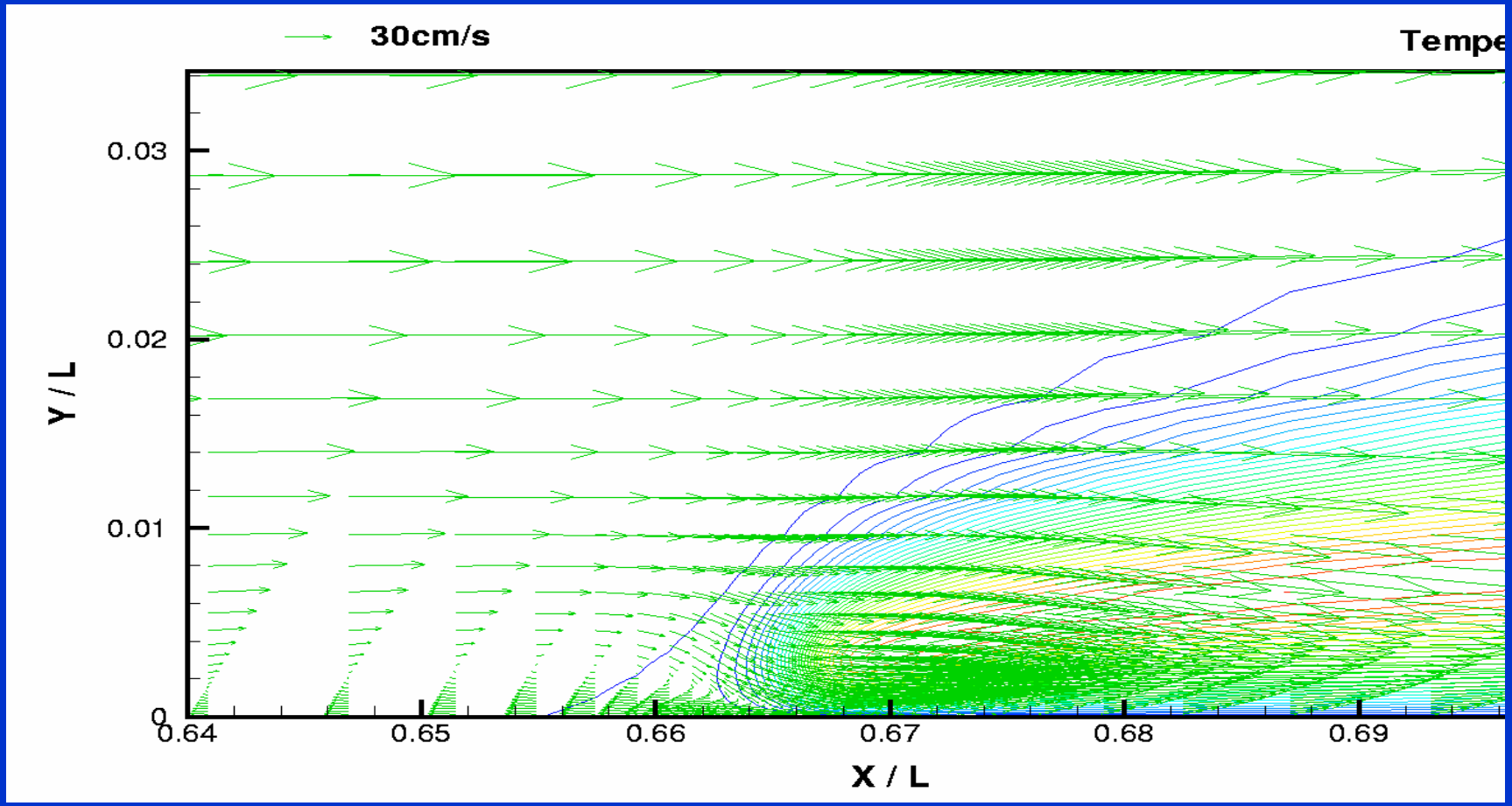


x/L =.75



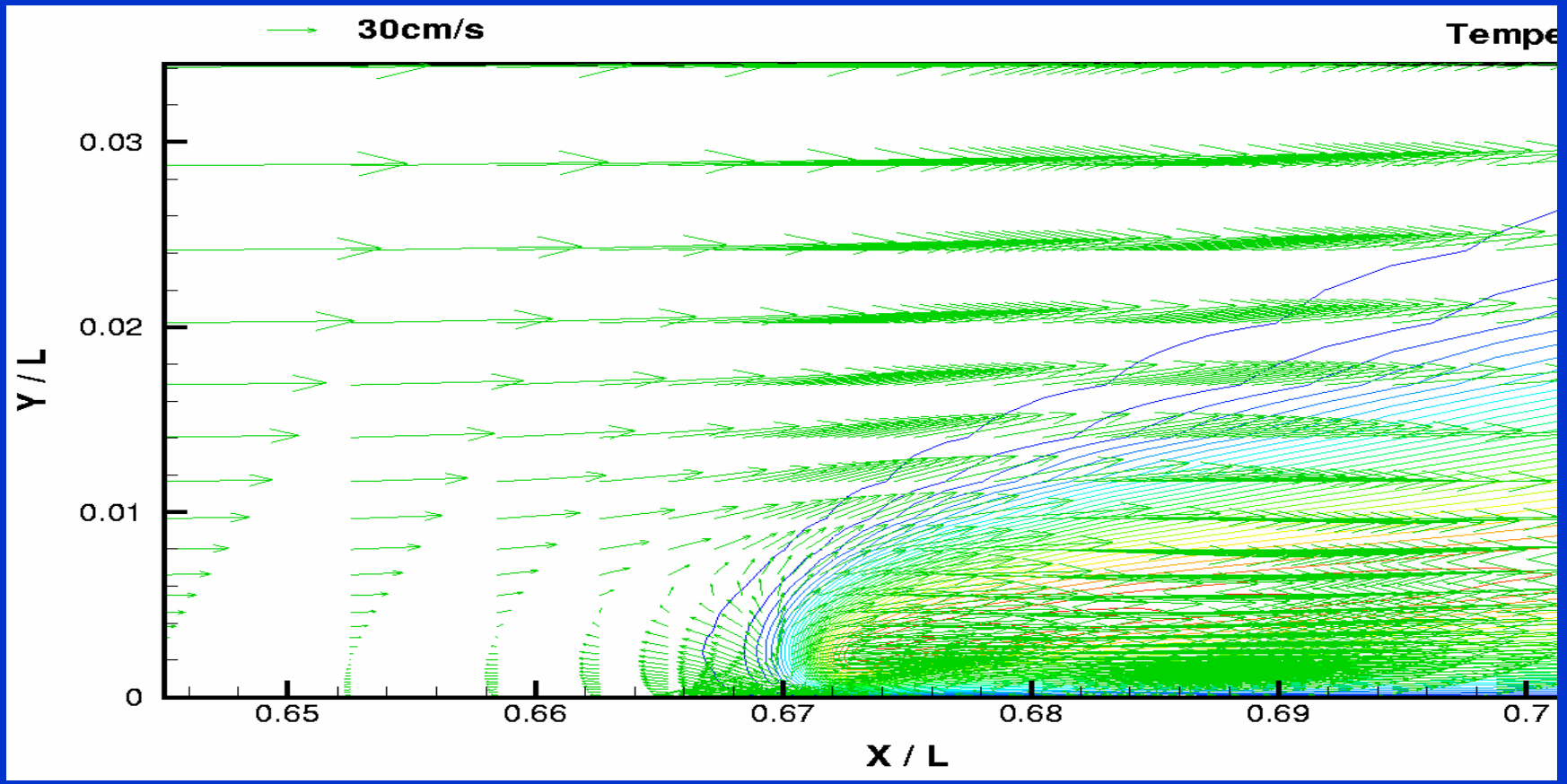
13 °C, pulsating case, 1-g, t=1.8s. Cold tunnel floor.

Temperature Contours & Velocity Vectors – Slow Flame Phase



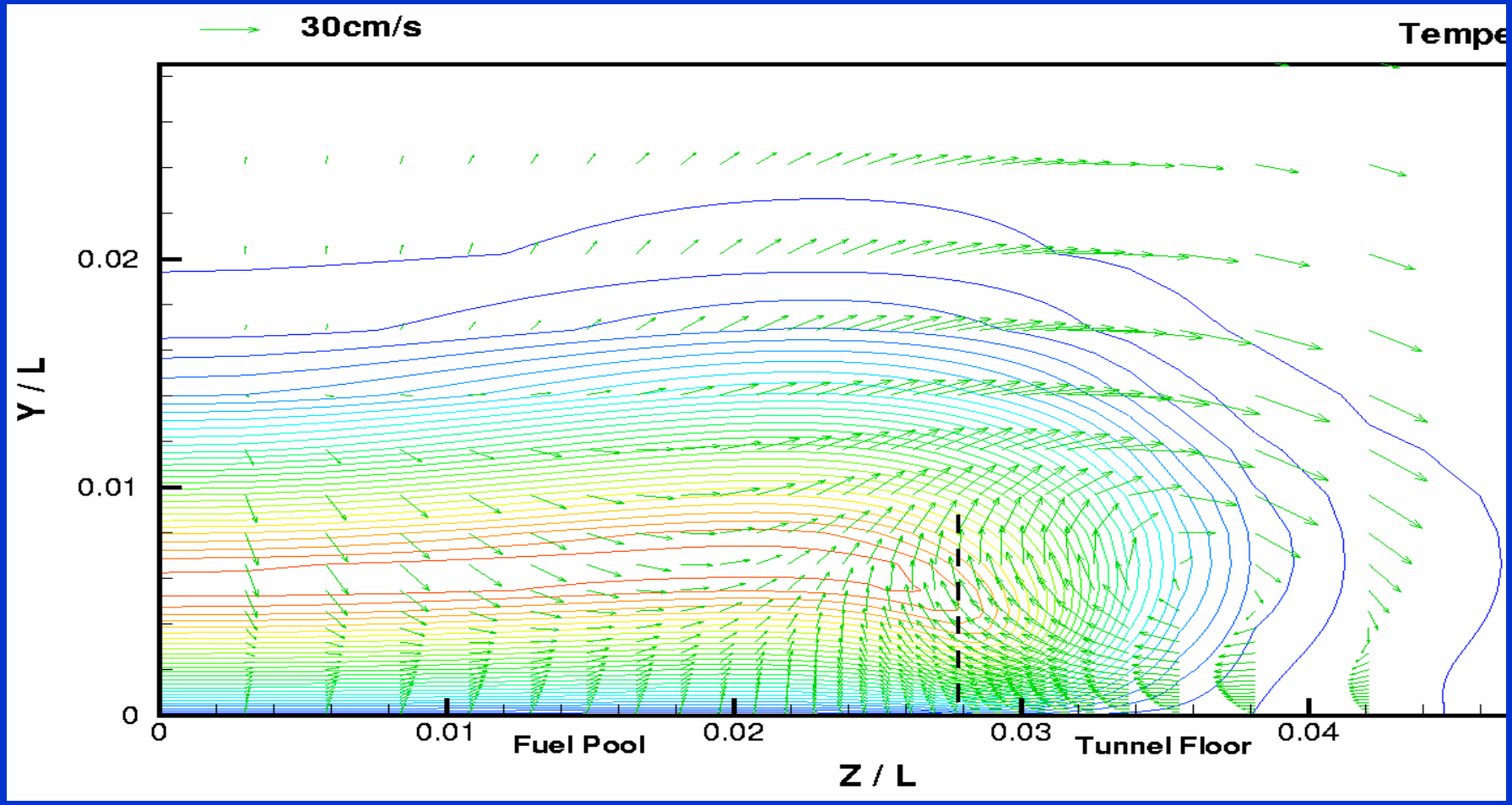
1g, t=2.0s, z=0. Recirculation zone forms allowing fuel vapor accumulation.

Temperature Contours & Velocity Vectors – Fast Flame Phase



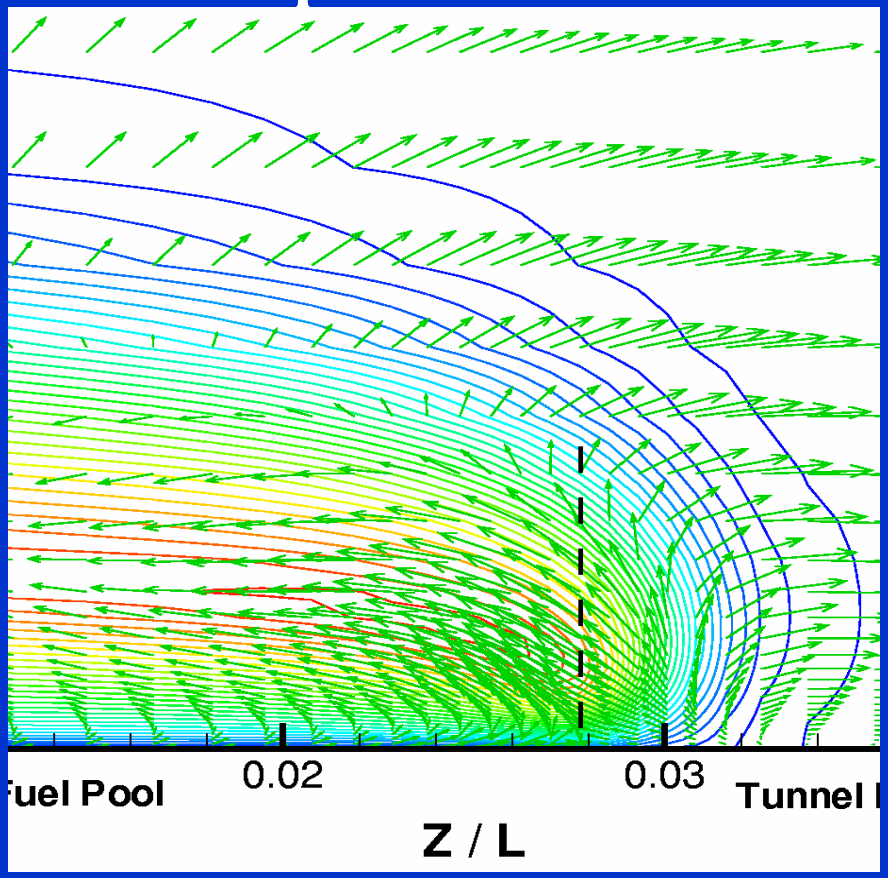
1g, t=1.8s, z=0. Less recirculation, more hot gas expansion.

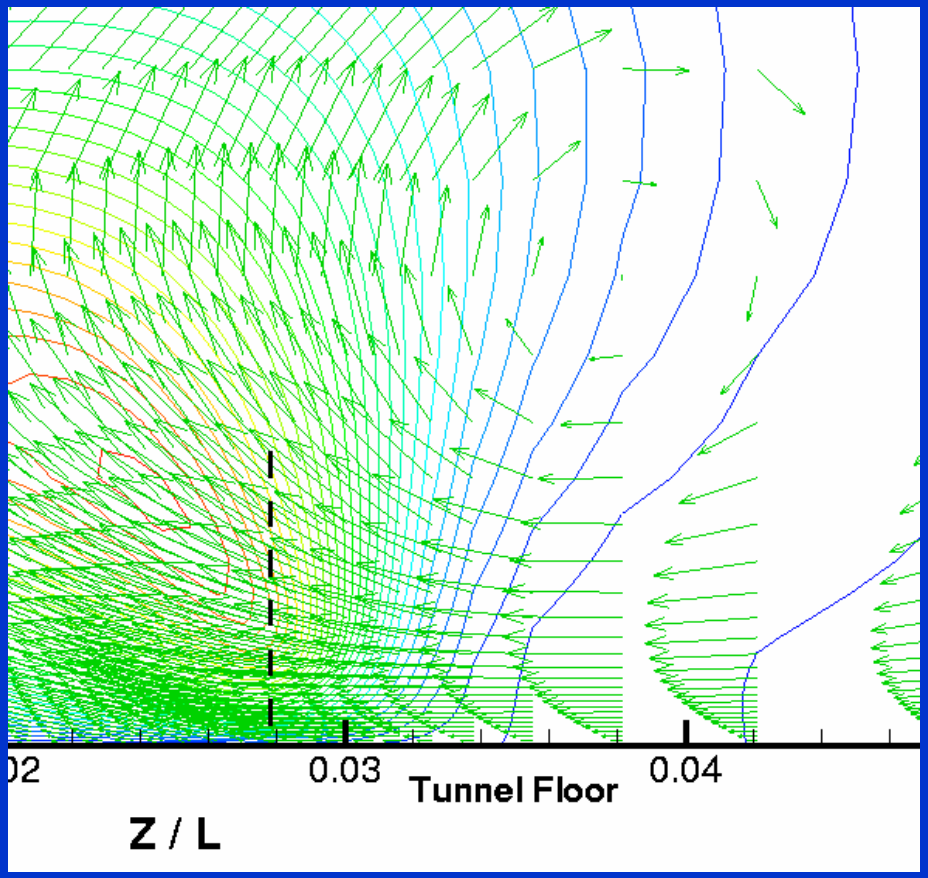
Cross View - Velocity Vectors & Temperature Contours – Slow Phase



13°C, 1g, t=2s. Cold floor. x/L= 0.68, recirculation.

Cross View - Velocity Vectors & Temperature Contours – Fast Phase

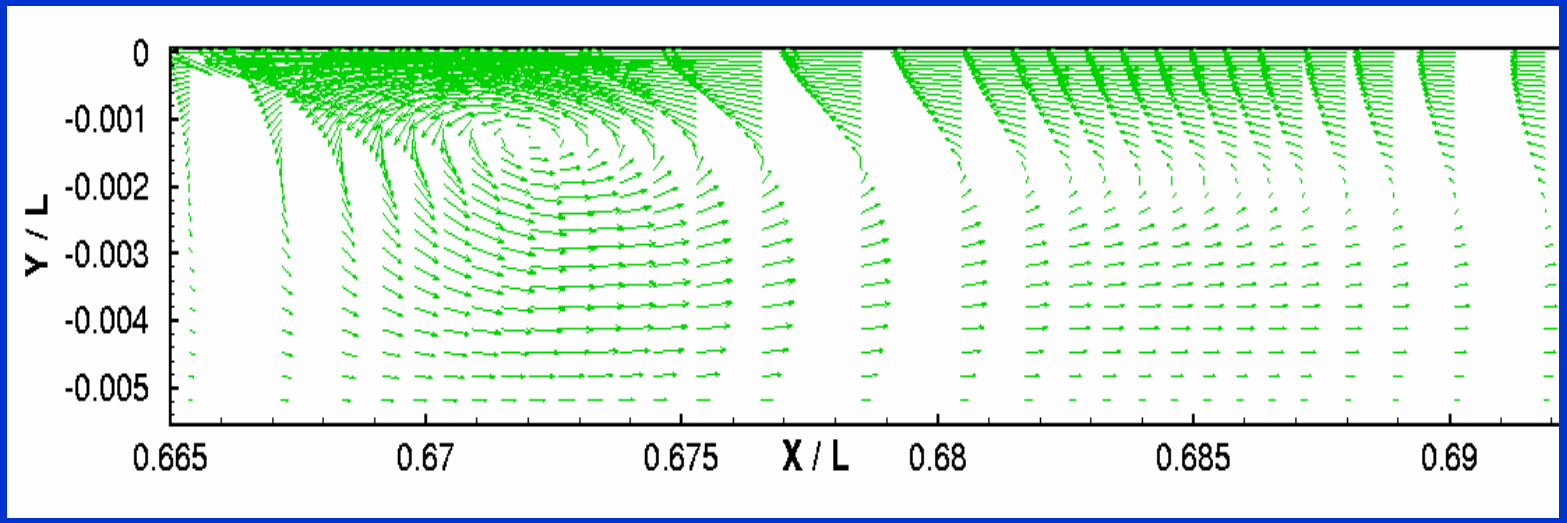




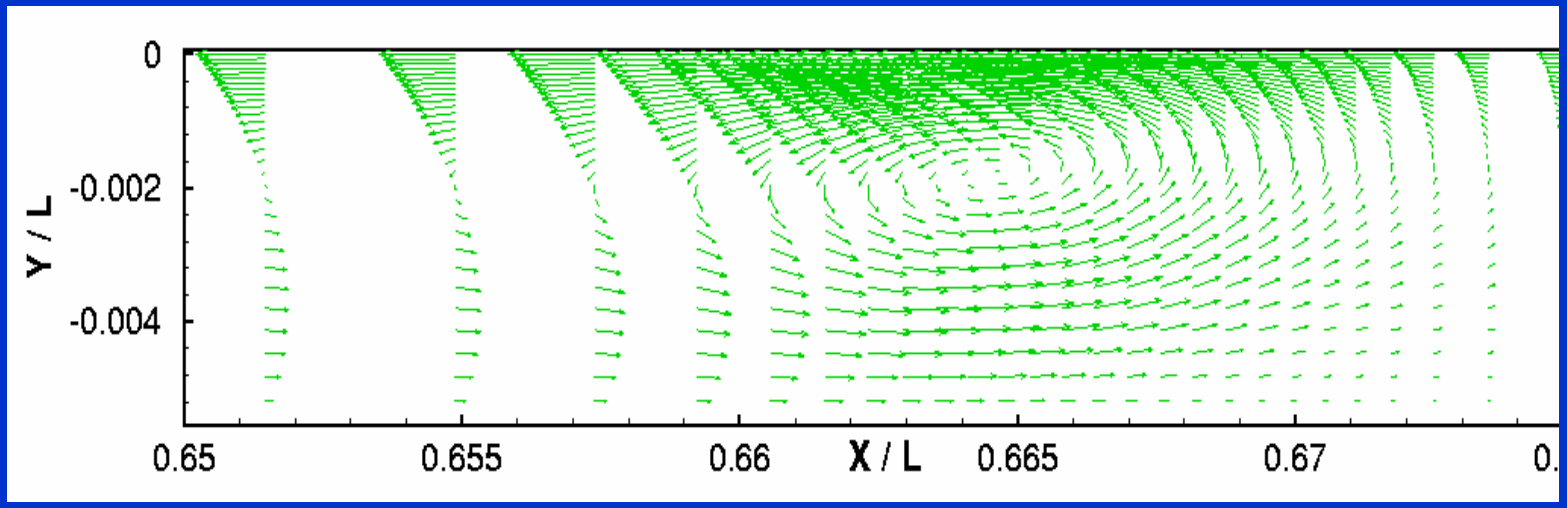
13°C, 1g, t=1.8s. Cold Floor. x/L= 0.69; expansion near flame front. x/L=.75, recirculation.

Liquid Velocity

t=1.8s, fast phase

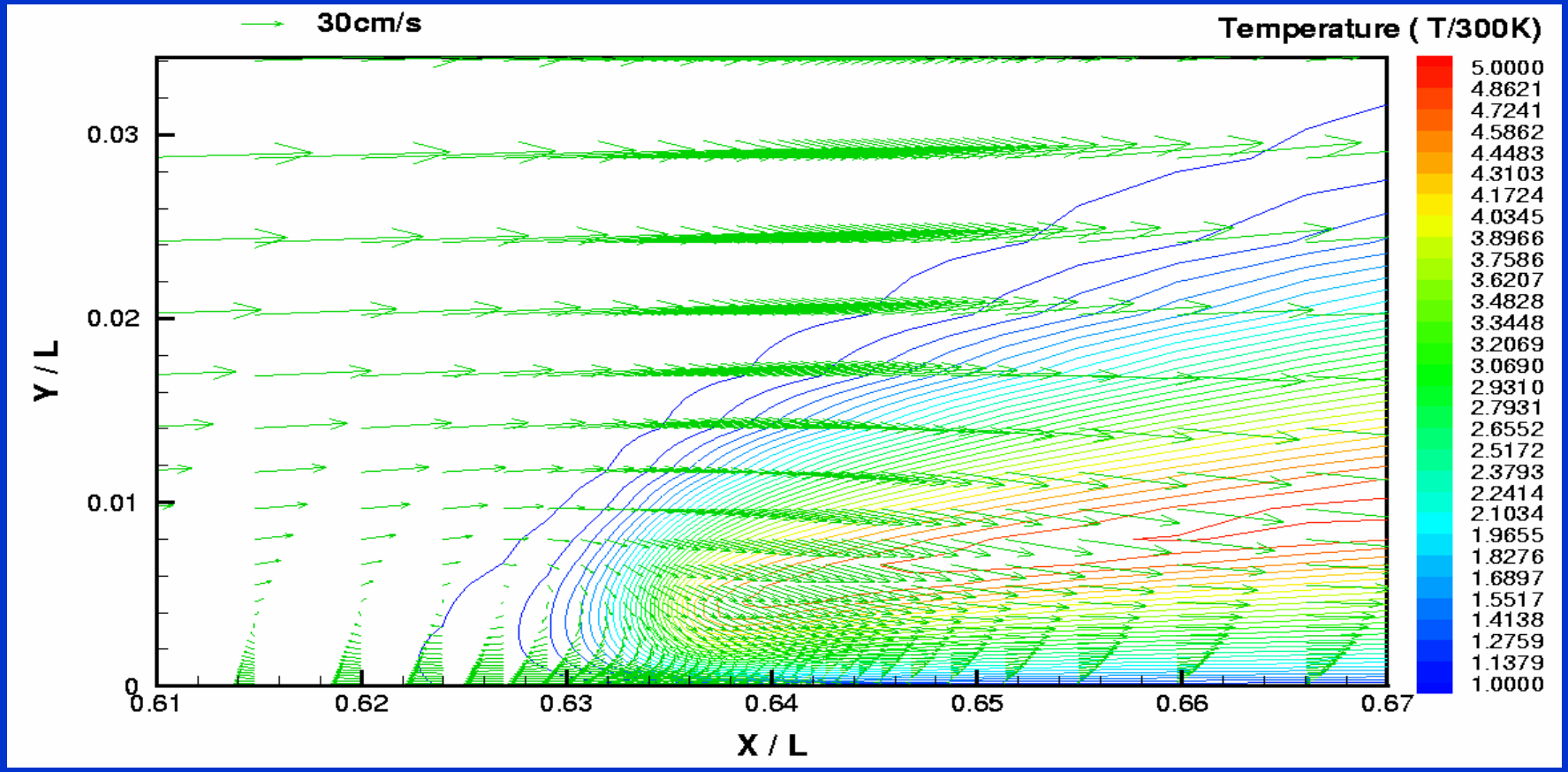


t=2s, slow phase



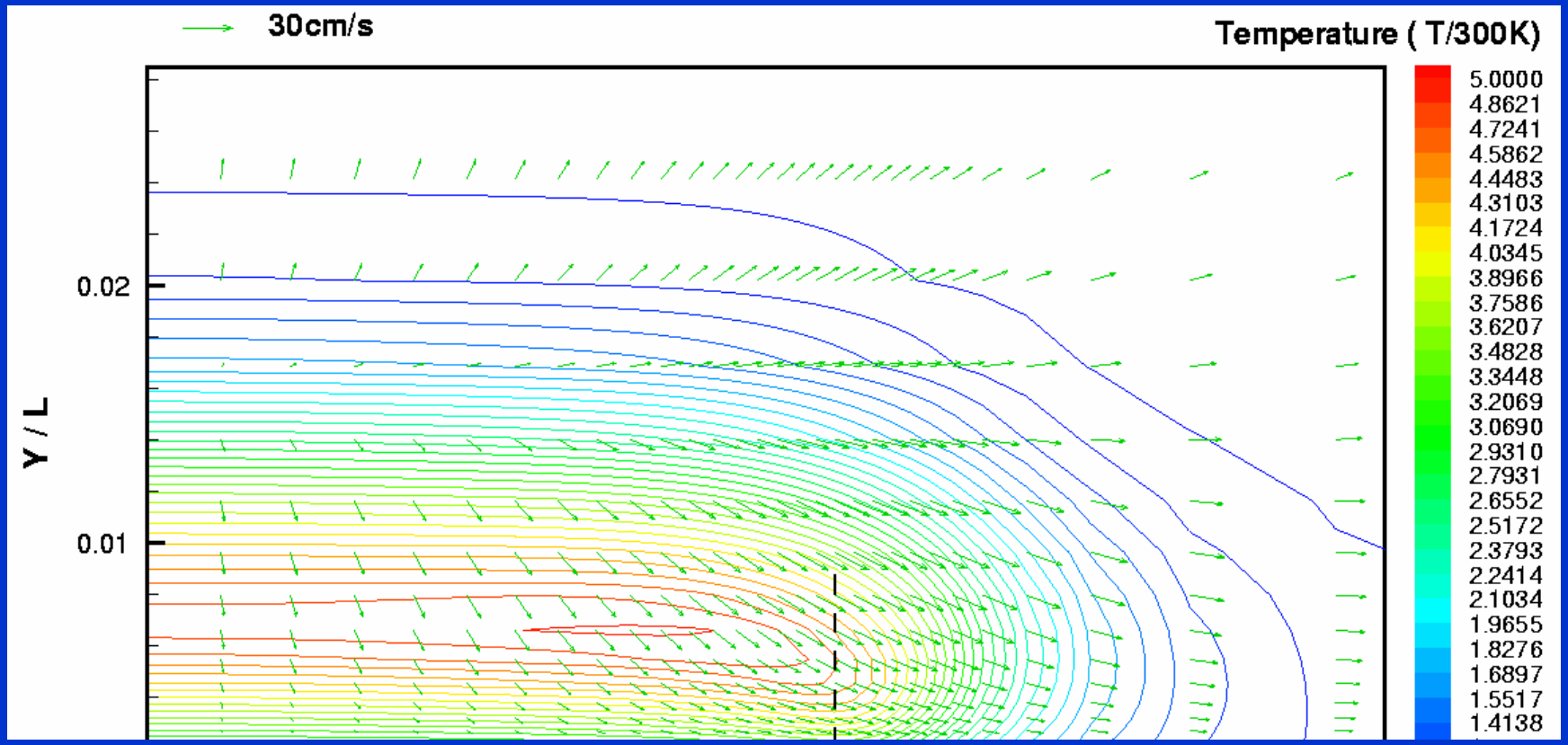
13°C, 1g, t=1.8s. Cold floor. Surface tension plus buoyancy causes recirculation.

Velocity & Temperature in Symmetry Plane



13°C, 0-g, t=2.3s, slow phase. Forced convection together with surface tension causes recirculation.

Cross View - Velocity Vectors & Temperature Contours – Slow Phase



13°C, 0g, t=2.3s. Cold floor. x/L= 0.65.
No side recirculation without buoyancy.

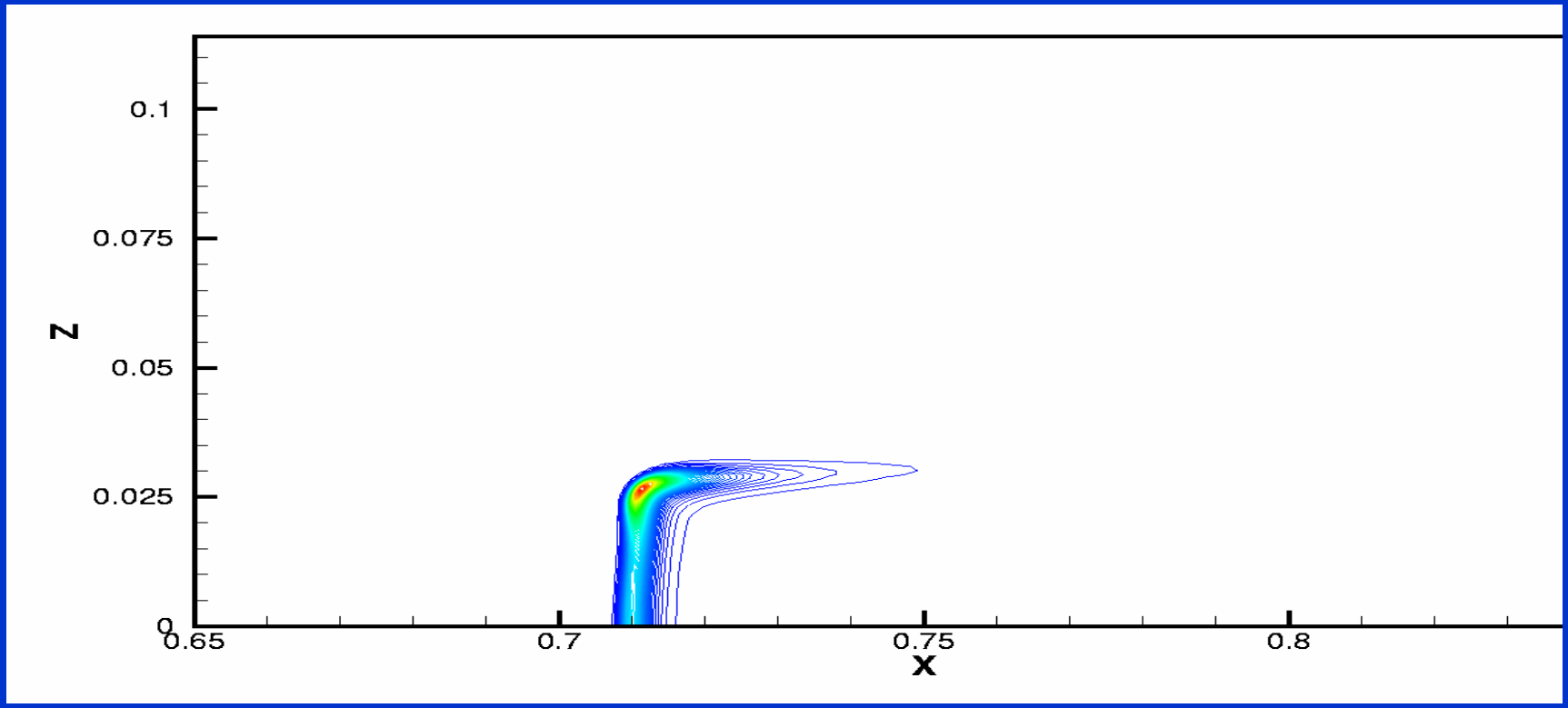
CONCLUSIONS

- Pulsations are found at both 0-g and 1-g with forced convection.
- Recirculation zone is key to mechanism for pulsation. Fuel vapor concentration increases during slow phase. Flammability limits are extended.
- Flame speed and pulsation frequency increase with initial fuel temperature.
- Improved diffusion model predicts faster propagation and uniform-rate spread / pulsating spread boundary moves to lower initial temperature.

CONCLUSIONS (continued)

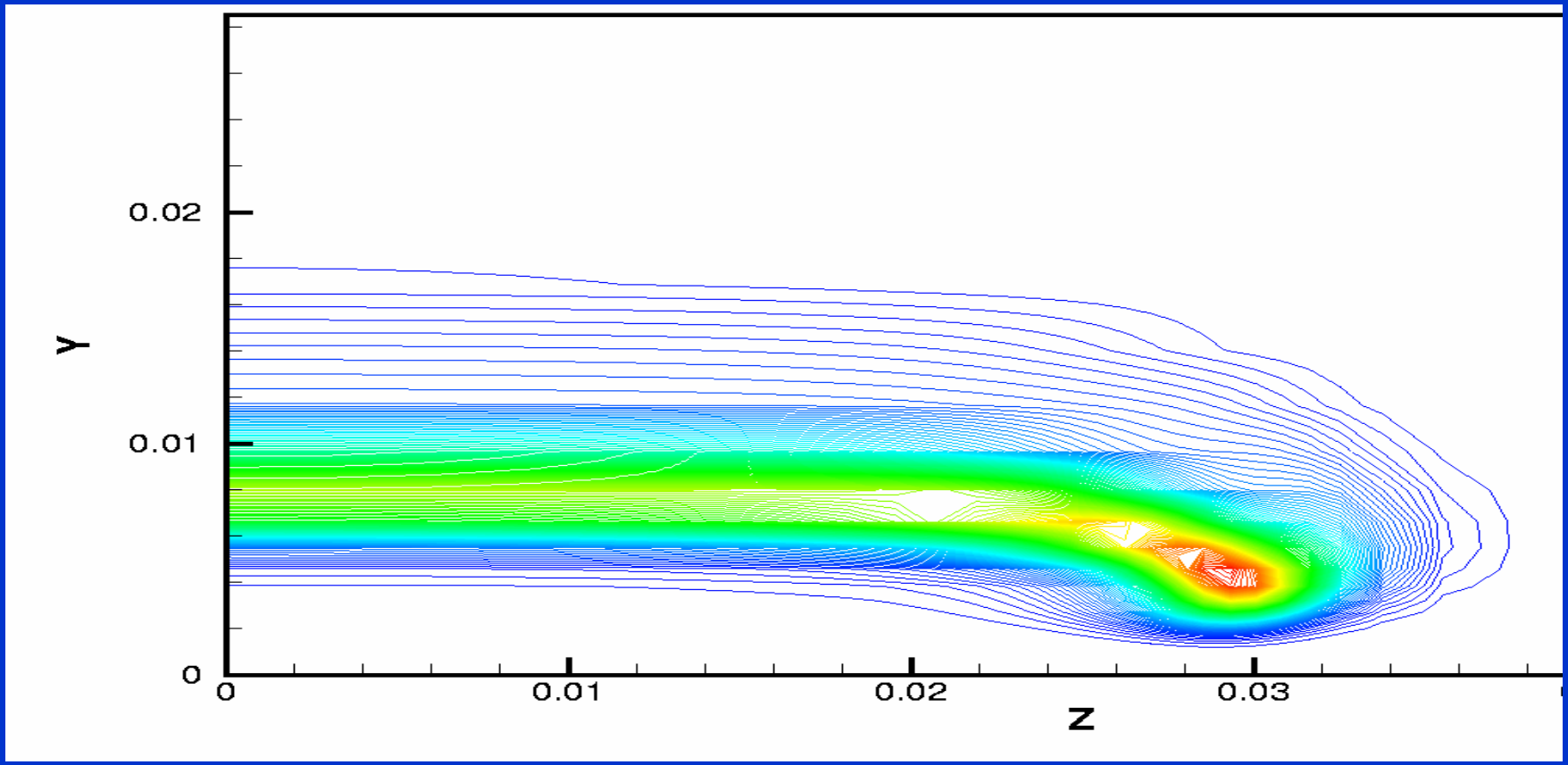
- Three-dimensional spread rate exceeds two-dimensional spread rate due to increased influx of oxygen.
- Increase in side heat losses reduces pulsating flame spread rate but has minor effect on uniform spread rates
- Flame front curves around pool edge extending along and setting over the pool edge.
- In 1-g case, buoyancy causes side vortices to form in pulsating spread.

Top View – Fuel Consumption Rate



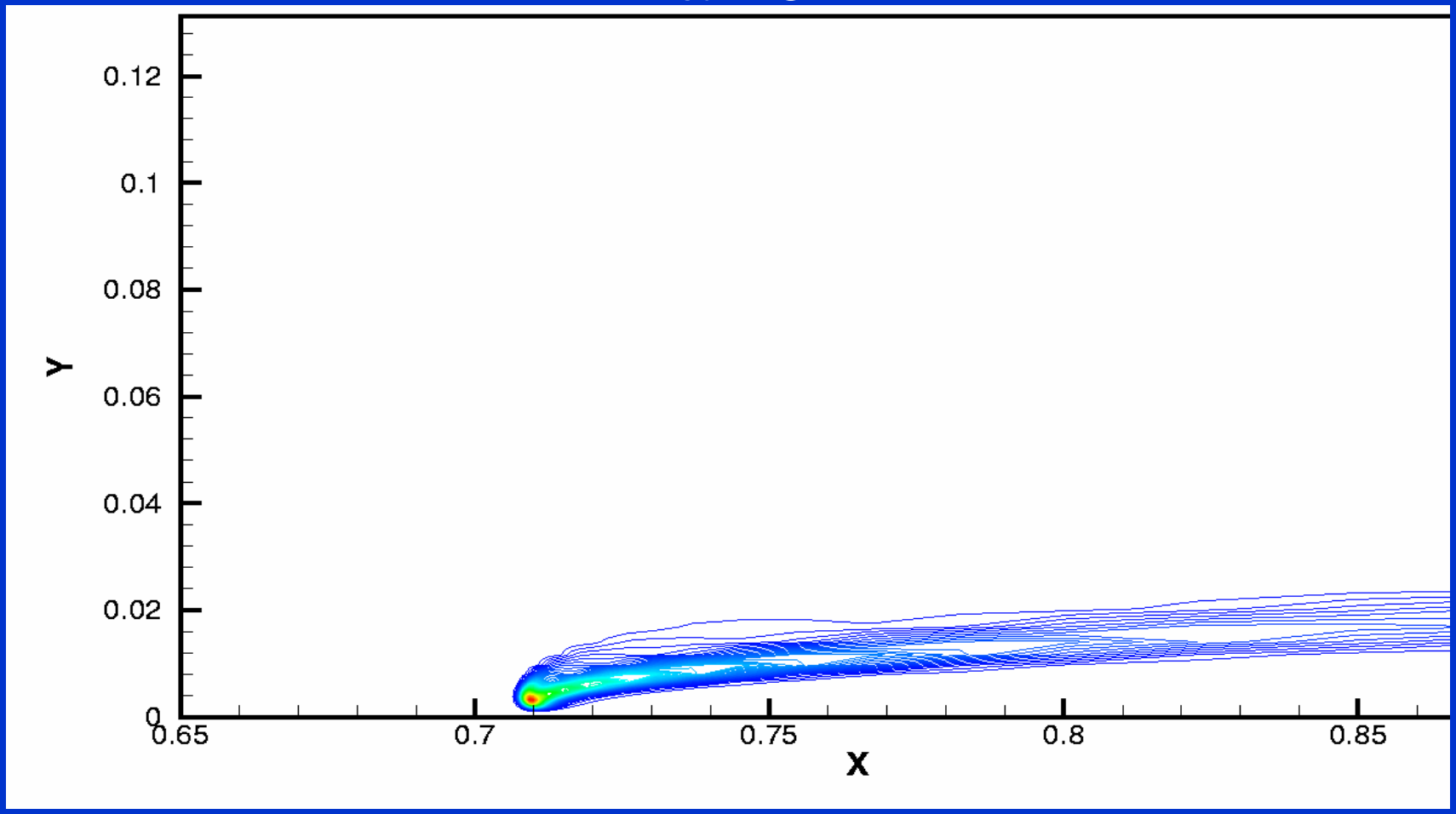
13 °C, pulsating case, 0-g, t=1.74s, y=1mm. Cold Tunnel Floor. Flame tails along pool edge are short.

Cross View, Behind Flame – Fuel Consumption Rate



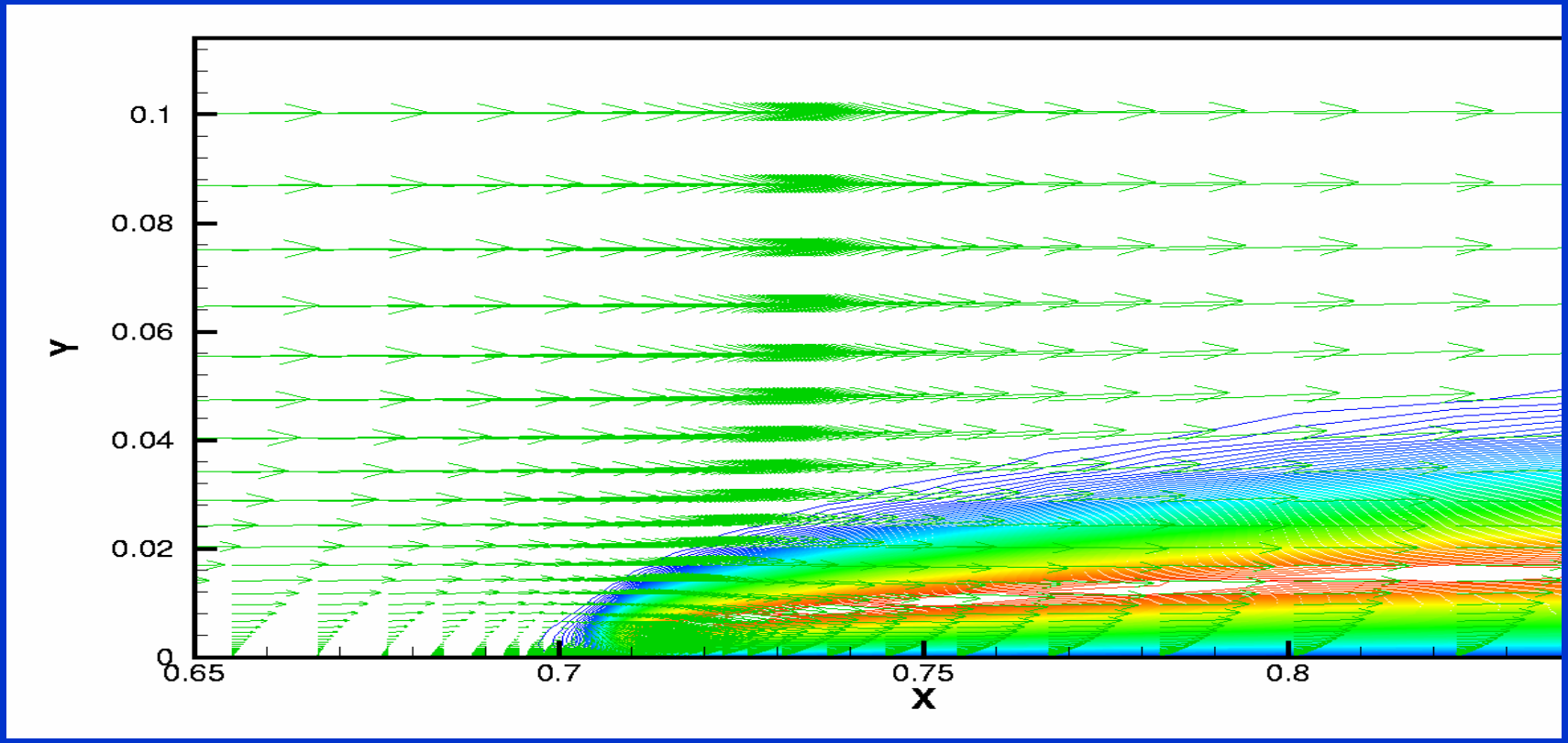
13 °C, pulsating case, 0-g, t=1.74s, x/L=.73. Cold Tunnel Floor.

Fuel Consumption Rate in Symmetry Plane



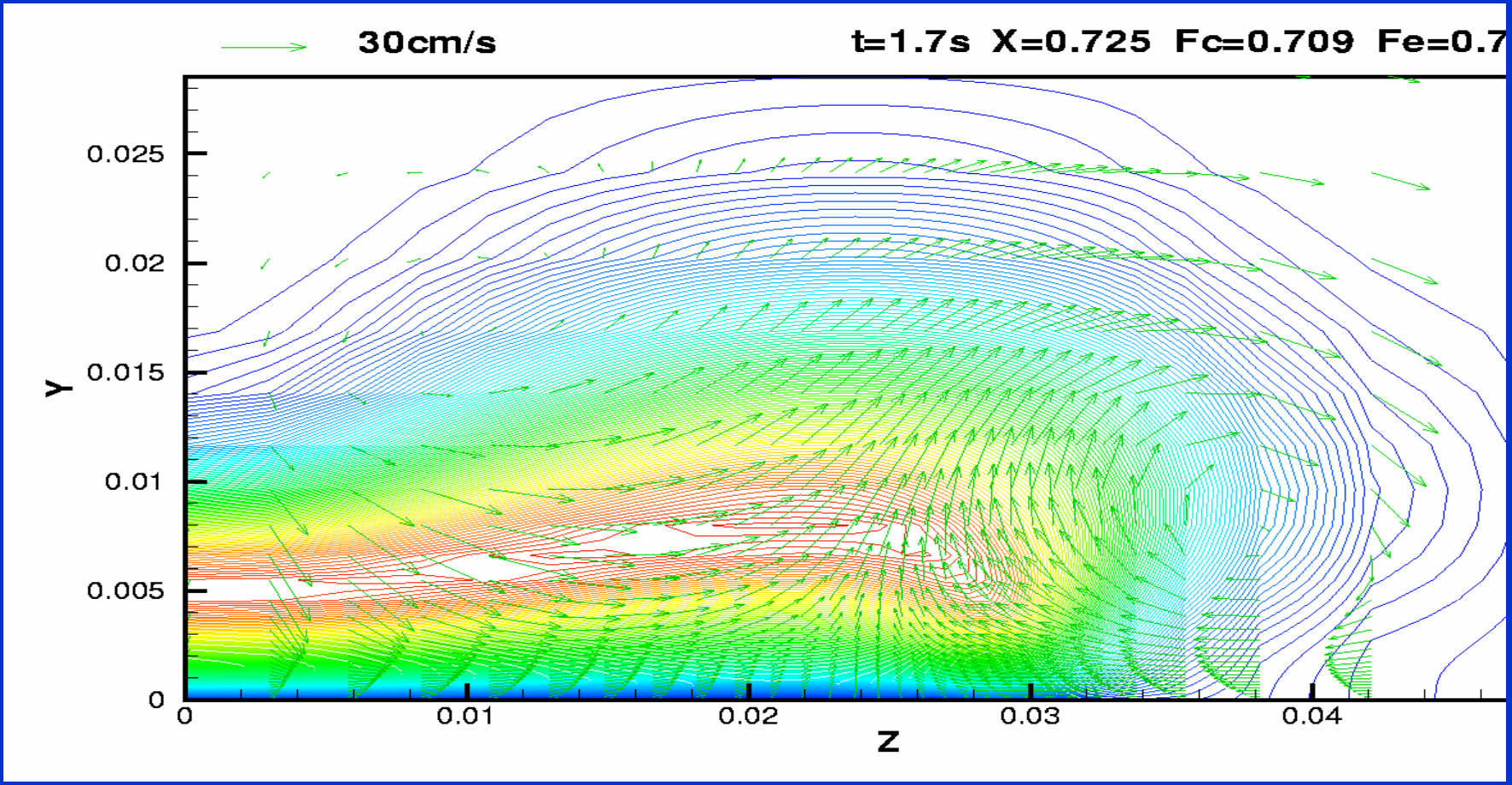
13°C, 0-g, t=1.74s, Cold Floor

Velocity & Temperature in Symmetry Plane



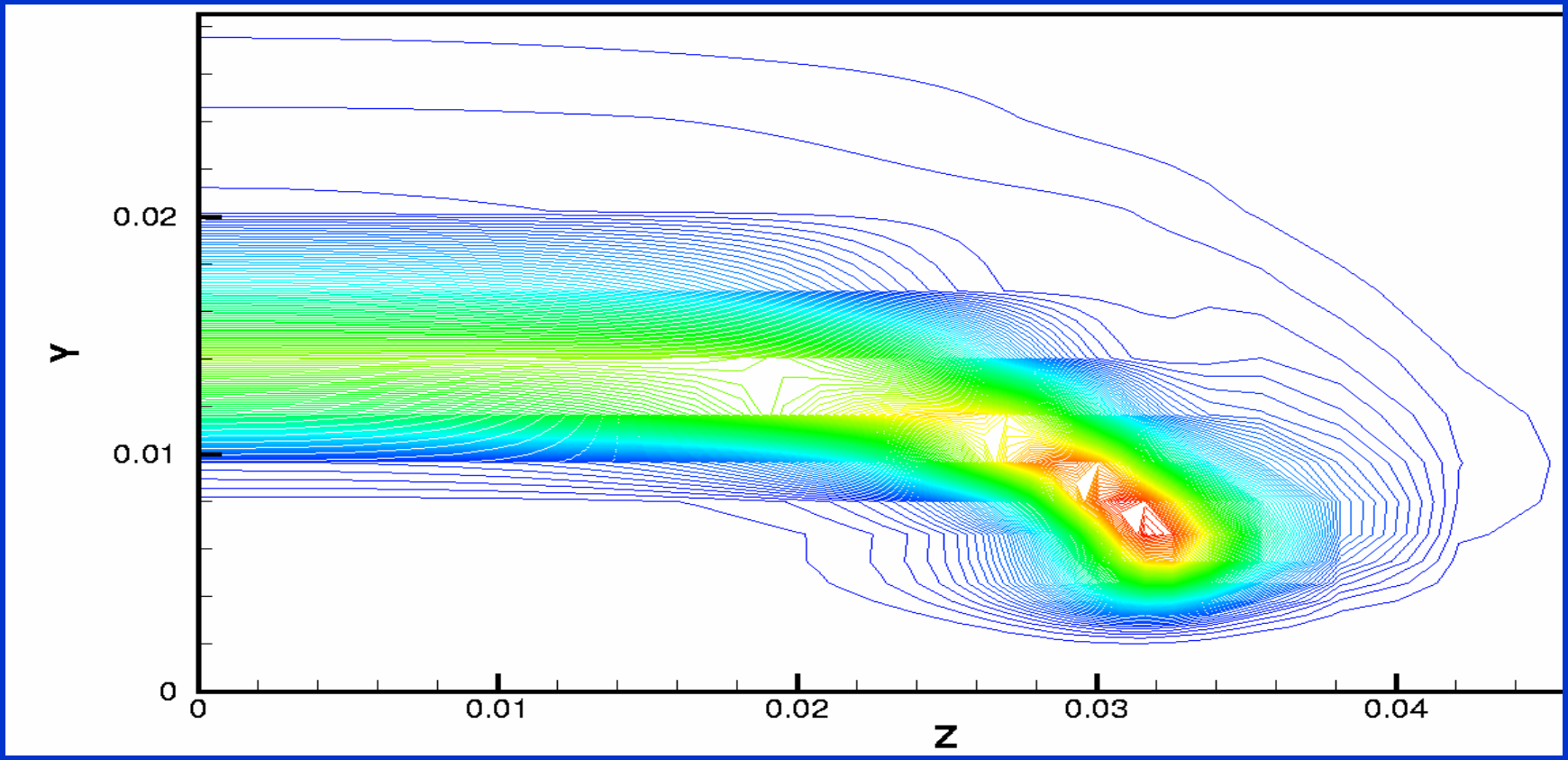
13°C, 0-g, t=1.74s. Flame remains close to surface in absence of buoyancy.

Cross View - Velocity Vectors & Temperature Contours



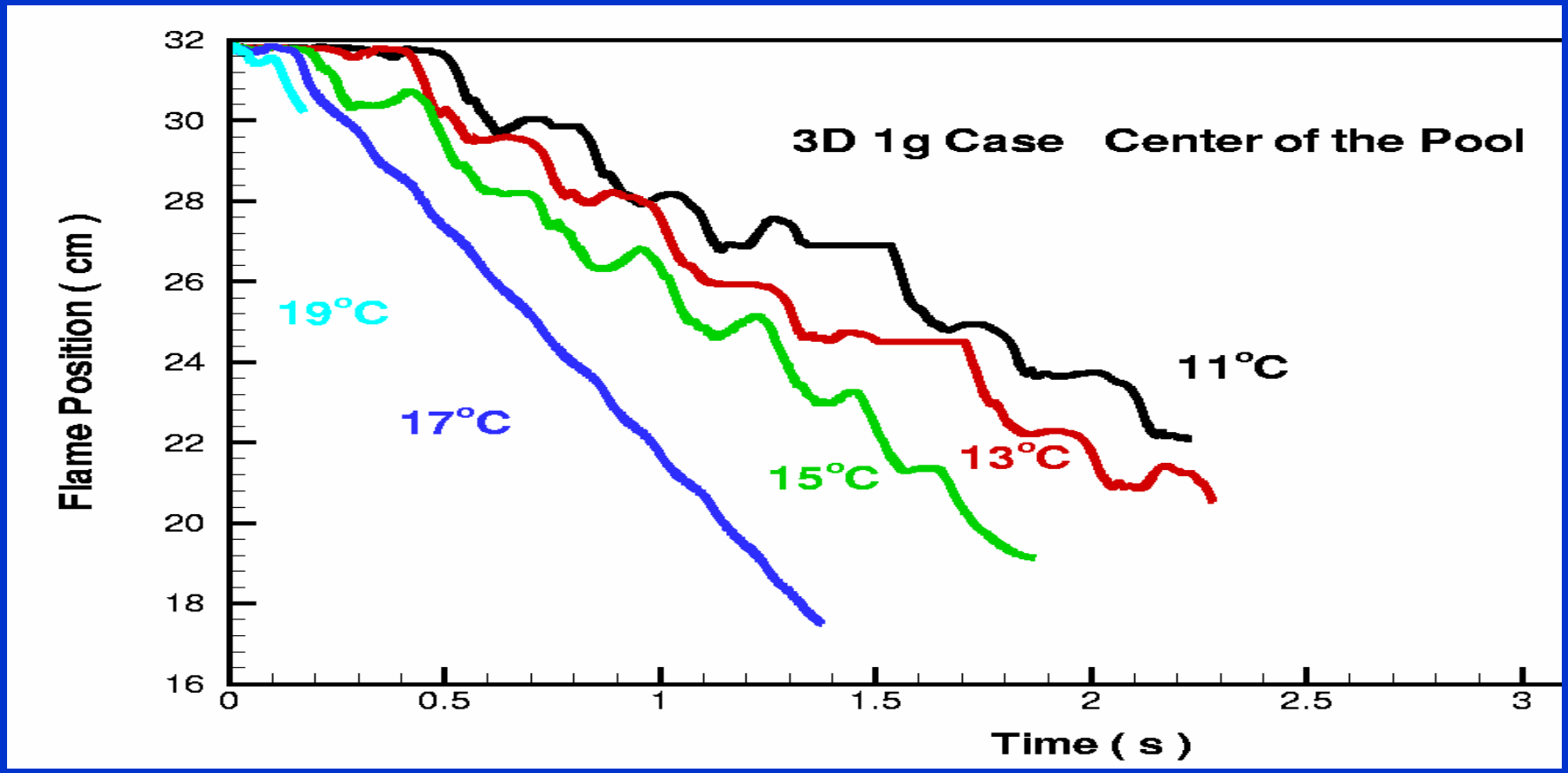
13 ^{o}C, 1-g, t=1.7s, x/L=.725. Cold floor. Vortex on side.

Cross View, Behind Flame – Fuel Consumption Rate



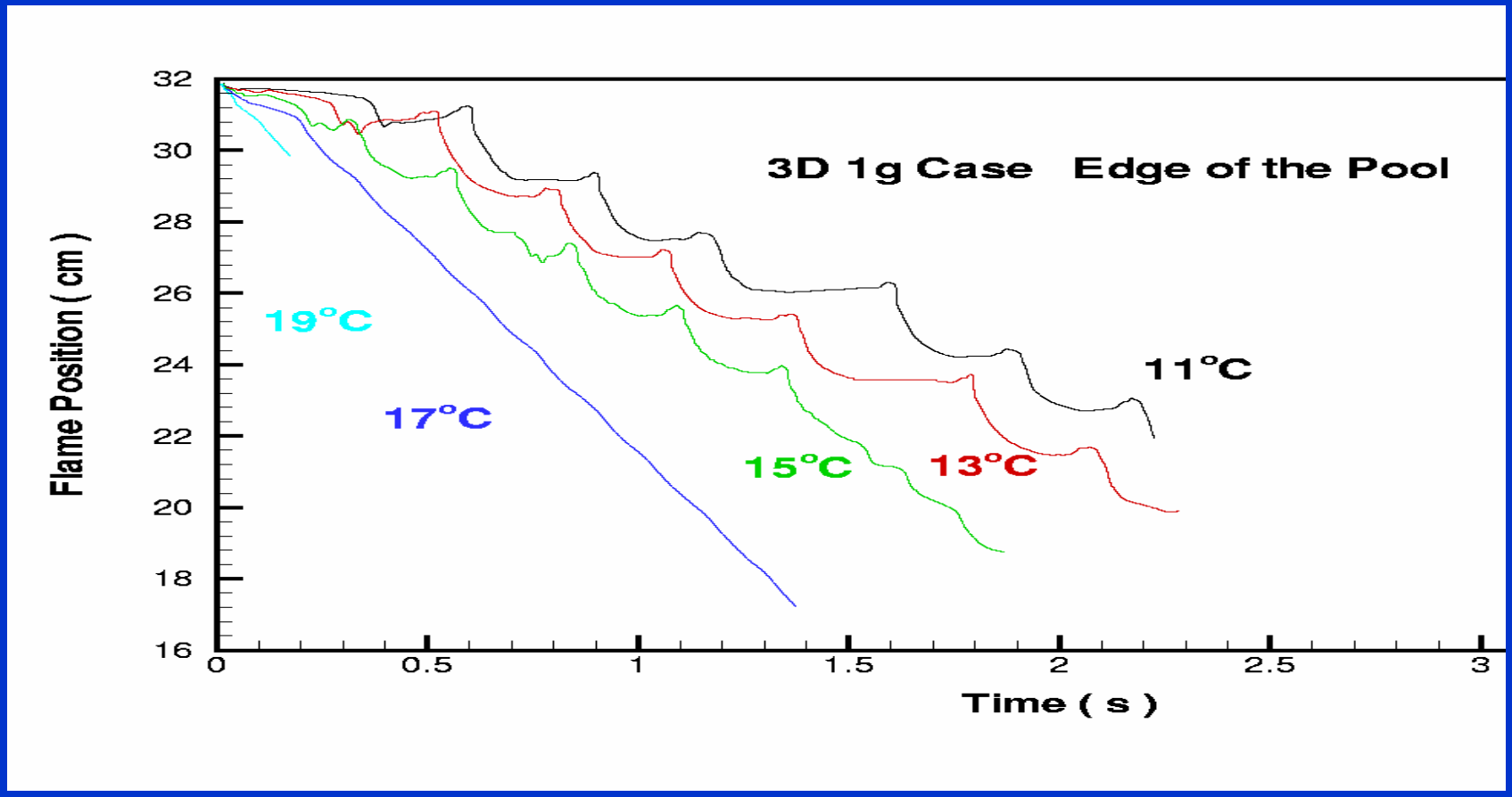
13 °C, pulsating case, 0-g, t=1.74s, x/L=.80.
Cold tunnel floor.

FLAME POSITION VS. TIME
Symmetry Plane



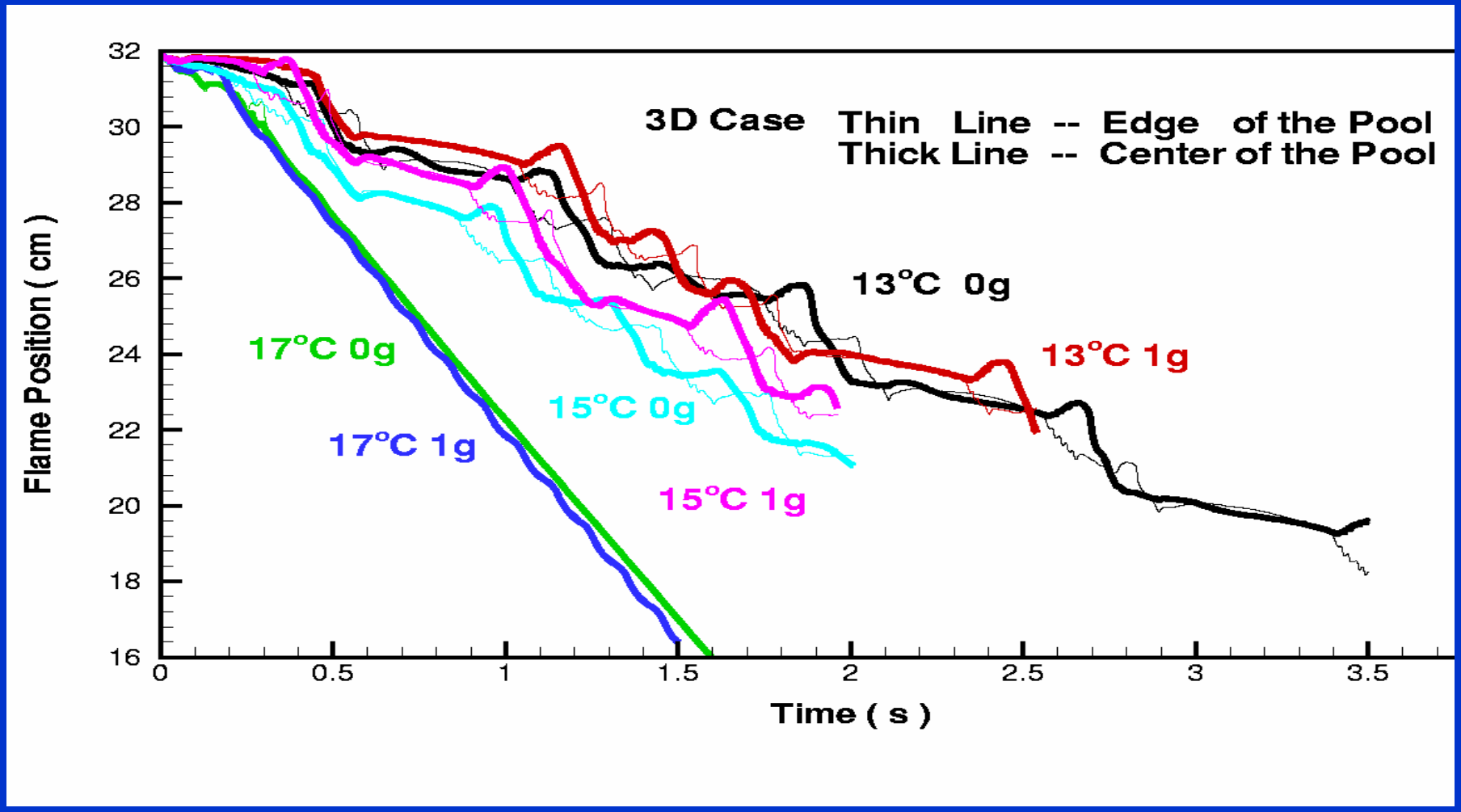
Hot floor, 30cm/s, 1-g , 13°C

FLAME POSITION VS. TIME
Edge of Pool

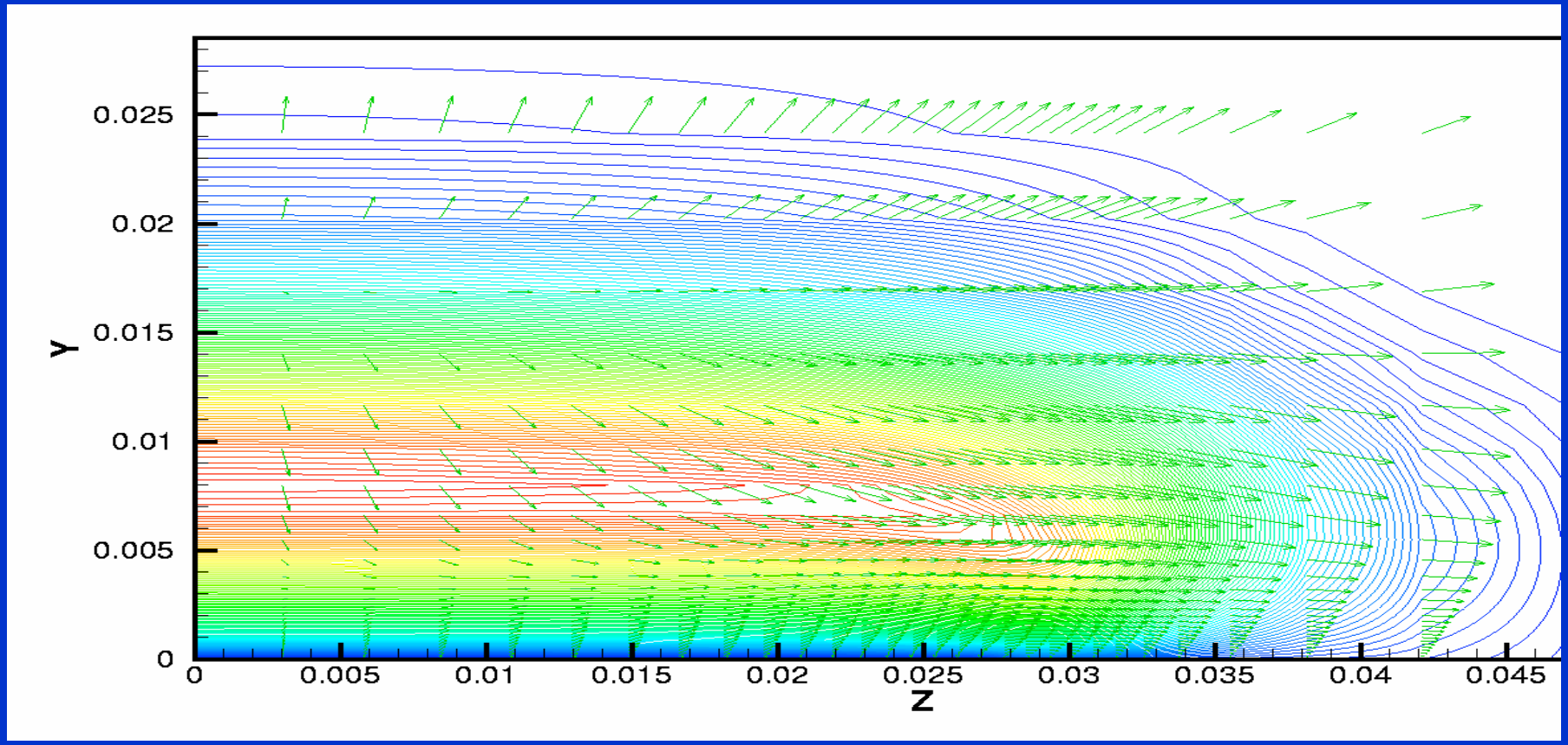


Hot floor, 30cm/s, 1-g , 13°C

3D 0, 1g


3D Case
Thin Line -- Edge of the Pool
Thick Line -- Center of the Pool
13°C 0g
13°C 1g
17°C 0g
17°C 1g
15°C 0g
15°C 1g
Flame Position (cm)
Time (s)
32
30
28
26
24
22
20
18
16
0
0.5
1
1.5
2
2.5
3
3.5

Cross View - Velocity Vectors & Temperature Contours



13 °C, 0-g, t=1.74s, x/L=.73. Cold floor.
No vortex on side in absence of buoyancy.