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Detailed Modeling of Flame Spread Processes Over Solid: Progress and Prospect

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Outline

-Types of flame spreading models

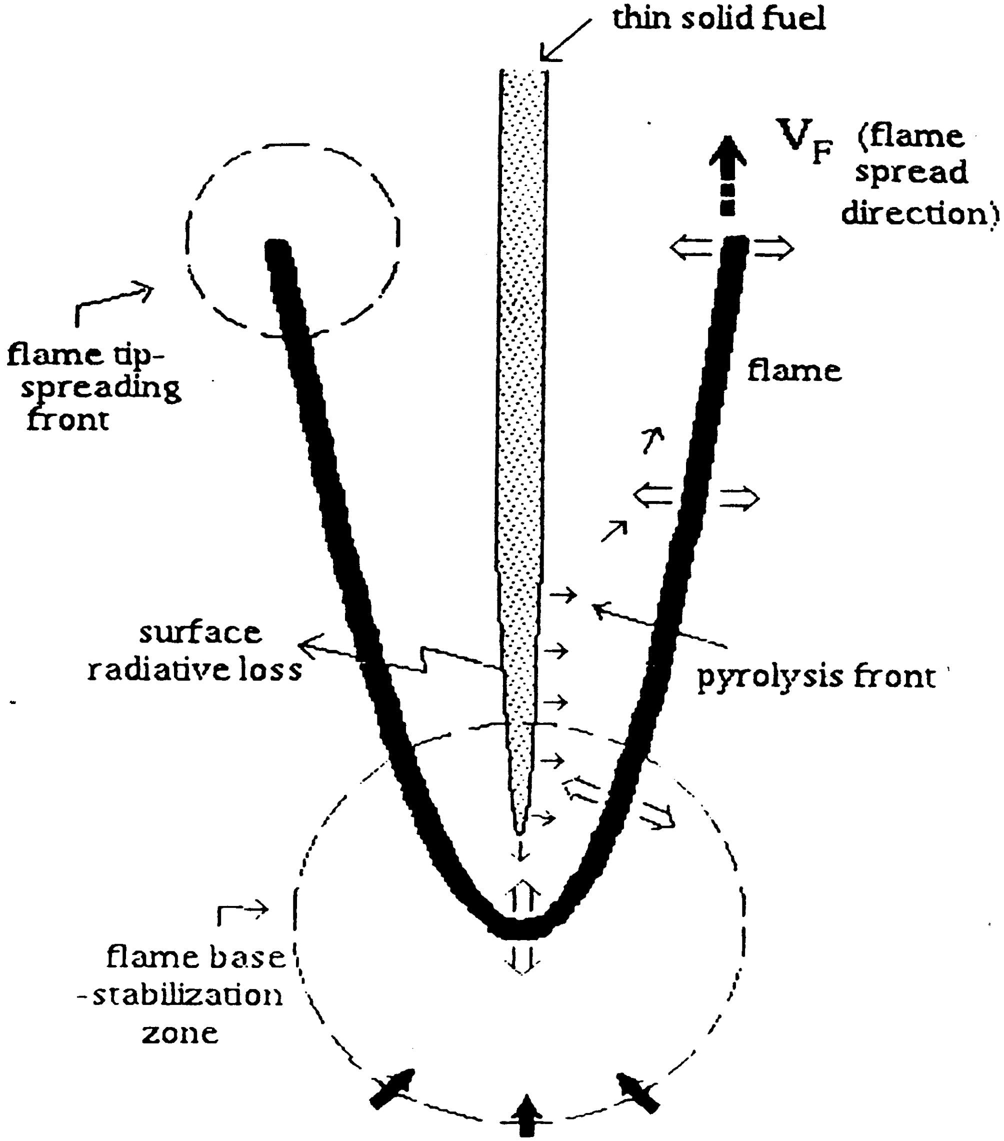
-Example results from detailed models

-Current capability of detailed models

-Potential application of current models

-Longer-term research needs

concurrent flow



- Flame stabilization zone-upstream
- Controlling zone for spread-downstream (pyrolysis and preheat)
- Size of stabilization zone $\ll$ size of pyrolysis and preheat zones in high-speed flows

Types of Flame Spreading Models:

- Correlations/Dimensional Consideration
- Heat transfer model
- Thermal/diffusive model
- Model with fluid mechanics (including momentum equations)
- Model with finite-rate chemistry
- Model including detailed solid processes

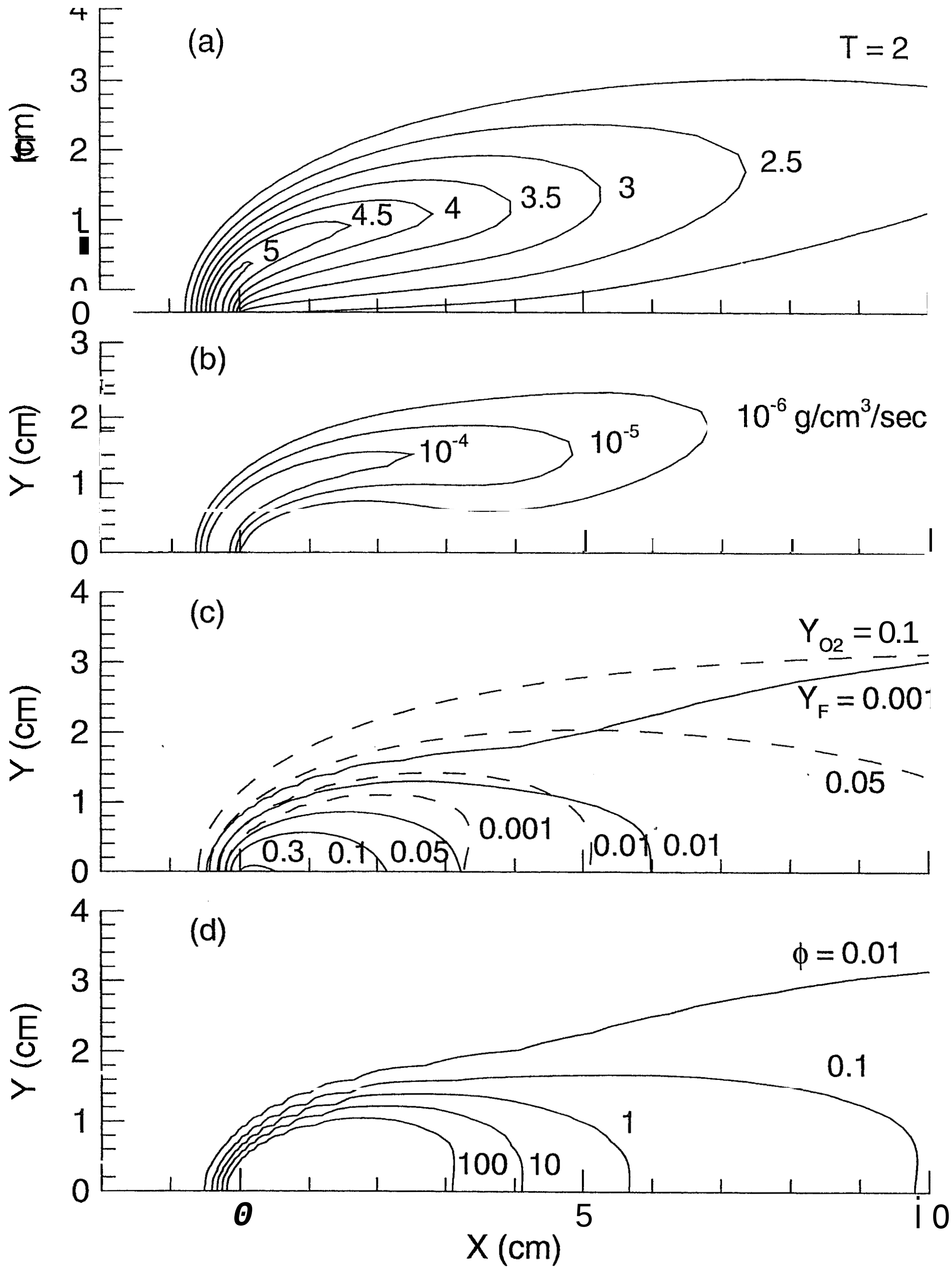
More details

MODELING LOW-SPEED CONCURRENT-FLOW FLAME SPREAD OVER A THIN SOLID

- **Conservation equations**
    - **Mass**
    - **Momentum**
    - **Energy**
    - **Species**
- **Including flame stabilization zone**
- **Including flame radiation**

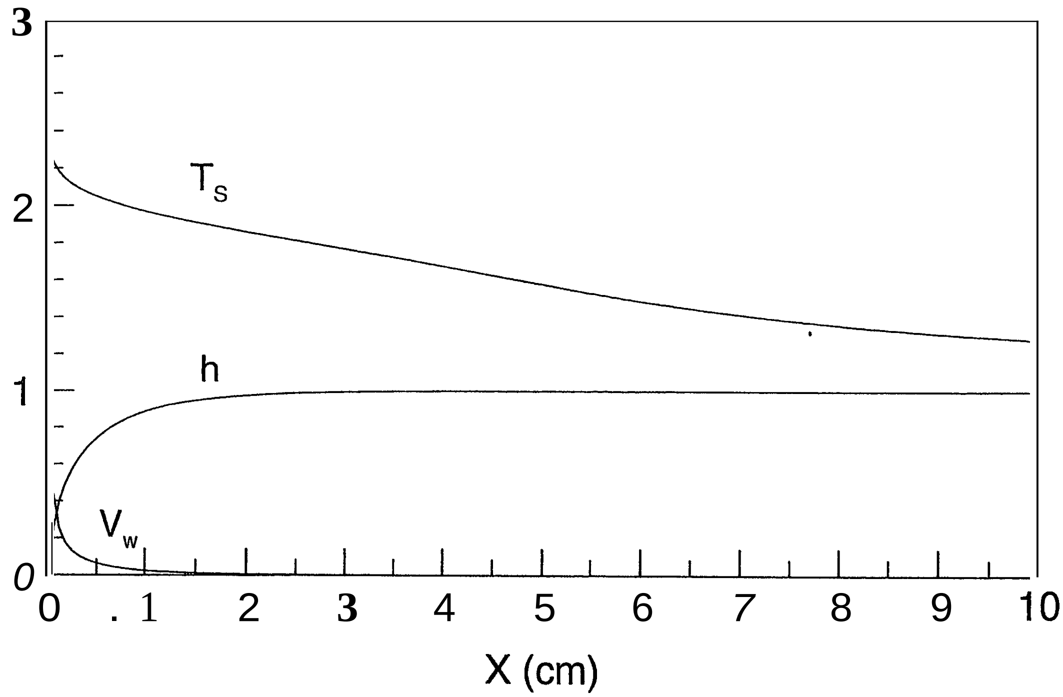
RADIATION TREATMENT

- **Surface and gas**
- **No soot, no soot radiation**
  Why?   Justification!
  (limited range of applicability)
- **Theoretical computation in multi-dimensional flame is difficult**
- **A gray gas model will be used here (need calibration)**

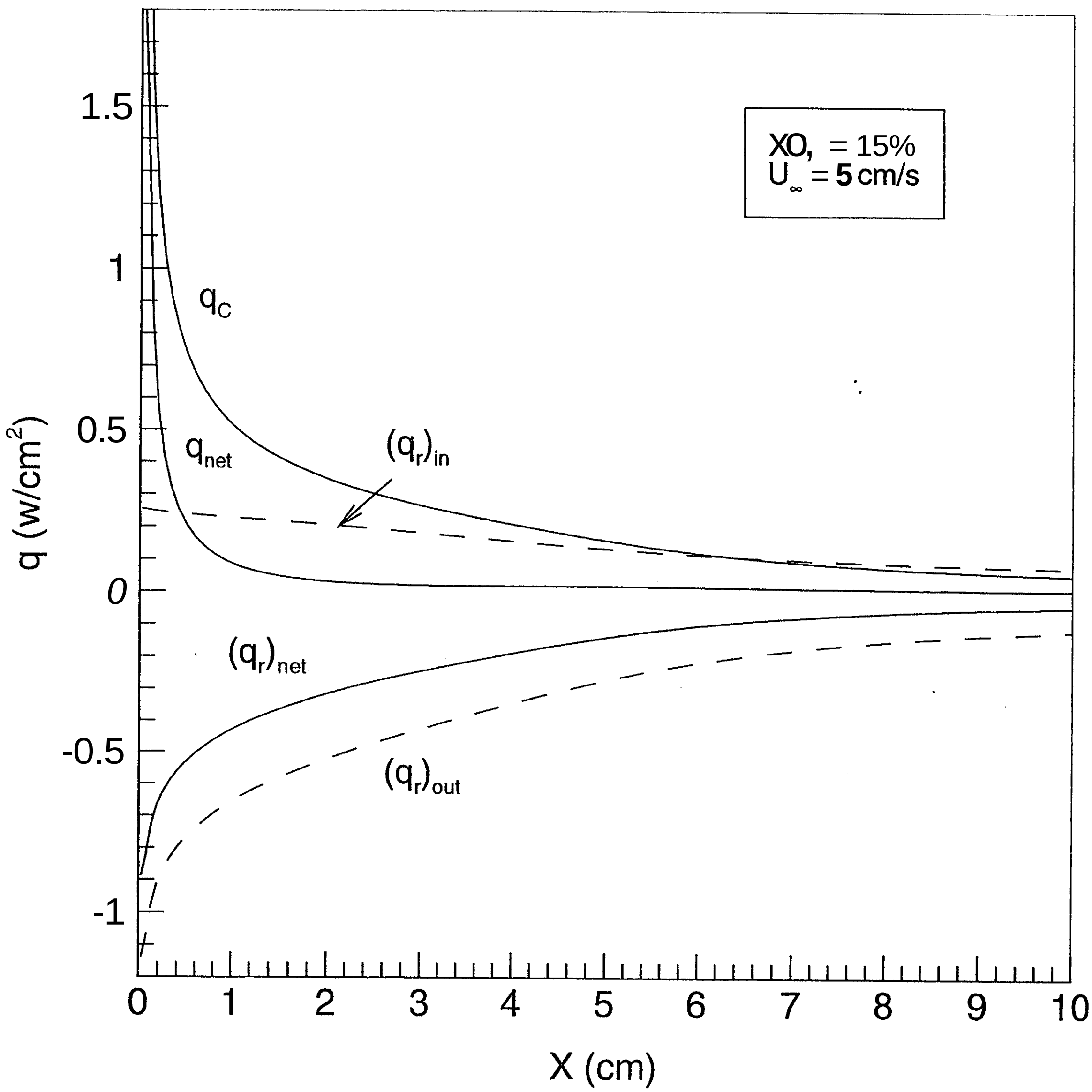


Flame structures at $U_\infty = 5$ cm/s, 15% O, (a) nondimensional gas temperature (1 unit = 300 K) (b) fuel vapor consumption rate (c) mass fractions of fuel and oxygen (d) local fuel/oxygen equivalence ratio.

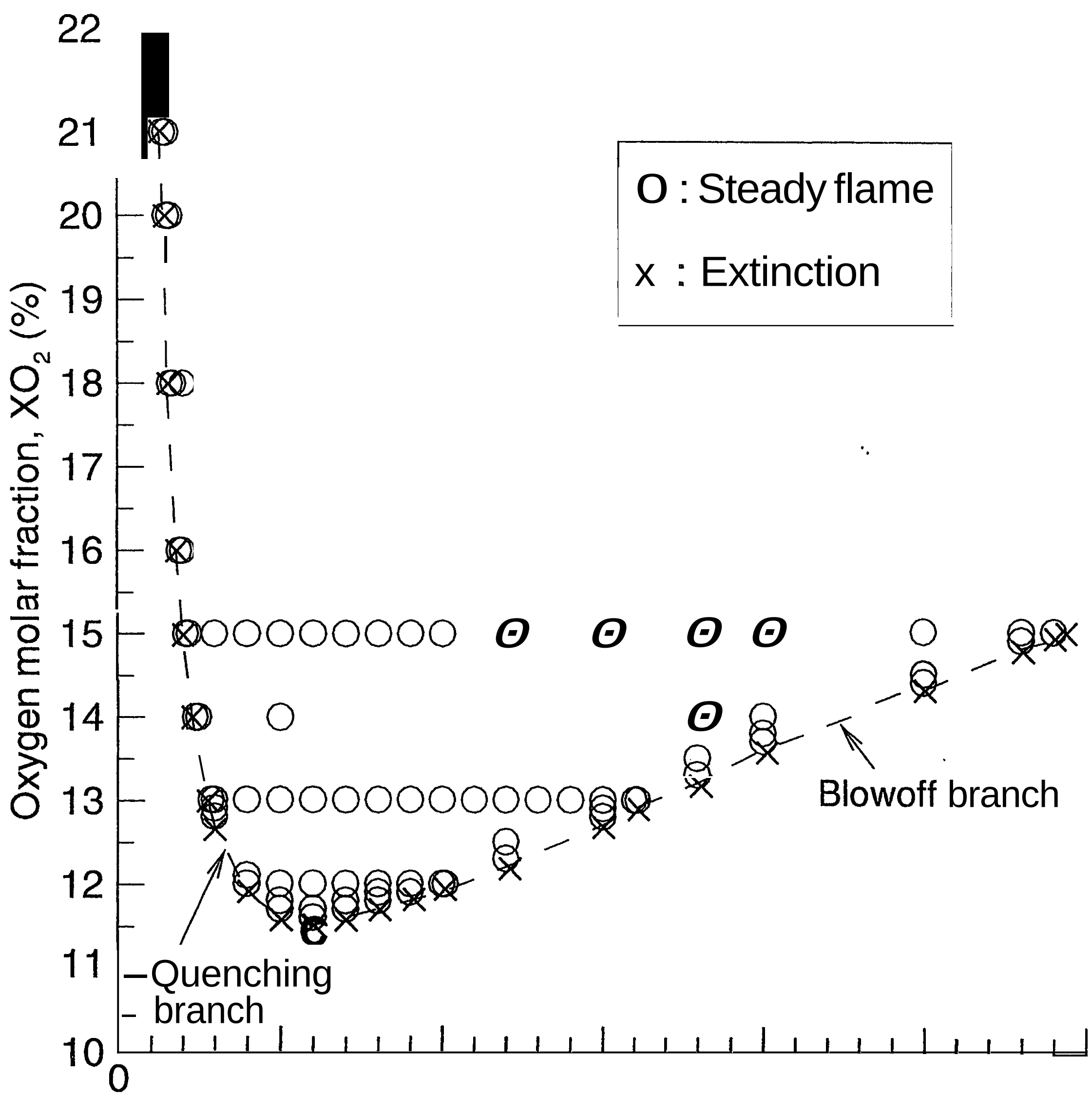
2-D Solid, Low-speed Pure Forced Flow (Laminar)



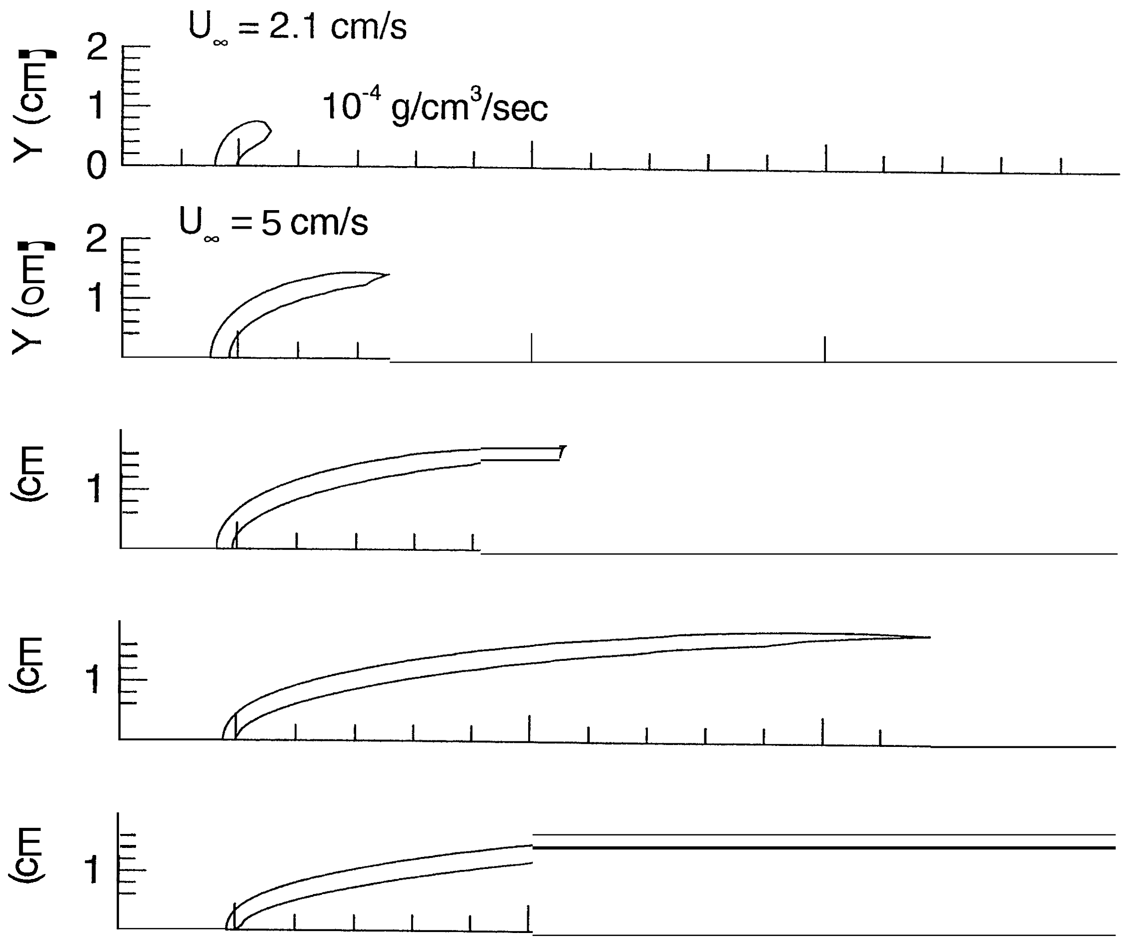
Solid-phase profiles including solid temperature T_s (normalized by 300 K), solid thickness h (normalized by $\tau = 3.8 \times 10^{-3}$ cm) and blowing velocity, v_w (normalized by $U_R = 4.53$ cm/s).



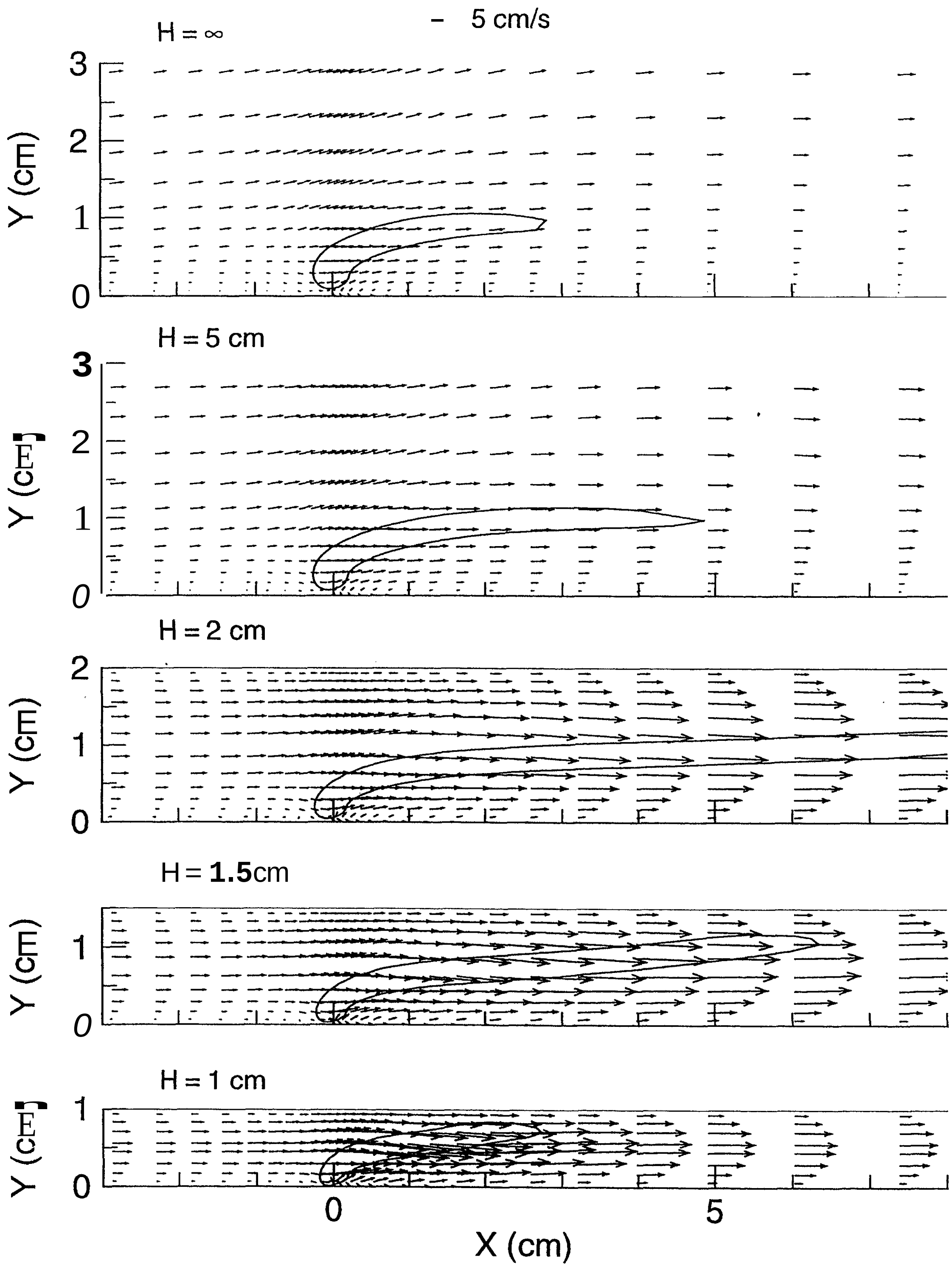
Heat fluxes along the solid including conduction q_c, incoming radiation, $(q_r)_{in}$, outgoing radiation $(q_r)_{out}$, net radiation $(q_r)_{net}$ and total net heat flux q_{net}.



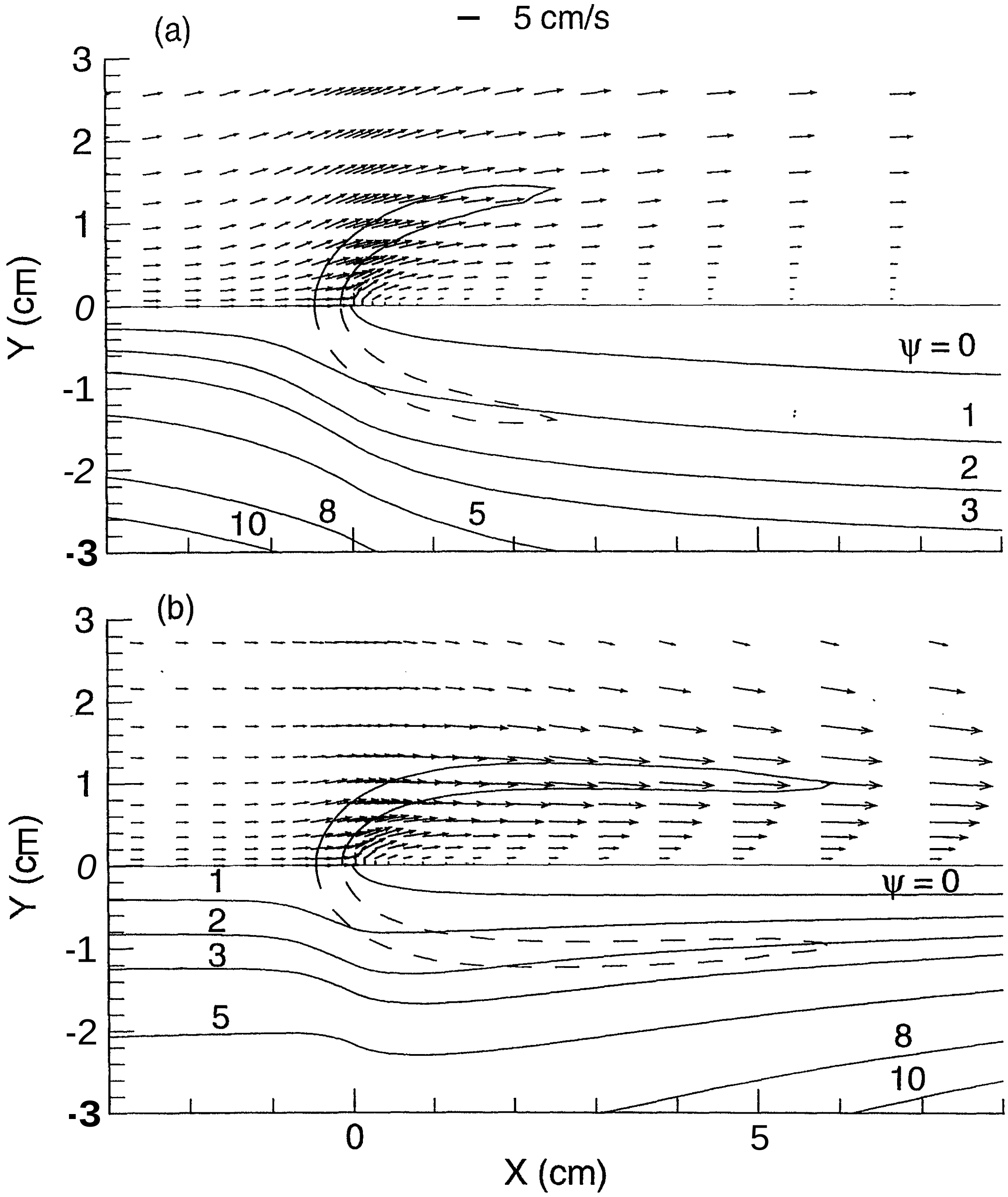
. The extinction boundary using oxygen concentration and free stream velocity **as** coordinates.



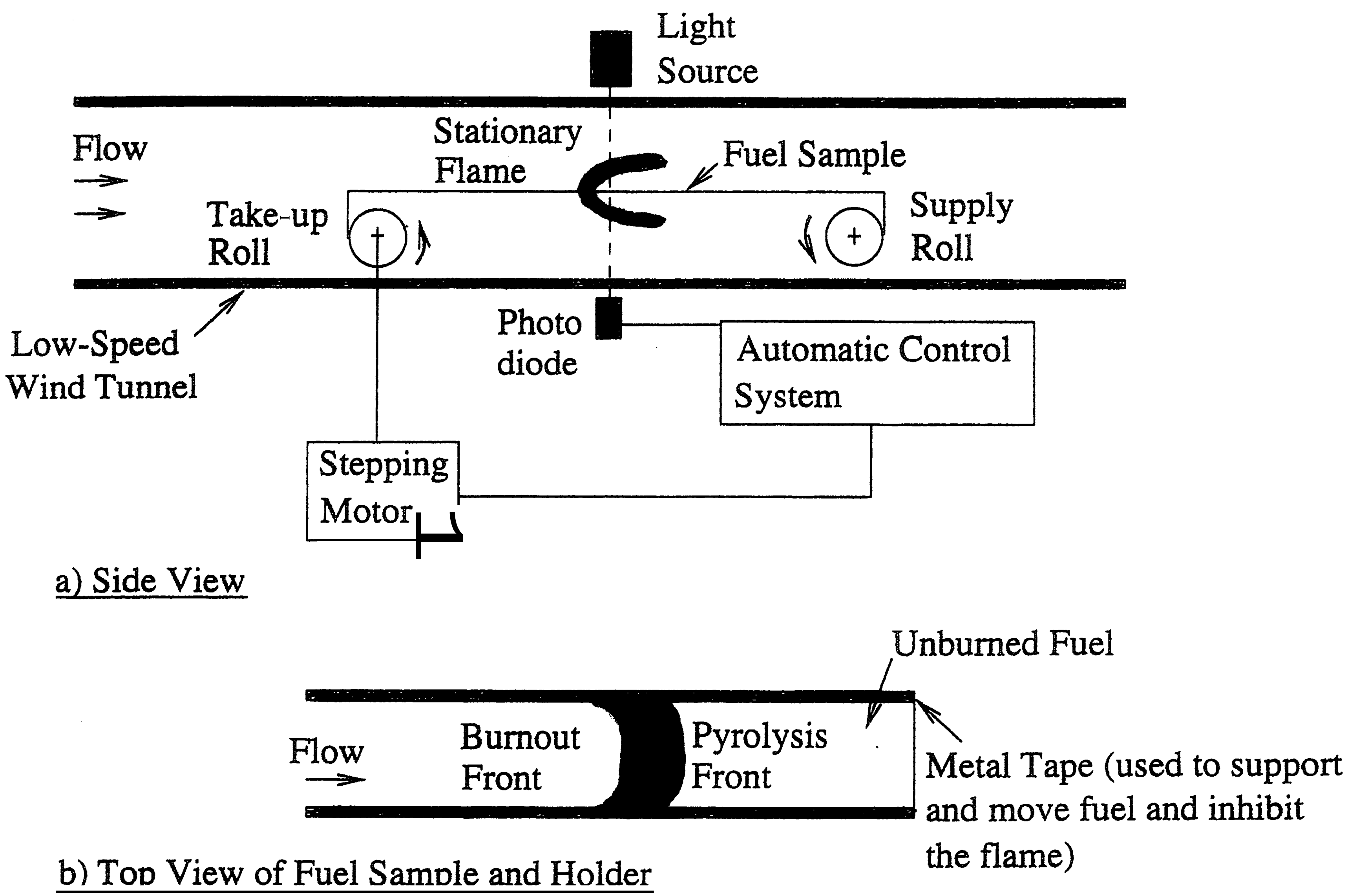
The visible flame shapes at 15% O_2 at different flow velocities, from U_∞ = 2.1 cm/s (quenching limit) to 29 cm/s (blow-off limit)



The velocity profiles around the visible flames at different tunnel heights, $XO_2 = 15\%$, $U_\infty = 5$ cm/s.

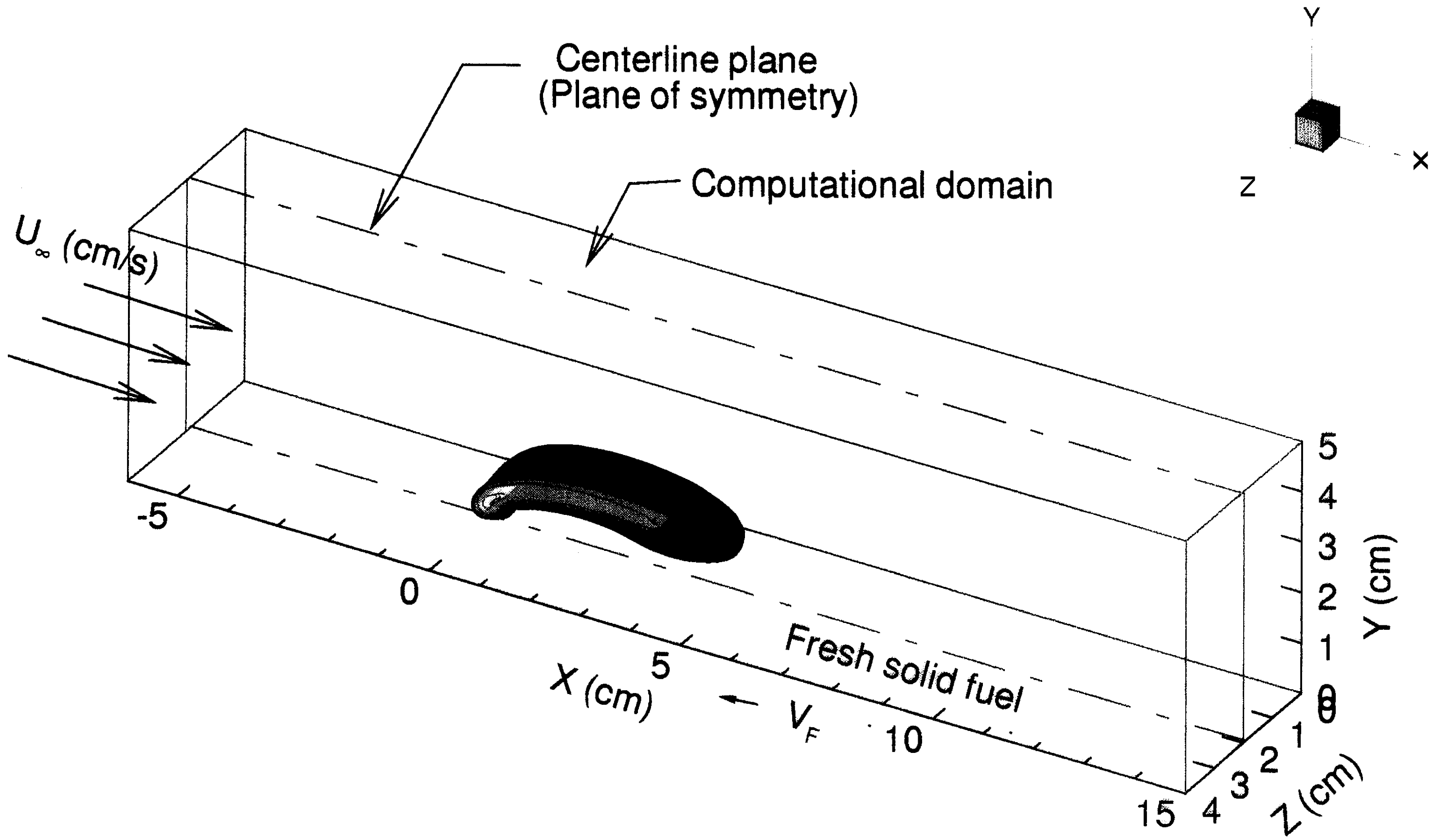


Velocity streamlines and velocity vectors around the flame (depicted by fuel reaction rate 10^{-4} g/cm^3/s) **(a)** Forced flow case, $U_\infty = 5$ cm/s (b) buoyant case, $g = 0.01g_e$, XO, = 15%.



Schematic of Experiment Concept

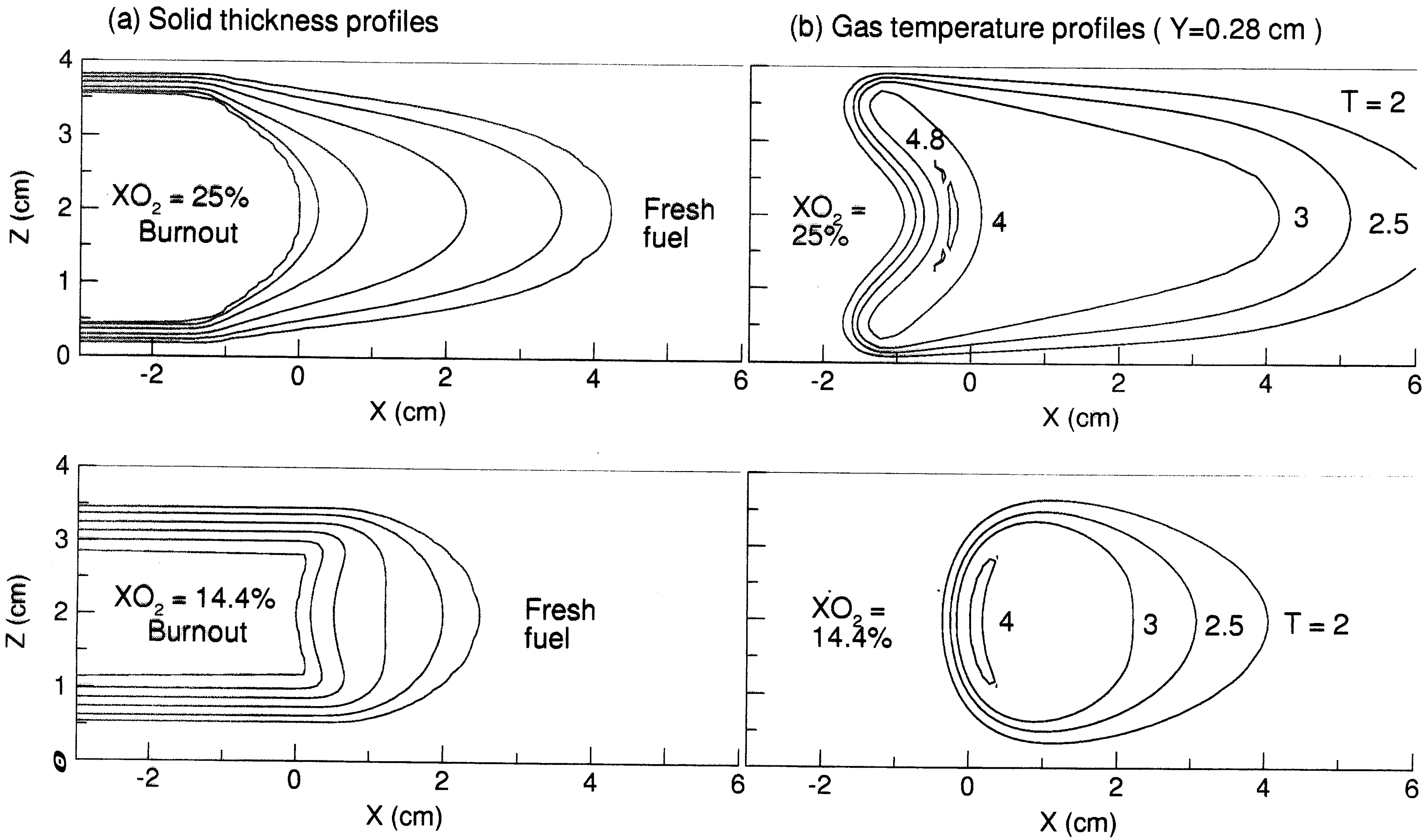
Schematic of 3D flame and the flow tunnel



Tunnel dimension : 21 cm x 10 cm x 4 cm
Temperature of side walls and top wall : 300 K
Solid fuel (Y=0 plane) : 80% combustible fuel + 20% inert

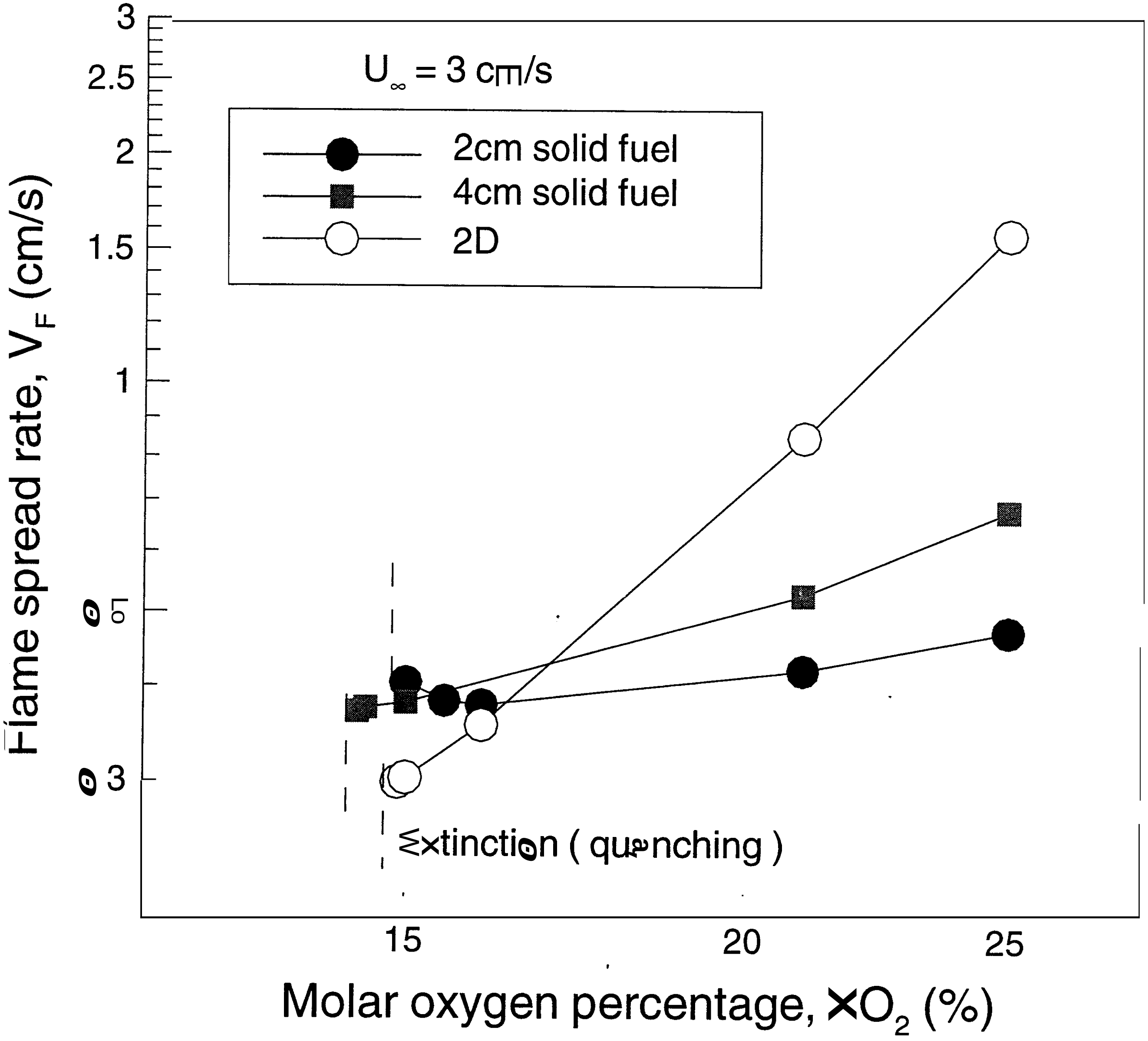
Solid thickness and gas temperature profiles on the horizontal plane

(XO_2 = 25% and 14.4% for 4cm width solid)



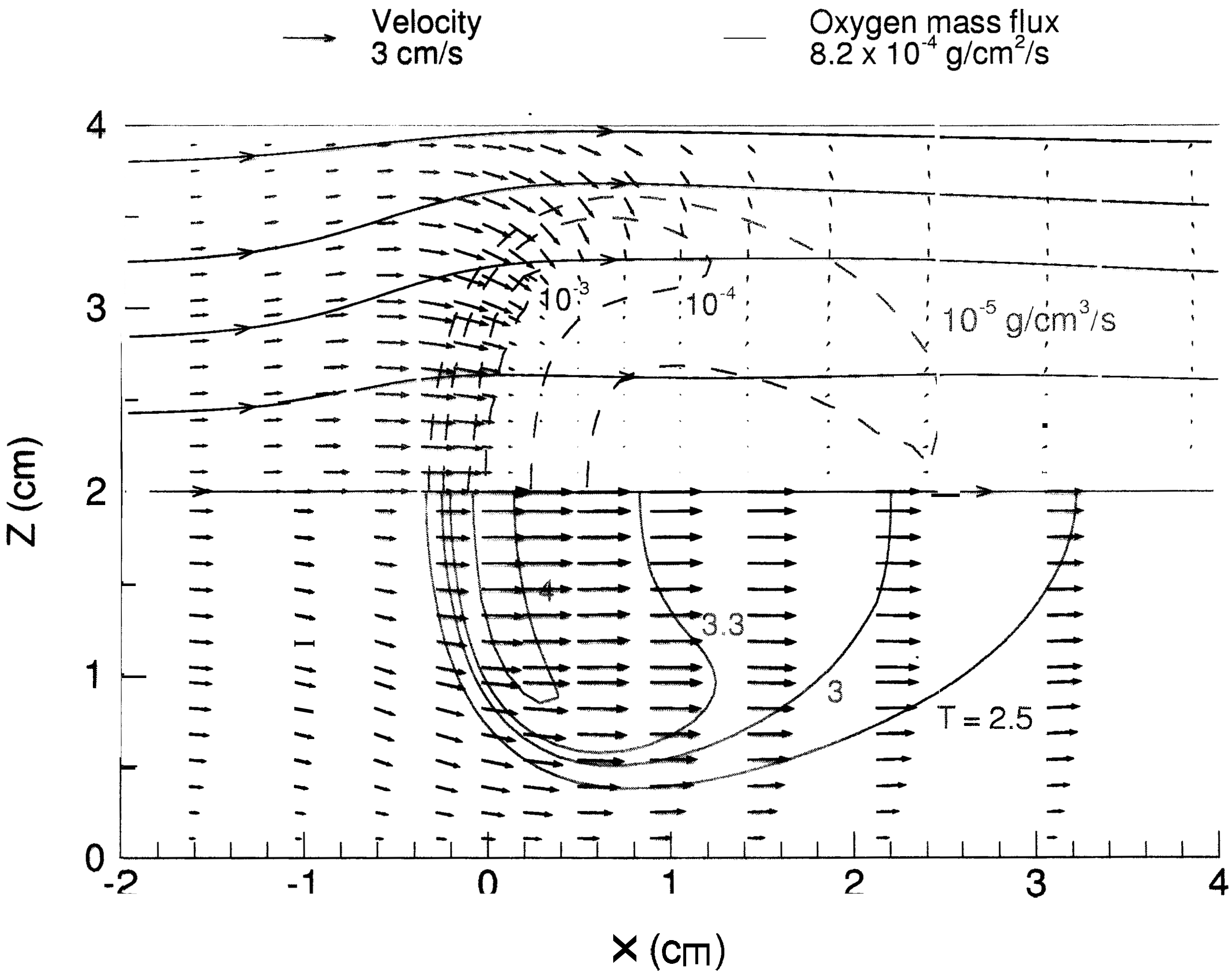
Steady flame spread rate v.s. Molar oxygen percentage

(2cm , 4cm width solid and 2D case)

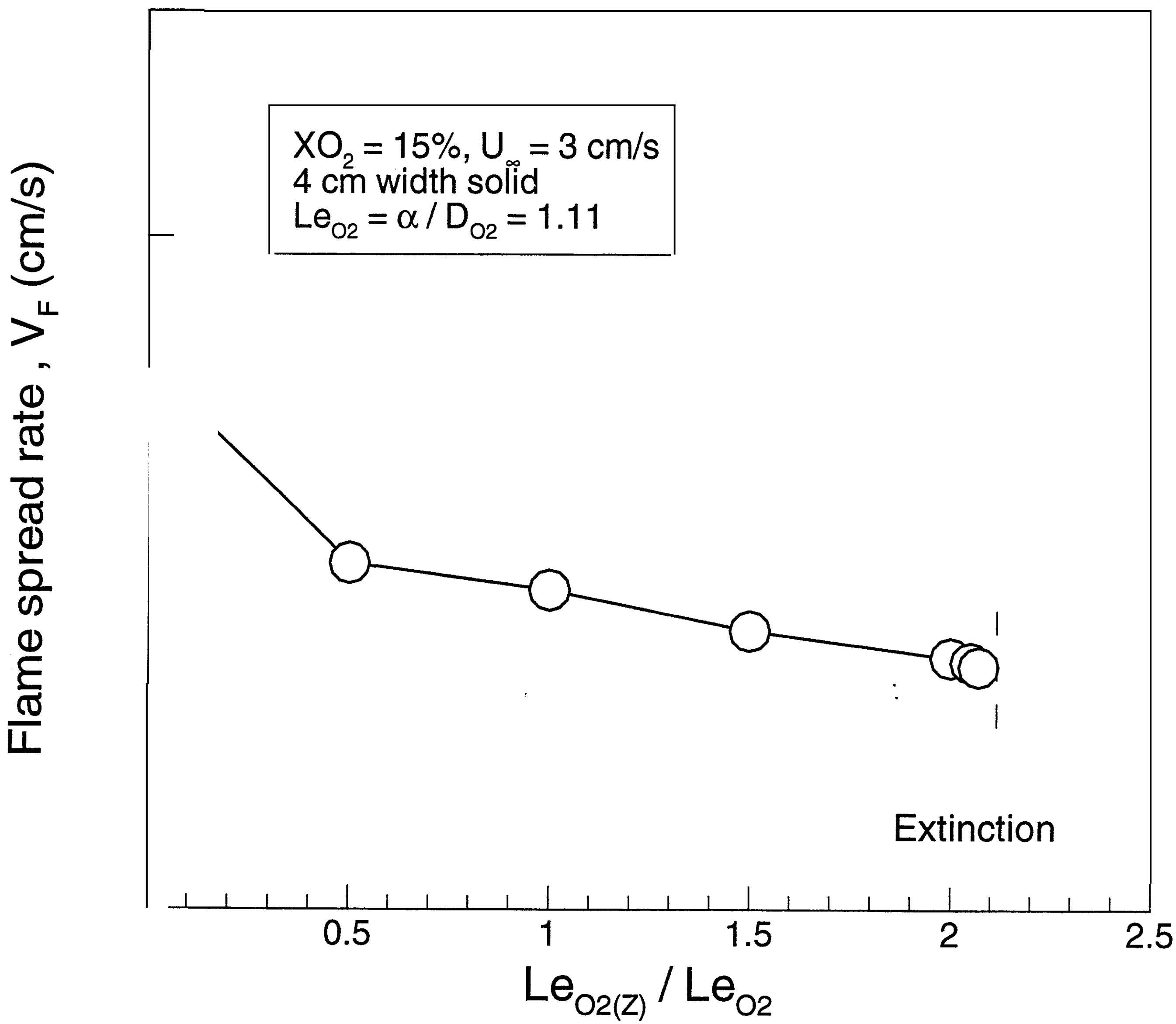


3D Flame structure on the horizontal plane

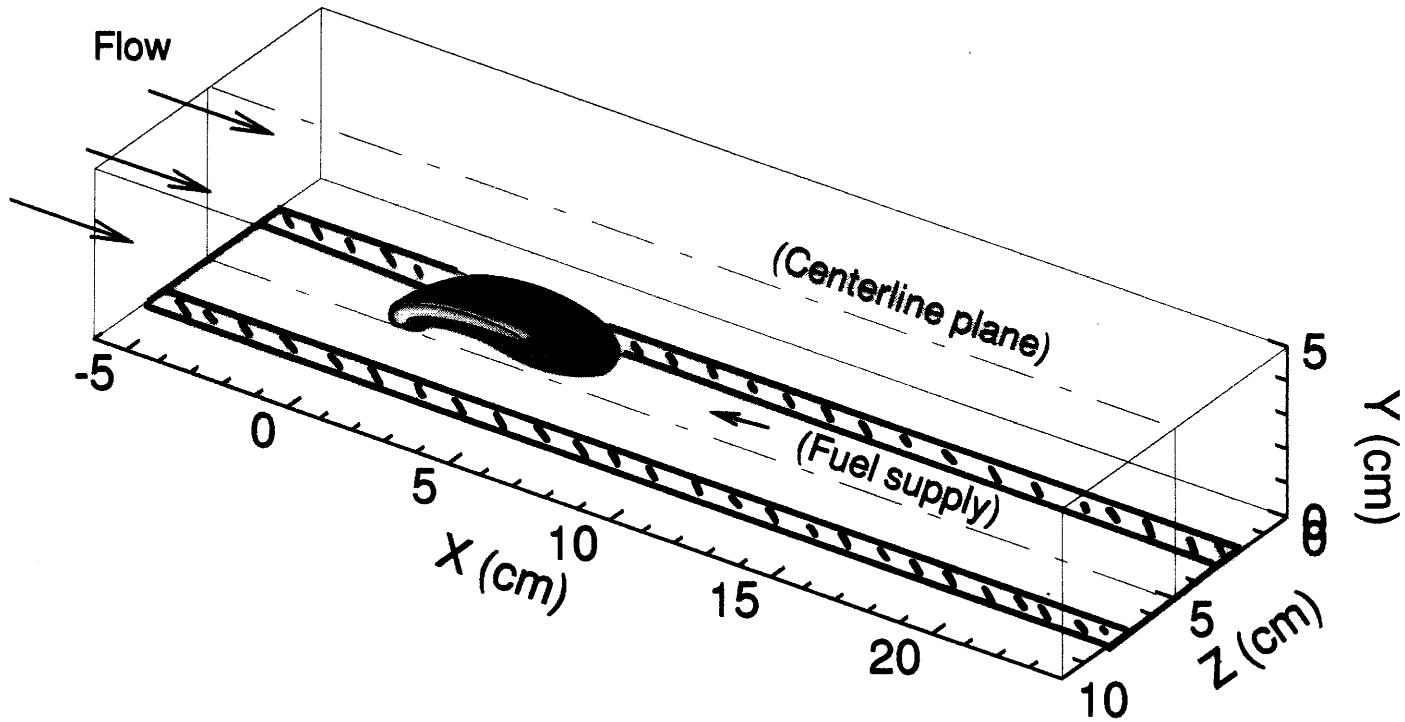
(15% O_2, 3 cm/s, 4cm solid width, plane of Y = 0.28 cm)



Flame spread rate v.s. Lewis number of oxygen$_{(Z)}$



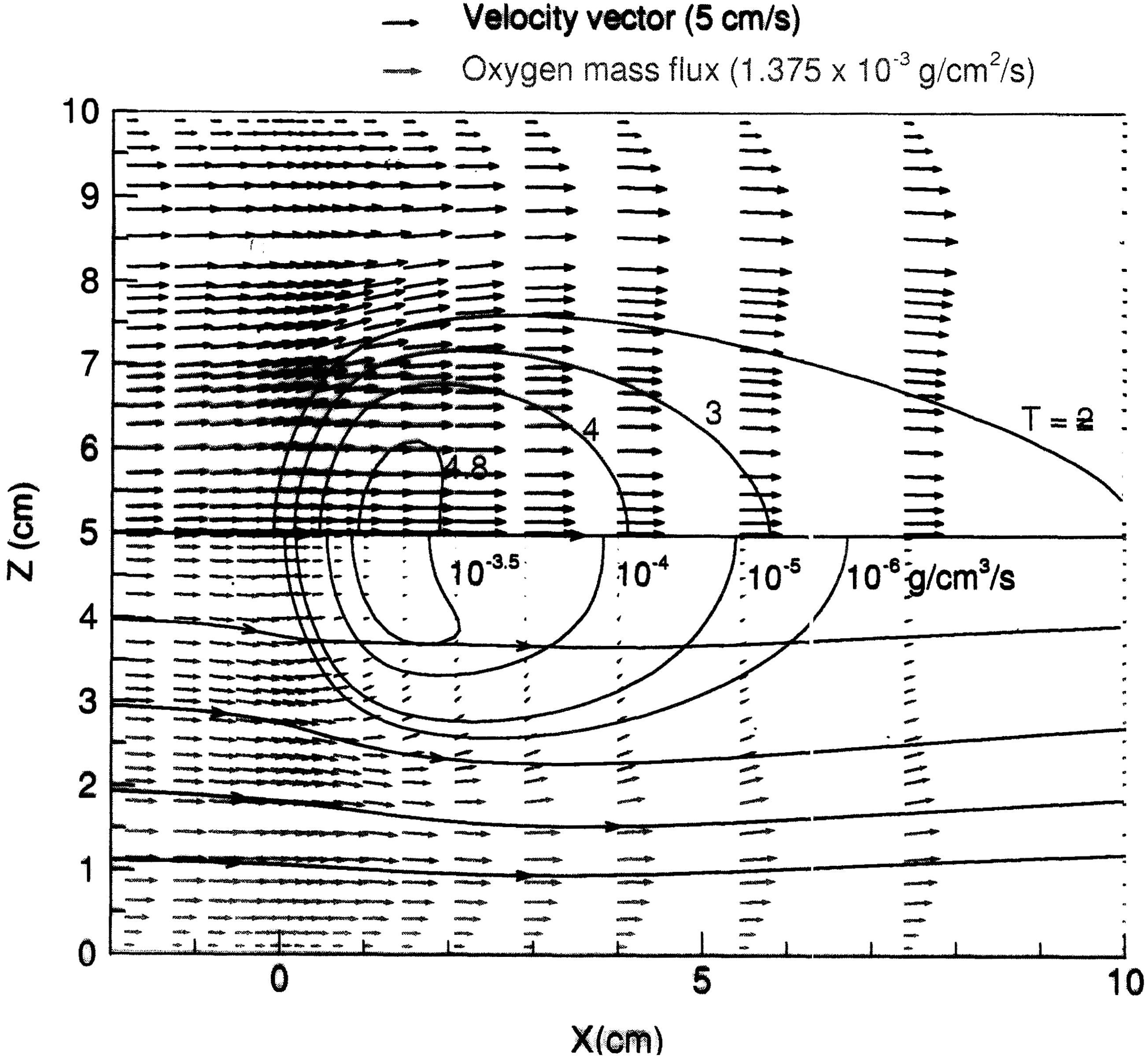
Three-dimensional flame simulation in the FEANICS tunnel



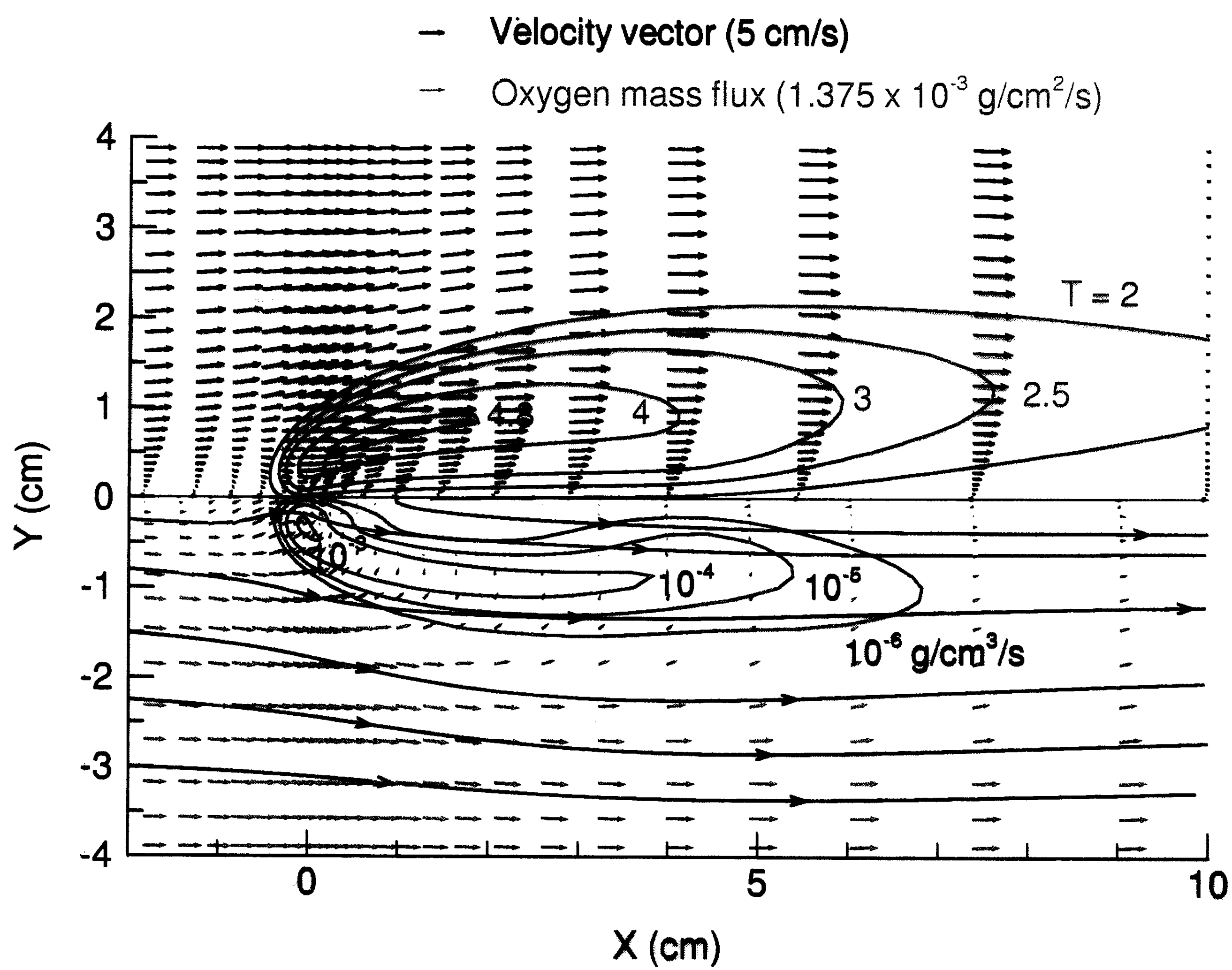
* Tunnel dimensional: 30 cm x 10 cm x 10 cm
XO_2 = 15%, U_∞ = 5 cm/s

* 4-cm solid (80% Kimwipes, 20% inert) + 1-cm inert strips
The thermal inertia of strip is 100 times of the fuel

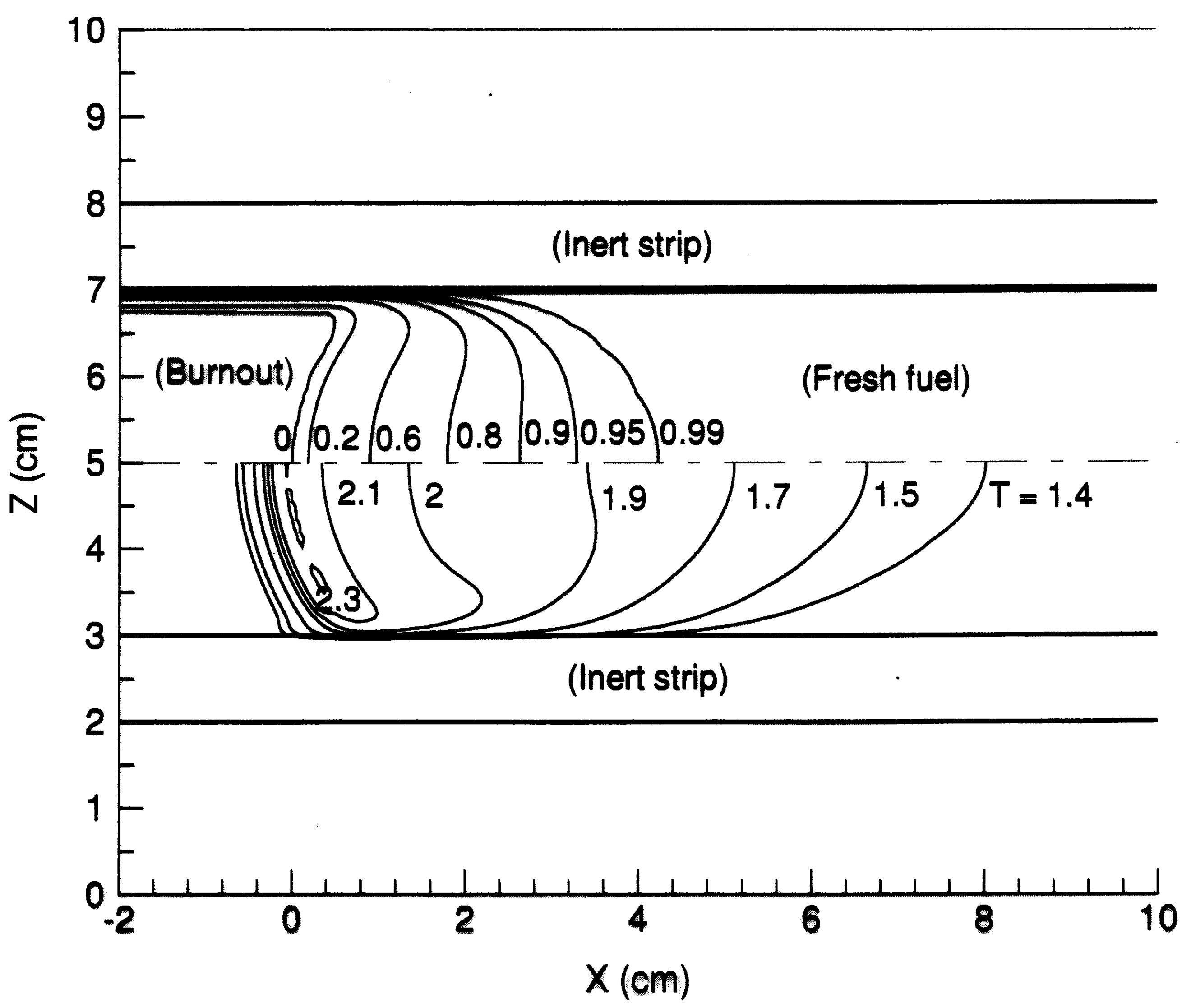
Flame structure on the horizontal plane (Y=8.5 mm)

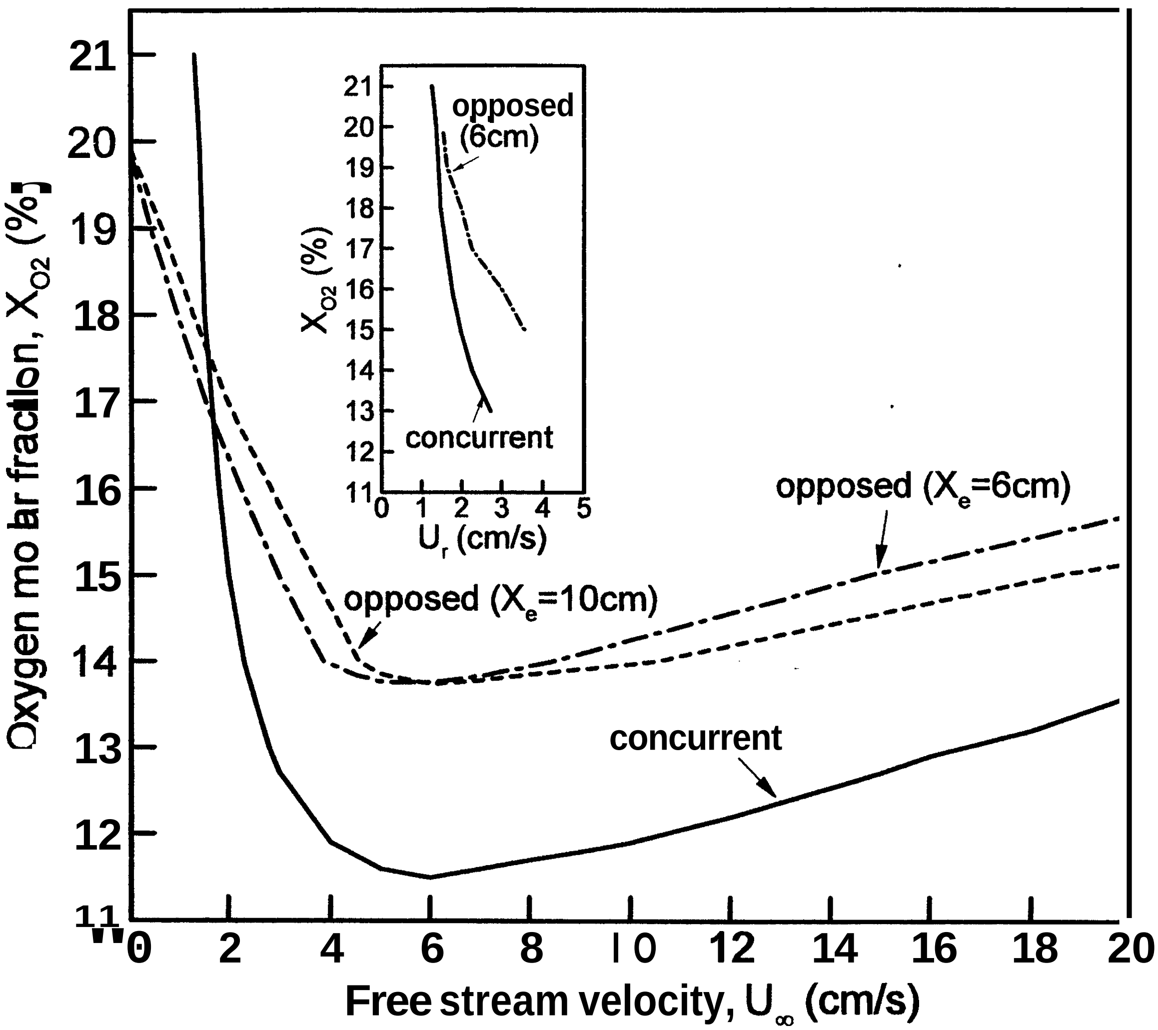


Flame structure on the centerline plane



Solid thickness and solid temperature profiles




opposed (6cm)
concurrent
X_{O2} (%)
U_r (cm/s)
opposed (X_e=6cm)
opposed (X_e=10cm)
concurrent
Oxygen molar fraction, X_{O2} (%)
Free stream velocity, U_∞ (cm/s)

Current Capability of Detailed Models

Fluid mechanics:
- Laminar
- Steady and unsteady
- 2-D and 3-D
- Forced, buoyant and mixed flows

Heat transfer:
- Radiation
  - Gas species: Spectral (1-D only)
    Gray gas (2-D)
  - Soot: need capability to model formation
  - Interaction with solid surface: Solution of radiation transfer equation and solid radiation properties

Gas-phase chemistry:
- One-step overall finite rate kinetics (empirical)

Solid thermal decomposition:
- One or two steps

Solid in-depth processes:
- Heat conduction only

Possible Application of Current Models:
(With minor amendment)

(1) Mechanism(s) of flame growth limit

(2) Solid flame spread in an atmosphere with fuel vapor and transition to flashback

(3) Suppression of incipient fires

Longer-term Research Needs to Improve Model Capabilities:

(1) Detailed gas-phase kinetic data and their implementation into the model

(2) Solid thermal decomposition processes including char formation and oxidation

(3) Efficient multi-dimensional computation scheme for flame radiation and flame-radiation coupling. Radiative properties of solids.

(4) Turbulent flame over solid? (enough!)

Detailed models can be very useful contributors to the fire safety research effort!