11th Premixed Turbulent Flame Workshop, Montreal, August 9-10, 2008

LES and laser diagnostics of a low swirl methane/air flame

K. Nogenmyr, P. Petersson,
X. S. Bai, M. Linne, M. Alden
Lund University, Sweden

C. Fureby
FOI – Swedish defense research agency

Sponsored by
Swedish Centre for Combustion Science
and Technologies (CeCOST)

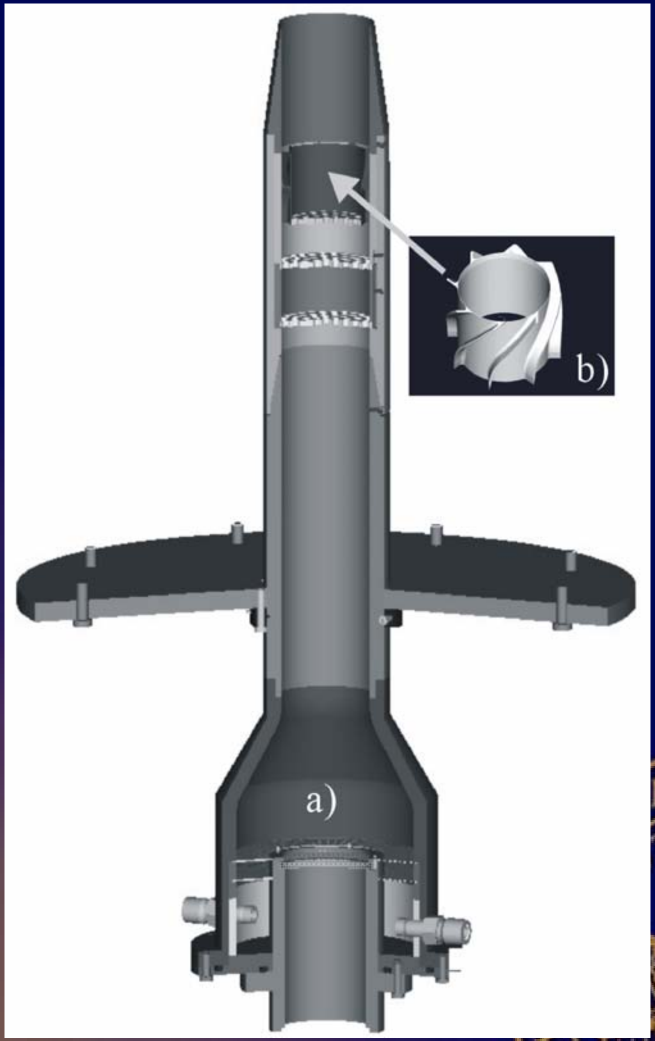
Swedish CeCOST Modeling Project

Lund University, Chalmers University of Technology, FOI

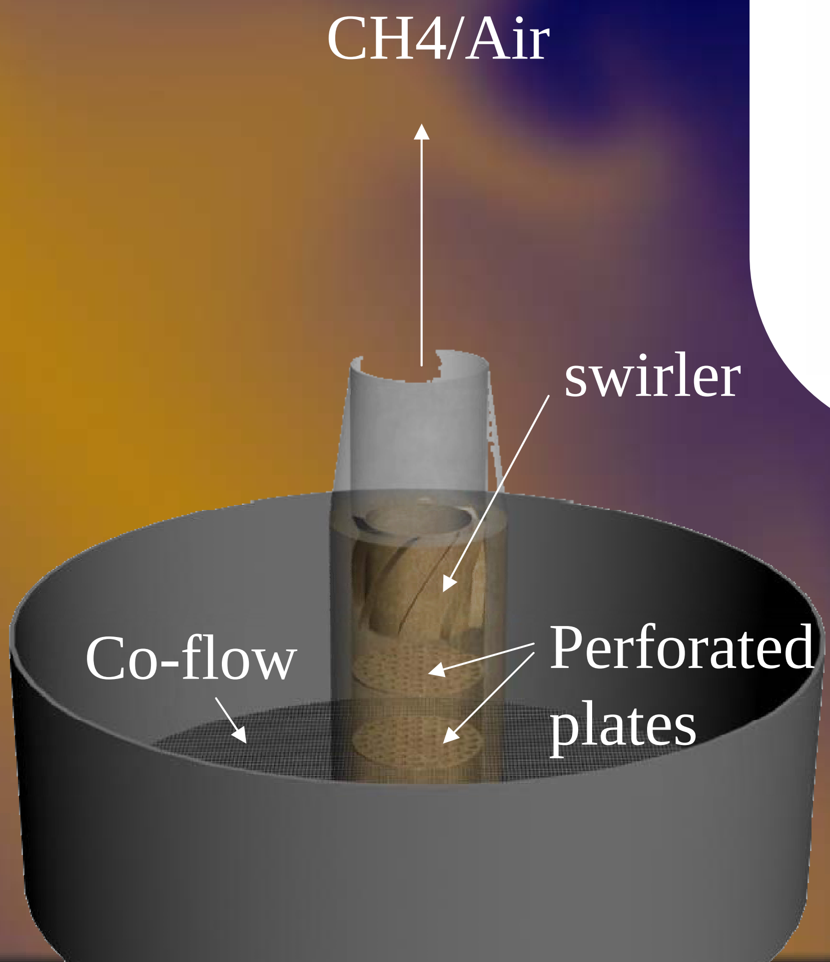
- Industry motivation – low NOx Gasturbine combustion
    - Lean premixed flames, thin reaction zone regime
- Develop and validate models for turbulent premixed flames in the thin reaction zone regime
- Develop validation data base for turbulent premixed flames in the thin reaction zone regime using laser diagnostic methods
- Improve the understanding of flame/flow interaction in turbulent premixed flames

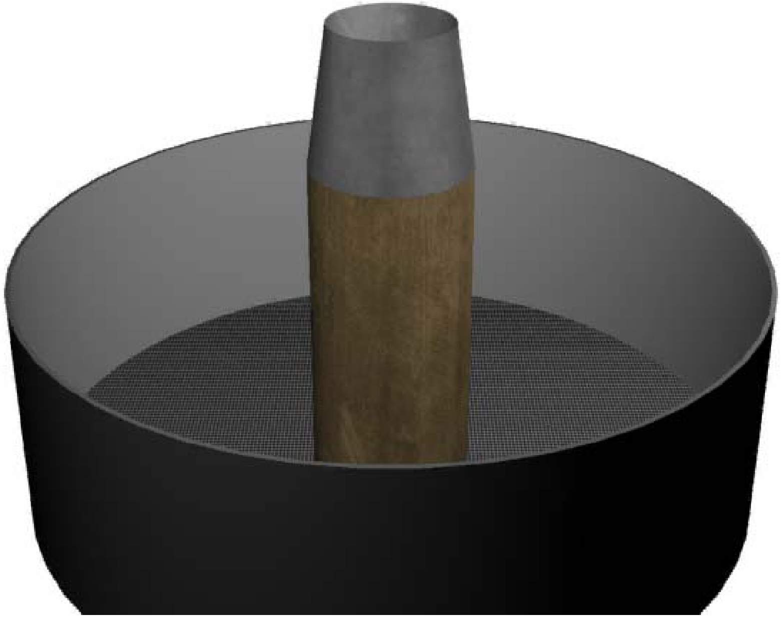
Low swirl burner

- R.K. Cheng et al. (1995)
- Low NOx, low noise, low PVC ...
- A burner chosen for validation of simulation models
- Lund, Darmstadt ...



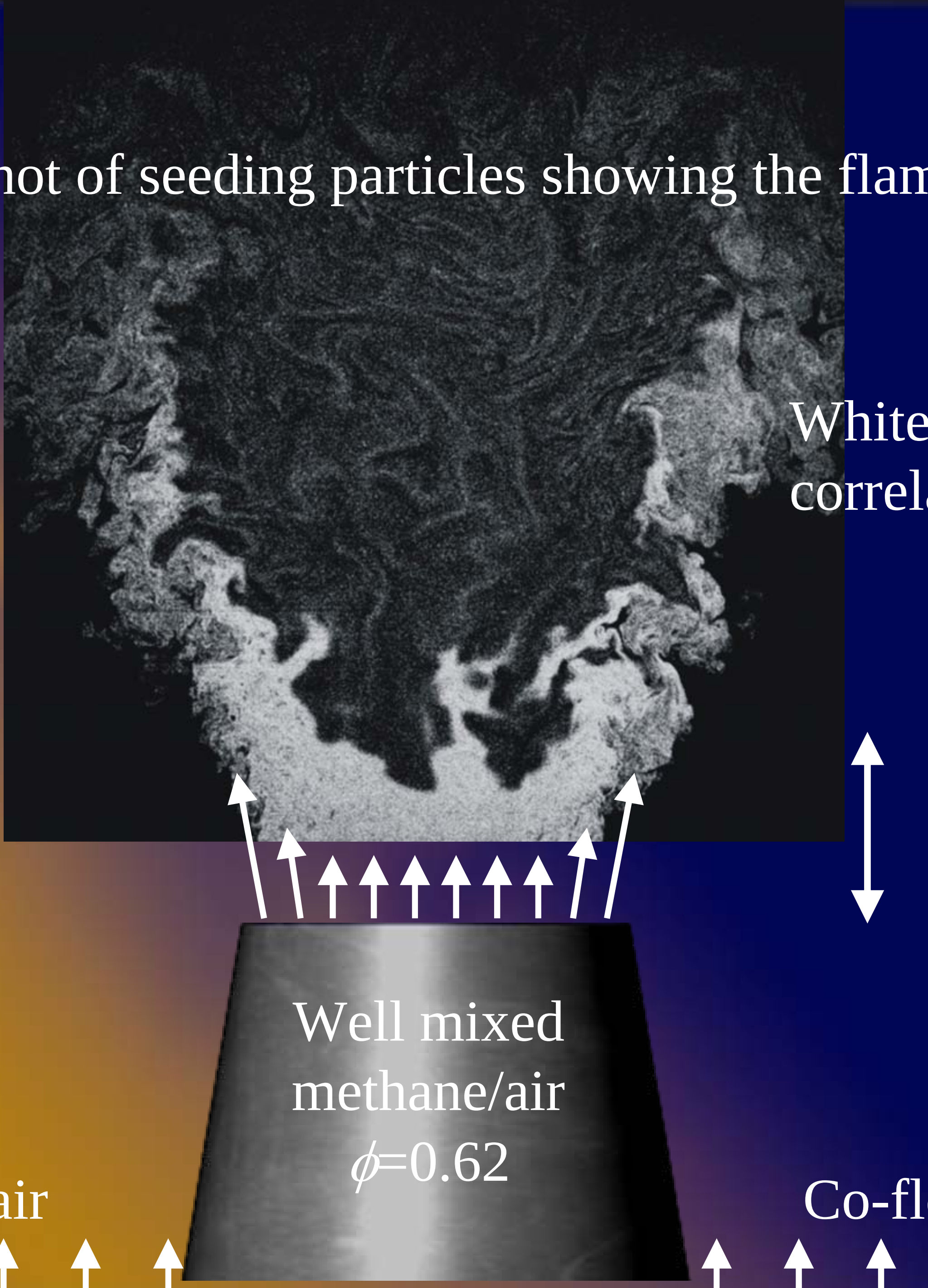
Burner details





40 % through plate
60 % through swirler

⇒ Swirl number 0.55



Snap-shot of seeding particles showing the flame front

White zone likely correlated to fuel

Lift-off
x/D=0.65

Re: 20000
Ka: 0.13 – 18
u’: 0.5 – 2 m/s
U: 2 – 10 m/s
Coflow: 0.3 m/s

Well mixed
methane/air
ϕ=0.62

Co-flow of air

Co-flow of air

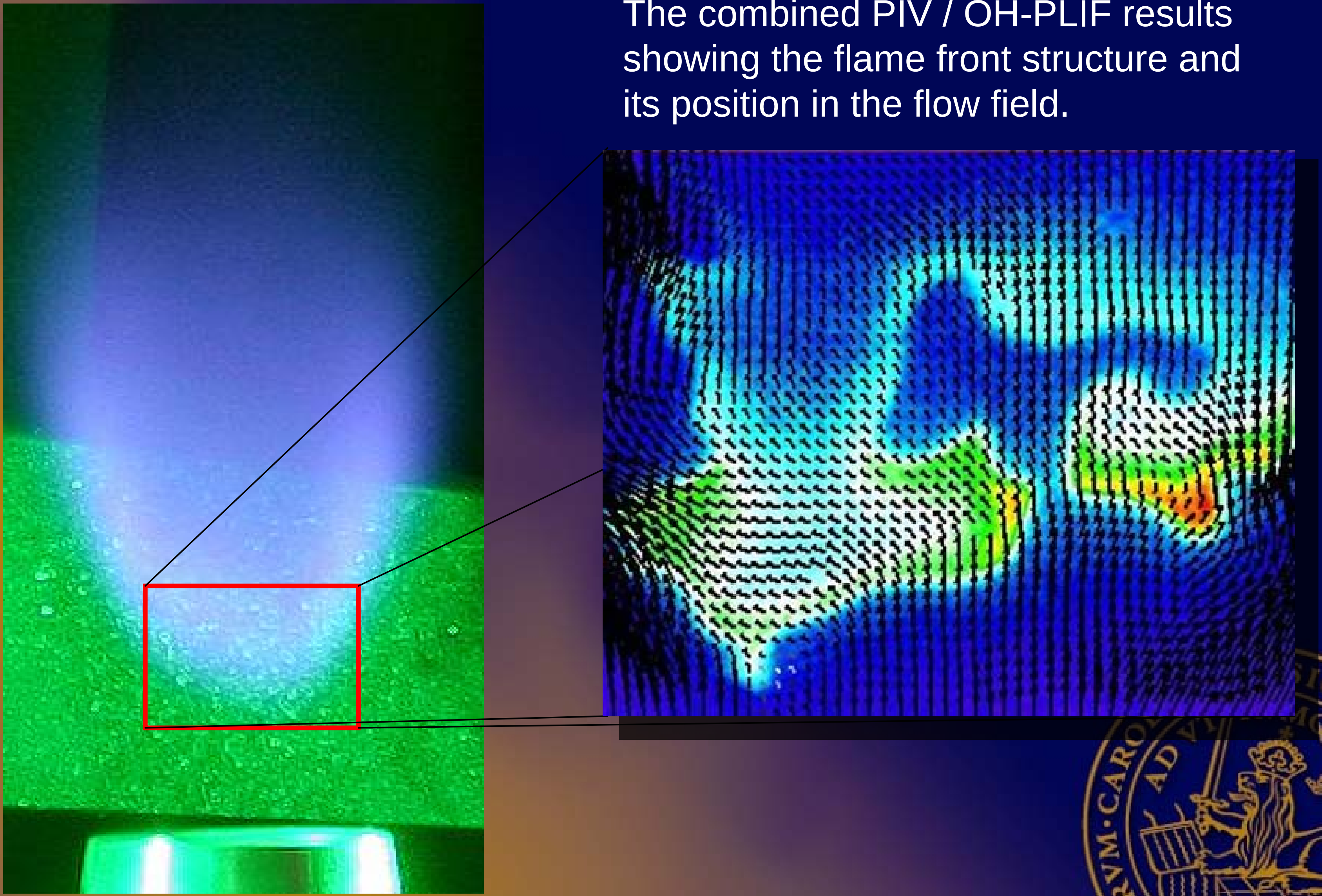
Summary of investigations

- Laser diagnostics
  - 3-component PIV at the plane 1 mm above the burner
  - 2-component PIV
  - Simultaneous OH PLIF and PIV
  - Filter Rayleigh scattering for 2D temperature field
  - Simultaneous PLIF of OH and acetone (fuel tracer)
  - Statistical fields: velocity, temperature, fuel, OH

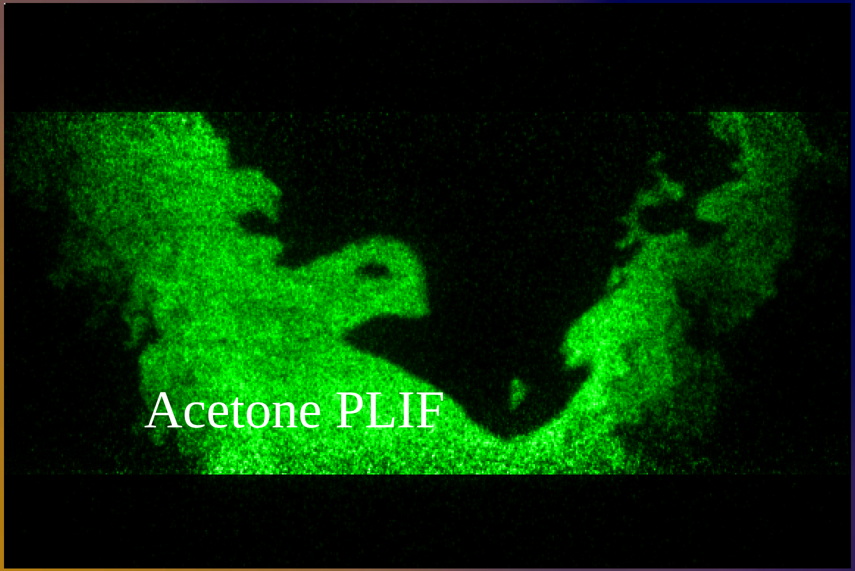
- Model development and validation
  - Flamelet type models: two-scalar flamelet model (mixture fraction and level-set G-function)
  - Thickened flame model based on reduced chemistry

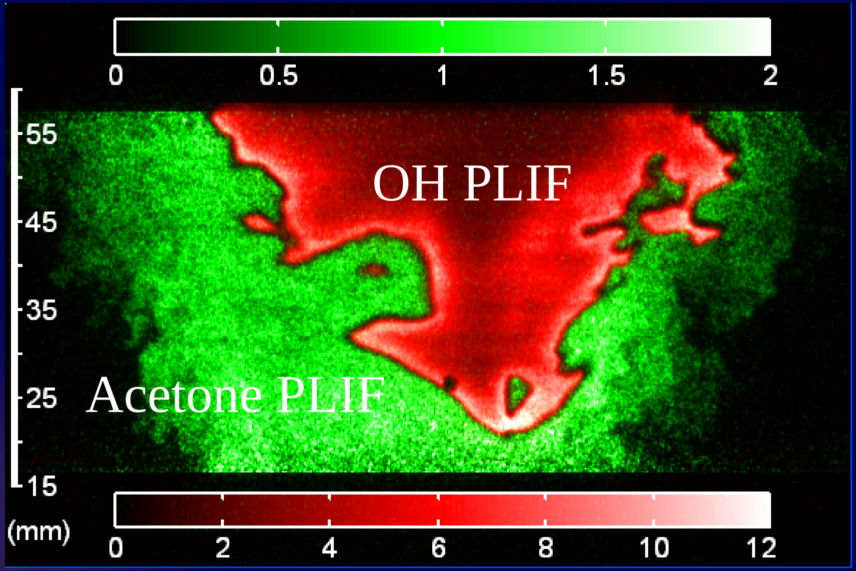
Simultaneous PIV / PLIF

The combined PIV / OH-PLIF results showing the flame front structure and its position in the flow field.



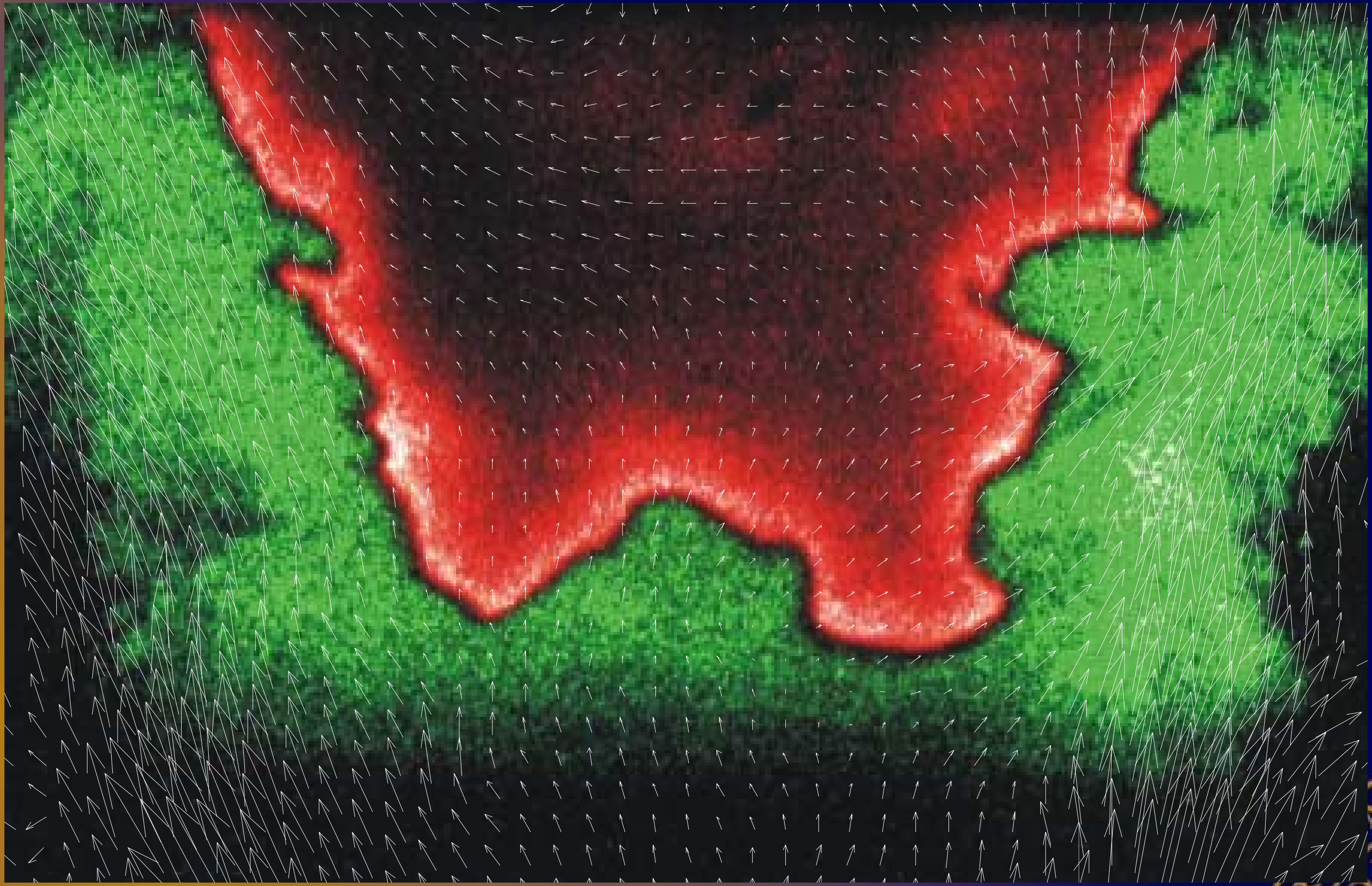
Simultaneous OH/acetone PLIF



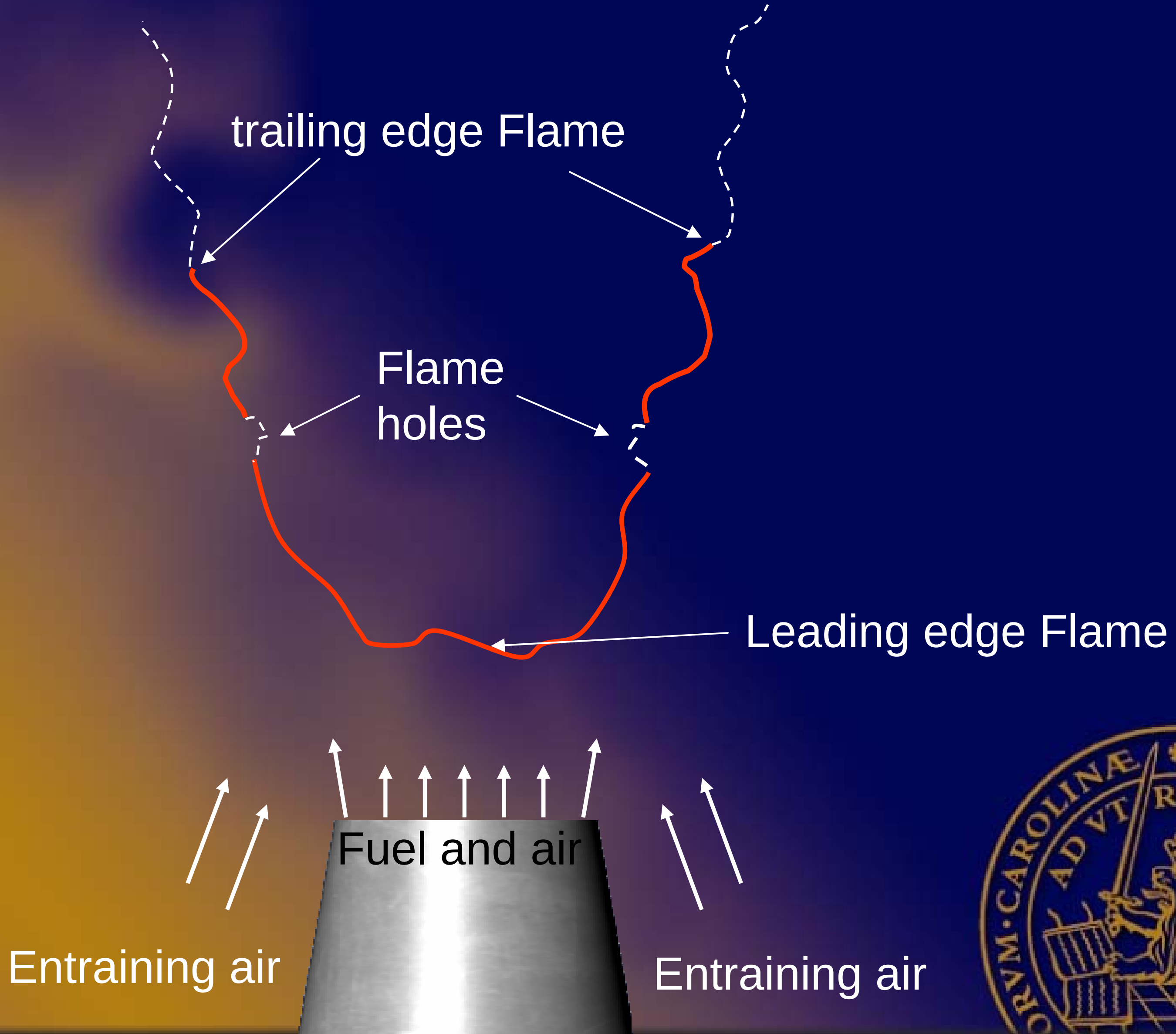


- Acetone as a fuel tracer
    - fuel leaks due to stratification
- fuel consumption zone and OH formation zone do not overlap
    - flamelet combustion?

Simultaneous PIV, OH/acetone PLIF



Flame front tracker and level-set approach



trailing edge Flame

Flame holes

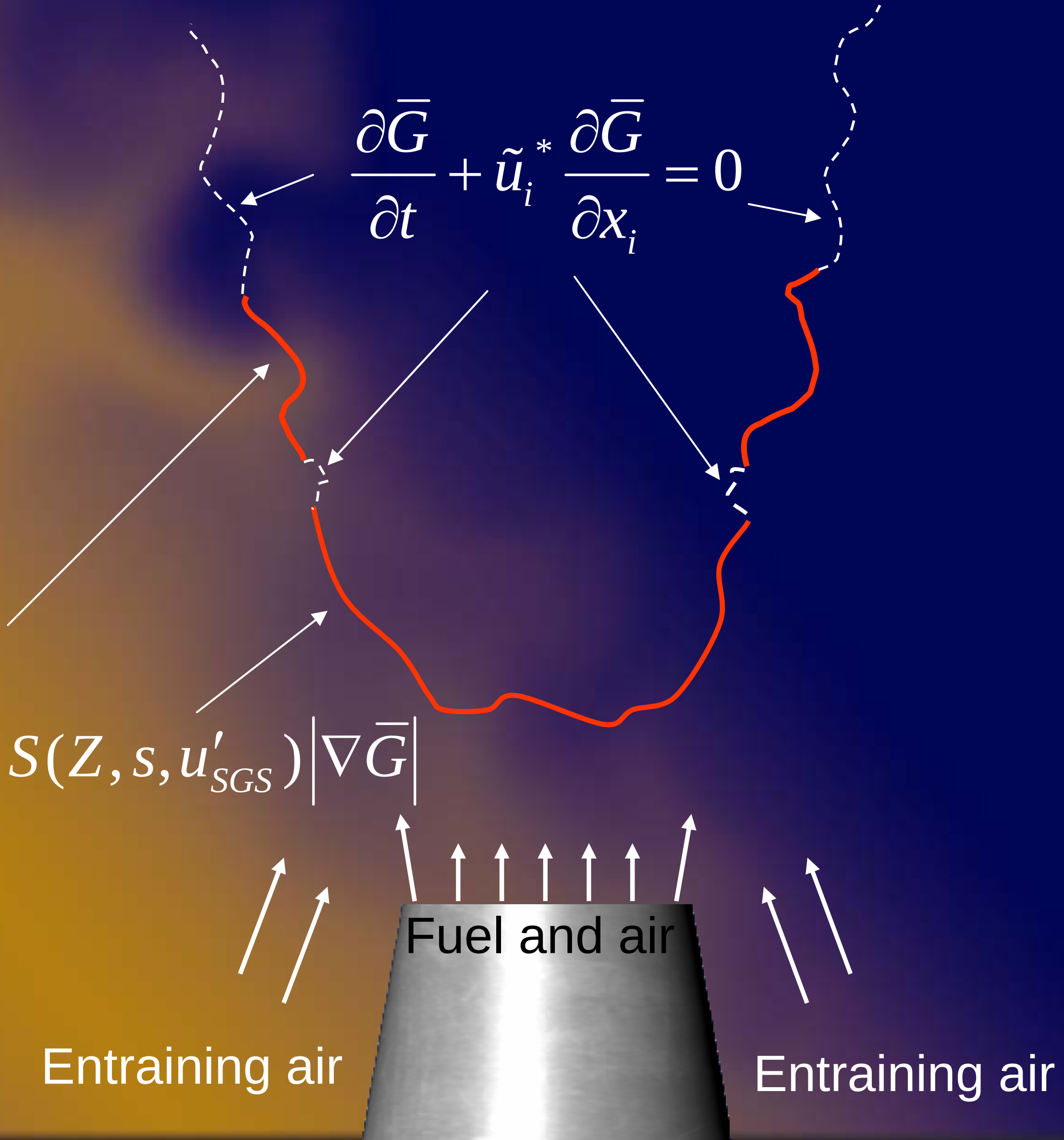
Leading edge Flame

Fuel and air

Entraining air

Entraining air

Flame front tracker and level-set approach



$$\frac{\partial \bar{G}}{\partial t} + \tilde{u}_i^{\,*} \frac{\partial \bar{G}}{\partial x_i} = 0$$

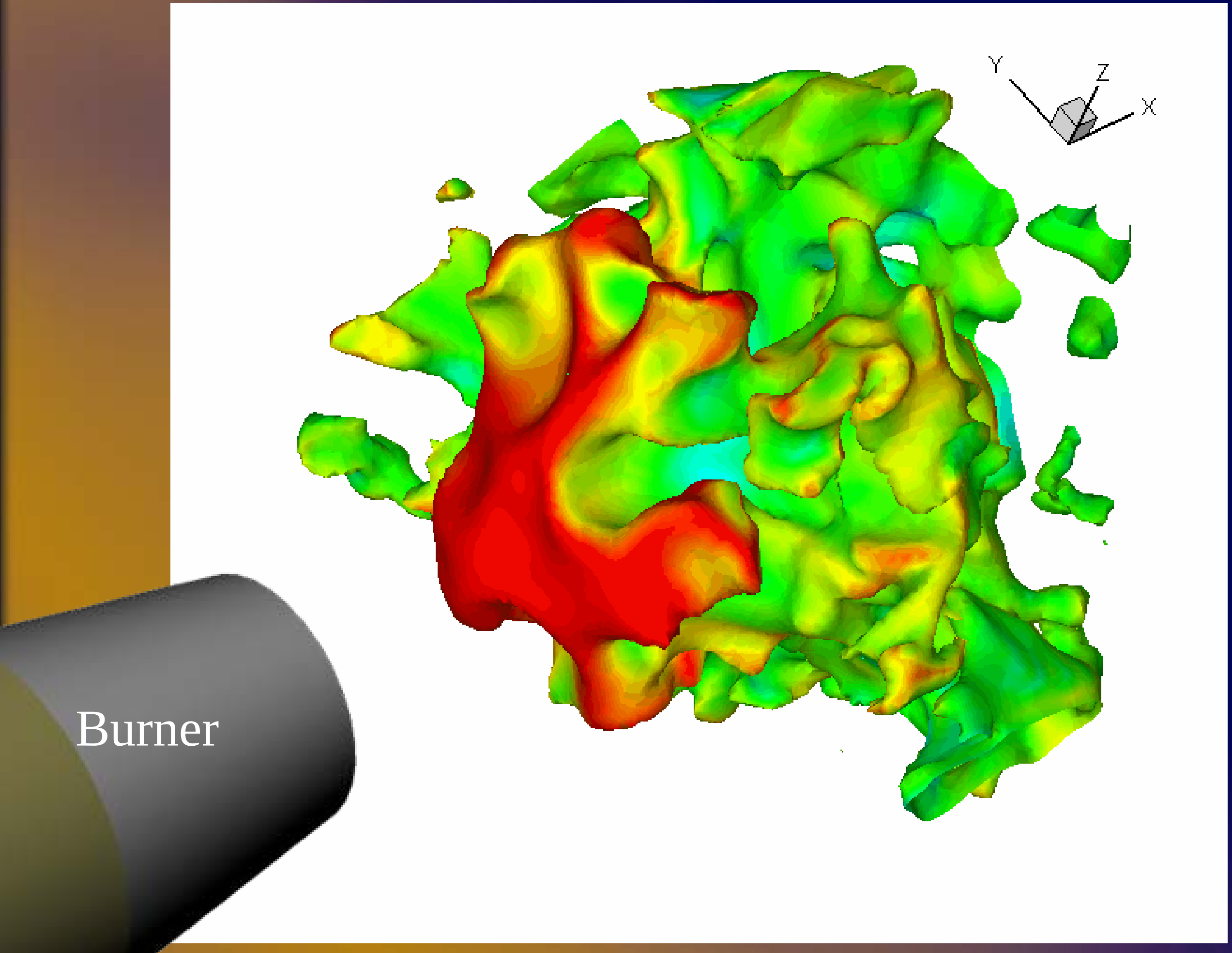
$$\frac{\partial \bar{G}}{\partial t} + \tilde{u}_i \frac{\partial \bar{G}}{\partial x_i} = S(Z, s, u'_{SGS}) \left|\nabla \bar{G}\right|$$

Fuel and air

Entraining air

Entraining air

Simulation of the flame holes using level-set approach



Snap shot of flame surface colored by mixture fraction. Flame front is highly affected by turbulence.

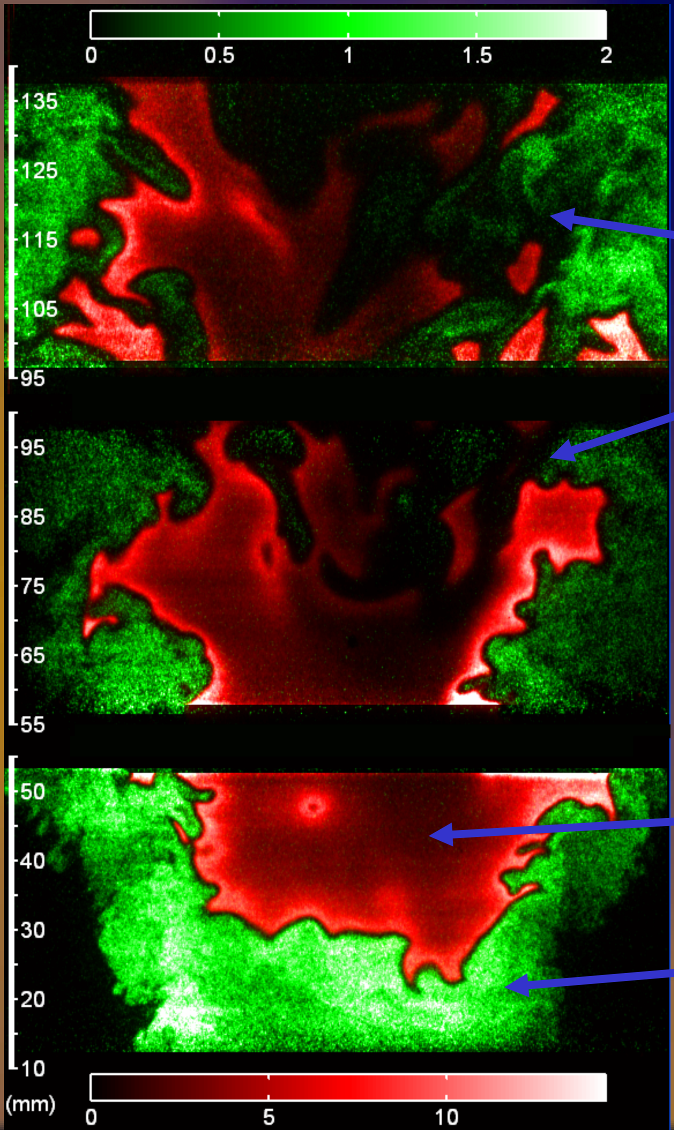
<u>Combustion model:</u>

- Mixture fraction T.E.
- Fuel T.E.
- Flame front by Level-set G
- OH radical T.E.

- Inner layer chemistry by flame-let library approach extended to stratified mixtures.

Stratification effects – flame quenching

Fuel and OH-PLIF

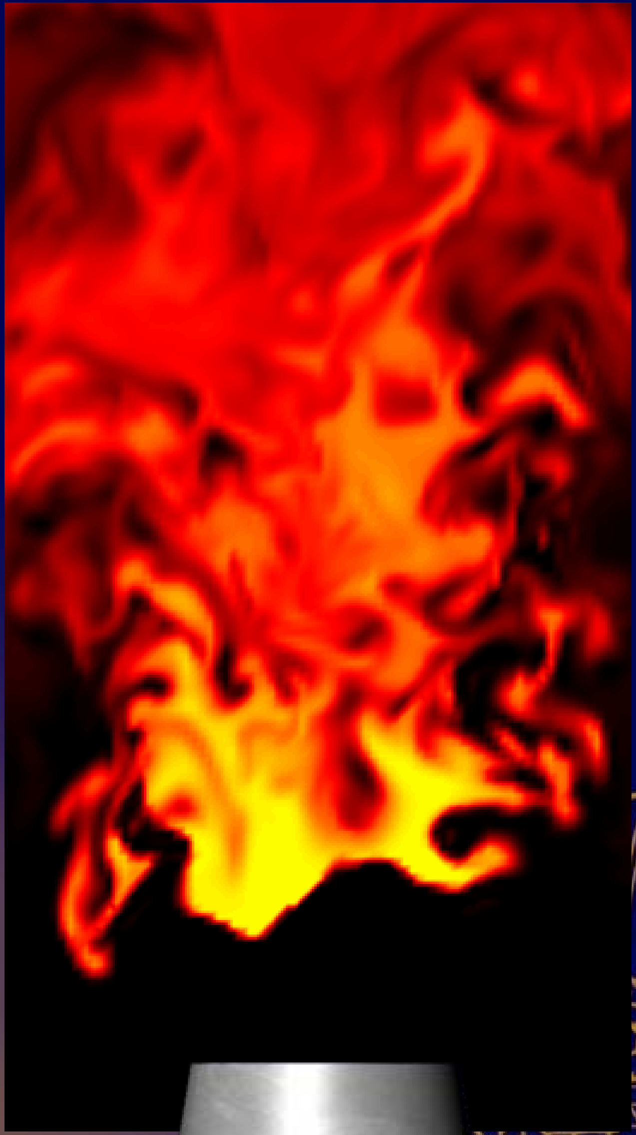


Air pockets entrained into the flame

OH

Acetone

LES Temperature



Published data source

- Nogenmyr et al, Proc Combust Inst 31 (2007) 1647-1675
- Petersson et al, Applied Physics 46 (2007) 3928-3936
- Nogenmyr et al., Combustion and Flame (2008) in press

- Web site for the data under construction

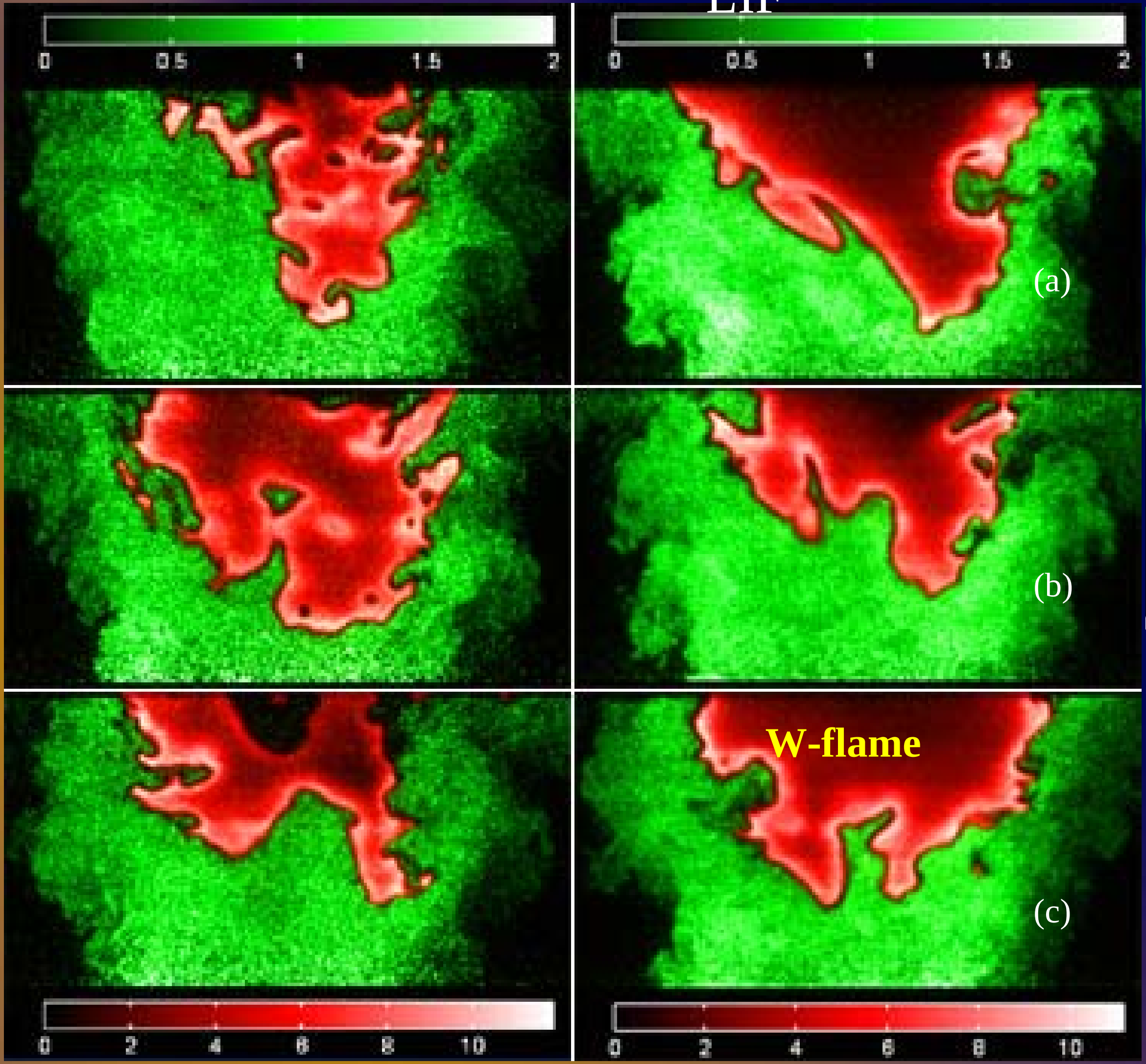
Mean flame position (’lift-off height’) and mechanism of flame stabilization

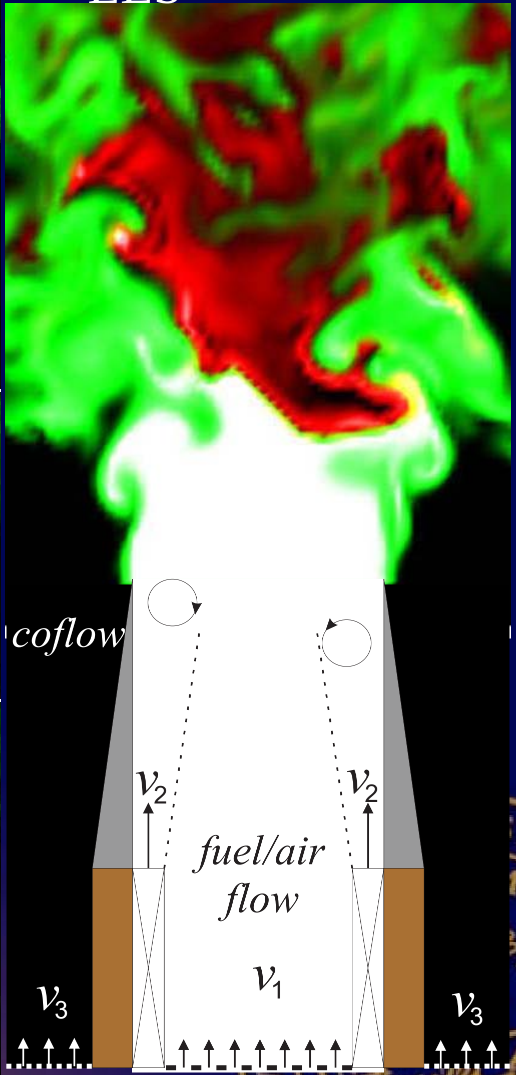
Flame stabilization

Re 30000,
LIF

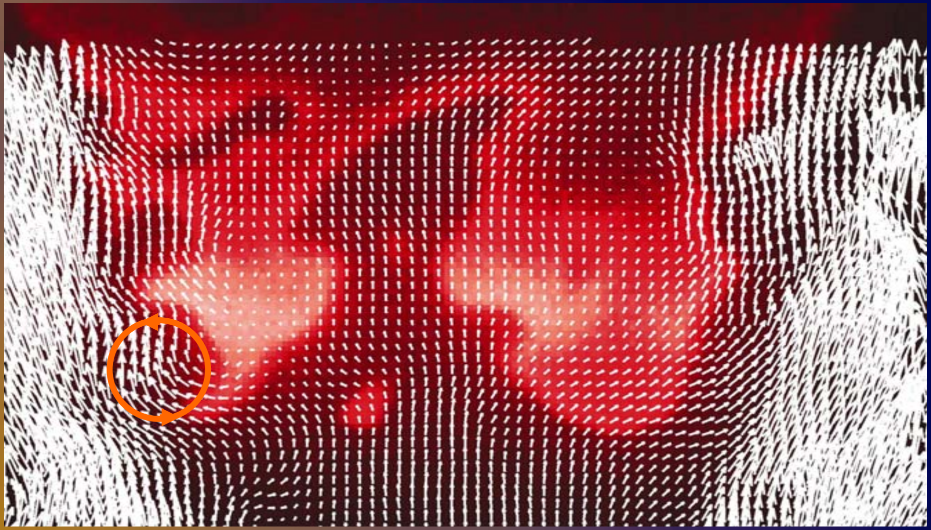
Re 20000,
LIF

Re 20000,
LES

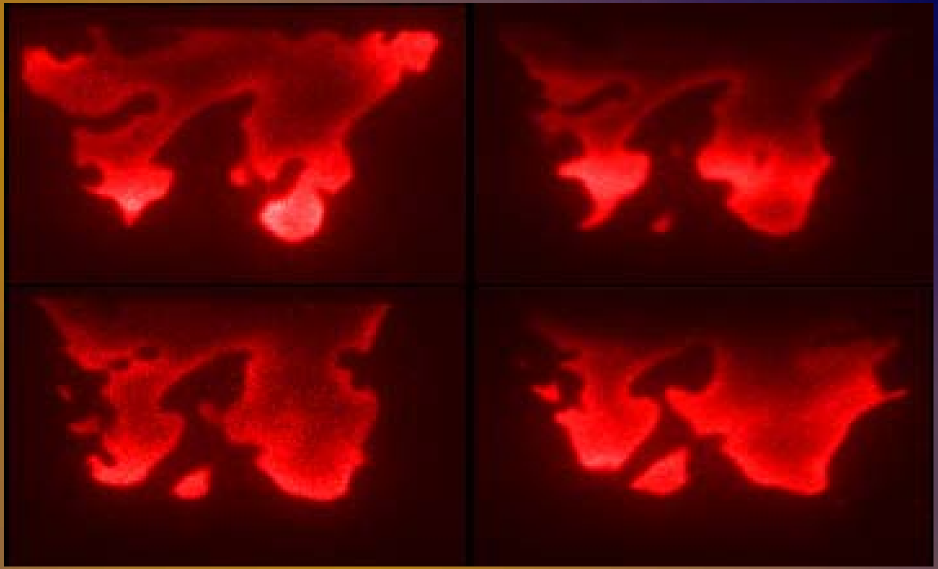




Time evolution of the temperature and velocity field

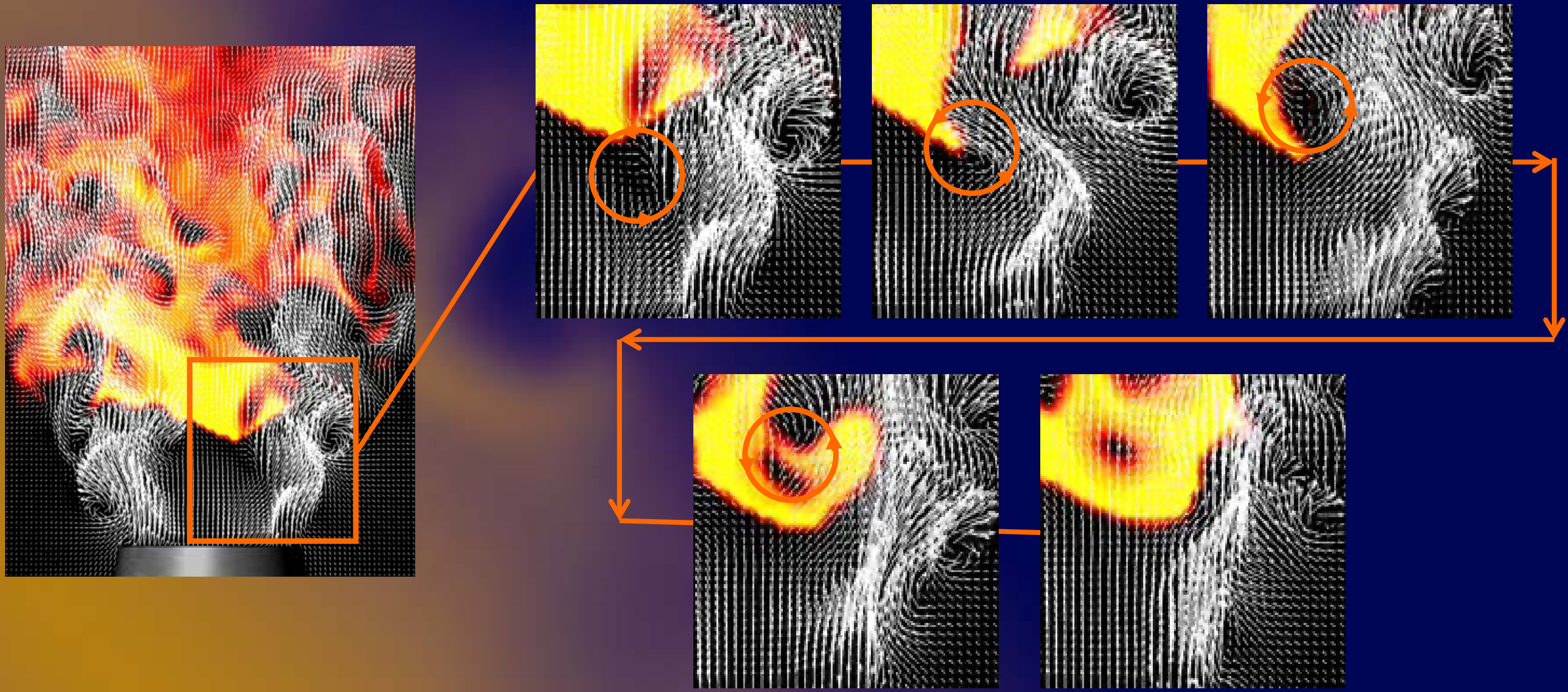


Simultaneous PIV/OH PLIF
1.6 ms frame rate



Time separation 1.6ms

Time evolution of the temperature and velocity field



The flame is stabilized by large vortices formed in the shear layer in the burner.

Traditional RANS models fail to capture such a mechanism,
due to the strong dependence on the large scale structures.

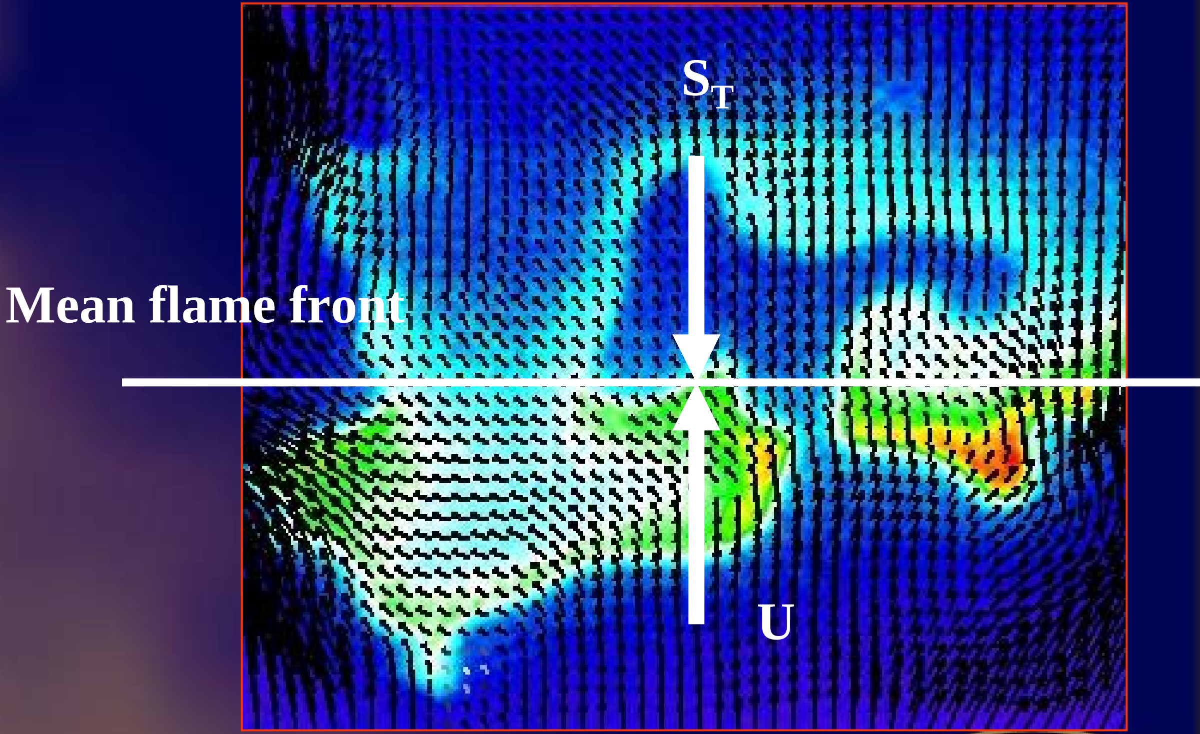
Flame stabilization

- It appears that the flame is not stabilized by the low speed central core zone, but rather it is the high speed shear-layer where large scale vortex shedding structures hold the flame
- LES seems predicted the large scale vortex shedding and thus the flame fronts
- Can RANS type model do the work
- Can we use the experimental data to determine the turbulent speed (controversy starts here …)

Mean flame position
(RANS mean planar flame model)

$$\begin{array}{ccc} \cancel{\dfrac{\partial \bar{G}}{\partial t}} & + \tilde{u}_i \dfrac{\partial \bar{G}}{\partial x_i} & = S_T \left|\nabla \bar{G}\right| \\ \swarrow & \downarrow & \downarrow \\ 0 & \mathbf{U} & \mathbf{S_T} \end{array}$$

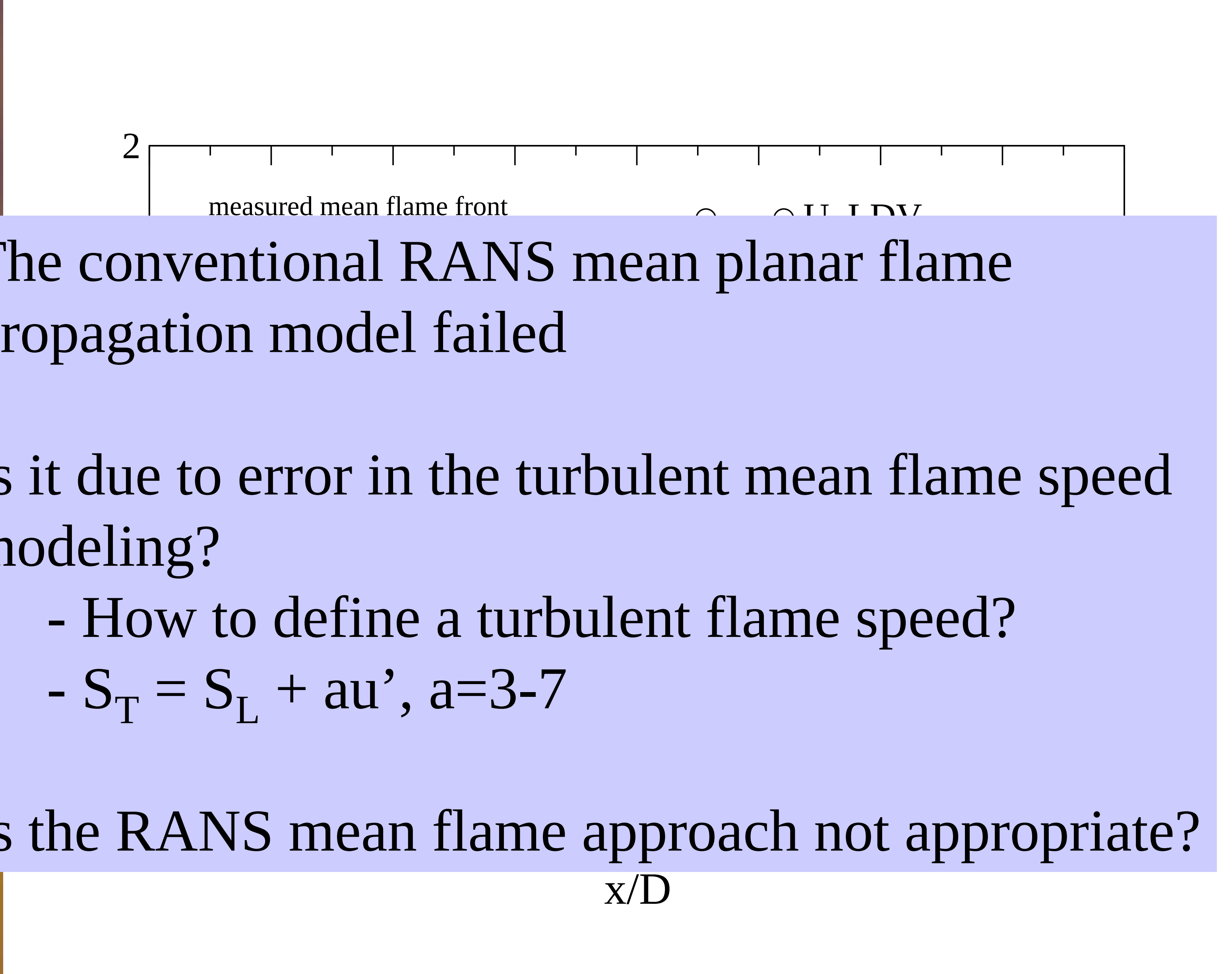
$\longrightarrow$ **$U = S_T(S_L, u')$**



S_T models:

Damköhler, Peters, Gulder, Bradley …

Mean flame position



The conventional RANS mean planar flame propagation model failed

Is it due to error in the turbulent mean flame speed modeling?

- How to define a turbulent flame speed?
- $S_T = S_L + au'$, a=3-7

Is the RANS mean flame approach not appropriate?

Summary

- A low swirl flame database developed
  - A challenging and interesting case
  - Inflow rather complex to accurately characterize
- Model development and validation
  - Flamelet model accounting for local extinction
  - Compared also with thickened flame model
- Flame stabilization
  - Original speculation of low speed zone stabilization may not be true
  - Shear-layer large-scale vortex shedding may be responsible for the flame stabilization