COMBEX-2013, Ramsau, Austria

Large Eddy Simulation of bluff-body stabilized flames using novel Flame Tracking method

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Outline

- **Flame tracking-particle method**
- **Validation results**
- **First LES calculations**
- **Flame stabilization with flame holder**
- **3D piloted premixed Bunsen burner**
- **Conclusions**

Background

Frolov S.M., Ivanov V.S., Smetanyuk V.A., Basara B., Suffa M. Numerical simulation of propane - air turbulent flame acceleration in straight tubes of different length. **2009**

Frolov S.M., Ivanov V.S., Smetanyuk V.A., Basara B. Tracking of propagating turbulent flames and autoignition in enclosure. **2009**

Frolov S.M., Ivanov V.S. Combined Flame Tracking - Particle method for numerical simulation of deflagration-to-detonation transition. **2010**

Ivanov V. S., Frolov S. M. Numerical simulation of the operation process and thrust performance of an air-breathing pulse detonation engine in supersonic flight conditions. **2011**

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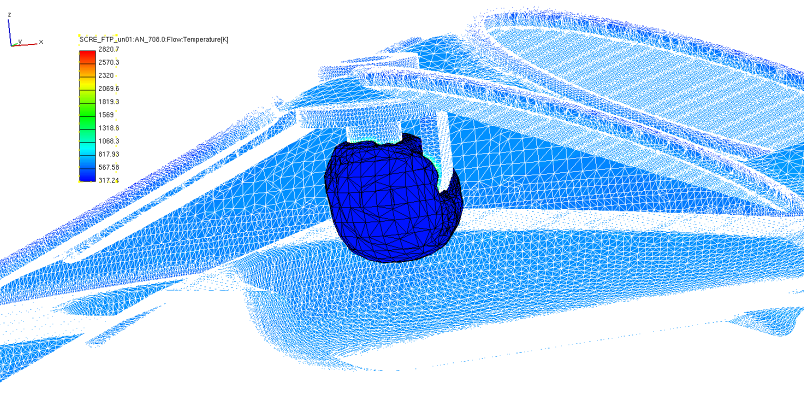
2012



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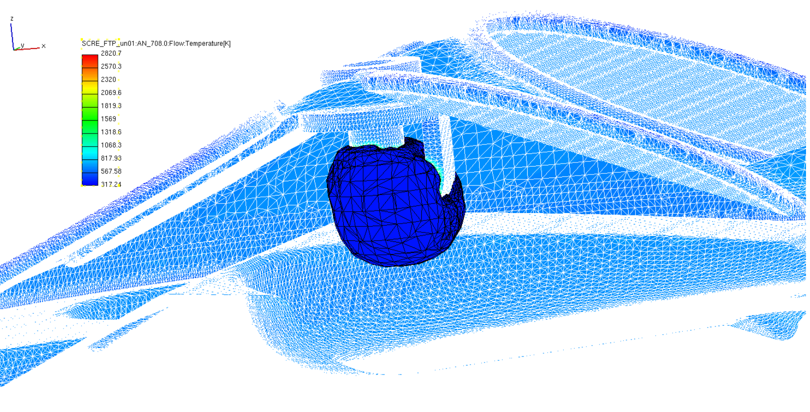

→ LES modeling

Objective:

develop a coupled Large Eddy Simulation – Flame Tracking method for premixed combustion

RANS vs. LES

RANS

$$
\begin{cases}
\dfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \\
\dfrac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{t}}), \\
\dfrac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot [\vec{u} \cdot (\boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{t}}) + +(\vec{q}_m + \vec{q}_t)] \\
\rho = pm/(RT)
\end{cases}
$$

m – molecular
t - turbulent

$$
\boldsymbol{\tau}_t = 2\mu_t \left(\mathbf{S} - \frac{1}{3} \mathbf{I} \, \nabla \cdot \vec{u} \right) + \frac{2}{3} k \, \mathbf{I}, \quad \vec{q}_t = -\lambda_t \nabla T
$$

LES

$$
\begin{cases}
\dfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \\
\dfrac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{SGS}}) \\
\dfrac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot [\vec{u} \cdot (\boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{SGS}}) + (\vec{q}_m + \vec{q}_{SGS})]
\end{cases}
$$

m – molecular
sgs - subgrid

$$
\boldsymbol{\tau}_{\mathbf{SGS}} = 2\mu_{SGS} \left(\mathbf{S} - \frac{1}{3} (\nabla \cdot \vec{u}) \mathbf{I} \right) + \frac{2}{3} k_{SGS} \mathbf{I}, \quad \vec{q}_{SGS} = -\lambda_{SGS} \nabla T
$$

Smagorinsky model

$$
\nu_{SGS} = (C_S \Delta)^2 S
$$

Smagorinsky constant (C_S)

cell size (Δ)

RANS vs. LES

RANS

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \\ \dfrac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{t}}), \\ \dfrac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot [\vec{u} \cdot (\boldsymbol{\tau}_{\mathbf{m}} + \boldsymbol{\tau}_{\mathbf{t}}) + +(\vec{q}_m + \vec{q}_t)] \\ \rho = pm/(RT) \end{cases}$$

m – molecular
t - turbulent

$$\boldsymbol{\tau}_t = 2\mu_t \left(\mathbf{S} - \frac{1}{3} \mathbf{I} \, \nabla \cdot \vec{u} \right) + \frac{2}{3} k \, \mathbf{I}, \quad \vec{q}_t = -\lambda_t \nabla T$$

LES

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m – molecular
sgs - subgrid

$$\boldsymbol{\tau}_{\mathbf{SGS}} = 2\mu_{SGS} \left(\mathbf{S} - \frac{1}{3} (\nabla \cdot \vec{u}) \mathbf{I} \right) + \frac{2}{3} k_{SGS} \mathbf{I}, \quad \vec{q}_{SGS} = -\lambda_{SGS} \nabla T$$

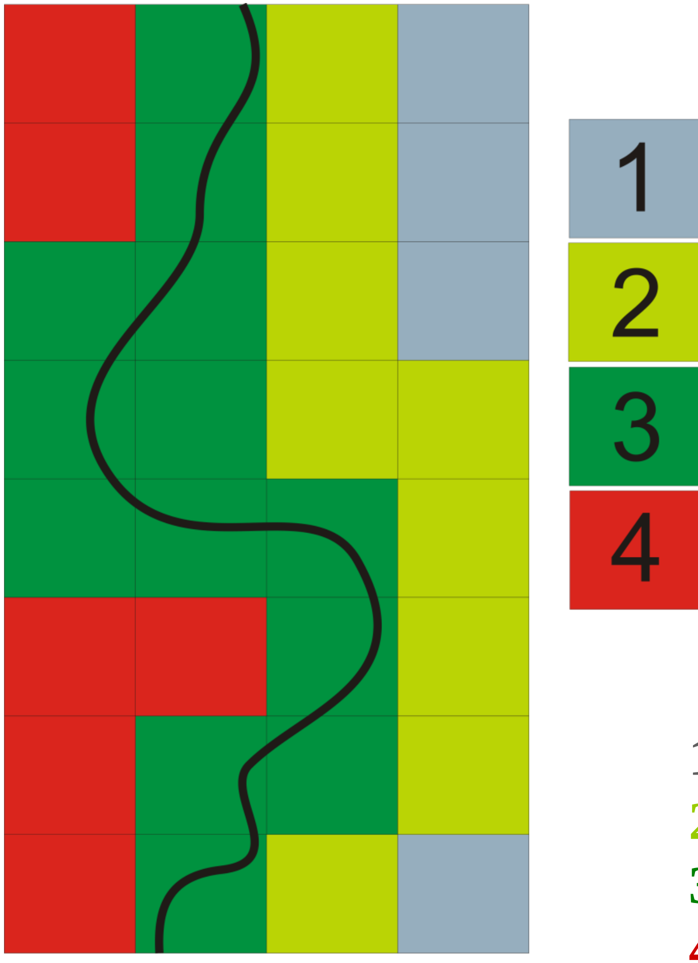
Smagorinsky model

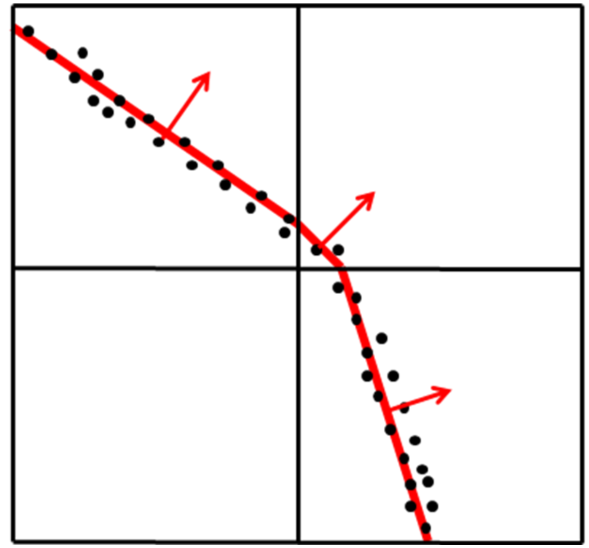
$$\nu_{SGS} = (C_S \Delta)^2 S$$

Smagorinsky constant

cell size

Approach





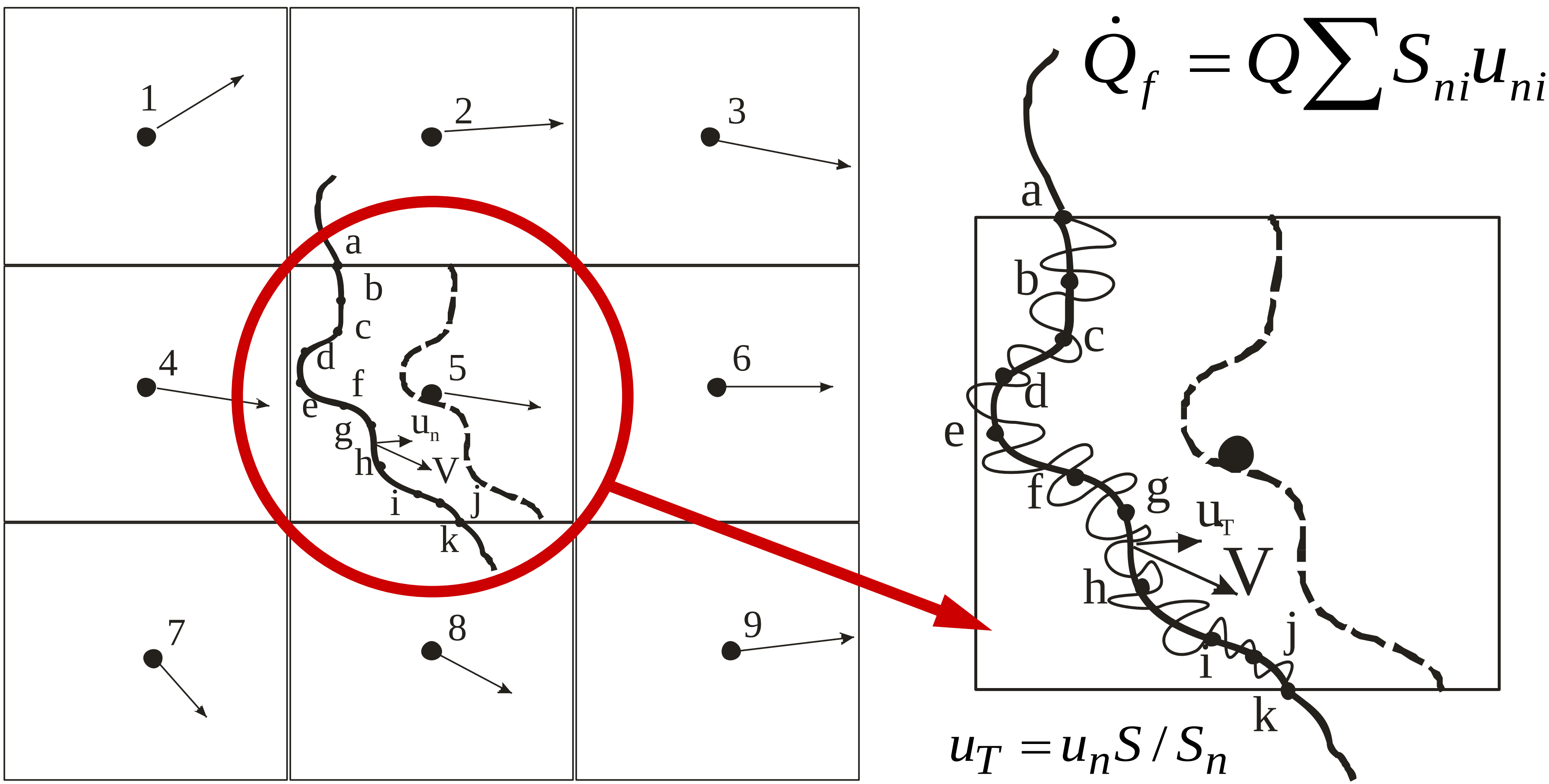
1 – cells with fresh mixture

2 – nearest to flame cells with fresh mixture

3 – mixed cells with flame front

4 – nearest to flame cells with products

Flame Tracking method for RANS



$$\dot{Q}_f = Q \sum S_{ni} u_{ni}$$

$$u_T = u_n S / S_n$$

Any combustion model:

Damkoehler
Shelkin
Zimont
Gulder

Bradley
Liu, Ziegler, Lenze
Peters

Transition from RANS to LES

$$\frac{u_T}{u_n} = F(u', l, \delta, \ldots)$$

Damkoehler $$F = 1 + \frac{u'}{u_n}$$

Shelkin $$F = \left(1 + \frac{u'^2}{u_n^2}\right)^{1/2}$$

Zimont $$F = 1 + 0.52\left(\frac{u'}{u_n}\right)^{1/2}\left(\frac{u'l}{\nu}\right)^{1/4}$$

Gulder $$F = 1 + 0.62\left(\frac{u'}{u_n}\right)^{1/2}\left(\frac{u_n l}{\nu}\right)^{1/4}$$

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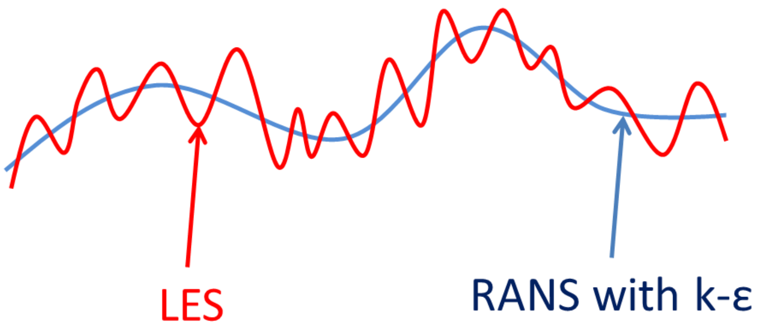
→ $u' \rightarrow u'_{SGS}$

$u_T \rightarrow u_{TSGS}$



Database: laminar flame

- Hydrogen
- Methane
- Propane
- n-Heptane
- n-Octane
- Decane
- Thetradecane
- PRF95
- Ethanol

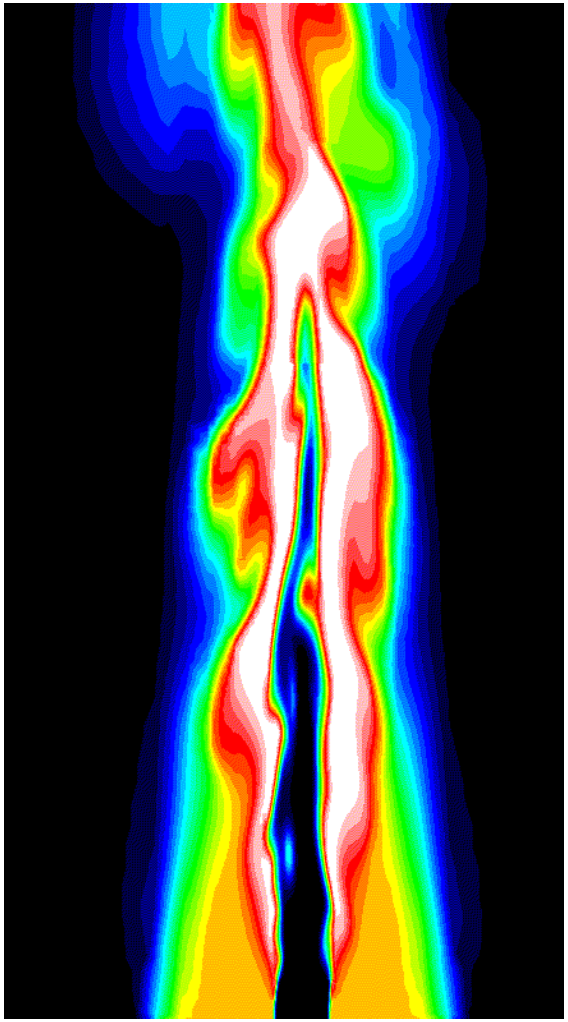
→

Speed
Thickness
NO
Soot
CO
O2
Lewis number
Viscosity

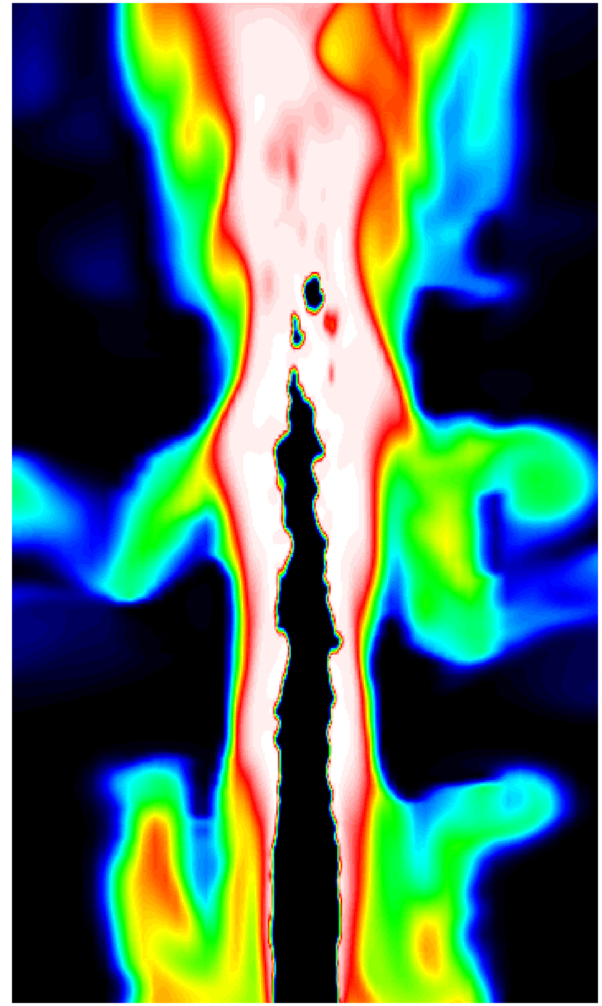
Pressure: 1-100 atm
Temperature: 300-900 K
All range of eq. ratios
EGR: 0-60%

Advantages of the FTPM

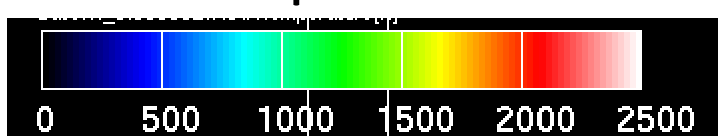
Standard combustion model (CFM)



Flame tracking-particle method

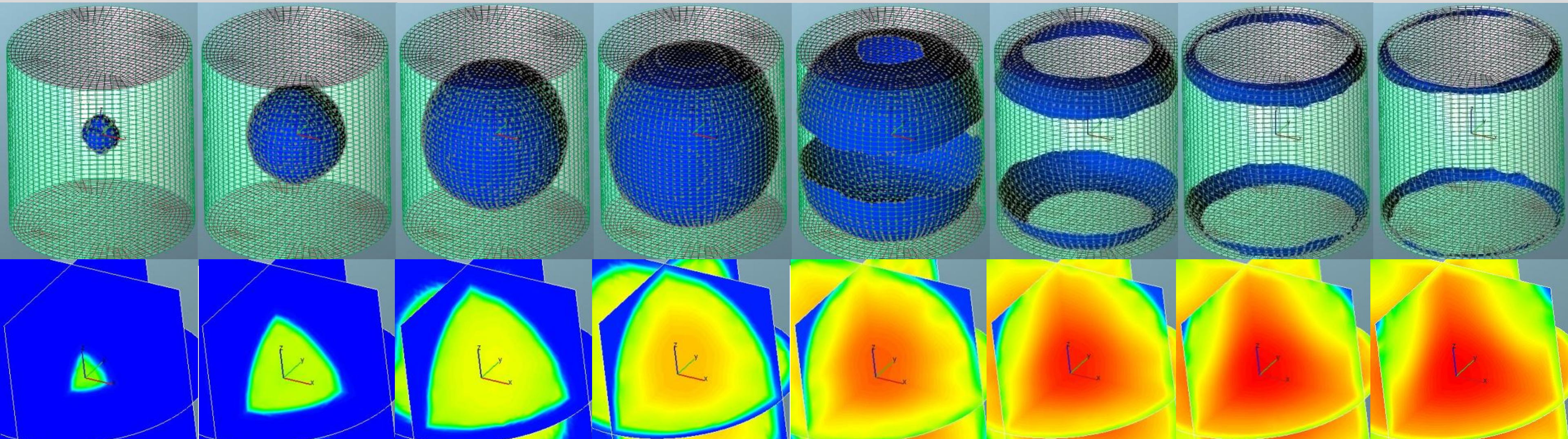


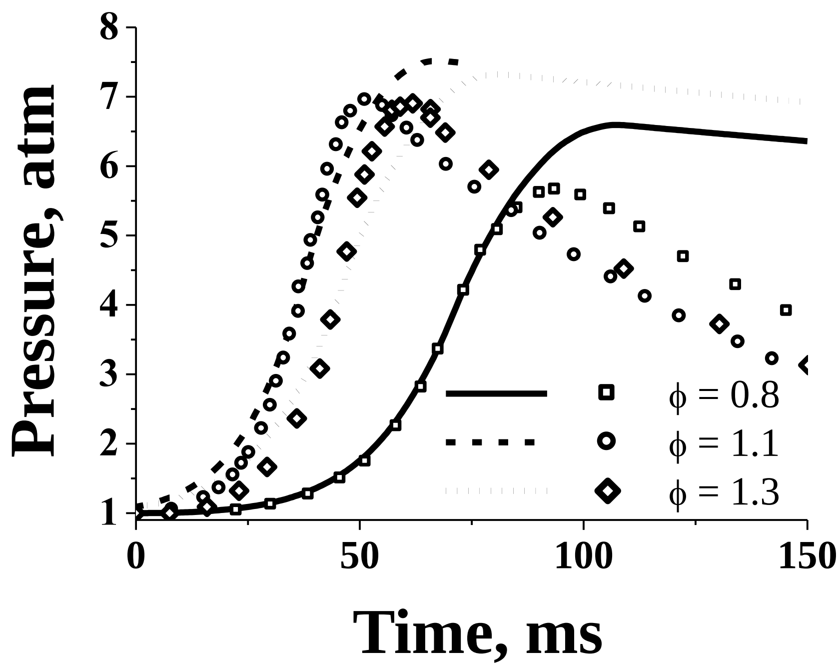
Temperature

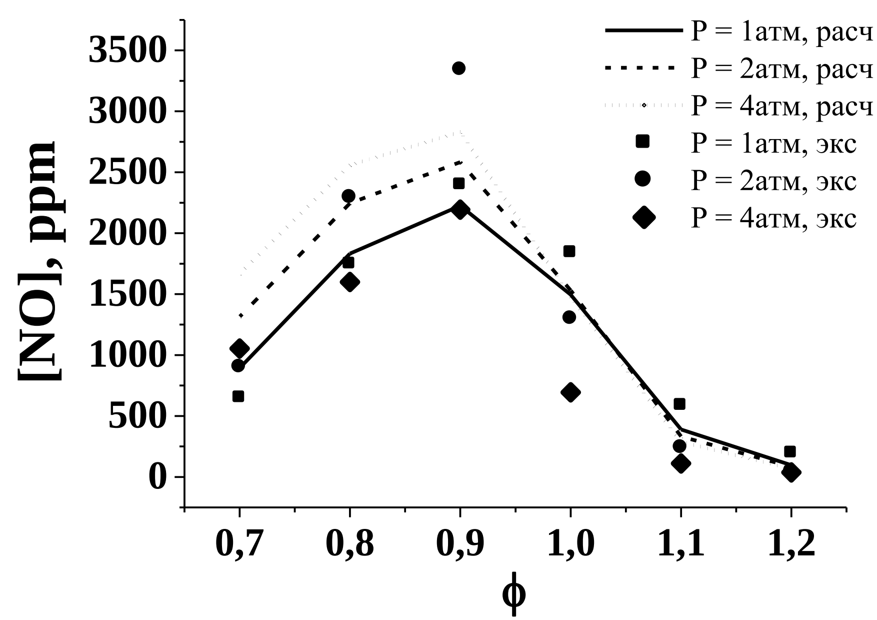


Validation:
Combustion in enclosures (RANS)

Combustion in enclosures



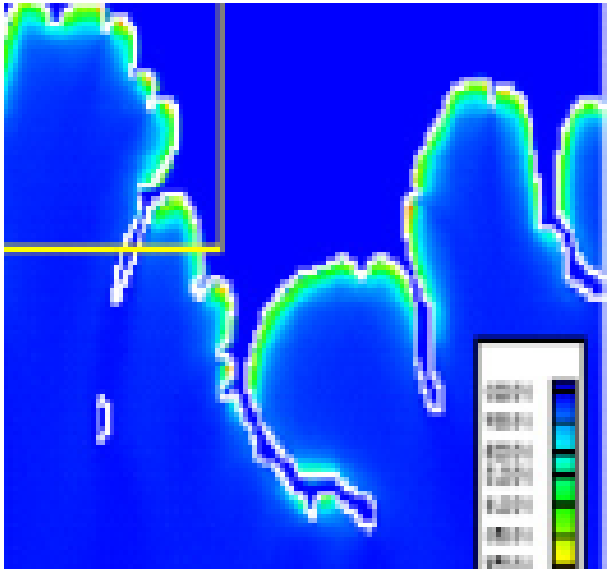




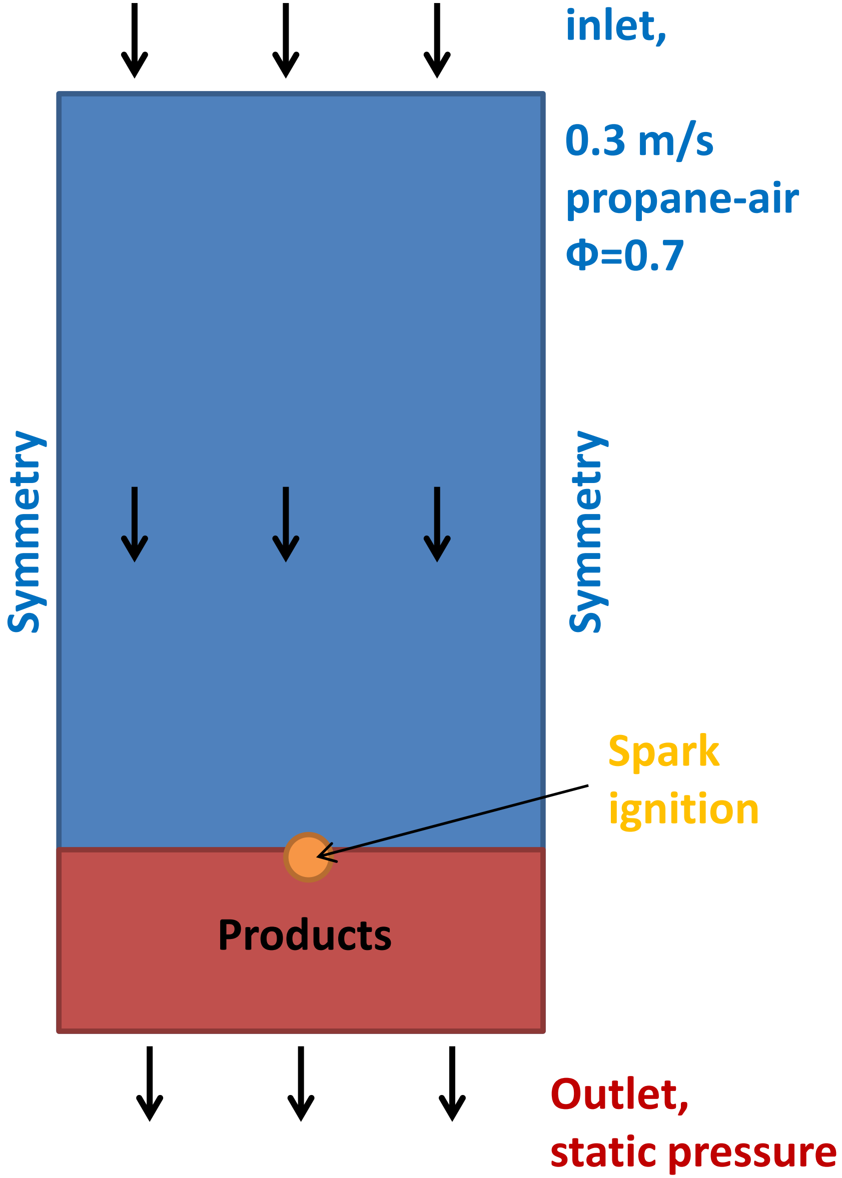
Validation:
Test calculations for LES combustion

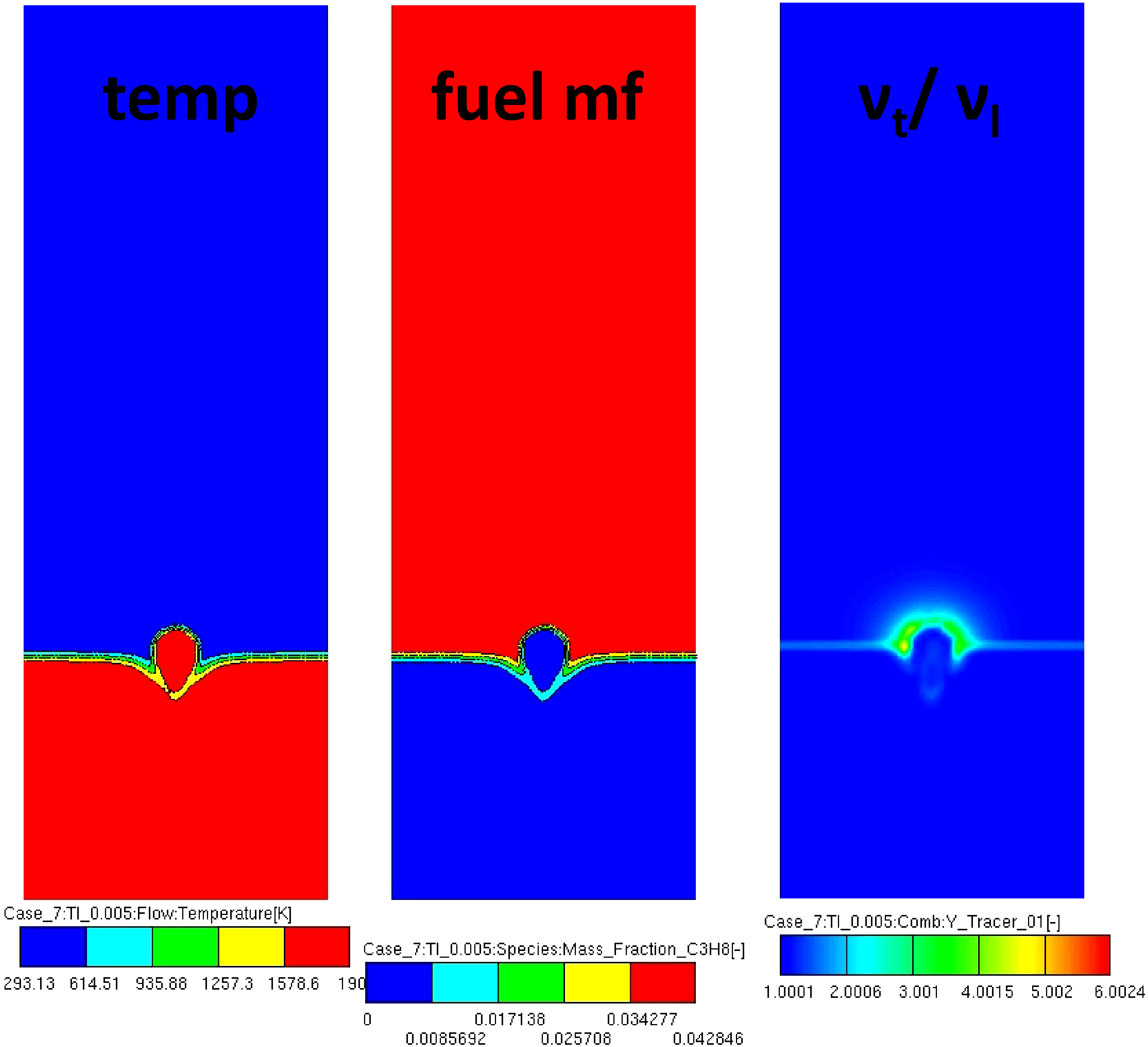
Simple test case

DNS

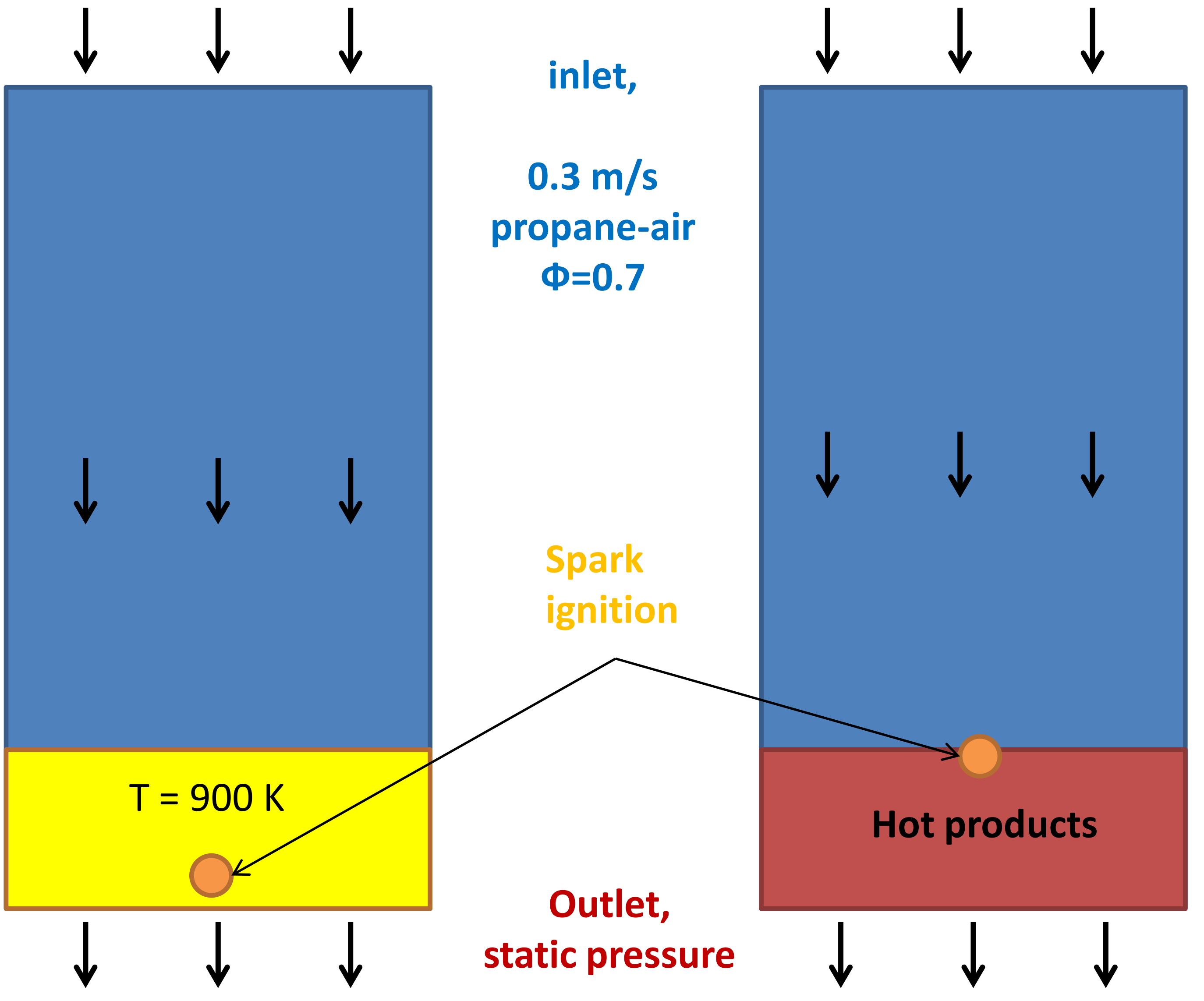


Bell et al.

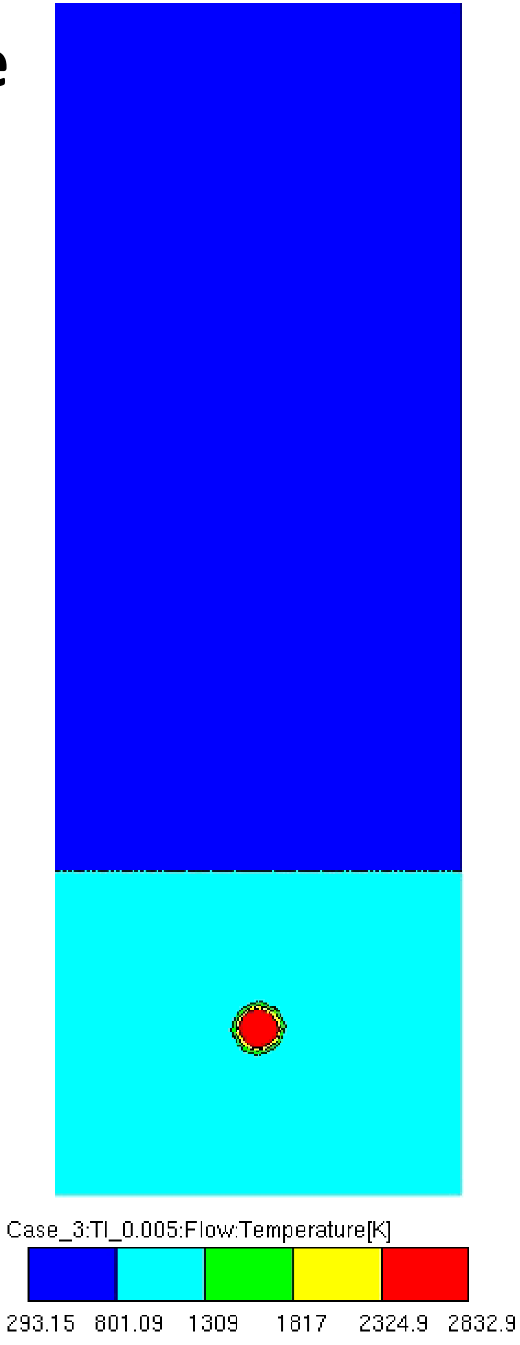


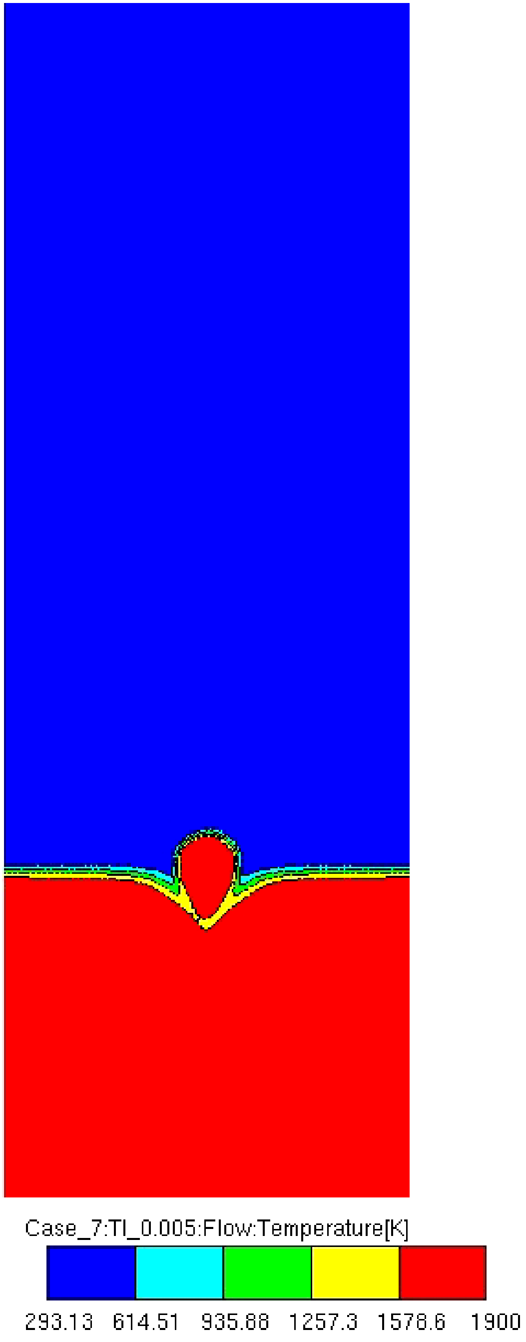

temp
fuel mf
vt/ vl
Case_7:TI_0.005:Flow:Temperature[K]
293.13 614.51 935.88 1257.3 1578.6 190
Case_7:TI_0.005:Species:Mass_Fraction_C3H8[-]
0 0.017138 0.034277
0.0085692 0.025708 0.042846
Case_7:TI_0.005:Comb:Y_Tracer_01[-]
1.0001 2.0006 3.001 4.0015 5.002 6.0024

Different initial conditions



temperature

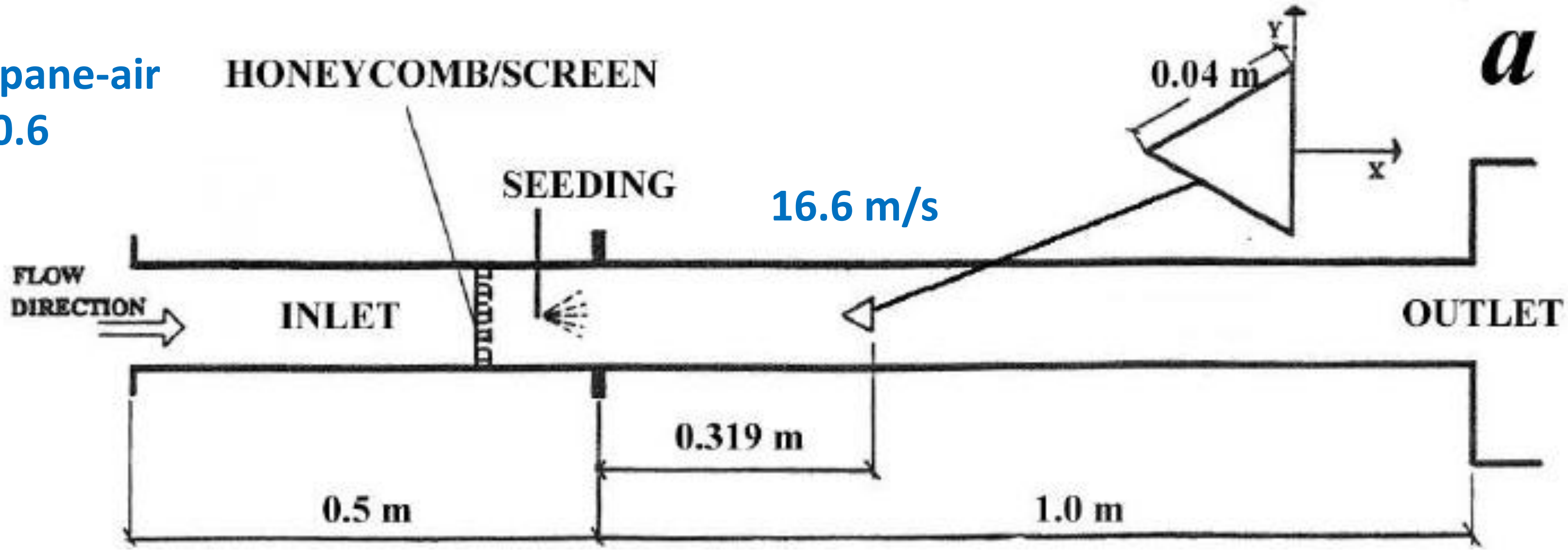


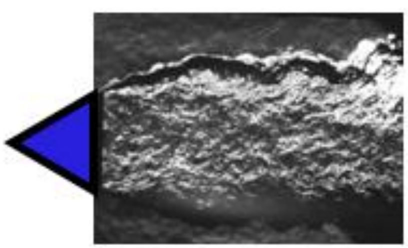


Flame stabilization with flame holder

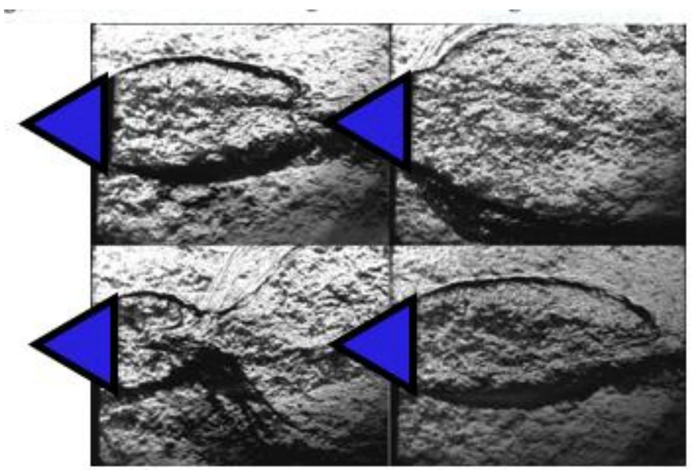
Experiments

propane-air
Φ=0.6

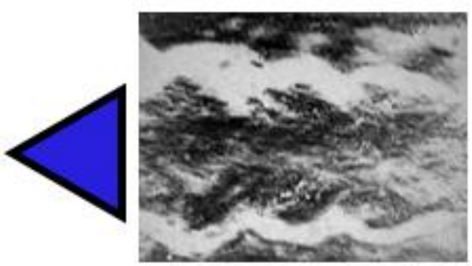




Stable flame



Buzz mode

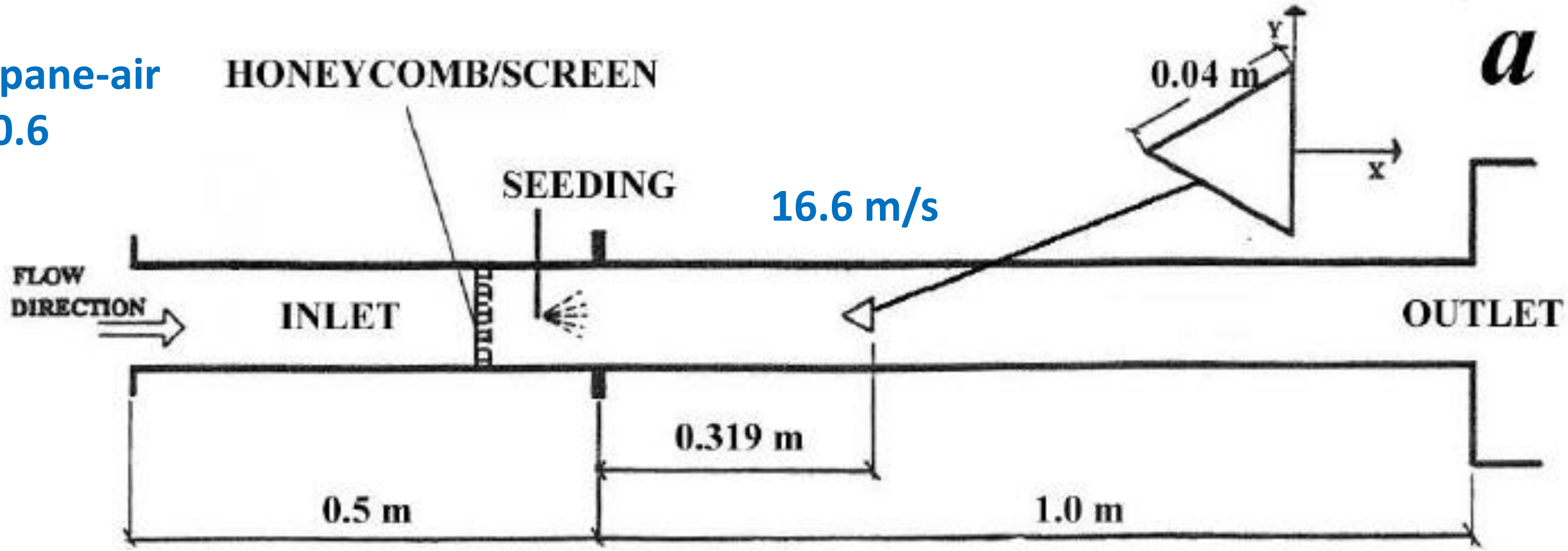


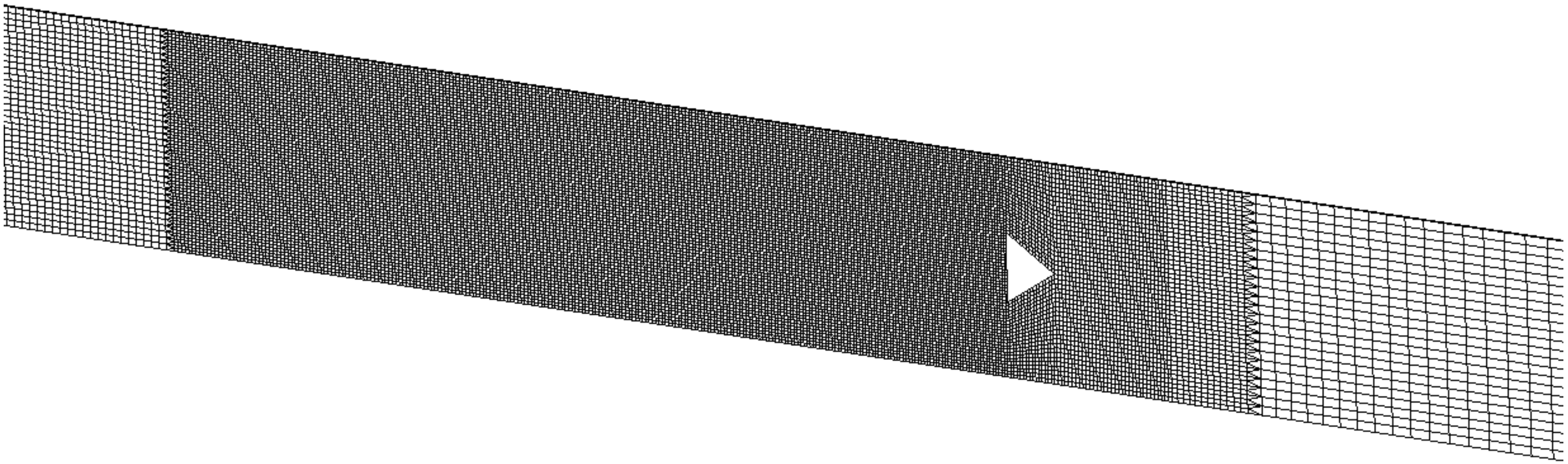
Screech mode

G. Jourdain, L.-E. Eriksson

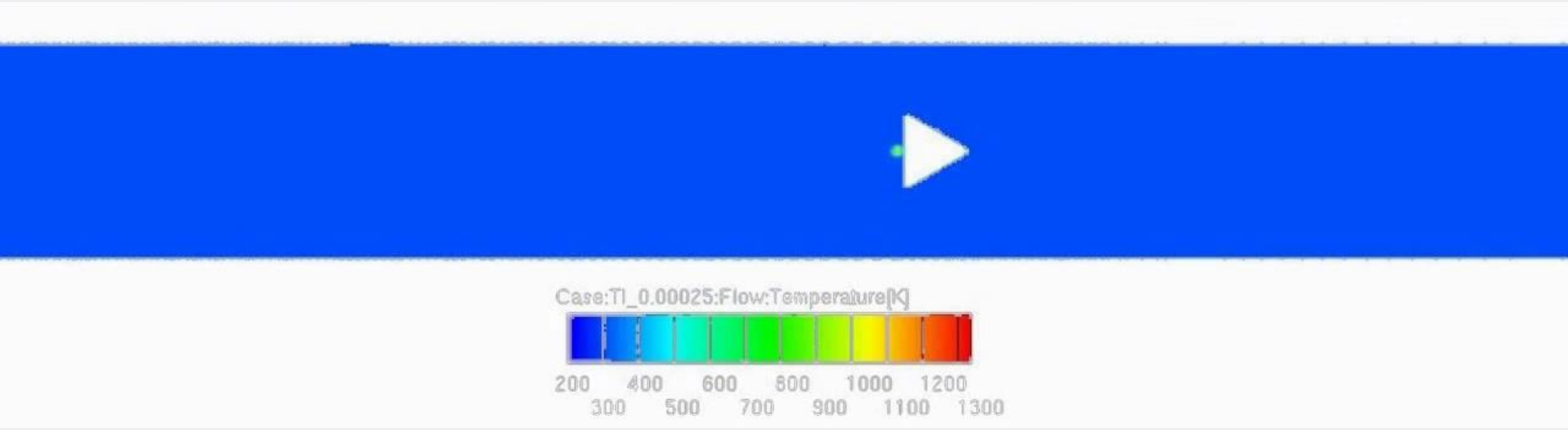
Experiments

propane-air
Φ=0.6

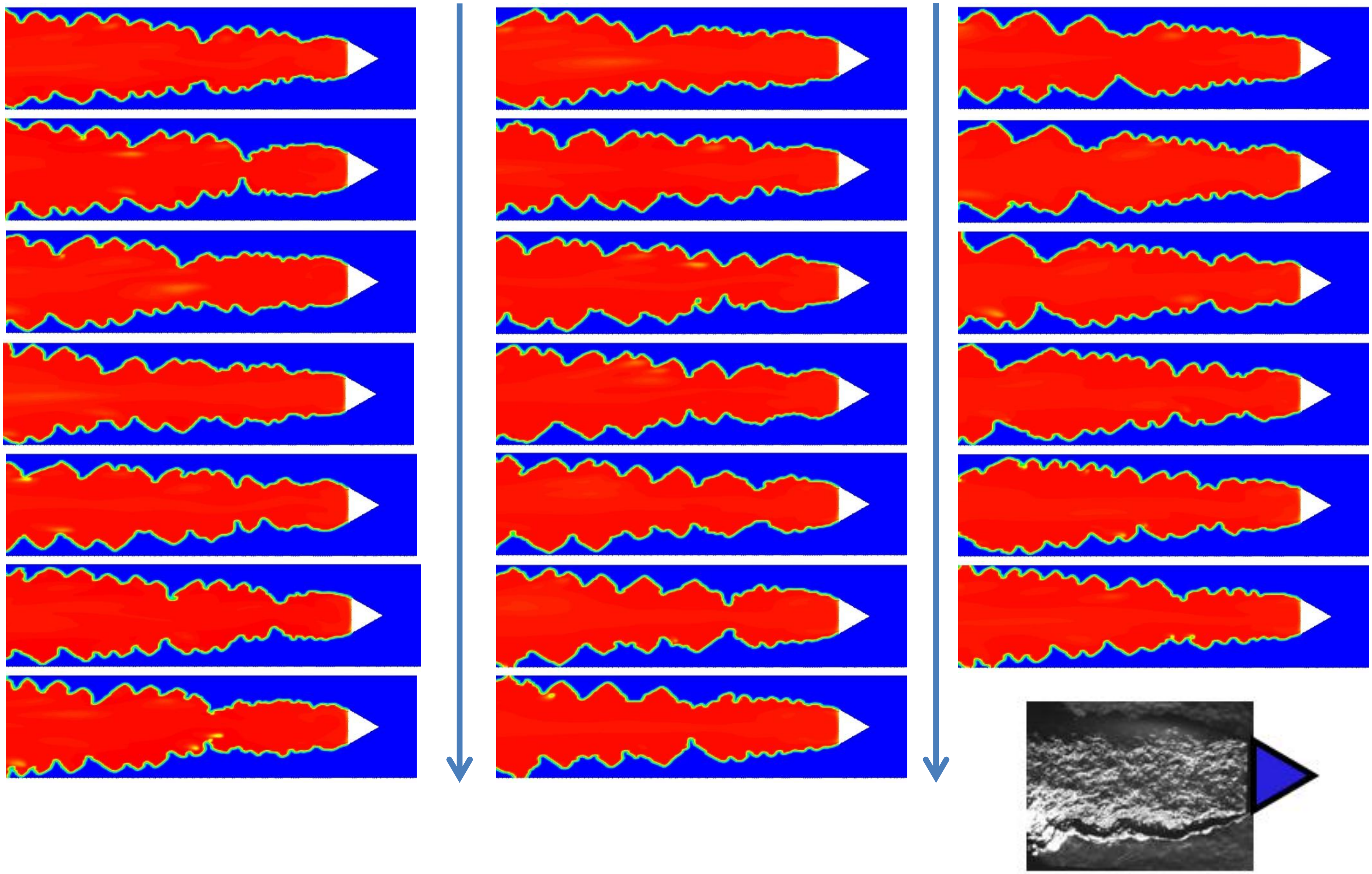




Animation


Case:TI_0.00025:Flow:Temperature[K]
200 400 600 800 1000 1200
300 500 700 900 1100 1300

Temperature snapshots

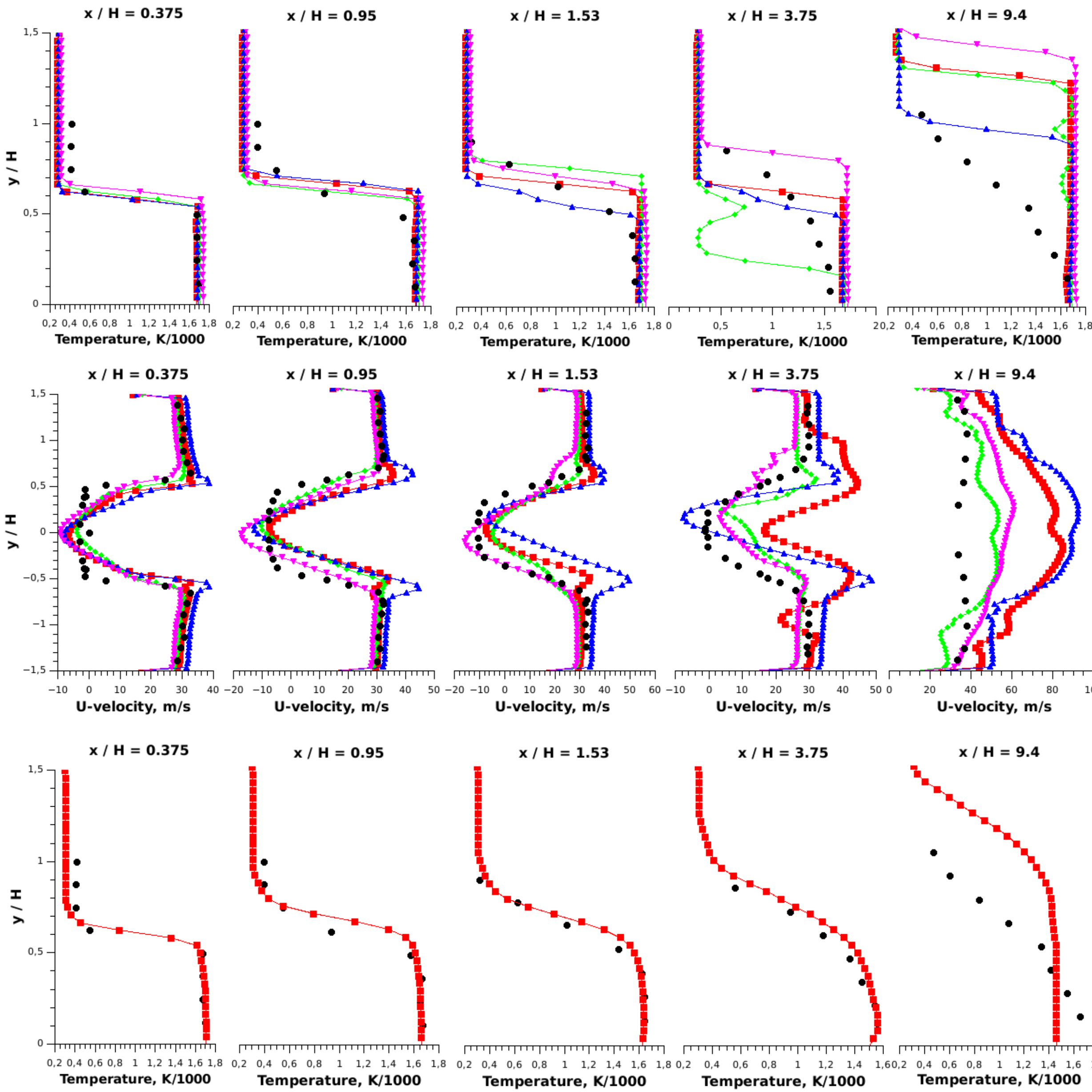


Profiles

instantaneous profiles of temperature

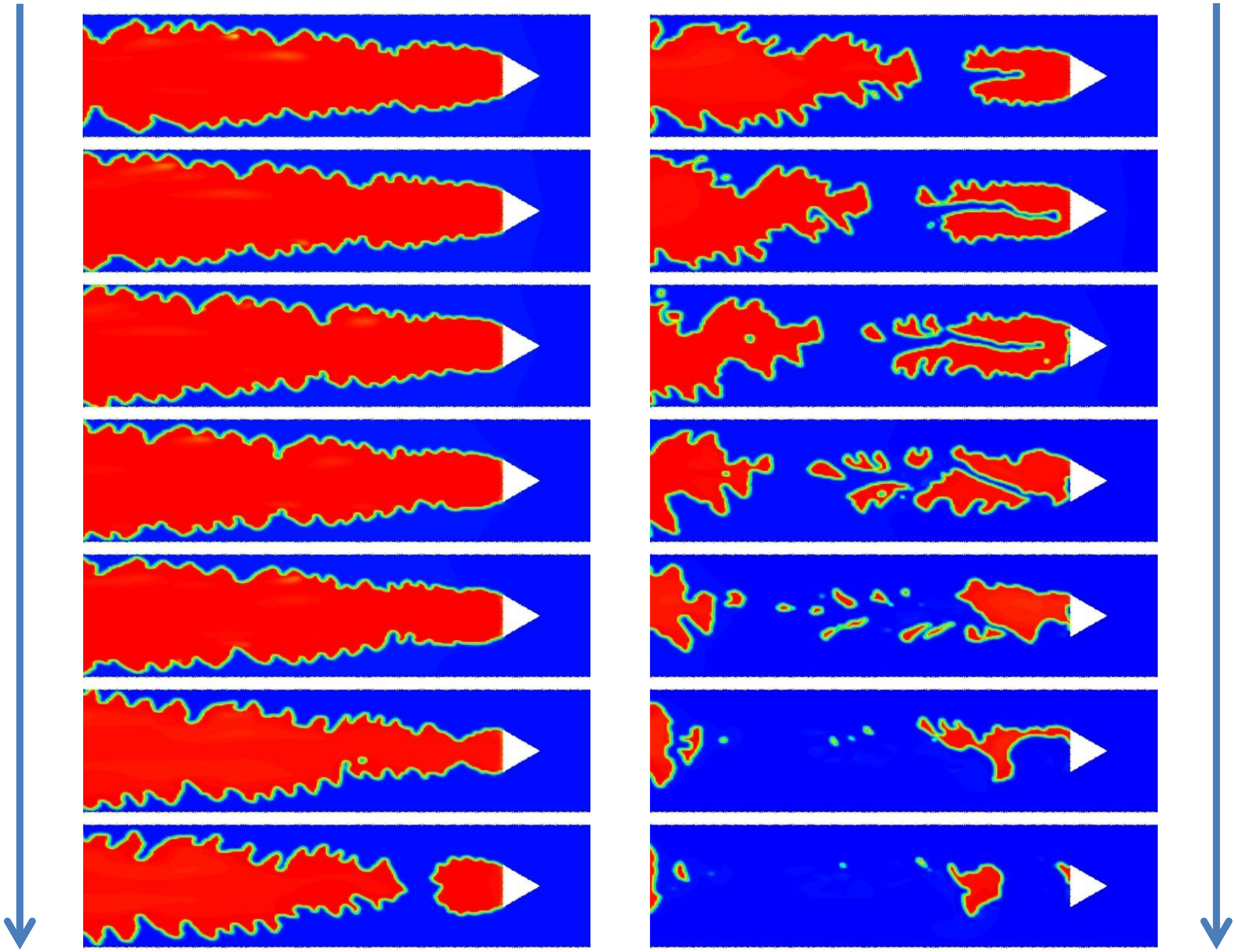
instantaneous profiles of velocity

averaged profiles of temperature



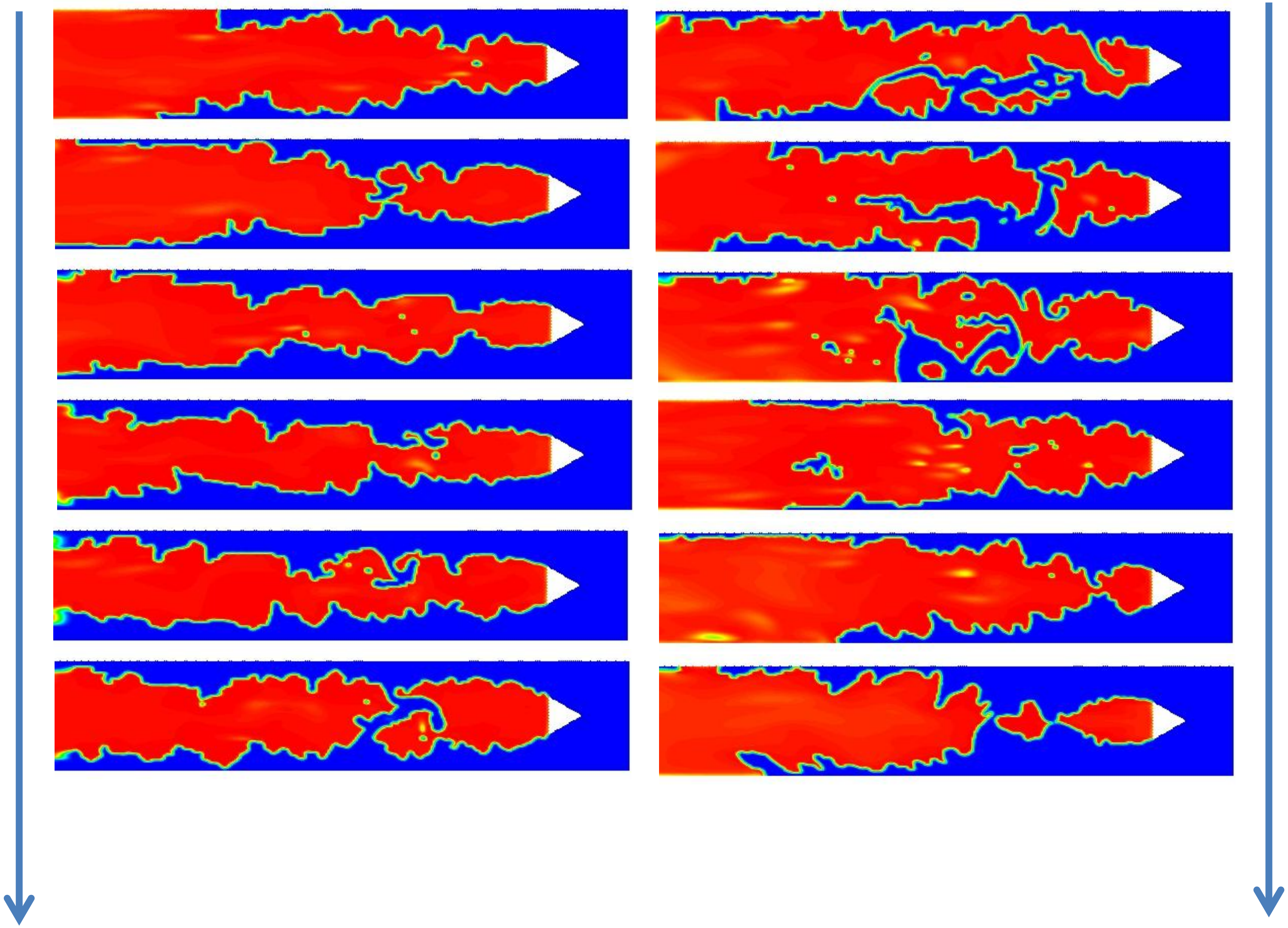
Flame blow-off

increase of stream velocity from 15 to 20 m/s



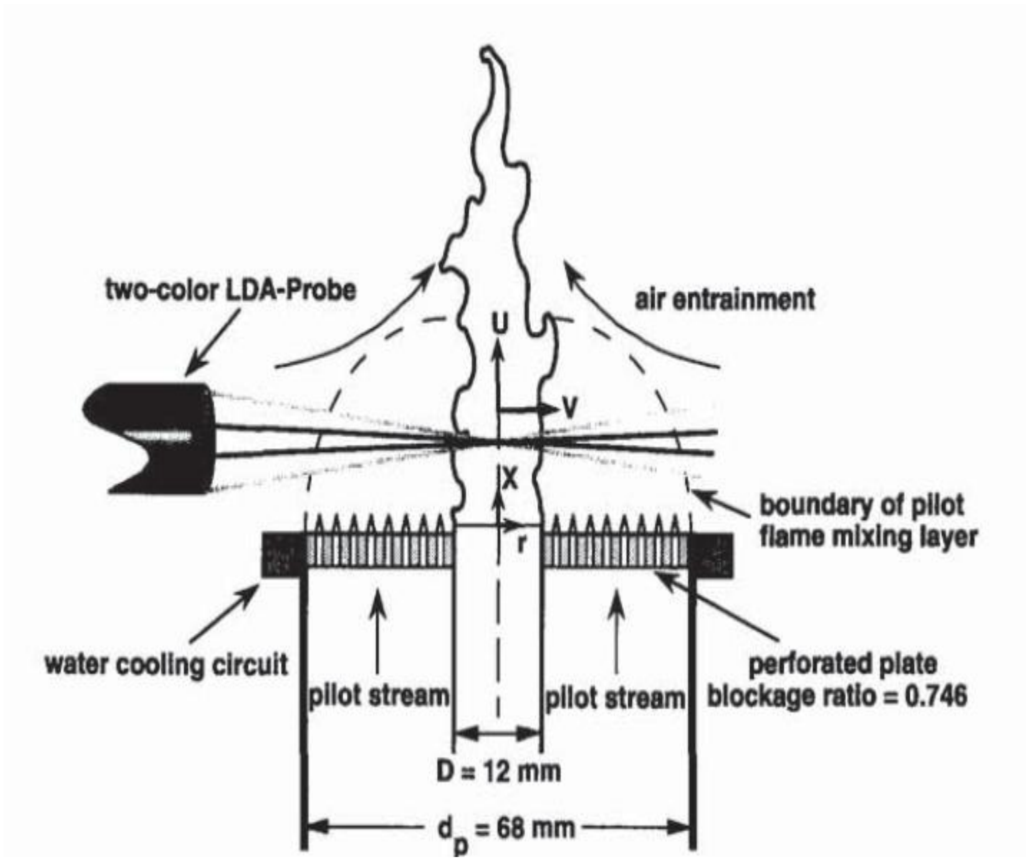
Flame blow-off

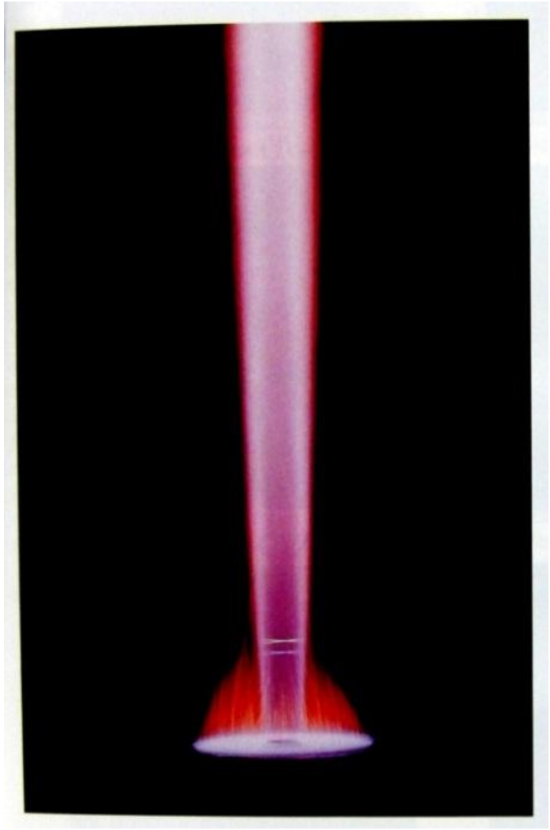
change equivalence ratio from 0.7 to 0.6



Bunzen burner

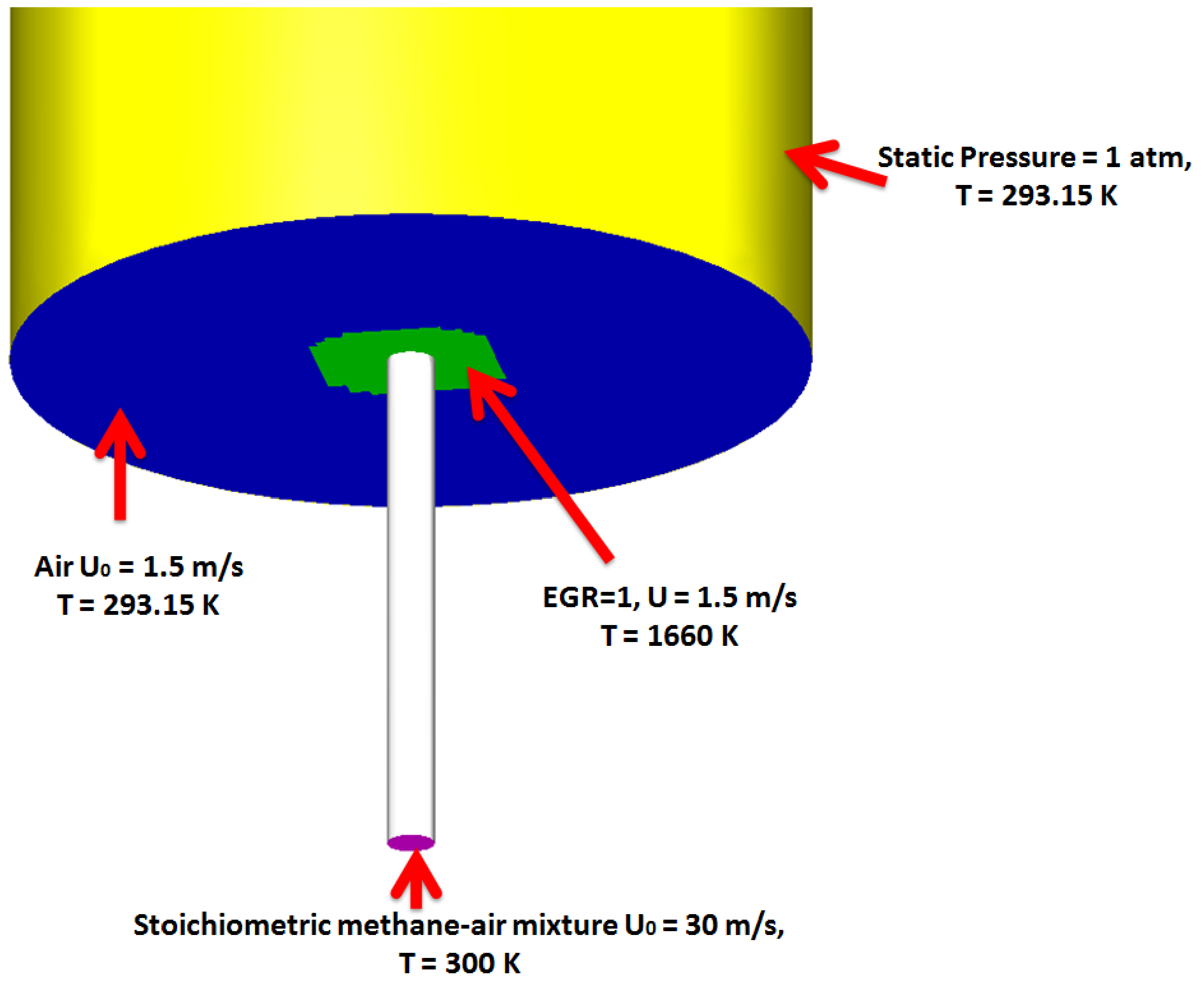
Experiments





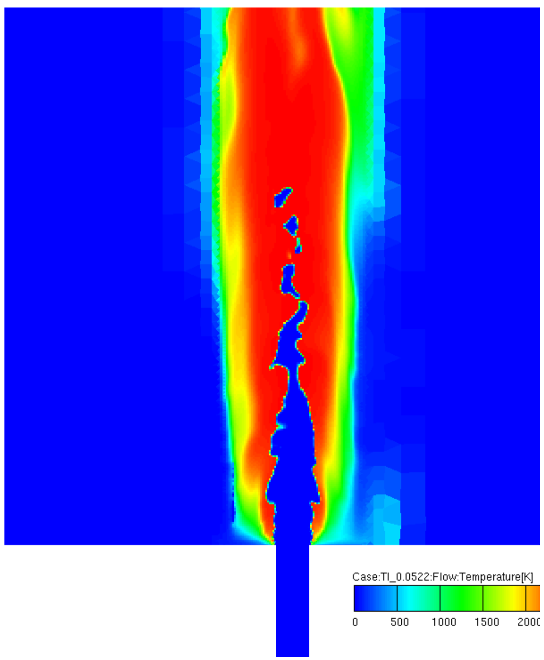
Y.-C. Chen, N. Peters, G.A. Schneemann, N. Wruck, U. Renz, M. S. Mansour

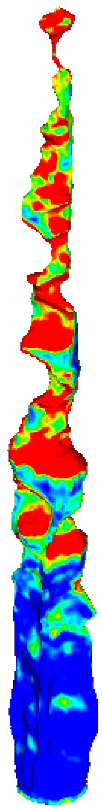
Computation setup

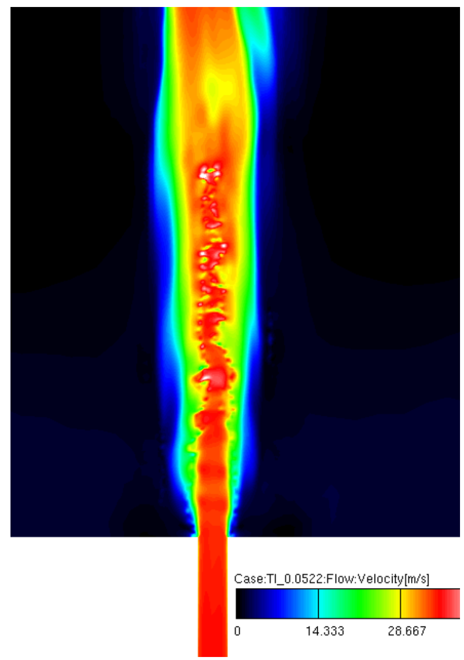


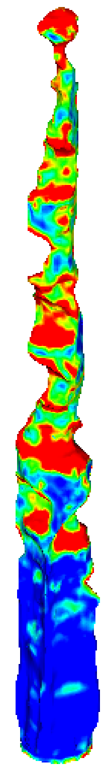
Snapshots

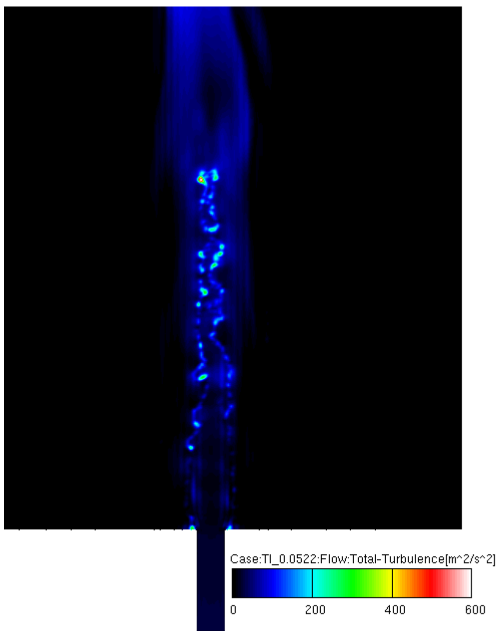
temperature **velocity** **turbulence**

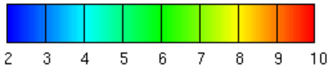








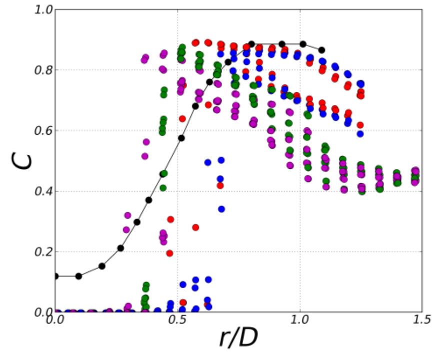


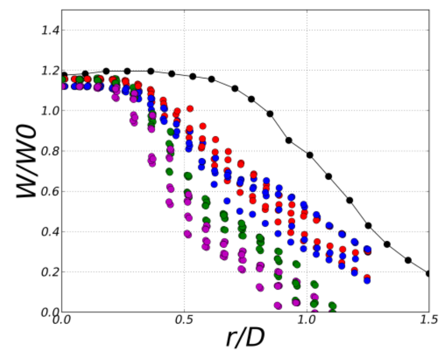


Results

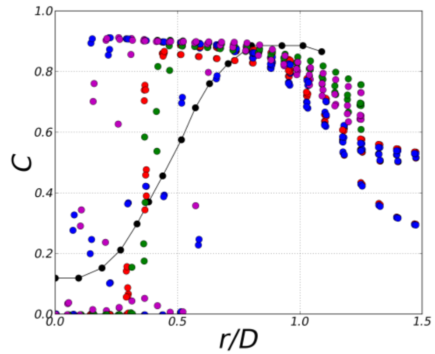
temperature | **velocity**

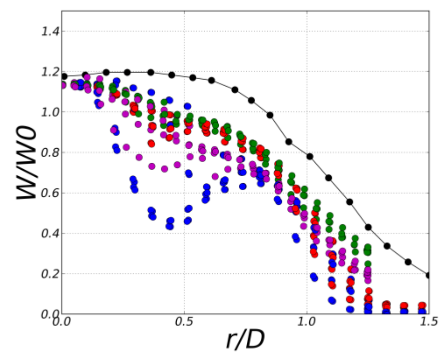
x/D = 2.5



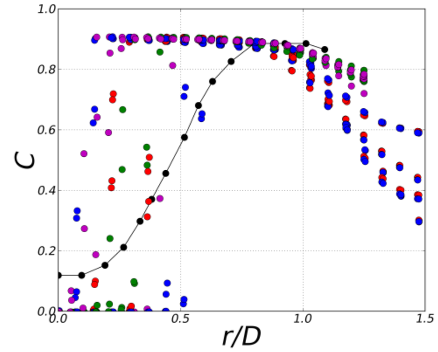


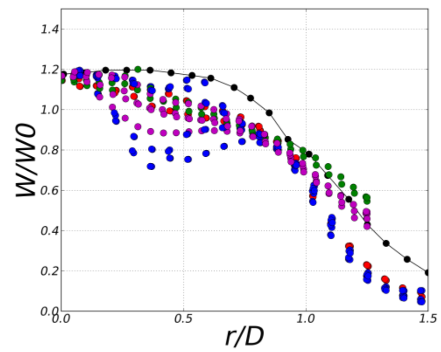
x/D = 4.5





x/D = 6.5



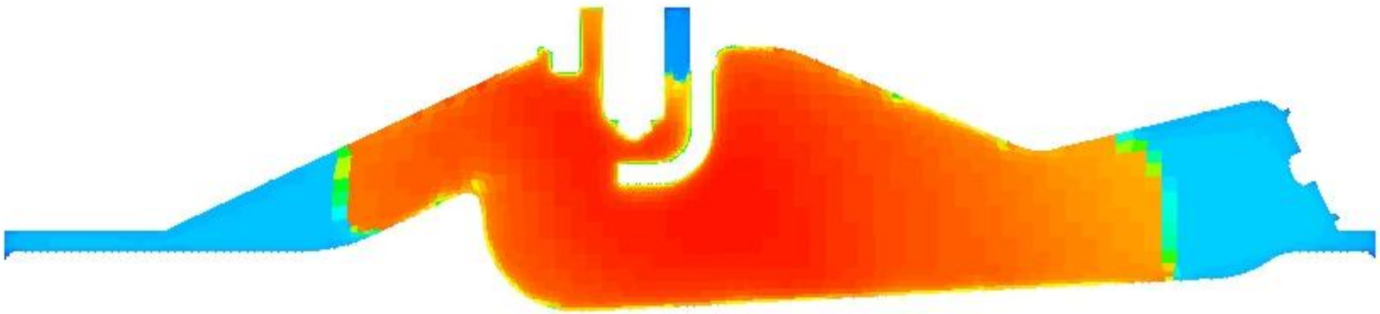


Conclusions

- The algorithm of coupled **Large Eddy Simulation Flame Tracking Method** in 3D geometries has been developed and implemented into a CFD code.
- The method is **(conditionally!) parameter free** and very efficient in terms of CPU requirements.
- Results of calculations were **compared with experimental data**.
- The method can be readily applied to studies of **combustion phenomena in different applications.**

Advantages of the FTPM

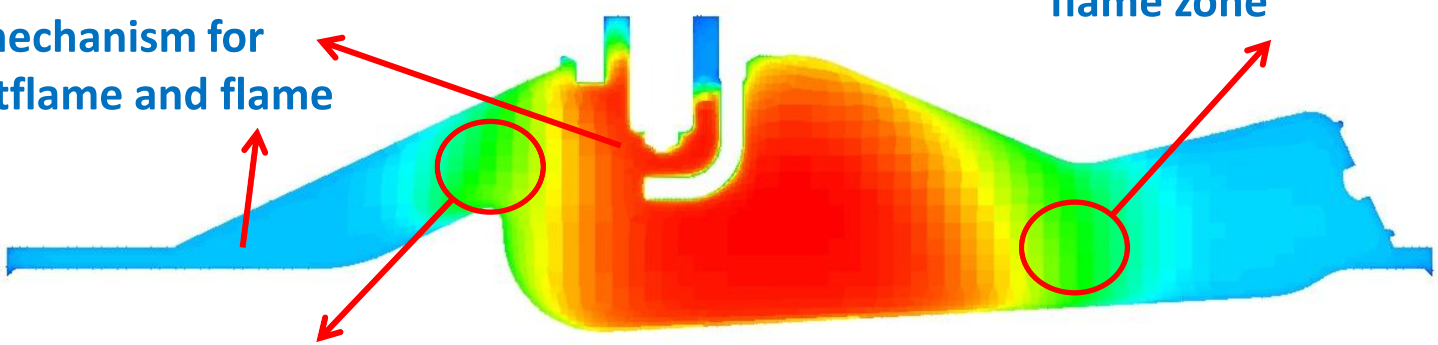
Flame tracking-particle method



Standard combustion model (CFM)

Autoignition in smooth flame zone

One kinetic mechanism for preflame postflame and flame reactions



Problem with calculation of the pollutants in the flame