Stabilization of a Premixed Laminar Flame on a Rotating Cylinder

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36th International Symposium on Combustion

Tuesday, 2nd August 2016
Seoul, South Korea

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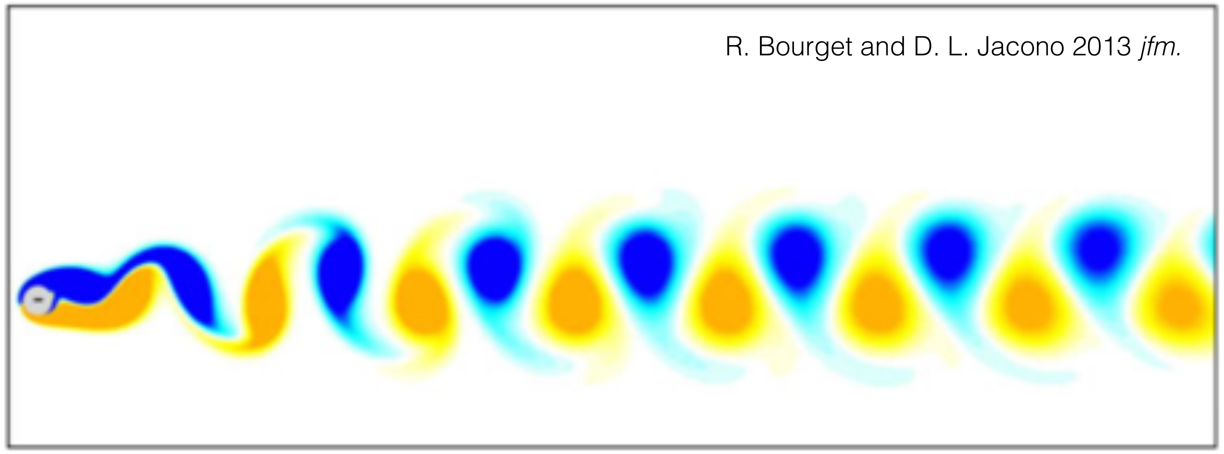
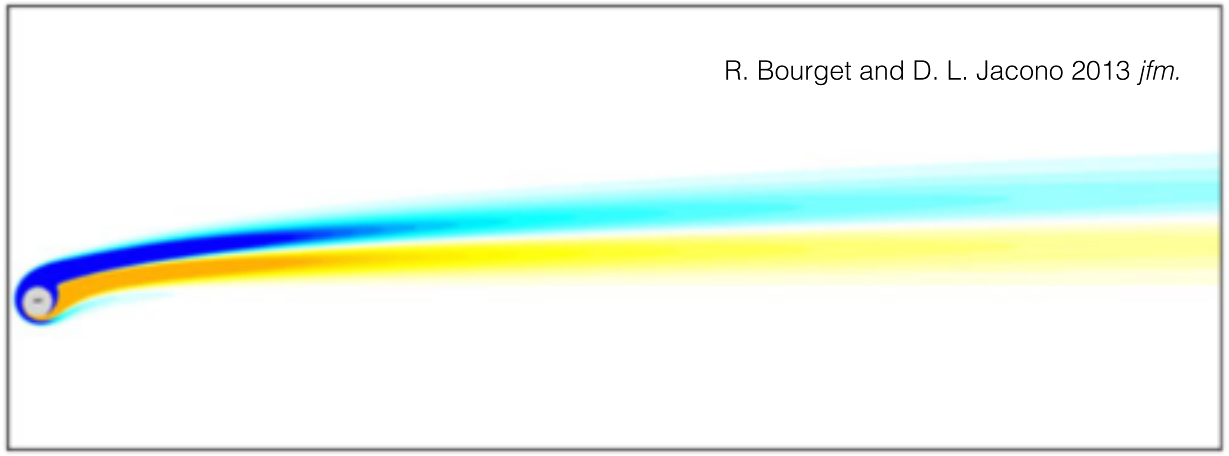
Introducing Exascale Computing in Combustion Instabilities Simulations

Context

The stability of the flow in the wake of a cylinder is a classical problem of fluid mechanics.



Now if the cylinder is rotating, things are different[1,2,3]… This is called symmetry breaking and its a big topic[4,5,6].

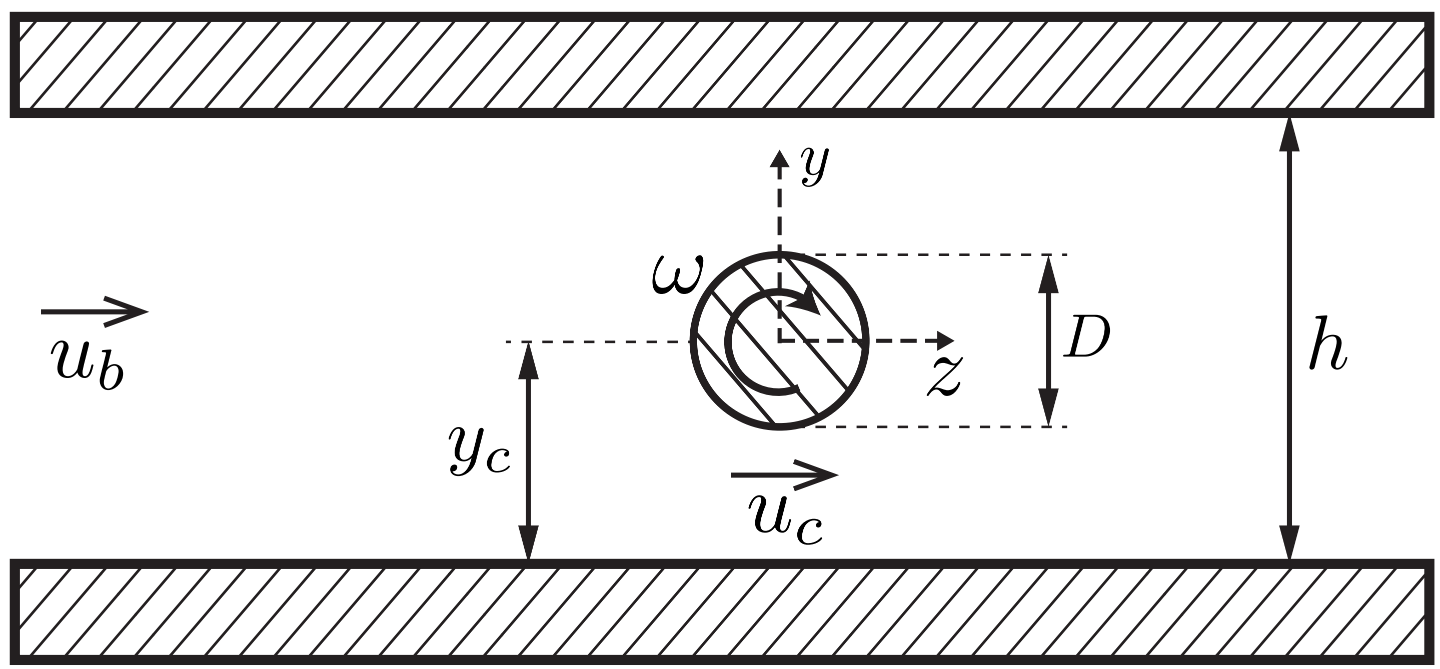


1. S. Mittal and B. Kumar 2003 *jfm.*
2. S. Camarri and F. Giannetti 2010 *jfm.*
3. R. Bourget and D. L. Jacono 2013 *jfm.*
4. Z. Ferig and P. Sethna 1989 *jfm.*
5. M. Bauerheim et al 2014 *cf.*
6. M. Bauerheim et al 2014 *jfm.*

What happens if we add combustion? Why should we study flames stabilized behind rotating flame holders ?

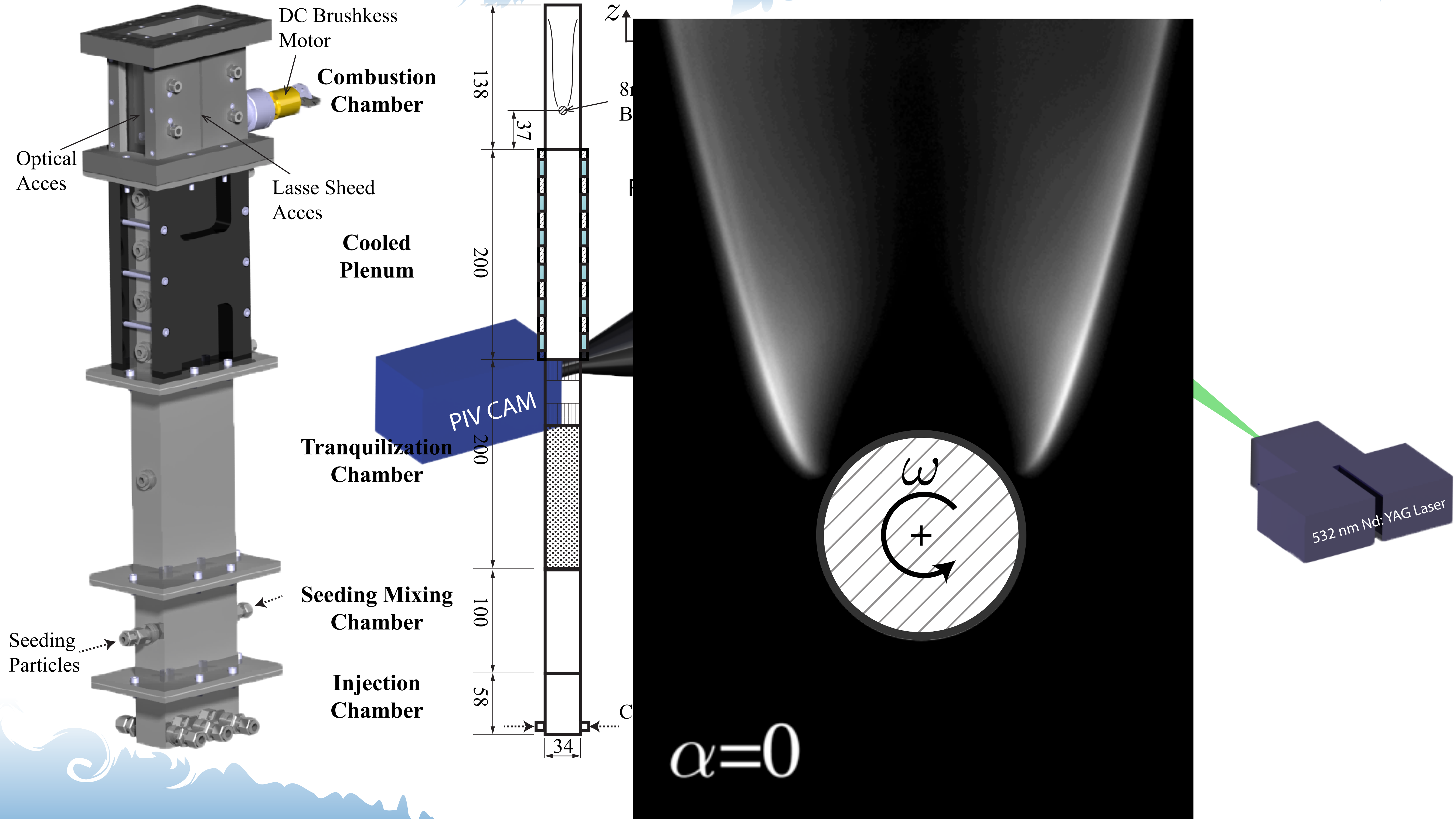
- ★ New engine concepts, such as constant volume chambers, use rotating valves which can interact with the flame
- ★ Rotating flame holders might provide control systems for combustion instabilities
- ★ Good test case for fundamental understanding of flame dynamics.

Flow behind a rotating cylinder is controlled by four parameters

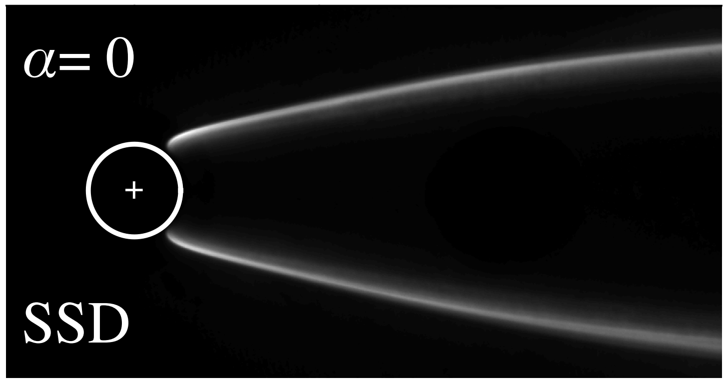


Reynolds number	Blockage ratio	Eccentricity	**Rotating rate**
$Re = \frac{u_b D}{\nu}$	$\varepsilon = \frac{D}{h}$	$\gamma = \frac{y_c - 1}{y - 1}$	$\alpha = \frac{\omega D}{2u_b}$
$Re \approx 500$	$\varepsilon = 0.24$	$\gamma = 1$	$\alpha = 0 - 5$

Experimental Set-UP



Flame Topologies

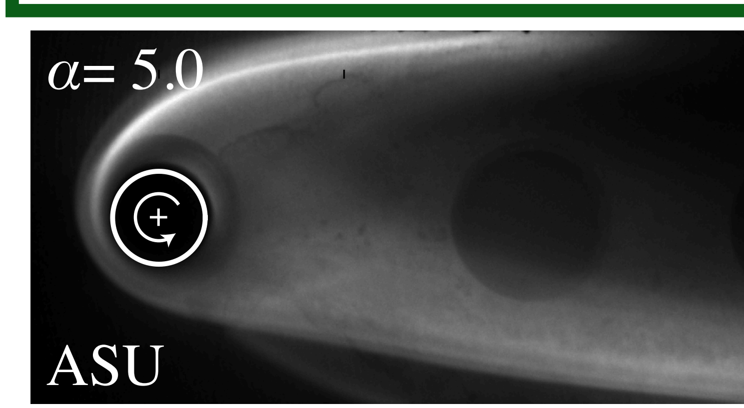


Symmetrical **S**tabilized **D**ownstream

- Influence of the flame/wall interaction on the flame anchoring mechanism.
  M. Brebion et al *cf.* 2016

Asymmetrical **S**tabilized **D**ownstream

- Why is the upper branch quenched?
  D. Mejia et al *pci.* 2016



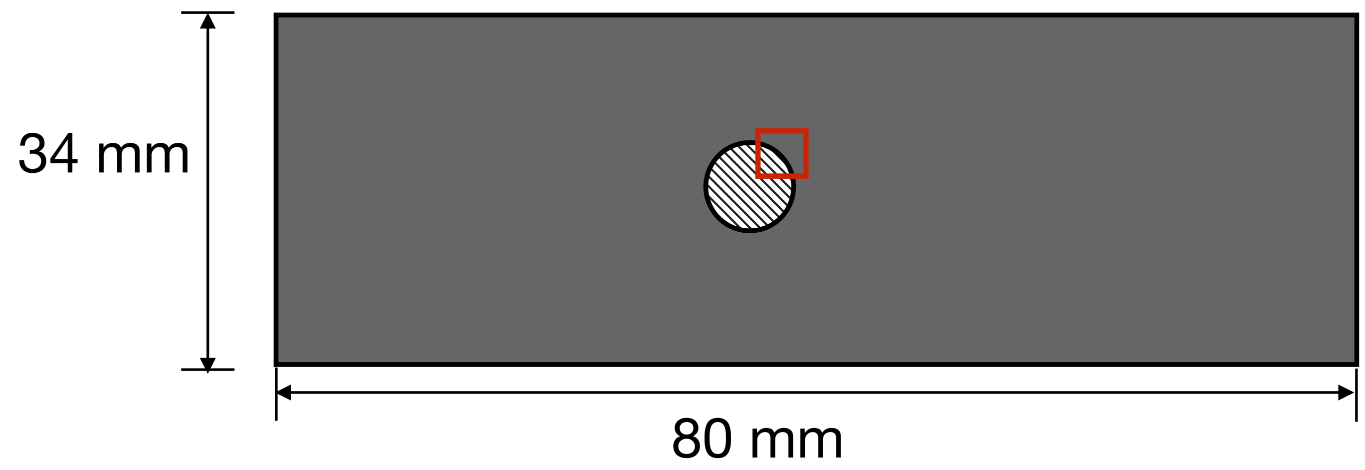
Asymmetrical **S**tabilized **U**pstream

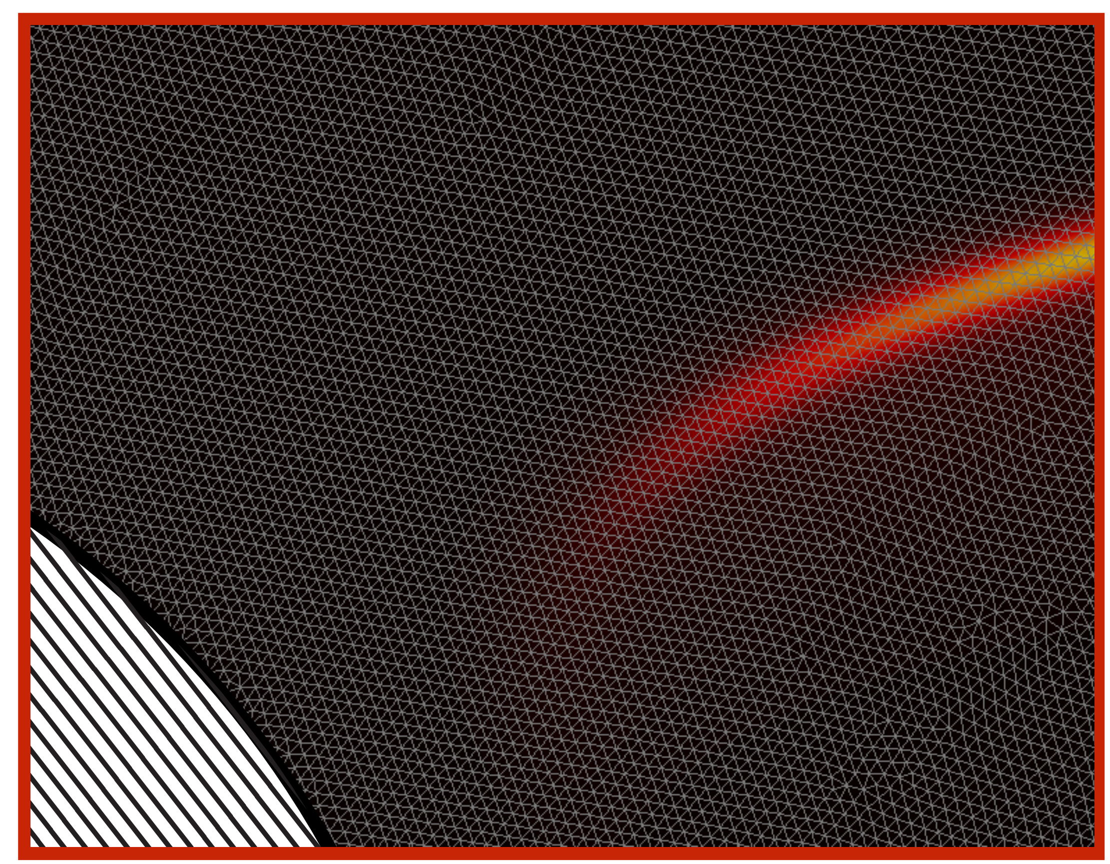
- What is the mechanism that allows the flame to go from ASD to ASU?

Numerical Set-up

DNS

- ★ Code: **AVBP**
- ★ Flow solver: **TTGC**
  - Third order in space,
  - Third order in time.
- ★ Chemistry: **LU19** Scheme,
  - Analytically reduced mechanism,19 transported species.
- ★ Boundary conditions:
  - inlet\outlet: **NSCBC**
  - walls: **walls_no_slip_isoT**
    - side walls : 300 K (imposed),
    - flame holder : adaptive temperature (unsteady heat equation with radiation)
  - rotation: $\vec{u}(\theta) = \alpha u_b \vec{e}_\theta$
- ★ Mesh: **Unstructured**
  - cells: 0.7 M,
  - minimum cell size: 60 µm (12 points in the flame front)





Comparaison PIV-DNS (non-reacting)

Operating point:

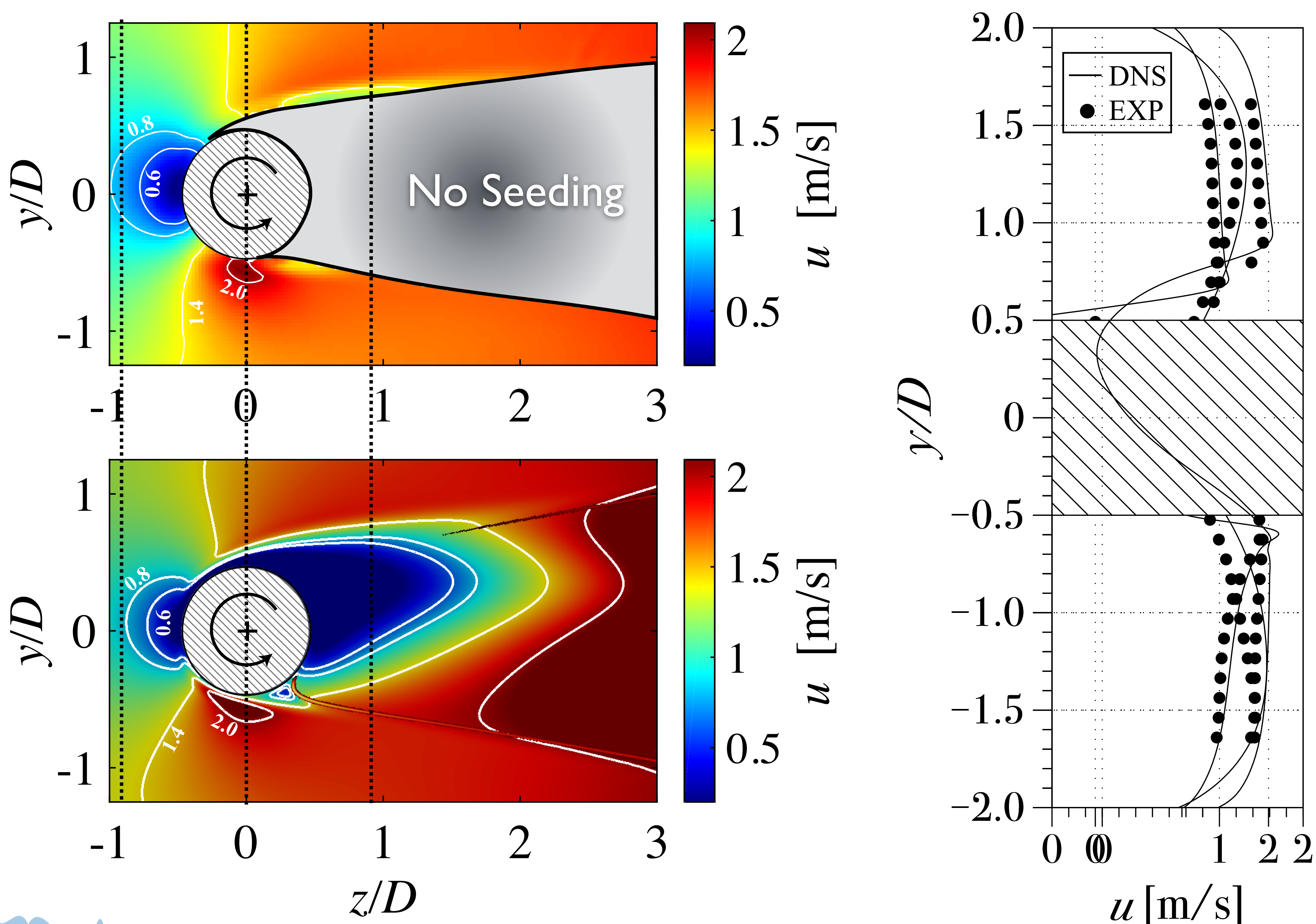
$\Phi = 0.70$

$u_b = 1.07 \text{ ms}^{-1}$

$T^u = 300 \text{ K}$

$P = 1 \text{ bar}$

$\alpha = 1.16$



Comparaison CH*-DNS (reacting)

Operating point:

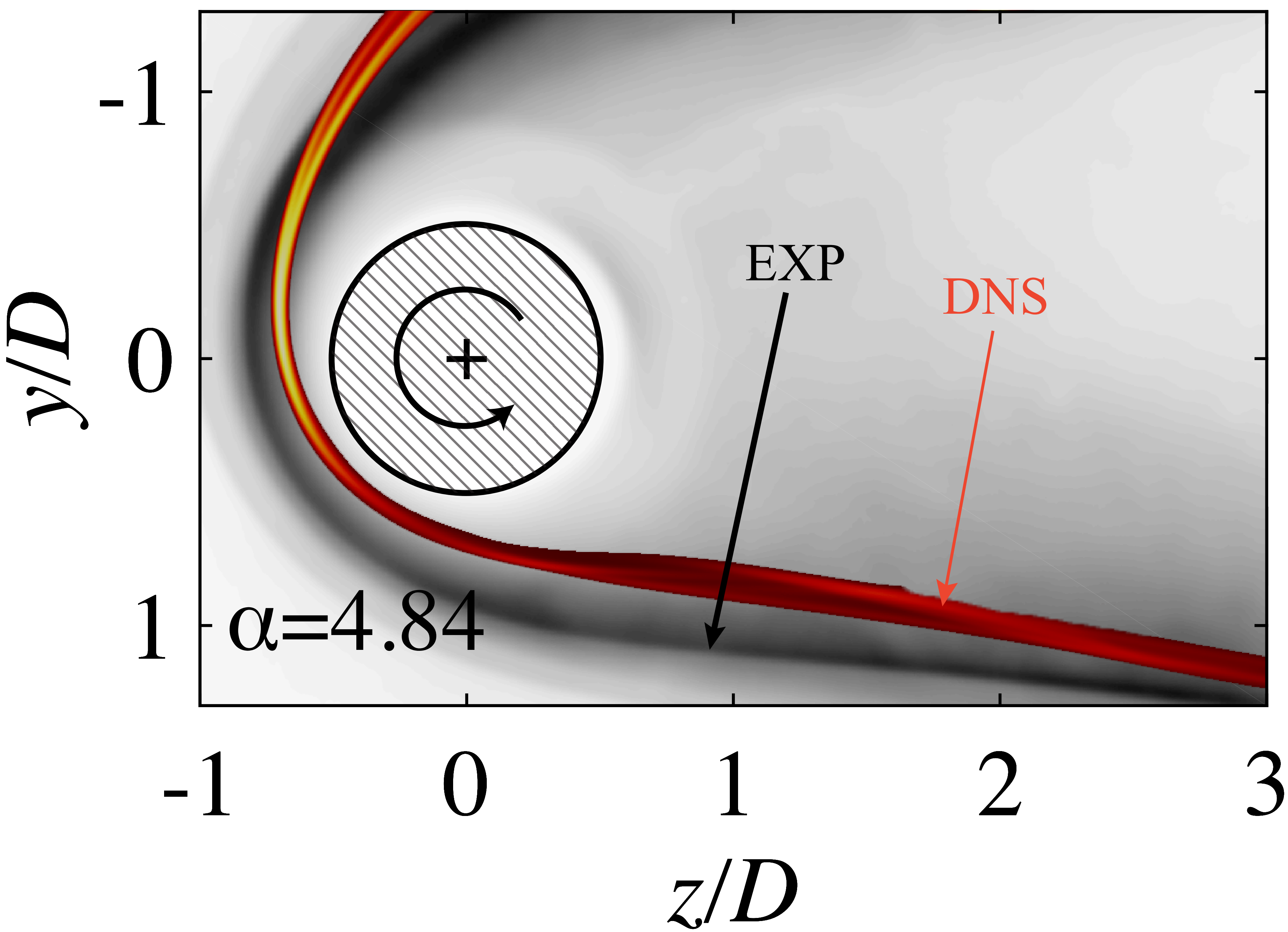
$\Phi = 0.70$

$u_b = 1.07 \text{ ms}^{-1}$

$T^u = 300 \text{ K}$

$P = 1 \text{ bar}$

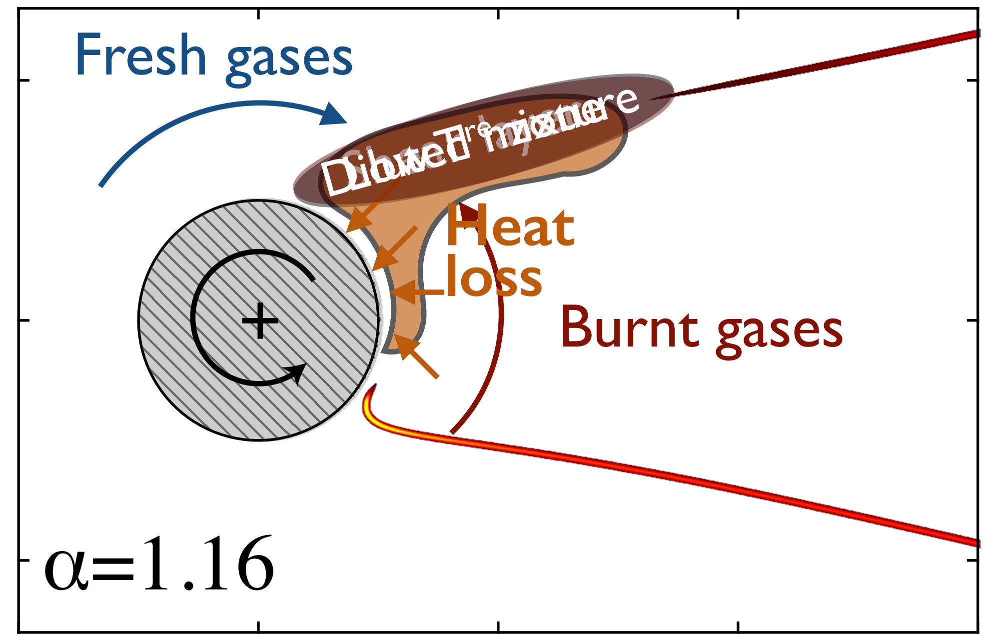
$\alpha = 1.16$



Experiments and Direct Numerical Simulations are in good agreement. The PIV velocity fields and the flame front position are well reproduced by the DNS.

Flame stabilization

Why does the upper branch of the flame detach from the cylinder?



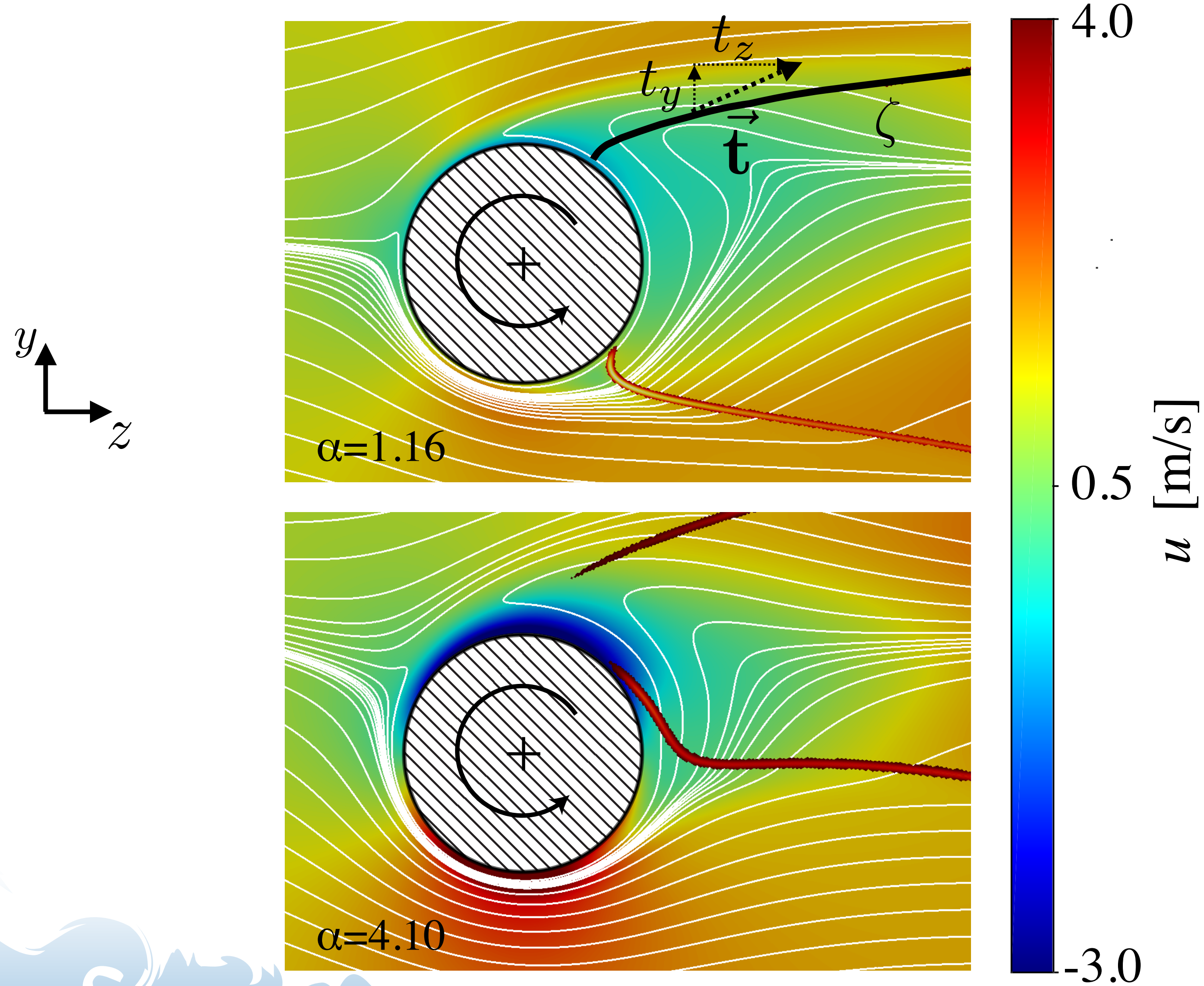
1. **Stretch** due to cylinder rotation,
2. **Dilution** of the fresh gases by the burnt gases
3. **Heat losses** from the burnt gases to the 'cold' cylinder.

To evaluate this hypothesis we compare the cases α=1.16 and α=4.10

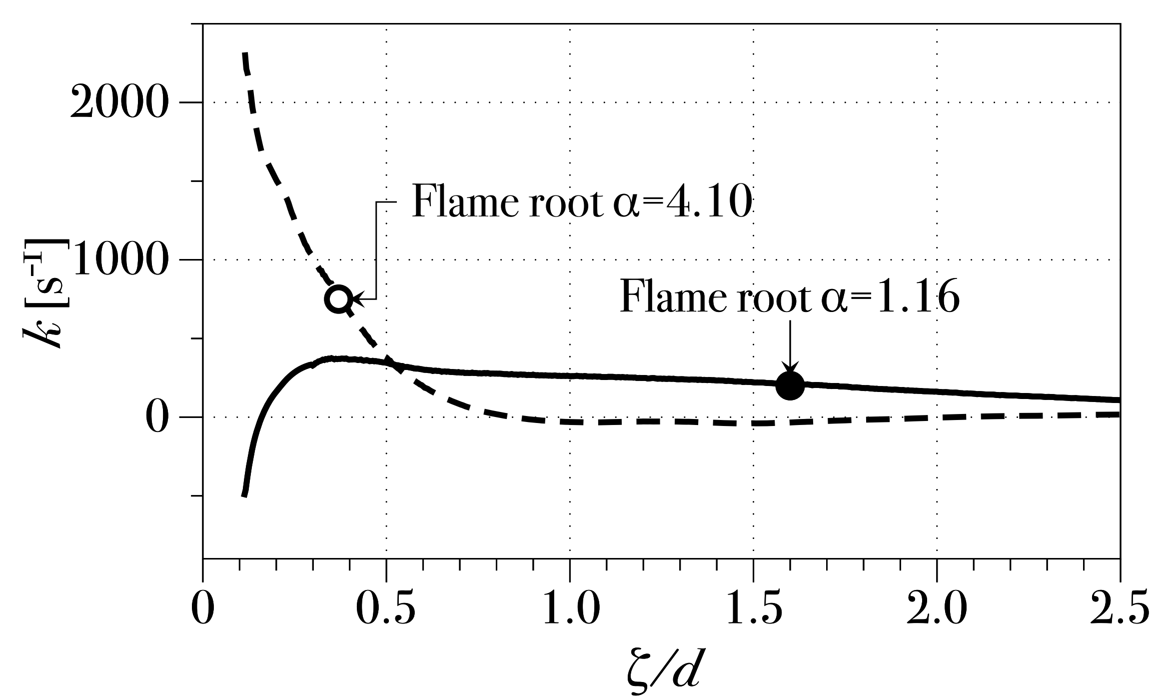
Stretch

$$k = -\vec{\mathbf{n}}\vec{\mathbf{n}} : \nabla\vec{\mathbf{u}} + \nabla\cdot\vec{\mathbf{u}} + s_d(\nabla\cdot\vec{\mathbf{u}})$$

$$k = \nabla_t \cdot \vec{\mathbf{u}}_t = t_z^2 \frac{\partial u}{\partial z} + t_z t_y \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial z}\right) t_y^2 \frac{\partial v}{\partial y}$$ ⟶ **Stretch** of a stationary flame



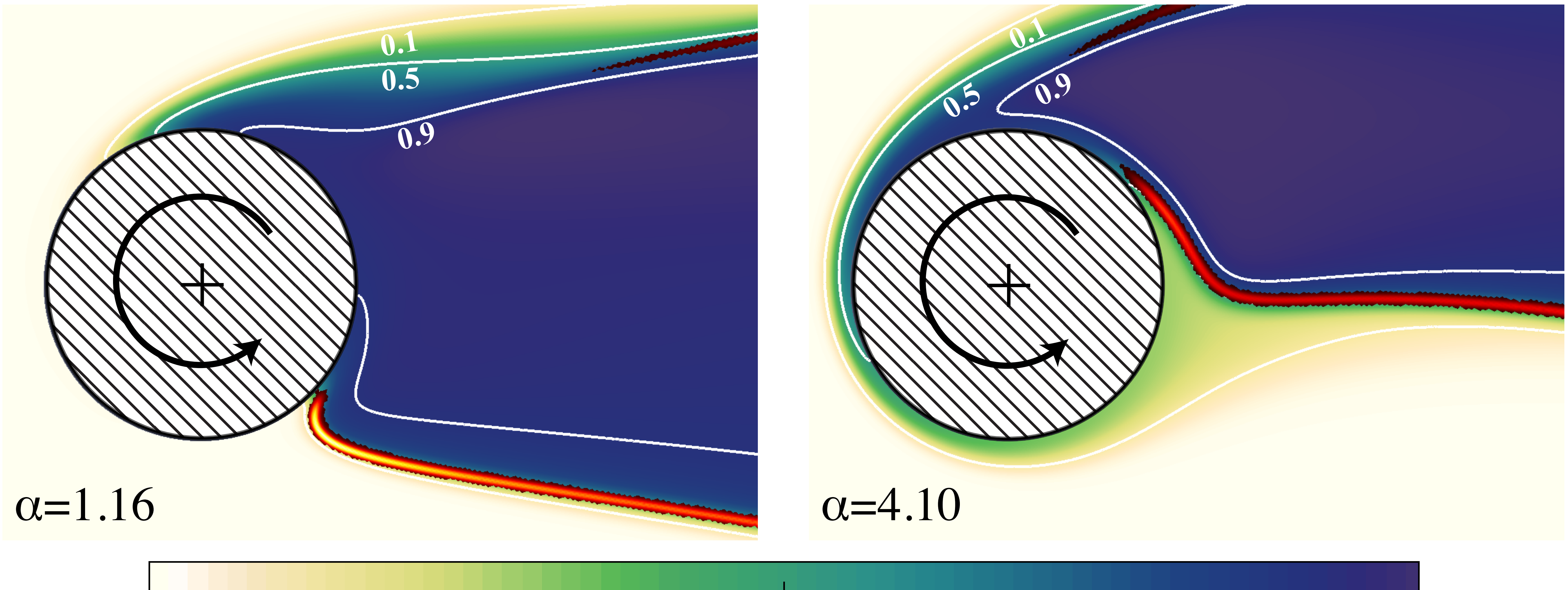
$$k_{ext} = 4000\ \mathrm{s}^{-1}$$



Dilution

Dilution of the fresh gases by burnt gases due to the cylinder rotation.

$$\mathcal{D} = \frac{Y_{CO_2}}{Y_{CO_2}^{max}}$$

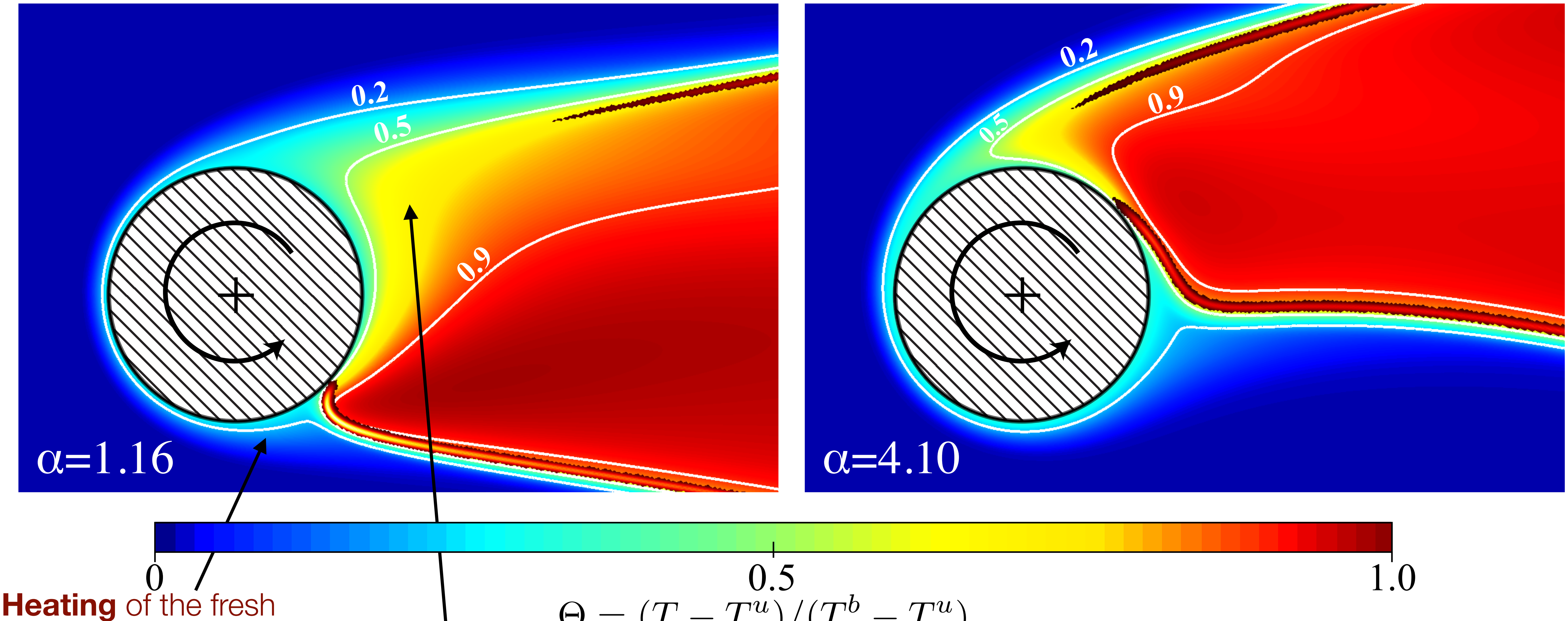


$$\mathcal{D} = Y_{CO_2}/Y_{CO_2}^{max}$$

Heat losses

Cooling of the burnt gases near the "cold" cylinder.

$$\Theta = \frac{T - T^u}{T^b - T^u}$$

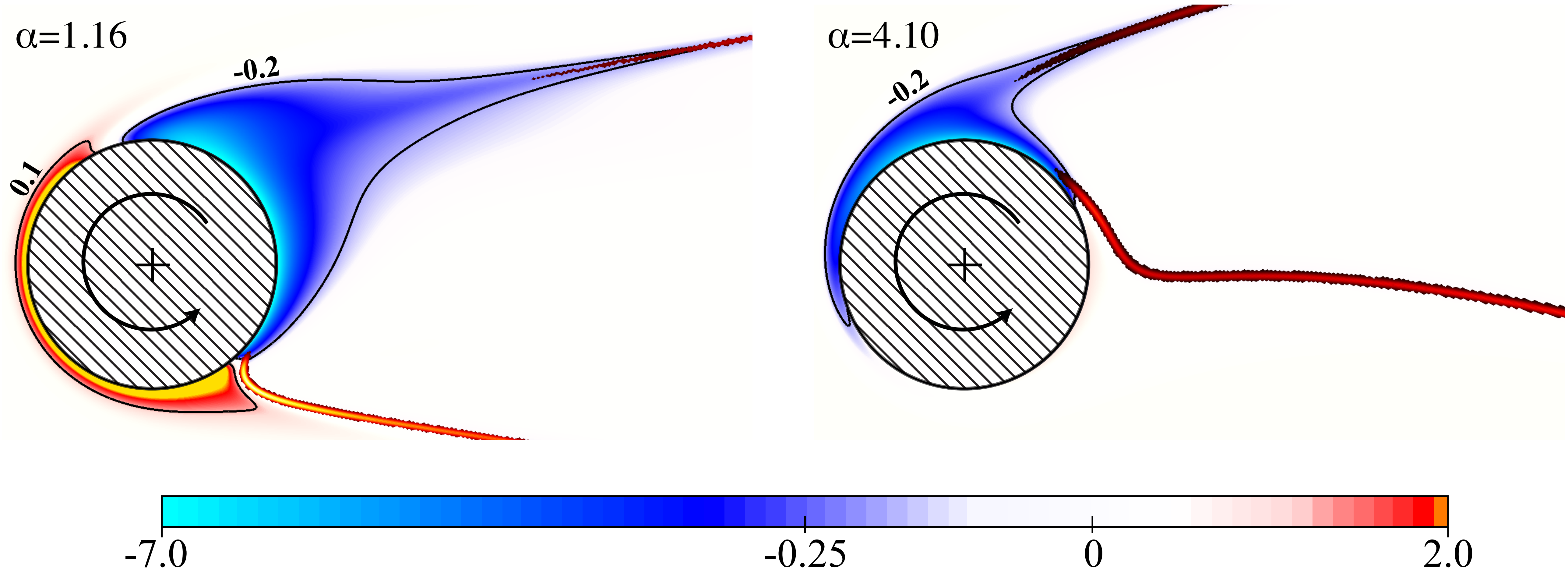


Heating of the fresh gases by cylinder.

Cooling of the burnt gases by the cylinder

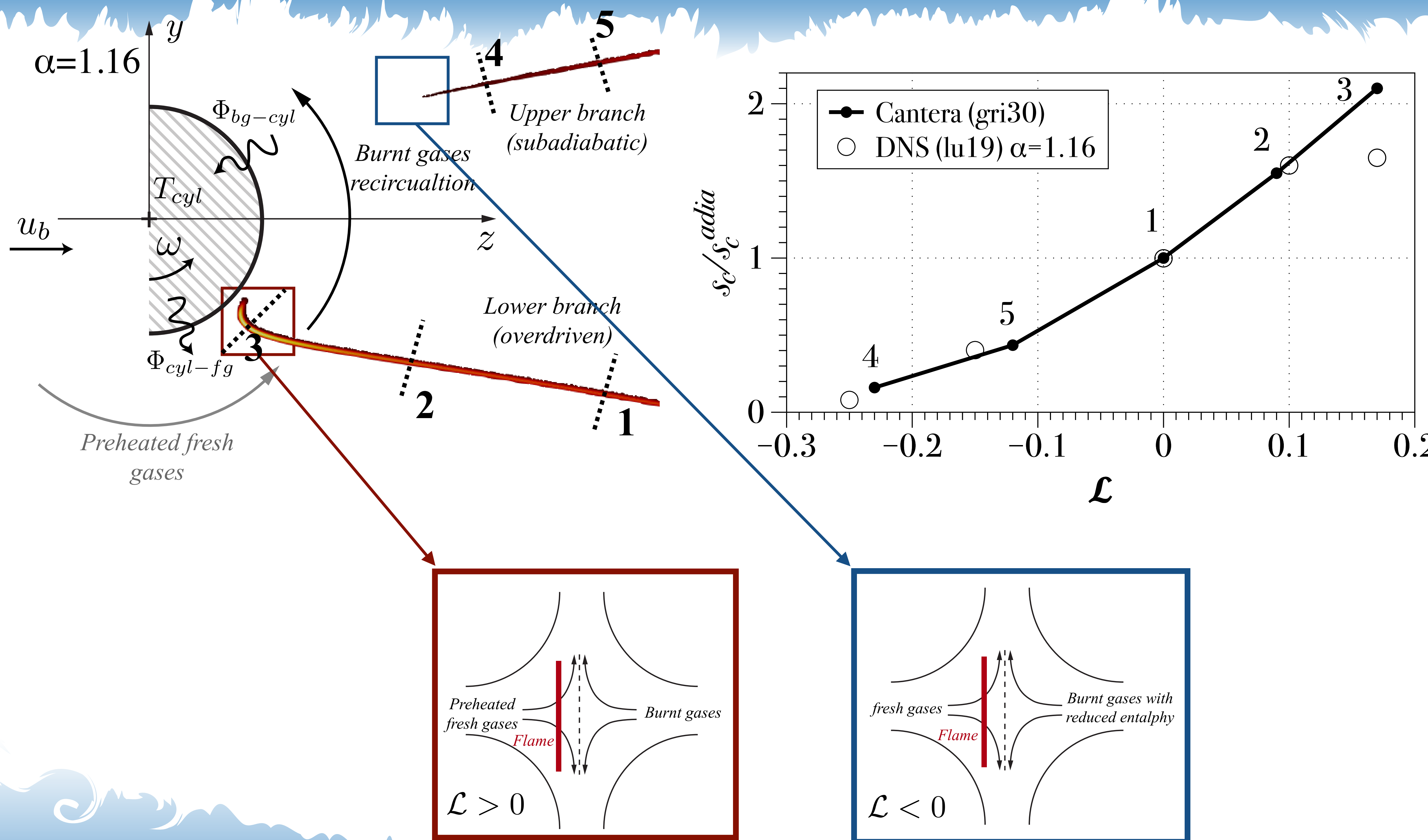
Enthalpy losses

$$\mathcal{L} = \frac{h_t - h_t^u}{QY_F^u} \quad \text{or,} \qquad \mathcal{L} = \underbrace{\frac{1}{QY_F^u}\left[\int_{T_0}^{T} C_p \mathrm{d}T\right]}_{\mathcal{L}_s} + \underbrace{\frac{1}{QY_F^u}\left[\sum_k \Delta h_{f,k}^0 Y_k\right]}_{\mathcal{L}_c}$$



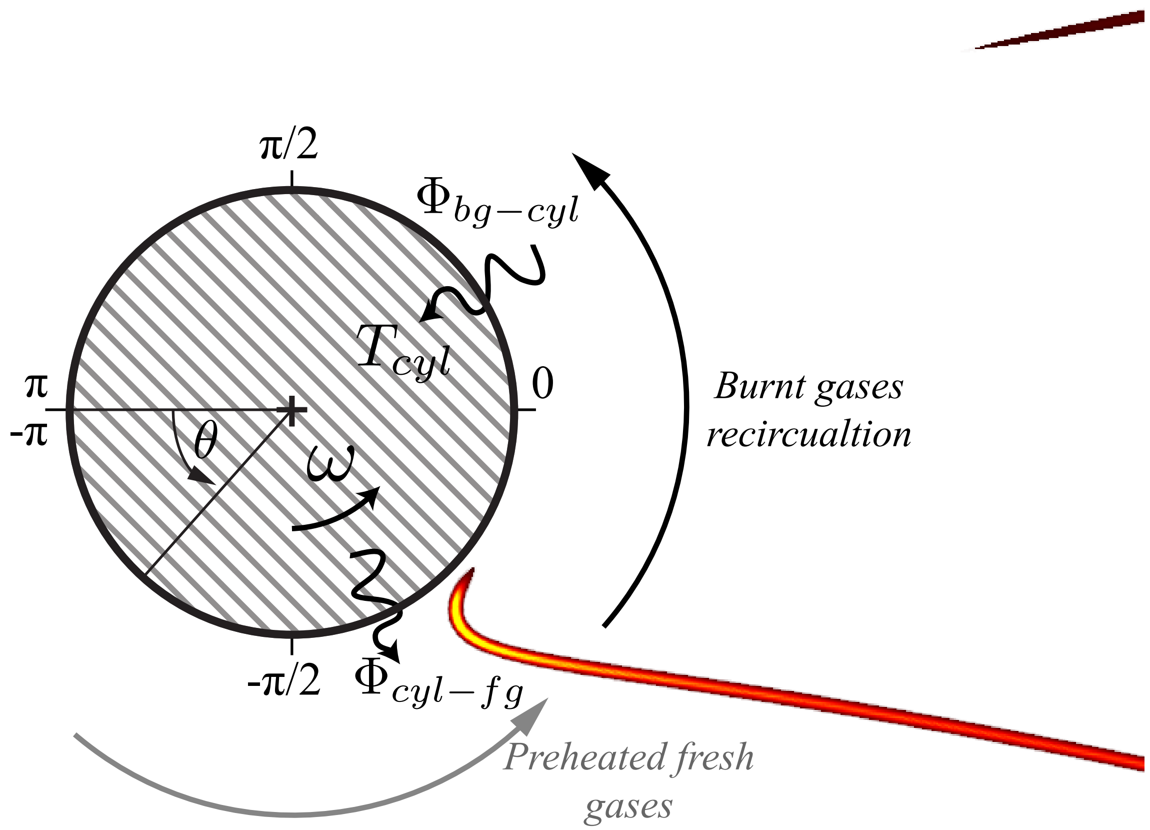
$$\mathcal{L} = \left(h_t - h_t^u\right) / \left(QY_F^u\right)$$

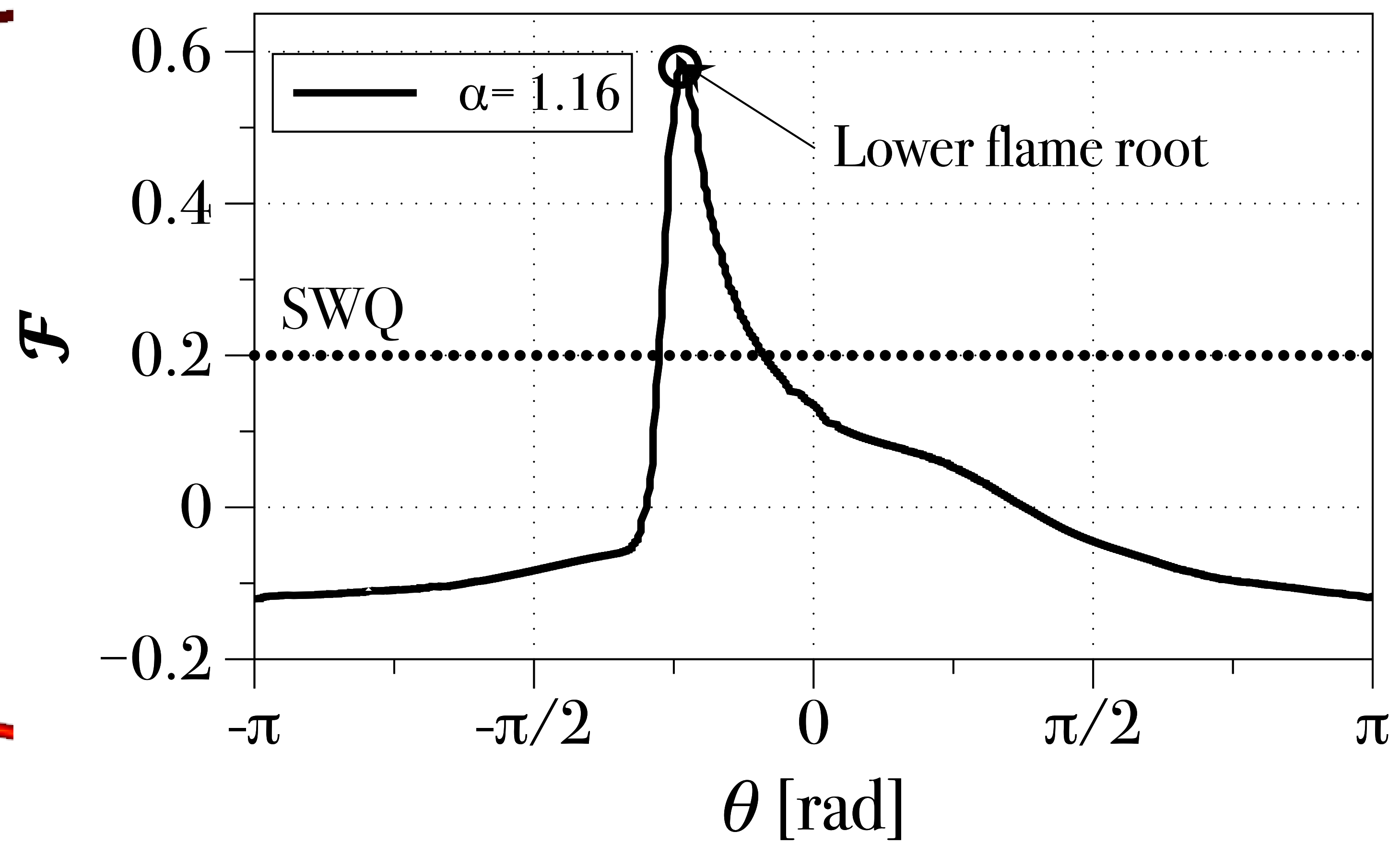
Non-adiabatic stretched planar flames



Flame / Moving wall interaction

$$\Phi = -\lambda \frac{\partial T}{\partial y}|_W \qquad \mathcal{F} = \frac{\Phi}{\rho^u s_L^0 Y_F Q}$$

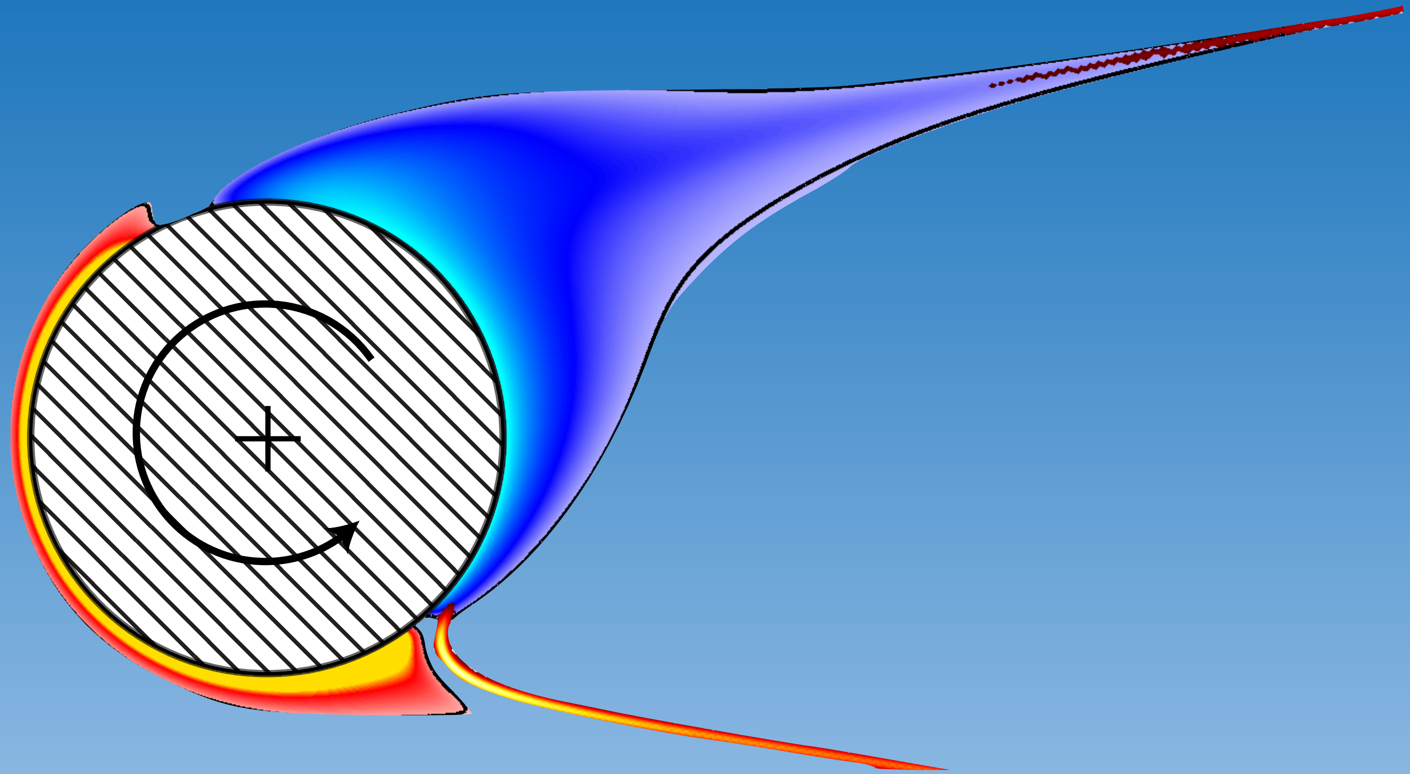




Conclusions

Experiments and direct numerical simulations were performed in a premixed laminar flame stabilized on a rotating cylinder.

- ★ The flame topology is strongly dependent on the rotation rate, three type of flames were found: SSD, ASD and ASU.
- ★ Experiments and DNS simulations are in good agreement. The PIV velocity field is well reproduced by the DNS, as well as the CH^* flame front position.
- ★ For low rotation rates, the upper branch of the flame detaches from the cylinder. The DNS simulation showed that this effect is not due to stretch but to the enthalpy losses, which is caused by the increased heat transfer from the burnt gases by to the cylinder due to the rotation of the flame holder.



Thank you for your attention

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