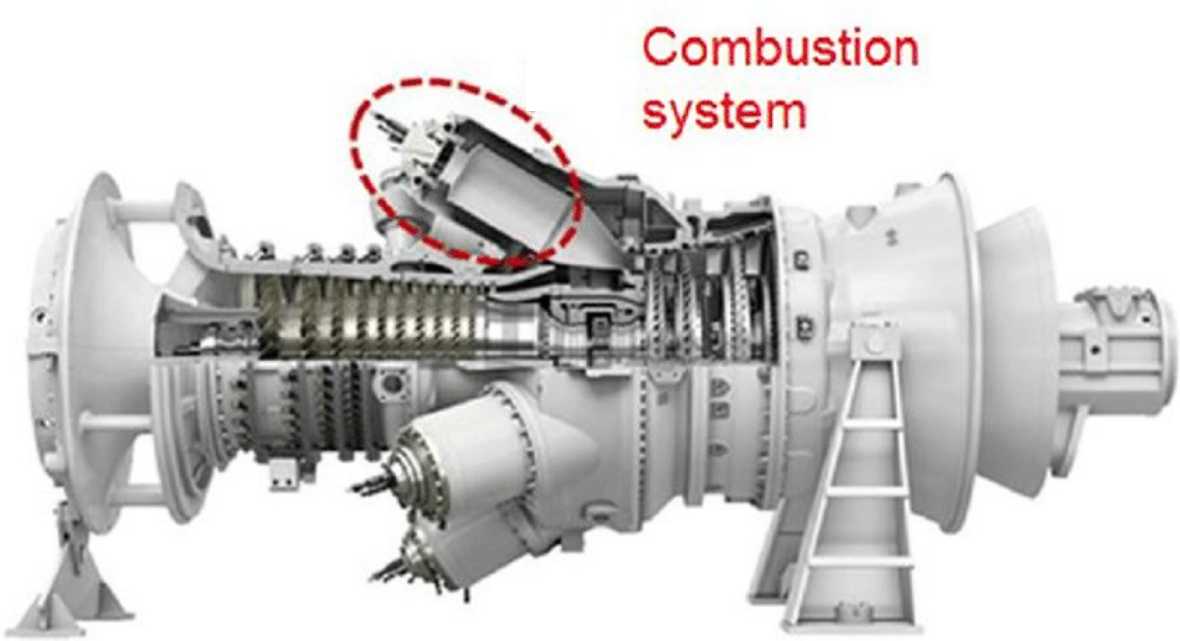
Analysis of hydrogen flame flashback in swirling annular flows

James Bailey

Edward Richardson



16/09/2020

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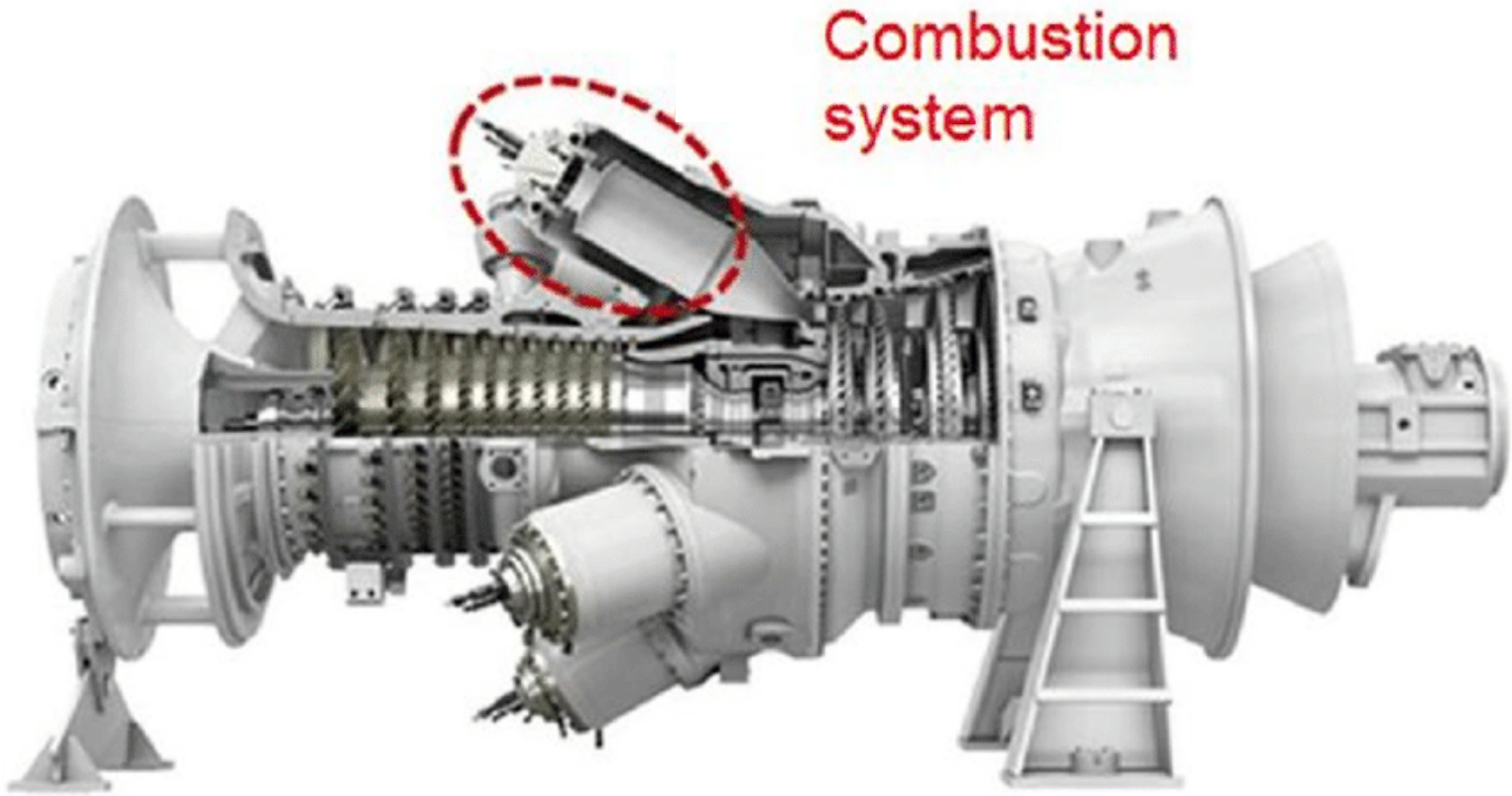
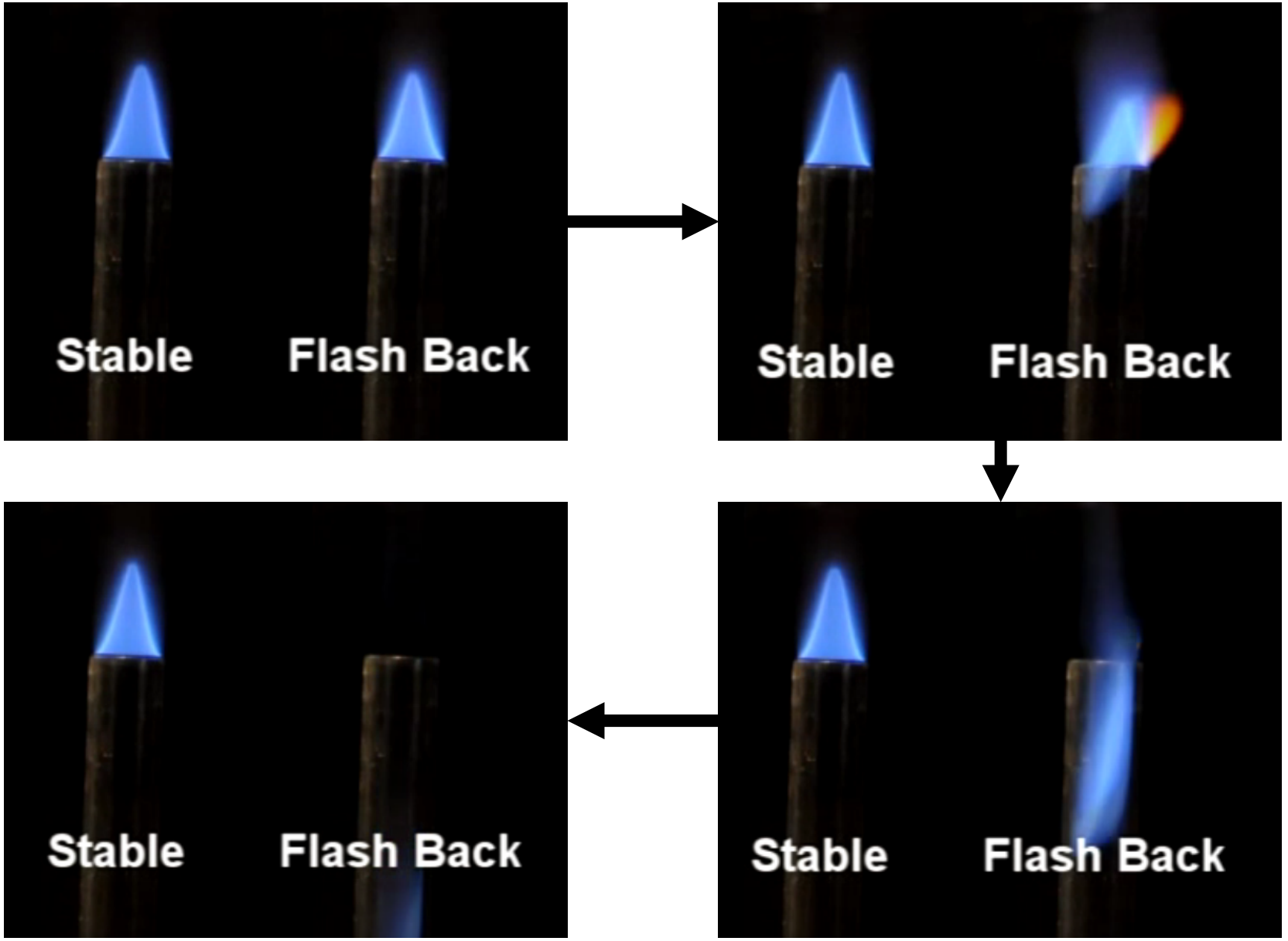
Background

- Industrial gas turbines
- Fuel-flexible burner and alternative fuels

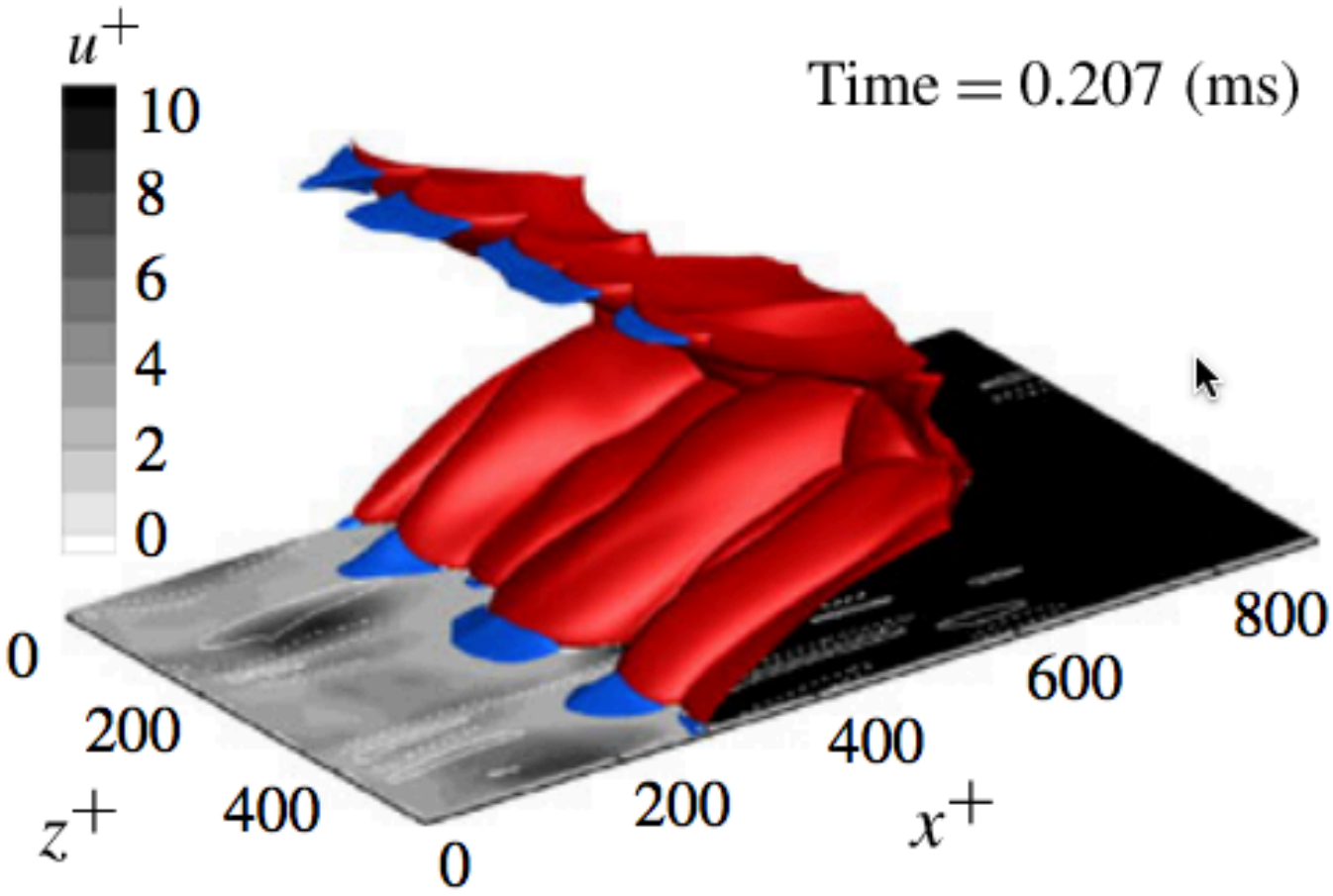


https://www.researchgate.net/profile/Ieuan_Owen/publication/282796815/figure/fig14/AS:668870398464013@1536482538619/A-Siemens-industrial-gas-turbine-engine-showing-the-components-of-a-generic-DLE.png

Flashback

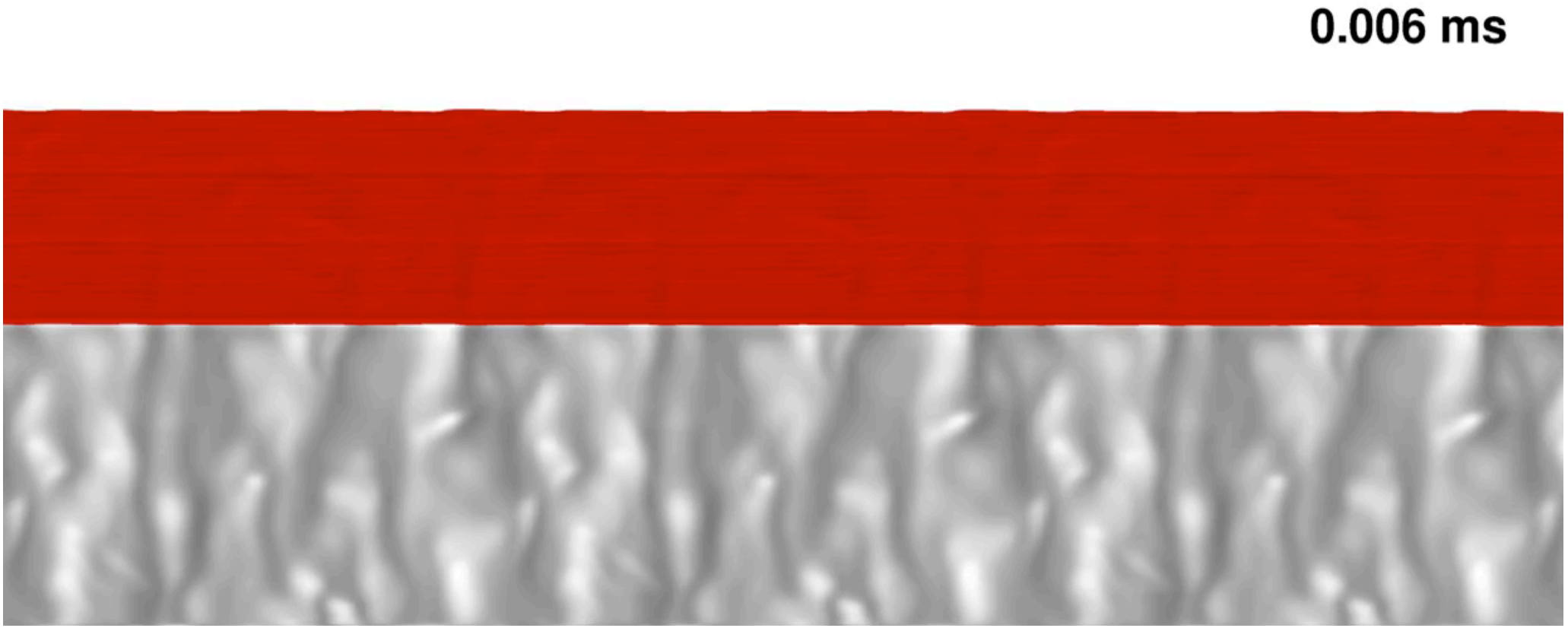

Stable
Flash Back
Stable
Flash Back
Stable
Flash Back
Stable
Flash Back

Boundary Layer Flashback

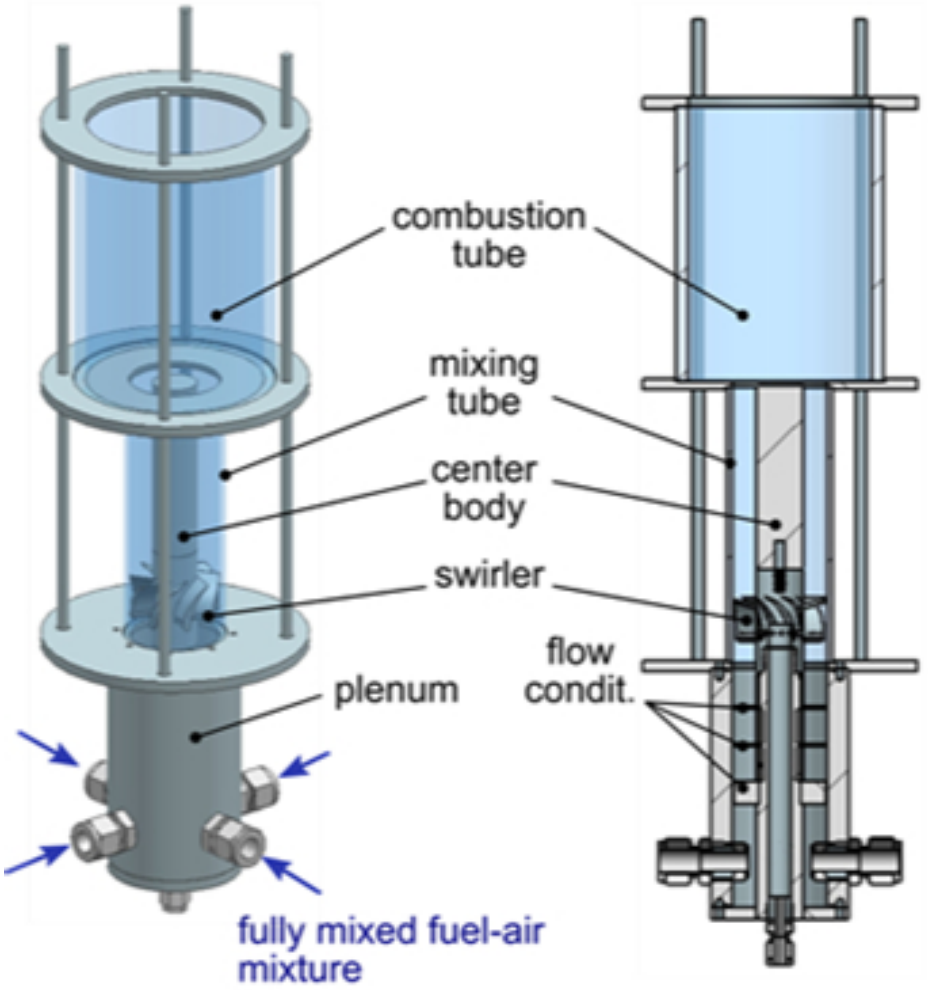


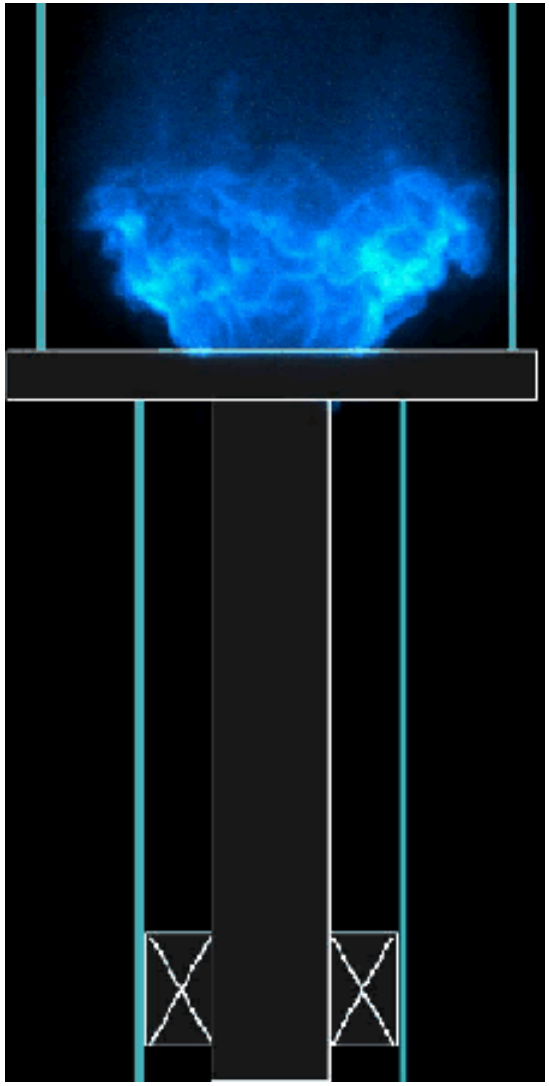
Gruber et al., Journal Fluid Mechanics, 2012, 709, 516-542

Boundary Layer Flashback



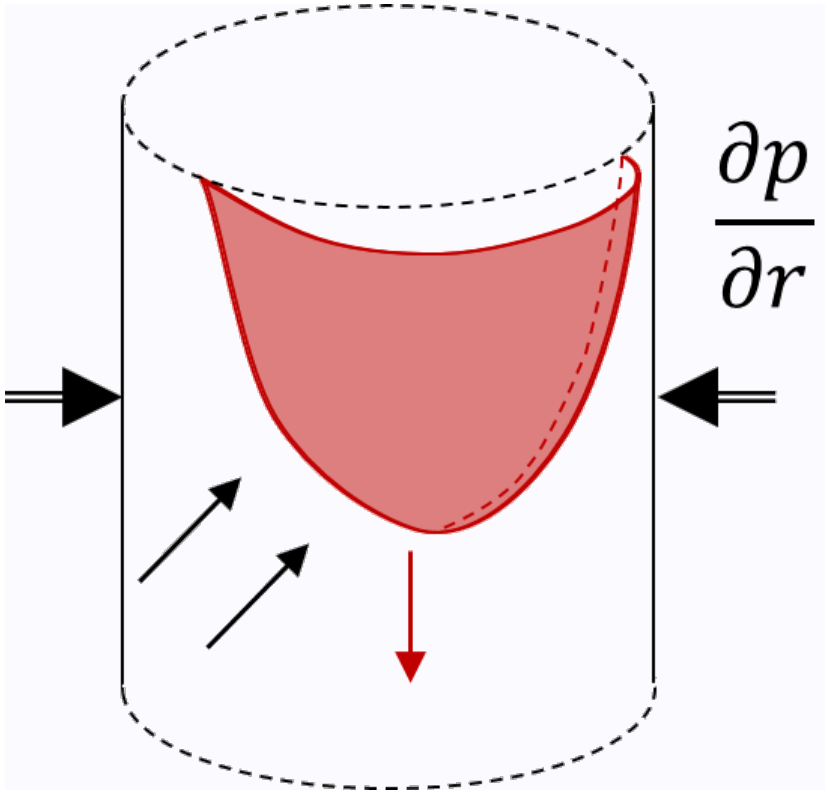
Flashback in Swirling Flows





Ebi and Clemens, Combustion and Flame, 2016, 168, 39-52 (CC BY 4.0 Licence)

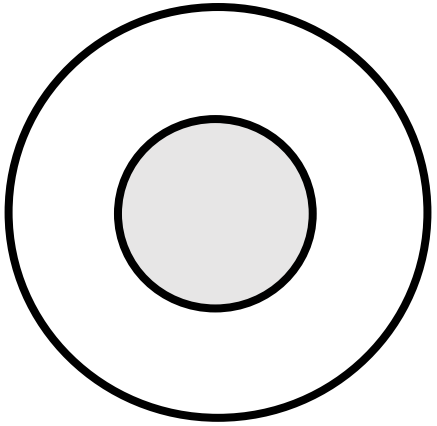
Flashback in Swirling Flows



Radial pressure gradient

$$\frac{\partial p}{\partial r} = \rho \frac{V_\theta^2}{r}$$

Curvature

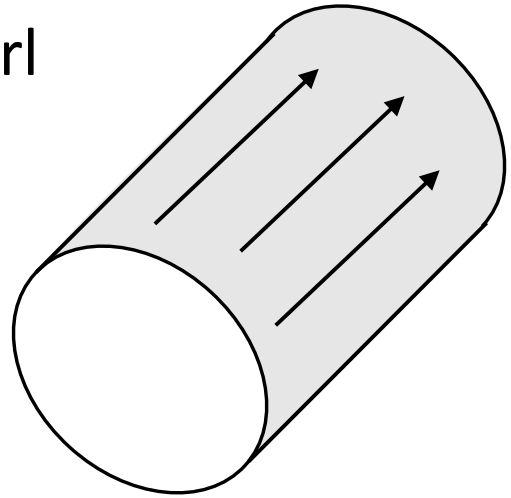


Methodology

Methodology

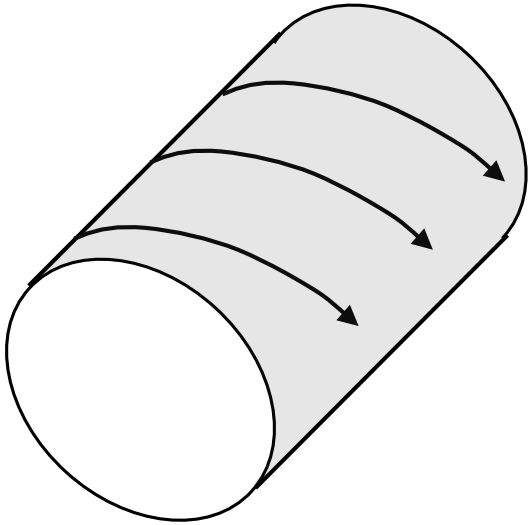
No Swirl

$Sw = 0$



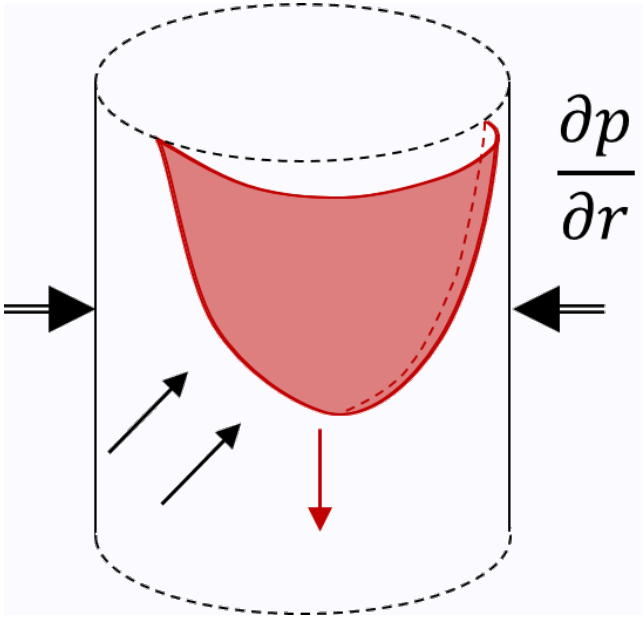
Swirl

$Sw \sim 1$



Radial pressure gradient

$$\frac{\partial p}{\partial r} = \rho \frac{V_\theta^2}{r} = g$$

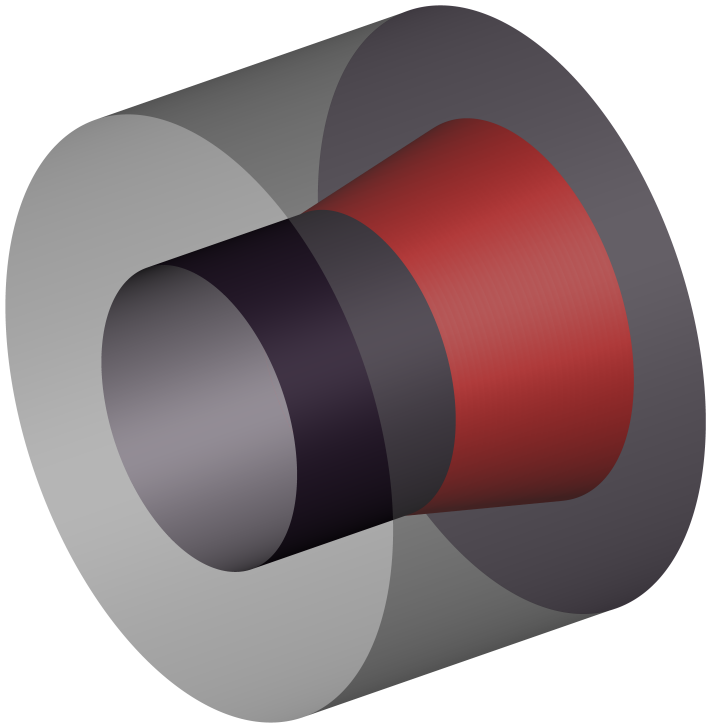


Methodology

- Direct Numerical Simulation using cylindrical version of S3D
- Solve fully compressible, reacting Navier-Stokes
  - 9 species, 21 reactions in H2-Air Mechanism

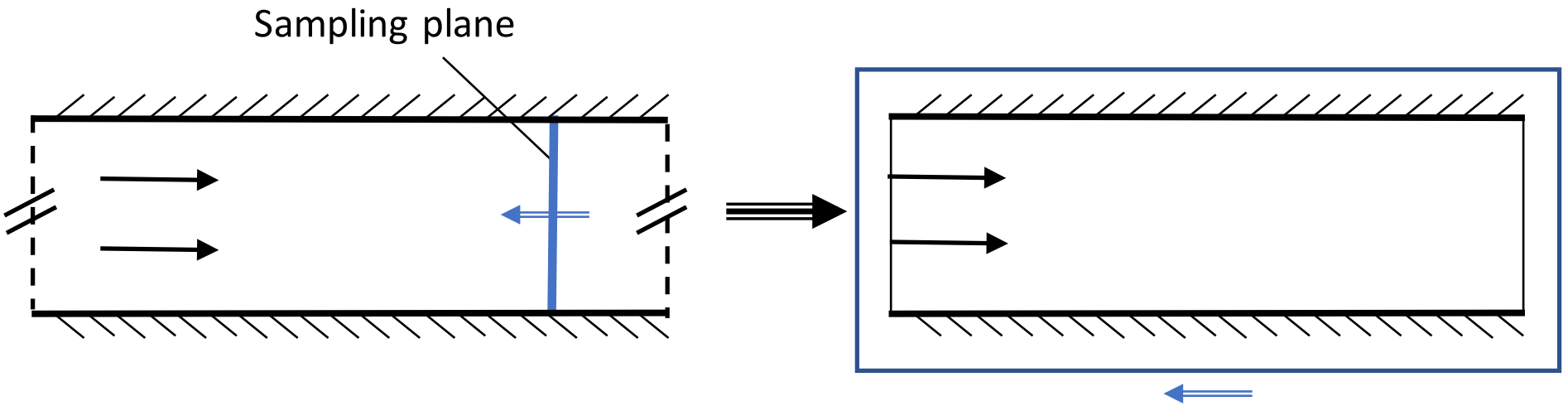
- $Re_\tau = 180$

- Grid points:
  - ~175 million for quarter-annulus
  - ~350 million for half-annulus
- Run on 480 and 1920 processes
- Simulation time: 0.4 ms
- Total Computational Cost
  - ~400 000 CPU-hours (6 000 kAUs)



Methodology

- Realistic, time-evolving turbulence with moving frame-of-reference

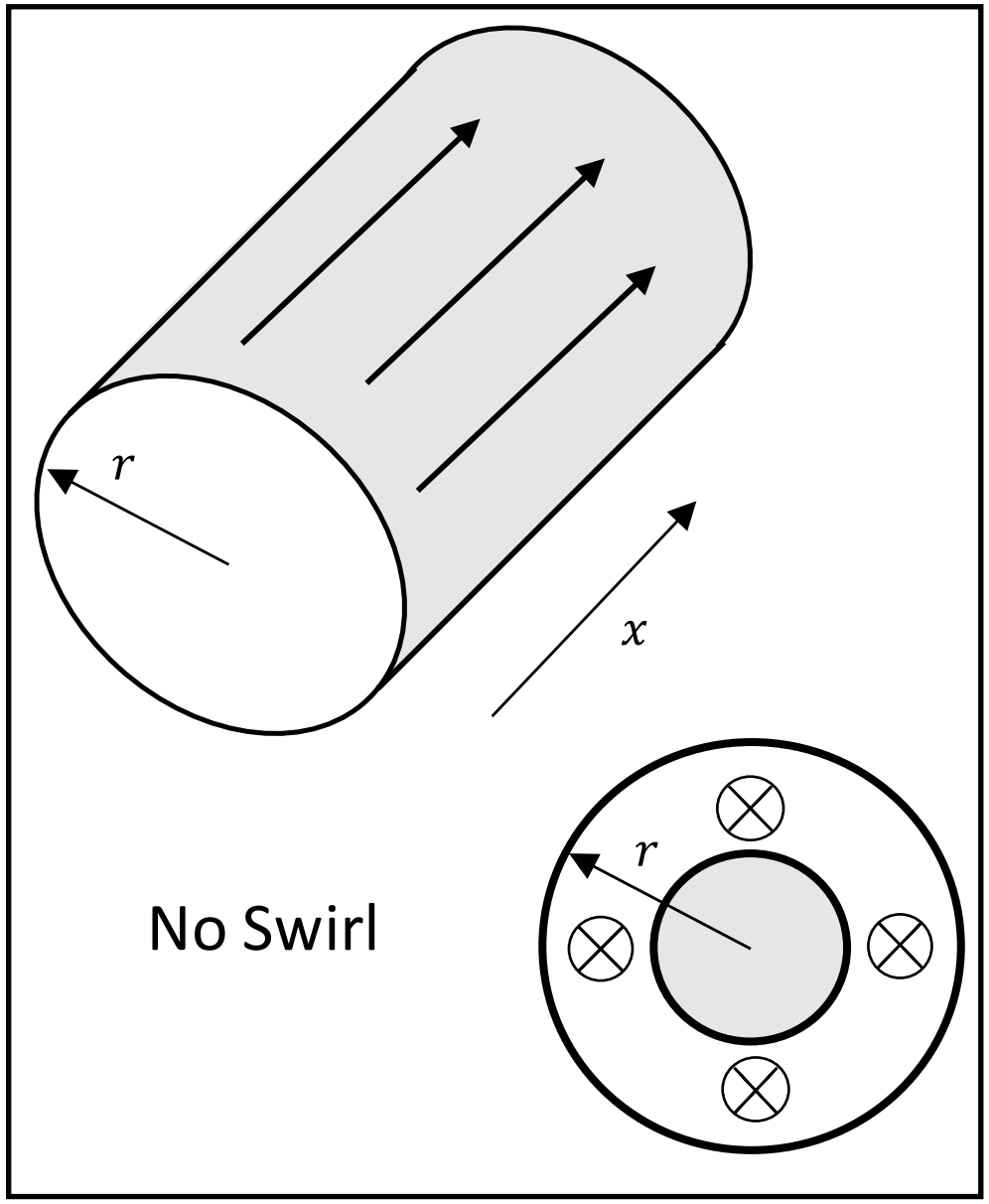


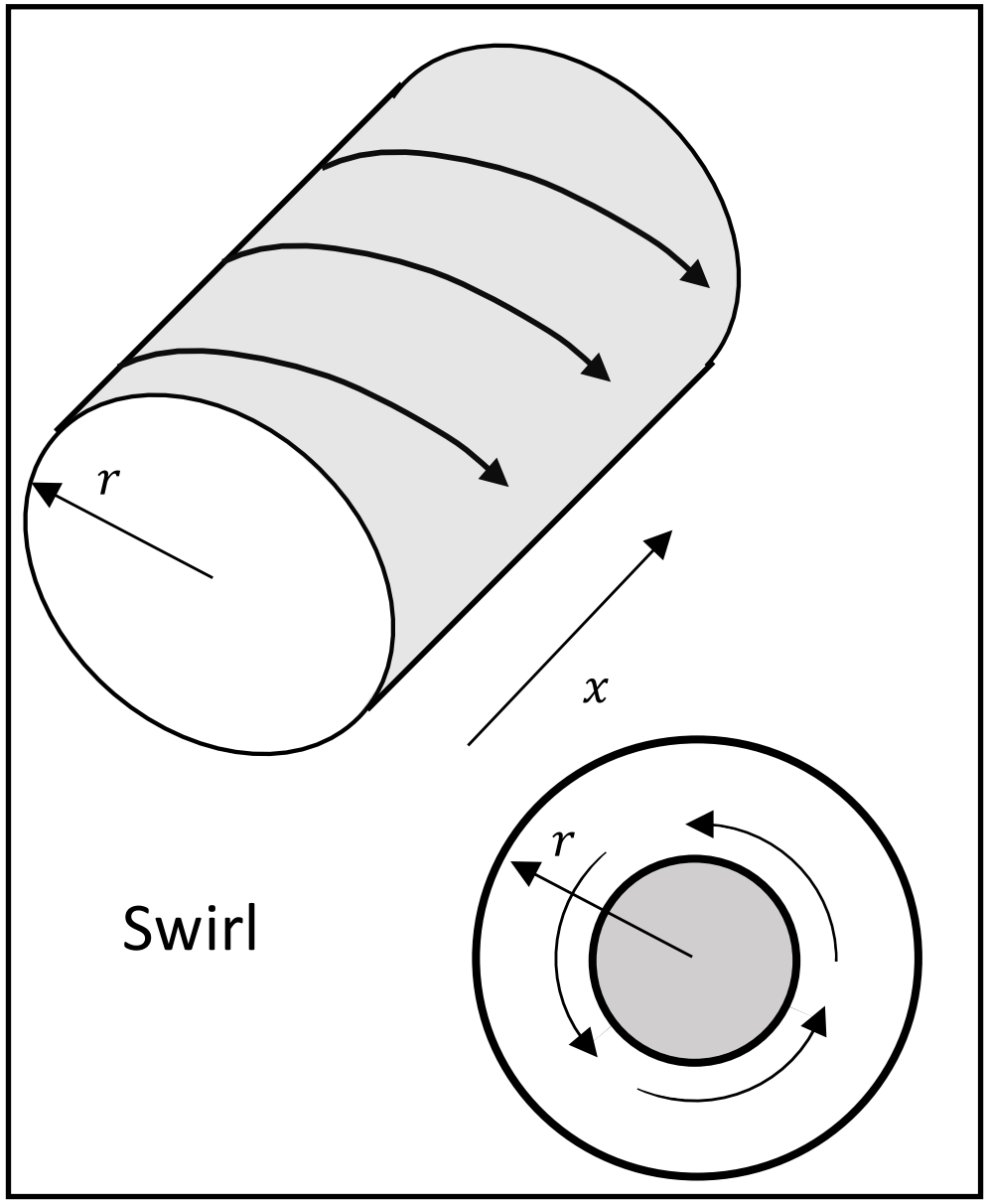
Auxiliary, non-reacting, turbulent annular flow

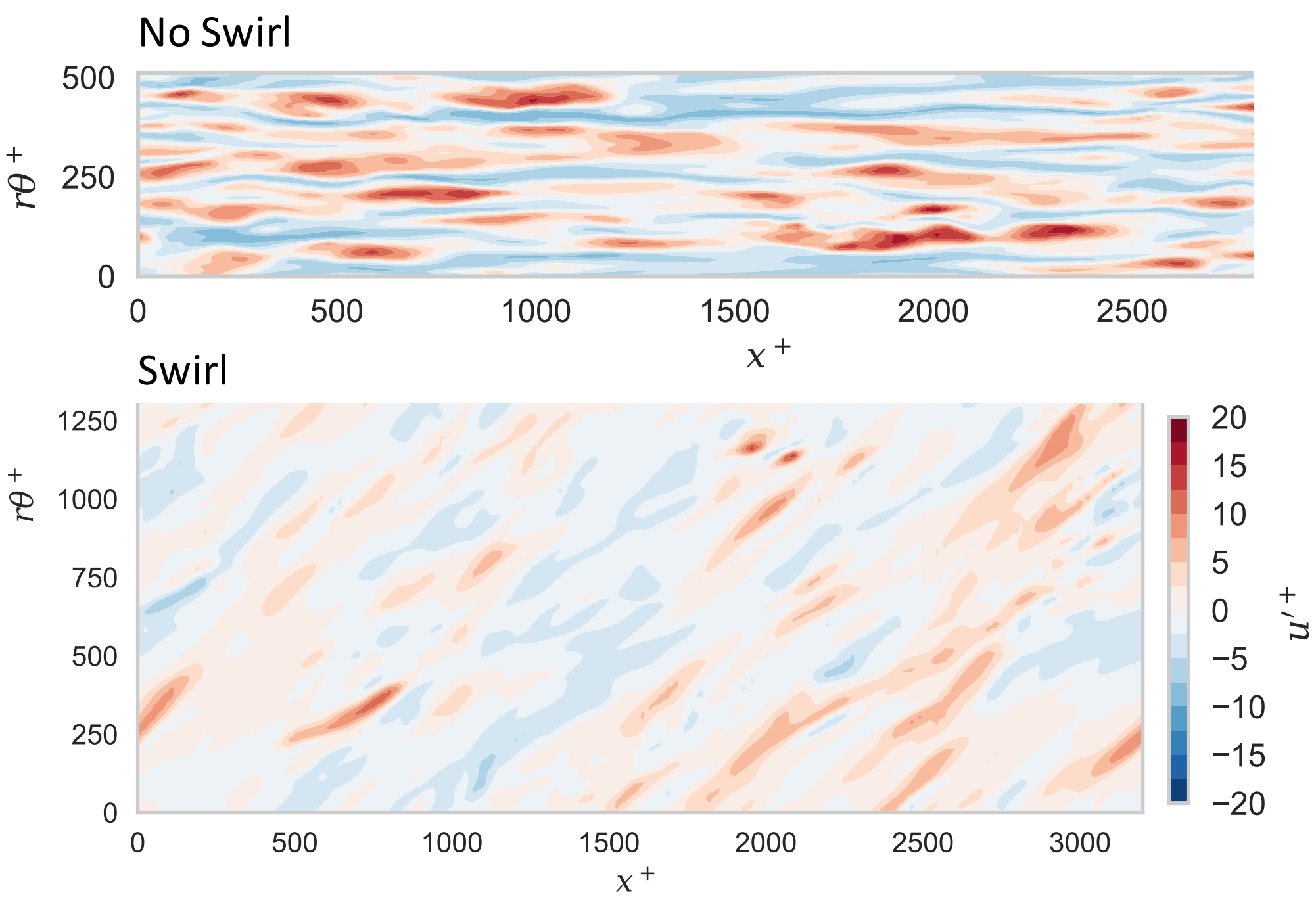
Reacting annular flow with realistic, time-evolving turbulence

Results – Non-Reacting

Curvature effects

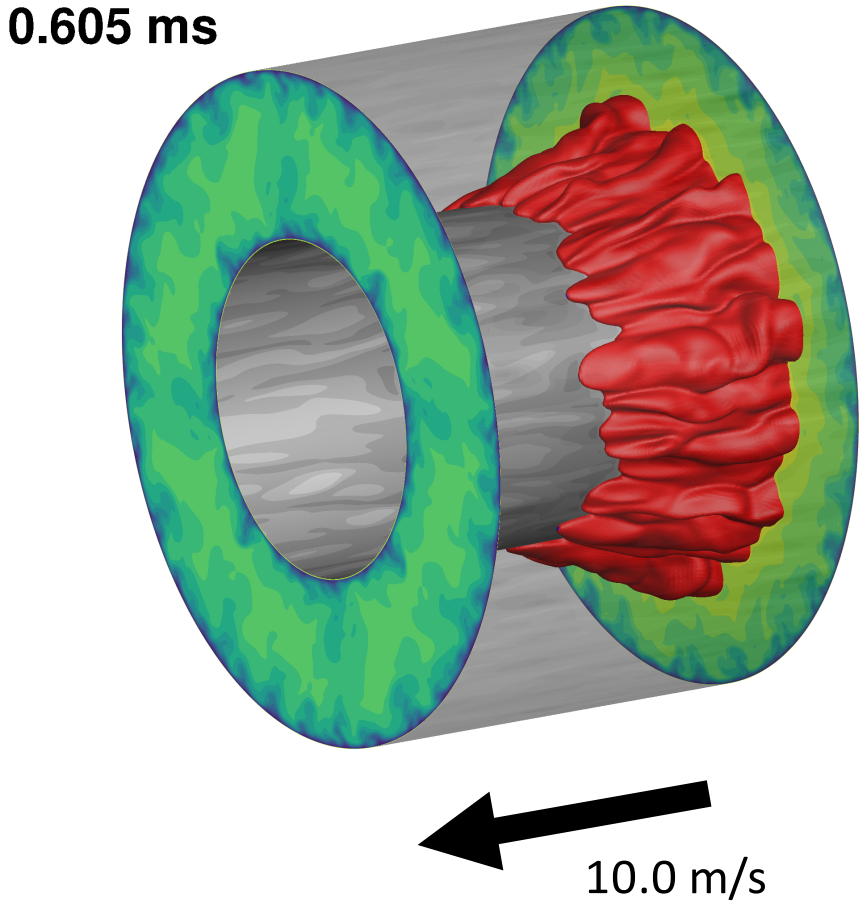




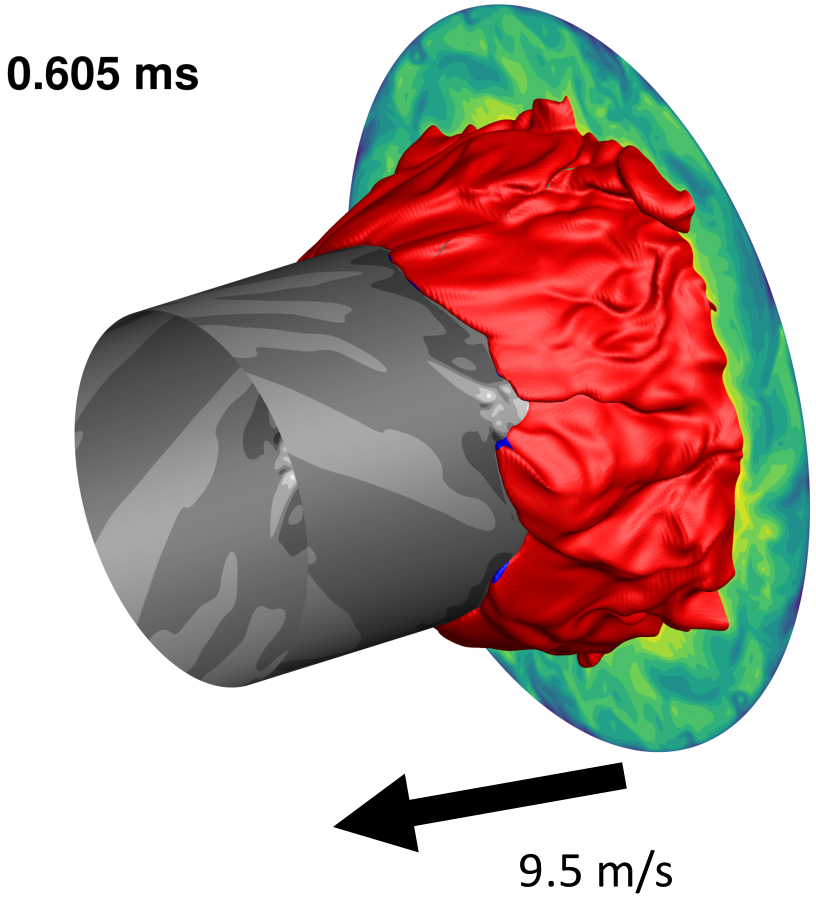

No Swirl
500
250
0
$r\theta^+$
0
500
1000
1500
2000
2500
x^+
Swirl
1250
1000
750
500
250
0
$r\theta^+$
0
500
1000
1500
2000
2500
3000
x^+
20
15
10
5
0
−5
−10
−15
−20
u'^+

Results – Reacting

Flashback

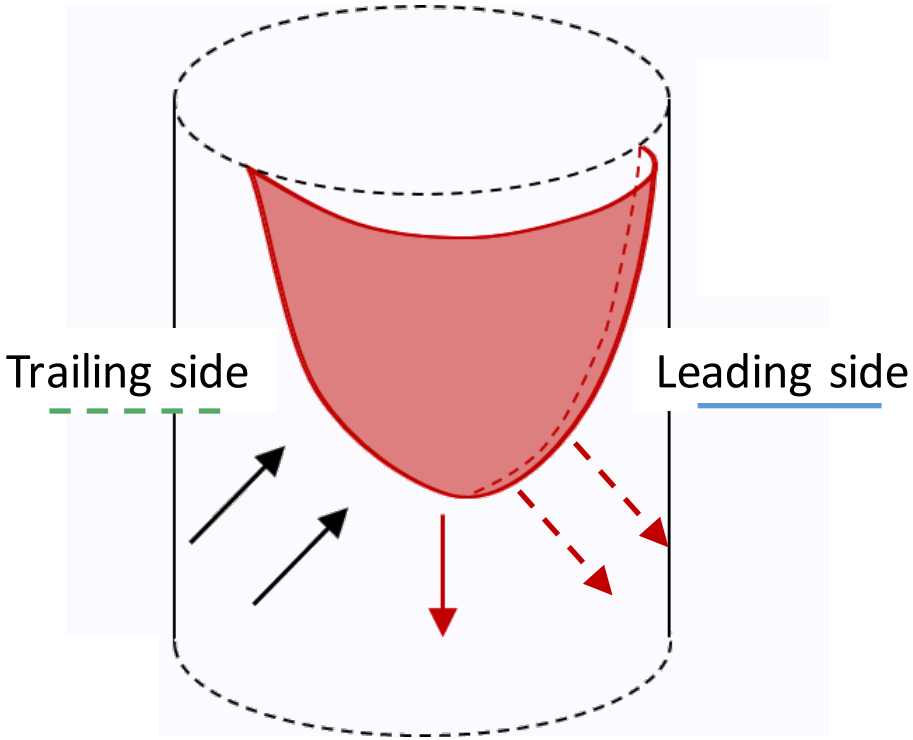


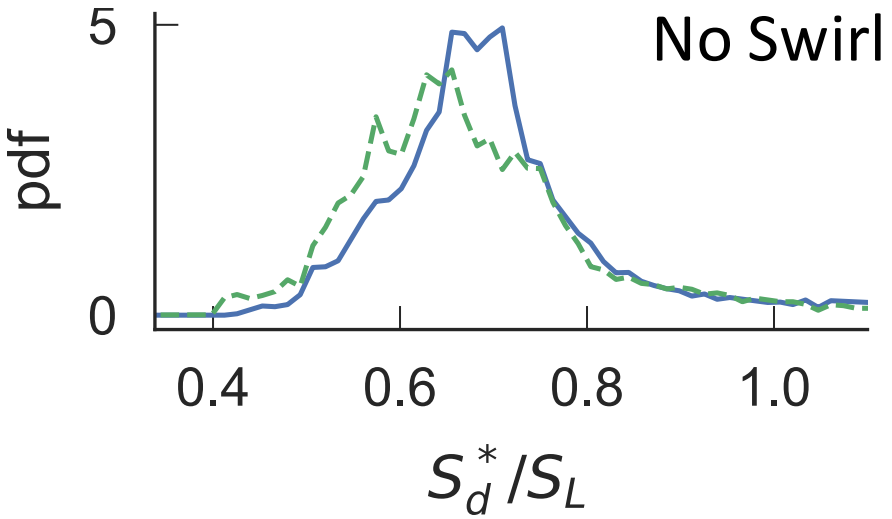
No Swirl

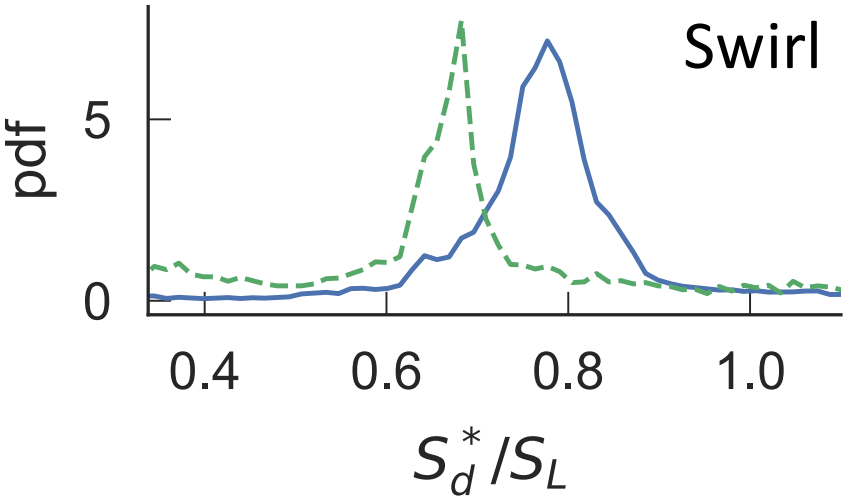


Swirl

Oblique flow orientation





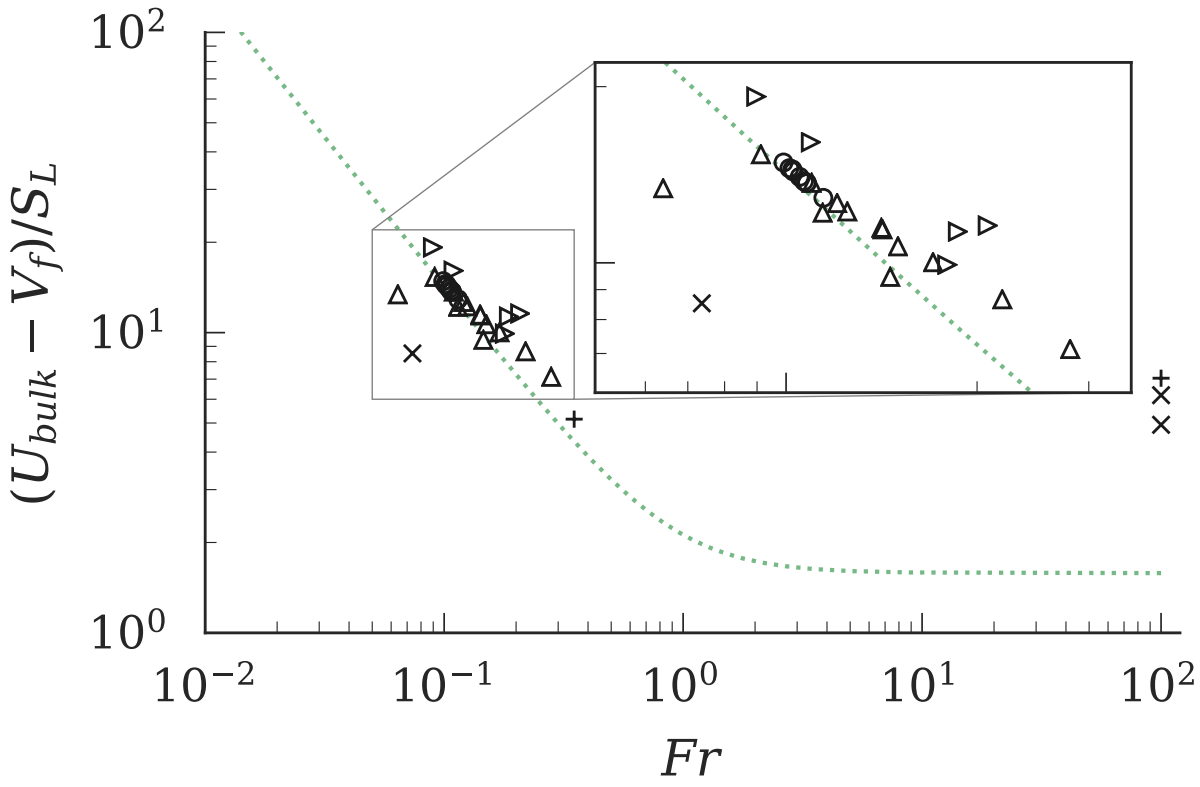


Radial pressure gradient

$$\frac{U_{bulk} - V_f}{S_L} = \sqrt{D + \frac{2}{Fr^2}}$$

$$D = \frac{\rho_u}{\rho_b}$$

$$Fr = \frac{S_L}{\sqrt{g\left(\frac{\rho_u - \rho_b}{\rho_u}\right)\delta}}$$



J Bailey, ES Richardson. DNS analysis of boundary layer flashback in turbulent flow with wall-normal pressure gradient, Proceedings of the Combustion Institute [In Press].

Summary

- Annular turbulent boundary-layer flashback in non-swirling and swirling flows
- Curvature - non-reacting swirling flow has weaker turbulent boundary-layer streaks, slowing growth of bulges and cusps in reacting flow
- Oblique flow orientation causes asymmetric propagation of bulges
- Radial pressure gradient - trend in flashback speed with swirl described by momentum-balance model using uniform body force

Thank you

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Acknowledgements

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