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Vortex breakdown in swirling jets: origin and control

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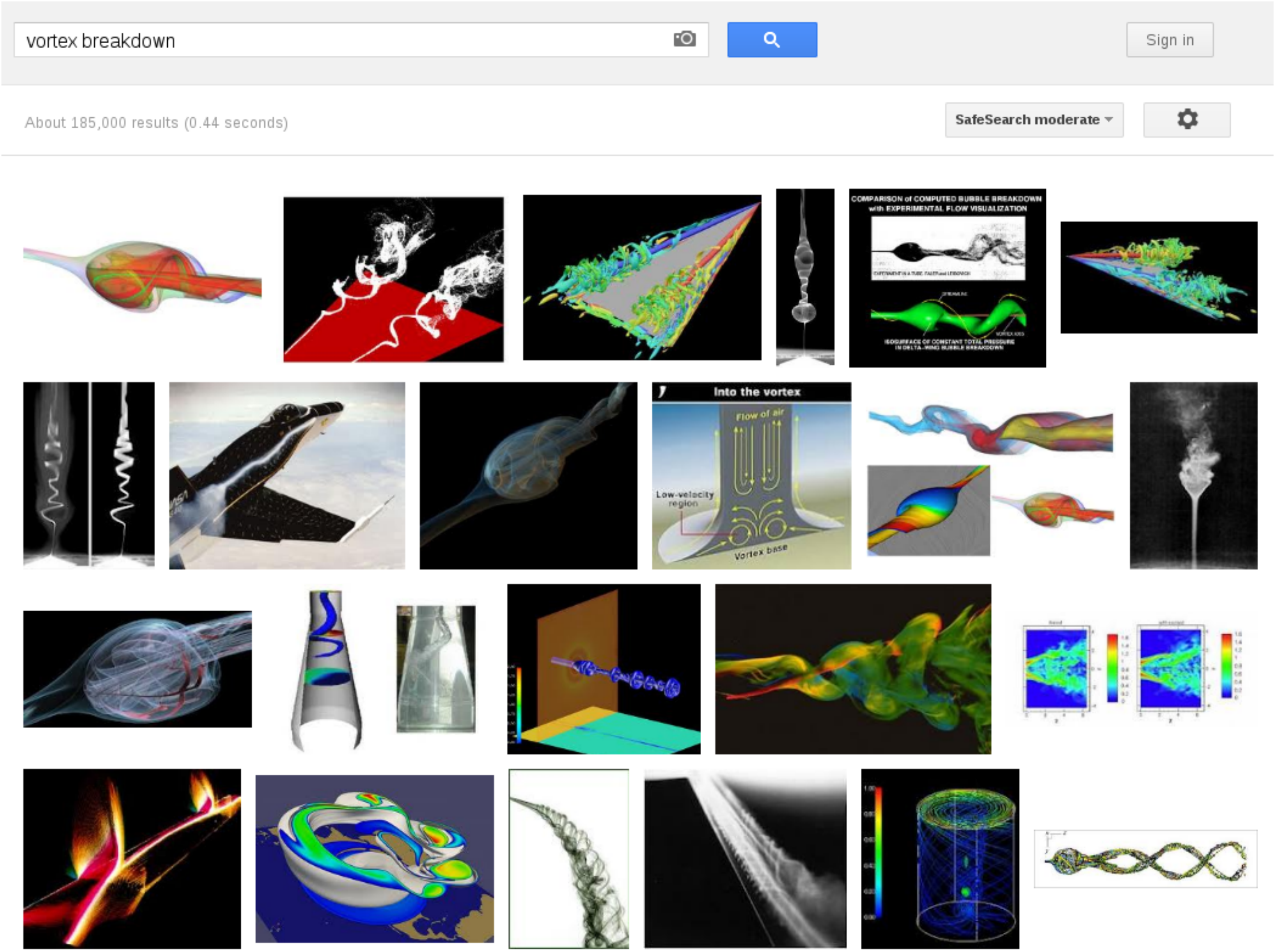
You probably have the following questions in mind. . .

- Why are you interested in this?
- What exactly do you want to work out?
- How do you work out whatever it is you want to work out?
- What exactly do you find?
- So what? Is it of any use?

Vortex breakdown occurs in many practical flows:
over delta wings, tornadoes and in combustion chambers.



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Why do we want to study this?

Vortex breakdown is characterised by the formation of a steady recirculation zone. In combustion chamber chambers, this helps to stabilise the flame.

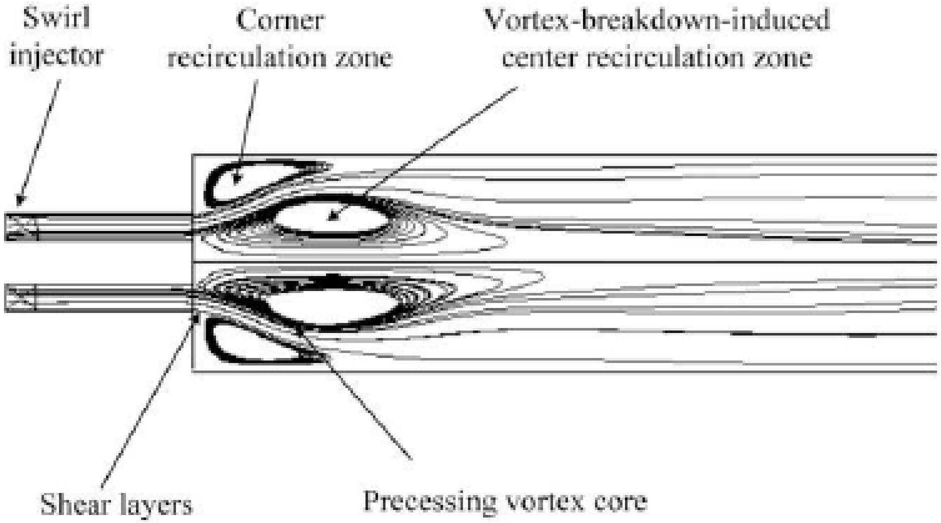

Fig. 14. Flow structures of a typical gas turbine combustor with a coaxial injector.

Y. Huang, V. Yang / Progress in Energy and Combustion Science 35 (2009) 293–364

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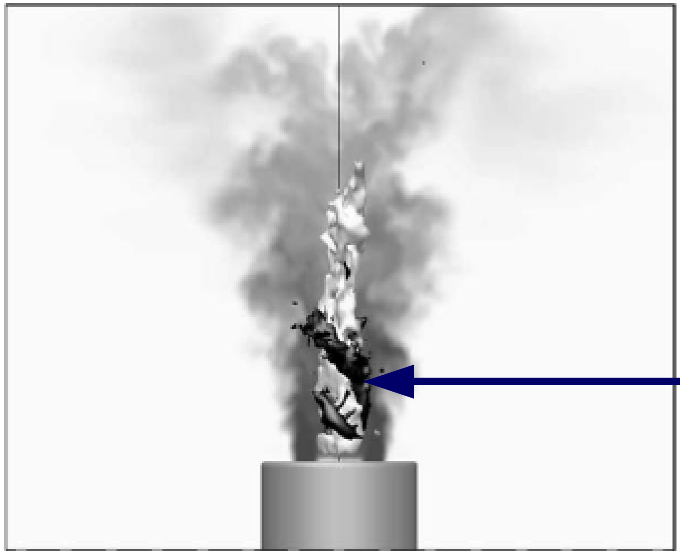
Why do we want to study this?

An unsteady spiral mode grows around the recirculation zone. This can lead to combustion instabilities.

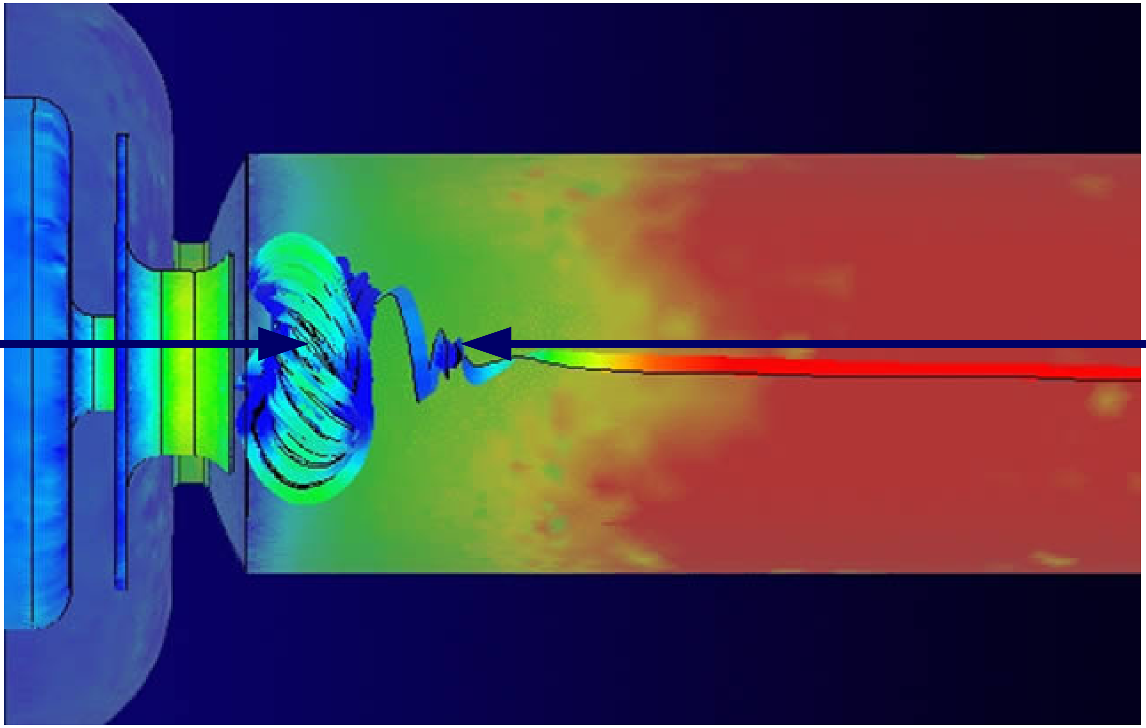


M. Freitag et al. / Int. J. Heat and Fluid Flow 27 (2006) 636–643

Spiral mode of vortex breakdown or “Precessing Vortex Core (PVC)”

Designers would like to know:
Which regions of the design are most influential in affecting flow behaviour?

Steady axisymmetric vortex breakdown bubble

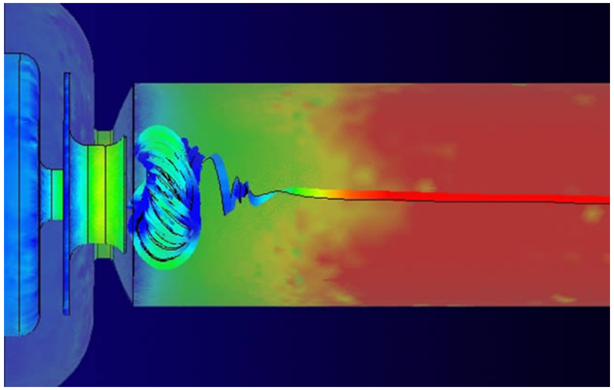


Unsteady spiral vortex breakdown

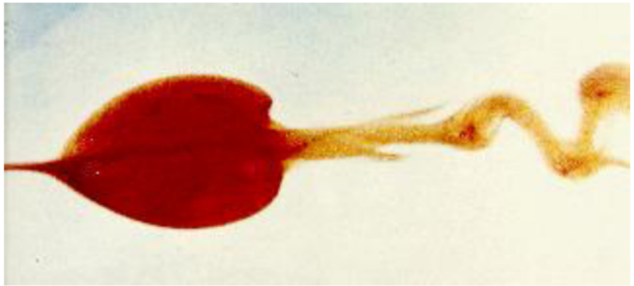
http://www-edc.eng.cam.ac.uk/projects/combustor/

To understand the physical mechanisms involved, we consider a laminar swirling jet at Re~400. To a first approximation, a fuel injector is like a jet.

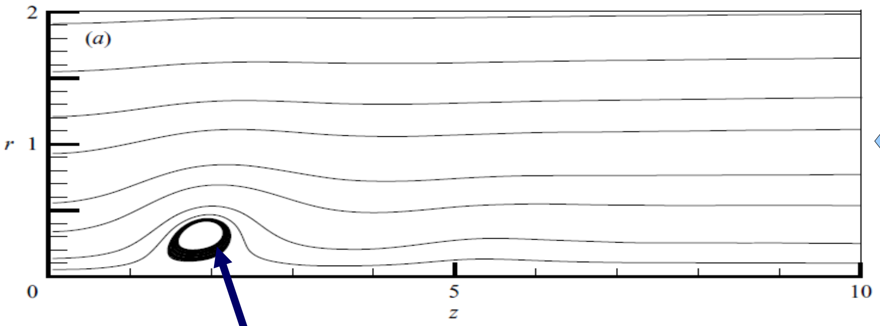
Gas turbine combustion (Re ~ 10^6)

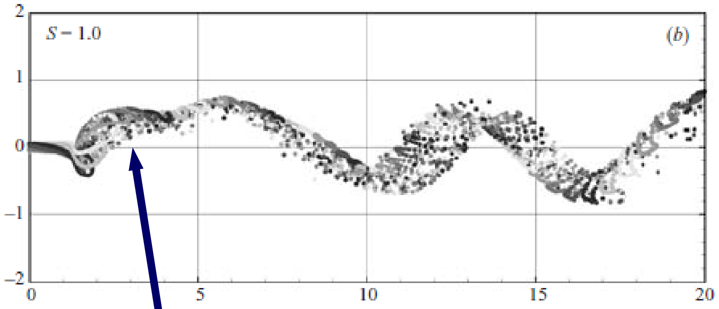


Vortex breakdown bubble (Re ~ 400)



Previous studies have shown that the spiral mode is caused by the self-excited growth of helical perturbations around the steady breakdown bubble. This is a **global mode**.



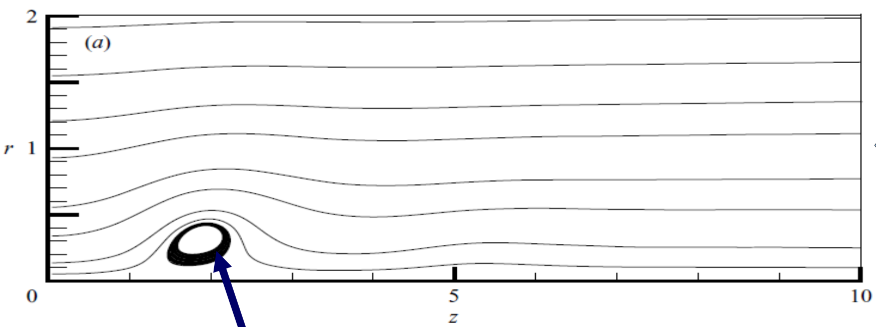


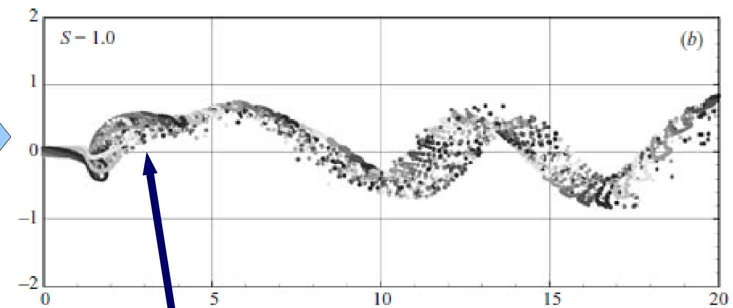
Steady axisymmetric vortex breakdown bubble

Unsteady spiral vortex breakdown

Ruith M.R. *et al.* 2003, J. Fluid Mech. 486, 331-378

We want to find out which regions of the flow cause the spiral mode and how it might be controlled.





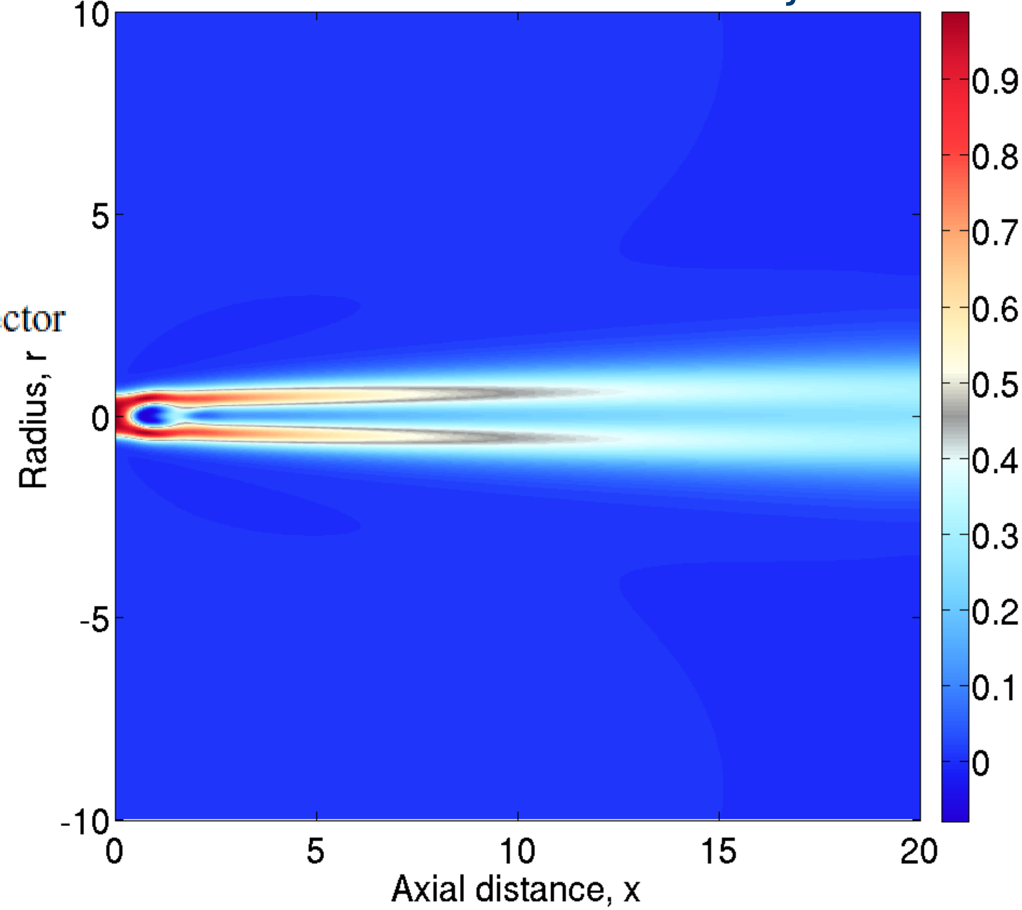
Steady axisymmetric vortex breakdown bubble

Unsteady spiral vortex breakdown

Ruith M.R. *et al.* 2003, J. Fluid Mech. 486, 331-378

We obtain a steady axisymmetric solution to the Navier-Stokes equations.

Domain size non-dimensionalized in terms of jet diameter



Navier-Stokes equations
In a cylindrical domain

$$\frac{\partial \mathbf{q}}{\partial t} = \mathcal{N}\mathbf{q},$$

where $\mathbf{q} \equiv (m_x, m_r, m_\theta, T, p)^T$ is the state vector

Reynolds number $\frac{U_x . D}{\nu} = 437$

How do we go about it?

We obtain a steady axisymmetric solution to the Navier-Stokes equations.

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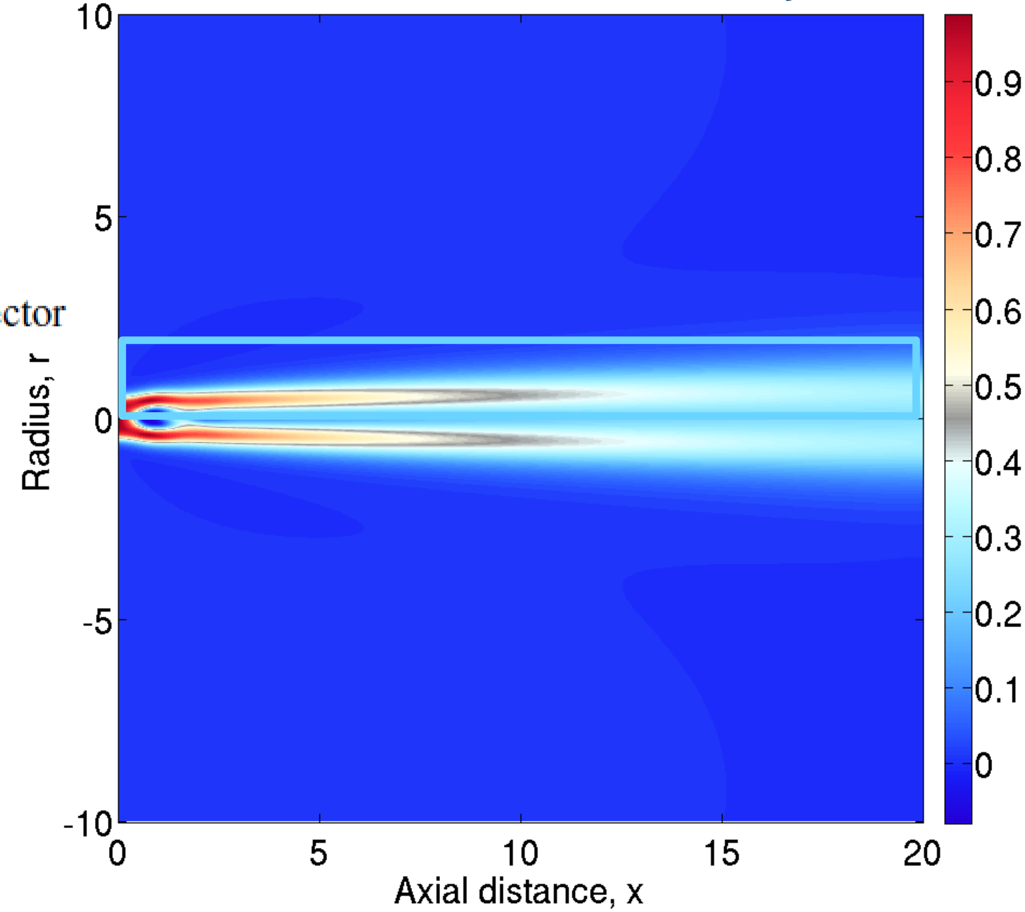

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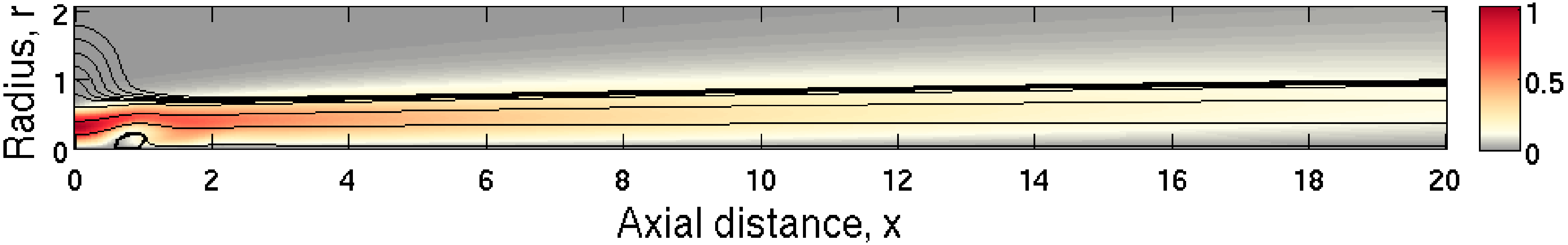
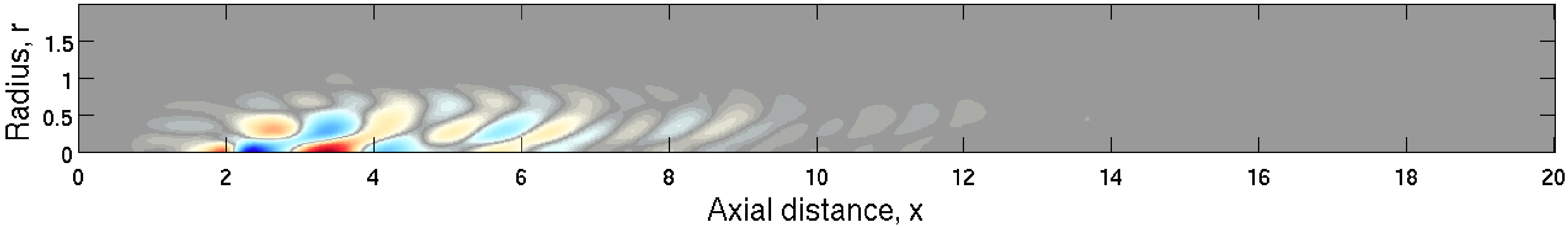


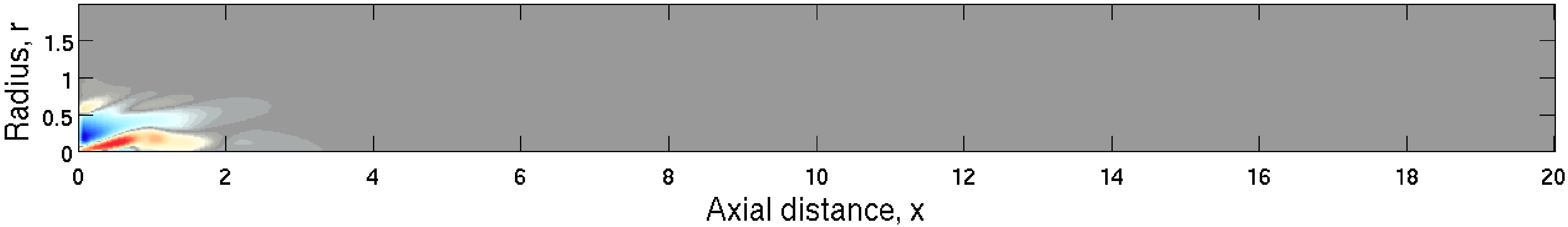
Streamlines of baseflow with azimuthal velocity in colour

We study how small perturbations evolve around the steady solution and obtain the shape of the most unstable mode that grows on top of the steady flow.



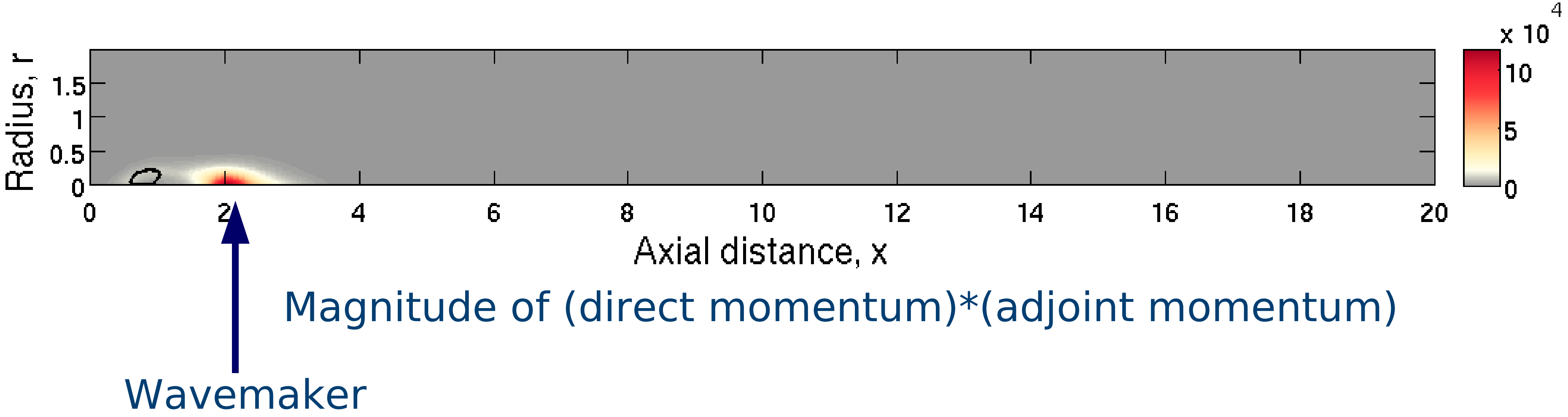
Azimuthal velocity of direct global mode for m=-1

We use the adjoint of the equations to find the initial conditions that would optimally excite the unstable mode.



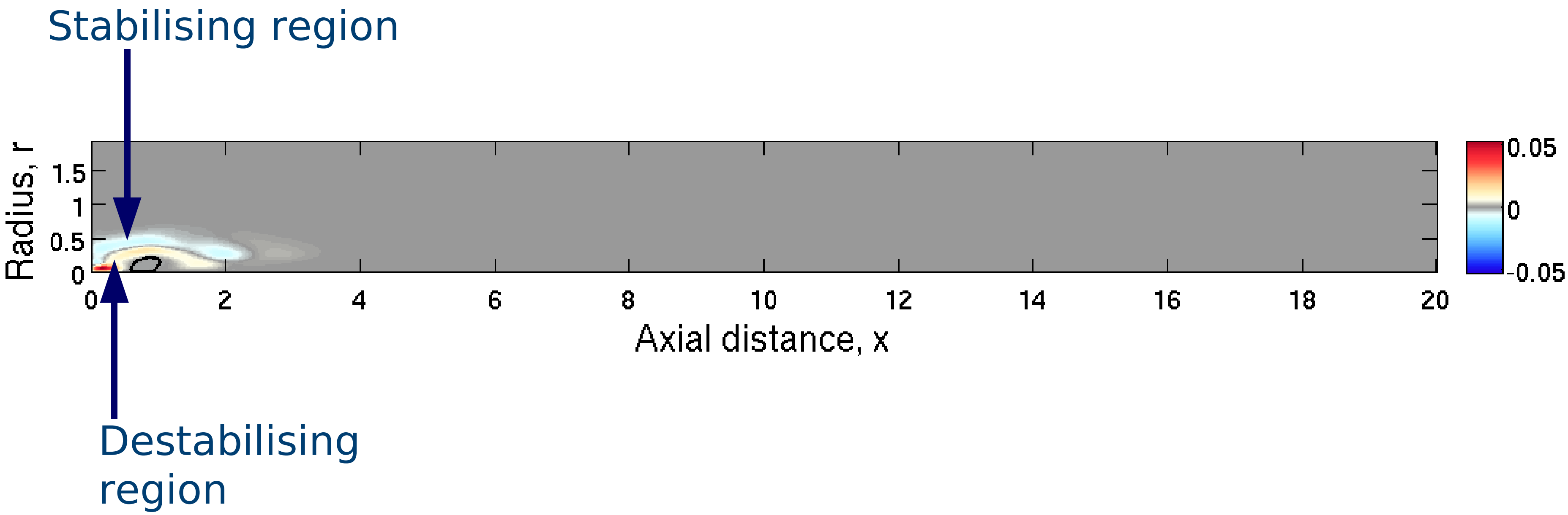
Azimuthal velocity of adjoint global mode for m=-1

We overlap the direct and adjoint modes to find the regions of the flow that are most sensitive to internal feedback. This identifies the wavemaker region, which is responsible for causing spiral vortex breakdown.

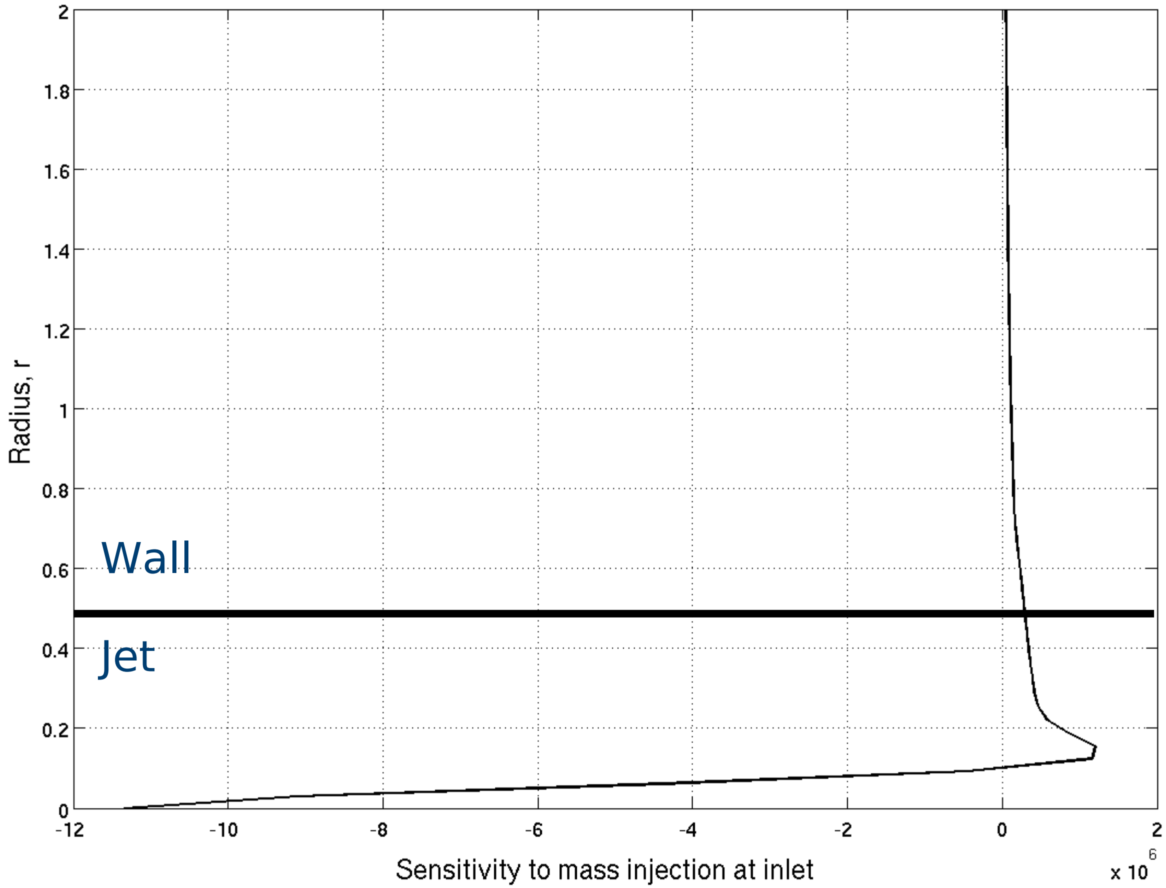


Magnitude of (direct momentum)*(adjoint momentum)

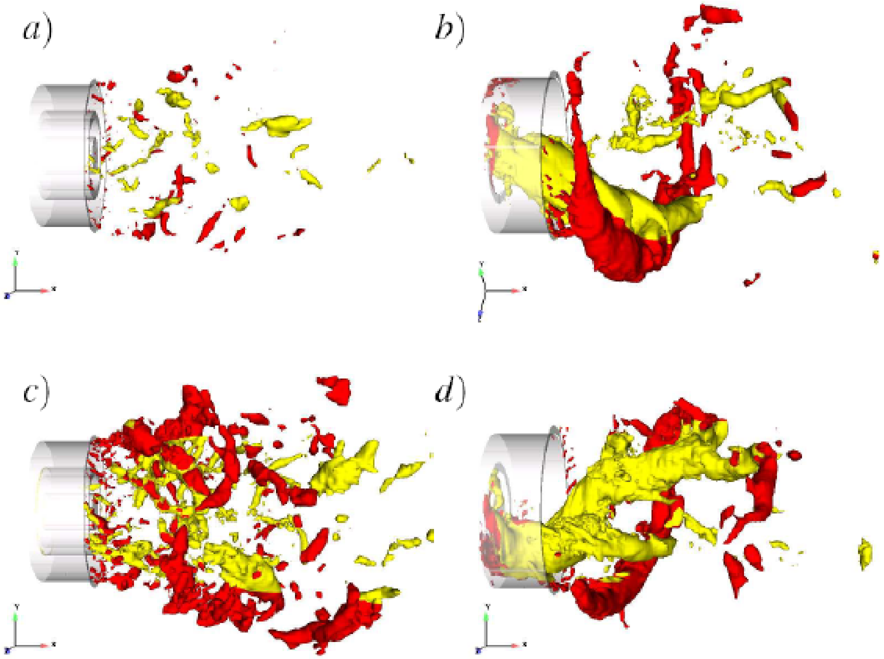
We solve a constrained optimisation problem to predict the regions of the flow where a passive control device would suppress or promote the unstable mode.



This technique can even tell us how and where mass injection would suppress or promote the unstable mode.



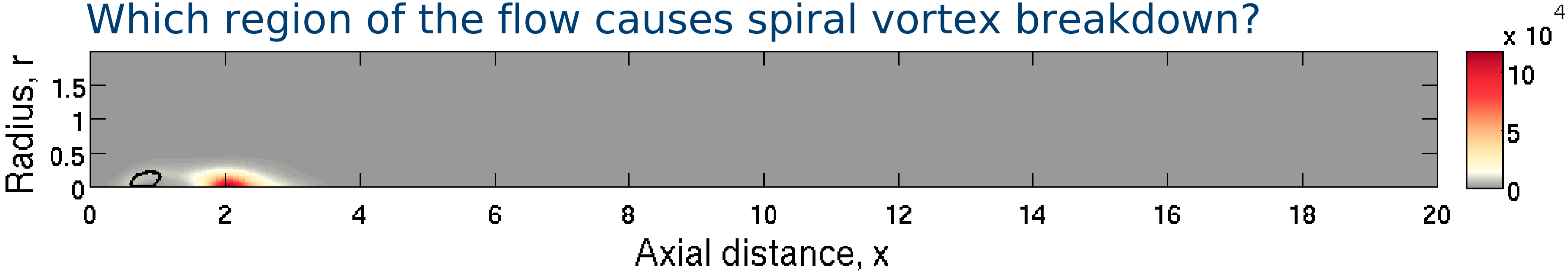
These tools are now being applied to flows with variable density and combustion and can be extended to more realistic geometries and flow speeds.



NUMERICAL SIMULATIONS OF ISOTHERMAL FLOW IN A SWIRL BURNER
Garcia-Villalba, Frohlich, Rodi, ASME Turbo Expo 2006 GT2006-90764

Thank you. Questions?

Which region of the flow causes spiral vortex breakdown?



Where should you place a small control cylinder to control it?