Course Outline

A) Introduction and Outlook

B) Flame Aerodynamics and Flashback

C) Flame Stretch, Edge Flames, and Flame Stabilization Concepts

D) Disturbance Propagation and Generation in Reacting Flows

E) Flame Response to Harmonic Excitation

- Boundary Layer Flashback
- Core Flow Flashback and Combustion Induced Vortex Breakdown

Flashback and Flameholding

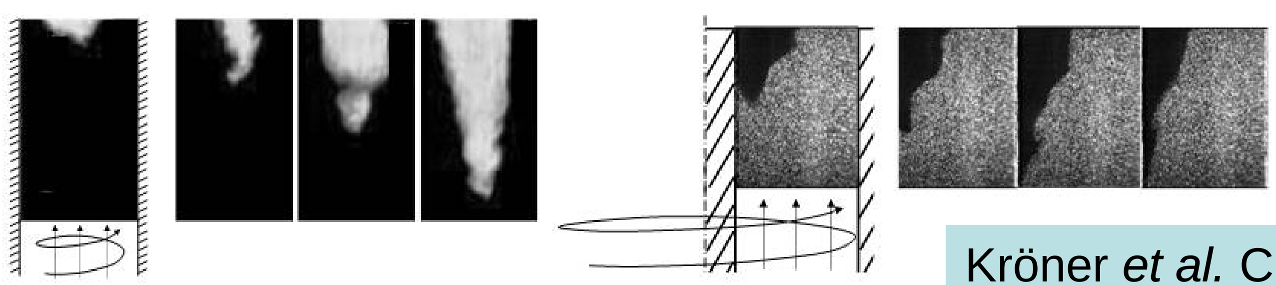
- Flashback:
  - Upstream propagation of a premixed flame into a region not designed for the flame to exist
  - Occurs when the laminar and/or turbulent flame speed exceeds the local flow velocity
    - Reference flow speed and burning velocity?
- Flameholding:
  - Flame stabilizes in an undesired region of the combustor after a flashback/autoignition event
  - Problem has hysteretic elements
    - Wall temperature effects
    - Boundary layer and swirl flow stability effects

Flashback and Flameholding Mechanisms

- Flashback in the boundary layer
- Flame propagation into core flow
  - We'll focus on swirl flows
- Combustion instabilities
  - Strong acoustic pulsations lead to nearly reverse flow
    - Note: $p'/p \sim u'/c = Mu'/u$
    - i.e. $u'/u = (1/M)p'/p$
- Significance of above mechanisms is a strong function of:
  - Fuel composition
  - Operating conditions
  - Fluid mechanics

Show video

Heeger *et al.*
Exp. In Fluids
2010



Kröner *et al.* CST 2007

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- ***Boundary Layer flashback***
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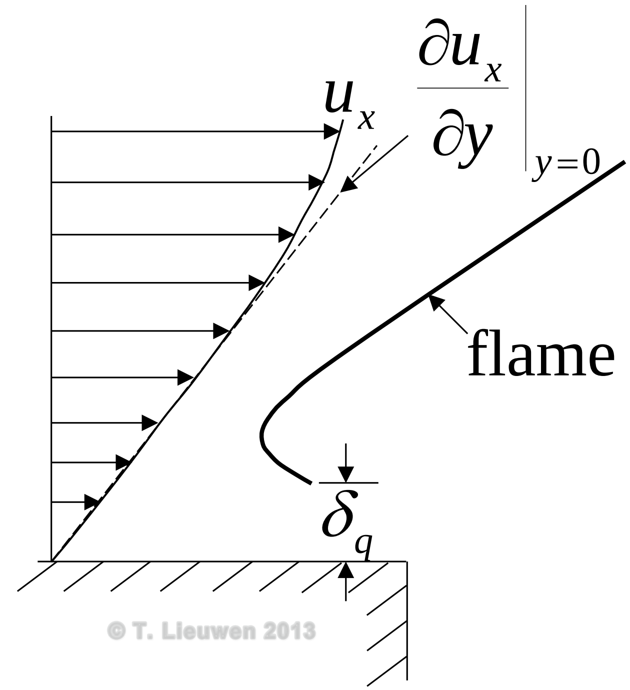
Boundary Layer Flashback-Classical Treatment

- Neglects effects of
  - Heat release (changes approach flow)
  - Stretch (changes burning velocity)
- Flashback occurs if flame speed exceeds flow velocity at distance, δ_q, from the wall

$$u_x(y=\delta_q) = s_d^u(y=\delta_q)$$



  - Expanding velocity in a Taylor series, establish flashback condition:

$$u_x(y=\delta_q) \approx \underbrace{\frac{\partial u_x}{\partial y}}_{g_u}\delta_q \Rightarrow \frac{g_u \delta_q}{s_d^u} = 1$$

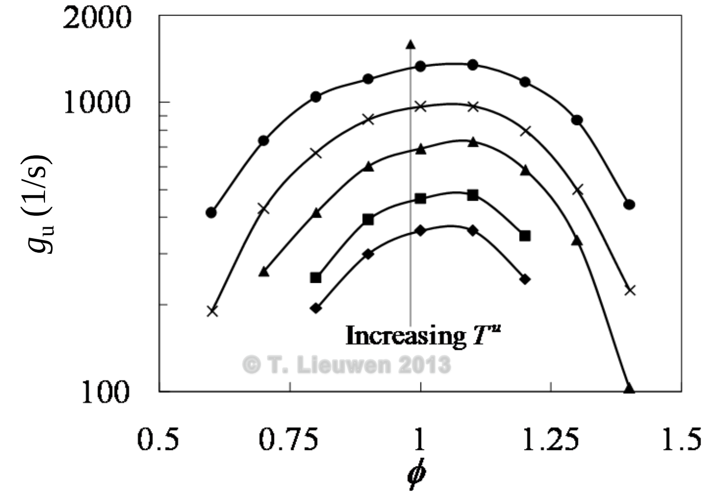
  - Assuming, $\delta_q \sim \delta_F$, define flashback Karlovitz number

$$Ka = \frac{g_u \delta_F}{s_d^u}$$

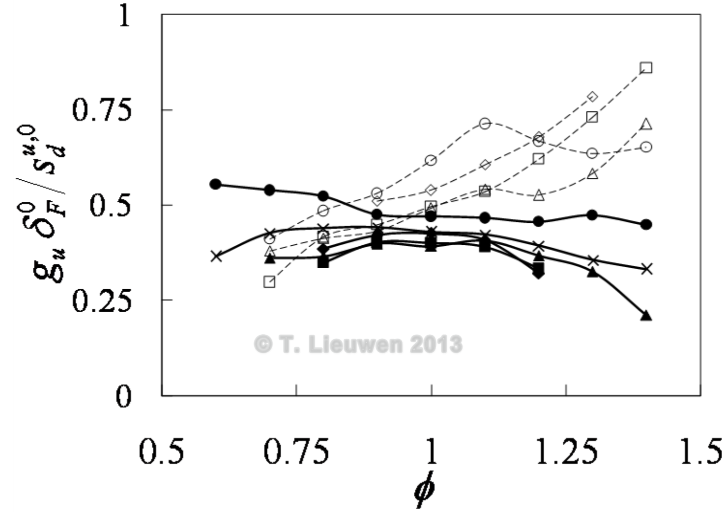
Boundary Layer Flashback

- Flashback Karlovitz number approach is well validated for open flames, such as Bunsen burners
  - Performed detailed kinetics calculations to determine flame speed and thickness for several data sets
  - Shows how prior burning velocity, flame thickness tendencies can be used to understand tendencies
    - Pressure
    - Preheat temperature
    - Stoichiometry

CH_4-air



CH_4-air (solid) and C_3H_8-air (dashed)



Data for figures obtained from:
Grumer Ind. & Eng. Chem. 1954
Dugger Ind. & Eng. Chem 1955

Boundary Layer Flashback

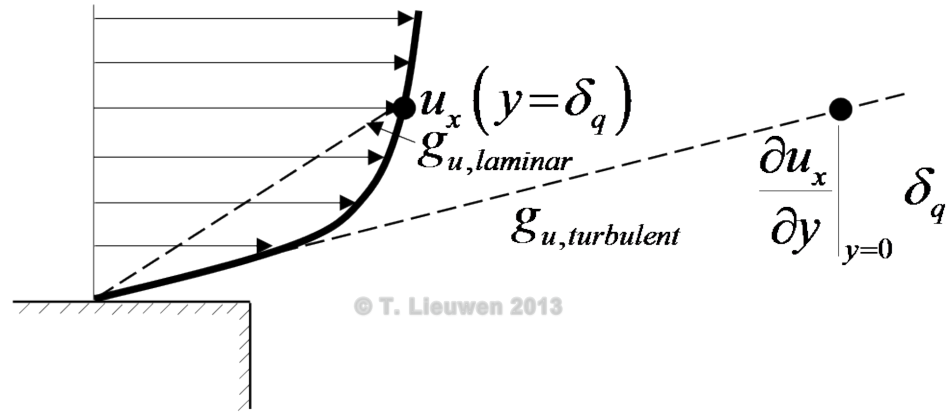
- Turbulent Boundary Layers
  - Multi-zoned
    - Near wall→ laminar sublayer, δ_ν
  - Basic scaling developed for laminar flows holds if:

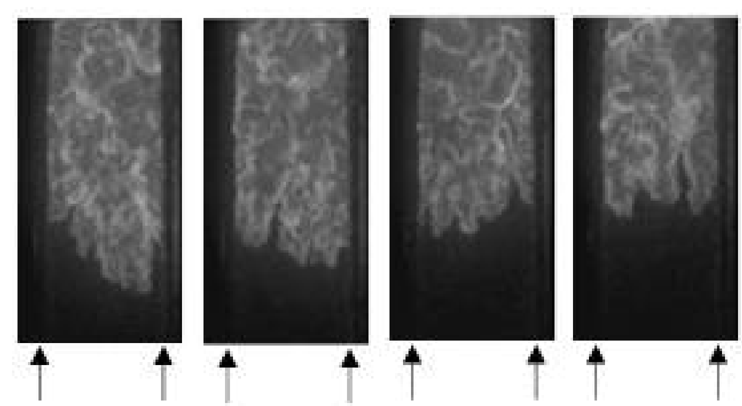
$$\delta_q < \delta_\nu$$

  - Most literature data shows

$$g_{u,turbulent} \sim 3\, g_{u,laminar}$$

  - Significant space-time variation during flashback
    - Images suggest flame interactions with boundary layer instabilities





C. Eichler Exp. In Fluids 2012

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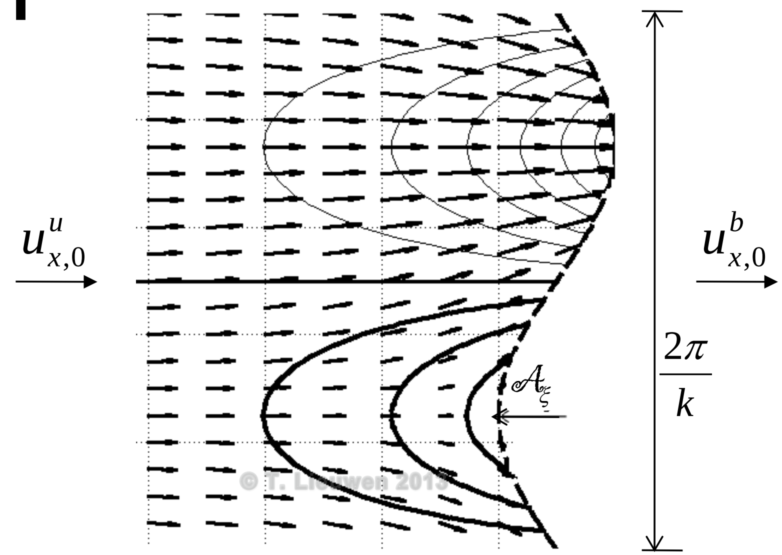
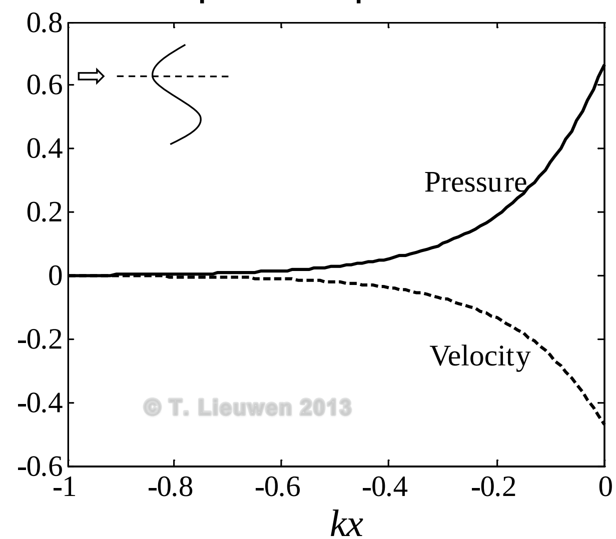
Coupled Effects of Flame Curvature and Gas Expansion

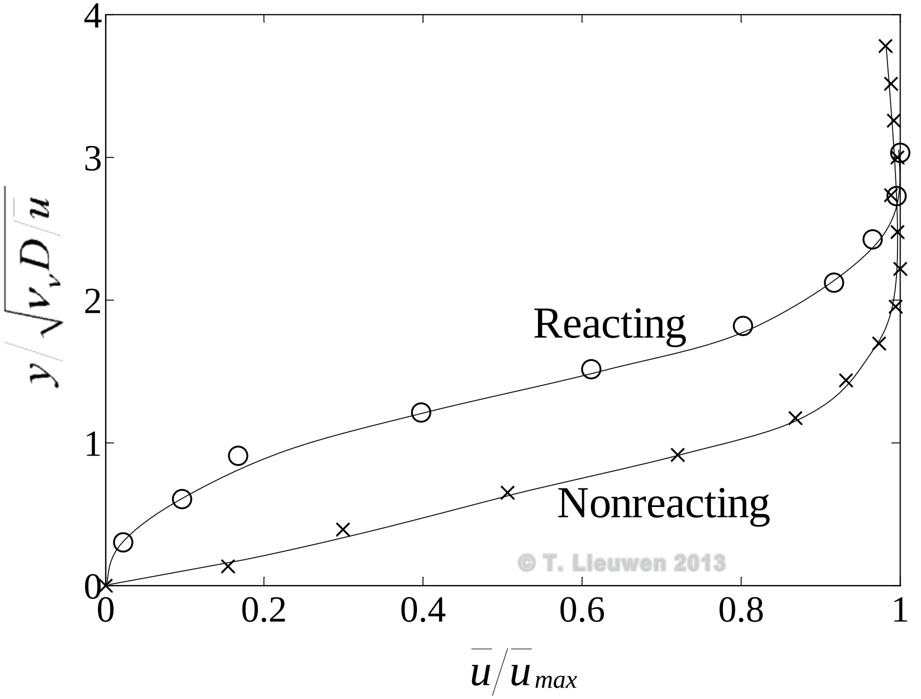
- Flame bulging into reactants
  - Approach flow decelerates
  - Streamlines diverge
  - Adverse pressure gradient
- Implications:
  - Boundary layers – adverse pressure gradients lead to separation
  - Swirl flows – adverse pressure gradients can lead to vortex breakdown
  - Triple flames – flame can propagate into region with velocity that is higher than flame speed
  - Flame stability – flame spontaneously develops wrinkles



Solid thick contours: positive pressure fluctuations



Heat Conduction Influences on Boundary Layers



- Important implications for
  - Scaling velocity gradients in shear layers
  - Flame stretch rates
  - Shear layer instability frequencies – acoustic sensitivities

Heat Release and Stretch Effects

- Heat release modifies approach flow

- Stretch modifies burning velocity

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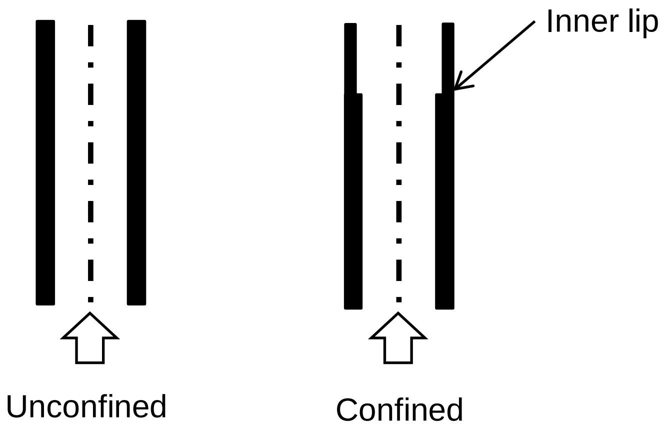
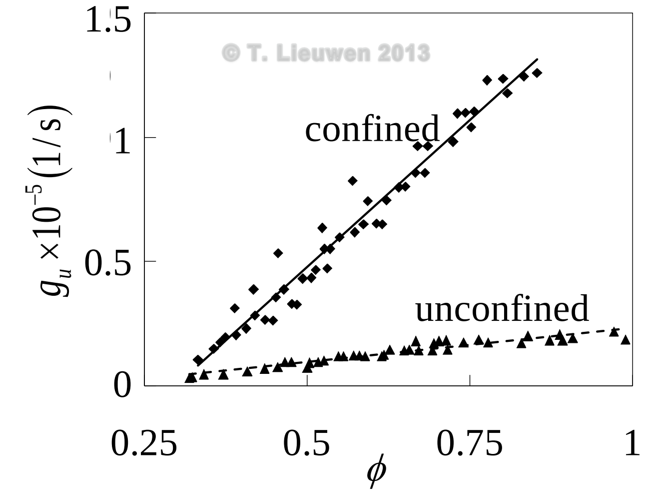
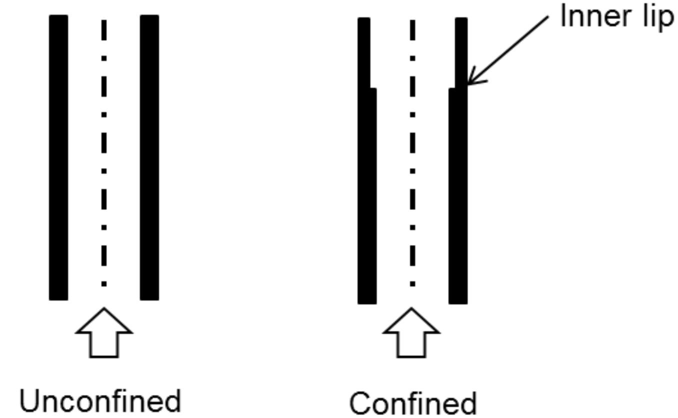


Heat Release and Stretch Effects

- Particularly important in explaining flameholding phenomenon
- Once a flashback event has occurred, difficult to expel flame from combustor
- Leading point of advancing flashback event subject to positive curvature
- Effect of gas expansion due to heat release on local flow velocity





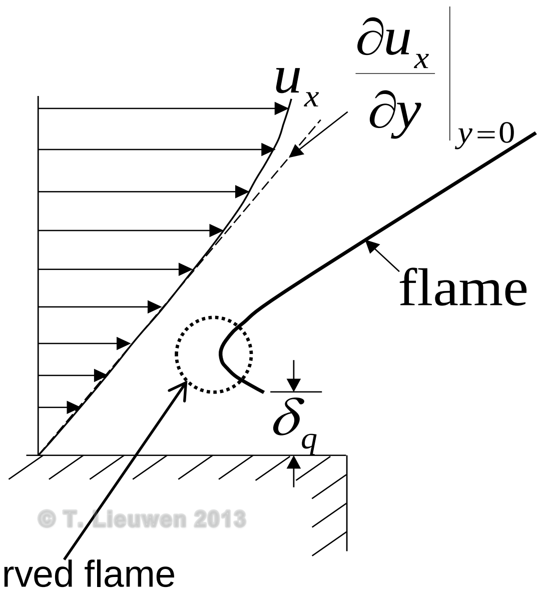
C. Eichler Turbo Expo 2011

Stretch Effects

- Leading point of advancing flashback event subject to positive curvature
  - For $Ma < 0$, this can cause:

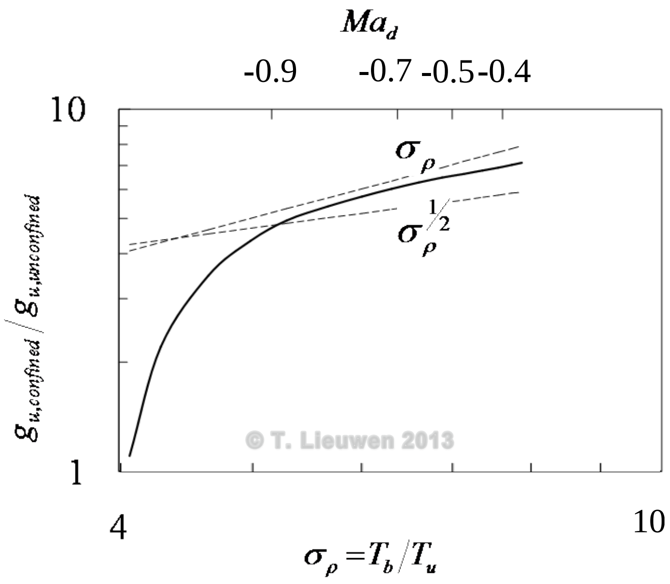
$$s_d^u(y = \delta_q) >> s_d^{u,0}$$

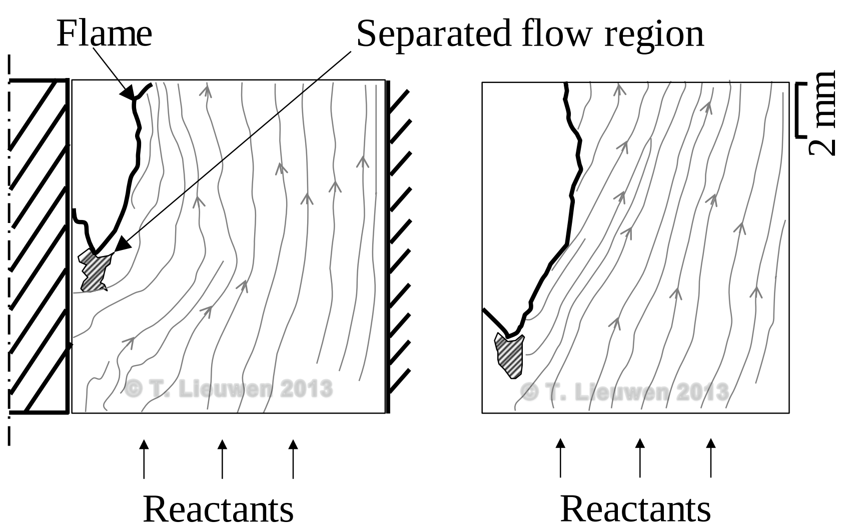
    - $s_d^{u,0}$ can be a significant underestimate of flame speed



Heat Release Effects

- Gas expansion across a curved flame alters the approach flow
  - Resulting adverse pressure gradient ahead of flame decelerates flow
    - In extreme cases, can cause boundary layer separation
    - Approach flow "sucks" flame back into nozzle





Figures:
C. Eichler Turbo Expo 2011
Heeger *et al.* Exp. In Fluids 2010

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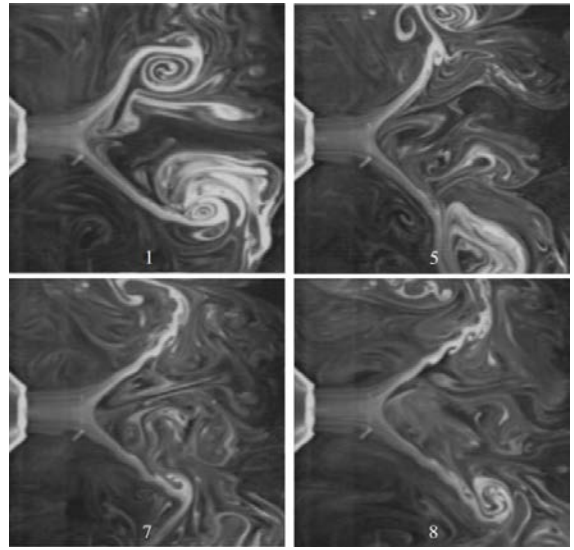
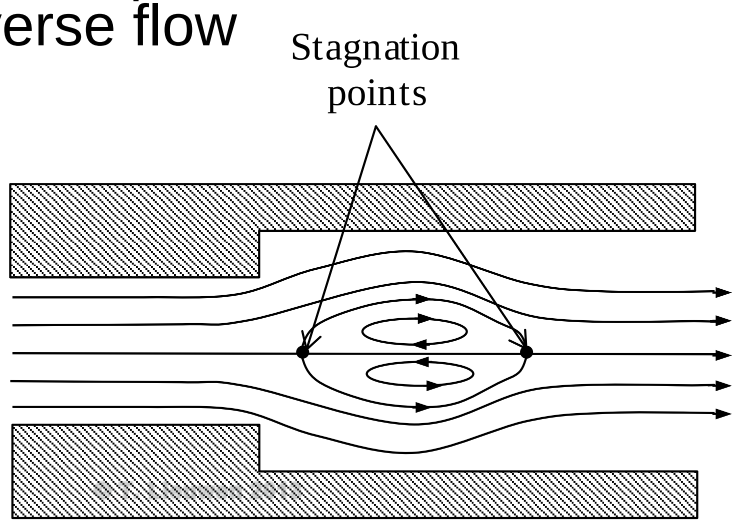
Flow Stability and Vortex Breakdown

- The degree of swirl in the flow, *S*, has profound influences on the flow structure
- Most prominent feature of high swirl number flows is the occurrence of “vortex breakdown”, which is manifested as a stagnation point followed by reverse flow

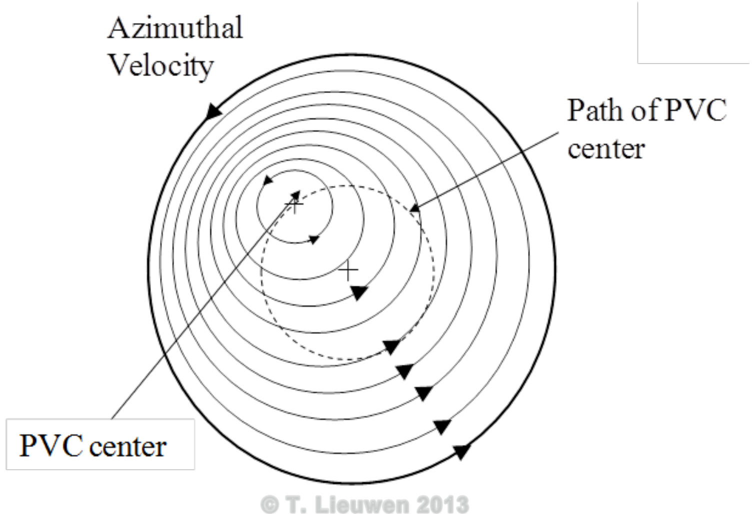


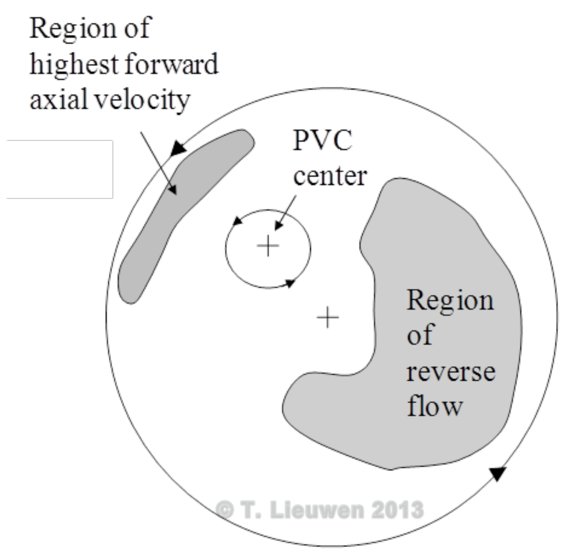


Billant et al., JFM, 1998
Sarpkaya, JFM, 1971

Prominent Features of Swirling Flows with Vortex Breakdown: Precessing Vortex Core

- The flow does not instantaneously rotate about the geometric centerline
- The location of zero azimuthal velocity is referred to as the “precessing vortex core” (PVC)
  - The frequency of rotation of the precessing vortex core scales with a Strouhal number based on axial flow velocity and diameter
  - Leads to a helical pattern in instantaneous axial flow velocity
  - Important to differentiate the PVC from the other helical shear flow structures which may also be present

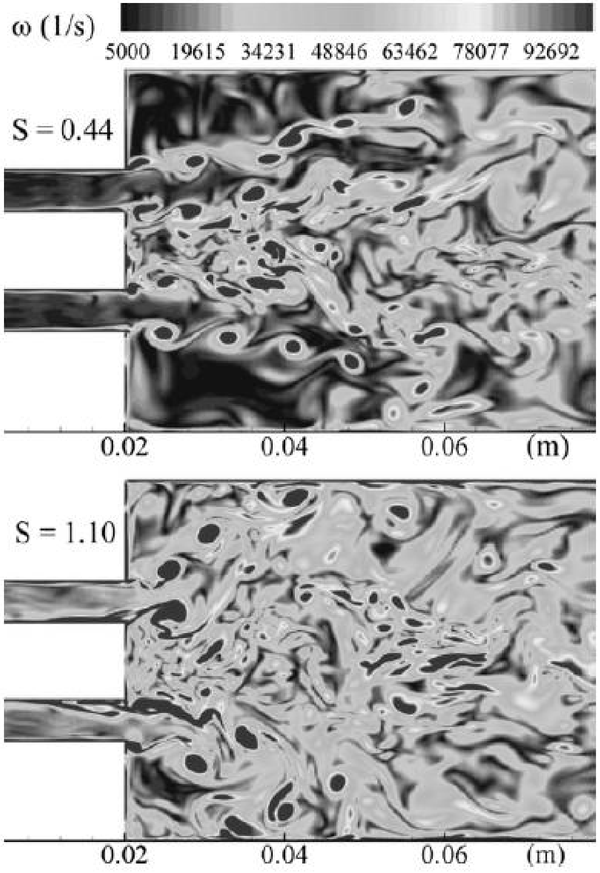


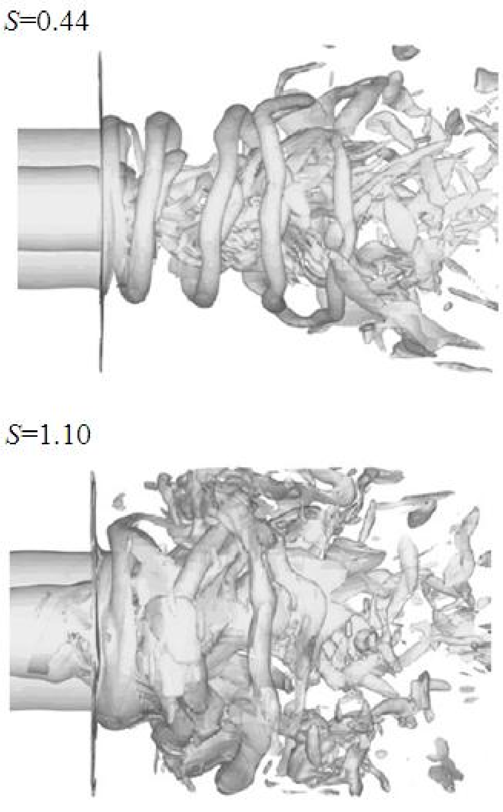


Source: Syred, Prog. Energy and Comb. Sci., 2006

Prominent Features of Swirling Flows: Shear Layer Instability

- Shear layers exist in both span- and streamwise directions
  - Can be axisymmetric or helical

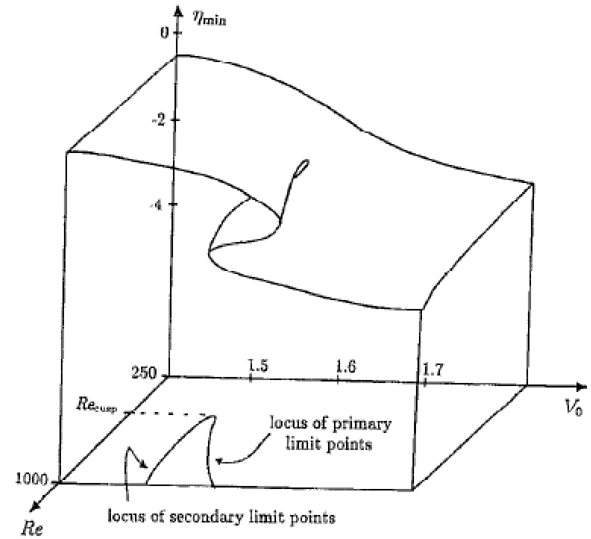




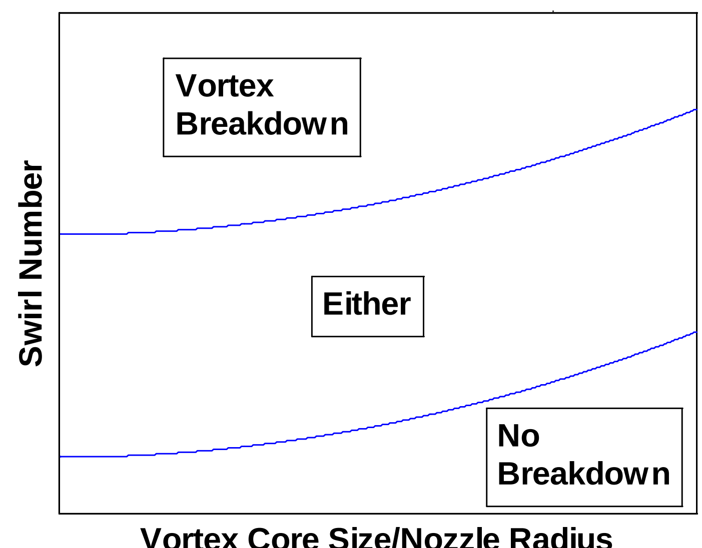
Huang and Yang, Proc. Comb. Inst., 2005

Flow Stability and Vortex Breakdown

- Vortex breakdown can be described as a “fold catastrophe”
  - Bifurcation of the possible steady state solutions to the Navier-Stokes equations
- In high Re flows, there is an intermediate swirl number range where flow is bi-stable and hysteretic
  - i.e., either vortex breakdown or no vortex breakdown flow state possible

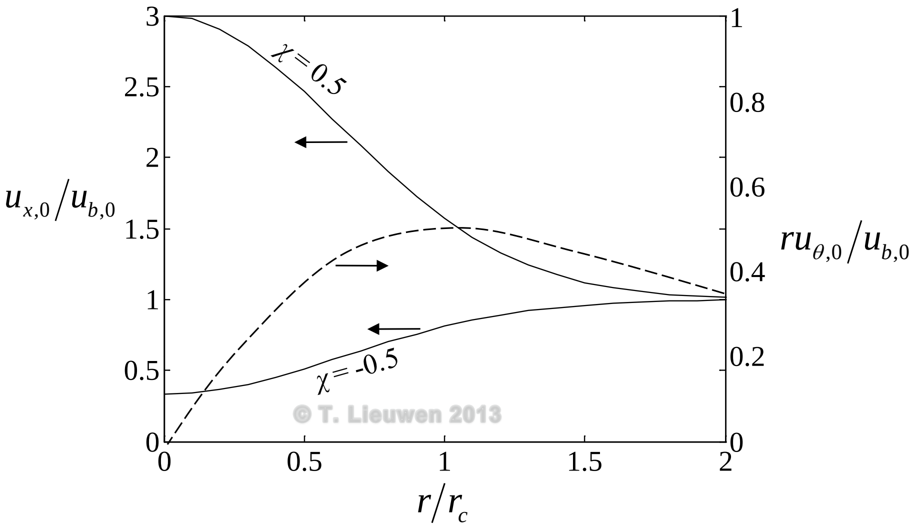


Source: Lopez, Physics of Fluids, 1994



Flow Stability and Vortex Breakdown: Example calculation

- Vortex breakdown can be predicted for given velocity profile
  - "Q-vortex" velocity profile:



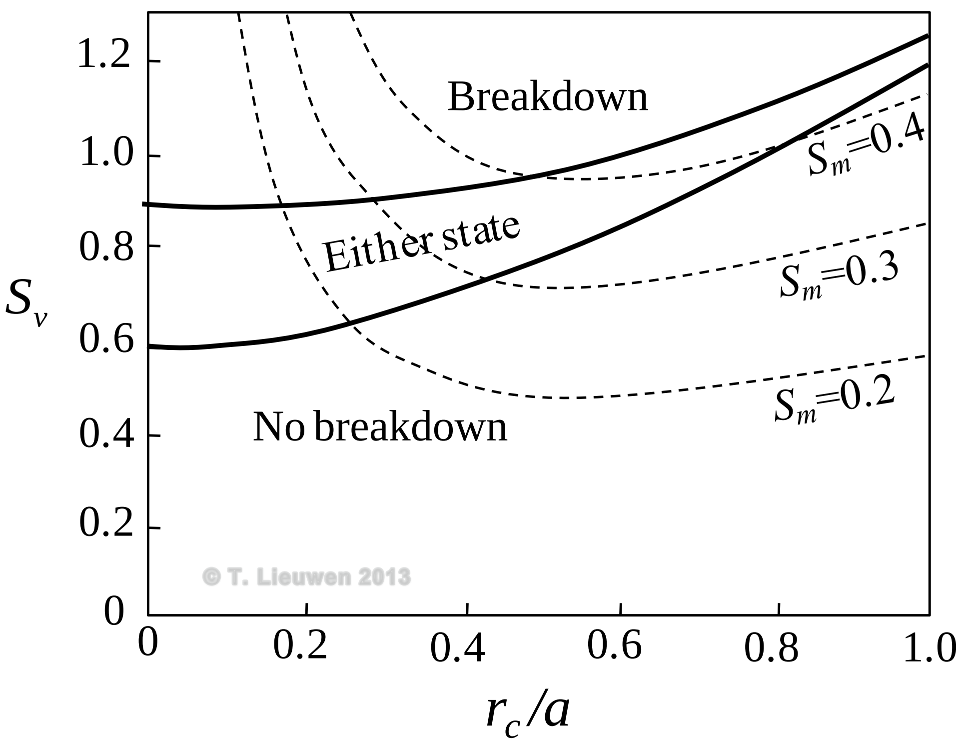
Axial and azimuthal velocity profiles used for vortex breakdown calculation, using S_v=0.71 for $u_{\theta,0}$plot.

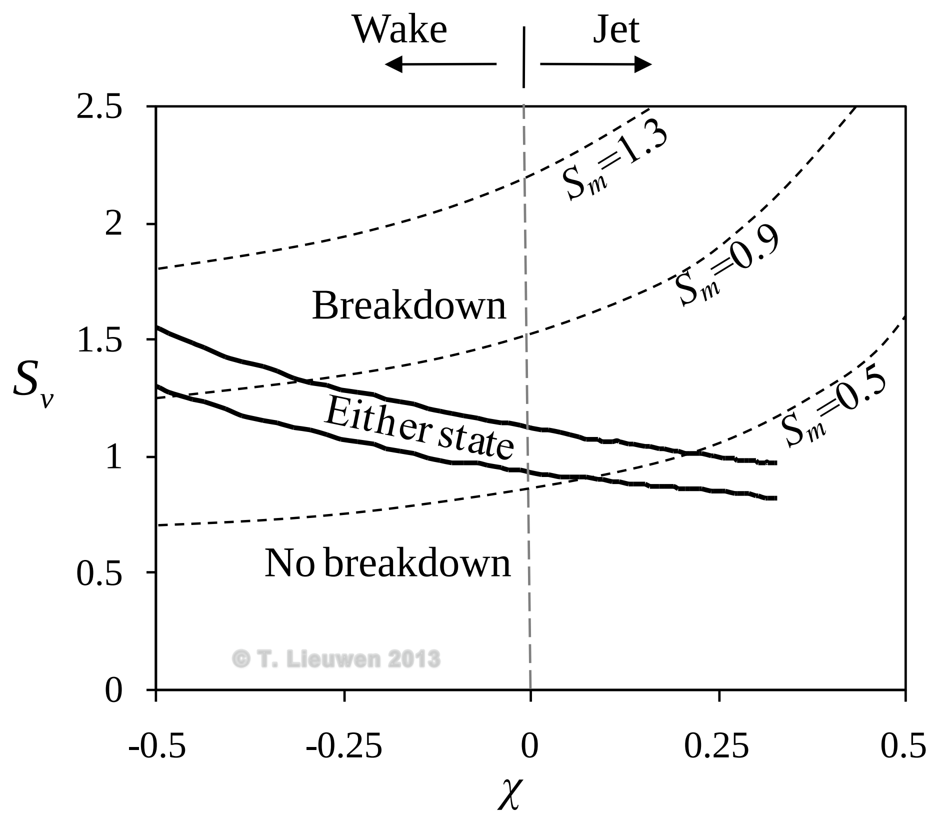
$$\frac{u_{x,0}}{u_{b,0}} = 1 + \frac{2\chi}{1-\chi}\exp\left(-\frac{5}{4}\left(\frac{r}{r_c}\right)^2\right)$$

$$\frac{ru_{\theta,0}}{u_{b,0}} = \frac{S_v}{(r/r_c)}\frac{\left(1-\exp\left(-\frac{5}{4}\left(\frac{r}{r_c}\right)^2\right)\right)}{(1-\exp(-5/4))}$$

$$\chi = \frac{u_{a,0} - u_{b,0}}{u_{a,0} + u_{b,0}}$$

Flow Stability and Vortex Breakdown: Example Calculation





Following Z. Rusak

Core Flow Flame Propagation

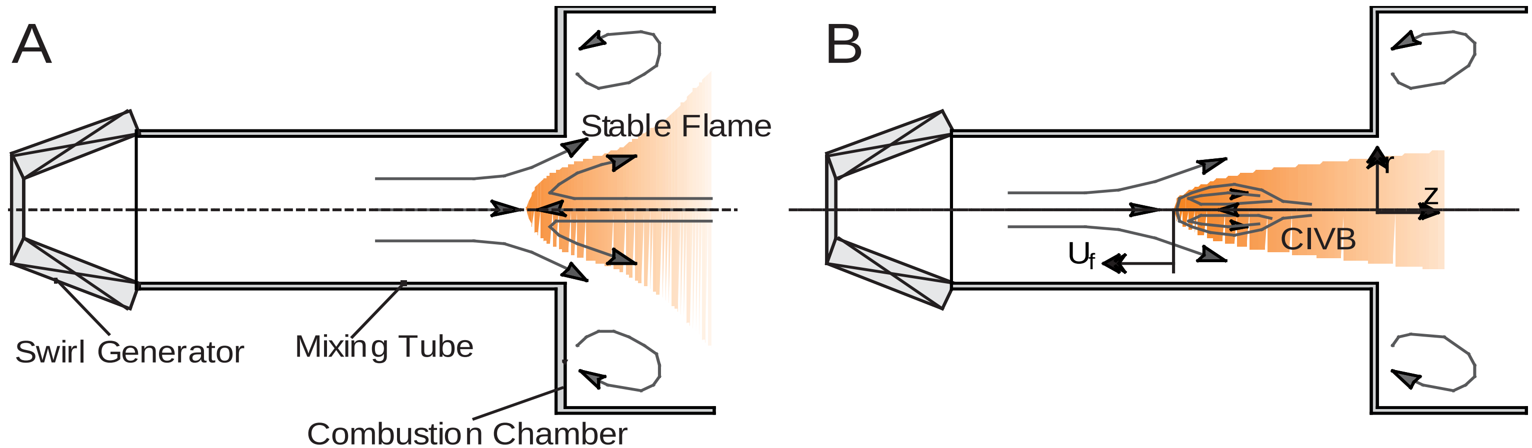


Image reproduced from T. Sattelmayer

- Vortex breakdown – flame interaction
  - Can occur even if flame speed everywhere less than flow speed
  - Gas expansion across a curved flame:
    1. Adverse pressure gradient & radial divergence imposed on reactants
    2. Low/negative velocity region generated upstream of flame
    3. Flame advances further into reactants
    4. Location of vortex breakdown region advances upstream
  - Due to bi-stable nature of vortex breakdown boundaries
    - CIVB itself not necessarily bi-stable