SAND2012-1481P

Physical Fluid Dynamics in Reciprocating Engines

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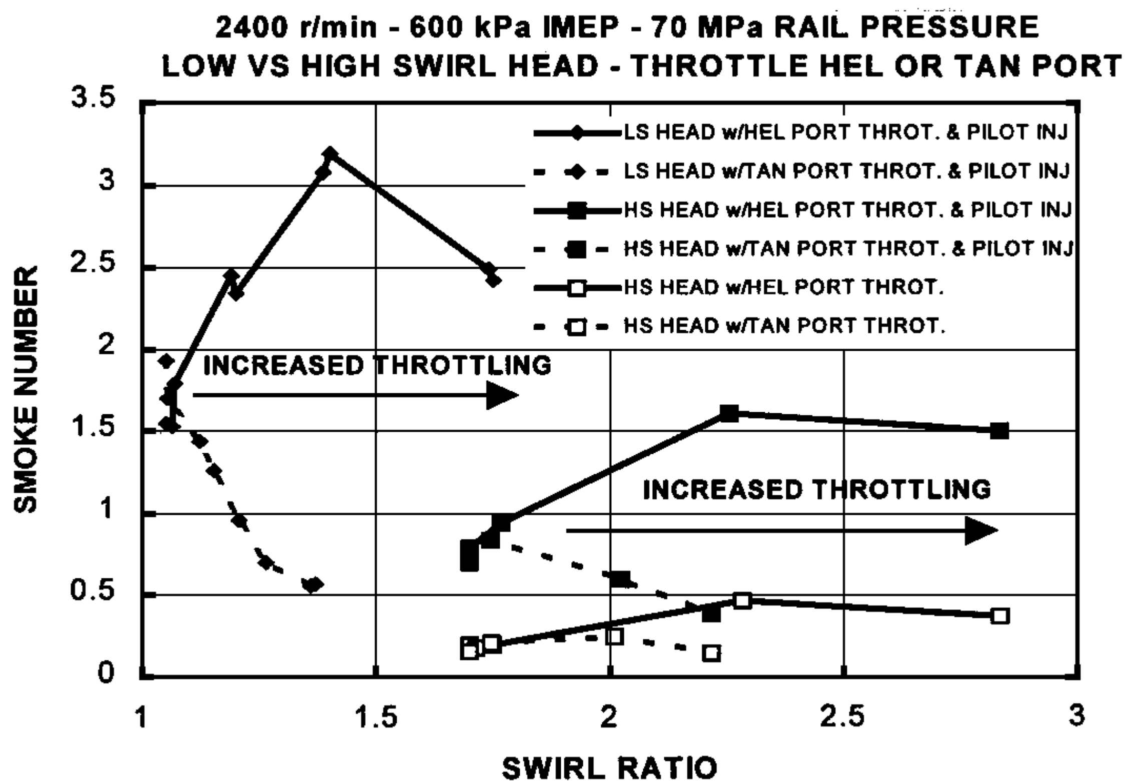
1 March, 2012

Fluid mechanics and mixing processes are critical aspects of all reciprocating engine technologies

SI engines:	Breathing efficiency, tumble generation and breakdown, turbulent flame kernel initiation and subsequent propagation
DISI engines:	+ spray/flow interactions, mixture formation processes
Diesel engines:	+ swirl effects, ignition, late-cycle mixing processes for soot and CO burnout
HCCI/CAI engines:	+ mixture stratification, thermal stratification

> The subtle interaction of air motion and fuel spray...
>
> ...is the cornerstone of development of future ultra-low emissions and high performance diesel engines
>
> *Ricardo Consulting Engineers, 1994*

Characterization of the flow by global parameters is insufficient



Krieger, et al., SAE 972683

- Gross differences in soot emissions are seen at the same swirl ratio
- Trends observed with changing swirl ratio are opposite

These differences must be associated with differences in the details of the mean flow structure and associated turbulence generation mechanisms

Outline

- Building blocks
  - Understanding the momentum equations
  - Conservation of angular momentum
  - Rotational kinetic energy
- Mean flow examples
  - Tumble and swirl flows
  - Squish-swirl interaction
  - Spray-swirl interaction
- Turbulence
  - Identifying the sources
  - Close-up of swirl effects
  - Examples

Understanding the mean momentum equations is key to understanding the flow development

Radial-momentum

$$\frac{\bar{D}\langle U_r\rangle}{\bar{D}t} - \frac{\langle U_\theta\rangle^2}{r} = -\frac{1}{\rho}\frac{\partial\langle P\rangle}{\partial r} - \left(\frac{1}{r}\frac{\partial\left(r\langle u_r'^2\rangle\right)}{\partial r} + \frac{1}{r}\frac{\partial\langle u_r' u_\theta'\rangle}{\partial\theta} + \frac{\partial\langle u_r' u_z'\rangle}{\partial z} - \frac{\langle u_\theta'^2\rangle}{r}\right)$$

but $\langle U_\theta\rangle^2 + \langle u_\theta'^2\rangle = \langle U_\theta^2\rangle$

$$\frac{\bar{D}\langle U_r\rangle}{\bar{D}t} - \frac{\langle U_\theta^2\rangle}{r} = -\frac{1}{\rho}\frac{\partial\langle P\rangle}{\partial r} - \left(\frac{1}{r}\frac{\partial\left(r\langle u_r'^2\rangle\right)}{\partial r} + \frac{1}{r}\frac{\partial\langle u_r' u_\theta'\rangle}{\partial\theta} + \frac{\partial\langle u_r' u_z'\rangle}{\partial z}\right)$$

neglecting turbulent diffusion

Radial Acceleration	=	Centripetal Forces	$\Leftrightarrow$	Pressure Forces

Understanding the mean momentum equations is key to understanding the flow development

Tangential-momentum

$$\frac{\overline{D}\langle U_\theta \rangle}{\overline{D}t} + \frac{\langle U_r \rangle \langle U_\theta \rangle}{r} = -\frac{1}{\rho}\frac{1}{r}\frac{\partial \langle P \rangle}{\partial \theta} - \left(\frac{1}{r}\frac{\partial \left(r \langle u'_r u'_\theta \rangle \right)}{\partial r} + \frac{1}{r}\frac{\partial \langle u'^2_\theta \rangle}{\partial \theta} + \frac{\partial \langle u'_\theta u'_z \rangle}{\partial z} + \frac{\langle u'_r u'_\theta \rangle}{r} \right)$$

but we can simplify greatly by writing in terms of $\langle rU_\theta \rangle$:

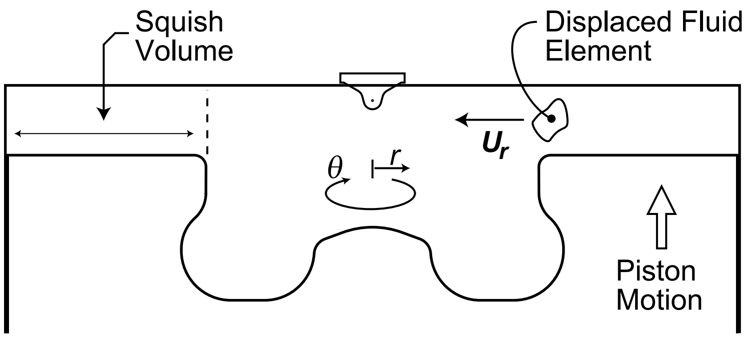
$$\frac{\overline{D}\langle rU_\theta \rangle}{\overline{D}t} = -\frac{1}{\rho}\frac{\partial \langle P \rangle}{\partial \theta} - \left(\frac{1}{r}\frac{\partial \left(r^2 \langle u'_r u'_\theta \rangle \right)}{\partial r} + \frac{1}{r}\frac{\partial \left(r \langle u'^2_\theta \rangle \right)}{\partial \theta} + \frac{\partial \left(r \langle u'_\theta u'_z \rangle \right)}{\partial z} \right)$$

neglecting turbulent diffusion and tangential pressure gradients,

Angular momentum is conserved

$$\langle U_\theta \rangle = \frac{r_0 \langle U_\theta \rangle_0}{r}$$

The squish/swirl interaction

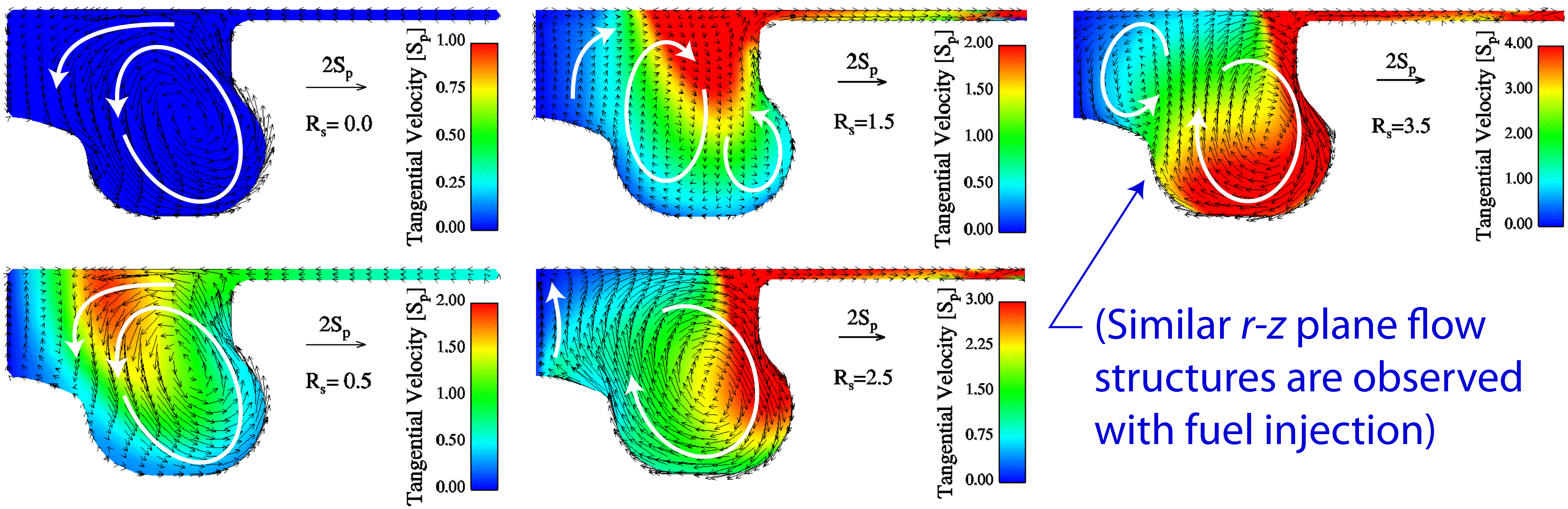


The dominant factor affecting the inward penetration of a fluid element is centrifugal force...

$$\frac{\bar{D}\langle rU_\theta\rangle}{\bar{D}t} = 0 \quad \Rightarrow \quad \langle U_\theta\rangle = \frac{r_0\langle U_\theta\rangle_0}{r} \qquad (\theta\text{-mom})$$

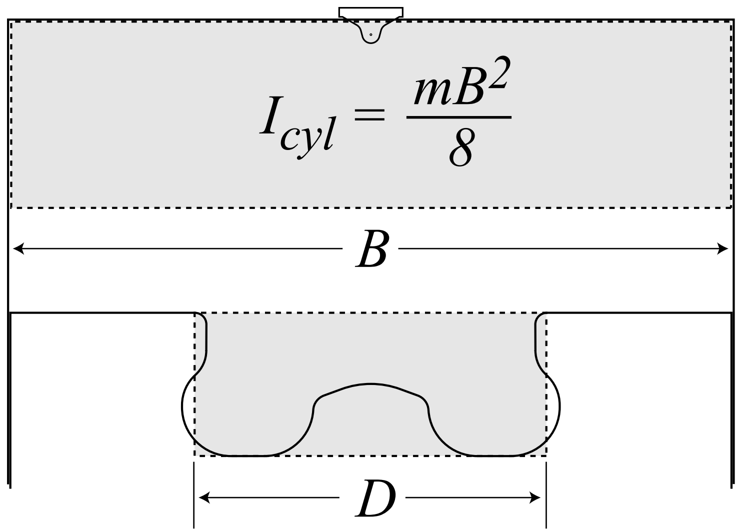
$$\frac{\bar{D}\langle U_r\rangle}{\bar{D}t} = -\frac{1}{\rho}\frac{\partial\langle P\rangle}{\partial r} + \frac{\langle U_\theta^2\rangle}{r} \qquad (r\text{-mom})$$

Near-TDC Flow Structure:



(Similar *r-z* plane flow structures are observed with fuel injection)

Squish-swirl interaction also changes the rotational kinetic energy of the flow



$$I_{bowl} \approx \frac{mD^2}{8}$$

Compressing the flow into the bowl and conserving angular momentum

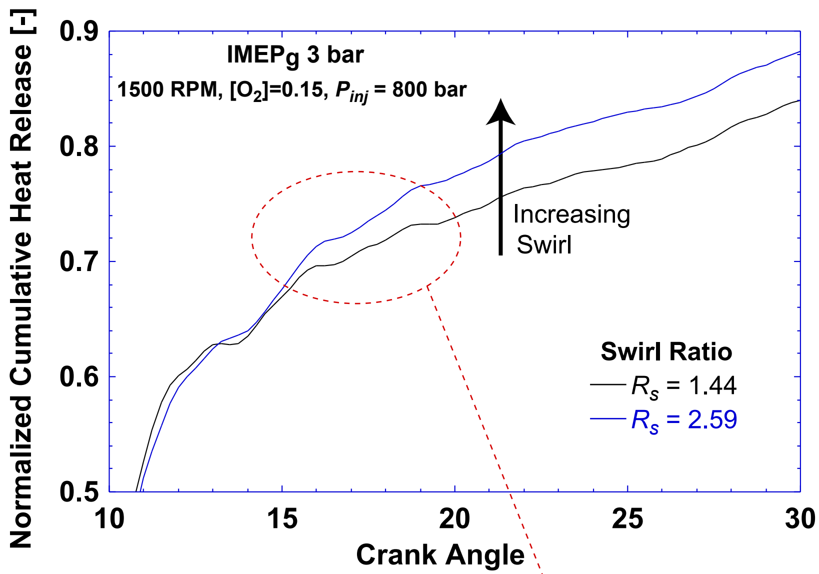
$$\frac{\Omega_{bowl}}{\Omega_{cyl}} \approx \frac{I_{cyl}}{I_{bowl}} \approx \frac{B^2}{D^2}$$

The kinetic energy ratio is

$$\frac{K.E._{bowl}}{K.E._{cyl}} = \frac{I_{bowl}\,\Omega^2_{bowl}}{I_{cyl}\,\Omega^2_{cyl}} \approx \frac{B^2}{D^2}$$

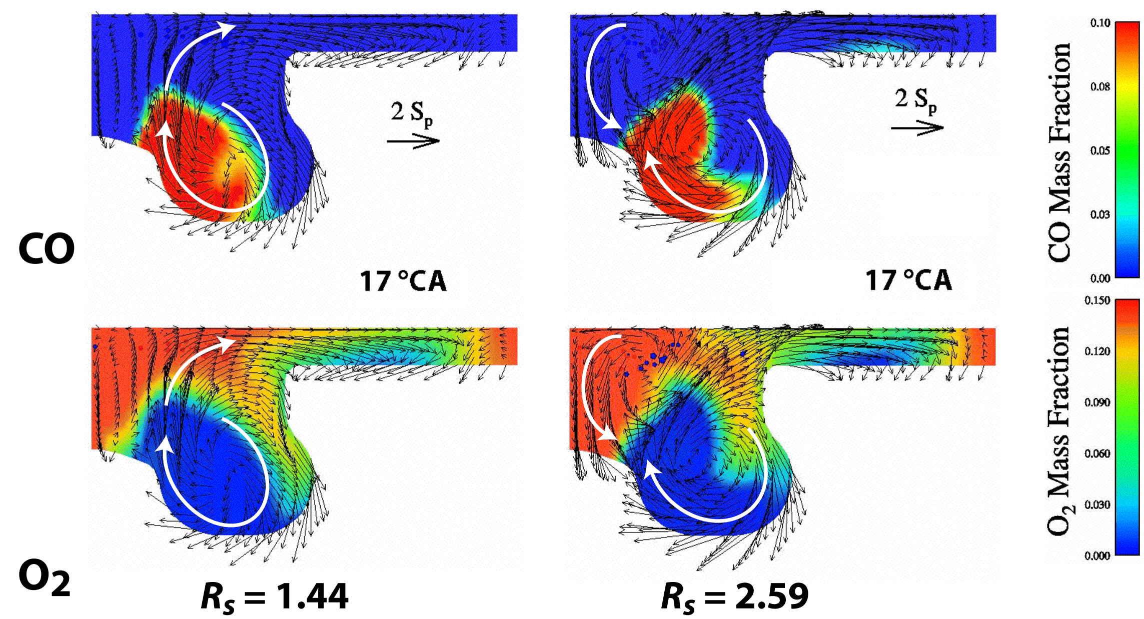
- For typical conservation efficiencies of angular momentum (≈ 60%) and B/D ≈ 2, a 40–50% increase in rotational kinetic energy is expected.
- The source of this increased energy is work done by the piston.

Flow structures formed by a similar "spray–swirl" interaction can enhance mixing rates during combustion

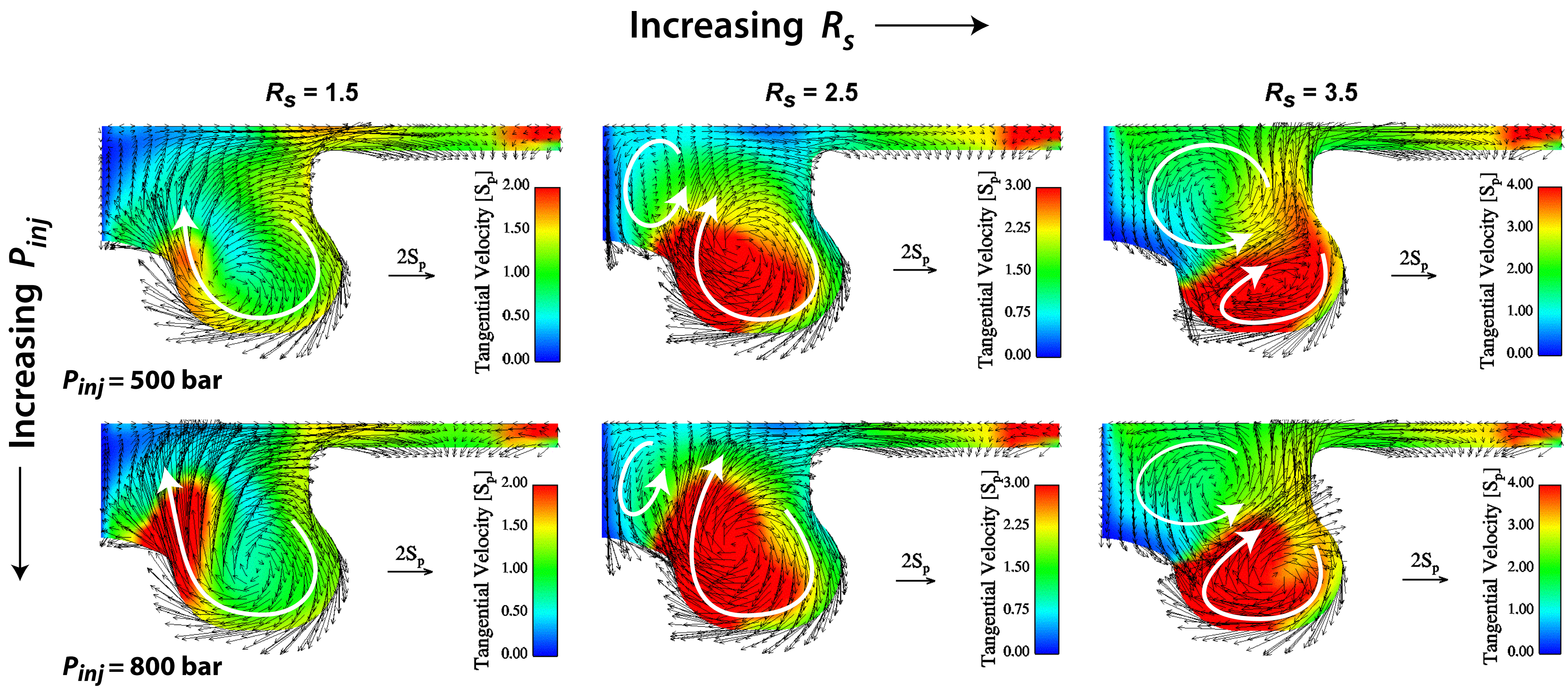


Increased swirl increases the late-cycle rate of heat release

Numerical simulations indicate that the increased heat release due to beneficial flow structures formed with higher swirl levels

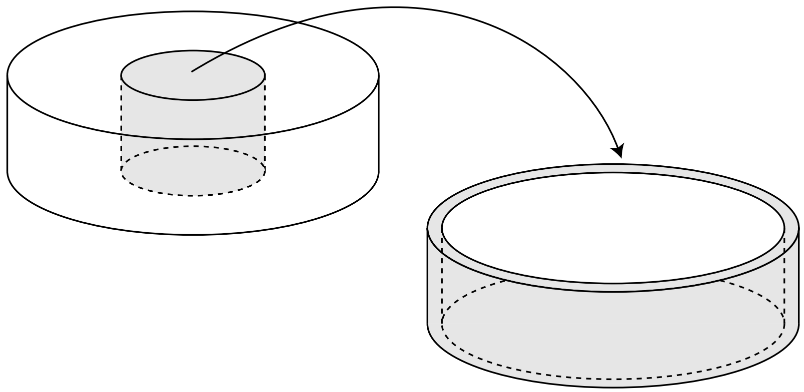


These structures are also formed from the displacement of high angular momentum (Ω) fluid



- High swirl limits inward penetration of high-Ω fluid, and promotes its rapid return towards larger radii: Bowl vortex is smaller and lower in the bowl
- Higher P_{inj} promotes inward and upward penetration of high-Ω fluid: Bowl vortex is larger and higher in the bowl
- Flow structures are under the designer's control via R_s, P_{inj}, bowl geometry and spray targeting — Speed and load effects follow inductively

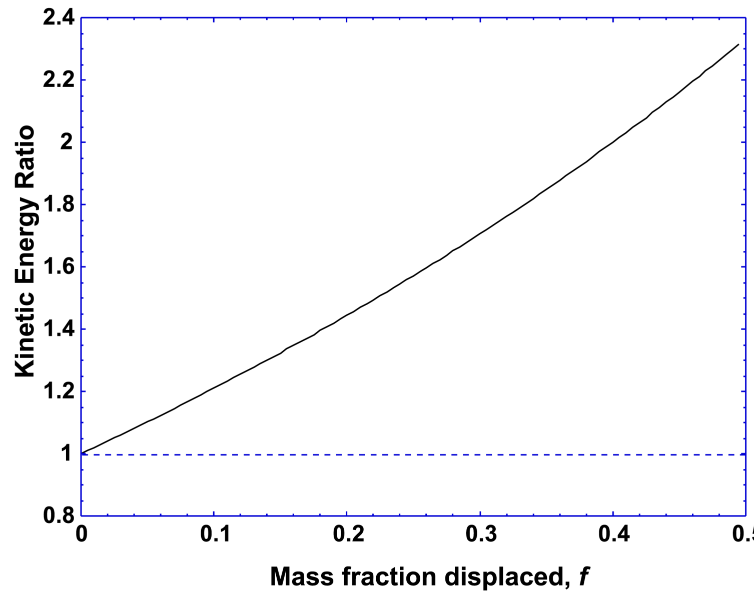
Displacement of angular momentum can lead to an increase in the bulk rotational kinetic energy



Fuel injection transports entrained low momentum fluid to the bowl periphery, high momentum fluid is displaced inward

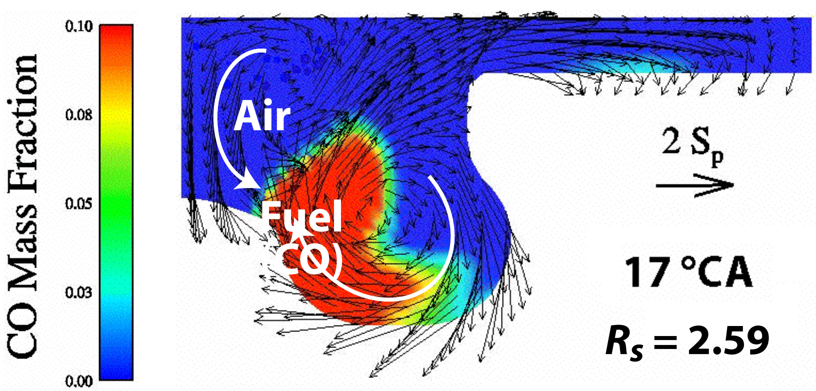
An idealized 2-zone analysis, conserving total angular momentum, suggests that the increase in rotational kinetic energy may be significant

The source of this additional rotational energy is the kinetic energy of the fuel spray



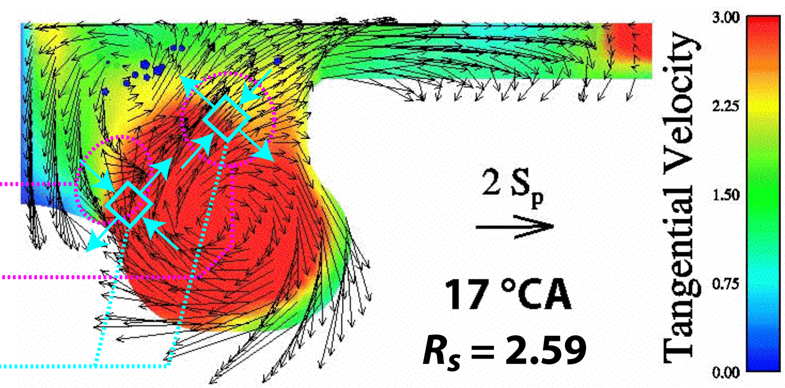
Kinetic energy of the fuel spray can be stored in the bulk rotational motion for later release

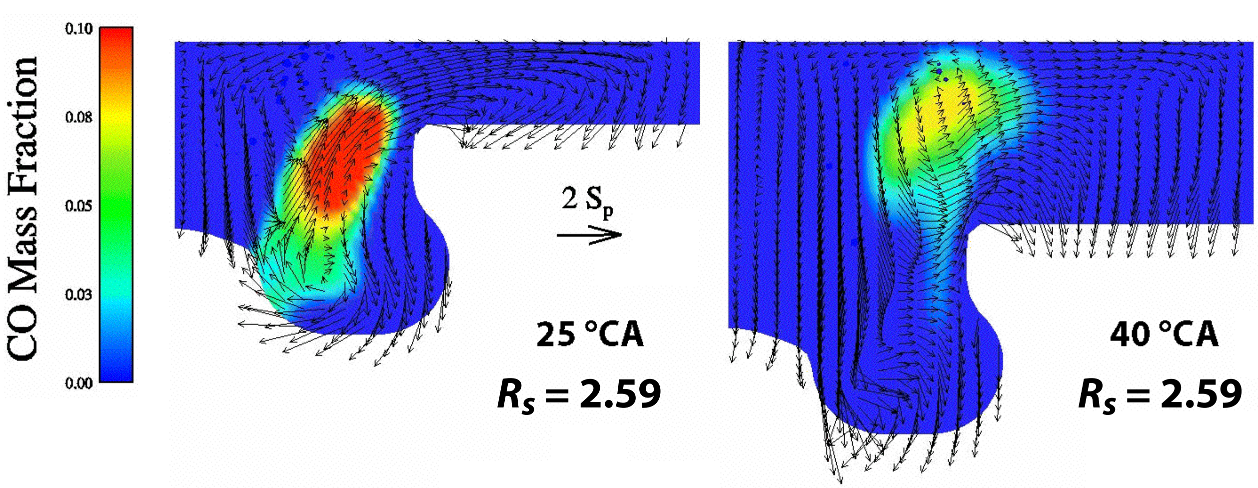
These structures form an effective mixing *system*



- Counter-rotating vortices transport unburned fuel and fresh air to a common interface

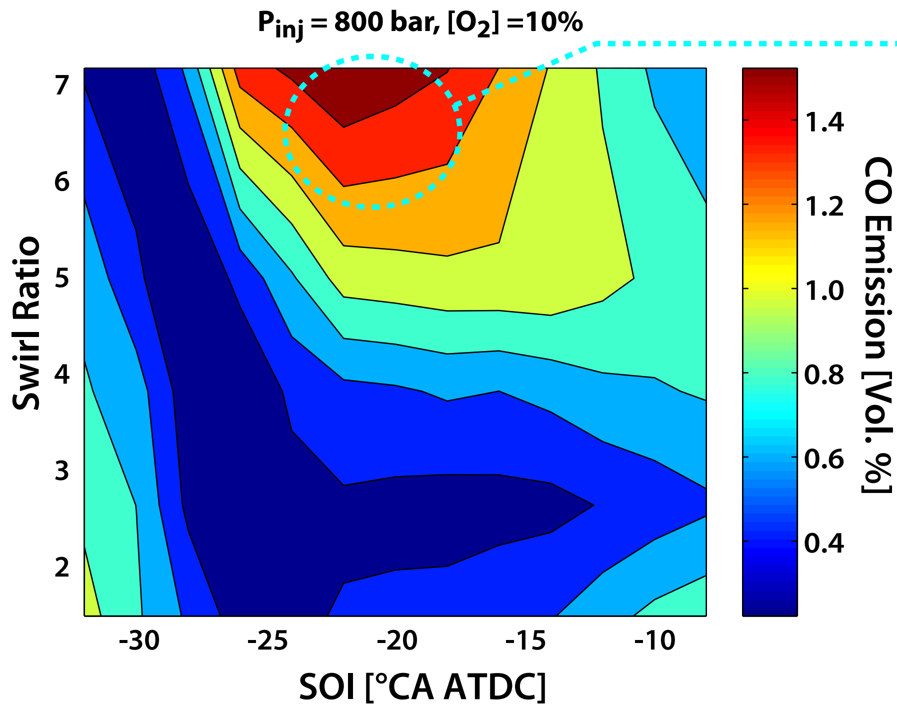
- These vortices also generate high levels of flow turbulence at the interface via:
  - High shear (+ swirl velocity gradients)
  - Negative swirl velocity gradients
  - High rates of *r-z* plane deformation



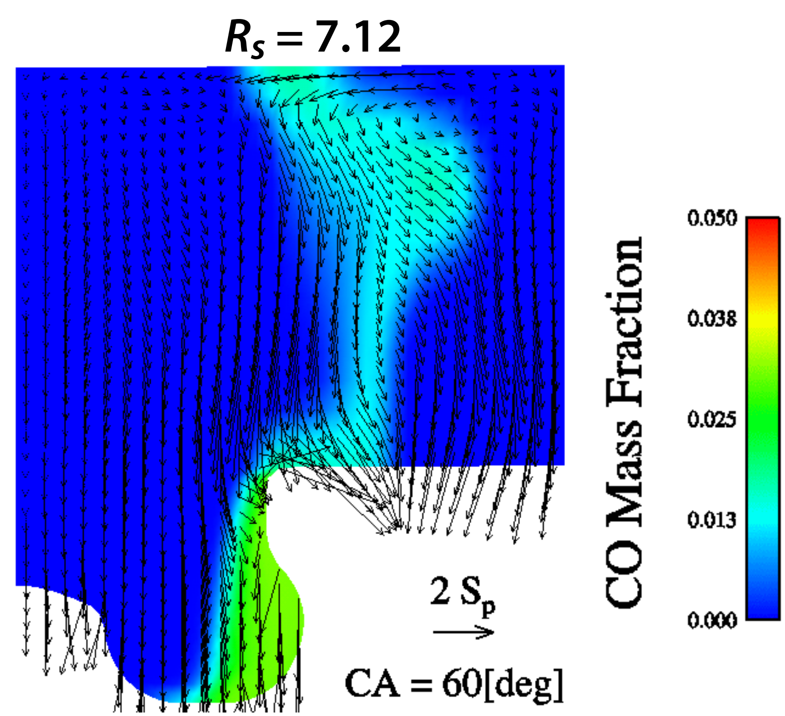


- Late in the cycle, these structures transport remaining unburned fuel (CO, soot) into the squish volume... Careful!

These structures can inhibit mixing when swirl is excessive

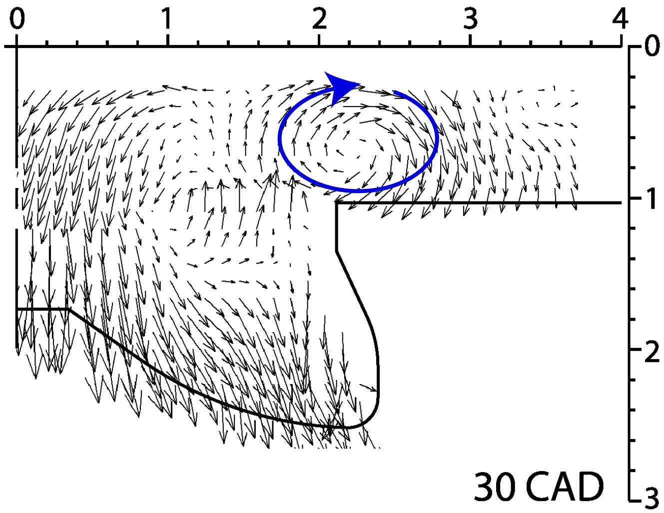


Very high CO emissions are observed at high swirl ratio (similar to MK system swirl)

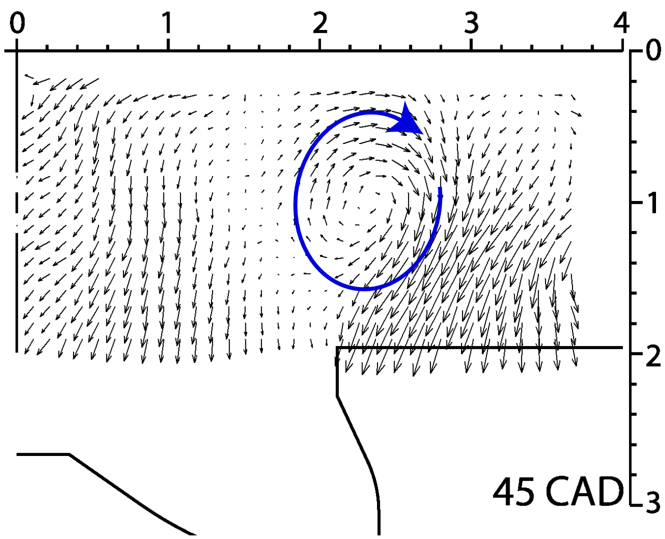


- Simulations point to CO trapped by high centrifugal forces in the periphery of the bowl as a major source of CO emissions
- This phenomenon may be a cause of the need to reduce swirl at high engine speeds

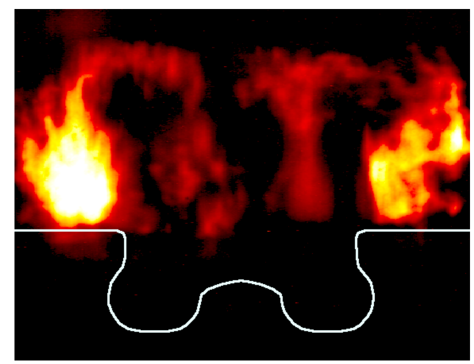
Detrimental flow structures can also form in the squish volume



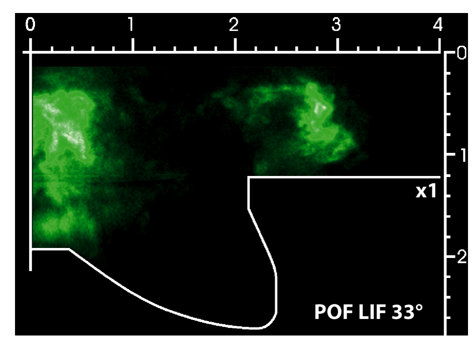
MK-like combustion
15% O_2, SOI = -4°
1200 rpm, 4 bar gIMEP



- Fluid exiting the bowl can trigger formation of a toroidal vortex above the bowl lip
- The vortex is stable and long-lived
- It also forms when no heat release occurs (motored operation) but its formation is delayed
- It impedes mixing in at least two possible ways:
  - It forms a barrier that prevents mixing of fluid exiting the bowl with fluid in the squish volume
  - It may trap soot/partially-burned fuel within the vortex



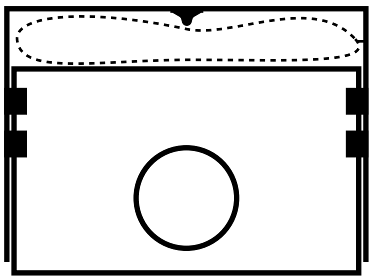
Conventional combustion
20% EGR, 2000 rpm, 5 bar gIMEP



Low-temperature combustion
56% EGR, 1200 rpm, 4 bar gIMEP

Our understanding of engine turbulence is largely empirical

Pancake:



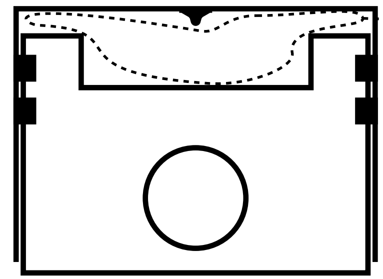
$u' \approx 0.5 S_p$

Approximately Homogeneous

Little effect of swirl

Increasing A_{squish}

Open cylindrical bowl:



No swirl

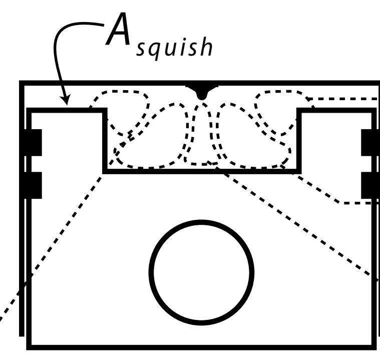
$u' \approx 0.5\text{–}0.6 S_p$

Swirl

$u' \approx 0.7 S_p$

No significant inhomogeneity

Deep cylindrical bowl:



Swirl

$u' \approx 1.2 S_p$

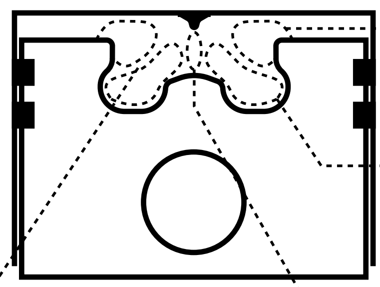
$u' \approx 0.7\text{–}0.8 S_p$

$u' \approx 1.1 S_p$

Homogeneity decreases with increasing swirl or A_{squish}

Increased centerline turbulence often attributed to swirl center precession

Re-entrant:



Swirl

Largest u' near -10°

$u'_\theta > u'_r$

$u' \approx 0.5\text{–}1.8 S_p$

(Increases with swirl or A_{squish})

Generally less homogeneous than cylindrical

Modeling studies often predict a local maximum

The angular momentum distribution can also profoundly impact the turbulence field

Radial Equilibrium:

$$\frac{\partial P}{\partial r} = \rho \frac{\langle U_\theta \rangle^2}{r}$$

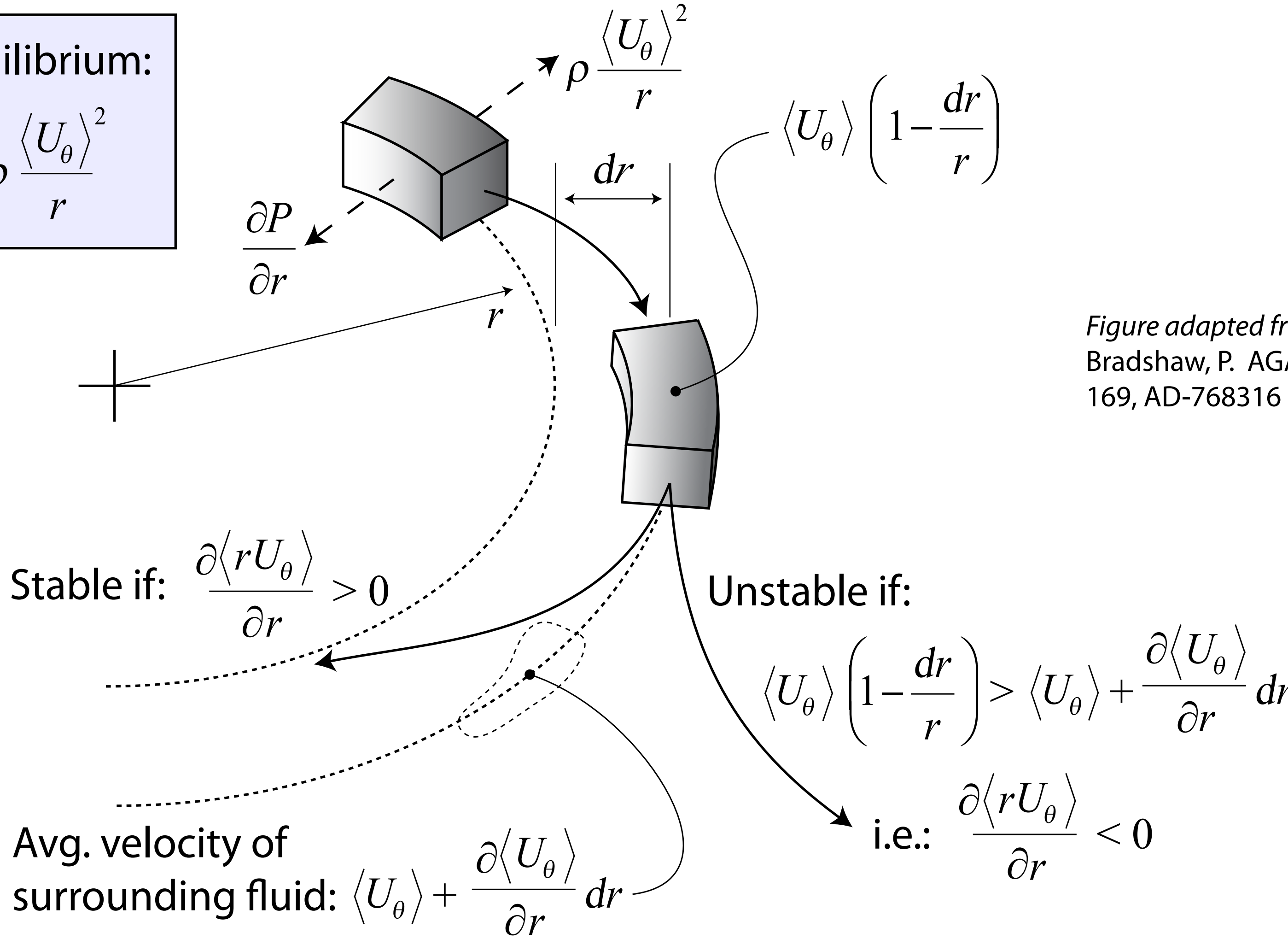
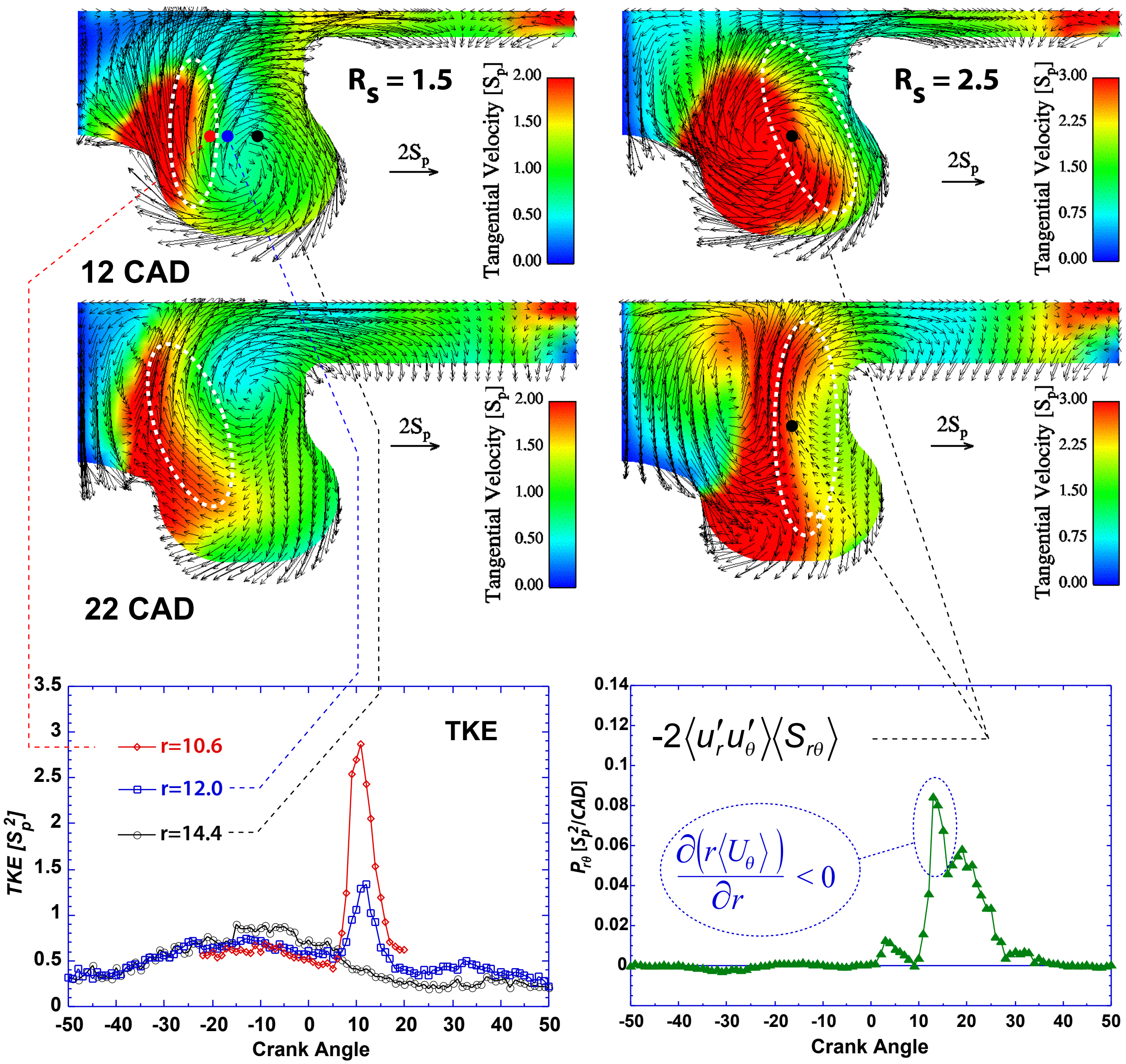


Figure adapted from:
Bradshaw, P. AGARDograph 169, AD-768316 (1973)

A swirling flow characterized by a negative mean radial gradient in angular momentum is inherently unstable

Any perturbation of a fluid element will be amplified

Negative mean radial gradients of angular momentum are not just an academic curiosity



- At low swirl ratios, measured turbulence energy increases by an order of magnitude as the negative momentum gradient region is approached
- With higher swirl, we measure the negative momentum gradient directly—along with increased production & turbulence energy

Stored mean flow energy can be released to turbulence very effectively by forming negative Ω gradients

RANS equations describing the production* of k can help us understand turbulence generation by swirl

$$\frac{\bar{D}k}{\bar{D}t} = -\langle u_i u_j' \rangle \langle S_{ij} \rangle - \varepsilon + Diffusion$$

Production by anisotropic stresses

$$-\left(\left\langle u_i' u_j' \right\rangle - \frac{2}{3} k \delta_{ij}\right)\left\langle S_{ij} \right\rangle$$

Vertical, diametral plane "squish" generated turbulence

$$-\left\langle u_r' u_z' \right\rangle \left(\frac{\partial \langle U_r \rangle}{\partial z} + \frac{\partial \langle U_z \rangle}{\partial r} \right)$$

Additional terms exist that are not considered here

Horizontal plane "swirl" generated turbulence

$$-\left\langle u_r' u_\theta' \right\rangle \left(\frac{1}{r} \frac{\partial \left(r \langle U_\theta \rangle \right)}{\partial r} - \frac{2 \langle U_\theta \rangle}{r} \right)$$

Dominant shear related production term in swirl-supported diesels

Production by isotropic stresses

$$-\frac{2}{3} k \left(\nabla \cdot \langle \mathbf{U} \rangle \right)$$

$$\nabla \cdot \langle \mathbf{U} \rangle \approx -\frac{1}{\rho} \frac{\partial \rho}{\partial t}$$

$$\approx \frac{1}{V} \frac{\partial V}{\partial t} \approx \frac{1}{P^{1/\gamma}} \frac{\partial P^{1/\gamma}}{\partial t}$$

Independent of flow structure

$$-\frac{2}{3} k \left(\nabla \cdot \langle \mathbf{U} \rangle \right)$$

$$-\frac{2}{3} k \left(\frac{\partial \langle U_r \rangle}{\partial r} + \frac{1}{r} \frac{\partial \langle U_\theta \rangle}{\partial \theta} + \frac{\langle U_r \rangle}{r} + \frac{\partial \langle U_z \rangle}{\partial z} \right)$$

$\left\langle u_r'^2 \right\rangle$ $\left\langle u_\theta'^2 \right\rangle$ $\left\langle u_r'^2 \right\rangle$

Often determines normal stress anisotropy

* The redistributive terms associated with convection of the normal stresses in a curvilinear coordinate system are included here

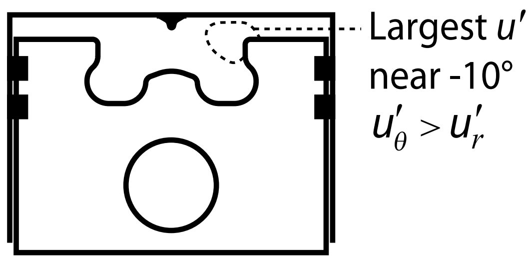
A closer examination of the swirl related production

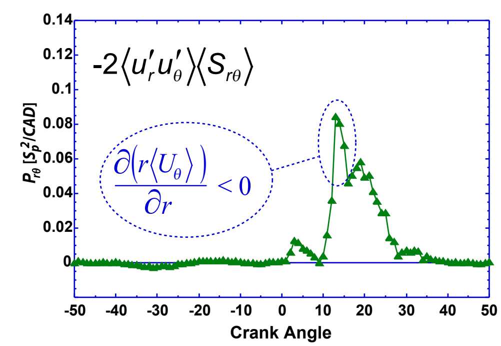
$$-\langle u_r' u_\theta' \rangle \left(\underbrace{\frac{1}{r}\frac{\partial\left(r\langle U_\theta\rangle\right)}{\partial r}}_{\langle u_\theta'^2\rangle \; (+)} - \underbrace{\frac{2\langle U_\theta\rangle}{r}}_{\langle u_r'^2\rangle \; (-)} \right)$$

- For positive $\frac{\partial\left(r\langle U_\theta\rangle\right)}{\partial r}$ and $\langle U_\theta\rangle$, the two terms are of opposite sign. If $\langle u_r' u_\theta' \rangle < 0$, then $\langle u_\theta'^2 \rangle$ can be expected to dominate
- For solid-body flow ($\langle U_\theta\rangle \propto r$), the production is zero

Swirl generally tends to redistribute energy

- When $\frac{\partial\left(r\langle U_\theta\rangle\right)}{\partial r} < 0$, both terms are sources of turbulence, provided $\langle u_r' u_\theta' \rangle > 0$





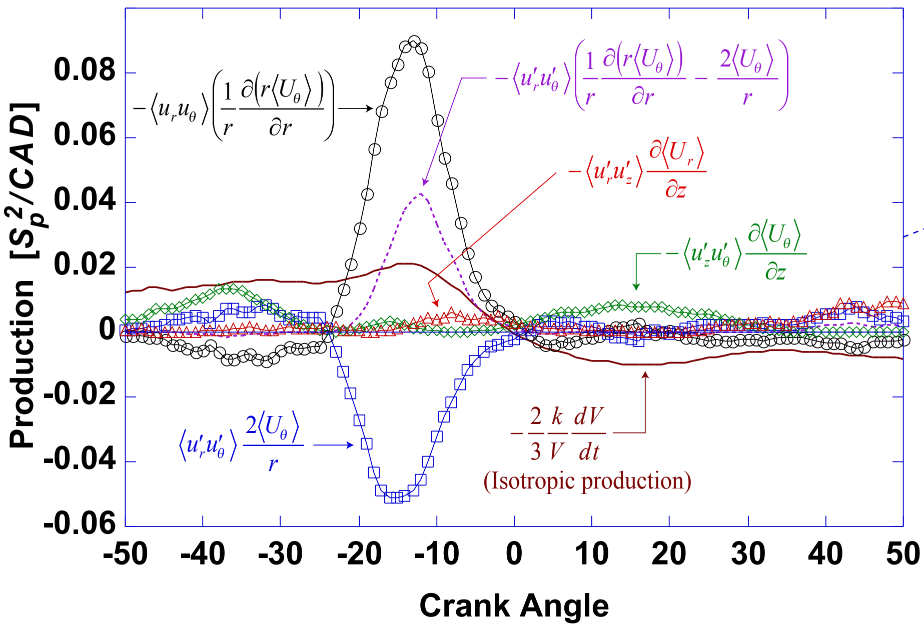
For an axially-uniform, axisymmetric flow on circular streamlines:

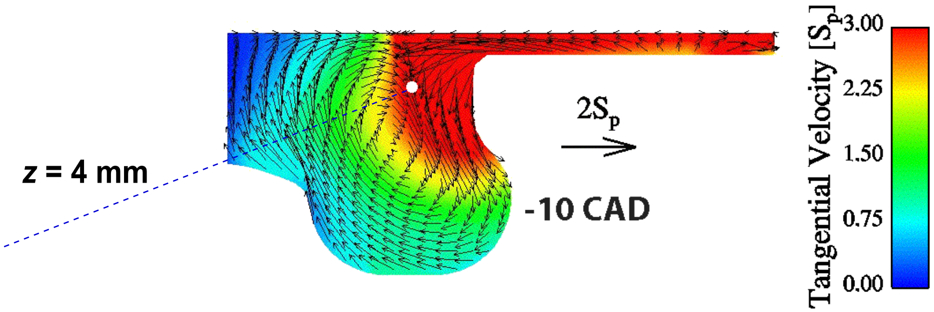
$$\langle u_r' u_\theta' \rangle \propto -\langle u_r'^2 \rangle \frac{1}{r}\frac{\partial\left(r\langle U_\theta\rangle\right)}{\partial r} + \langle u_\theta'^2 \rangle \frac{2\langle U_\theta\rangle}{r}$$

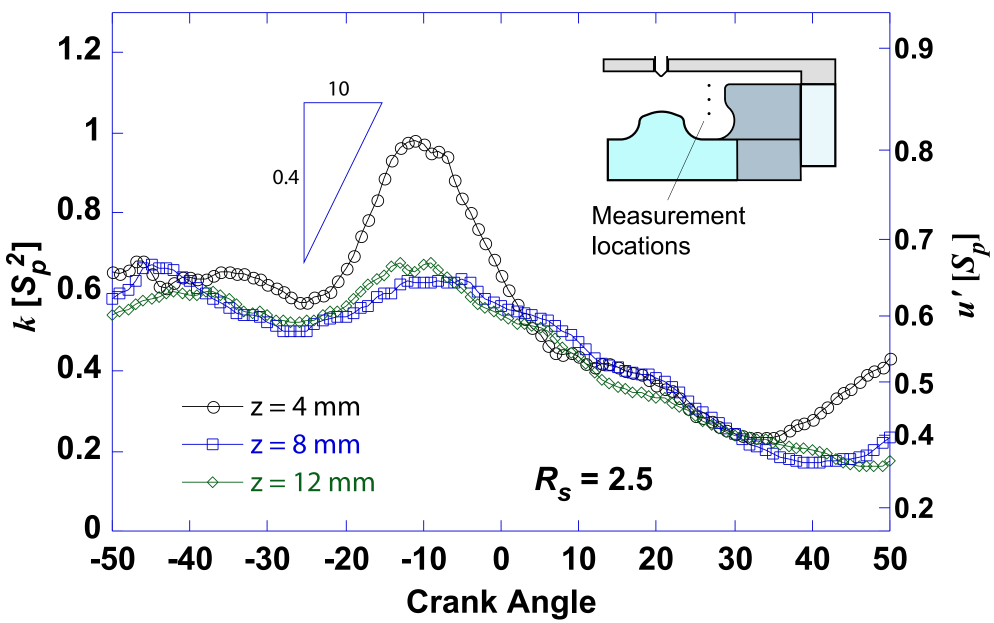
(Assumes shear stress is proportional to its production)

Both terms can be understood in terms of the same momentum conservation principles

Direct measurements of turbulence production confirm these ideas







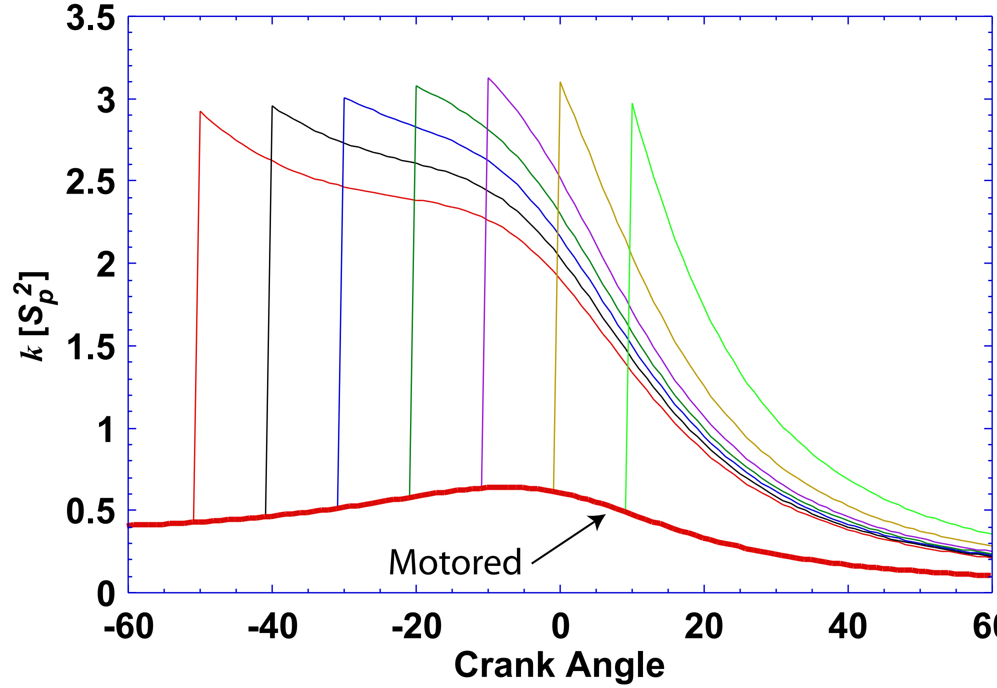
- Radial gradients in $\langle U_\theta \rangle$ dominate production (and anisotropy) near TDC
- Squish generated turbulence is negligible
- Axial gradients in $\langle U_\theta \rangle$ contribute early in the compression stoke and during expansion
- Over the course of the compression stroke, bulk compression dominates—especially lower in the bowl
- During expansion, bulk compression is negative—and typically dominates

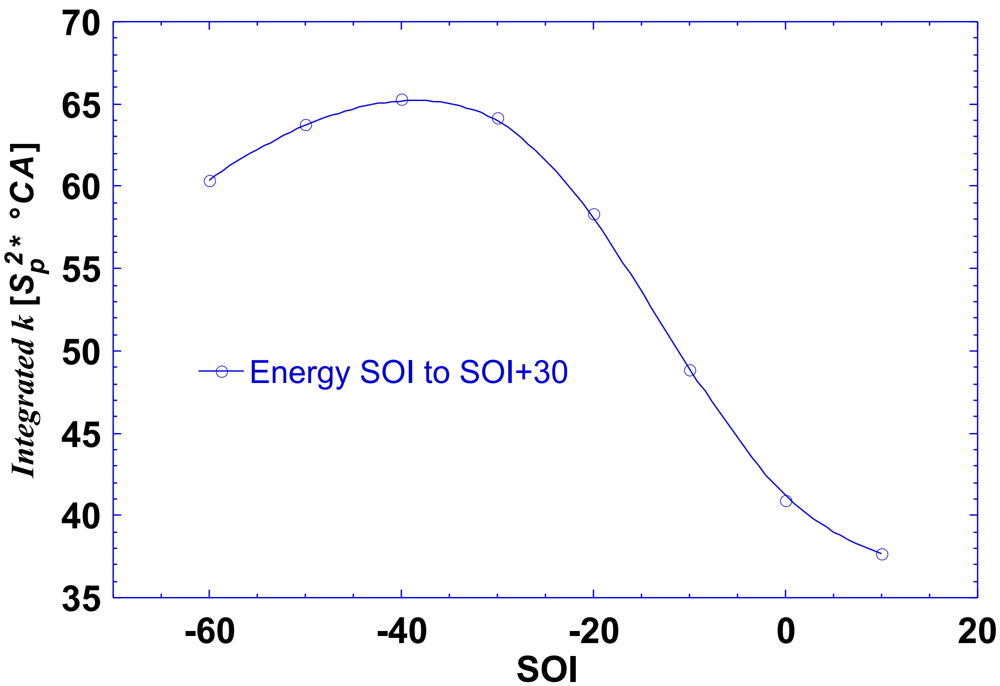
We can take advantage of production by compression to amplify turbulence 'injected' into the cylinder

For homogeneous turbulence:

$$\frac{dk}{dt} = P - \varepsilon = -\frac{2}{3}k\frac{1}{V}\frac{dV}{dt} - CA\frac{u'^3}{\ell}$$

To explore the influence of compression on the utilization of the turbulence generated by the injection event, we "inject" a fixed quantity of k at discreet crank angles





We integrate the turbulence energy in the bowl for the first 30 °CA after injection.

The turbulence energy available for mixing is maximized with fuel injection at -30 to -40 CAD

Closure

- Many aspects of in-cylinder flows can be readily understood through a relatively simple consideration of the governing equations
- These flows are not necessarily subtle. Several "textbook" flow structures (toroidal vortices, negative radial angular momentum gradients) can be identified.
- In swirling flows, the distribution (and re-distribution) of angular momentum plays a dominant role in determining both the mean flow evolution and the shear generated turbulence.
- Turbulence generation by bulk compression is a dominant, and often overlooked source (and sink) of in-cylinder turbulence.