In-cylinder Flow and Mixing Processes in Low-Temperature Diesel Combustion Systems

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Paul Miles
Sandia National Laboratories

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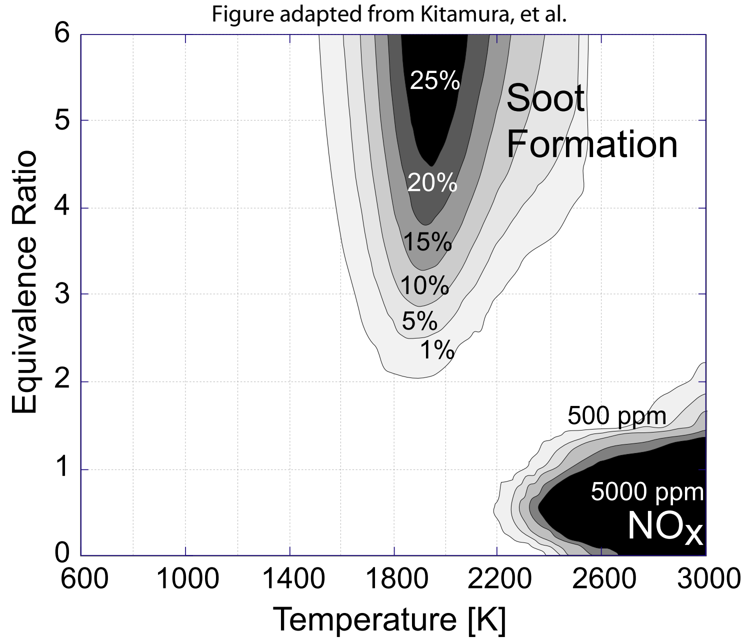
Introduction to the ϕ-T plane

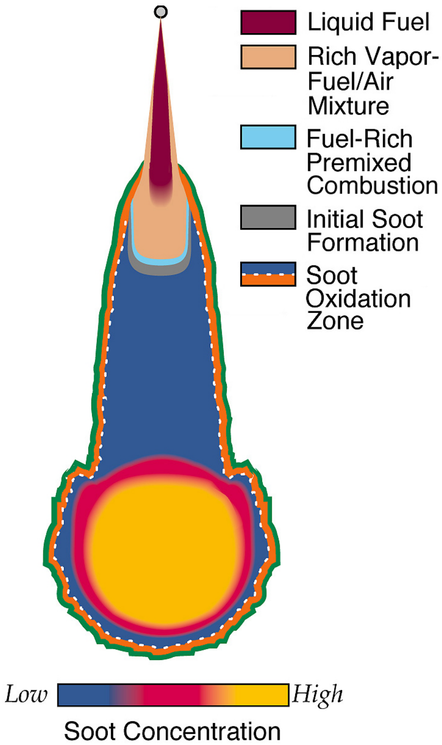
- Introduced by Kamimoto & Bae, (SAE 880423)
- Quantitative calculations based on detailed chemistry from Akihama, et al. (SAE 2001-01-0655) and Kitamura, et al. (JER 3: 2002)
- Analysis of the path followed by a fuel element in the ϕ-T plane provides an intuitive framework for understanding emission formation during combustion
- Pickett, et al. (JER 2006, in press) allow for changing temperature, residence time, and ϕ
  - Soot formation zones vary with operating conditions (path)
  - Validates the use of these ϕ-T diagrams for gaining qualitative understanding

Figure adapted from Kitamura, et al.

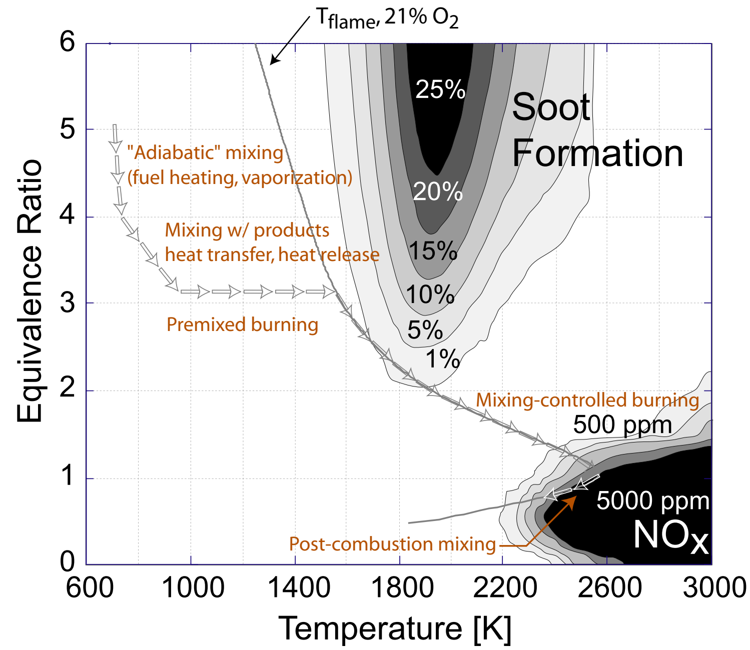


Mixing processes influence the path of the combustion process in the ϕ-T plane

"Steady" combustion in a heavy-duty diesel engine (Flynn, et al., SAE 1999-01-0509; Dec, SAE 970873)

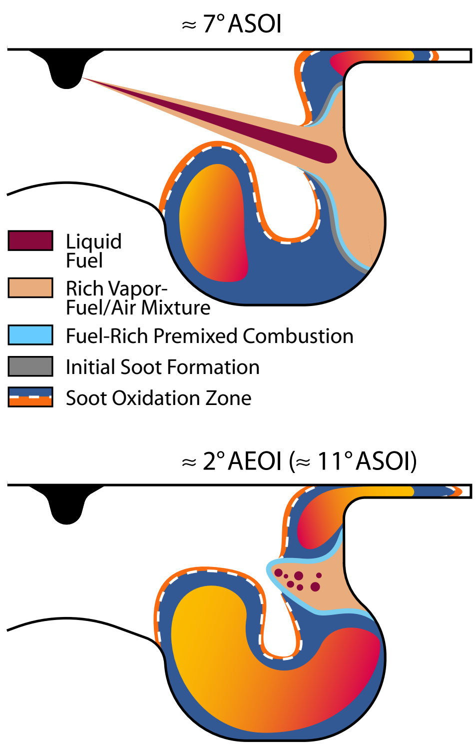


Graphic courtesy of JE Dec

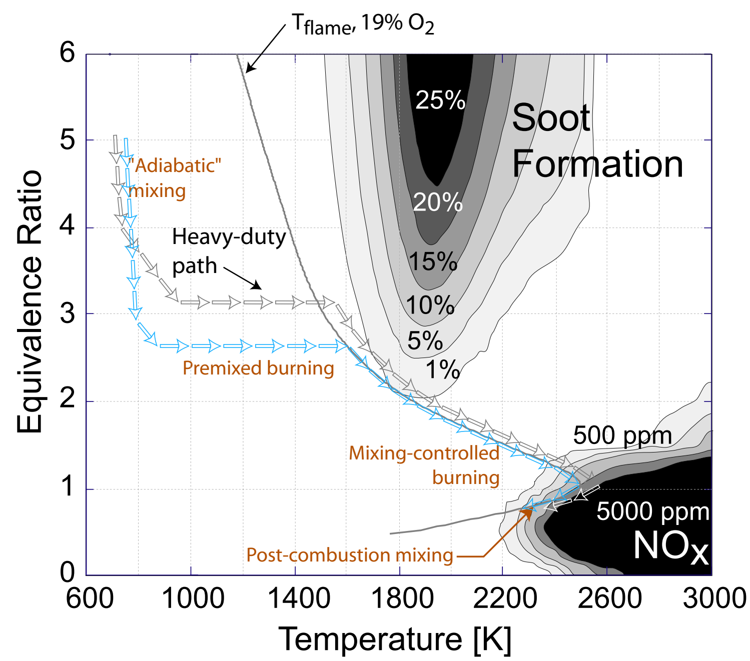


...residence time must also be considered

Despite large differences in geometry and operation, the conventional light-duty diesel path differs little



Hypothesized structure & timing at a 5 bar load



Mixing of the products of rich, incomplete combustion proceeds relatively slowly

Large path changes are obtained when the mixing time scales are less than the chemical time scales

- For HCCI, low ambient temperature (early injection) keeps chemical time scales large
- Mixing rates can also be increased through use of:

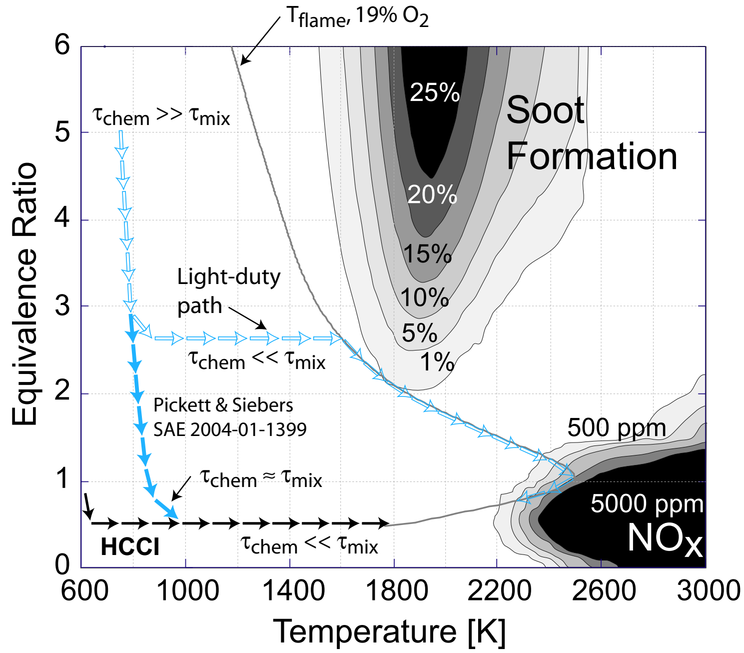
  High injection pressure

  Jet spatial structure invariant, but development more rapid

  Small nozzle diameters/boost:

  Relative air entrainment rate increases, penetration rate decreases

  Pickett & Siebers have demonstrated mixing-controlled, soot free combustion with this strategy



Technological challenges/limits make these paths difficult to reach in practice

Low-temperature combustion systems achieve greater premixing and lower peak temperatures

- Greater premixing is achieved using:
  - High injection pressure
  - Boost

    (*keeps τ_{mix} small*)

  - Low ambient temperature

    EGR cooling

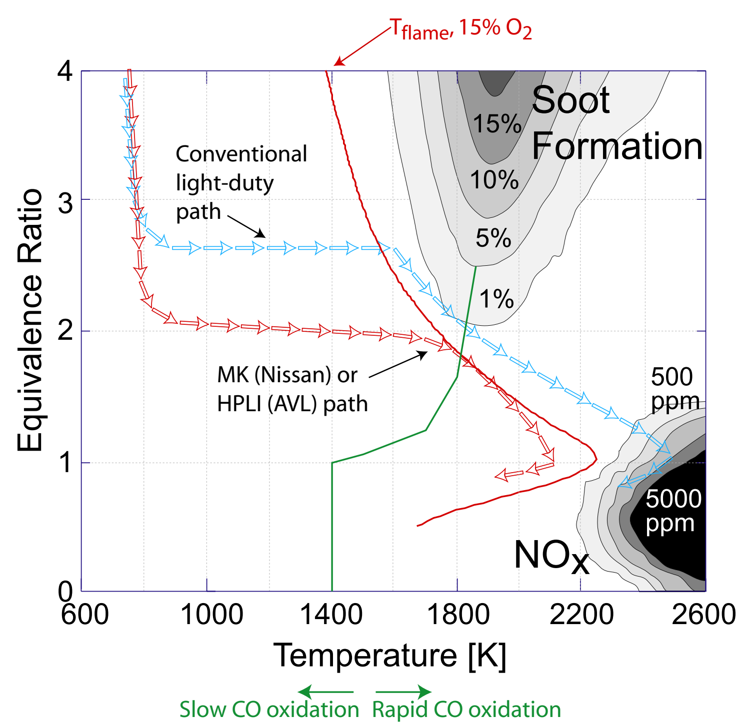
    Low compression ratio

    Late-injection

    (*keeps τ_{chem} large*)

- Lower peak temperatures are achieved with low ambient temperatures and high EGR rates

  Increased ignition delay due to high EGR rates does not significantly influence premixing



Ambient temperature is a powerful tool for influencing pre-combustion mixing... EGR rate is less important

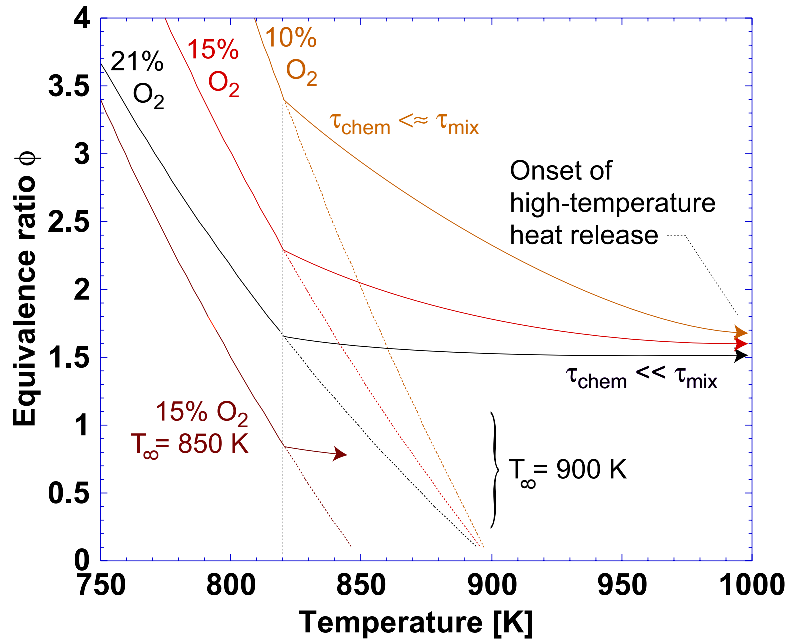
- A 50K decrease in ambient temperature reduces ϕ at the start of low-temperature reaction by over 40%

  Corresponds to:
  - Reduction in T_{in} by 20 K
  - Comp. ratio from 18.7 to 15.6

- Increased EGR raises ϕ at the start of reaction...

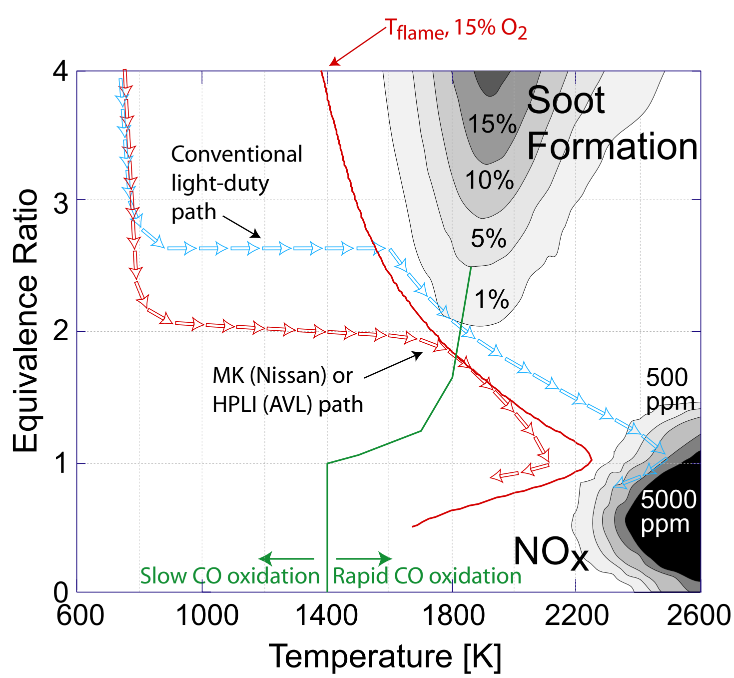
  ...but slower reaction (larger τ_{chem}) compensates

  Increasing EGR may *increase* ϕ at high-temperature ignition
  - HSDI engine heat release analysis (SAE 2005-01-3837)
  - ϕ measurement in free jets (Idicheria & Pickett, 31st Comb. Symp)



Mixing rates during the mixing-controlled burn must be kept high to minimize emissions and maximize efficiency

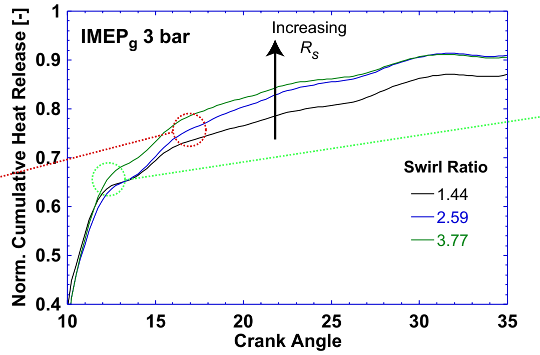
- At high EGR rates large quantities of ambient fluid are required to supply the needed O_2
- Volume expansion due to piston motion is rapidly lowering temperature and slowing oxidation rates
- Volume expansion (also due to heat release) dampens turbulence
- Bulk flow structures can both enhance and impede mixing processes
  - Transport fuel & air to common regions of the cylinder
  - Generate turbulence where fuel and air meet



CO oxidation zones from Adomeit, et al., THIESEL 2004

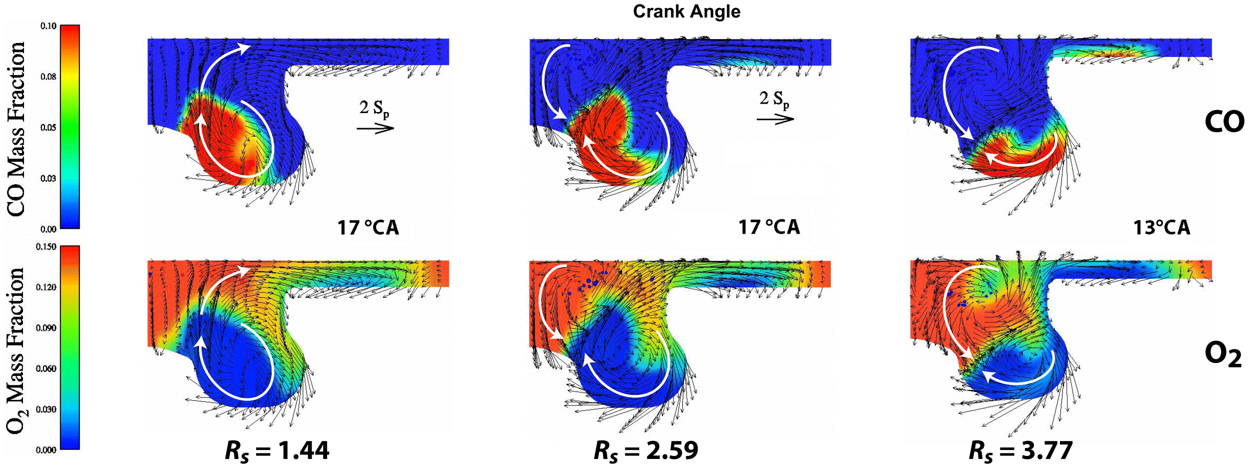
Bulk flow structures that increase late-cycle mixing have been identified

Why does the late-cycle heat release accelerate for R_S=2.59 and not for R_S=1.44?



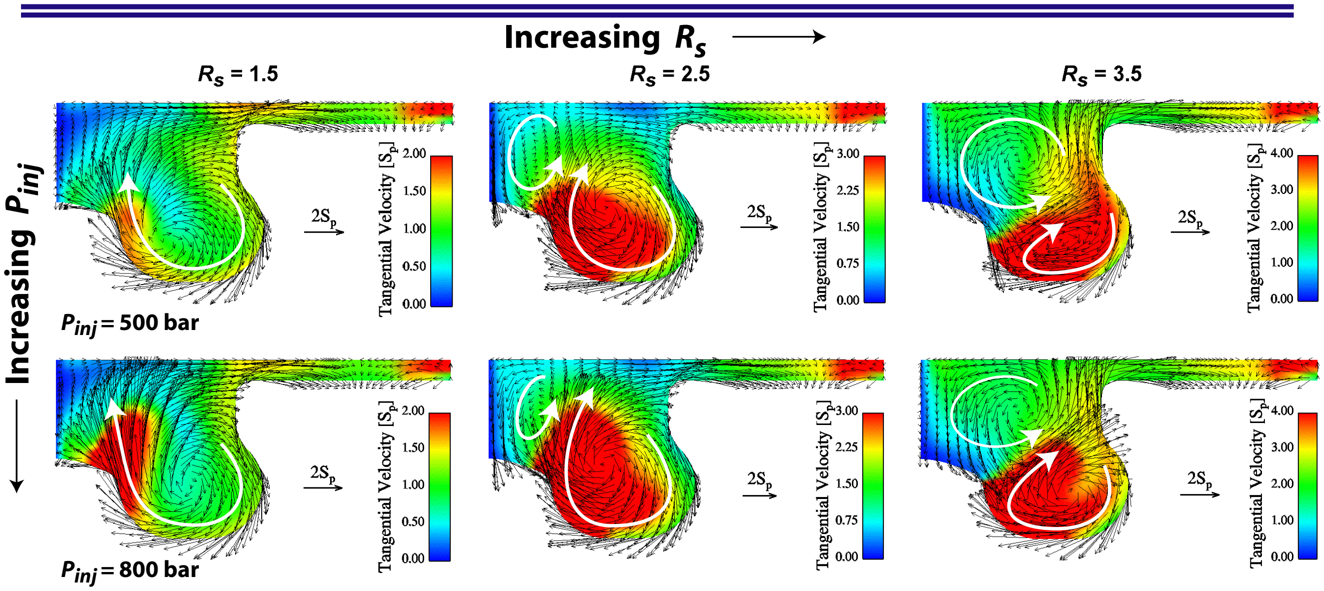
Similar flow structures form earlier at R_S=3.77

Numerical simulations courtesy of RD Reitz, University of Wisconsin



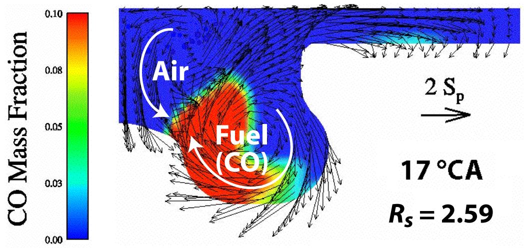
Unburned "fuel" and air are transported to a common interface

These structures are formed due to the "re-arrangement" of angular momentum (Ω) by the fuel sprays



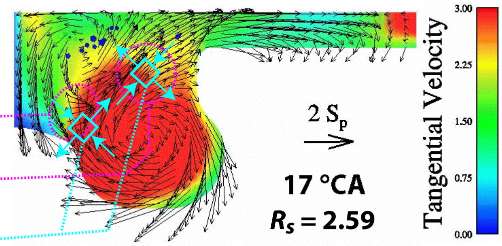
- High swirl limits inward penetration of high-Ω fluid, and promotes its rapid return towards larger radii: Bowl vortex is smaller and lower in the bowl
- Higher P_{inj} promotes inward and upward penetration of high-Ω fluid: Bowl vortex is larger and higher in the bowl
- Flow structures are under the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

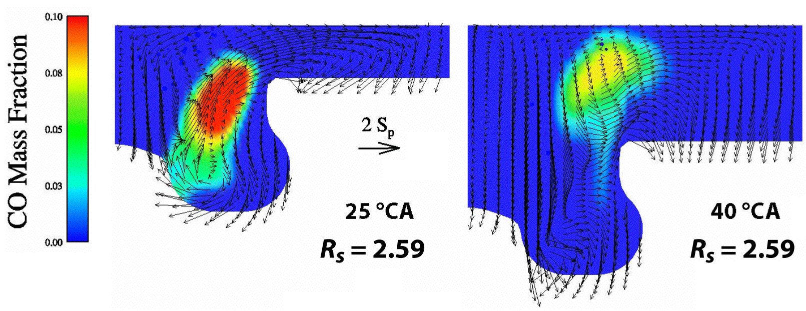
The structures form an effective mixing *system*



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

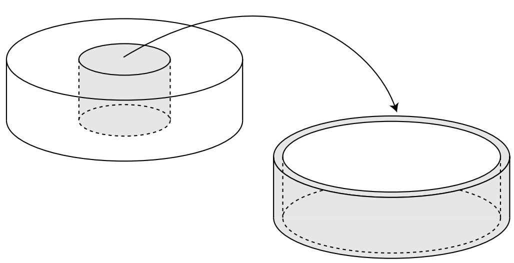
- These vortices also transport angular momentum, generating high levels of flow turbulence at the interface via:
  - High shear (+ swirl velocity gradients)
  - Negative swirl velocity gradients
  - High rates of *r-z* plane deformation





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

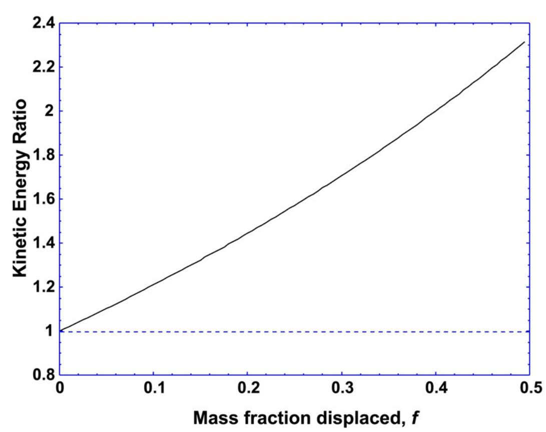
Re-arrangement of angular momentum can lead to an increase in the bulk rotational energy



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

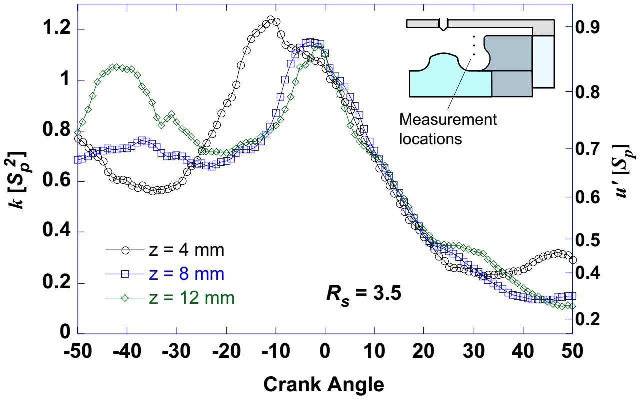
An idealized 2-zone analysis, conserving total angular momentum, suggests that the increase in rotational kinetic energy may be significant

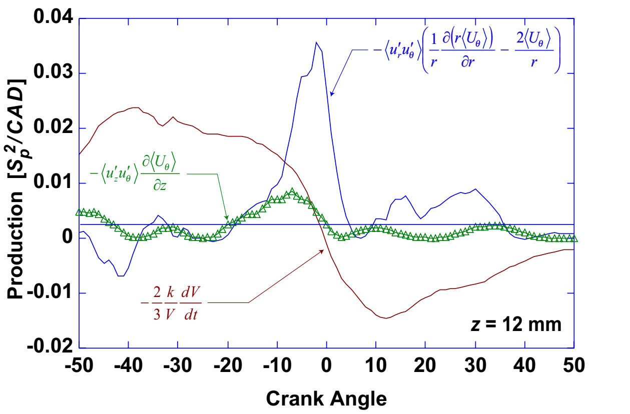
The source of this additional rotational energy is the kinetic energy of the fuel spray



Kinetic energy of the spray can be stored for later release

TKE decays rapidly during a motored expansion stroke... ...due to dissipation *and* negative production





- During expansion, the dominant turbulence production term is negative

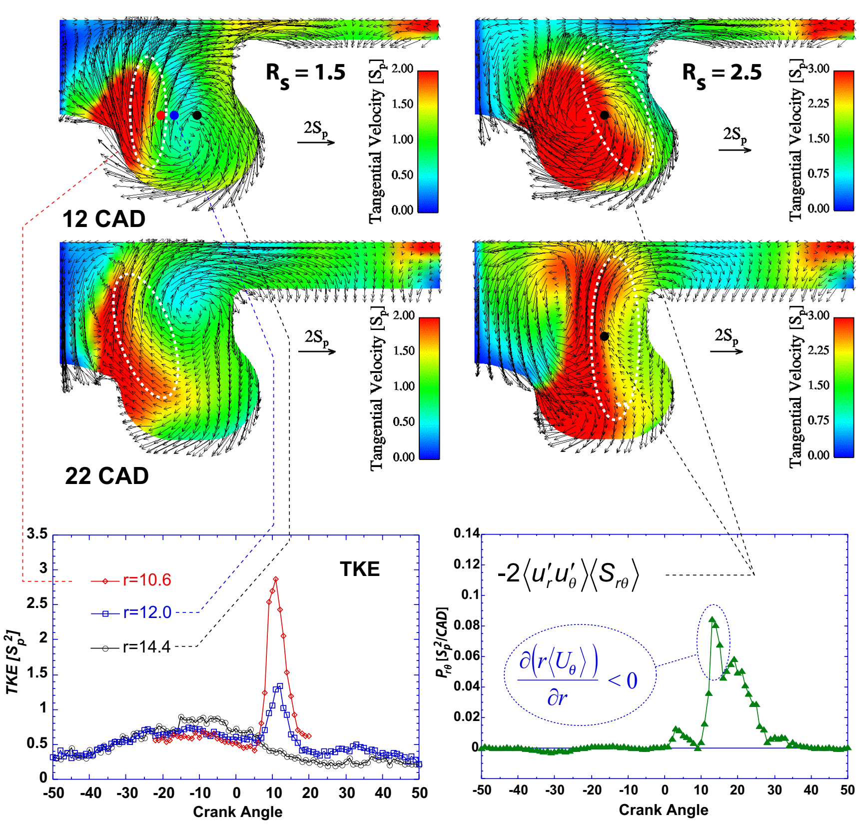
  This term is associated with the isotropic part of the normal stresses and bulk compression/expansion:

$$-\frac{2}{3}k\left(\nabla \bullet \overline{U}\right) \approx -\frac{2}{3}k\,\frac{1}{V}\frac{dV}{dt}$$

- Volume expansion due to piston motion peaks @ 20–25° ATDC, and is 50% of maximum from 5–70° ATDC
- During compression, this same term is the dominant source of k

  Gradients in the swirl velocity are the other important source

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

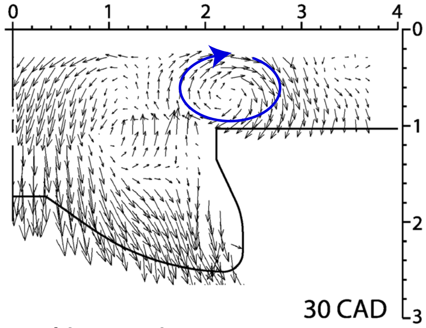


"Swirl Generated" Turbulence

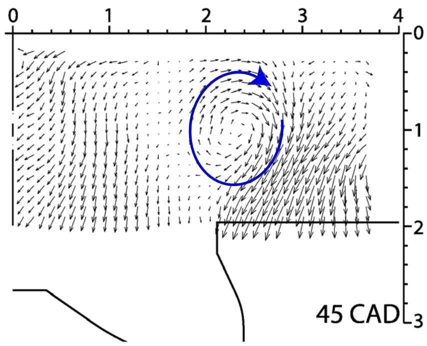
$$-\langle u_r' u_\theta' \rangle \left(\underbrace{\frac{1}{r}\frac{\partial \left(r\langle U_\theta \rangle\right)}{\partial r}}_{\langle u_\theta'^2 \rangle\ (+)} - \underbrace{\frac{2\langle U_\theta \rangle}{r}}_{\langle u_r'^2 \rangle\ (-)} \right)$$

- 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 & k

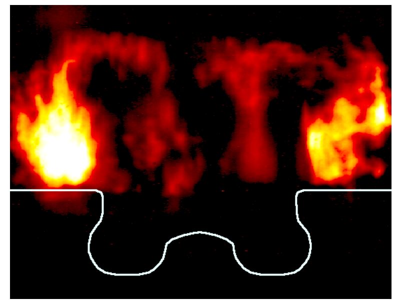
Bulk flow structures can also impede mixing



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



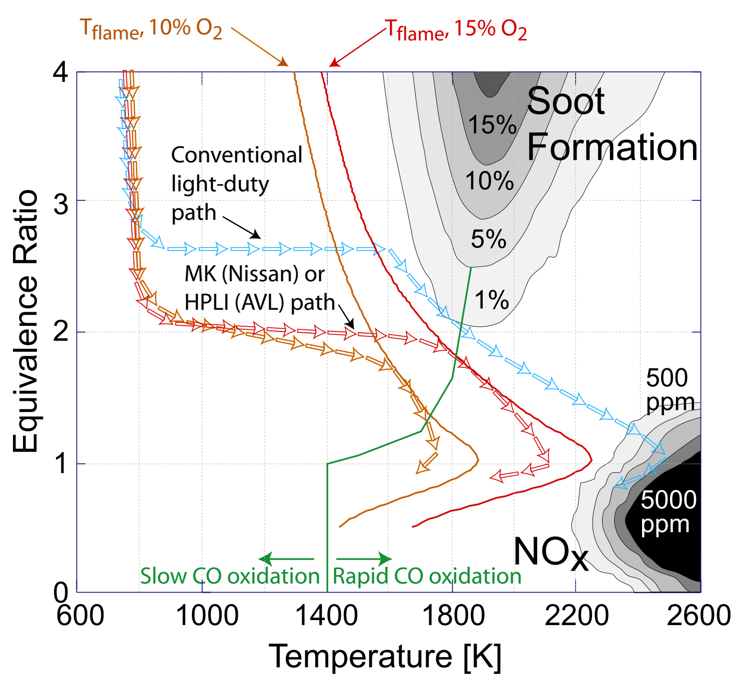
Conventional combustion
20% EGR
2000 rpm, 5 bar gIMEP

Very dilute, "smokeless" combustion systems present still greater mixing challenges

- Mixture stoichiometry at ignition is not expected to differ greatly from that seen with late injection

  Longer ignition delay balanced by need to mix more fluid
- Chemical and mixing timescales are likely comparable during pre-mixed combustion
- The mixing-controlled path segment is very close to the CO oxidation limit
- Inverse correlation of CO emissions with ignition delay and with injection pressure identifies "under-mixed" fuel as the dominant source of CO emissions

CO oxidation zones from Adomeit, et al., THIESEL 2004

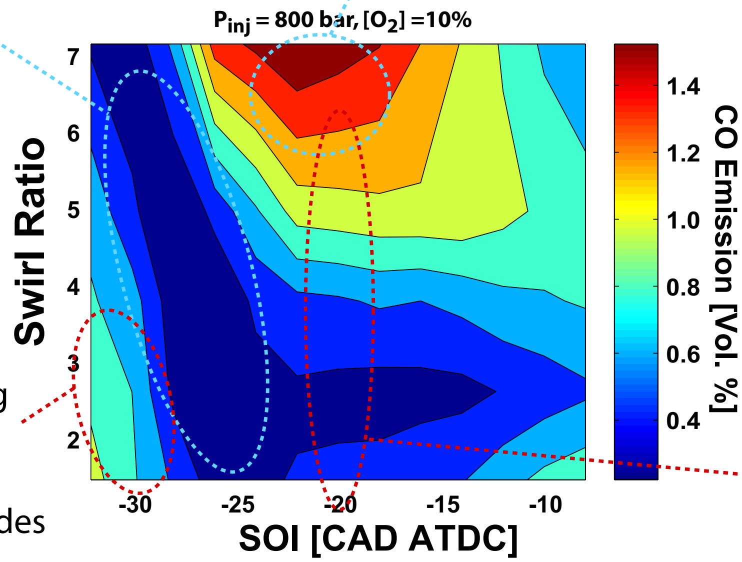


Increased mixing, both prior to ignition and in the late-cycle, reduces CO emissions

Major features of the changes in CO emissions (and ISFC) with SOI or swirl are explained by mixing processes

Due to enhanced early mixing

Very high CO emissions are observed at high swirl ratio



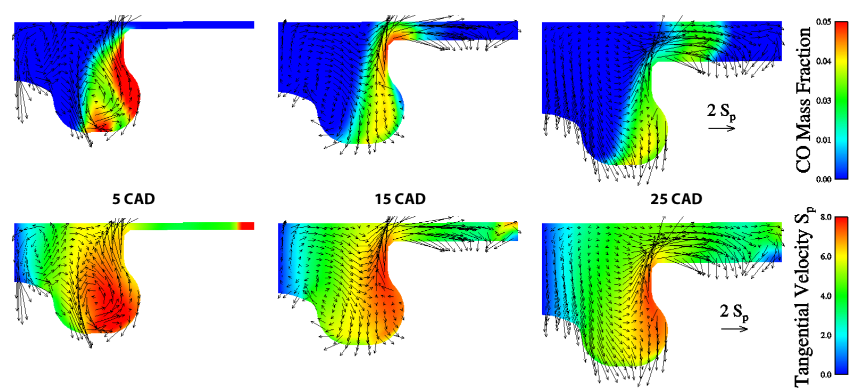
Piston top wetting and/or excessive squish volume penetration impedes mixing (less so at high swirl, more so at high injection pressure)

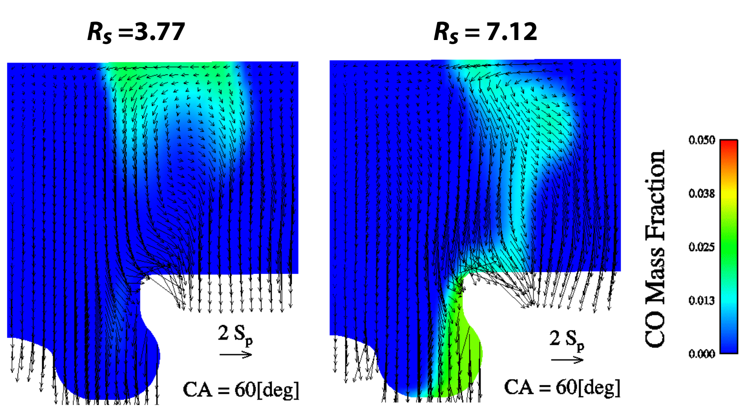
SAE 2006-01-0197

Optimal swirl ratio due to counter-rotating vertical plane bulk flow structures that enhance late mixing (similar to those observed with late injection timing)

Numerical results indicate that trapping of CO within the bowl is the cause of the high swirl CO emissions

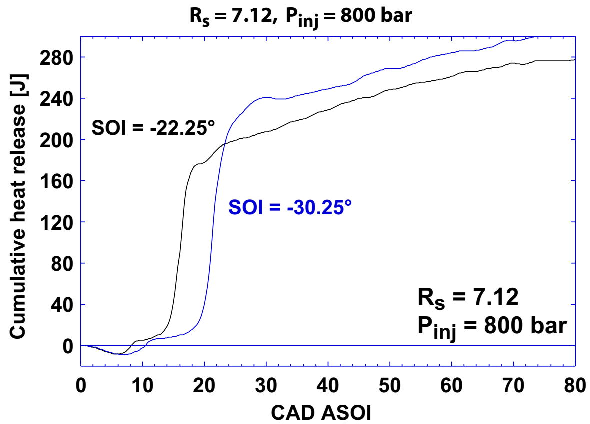
High swirl fluid and partially-burned fuel tend to be co-located

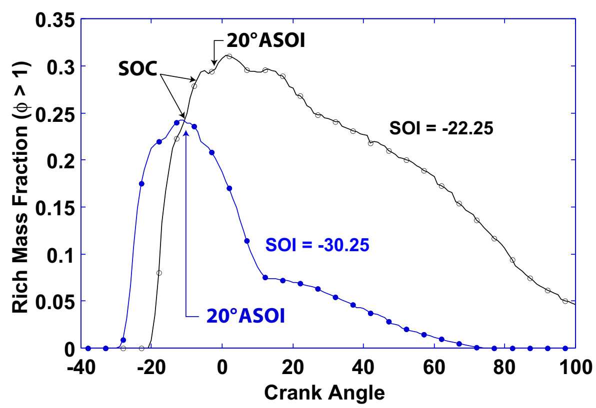




High centrifugal forces prevent this fluid from exiting the bowl, trapping the unburned CO

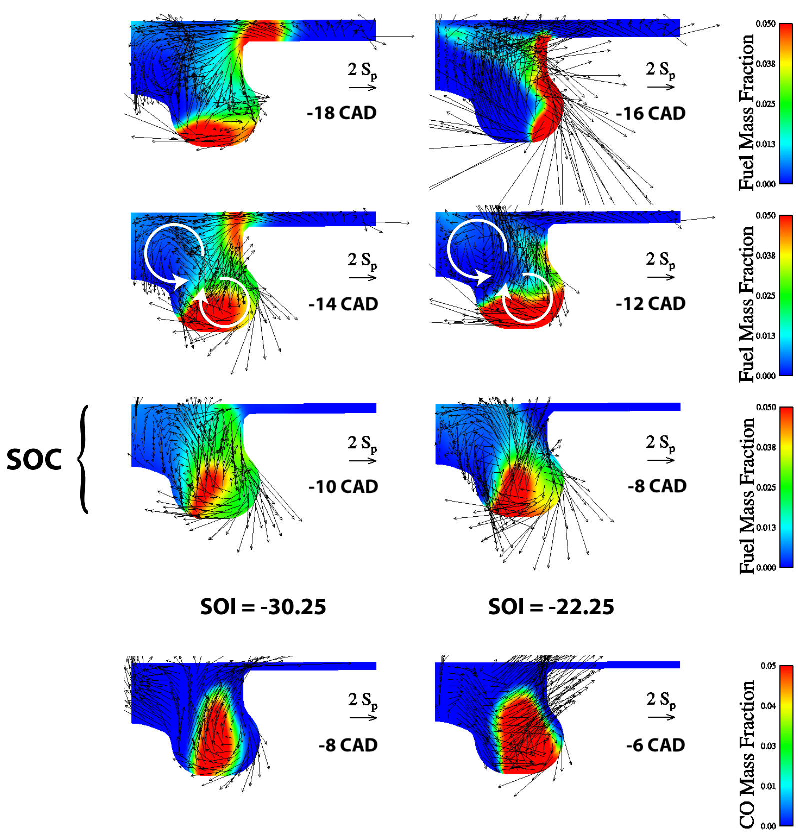
Both experiments and numerical simulations suggest early mixing processes reduce CO formation





- Larger cumulative heat release is clearly due to better mixing in the first 30° after SOI
- Increased premixing is not simply associated with increased ignition delay
- Model results also show a significantly leaner mixture with earlier injection (and corresponding low CO formation)
- Model results indicate that differences in mixing cannot be attributed to mixing inhibition by heat release

Simulations suggest the initial gaseous fuel distribution is an important factor



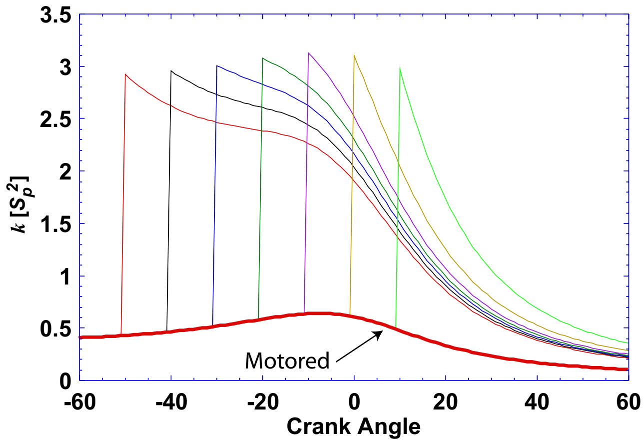
- Pre-combustion bulk flow structures are similar for both injection timings
- The broader fuel distribution at SOC with earlier injection is likely associated with the initial "splitting" of the injected fuel into the bowl/squish regions
- After combustion, the leaner mixture leads to less CO

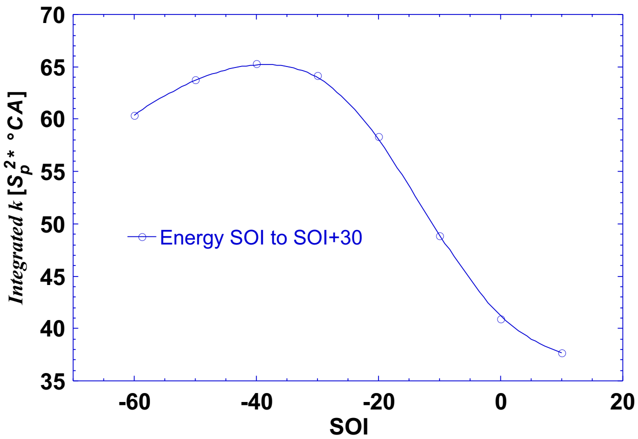
Recall that turbulence production by the isotropic normal stresses dominates during the late compression stroke

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





Integrating the turbulence energy in the bowl for the first 30 °CA after injection, shows that the turbulence energy available for mixing is maximized with pre-TDC injections

The relative contributions of spray targeting effects and increased turbulence are not known

Even early mixing can be influenced significantly though spray targeting and flow-related processes...

...jet-driven mixing processes, while dominant, are not the sole factor to be considered in the early mixing stage

Closure

Mixing processes are central to not only conventional diesel combustion systems, but also low-temperature systems

- **Early-mixing (premixing) is maximized by keeping mixing time scales small as compared to chemical time scales**
  - EGR cooling - Low Comp Ratio - Retarded injection (increases τ_{chem})
  - High Pinj - Small orifices - Boost (reduces τ_{mix})
  - Targeting and compression-generated turbulence also!
- **Late-mixing (post-ignition) remains important!**
  (Full pre-mixing is difficult to achieve)
  - Beneficial structures that enhance mixing rates can be formed
  - Detrimental structures that trap CO in the bowl or in stable toroidal vortex structures may also be formed
- **Key concepts for understanding flow structure development and turbulence:**
  - Fuel injection provides a means for tailoring the angular momentum distribution
  - Turbulence generation by the isotropic normal stresses dominates, followed by swirl velocity gradients