Challenge in Urea Mixing Design

Yong Miao
General Motors
• Introduction
• Spray
• Mixer
• Deposit Formation
• Test Condition for Mixing
• CFD Result vs. Test Result
• Summary
Introduction

• Urea SCR System
  – Liquid urea is introduced into exhaust flow
  – Urea droplet goes through vaporization, hydrolysis reactions to form ammonia gas
  – Ammonia adsorbs on catalyst first then reacts with NOx

( it is pre-stored ammonia to have SCR reaction, but not instant injected urea)

\[
(NH_2)_2CO \rightarrow (NH_2)_2CO \rightarrow NH_3 + HCNO
\]

\[
NH_3 + NO_x \rightarrow H_2O + N_2
\]
Introduction

• **Urea Mixing**
  – Why we need mixing/mixer?
    • Vehicle packaging constrain
    • Cold-start emission
  – How mixing/mixer works?
    • Droplet breakup
    • Surface for vaporization
    • Turbulent generator
  – What conditions have poor mixing?
    • Low temperature
    • Low residue time
  – How to measure mixing result?
    • No direct method available
    • Overall SCR efficiency (NOx conversion rate)
    • Uniformity index for **local mass flow rate ratio** (NH3 to NOx), not urea/NH3 concentration
- **Droplet size, small or large?**
  - Vaporization rate/droplet life time  
    (smaller is better)
  - Droplet number density  
    (smaller is better)
  - Flow impact

For same volume of total injected fluid, reduce droplet size by half can increase number of droplet by 8 times ($2^3$)
Spray

- **Droplet Behavior**
  - In gas phase
    - Breakup by shear stress
    - Vaporization
  - On Surface
    - Breakup by impingement
    - Liquid film
      - Vaporization
      - deposit (under certain condition)
## Where to inject?

- **Side Injection**
  - Pros: Easy for packaging
  - Cons: Poor mixing, Wall wetting (deposit)

- **Center Injection**
  - Pros: Good mixing
  - Cons: Difficult for injector packaging

- **Elbow Injection**
  - Pros: Relative good mixing and packaging
  - Cons: Back pressure, Flow impact
Spray

• Vaporization Rate, Does It Matter?
  – High vaporization rate can help to have good mixing of urea/NH3, however, it is not critical if the droplet size is small and uniformly distributed.

Test Condition: 180°C, SV 100000/hr, inlet NO = 400ppm, alpha ratio = 0.5
Uniformity Index > 0.9 within 7 inches mixing length (high efficient mixer installed)
• Droplet Breakup
  – Impingement (on surface)
  – Shear stress (downstream mixer)

• Liquid Vaporization
  – Surface for heat transfer
    (between surface and liquid, and between surface and exhaust)
  – Temperature difference between exhaust and surface

• Mixing Enhancement
  – flow turns to turbulent after the mixer, which helps transport in cross stream direction

\[ T^* = \frac{T_w}{T_{sat}} \quad K = \frac{(\rho D_0^{1/4} a_d^{5/4})}{\sigma^{1/2} \mu_d^{1/4}} = C a_d^{5/4} L a^{3/4} \]

Kuhnke, PhD thesis, University Darmstadt 2004

Birkhold SAE paper 2006-01-0643
• Trade-off between mixing effect and pressure drop
• Trade-off between mixing effect and cost
• Future mixer may require different structure if new injector with finer droplet or NH3 gas dosing is applied (mixing enhancement will be more important than droplet breakup and liquid vaporization)
• Key Factors for Deposit Formation
  – Temperature
  – Exhaust gas flow rate
  – Urea dosing rate

• Correlation for Deposit Formation
  – Root cause is surface temperature
  – Based on heat transfer balance

\[ m_{\text{urea}} \Delta h_{fg} = hA(T^g - T^s) \]

\[ \Rightarrow T^s = T^g - \frac{m_{\text{urea}} \Delta h_{fg}}{hA} \begin{cases} T^s > T^* \text{ no deposit} \\ T^s < T^* \text{ deposit formed} \end{cases} \]

\( h \) : convective heat transfer coefficient

( a function of flow rate for turbulent flow)

\( m_{\text{urea}} \) : surface vaporization rate of urea (≤ injection rate)
Conditions for Mixing Measurement

• Test Setup
  – NOx and NH3 are measured at SCR outlet
  – NH3 Distribution at SCR inlet is estimated with outlet information and mass balance
    \[ \text{NH3}_{\text{inlet}} = \text{NH3}_{\text{outlet}} + (\text{NOx}_{\text{inlet}} - \text{NOx}_{\text{outlet}}) \]

• Suitable Test Condition
  – Temperature < 400°C to minimize NH3 oxidation reaction
  – Temperature higher than T(?) to avoid deposit formation and NH3 storage upstream SCR(*)
  – NH3 to NOx ratio < 1 to eliminate NH3 storage effect
  – NO2 concentration as low as possible (slow SCR reaction has non 1:1 reaction ratio for NH3 and NO2)
  – Sampling gas flow rate should match the local exhaust flow rate.
  – Sampling pipe location should be close the catalyst brick.

Is there a more accurate and directly way to measure urea/NH3 distribution in front of SCR?
CFD vs. Test

- **CFD model**
  - Simplified spray model
  - Preciously defined initial and boundary condition
  - Instant picture of distribution
  - Clear reactions
  - True steady-state

- **Test Setup**
  - Complicated spray
  - Ambiguous initial and boundary condition
  - Time averaged measurement
  - Complicated reactions
  - State with small variations

- The difference in nature makes it difficult to match CFD result with test result, however, correct CFD model should predict similar distribution pattern as test result.
- Because of the local and time averaging effect, test seems to show higher uniformity than CFD prediction.
- Low temperature test (< 300°C) always has urea/NH3 mass balance error (calculated urea/NH3 at SCR inlet is less (10%+) than actually dosed urea (maybe due to NH3 adsorption?), which leads the question how should we distribute the unaccounted NH3 to the measured distribution to get the accurate map of inlet.
Summary

• Urea mixing is critical to meet more stringent emission standard
• Effective urea mixing design should be based on the nature of the selected injector (spray)
• It is challenge to measure the real distribution of urea/NH3
• People should be aware of the difference of measured and simulated mixing result.