Numerical and Experimental Investigation of Mixing Quality for Pulsed Mixing Flows with Application to Diesel Aftertreatment

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Ford Motor Company

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Ford Motor Company

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Outline

- **Literature Review and Motivation**

  Aftertreatment Mixing, LNT, RPR Mixing Requirement

- Preliminary Mixer Design and Analysis
- Experimental Study
- Test results and Discussion
- Numerical Analysis
- Conclusion and Future Work

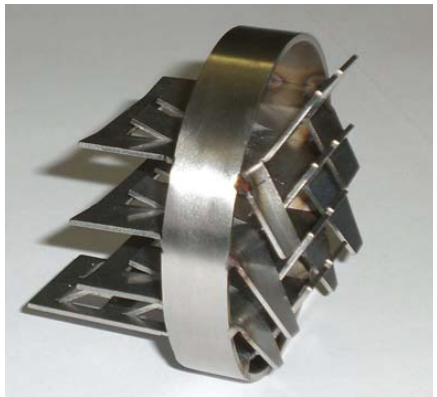
Literature

ixing uniformity is important for many Diesel Aftertreatment Methods [1-4]

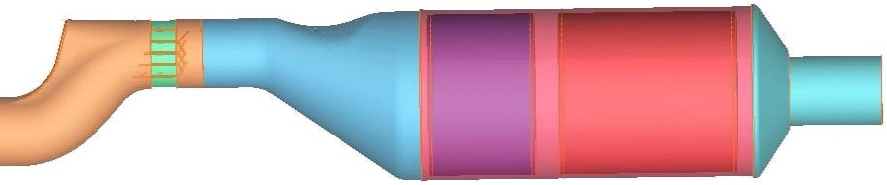
ifferent Designs have been used, both experimental and numerical (CFD) studies [2,5,6]

rea SCR

Cone Mixer [2]



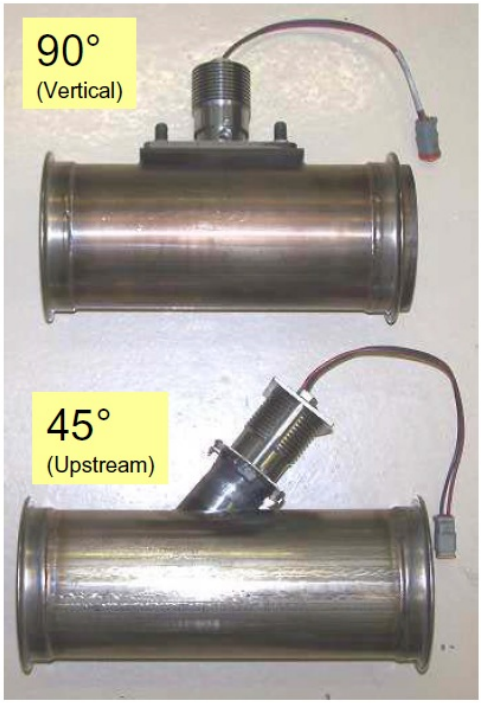
Stage Mixer [2]



Mixer Tube Geometry [3]

Zheng et al.

- DPF Regenerations



Injection Orientation [4]

Flapper [4]

Twister [4]

Gardner et

Motivation

eater mixing challenge occurs with a process referred to as:

ly Pulsed Reductants (RPR)

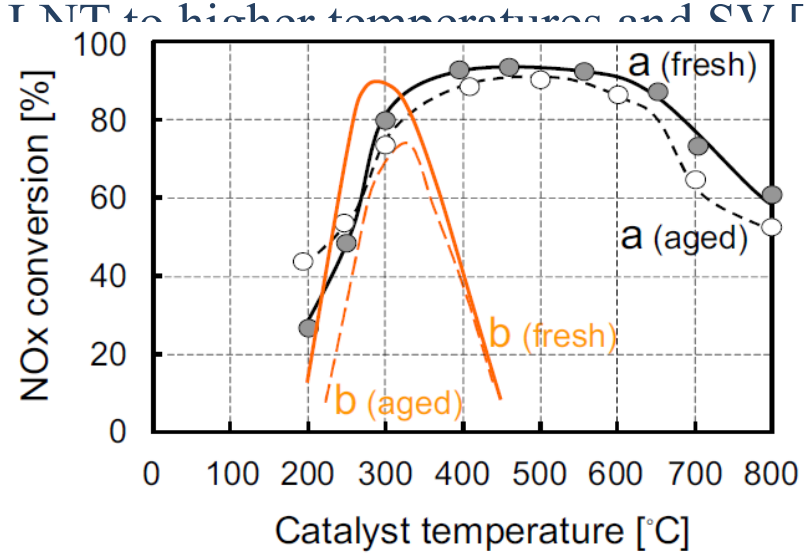
Reductants injected as high frequency ($\sim 1Hz$) pulses ahead of a LNT

oved NOx conversion - Expanded the operating window of LNT to higher temperatures and SV [7-9

enge:

rm radial mixing, *and well separated rectangular*

s in the axial direction (i.e. ***minimal axial mixing****)*



NOx conversion vs Temperature [9]

Bisaiji et al. Toyo

Literature review and Motivation

➢**Preliminary Mixer Design and Analysis**

Mixer Design and Simulation, Uniformity Index for RPR

Experimental Study

Test results and Discussion

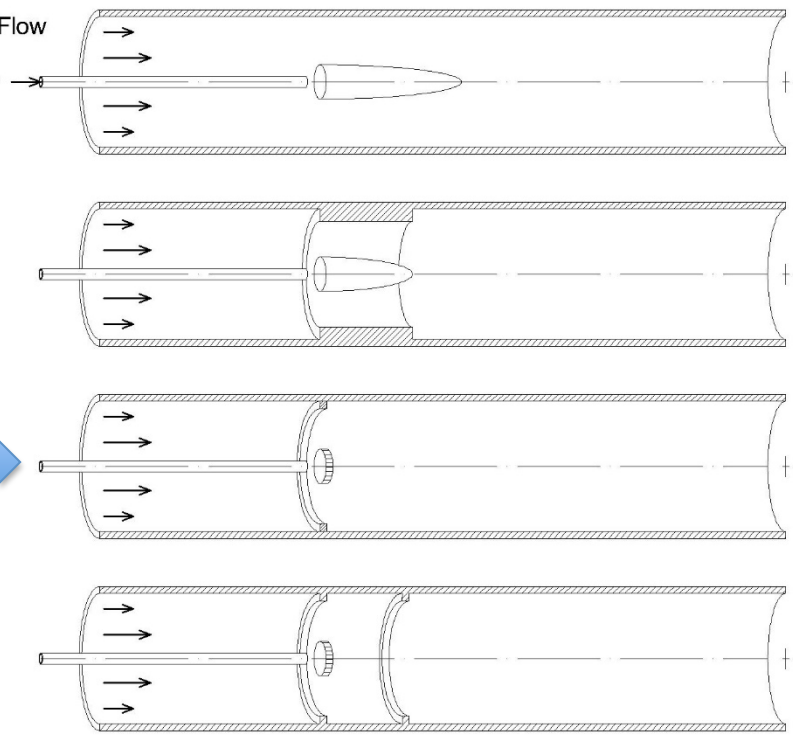
Numerical Analysis

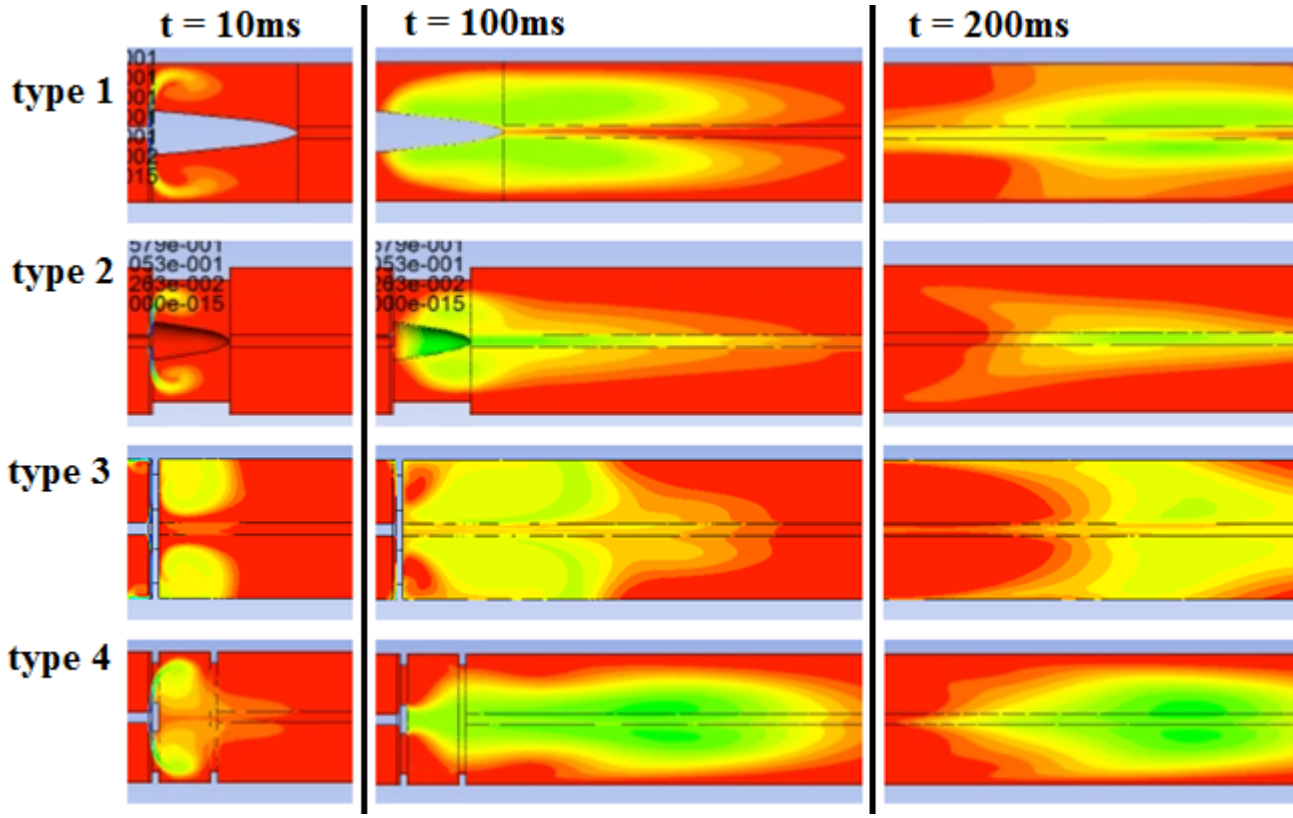
Conclusion and Future Work

Preliminary Mixer Design

design based on radial reductant jet and generation of **Counter Rotating Vortices** (CRV) to form plug flow

ent designs were investigated using 3D unsteady two phase flow simulation of mixing





Figures of merit for mixing

hiometric Area Index (SAI)

$$I = Surface\ area\ within\ acceptable\ mole\ fraction / Total\ face\ area\ *100$$

Usually, used in SCR [10]

ng quality

$$(1-\sigma/T\ )*100$$

Used in EGR [11]

where: σ – Standard deviation of temperature at a ection

T - Mass weighted average temperature at a cross section

Uniformity index (UI)

lly defined over the inlet face of the catalyst [12]

$$(\emptyset)=1-\sum\uparrow\ |\emptyset\downarrow f-\emptyset\ |A\downarrow f\ /2\emptyset\ \sum\uparrow A\downarrow f$$

e, axial distribution is also important

PR, we define: $\emptyset=1/\lambda$ $\quad UI\ (\emptyset)=1-\int\uparrow |\emptyset-\emptyset\ |$

Literature review and Motivation

Preliminary Mixer Design and Analysis

➢ **Experimental Study**

- **Method, Uniformity Index Measurement**
- Test Condition
- Parameters and Measurement Procedure

Test results and Discussion

Numerical Analysis

Conclusion and Future Work

Experimental Method

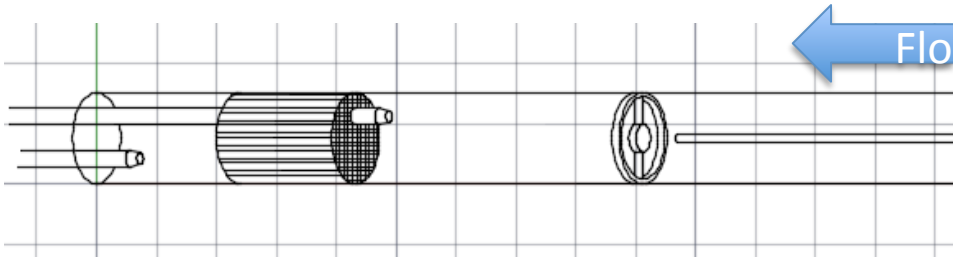
ing a DOC, two Fast Flame Ionization Detector (f FID) channels

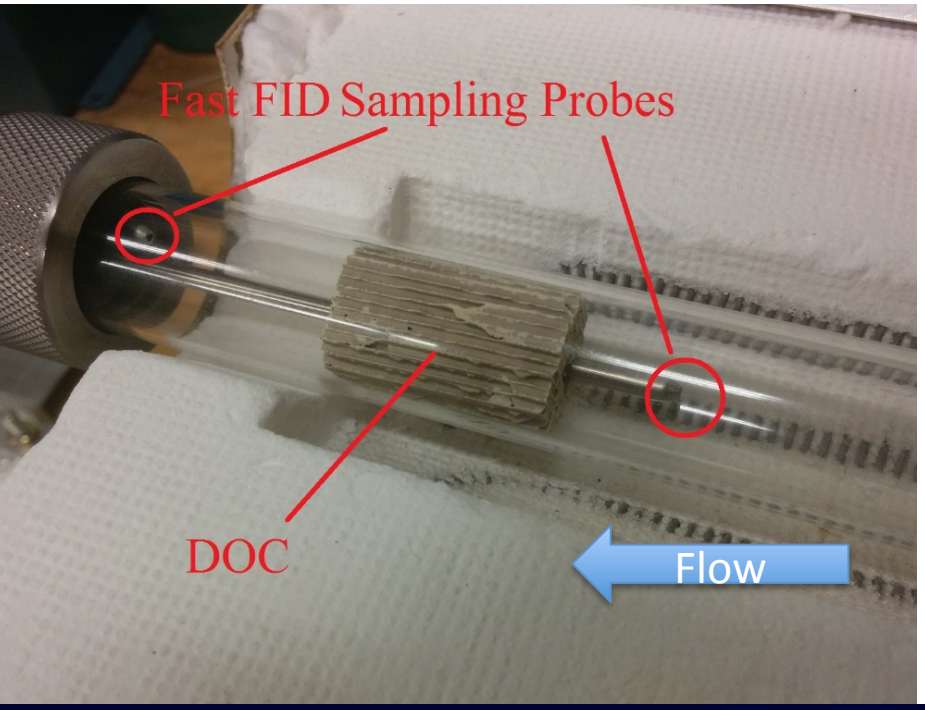
am and downstream of DOC.

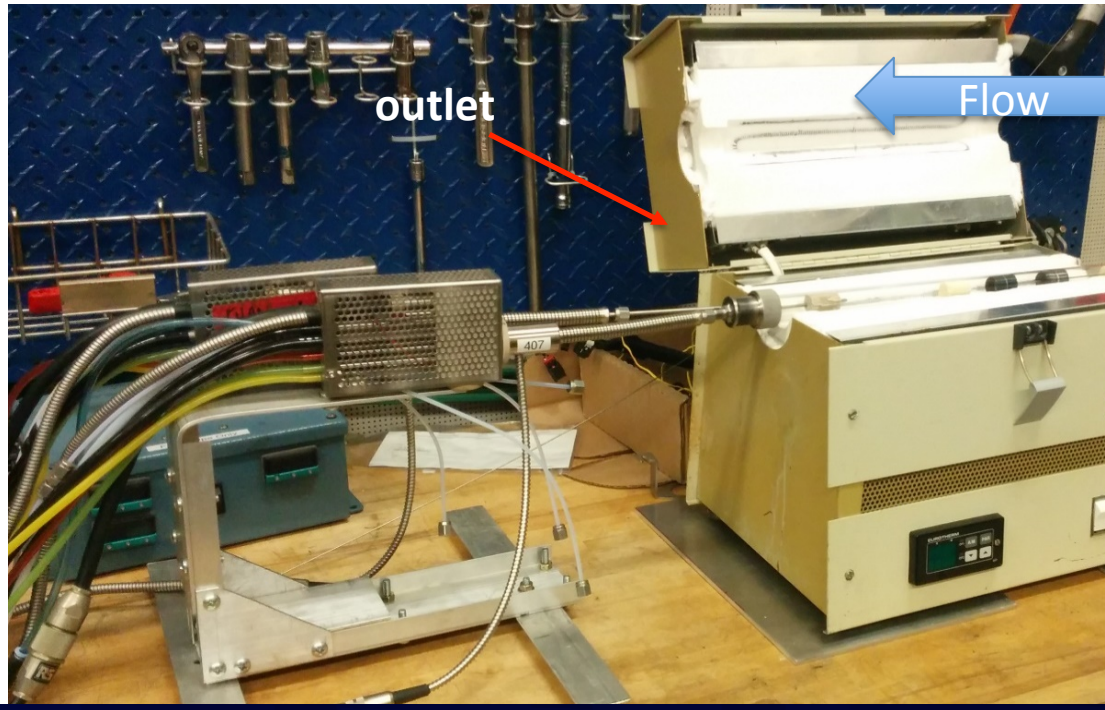
C concentrations were measured with 200Hz frequency.

ing the axial distribution of HC (upstream probe)

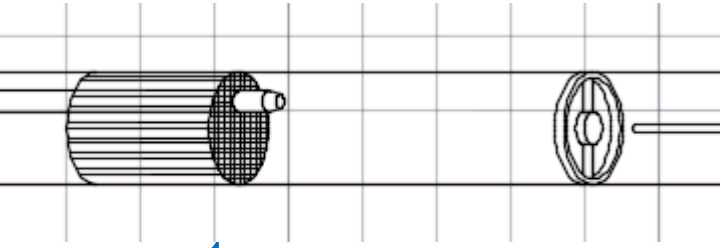
C break through (downstream probe) pulse characteristics defined.







How to relate measurements to UI



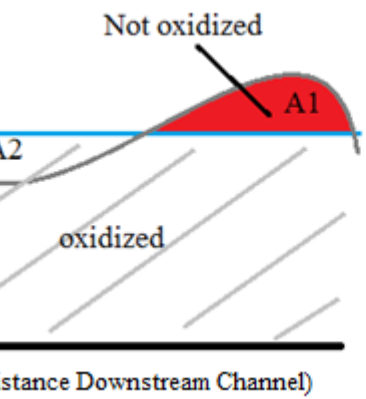
urements

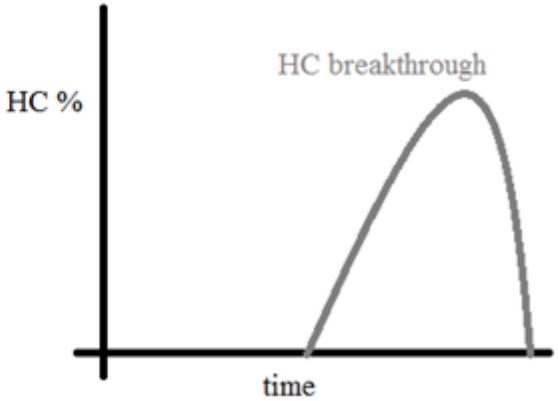
centration of HC downstream of DOC
centration of HC upstream of DOC

eakthrough:

vithout OSC:

downstream f-FID probe



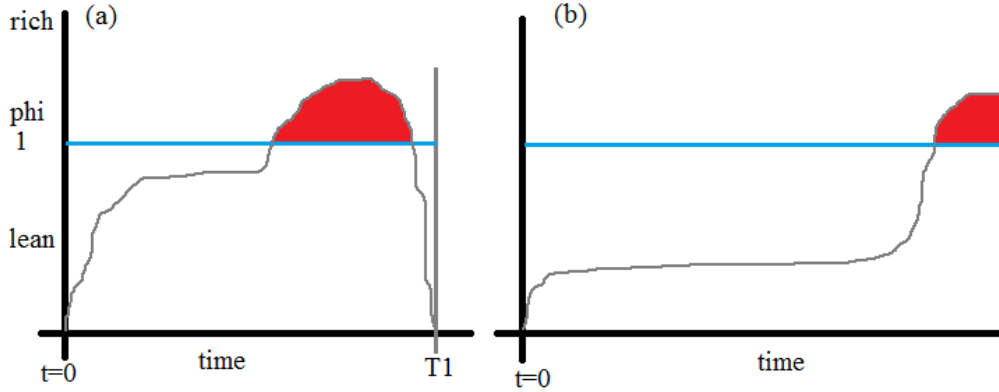


wn, But the lean portion (A2) is still unknown !

The lean portion (A2)

Equal amount of injected HC and HC breakthrough:

upstream f FID probe



Mixing quality of (a) is better

$t\downarrow 1$, $t\downarrow 2 \neq t\downarrow inj$ (due to axial mixing) data from **upstream probe.**

$$UI\ (\emptyset) = 1 - (\int\uparrow\blacksquare(\varphi - \varphi)dv)\downarrow lean + (\int\uparrow\blacksquare(\varphi - \varphi)dv)\downarrow rich\ /2\varphi V$$

Literature review and Motivation

Preliminary Mixer Design and Analysis

➢ Experimental Study

- Method, Uniformity Index Measurement
- Test Condition

1-DOC Temperature,2-Oxygen Concentration,3-Probe Location,4-Space Velocit

- Parameters and Measurement Procedure

Test Results and Discussion

Numerical Analysis

Conclusion and Future Work

Experimental Condition

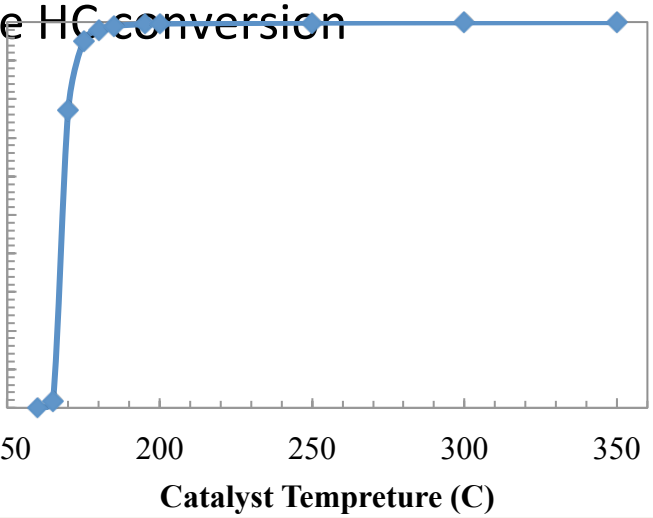
C Temperature

OC light-off temperature: 175°C

ixing tests were performed at

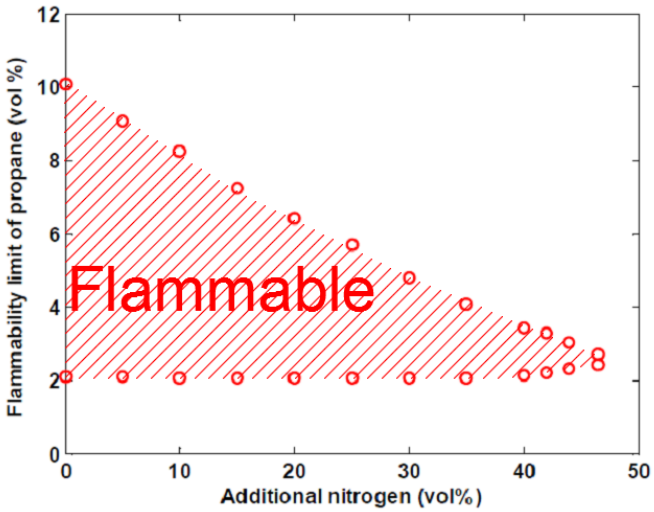
00°C to

e HC conversion



2- Oxygen Concentration (Flammability Limits)

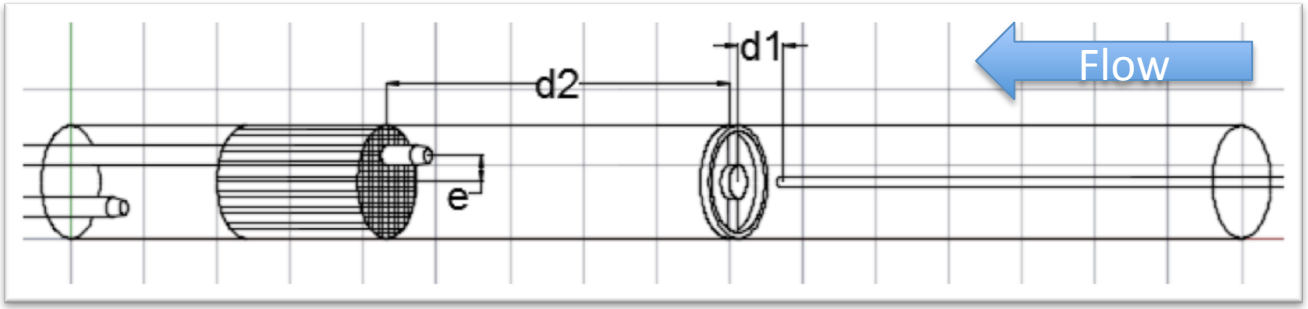
- Flammability limits not available (i.e. diluted and elevated
- Steady PSR simulation was performed in CHEMKIN
- Deflagration flame was initiated from glowing DOC
- Oxygen concentration was reduced from 6.8% to 4%



Zhao, F

Experimental Condition

ream probe location: The effect of eccentricity (e) of upstream Fast FID probe was investigated

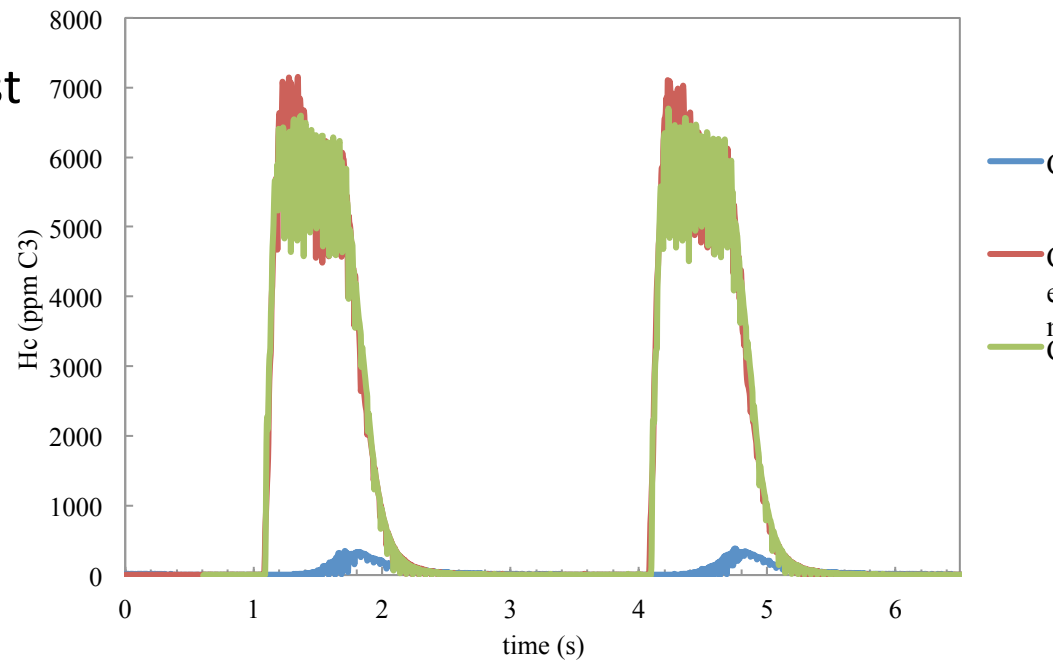


entricity (e) was limited to $4.5\ mm$ by catalyst re.

ference in measured uniformity index was very

fference in UI was 1.8%).

entricity of 4.5mm was chosen for experiments.

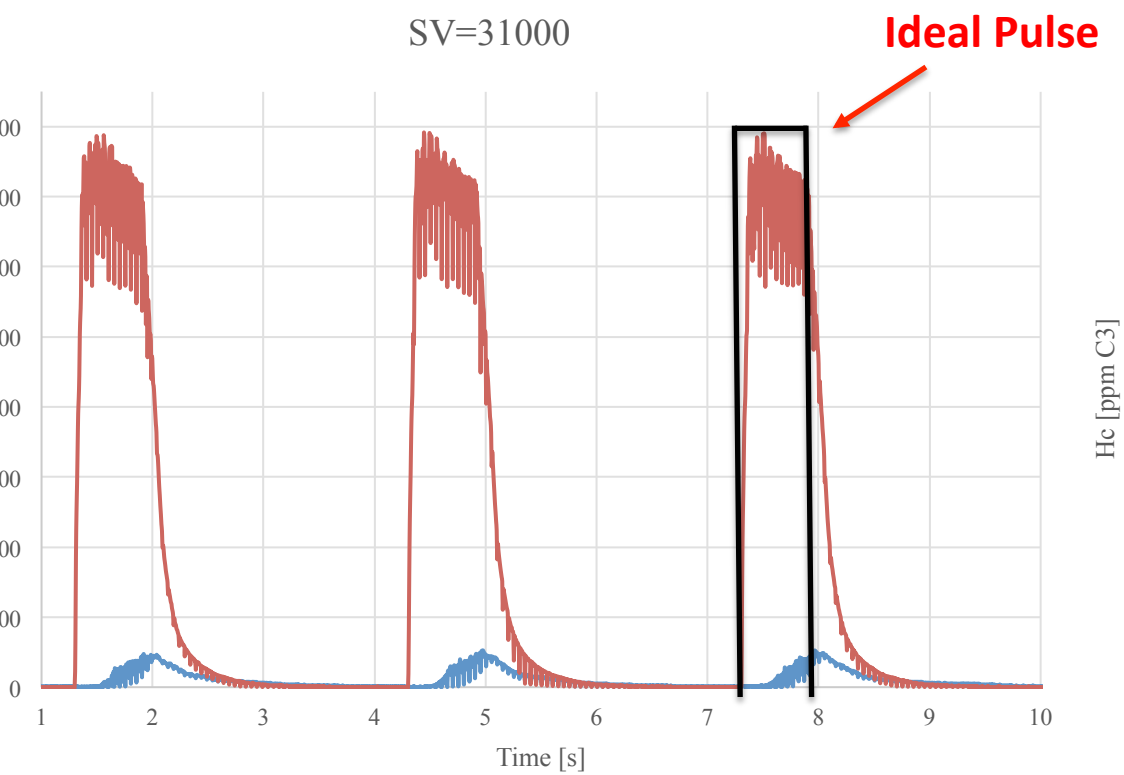


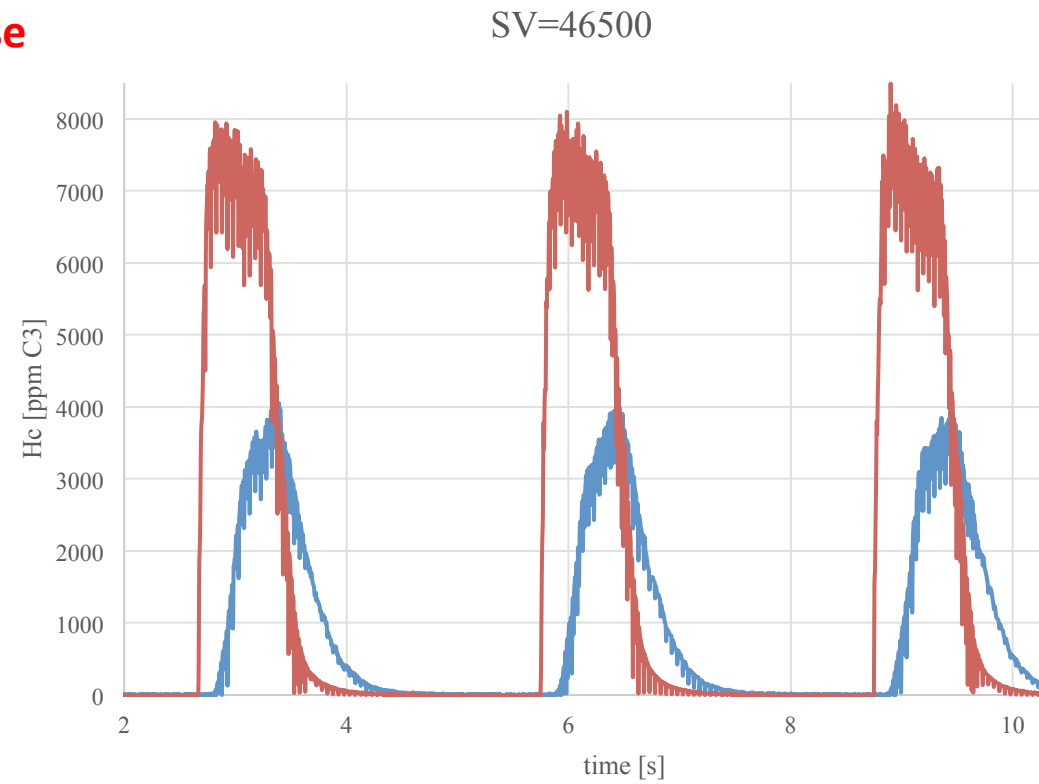
Experimental Condition

ce Velocity

breakthrough was observed to be dependent on SV

periments done with constant $SV=310001/h$ using DOC samples with different volume (constar





Literature review and Motivation

Preliminary Mixer Design and Analysis

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Experimental Parameters

Parameters for Mixing:

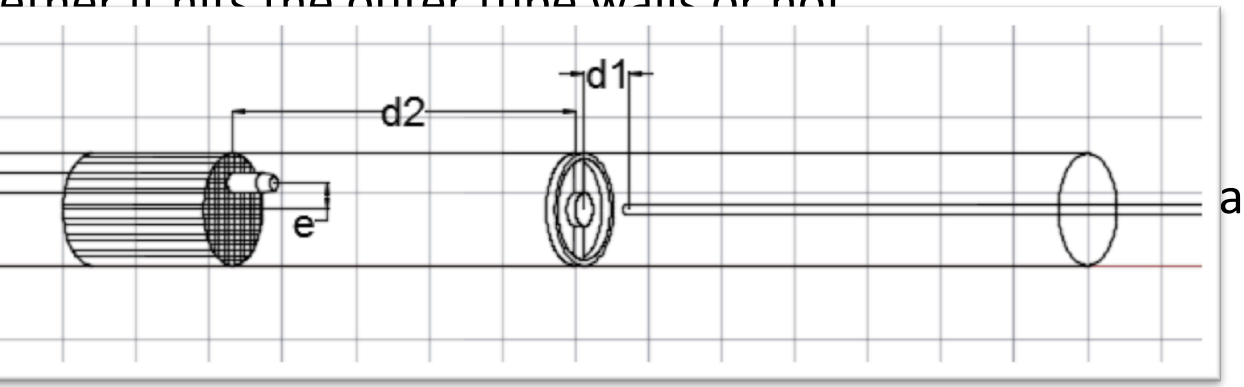
eynolds Number: Determines the turbulence intensity of the jet flow. $Re_{Jet} = \rho_{Jet}$

$et\ D_{Injector} / \mu_{Jet}$

nentum ratio: Determines the length of jet penetration in the main flow, $mr = \rho_{Jet}\ V_{Je}$

$ain\ V_{main}$

ether it hits the outer tube walls or not



ata

Jet Reynolds number	Momentum Ratio, by d1	Mixer to D distance d2
9000	6.3	20
18000	12.6	40
27000	25.3	60

Measurement Procedure

ree level full factorial experiments

ncentrations of HC upstream and downstream of DOC were recorded with

$0Hz$ sampling rate

each test point 5 consecutive pulses were measured

easurements were averaged and uniformity index was calculated using the

owing formula:

$$\emptyset)=1-\int\uparrow\blacksquare|\varphi-\varphi|dv/2\varphi\ V=1-(\int\uparrow\blacksquare(\varphi-\varphi)dv)\downarrow lean$$

$$\blacksquare(\varphi-\varphi)dv)\downarrow rich\ /2\varphi V$$

ynomial response surface was fitted to data, to investigate the optimum mi

ndition

Literature review and Motivation

Preliminary Mixer Design and Analysis

Experimental Study

➢ **Test Results and Discussion**

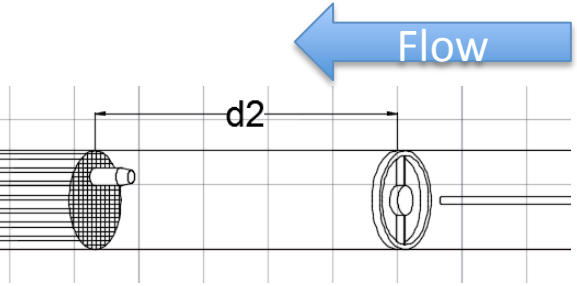
Numerical Analysis

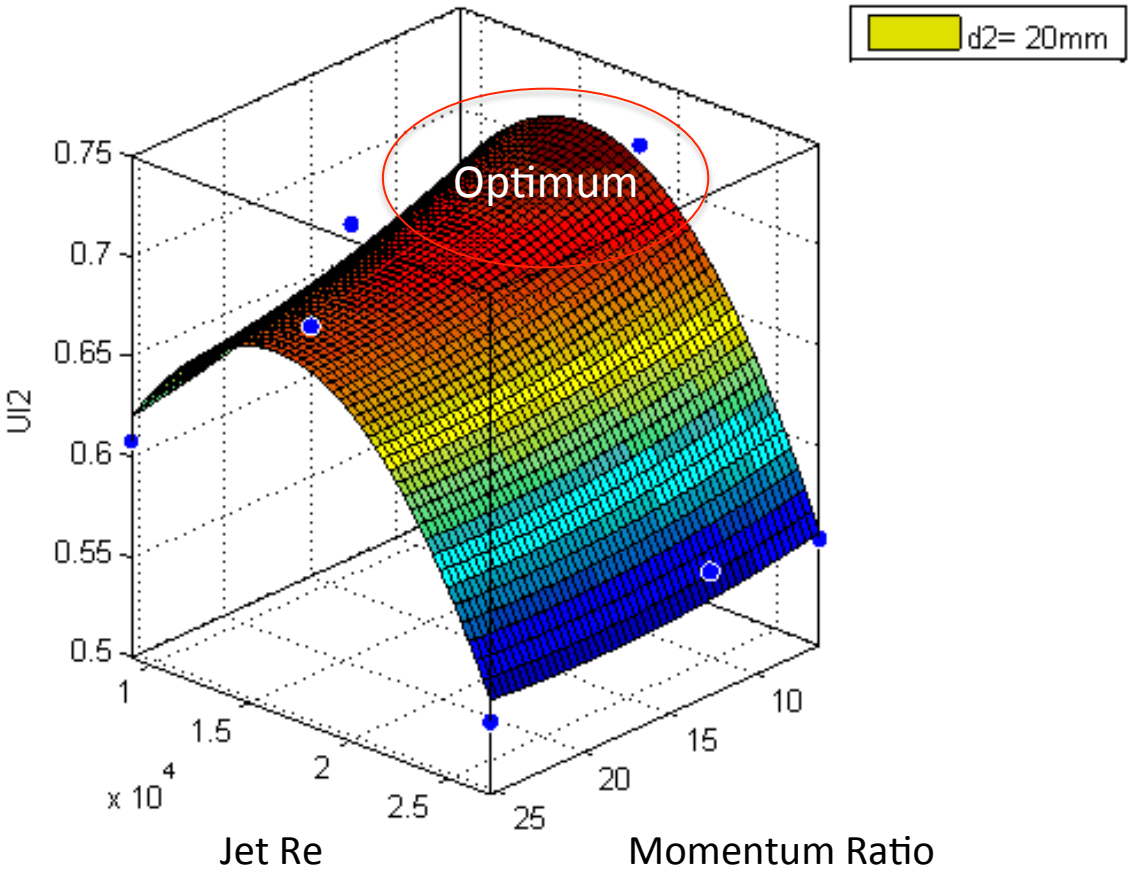
Conclusion and Future Work

Experimental Results

sponse Surface for $d_2 = 20mm$

aximum UI was found on rface; however, the region rp and the UI is sensitive Re number and to a lesser momentum ratio.

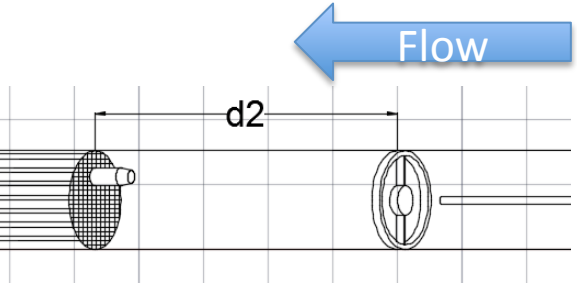


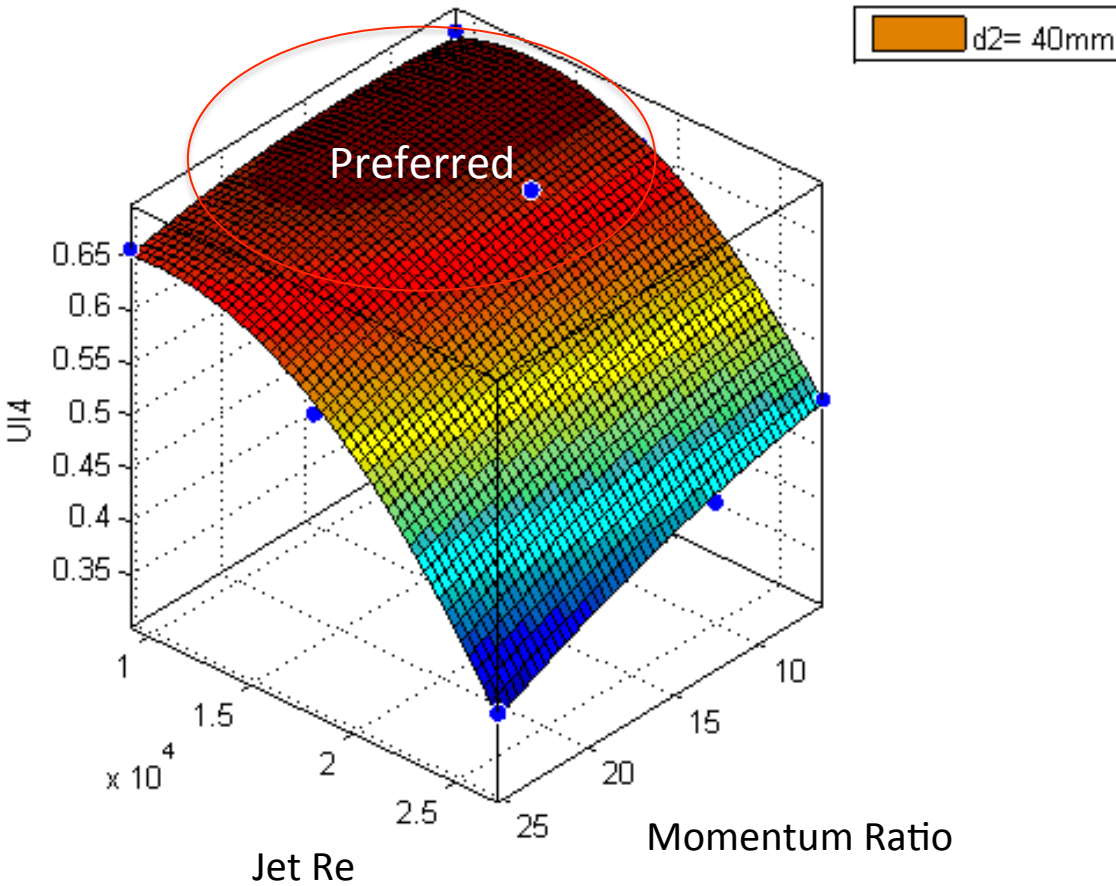


Experimental Results

sponse Surface for ***d↓2 =40mm***

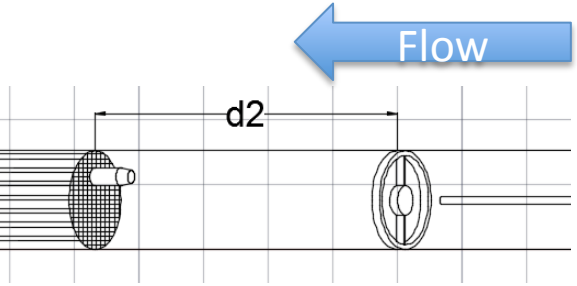
ear maximum efficiency, and
egion of surface, gives robust
g over a wide of operating
tion.

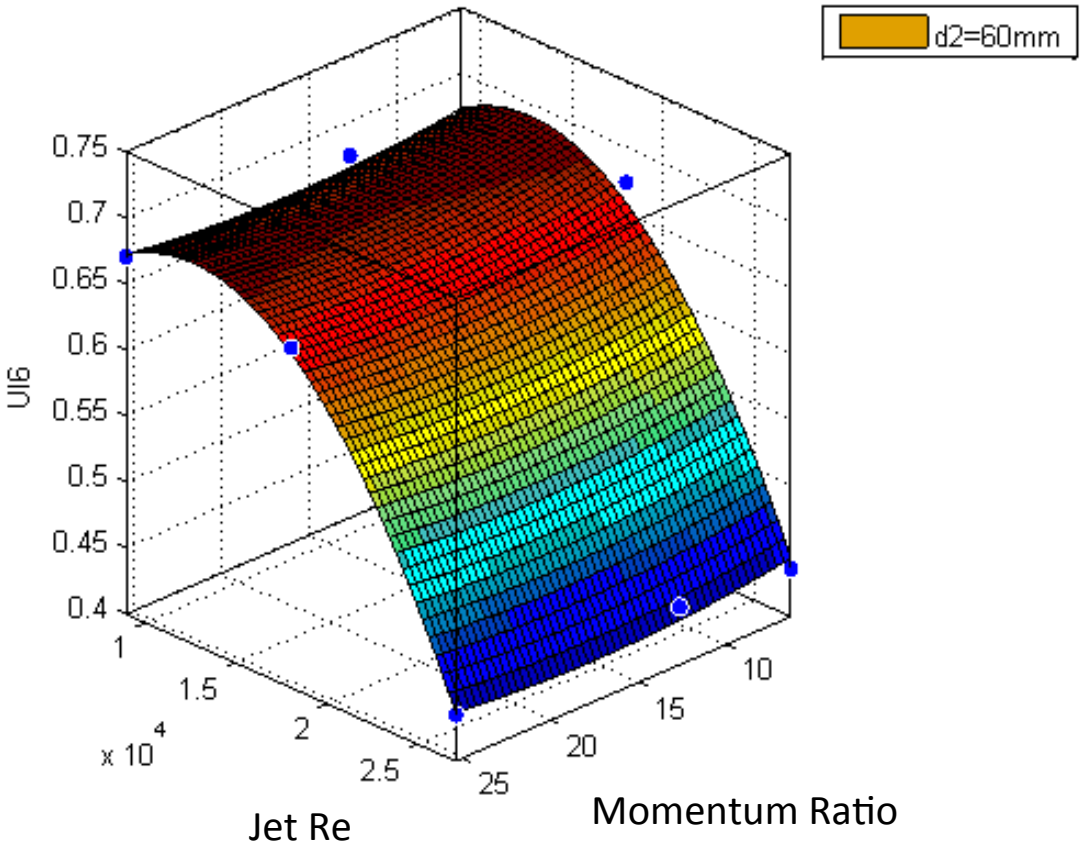




Experimental Results

sponse Surface for $d_2 = 60mm$



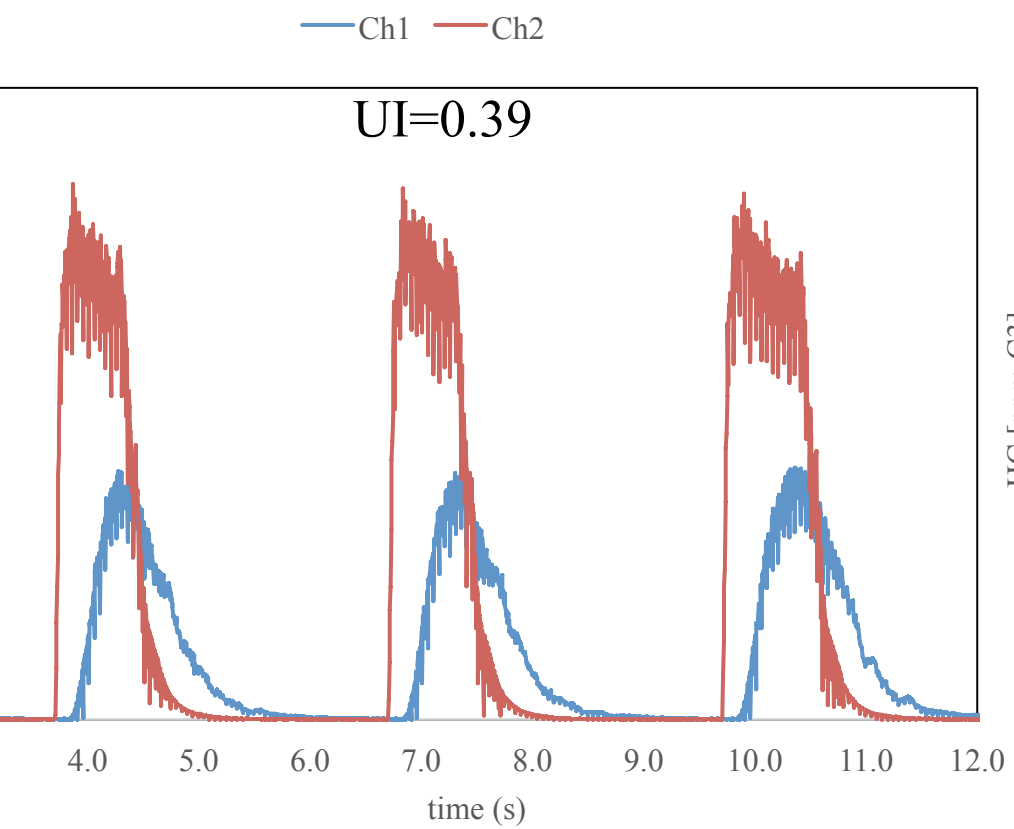


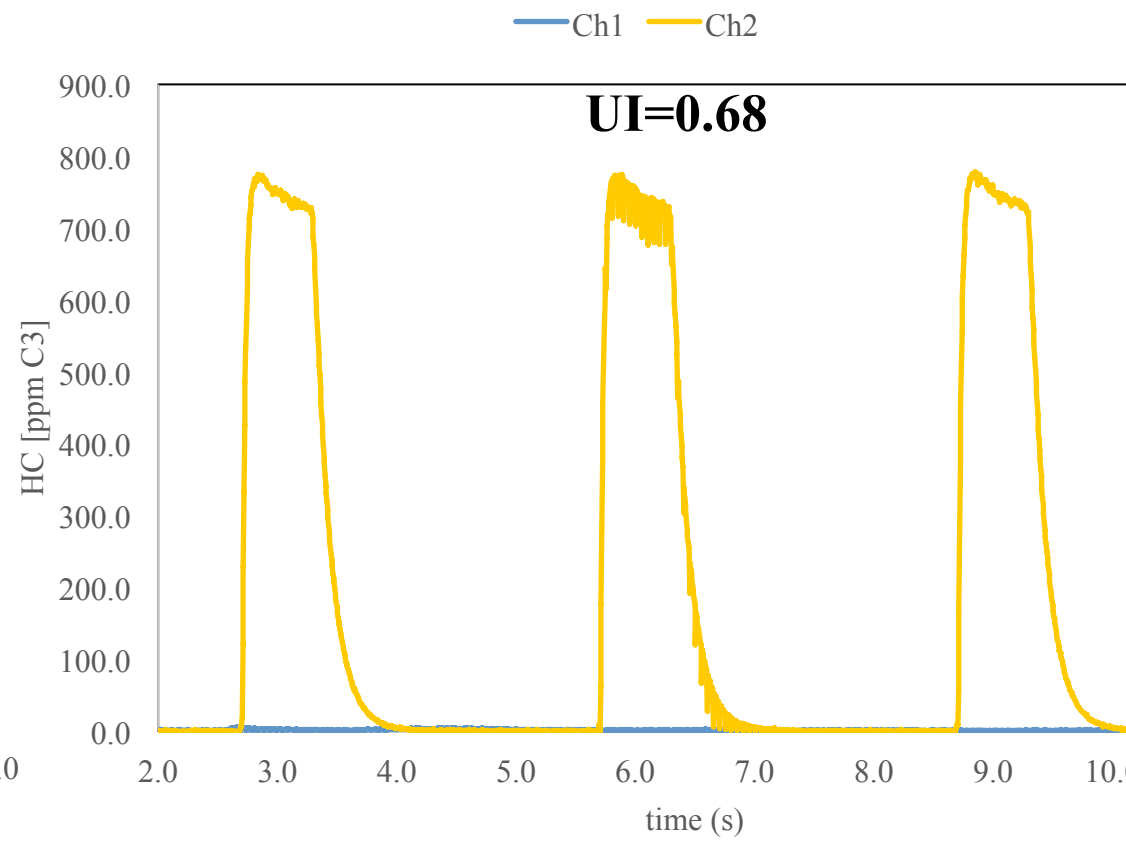
Experimental Results

d Mixing Condition

rectangular pulses with near zero HC breakthrough

les a broad range of operating condition: Low to moderate jet Re number/momentum ratio/d2





Literature review and Motivation

Preliminary Mixer Design and Analysis

Experimental Study

Test results and Discussion

➢ **Numerical Analysis**

- Models and Results

Conclusion and Future Work

rical Analysis Conducted at Experimental Condition

ence model and turbulent transport parameters have a significant effect on the spatia

ral distribution of species in the flow field.

NS (Reynolds Ave. N.S.) models $k-\varepsilon$ RNG [14] and

rbulent Schmidt number Sc_t [13] $Sc_t = \nu_t /$

general applications $Sc_t = 0.7 - 0.9$

ross flow jets $Sc_t = 0.2 - 1.5$ lower range is recommended

Numerical Results

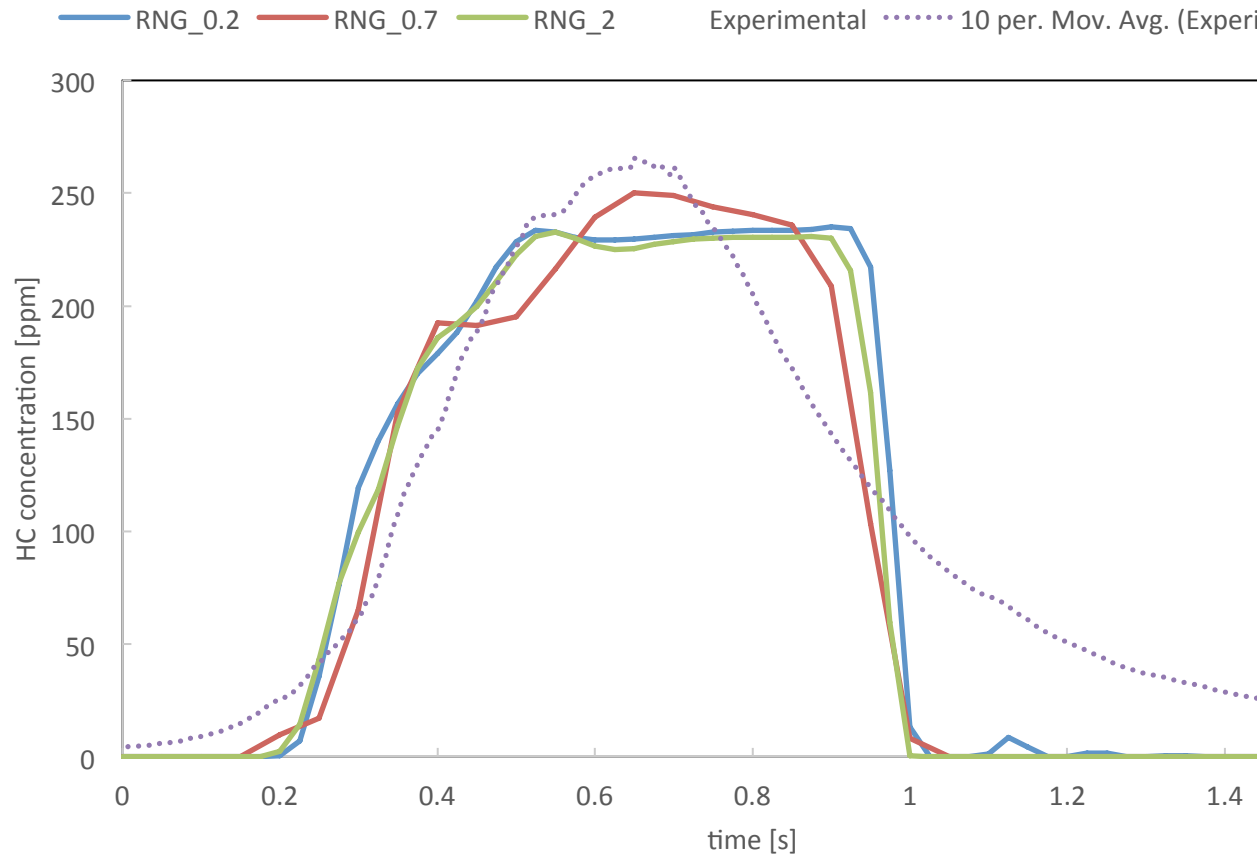
$-\varepsilon$ *RNG results for* $Sc_t = 0.2,\ 0.7,\ 2.0$

RNG model **underestimated**

due to calculation of only one

nt of Reynolds stress tensor.

hours]



Numerical Results

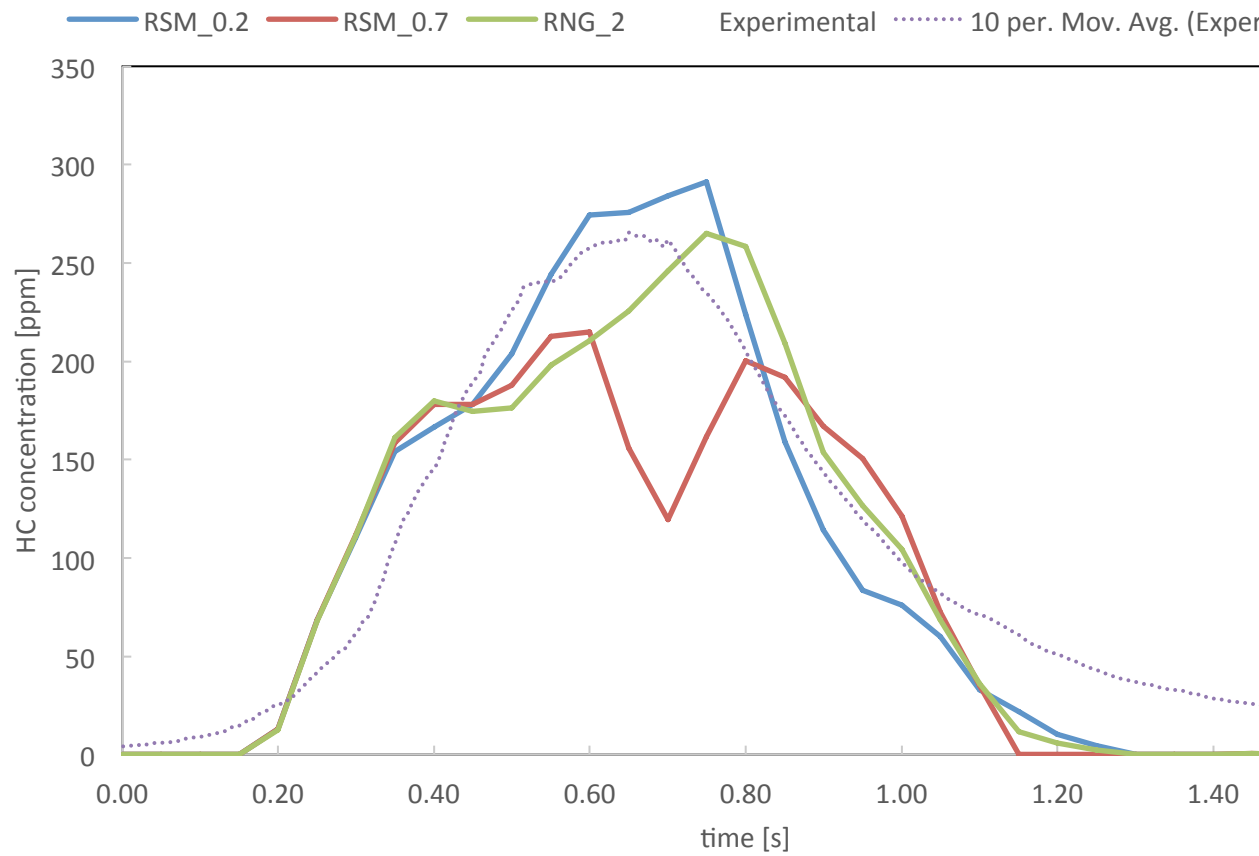
SM results for Sc↓t =0.2 , 0.7 , 2.0

e tail part of diagram, mixing is still

stimated, since turbulence is not

d in RANS models.

hours]



Conclusion and Future Work

r rectangular pulses with $UI \approx 0.7$ over a broad range of operating condition using new mixer d

to Moderate Re number, momentum ratio and mixer distance to catalyst gives the best Uniformit

x.

$Omega-RSM$ model with low $Sc \downarrow t$ good agreement with reasonable computation c

of Mixing on NOx Conversion

ct of Radial and axial mixing uniformity is being investigated separately on the NOx conversion of t

conventional LNT.

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Thanks for your attention
Questions?