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Combustion Modeling of Dual-fuel Engines

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Combustion Modeling of Dual-fuel Natural Gas Diesel Engines

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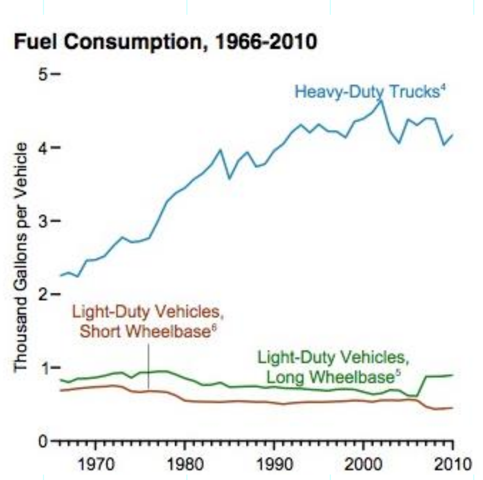
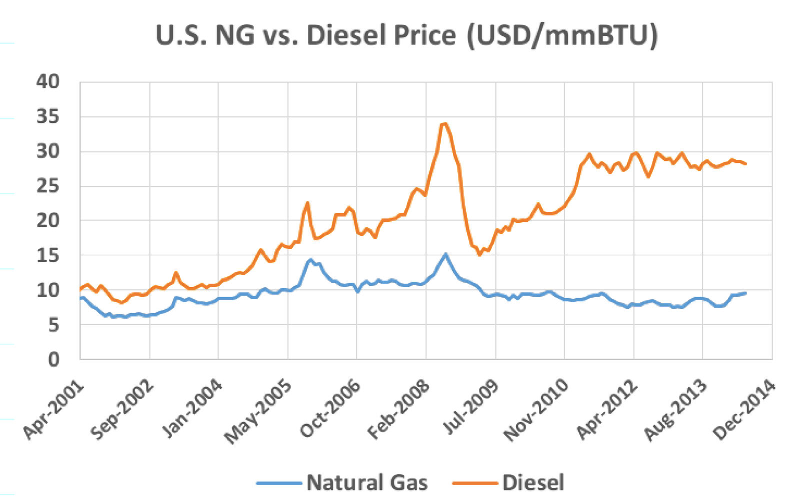
Motivation for Natural Gas as an Alternative Fuel

- Abundant supply & Lower cost
- Low carbon emissions potential
- NG for Heavy-Duty Trucks is the fastest Way to Increase NG Utilization





Properties of Natural Gas

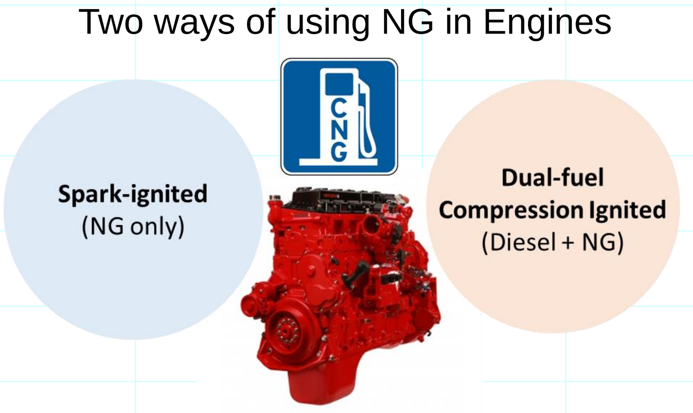
Pros
- High RON: potential for high compression ratio
- Renewable
- Low carbon emissions

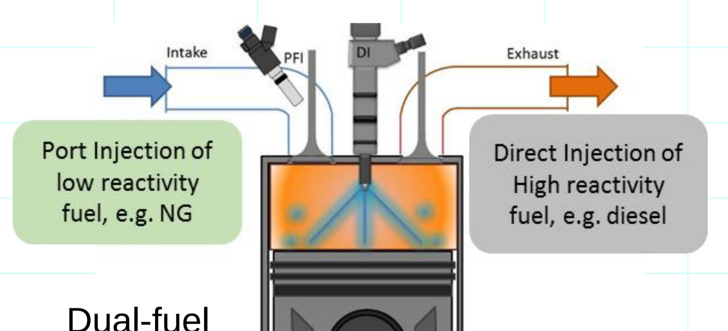
Cons
- Gaseous state: negative effect on volumetric efficiency
- Challenge with storage
- Low energy density

Fuel	Methane	Gasoline	Light diesel
Chemical Formula	CH_4	$C_nH_{1.87n}$	$C_nH_{1.87n}$
Lower Heating Value (MJ/kg)	50.0	44.0	42.5
Density (kg/m³)	0.72	750	850
Octane Rating (RON)	120	92-98	-

Dual-fuel Engines

Two ways of using NG in Engines



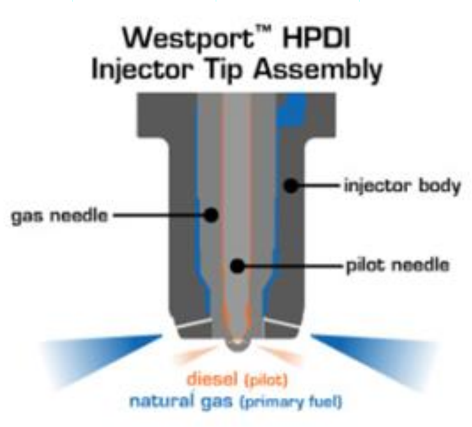


Dual-fuel engine illustration

Dual-fuel engines are directly converted from diesel engines

- Pilot injected diesel fuel to ignite NG-air charge
- Dual-fuel engines overcome major drawbacks presented with SI NG engines.
  - High CR of diesel is retained, which improves thermal efficiency
  - Mode switching between diesel only and dual-fuel can be realized real-time, which eliminates driver's range anxiety
- Additional benefits
  - Improved thermal efficiency: Unthrottled operation, Reduced pumping loss, Lean combustion
  - Improved emission performance: Less NOx and soot emissions compared to diesel only engines

Natural gas injector

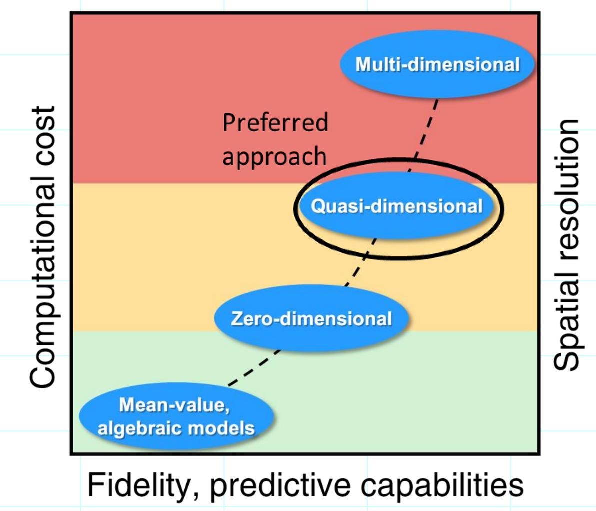


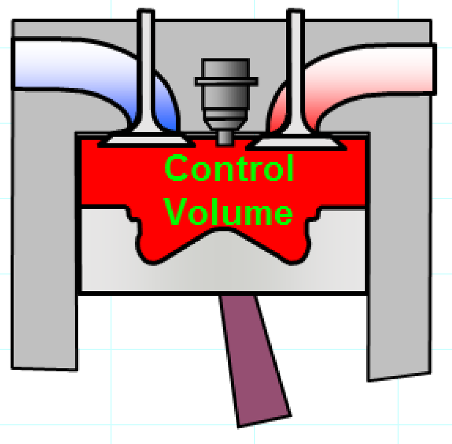
- Two ways of natural-gas injection: PFI (left) and HPDI(right)

Dual-fuel is a promising concept in realizing NG usage in transportation. However, it requires research and development to become ready for large scale market introduction.

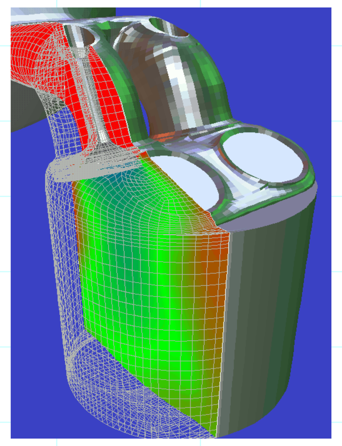
Motivation of Modeling Work

- Provide better understanding of dual-fuel combustion nature
- Enables investigation of a broader operating space
- Provide values of parameters that cannot be easily measured
- Enable efficient optimization of the engine fuel-injection calibration





0-D



3-D

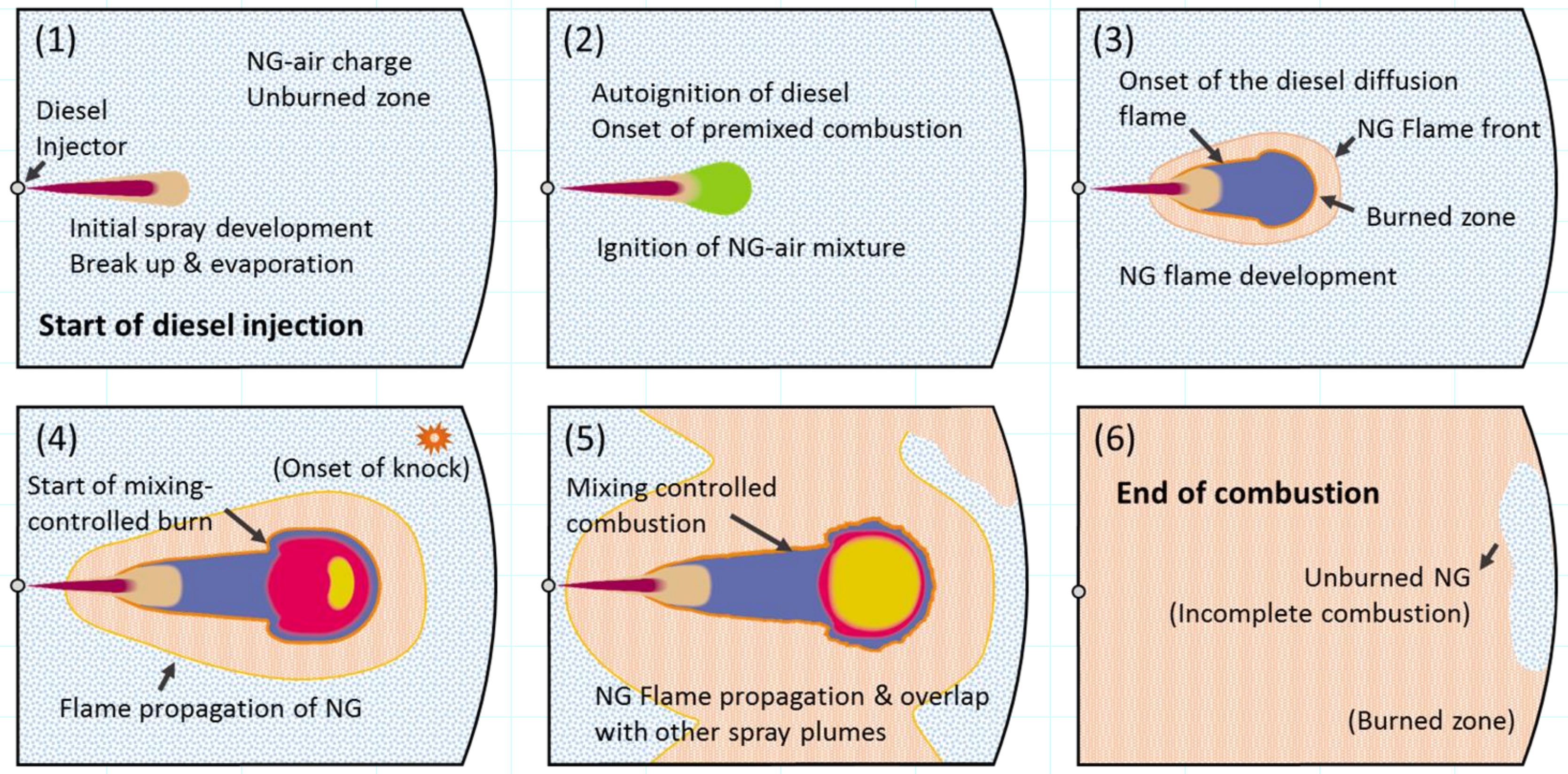
Selection of Modeling Approach Based on Simulation Goal:
- Reasonable level of predictiveness with light calculation load
- For application of system level analysis

Objective and Challenges

Objective:
- Develop a predictive quasi-D combustion model for dual-fuel combustion

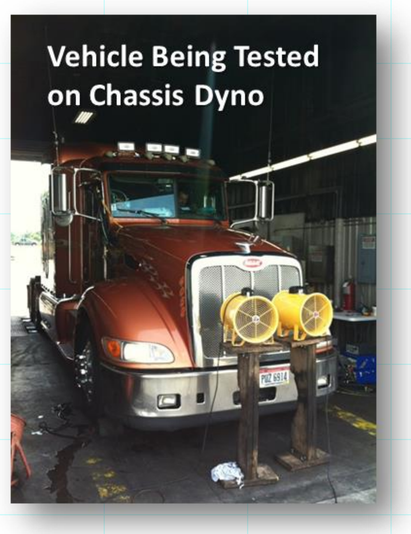
Challenges:
- Capture three types of combustion: Premixed & mixing controlled burning of diesel, NG turbulent flame propagation and auto-ignition (Knock)
- Model flame propagation of NG and air mixture from multiple ignition sites (simultaneous with diesel burning)
- Track evolution of temperature in the unburned zone, detect knock
- Model kinetics controlled combustion, if conditions enable HCCI type process. This leads to investigation of RCCI.

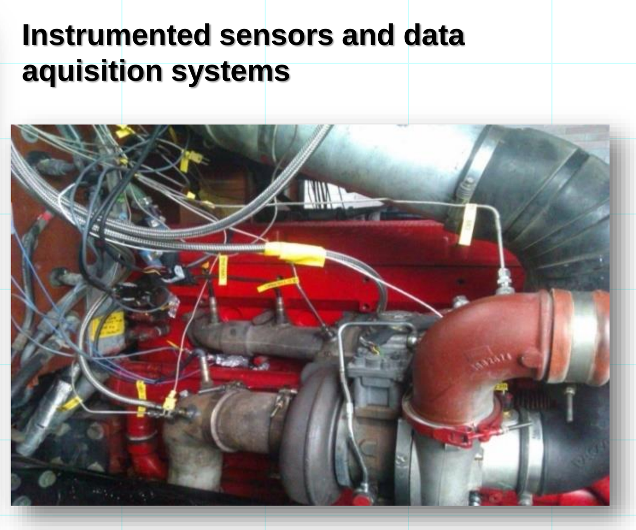
Phenomenological explanation of dual-fuel combustion:

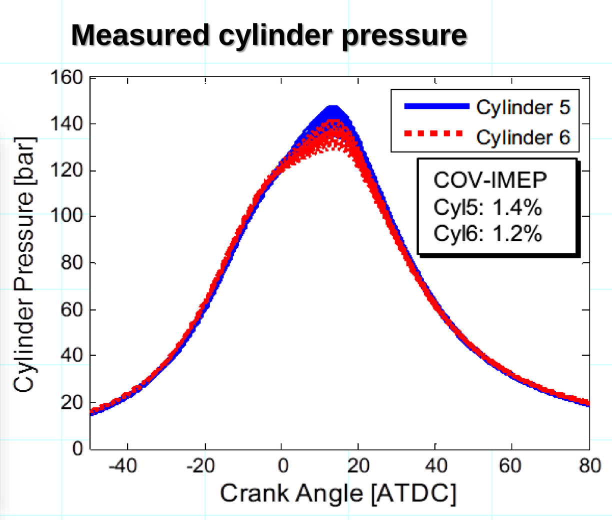


Experiment Insights

Instrumented test on a dual-fuel HD engine
- Experimental results provide insights and enable validation of simulation work

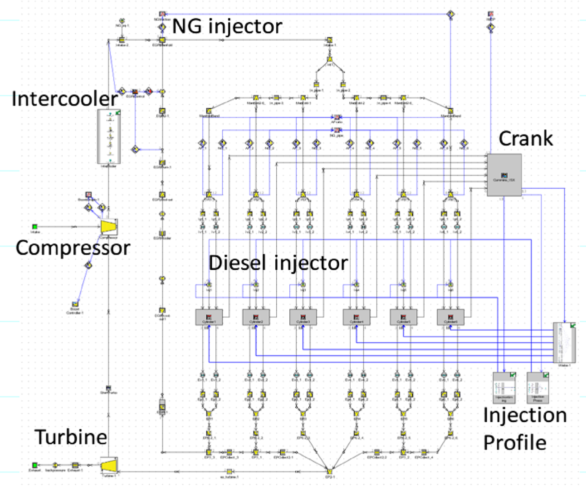


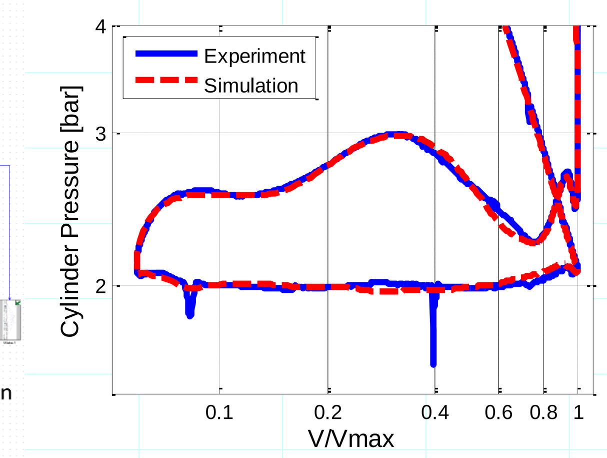


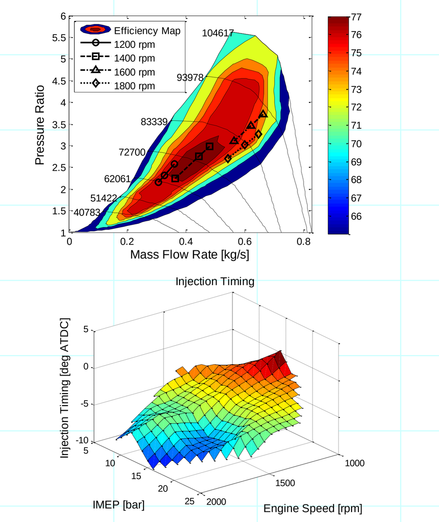


1-D Engine Modeling & Validation

- A comprehensive 1-D simulation of the Cummins ISX 550 dual-fuel natural gas diesel engine is developed in GT-Power
- Intake and exhaust geometry have been carefully measured and used to configure the model



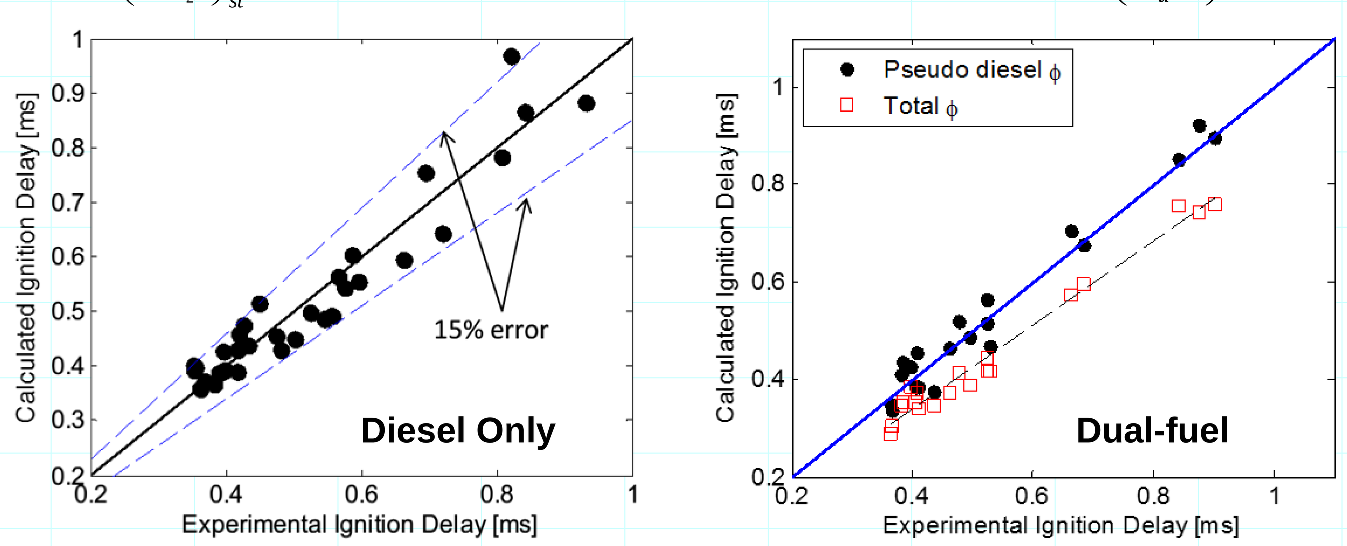




Predicting Ignition Delay

- Pseudo-diesel equivalence ratio is proposed for dual-fuel ID correlation
- Modified ignition delay correlation is validated with dual-fuel combustion

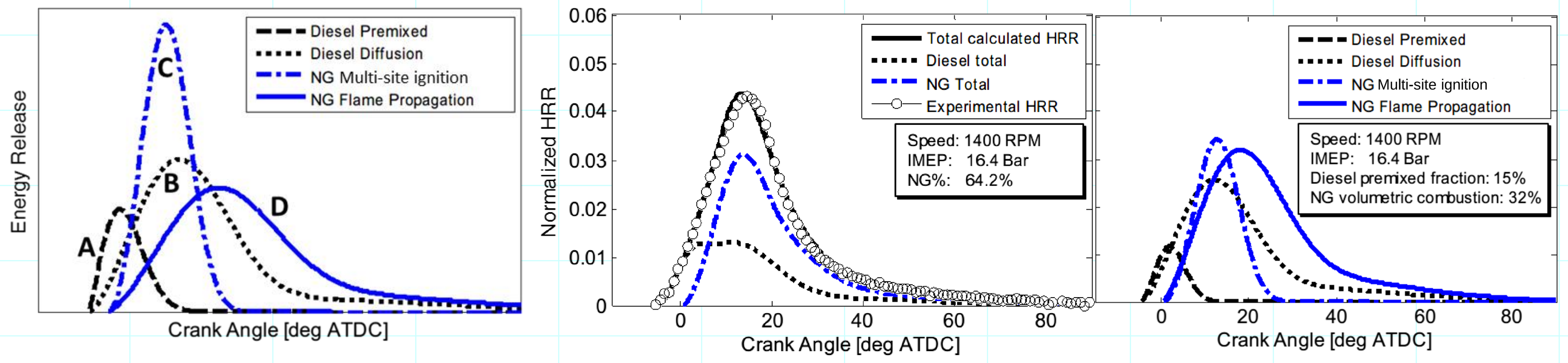
$$\left(\frac{m_{fuel}}{m_{O_2}}\right)_{st} = \frac{m_D + m_{NG}}{3.045\cdot m_D + 3.612\cdot m_{NG}} \qquad \tau_{ID} = 2.4\phi_{pD}^{-0.2}\bar{P}^{-1.02}\exp\left(\frac{E_a}{R_u\bar{T}}\right)$$



Modeling of Heat Release (Semi-empirical model)

- Reproduce heat release rate with Hybrid Triple-Wiebe function

$$\frac{m_{fb}}{m_{ft}} = \sum_{i=p,m,t} f_i \cdot \left\{1-\exp\left[-6.9\left(\frac{\theta-\theta_{ign}}{\Delta\theta_i}\right)^{m_i+1}\right]\right\} \qquad f_p + (f_m + f_t) = 1 \qquad f_p = 1-\frac{\phi^{0.25}}{\tau_{id}^{0.25}}$$



On-going Work:

Modeling of NG Combustion (Predictive model)

- Capture combustion of natural gas, including:
  - Ignition and flame front development
  - Turbulent flame propagation in lean NG-air mixture