Applying Aerospace Knowledge to Unconventional Wells

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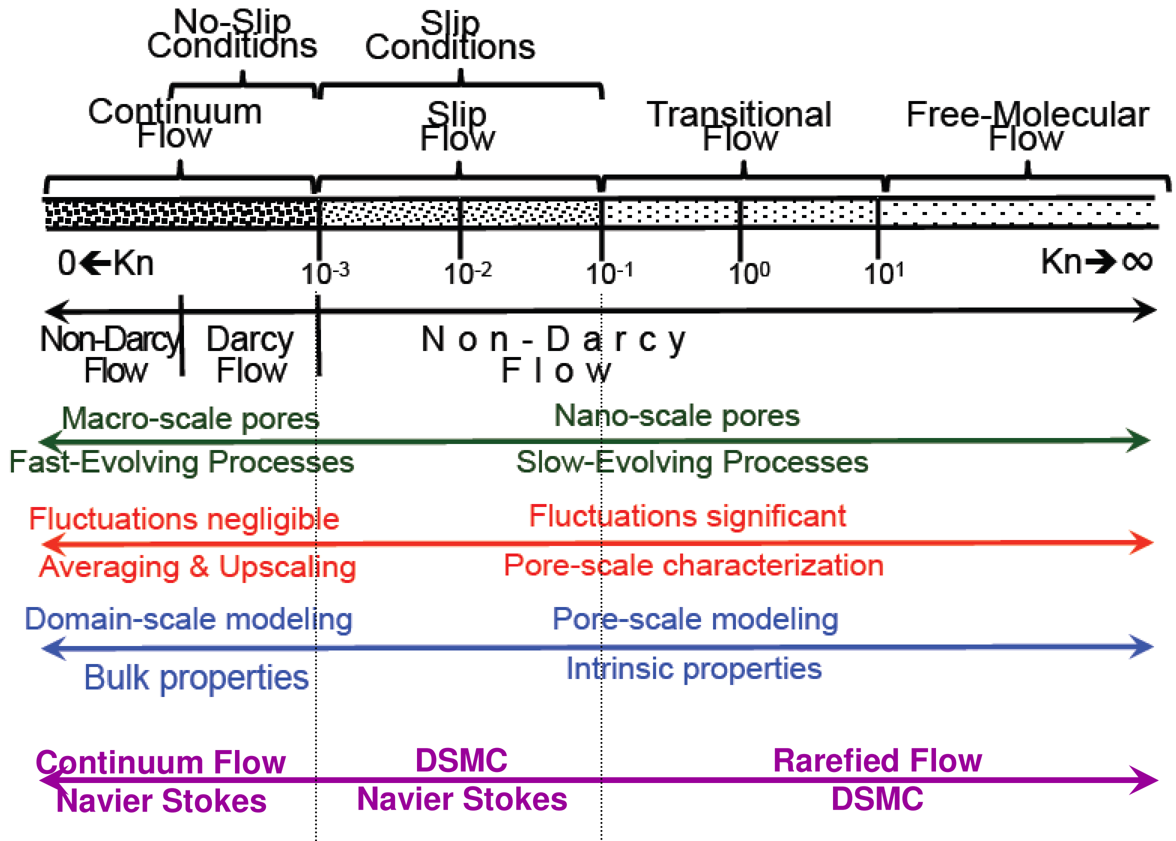
Rarefied Gas ≈ Nano-scale Pores

How we can use the HYBRID CONTINUUM-DSMC FRAMEWORK for unconventional wells?

Rarefied Gas ~> Unconventional Wells

$$\text{Knudsen Number: } Kn = \frac{\lambda}{\Lambda} = \frac{\text{Mean Free Path of Fluid Molecules}}{\text{Macroscopic-Average Pore-Diameter}}$$



- **Can use either DSMC or N-S (with slip effects) between 10^{-3} – 10^{-1}**
- **Continuum model requires adequate slip boundary treatment in this region**
- **Cost is cheaper the higher the Knudsen number at which Continuum/DSMC interface occurs**

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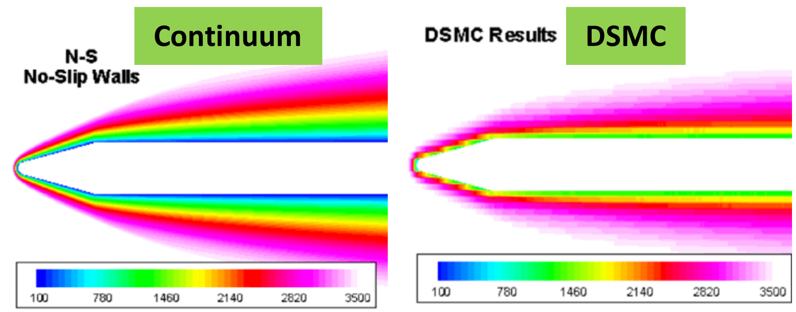
DSMC: Direct Simulation Monte Carlo

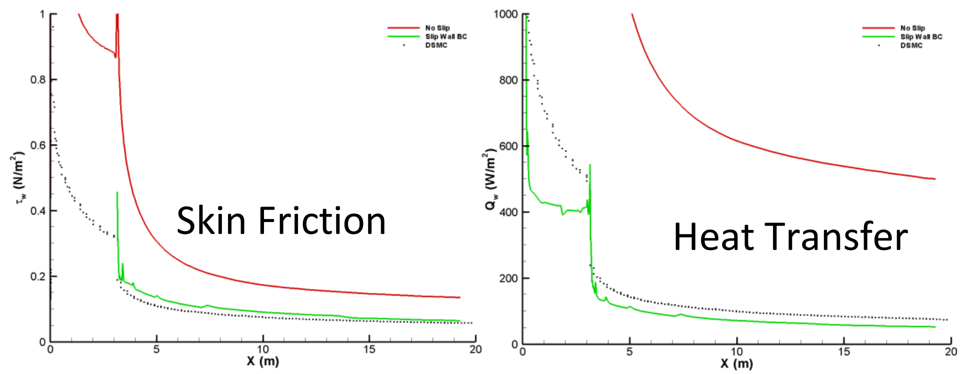
- **Particle-based technique for simulating rarefied fluid flows**
  - Knudsen number~0.1 or greater => rarefied flow
  - Low density fluids => large spacing between molecules (Aerospace)
  - Small pore size => large spacing between molecules (O&G)
- **Simulation molecules ~ large number of real molecules => probabilistic simulation to solve Boltzmann equation.**
- **Intermolecular collisions and molecule-surface collisions calculated using probabilistic models**
- **Fundamental assumption:**
  - Molecular movement and collision phases can be decoupled over time periods that are smaller than the mean collision time

Modeling Approaches

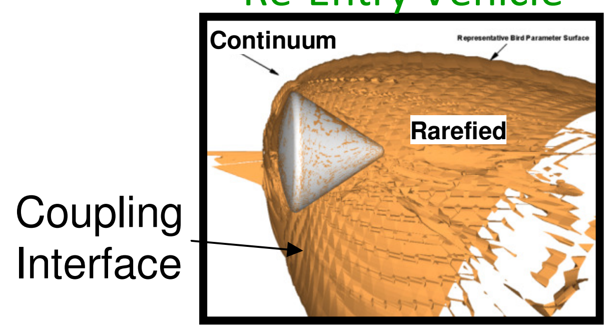
- **For high Kn, continuum models (N-S /Darcy) are not accurate**
  - Slip effects become important and flow does not equilibrate thermodynamically
  - Continuum code over-predicts near wall features such as skin friction and heat transfer
- **For low Kn, fully rarefied (DSMC) computations too expensive**
- **CRAFT Tech utilizes hybrid approach to cover all Kn**
  - Continuum model within continuum regions (typically Navier-Stokes) with possible enhancements to extend range to more rarefied regimes
  - Rarefied model within rarefied regions (typically Direct Simulation Monte-Carlo)
  - **Coupling occurs across interface surface or region**
  - Mitigates numerical inefficiencies
  - Modeling of important physical phenomena must be consistent across interface

High Altitude Flow





Re-Entry Vehicle



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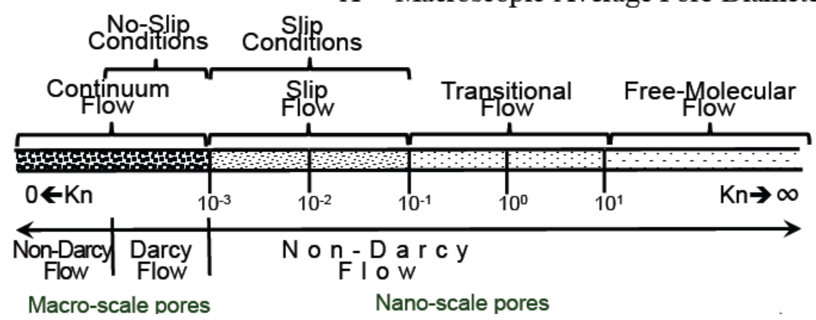
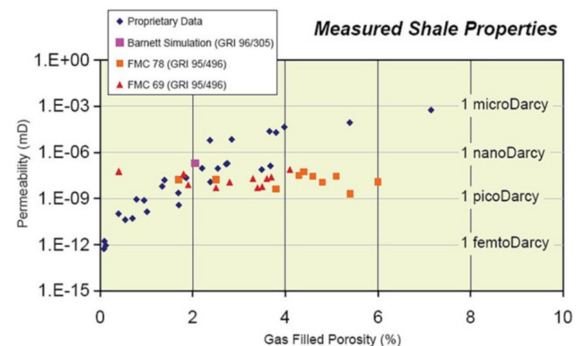
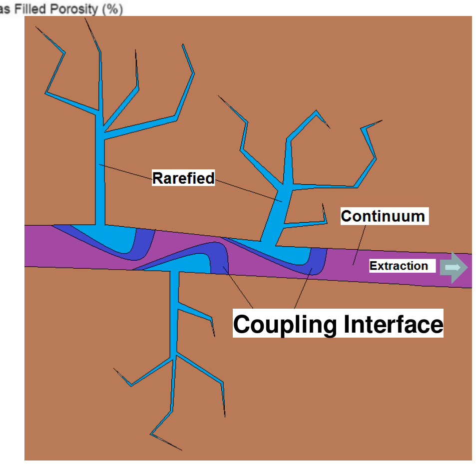
Application to Nano-Porous Unconventional Reservoirs

- Flow within pores are in non-continuum regime because geometric length scale is small
- For rarefied flow bulk, continuum transport properties (diffusion, viscosity, etc.) are no longer valid, requiring rarefied physical models
- Variation of length scale through extraction region also means there is mixture of continuum and rarefied regions
- Successful modeling of system requires hybrid analysis

Knudsen Number: $Kn = \frac{\lambda}{\Lambda} = \frac{\text{Mean Free Path of Fluid Molecules}}{\text{Macroscopic-Average Pore-Diameter}}$

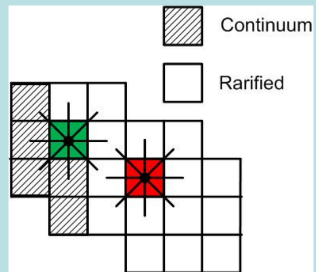


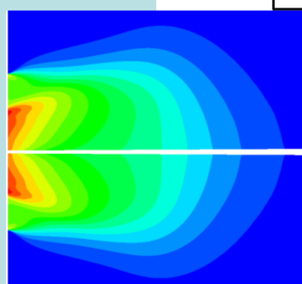


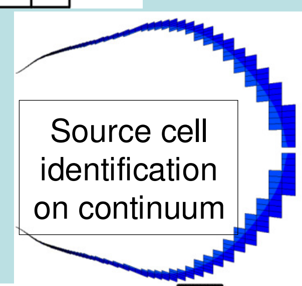


Unsteady Interface Methods

Interface Region

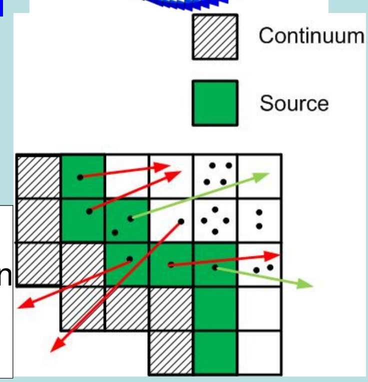






Source cell identification on continuum

Contours of density of continuum region



Source cell (green) contains at least one continuum cell in halo whereas rarefied cell (red) does not

CRAFT Tech Hybrid Paradigm

- **Apply most accurate physical models in each region**
  - Continuum – Navier-Stokes (CRAFT CFD® / CRUNCH CFD®)
    - Turbulence modeling
    - Finite rate chemistry
    - Two-phase flows
  - Rarefied (Nanoscale) – Direct Simulation Monte Carlo (DSMC) (HAMMRS)
    - Non-local thermodynamic equilibrium
    - Free-molecular flows
- **Identify interface regions in generic fashion using Knudsen number based criteria**
- **Numerical efficiency and physical accuracy improved by optimizing the location of the interface region and advanced methods for exchanging information at the interface**
  - Production level continuum-rarefied steady-state interfacing for even complex geometries and surfaces including two-phase flows through Automatic Efficient Generalized Interface Surface (AEGIS) Toolkit

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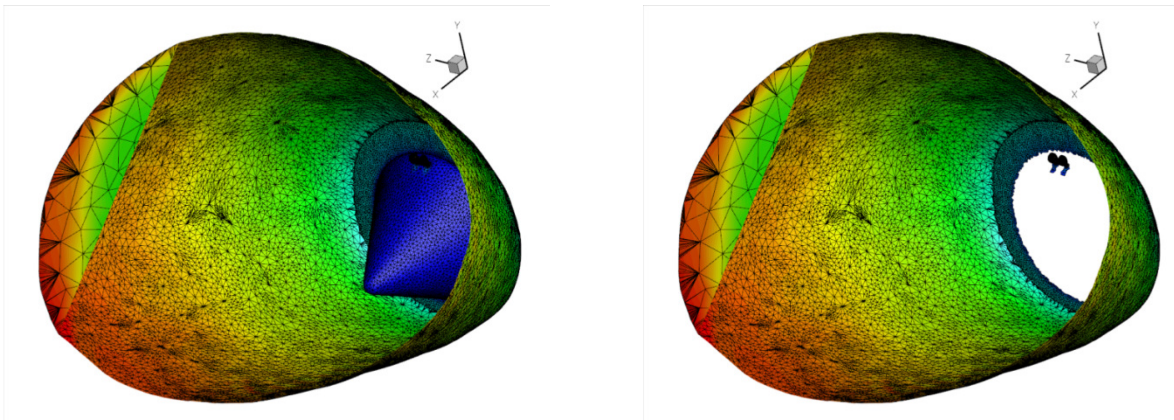
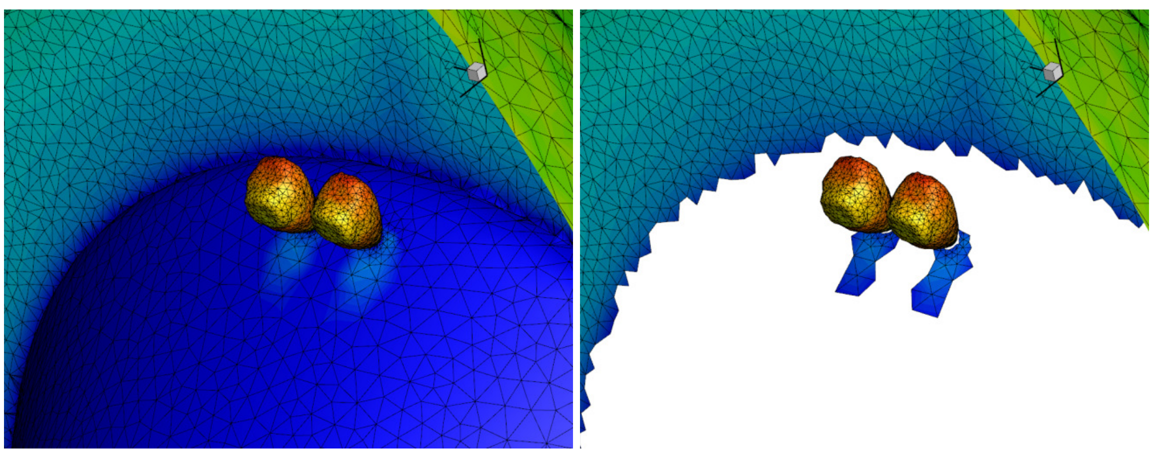
Apollo Capsule Reentry
Interface Surface Generation Interpolation



Mach Number (Clipped Below Sonic)



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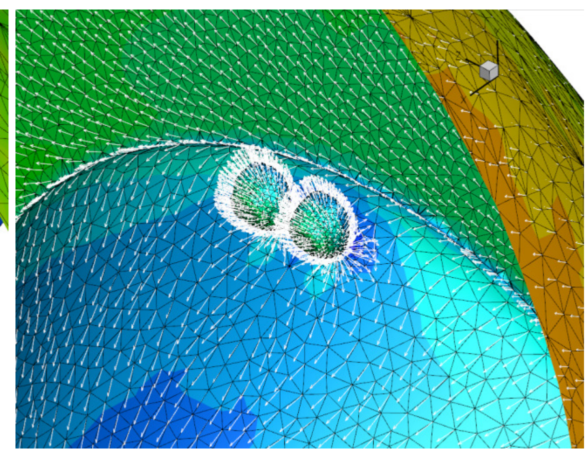

Velocity Vectors

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Generalized EOS
(Continuum Flows)

Experience with multi-phase, multi-component fluids

Thermo-Chemistry (Fluid Properties)

- **Generalized EOS models for mixtures of liquids and gases**
- **Compressible liquid EOS models**
- **Ideal gas EOS:**
  - Extensive database based on 7-coefficient NASA polynomials
- **Real fluid EOS based on SRK (Soave, Redlich and Kwong):**
  - Supported species: hydrogen, nitrogen, oxygen, methane, ethanol and ethane
  - Additional species can be added to EOS framework

$$P = \frac{RT}{V-b} - \frac{a}{V^2 + ubV + wb^2}$$

where

- R = universal gas constant
- V = molar volume
- u and w = model constants depending on PR or SRK
- a and b = constants for a given substance which maybe a mixture in which case they are dependent on mixture composition

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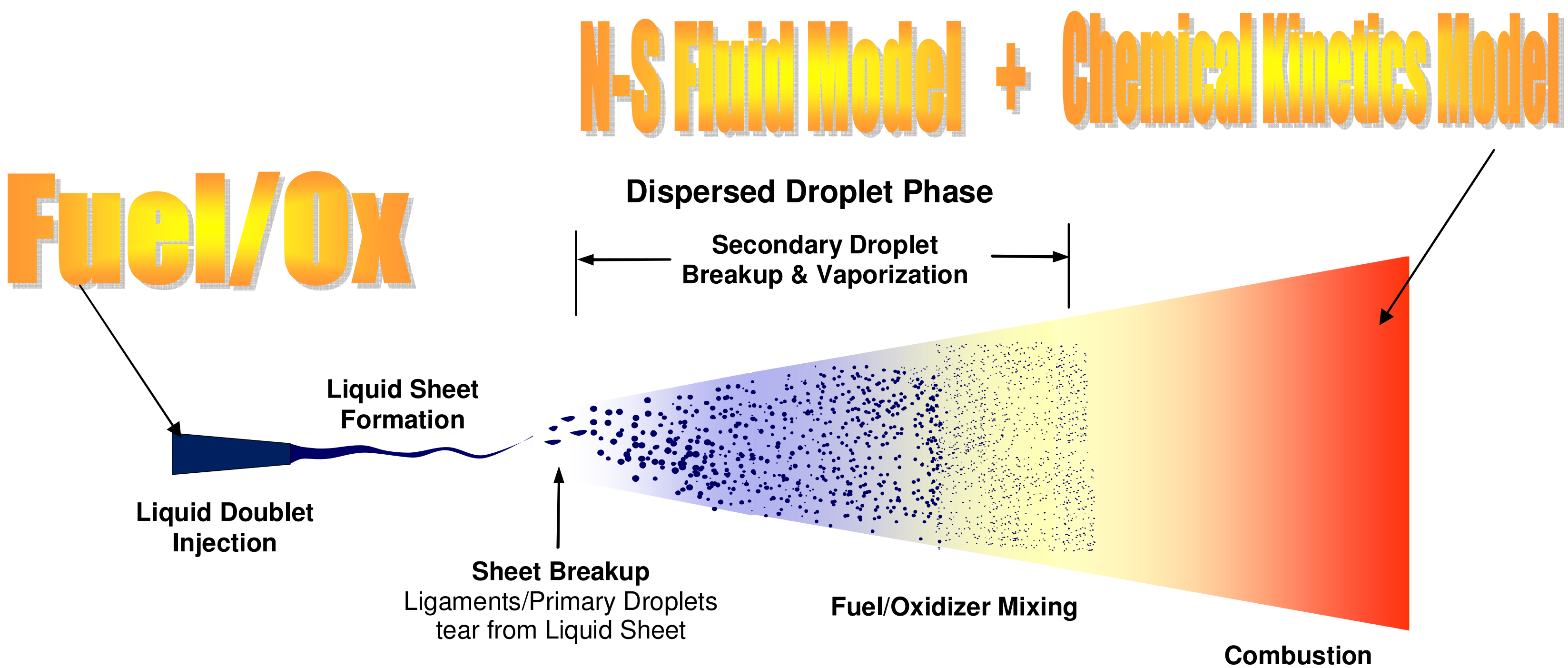
Combustion Modeling – How It Works!

- **A framework for simulating an impingement atomization/combustion sequence**

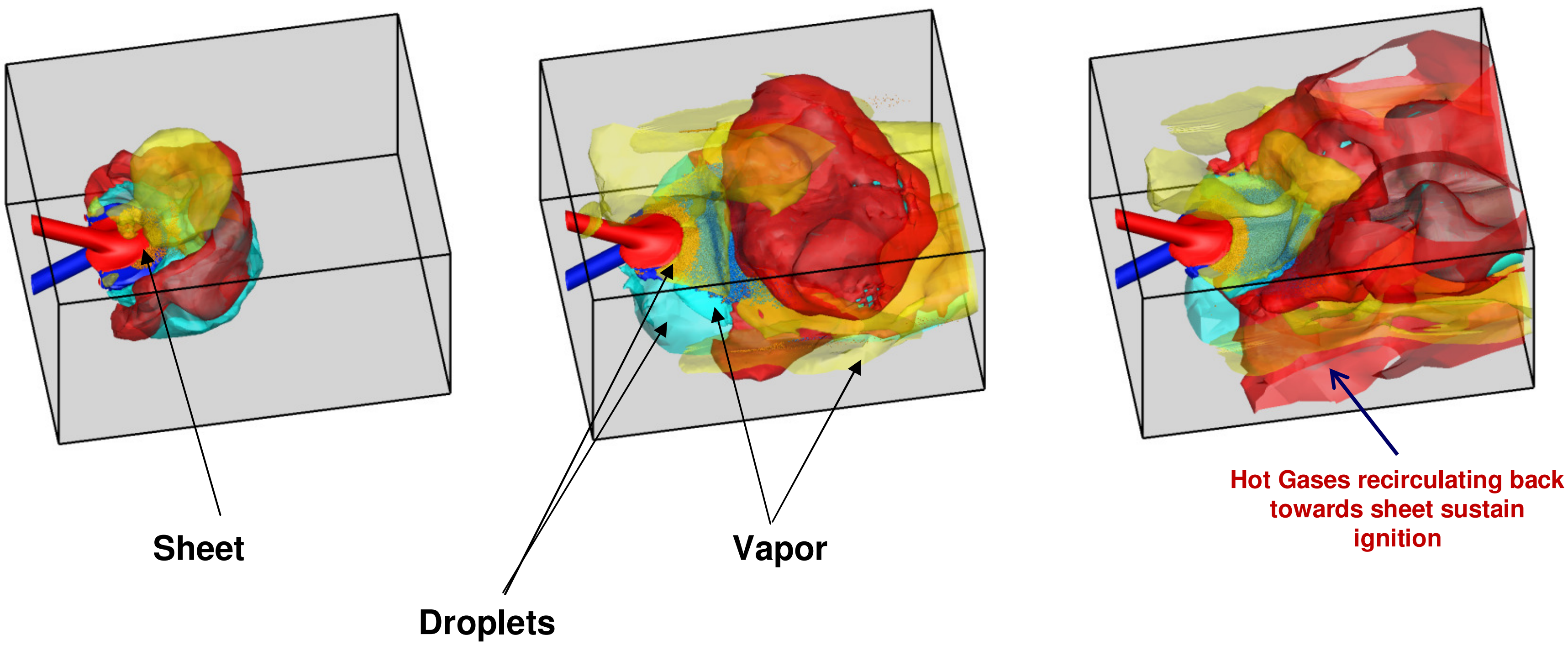


Schematic of the Injector/Combustion Sequence

Combustion Modeling – How It Works!

Red = CH_4 sheet
Orange = CH_4 droplets
Yellow = CH_4 vapor

Blue = LOX sheet
Metallic = LOX droplets
Aqua = O_2 vapor



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Summary

- DSMC and hybrid DSMC/Continuum technology can potentially be applied to modeling nano-porous unconventional reservoirs with additional technology development
- Characterize pores of different scales with DSMC or hybrid DSMC/Continuum procedures
- Integration into fast running system tools can potentially be achieved by using DSMC calculations to provide calibration of permeability as a function of porosity and pore size
- Framework for generalized EOS in place and easily modified for O&G fluids
  - Extensive experience with multi-phase, multi-component fluids

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