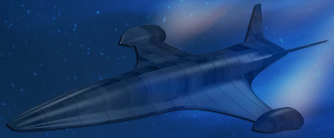

RE-ENTRY AND DEMISE

Hypersonic Open-Source Simulations

Vincent Casseau, Daniel E.R. Espinoza
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Centre for Future Air-Space Transportation Technology
Aerospace Centre of Excellence
University of Strathclyde
Glasgow, UK

Final Stardust Conference

ESTEC, 3 November 2016

University of Strathclyde Engineering

James Weir Fluids Laboratory

Centre for Future Air-Space Transportation Technology

cFASTT at Strathclyde

Hypersonic civilian transportation

cFASTT-1 design

Brown, R. E., "The future of air travel: Dinner in Sydney, London in time for 'The X-Factor'?" The Washington Post, Oct. 2014.

cFASTT at Strathclyde

Hypersonic civilian transportation

cFASTT-1 design

Subjects covered:

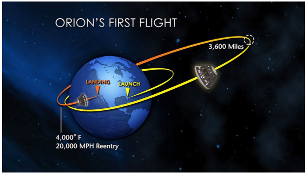
- low-fidelity modelling (***hyFlow***) and uncertainty quantification
- air-breathing and propulsion system (***hyPro***)
- trajectory optimisation
- ecological impact
- management of a fleet of spaceplanes

cFASTT at Strathclyde

Deep space exploration

ORION spacecraft

Parachutes testing (2012). Credit: NASA



Earth circumnavigation (2014). Credit: NASA

cFASTT at Strathclyde

Deep space exploration

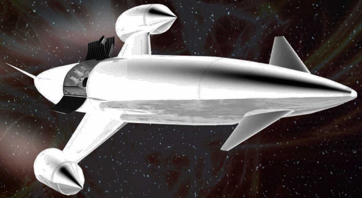
ORION spacecraft

Subjects covered:

- re-entry aerothermodynamics (***dsmcFoam***, ***hy2Foam***)
- hybrid modelling
- ablation studies
- satellite demise

Scope of Presentation

1. **Motivation**
   - Objectives
   - Open-source coding
2. **Open-Source Framework**
   - Direct simulation Monte-Carlo: *dsmcFoam*
   - Computational fluid dynamics: *hy2Foam*
3. **Hybrid CFD-DSMC code**
   - Formulation
   - Results
4. **Conclusions and Future Work**



1. Motivation

1.1 Objectives

To assess the aerothermodynamic performance of a vehicle / body through the spectrum of rarefied to continuum conditions.

The solution has to be engineering-friendly.

Trade-off between:

- computational cost
- accurate results

1.2 Open-source code development

Makes collaboration easier.

There is a paucity of hypersonic codes available to academic researchers/students.

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Makes collaboration easier.

There is a paucity of hypersonic codes available to academic researchers/students.

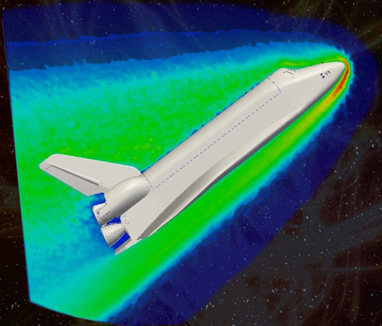
Motivated the development of a

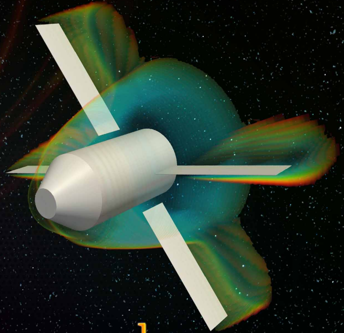
- direct simulation Monte-Carlo (DSMC) code
- conventional computational fluid dynamics (CFD) solver
- hybrid CFD-DSMC code

within OpenFOAM

The Open Source CFD Toolbox

DSMC vs. CFD





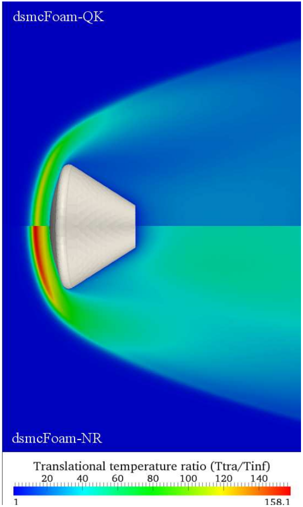
2. Open-source framework

2.1 Open-source framework: DSMC

dsmcFoam

- successfully developed and validated[1,2] at Uni. of Strathclyde

[1] Scanlon *et al.*: "Open-Source DSMC Chemistry Modelling for Hypersonic Flows" (2015)
[2] Rodrigo Palharini's PhD Thesis: "Atmospheric Reentry Modelling Using an Open-Source DSMC Code" (2014)



Temperature field for non-reacting (NR) and chemically reacting (QK) air flowing past an Orion capsule[2] (95 *km*)

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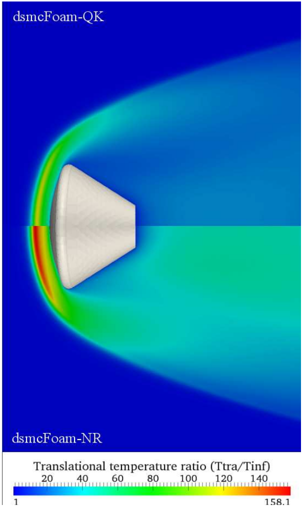
Two main aspects:

- Quantum Larsen-Borgnakke energy redistribution
- Quantum-Kinetics (QK)



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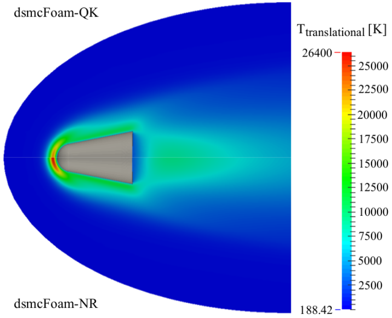

Temperature field around the Brazilian satellite SARA.

2.1 Open-source framework: DSMC

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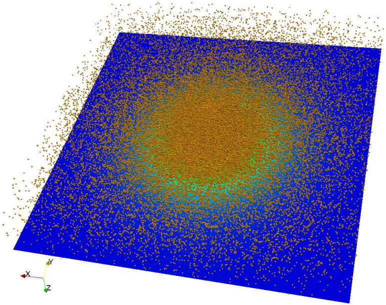
- R. C. Palharini *et al.*, "Assessment of Rarefaction Effects on the SARA Capsule", 30th RGD conference, 2016
- C. White *et al.*, "Numerical and Experimental Capabilities for Studying Rocket Plume-Regolith Interactions", 30th RGD conference, 2016



Shear stress plot and DSMC particles showing the plume of an expanding nozzle.

2.1 Open-source framework: DSMC

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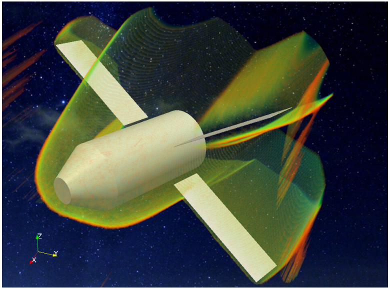
- R. C. Palharini *et al.*, "Assessment of Rarefaction Effects on the SARA Capsule", 30th RGD conference, 2016
- C. White *et al.*, "Numerical and Experimental Capabilities for Studying Rocket Plume-Regolith Interactions", 30th RGD conference, 2016
- T. J. Scanlon *et al.*, "Simulation of Satellite Re-entry Using the DSMC method", Stardust conference, 2016

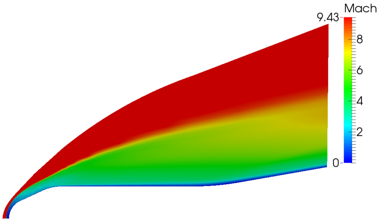


Flow patterns around a descending satellite at 90 km altitude

2.2 Open-source framework: CFD

hy2Foam

- High-speed, compressible flows
- Transient simulations



HB-2 simulation

2.2 Open-source framework: CFD

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- High-speed, compressible flows
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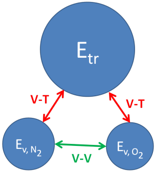
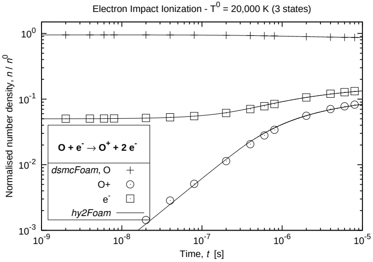
Physics:

- 2-T formulation with multiple T_{ve}
- 11-species air mixture
- CVDV chemistry-vibration model and QK rates





Heat bath simulation

2.2 Open-source framework: CFD

hy2Foam

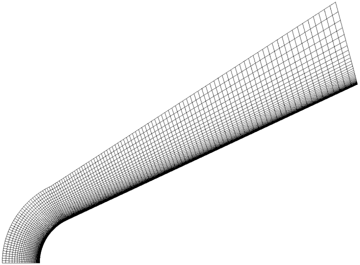
- High-speed, compressible flows
- Transient simulations

Physics:

- 2-T formulation with multiple T_{ve}
- 11-species air mixture
- CVDV chemistry-vibration model and QK rates

Numerics:

- Kurganov central-upwind schemes
- Hexahedral meshes preferably

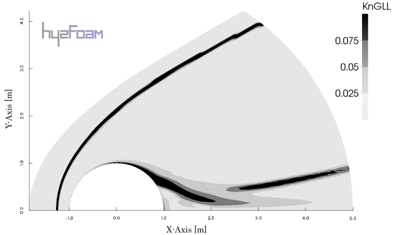


Blunted-cone mesh

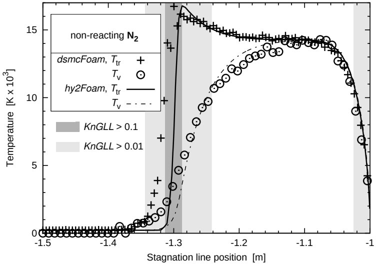
2.2 Open-source framework: CFD

hy2Foam

- V. Casseau *et al.*, "Hypersonic Simulations using Open-Source CFD and DSMC Solvers", 30^{th} RGD conference, 2016



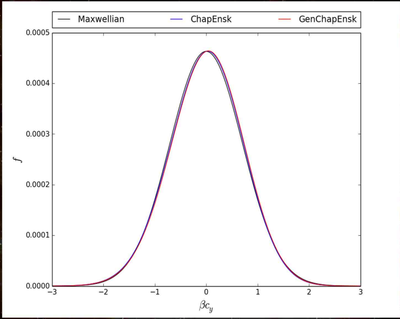
Mach 20 non-reacting flow past a circular cylinder.

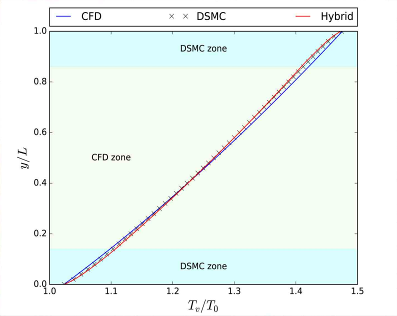


2.2 Open-source framework: CFD

hy2Foam :: Future work

- blend the Kurganov and the AUSM$^+$-up schemes to better capture the near-wall region
- test the 116 reactions to occur in a 11-species air using the newly *dsmcFoam*-derived QK rates
- model rotational non-equilibrium using the bulk viscosity
- verify the code capabilities for Mars entry conditions





3. Hybrid code

3.1 Formulation: Description

Flows with both continuum and rarefied regions:

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- Need to establish a criterion for region type identification
- Need to set a method for information coupling between regions

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Continuum breakdown parameter:

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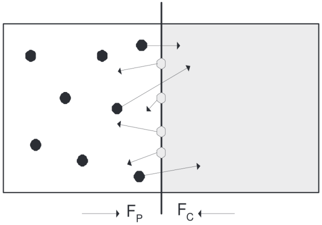
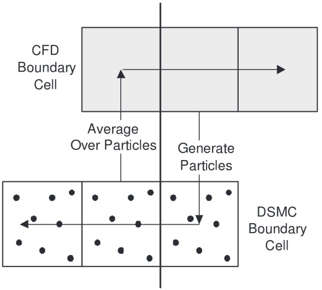
$$Br = max(Kn, Kn_{r-NEQ}, Kn_{GL-Q})$$

3.1 Formulation: Description

Coupling between regions:



(a) Flux-based coupling

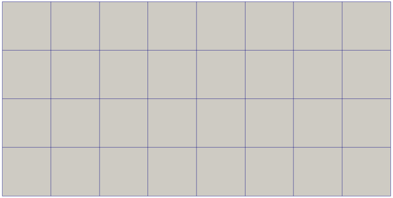


(b) State-based coupling

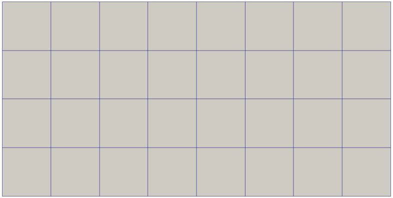
Typical coupling procedures

3.1 Formulation: Zones

meshCFD



meshDSMC



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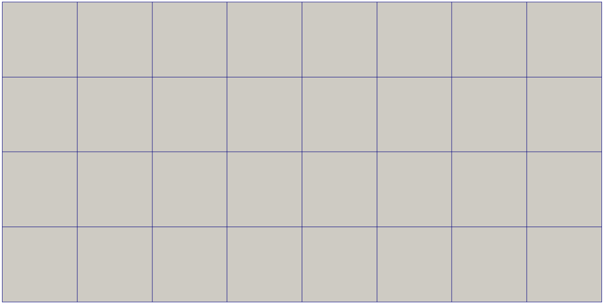

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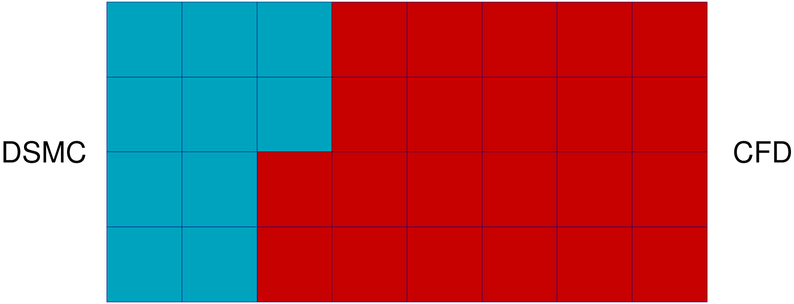

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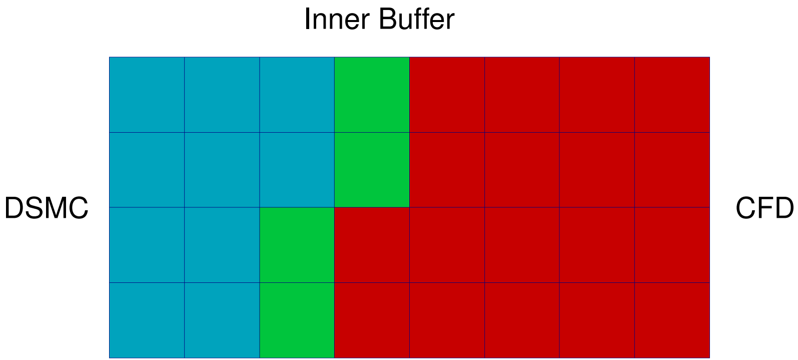

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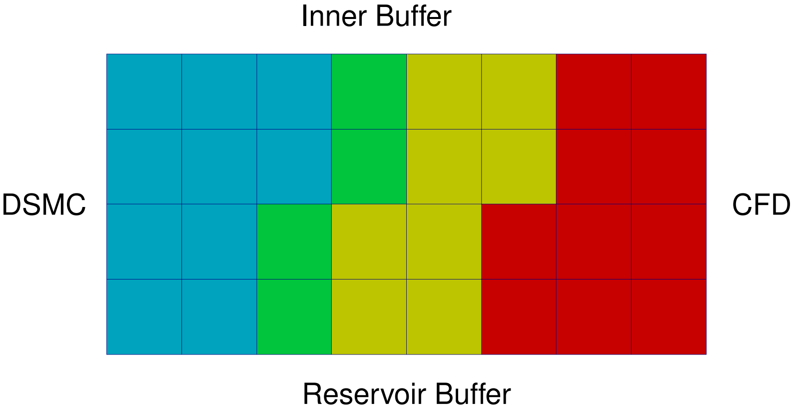
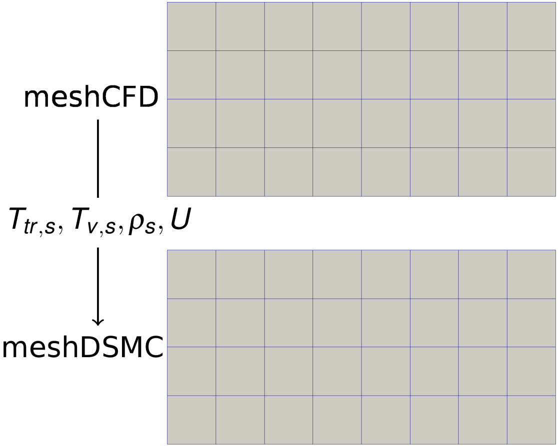


3.1 Formulation: Coupling - DSMC



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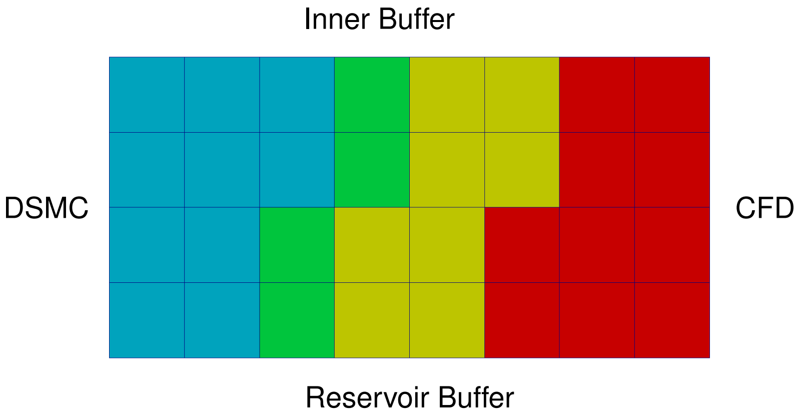

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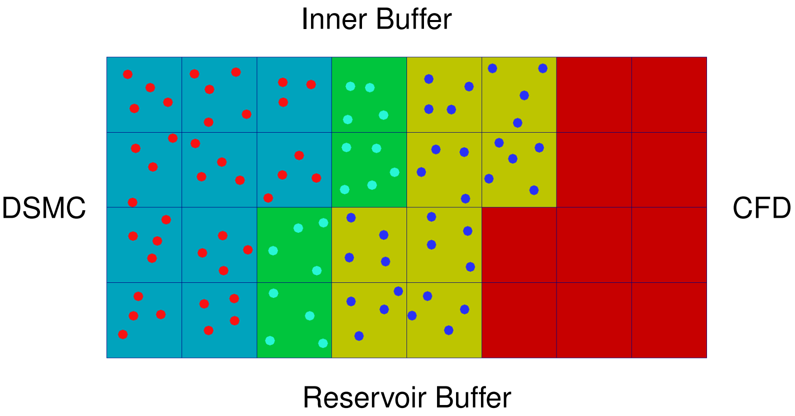

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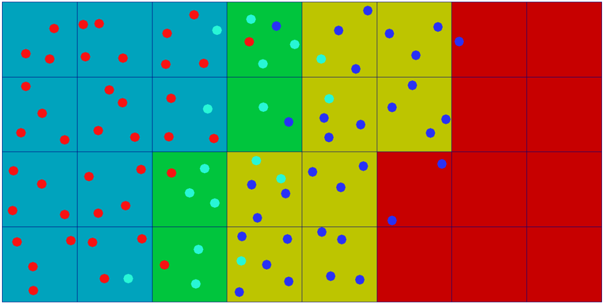
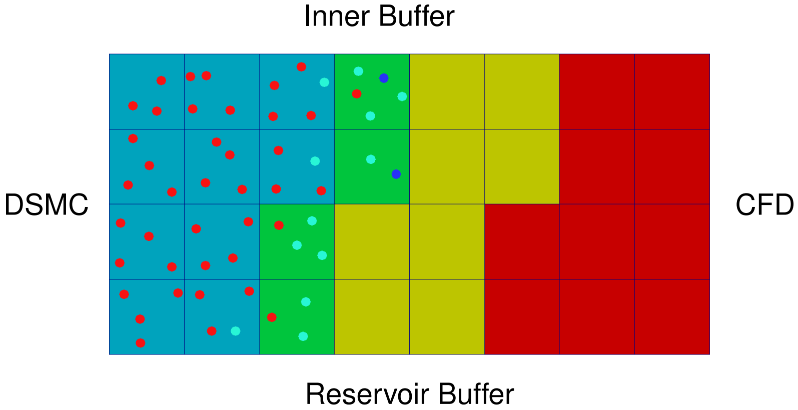
Inner Buffer

DSMC  CFD

Reservoir Buffer

3.1 Formulation: Coupling - DSMC



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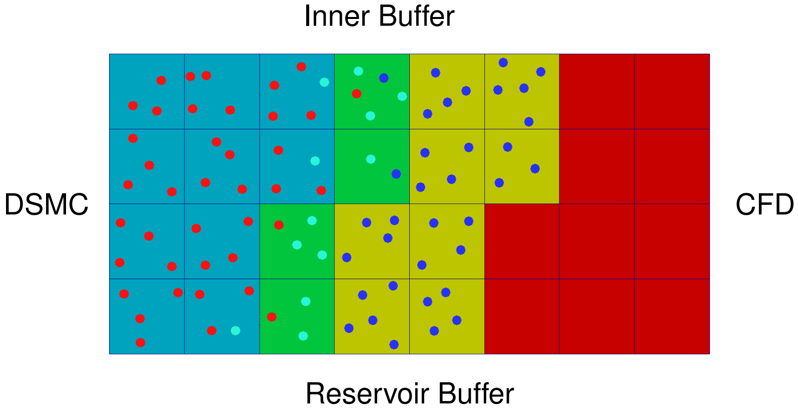

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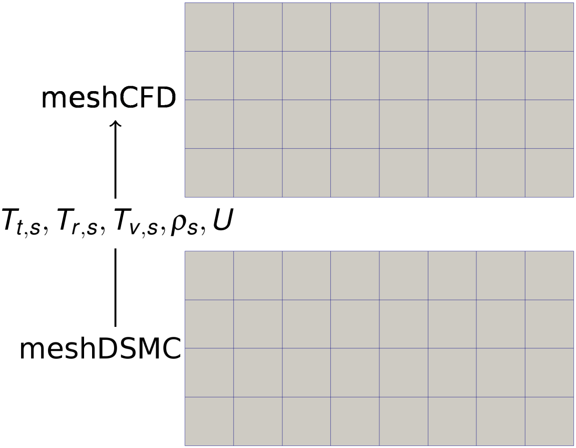

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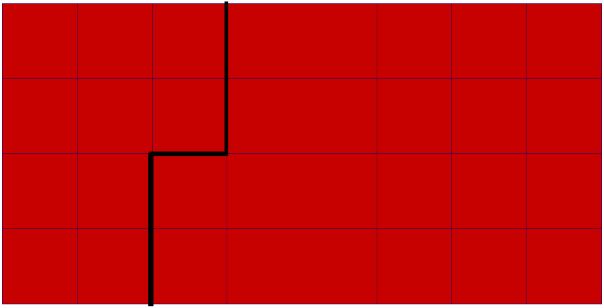

CFD

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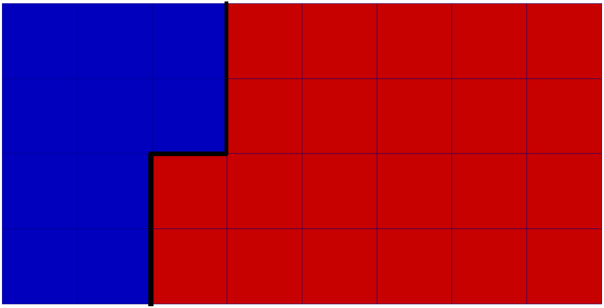

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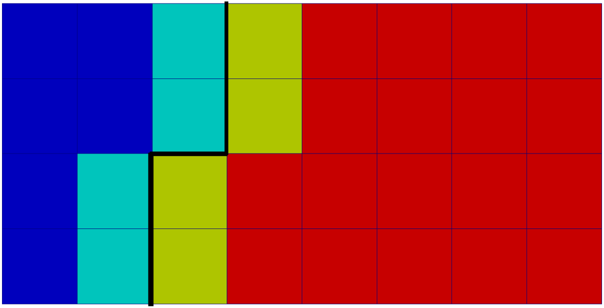

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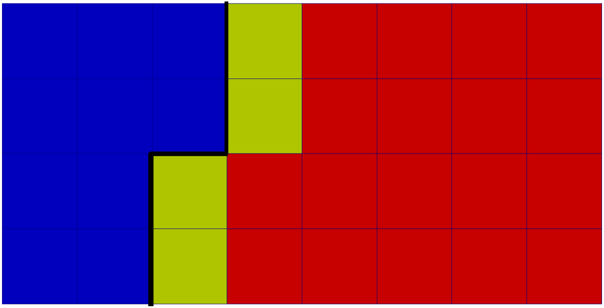

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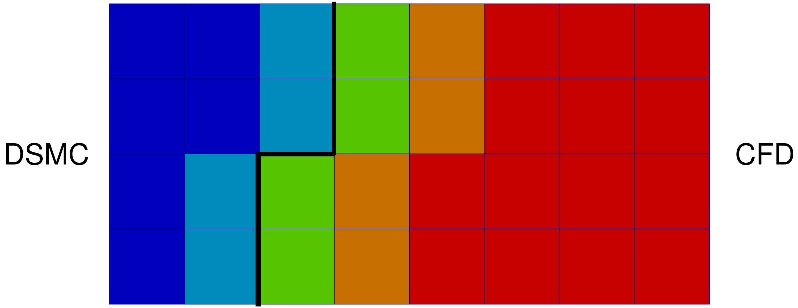

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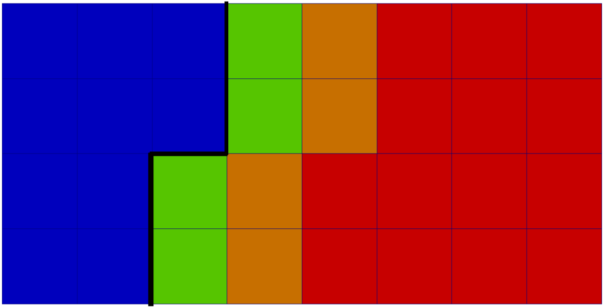

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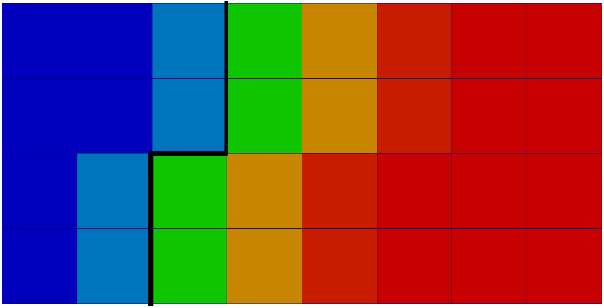

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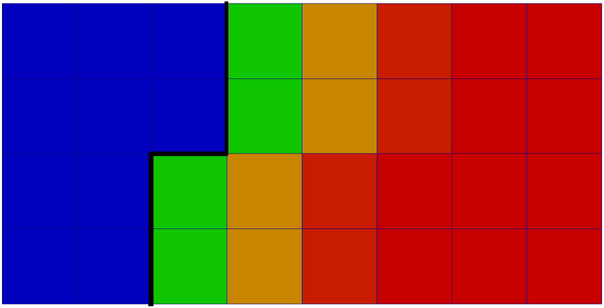
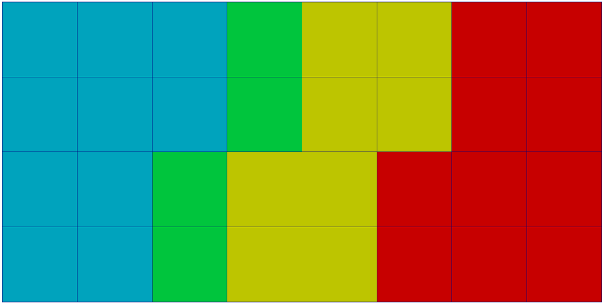


CFD

3.1 Formulation: Coupling - Zones

Inner Buffer

DSMC



CFD

Reservoir Buffer

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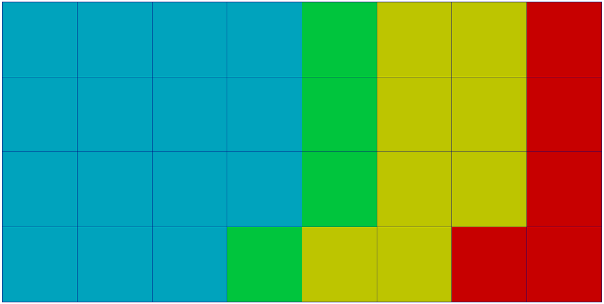

CFD

Reservoir Buffer

3.1 Formulation: Coupling - Distributions

- Maxwellian distribution:

$$f^{(0)}(\vec{c}) = \left(\frac{\beta}{\sqrt{\pi}}\right)^3 \exp\left[-\beta^2 \vec{c} \cdot \vec{c}\right]$$

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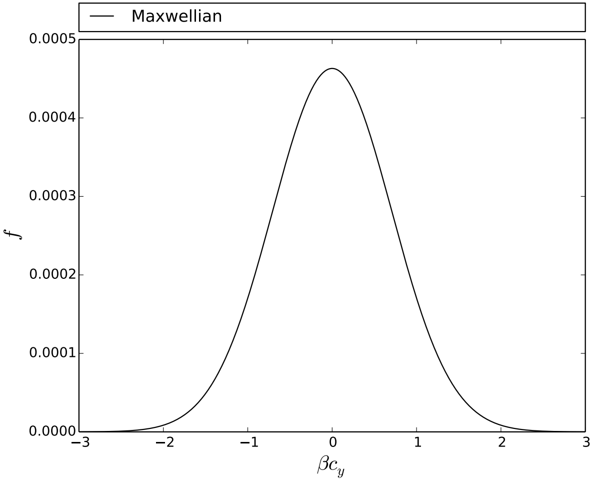

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- Chapman-Enskog distribution

$$f^{(1)}(\vec{c}) = f^{(0)}(\vec{c})\Gamma(\vec{c})$$

$$\Gamma(\vec{c}) = 1 + \left(\vec{q_t}\cdot\vec{\mathscr{C}}\right)\left(\frac{2}{5}\vec{\mathscr{C}}\cdot\vec{\mathscr{C}} - 1\right) - \vec{\mathscr{C}}\cdot\tau\cdot\vec{\mathscr{C}}$$

$$\vec{\mathscr{C}} = \beta\vec{c}$$

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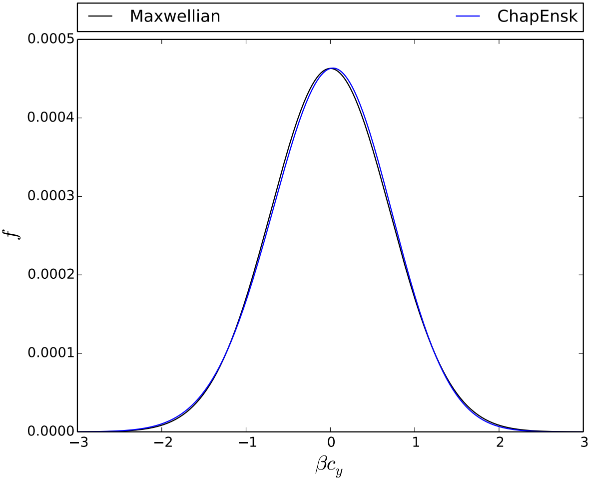

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- Chapman-Enskog distribution

$$f^{(1)}(\vec{c}) = f^{(0)}(\vec{c})\Gamma(\vec{c})$$

$$\Gamma(\vec{c}) = 1 + \left(\vec{q_t}\cdot\vec{\mathscr{C}}\right)\left(\frac{2}{5}\vec{\mathscr{C}}\cdot\vec{\mathscr{C}} - 1\right) - \vec{\mathscr{C}}\cdot\tau\cdot\vec{\mathscr{C}}$$

$$\vec{\mathscr{C}} = \beta\vec{c}$$

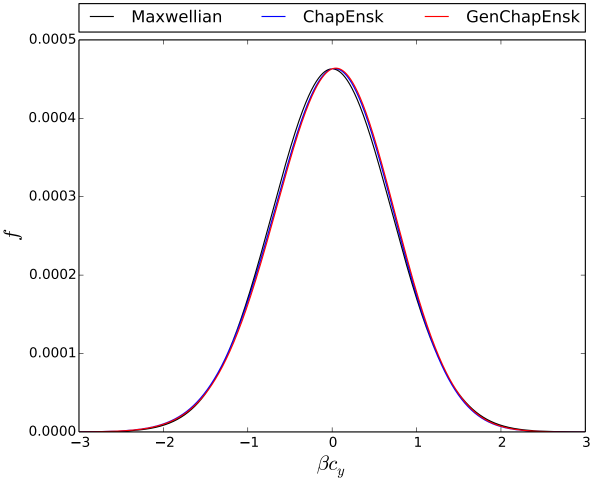
- Generalised Chapman-Enskog distribution:

$$f_s^{(1)}(\vec{c},\varepsilon_{int}) = f_s^{(0)}(\vec{c},\varepsilon_{int})\Gamma_s(\vec{c},\varepsilon_{int})$$

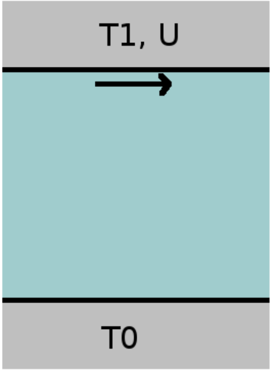
$$f_s^{(0)}(\vec{c},\varepsilon_{int}) = \frac{g_{int}}{Z_{int}}\exp(-\varepsilon_{int})f^{(0)}(\vec{c})$$

$$\Gamma_s(\vec{c},\varepsilon_{int}) = \Gamma(\vec{c}) + 2\vec{\mathscr{D}}\cdot\vec{\mathscr{C}} + \left(\overrightarrow{q_{int,s}}\cdot\vec{\mathscr{C}}\right)\left(\varepsilon_{int,s} - \overline{\varepsilon_{int,s}}\right)$$

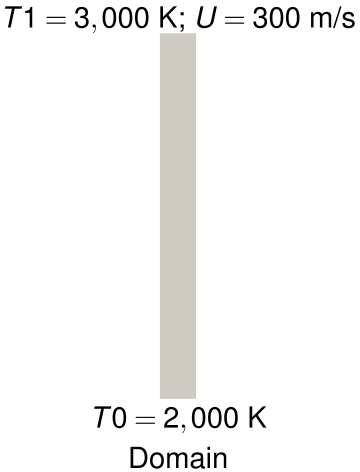
3.1 Formulation: Coupling - Distributions

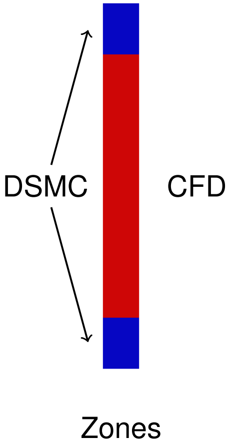


3.2 Results: Couette flow

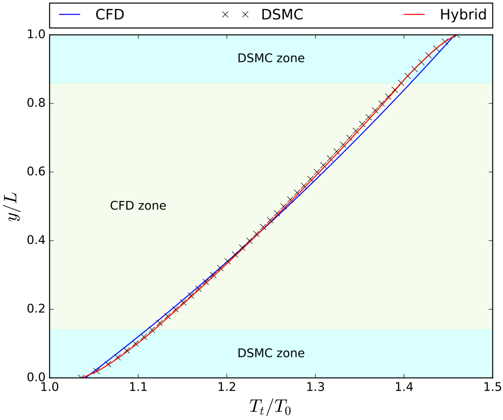


3.2 Results: Couette flow



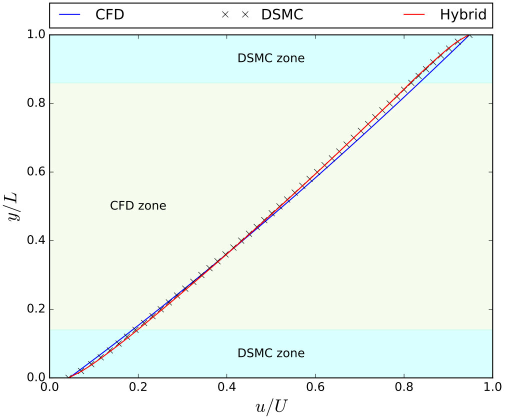


3.2 Results: Couette flow - Argon



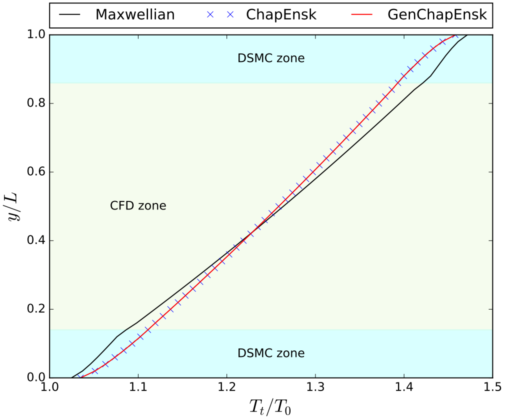
Translational temperature

3.2 Results: Couette flow - Argon



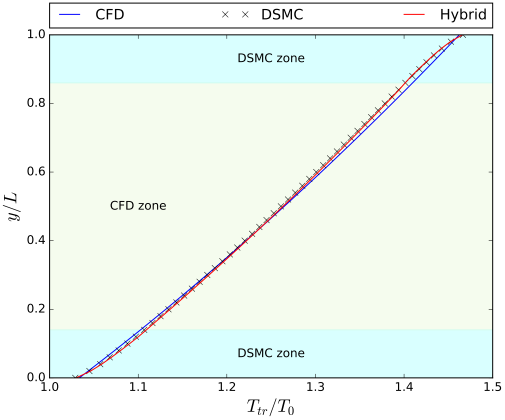
Velocity

3.2 Results: Couette flow - Argon



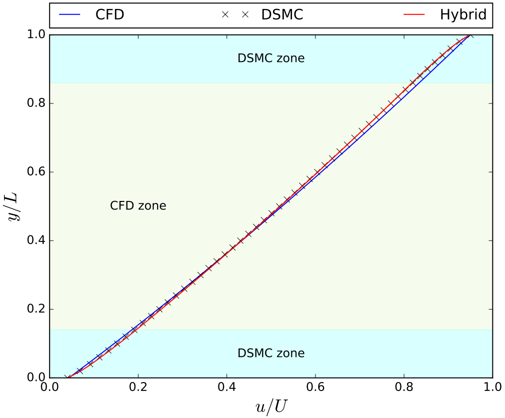
Comparison of different distributions

3.2 Results: Couette flow - Vibrationless N_2



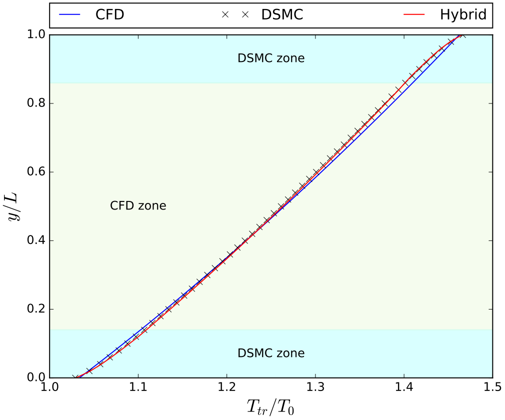
Trans-rotational temperature

3.2 Results: Couette flow - Vibrationless N_2



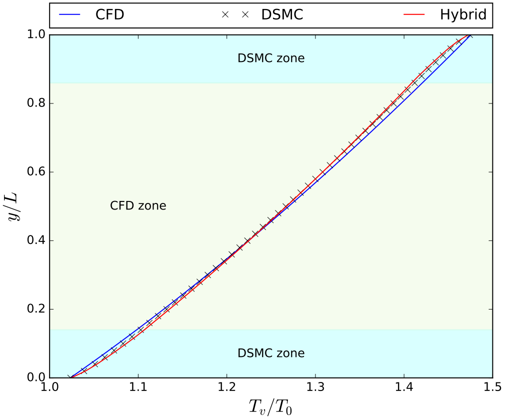
Velocity

3.2 Results: Couette flow - Nitrogen



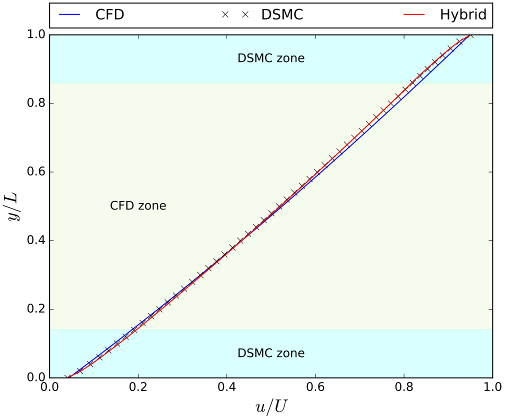
Trans-rotational temperature

3.2 Results: Couette flow - Nitrogen



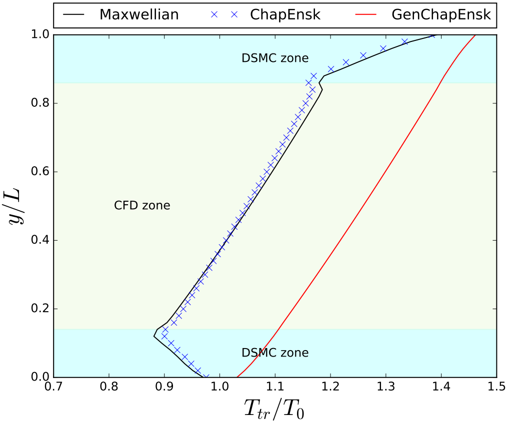
Vibrational temperature

3.2 Results: Couette flow - Nitrogen



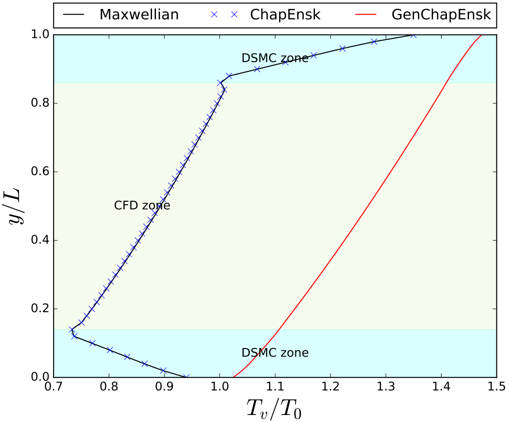
Velocity

3.2 Results: Couette flow - Nitrogen



Comparison of different distributions

3.2 Results: Couette flow - Nitrogen



Comparison of different distributions

4 Conclusions

- Open-source codes ***dsmcFoam*** and ***hy2Foam*** compared reasonably well with each other in the bottom range of the continuum-transition regime
- Elaborated a case study for DSMC / CFD code verification
- Initiated the development of a hybrid CFD-DSMC code

4 Conclusions and Future Work

- Open-source codes ***dsmcFoam*** and ***hy2Foam*** compared reasonably well with each other in the bottom range of the continuum-transition regime
- Elaborated a case study for DSMC / CFD code verification
- Initiated the development of a hybrid CFD-DSMC code

- Assess the performance of the hybrid code
- Model multi-dimensional and multi-species flows with both ***hy2Foam*** and the hybrid solver

5 Acknowledgements

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