Computational modeling of space re-entry aerothermodynamics and magnetized plasmas with COOLFluiD

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AMS Seminar 29th October 2019 @NASA
Presentation Outline

Background
- Von Karman Institute
- CmPA at KU Leuven

COOLFluiD overview
- Motivation & scope
- Main Capabilities
- Numerical algorithms

Aerothermodynamics modeling
- Introduction
- Applications

Magnetized plasma modeling
- Introduction
- Applications

Conclusions
- Development status & perspectives
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### Background
Mission as conceived today: Excellence Center in Fluid Dynamics
(Aerospace, turbomachinery, propulsion, environmental, industrial, …)

- Academic programs
  - Postgraduate Research Masters (1 academic year = 9 months) recognized (accredited) as Master after Master (60 ECTS)
  - PhD program (1 to 4 years)
  - Short Training Program (2-3 months) for undergraduates
  - Lifelong learning: Lecture Series (1 week duration short courses)

- Research & Development
  - Fundamental research in Fluid Dynamics (e.g. turbulence, transition …)
  - Applied research (Industry, ESA, EU, IWT, …)

- Stimulate International cooperation

Aeronautics Research Activities

- Cubesat engineering
- Atmosphere physics
- Electric propulsion
- Launch
- Reentry
- Hypersonic transition
- Gas-Surface Interaction
- Flow radiation
- Space debris
- Rarefied flow physics
- Re-enSat development

Aeronautics Research Activities

- Fairing aeroacoustic
- Cryogenic test rig
- Chilldown experiments
- Sloshing table
- Micro G flight
- Space

Aeronautics Research Activities
The CmPA

The Centre for mathematical Plasma Astrophysics (CmPA) was founded on January 1st, 1992 and is a division of the Department of Mathematics, Faculty of Science of the KU Leuven, Belgium.

Research areas

Mathematical modeling in plasma physics
- Fluid (Magnetohydrodynamics), multi-fluid, kinetic theory
- Hybrid, multi-scale/multi-physics modeling

Magnetoseismology
- Waves and instabilities in solar atmosphere/corona
- MHD spectroscopy for astrophysical jets, accretion disks, and tokamak (fusion) plasmas

Solar physics and Space Weather
- Solar wind / Coronal Mass Ejections: initiation and evolution
- Interaction solar wind/InterPlanetary CMEs with magnetospheres

High energy astrophysics
- (Extra-)galactic jets, accretion disks, relativistic outflows,

Numerical algorithm development
- HPC, solution AMR, PIC treatments, FD/FV/FE methods,

Background

CmPA at KU Leuven

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Leuven Computational Modeling Center

**Mission:** numerical modeling of multi-scale systems and their mapping onto modern HPC systems

**New structure and stakeholders since December 2018**
- Me (director), Ward Melis and Jorge Amaya (co-directors)
- CmPA (Prof. Poedts, president), CS (Prof. Roose, Prof. Samaey), Bioscience/eng. (Prof. Ramon), Mech. Eng. (Prof. Meyers, Prof. Steelant)

**Numerical methods and modelling tools (POC: Andrea Lani)**
- AMR, high-order CFD methods, particle algorithms (e.g. for graphics, radiation, MD)
- UQ, control & optimization problems, reduced order models

**HPC and data analysis (POC: Jorge Amaya)**
- Hardware, software, programming for heterogeneous systems
- Big Data science: methods/analysis for voluminous datasets, parallel I/O, visualization

**Multi-scale, multi-physics and control systems (POC: Ward Melis)**
- Dynamical networks (social networks, smart grids, ...)
- Materials, chemistry, fluids, plasma, kinetic problems (e.g. turbulence, reacting flows)
- Multi-scale modeling and simulation tools

| Background | COOLFluiD overview | Aerothermodynamics modeling | Magnetized plasmas modeling | Conclusions |
|------------|-------------------|-----------------------------|-----------------------------|-------------

**COOLFluiD overview**
COOLFluiD platform (T. Quintino & A. Lani, 2002)

Developing & consolidating **multi-disciplinary** modeling expertise ...
Collaborative Component-based Simulation Environment

... requires a flexible software platform and fruitful collaborations!

Open source: https://github.com/andrealani/COOLFluiD/wiki
Some statistics

**COOLFluiD team and quick facts**

- **16** defended & **3** ongoing PhD thesis
- **100+ contributors** since 2002 from various institutions
- **1,000,000+** lines of codes, **100+ modules**
- C++ / MPI / CUDA, interfaces to a few FORTRAN libraries
- **80+ scientific publications** (journal & conference articles)
- **20+ funded projects** so far (ESA, EU FP7, US AFOSR, national)
- Subversion repository and website on **Github**
- **Open source** under LGPL v3 license since 10/2014

**Wiki:** [https://github.com/andrealani/COOLFluiD/wiki](https://github.com/andrealani/COOLFluiD/wiki)

**Twitter:** [https://twitter.com/coolfluid](https://twitter.com/coolfluid)
Infrastructure for massively parallel HPC

Parallel I/O: reading/writing tested up to 60,000 cores (PRACE)

Parallel mesh extrusion to $10^9$ cells

Concurrent simulation infrastructure

Scalability on NASA Pleiades (Top13)

Heterogeneous HPC on CPU/GPU
Algorithmic & multi-physics modeling features

**Unstructured all-speed flow & plasma CFD solvers**
- Finite Volume, high-order Flux Reconstruction, FEM
- In-flight/laboratory re-entry aerothermodynamics
- Single-fluid ideal MHD
- Multi-fluid/Maxwell, reactive & radiative plasma

**Massively parallel radiation transport algorithms**
- Monte Carlo methods
- Finite Volume/Discrete Ordinate methods
- API’s to multiple spectroscopic databases
- Spectra reduction algorithms for LTE & non-LTE

**Mesh adaptation algorithms**
- Pseudo-elastic mesh deformation methods
- New generation shock-fitting/remeshing techniques

↑ $M_{\infty} = 1.3 \div 15$ re-entry flow over ESA vehicle
↓ ESA EXPERT: aerothermoelastic study

Shock-fitting around double ellipse at $M_{\infty} = 25$
Implicit Time Stepping

Newton Linearization

\[ \tilde{R}(P) = \frac{\partial U}{\partial P} \frac{\partial P}{\partial t} + R(P) = 0 \quad \Rightarrow \quad \tilde{R}(P) = \tilde{R}(P^k) + \frac{\partial \tilde{R}}{\partial P}(P^k) = 0 \quad \Rightarrow \quad \left[ \frac{\partial \tilde{R}}{\partial P}(P^k) \right] \Delta P^k = -\tilde{R}(P^k) \]

Implicit time integration schemes

\[ \tilde{R}(P) = \frac{U(P) - U(P^n)}{\Delta t} \Omega + R(P) \quad \text{Backward Euler (steady)} \]

\[ \tilde{R}(P) = \frac{U(P) - U(P^n)}{\Delta t} \Omega + \frac{1}{2}[R(P) + R(P^n)] \quad \text{Crank-Nicholson (unsteady)} \]

\[ \tilde{R}(P) = \frac{3U(P) - 4U(P^n) + U(P^{n-1})}{2\Delta t} \Omega + R(P) \quad \text{3-Point Backward (unsteady)} \]

Linear system solvers (e.g. from PETSc, PARALUTION, Trilinos)

- GMRES solver
- Matrix storing and Matrix free
- Parallel preconditioners: ASM, ILU, B-Jacobi, AMG, etc.
Finite Volume Method ($\mathcal{FV}$), cell-centered

\[ \frac{d}{dt} \int_{\Omega_i} U \, d\Omega_i + \int_{\partial\Omega_i} F^c \cdot n \, d\Omega_i = \int_{\partial\Omega_i} F^d \cdot n \, d\Omega_i + \int_{\Omega_i} S \, d\Omega_i \]

\[ \frac{\partial U}{\partial P} \left( P_i \right) \frac{dP_i}{dt} \Omega_i + R^{\mathcal{FV}}(P_i) = 0 \]

Cell-centered discretization

\[ R^{\mathcal{FV}}(P_i) = \sum_{f=1}^{N_f} F^c_f \Sigma_f - \sum_{f=1}^{N_f} F^d_f \Sigma_f - S_i \Omega_i \]

Linear Reconstruction + Flux Limiter $\Phi$

\[ \tilde{P}(x_q) = P_i + \Phi_i \nabla P_i \cdot (x_q - x_i) \]

Central discretization for interface diffusive flux

\[ F^d_f = F^d \left( P_f, \nabla P_f, n_f \right) \]

\[ \nabla P_f = \frac{1}{\Omega^f} \int_{\Sigma^f} P \, n \, d\Sigma^v = \frac{1}{\Omega^f} \sum_{s=1}^{N_f^i} \tilde{P}_i n_i \Sigma^v_f \] (Green-Gauss)

\[ \nabla P_f = \frac{p^R - p^L}{d_{LR}} (\hat{e} \cdot \hat{n}) n + \frac{1}{2} (1 - \hat{n} \otimes \hat{n}) \left( (\nabla P)^L + (\nabla P)^R \right) \]

Upwind schemes for interface convective flux

\[ F^c_f = \left\{ \begin{array}{ll}
\frac{1}{2} \left[ F^c_R + F^c_L - |\tilde{A} | (U_R - U_L) \right] & \text{Roe} \\
F^+ + F^- = A^+ U_L + A^- U_R & \text{S-W} \\
\hat{m}_{1/2} \Psi_L / R + p_{1/2} & \text{AUSM} \end{array} \right. \]
Residual Distribution Method ($\mathcal{RD}$), vertex-centered

$$\frac{\partial U}{\partial P}(P_l) \frac{dP_l}{dt} V_l + R^{RD}(P_l) = 0$$

**FEM linear interpolation**

$$P^h(x, t) = \sum_{j=1}^{d} P_j(t) N_j(x), \quad N_j(x_k) = \delta_{jk}$$

**Vertex-centered discretization**

$$R^{RD}(P_l) = \Phi^c_l - \Phi^d_l - \Phi^s_l$$

**Discretization of convective term**

$$\Phi^c_l = \sum_{\Omega \in \Xi_l} B^\Omega_l \left( K_l^{\pm} \right) \phi^c, \quad K_l^{\pm} = \frac{1}{N_d} \bar{R}_l \bar{\Lambda}_l^{\pm} \bar{L}_l$$

**Petrov-Galerkin discretization of source term**

$$\Phi^s_l = \sum_{\Omega \in \Xi_l} \int_{\Omega} w^\Omega_l S d\Omega \overset{1\text{-point}}{\rightarrow} \sum_{\Omega \in \Xi_l} B^\Omega_l S_c \Omega$$

**Galerkin discretization of diffusive term**

$$\Phi^d_l = - \sum_{\Omega \in \Xi_l} \frac{1}{\Omega_d} \int_{\Omega} F^d(P, \nabla P) \cdot n_l \, d\Omega$$
High-Order Flux Reconstruction ($\mathcal{FR}$) (PhD R. Vandenhoeck)

High-order Finite Element-type method (~DG, SD, SV)

- H. T. Huynh, 2007
- High-order reconstruction using correction polynomials: VCJH

\[
\frac{d\hat{u}^\delta_i}{dt} = -\frac{\partial \hat{F}^\delta}{\partial \xi}
\]

Gnoffo’s cylinder case ($M_\infty = 17.6$): FR vs. reference FV solution (AIAA-2019-1153)
High-Order Flux Reconstruction (\(\mathcal{FR}\)) (PhD R. Vandenhoeyeck)

Two key ingredients to stabilize FR in hypersonics: shock capturing and positivity preservation

**Shock Capturing**
- **Artificial Viscosity (AV) in shock area mitigates Gibbs phenomenon**
  \[
  \frac{\partial \mathbf{u}}{\partial t} = -\nabla \cdot \mathbf{f}_t + \mathbf{f}_u + \nabla \cdot \mathbf{f}_{\text{av}}
  \]
  \[
  f_{\text{av}} = \varepsilon \nabla \mathbf{u}
  \]
  - Persson and Peraire (2006) and Yu et al. (2015) for DG: **LLAV**
  - Compatible with implicit time integration
  - \(\varepsilon\) only added in shock region \(\rightarrow\) shock detector \(S\)

  \[
  \varepsilon = \begin{cases} 
  0 & \text{if } S < S_0 - \kappa, \\
  \varepsilon_0 & \text{if } S_0 - \kappa \leq S \leq S_0 + \kappa, \\
  0 & \text{if } S > S_0 + \kappa,
  \end{cases}
  \]

  \[
  S = \log_{10} \left( \frac{u_m - u^{P-1}_m}{u_m - u_m^{P-1}} \right)
  \]

  - Alleviate fine-tuning:
    \[
    S_0 = -5 \log_{10} P - 0.5
    \]

  \[
  \delta_s^* = 2 
  \]

  \[
  \delta_s^* = 4 
  \]

  \[
  \delta_s^* = 8 
  \]

**Positivity Preservation**

**LLAV cannot guarantee the physicality of conservative state** \(\mathbf{u} = (\rho, \rho \mathbf{v}, \rho e)\)

\[
\rho > 0 \quad \text{and} \quad p = (\gamma - 1) \left( \rho e - \frac{1}{2} \frac{||\mathbf{v}||^2}{\rho} \right) > 0.
\]

1. Loop over elements, mark element with negative \(\rho\) or \(\rho\) in a flux point. For \(\rho > 1\) also consider solution points
2. Define the lowest admissible value:
   \[
   \epsilon = \min(10^{-13}, \tilde{p}, p(0)).
   \]
3. Compute new density in solution points \(j\): (\(j\) refers to flux points)
   \[
   \tilde{p}_i = t_1 (\tilde{p}_i - \tilde{p}) + \tilde{p} \quad \text{with} \quad t_1 = \min \left( \frac{\tilde{p} - \epsilon}{p_{\text{min}}} - 1 \right)
   \]
4. Compute new state to limit pressure:
   \[
   \tilde{u}_j = t_2 (\tilde{u}_j - \tilde{u}) + \tilde{u} \quad \text{with} \quad t_2 = \min(t_j)
   \]
   by solving in each flux point \(j\): (2nd order polynomial equation)

\[
 p(t_j (\tilde{u}_j - \tilde{u}) + \tilde{u}) = \epsilon
\]

Mesh deformation solver \( (F. \text{ Huhn}, P. \text{ Santos}, F. \text{ Benameur}) \)

Minimize integral: \( I_{ij} = L_{ij} W_{ij} (X_j - X_i)^2 \)

- \( I_{ij} \) represents potential energy of a spring with stiffness \( W_{i,j} \) and zero equilibrium length
- Find equilibrium nodal positions of the spring system if \( \frac{\partial I}{\partial X} = 0 \) and \( \frac{\partial^2 I}{\partial X^2} > 0 \):
  \[
  \frac{\partial I_{ij}}{\partial X_i} = 2L_{ij} W_{ij} (X_i - X_j) = 0
  \]
- Collect contributions over all nodes:
  \[
  \sum_{j=1}^{n} L_{ij} W_{ij} (X_i - X_j) = 0, \text{ with } W_{ij} = |U_j - U_i|
  \]
- Solve the linear system:
  \[
  A \mathbf{X} = 0, \text{ where } A_{ij} = \begin{cases} 
  -L_{ij} W_{ij} & i \neq j \\
  \sum_{j=1}^{n} L_{ij} W_{ij} & i = j 
  \end{cases}
  \]
- BCs: \( X_i = X_i^0 \) or \( \frac{\partial (X_i \cdot n)}{\partial n} = 0 \).

\( \uparrow \) AMR on \( M_\infty = 2 \) flow on a wedge channel
\( \downarrow \) AMR on 2D MHD rotor case

Monte Carlo radiation algorithm (A. Sanna, P. Santos, B. Tershanski)

Radiative Transfer Equation (RTE)

\[
\frac{\partial I_\nu(r, \nu, \Omega)}{\partial r} = e_\nu(r, \nu, \Omega) - \alpha_\nu(r, \nu, \Omega)I_\nu(r, \nu, \Omega)
\]

1. Assign the total emitted radiative energy in each cell to \( N_e \) of virtual photons.
2. Send each photon to a random direction: \( d = d_r / |d_r|, \quad d_r = -1 + 2 \cdot R \)
3. A ray tracing algorithm traces the photon path through the computational domain:
   - Our algorithm is based only on vector operations for 2D/axi/3D unstructured grids.
4. Beer’s law defines absorption criteria in the gas: \( \int_0^s \alpha_\lambda ds \geq -\ln(1 - R_s) \)
5. At the wall, photons can be absorbed or reflected depending on local emissivity \( \epsilon \).
6. Domain decomposition strategies take care to allow photons to cross partition boundaries.
7. Assemble radiative heat flux divergence in cell \( i \) for each randomly selected frequency \( \nu_k \):

\[
Q_{rad} = \nabla \cdot q_{rad,i} = \sum_{k=1}^{N_\nu} \left( \frac{P_i(\nu_k)}{V_i} - \sum_{j \neq i} \frac{P_j(\nu_k)}{V_j} R_{ij}(\nu_k) \right)
\]

- \( R_{ij} \) determines which portion of \( P \) emitted by photons from cell \( j \) is absorbed by cell \( i \).

A. Lani, P. Duarte Santos, A. Sanna, AIAA-2013-2893

Monte Carlo radiation algorithm (A. Sanna, P. Santos, B. Tershanski)

Radiative heat flux (FV + Monte Carlo)

Fire II: Earth atmosphere, 11-species, 2500-50000 Å, 200k cells

Huygens: Titan atmosphere, 13-species, 2500-50000 Å, 350k cells

3D (left) and mid-plane (right) surface heat flux, PARADE (1000 rays/cell) vs. HSNB (40M rays)
Aerothermodynamics modeling
Governing equations for TCNEQ

Advection-diffusion-reaction PDE’s

\[
\frac{\partial \mathbf{U}}{\partial \mathbf{P}} \frac{\partial \mathbf{P}}{\partial t} + \nabla \cdot \mathbf{F}^c = \nabla \cdot \mathbf{F}^d + \mathbf{S}
\]

Conservative and natural variables for Multi-T model

\[
\mathbf{U} = \begin{bmatrix} \rho_s & \rho \mathbf{u} & \rho E & \rho_m \mathbf{e}_{v,m} & \rho_e \mathbf{e} \end{bmatrix}^T \quad \mathbf{P} = \begin{bmatrix} \rho_s & \mathbf{u} & T & T_{v,m} & T_e \end{bmatrix}^T
\]

Fluxes and Source Terms for Multi-T model (ionized mixture)

\[
\mathbf{F}^c = \begin{pmatrix} \rho_s \mathbf{u} \\ \rho \mathbf{u} \mathbf{u} + \rho \hat{\mathbf{l}} \\ \rho \mathbf{u} \mathbf{H} \\ \rho_m \mathbf{u} \mathbf{e}_{v,m} \\ \rho \mathbf{u} e_e \end{pmatrix}, \quad \mathbf{F}^d = \begin{pmatrix} -\rho_s \mathbf{u} \mathbf{s} \\ (\hat{\mathbf{r}} \cdot \mathbf{u})^T - \sum \rho_s \mathbf{u} \mathbf{s} \mathbf{h}_s - \mathbf{q} \\ -\rho_m \mathbf{u} \mathbf{m} h_{v,m} - \mathbf{q}_{v,m} \\ -\sum \rho_s \mathbf{u} \mathbf{s} \mathbf{h}_e,s - \mathbf{q}_e \\ \end{pmatrix}, \quad \mathbf{S} = \begin{pmatrix} \mathbf{e}_s \\ 0 \\ -\mathbf{Q}_{\text{rad}} \\ \Omega_m^v, t + \Omega_m^e, t + \Omega_m^c, t + \Omega_m^v, t + \sum_m \Omega_m^{v,e} - \mathbf{Q}_{\text{rad}} \\ -p_e \nabla \mathbf{u} + \mathbf{e}, t + \mathbf{I} - \sum_m \Omega_m^{v,e} - \mathbf{Q}_{\text{rad}} \end{pmatrix}
\]

MUTATION by T. Magin (VKI) & M. Panesi (UIUC), PLATO by A. Munafo’ (UIUC)

Computation of transport, thermodynamics, chemistry, energy transfer, radiative properties
COOLFluiD Aerothermodynamics

Models, algorithms, aero thermochemical properties are plugins.
ESA EXPERT (EXPERimental Re-entry Test-bed) vehicle

► Air-5, 2T ($T$, $T_v$), $M_\infty = 13.5$, $\alpha = 0^\circ$

EXPERT re-entry vehicle: to be launched soon

Computational mesh (3,840,453 hexa)

Mach number and $T_v$

FV AUSM+

M. Panesi, A. Lani et al., AIAA-2007-4317, 2007
FIRE II experiment: Collisional Radiative (CR) models

▶ Air-11, $2T$ ($T$, $T_{ve}$), $V_\infty = 11360$ [m/s], $\alpha_{esc} = 0$, $t=1634$ [s]

M. Panesi, A. Lani and O. Chazot, AIAA-2009-3920
M. Panesi and A. Lani, Phys. of Fluids, 2013
NATO STO experiments: double cone flows (AVT 136)

- **Nitrogen-2**, \(2T (T, T_{N_2}^\gamma)\), \(M_\infty = 11.5\)

Mach number field

Surface heat flux measurements:
COOLFluiD (CRD-Bx) vs. FV solvers

NATO STO experiments: double wedge flows (AVT 205)

Air, perfect gas, $M_\infty = 7.11$, unsteady

Movie: temperature field

Movie: wall heat flux (CFD vs. experiments at $t=0.327 \text{ ms}$)

Wedge configuration

D. Knight, O. Chazot, ..., A. Lani et al., J. Progr. Aerospace Sciences, 2017
Inductively Coupled Plasma: testing in VKI Plasmatron

**Air-11**, LTE, $\dot{m} = 8$ [g/s], $p = 10000$ [Pa], $P = 90$ [kW]

Incompressible subsonic testing

Temperature field *(Sartori)*
ICP-LTE solver, Rhie-Chow scheme

Temperature field *(V. Van der Haegen)*
ICP-LTE solver, modified AUSM+up scheme
Expanding hypersonic flows: VKI Longshot facility

**Nitrogen**, $P_0 = 3256.22$ [Pa], $T_0 = 2652.1$ [K]

Movie: expansion in nozzle up to $M=14$
Pressure, 3-point Backward Euler, FV Roe
(courtesy of K. Bensassi)

Stagnation heat flux: experiments vs. CFD

QARMAN Cubesat for Aerothermodynamics research

- **Air-5**, $2T \ (T, \ T_v), \ M_\infty = 8.46$, steady (PhD F. Ben Ameur)

- Effect of AMR (r-adaptation) on heat flux

- First high-order FR results with thermo-chemical NEQ (AIAA 2019-1391)
Radio blackout during re-entry (PhD V. Giangaspero)

Hypersonic speed → High temperature → Gas ionizations → Plasma Layer → RF Blackout

- Re-entry plasma
  - Ionized charged particles
- Ionization level
  - Electron number density
- Plasma Frequency $f_p$
  - Natural frequency of plasma
- Blackout Condition
  - $f_p > f_{radio}$

Methodology
- Re-entry trajectory
  - CFD solver
  - COOLFluiD
  - Thermodynamic Model
  - Mutation++
- Extract Density Fields
  - LARSEN
  - Raytracing
- Preliminary Results

Preliminary results:
- Blackout analysis on ExoMars re-entry module

Impact of prediction of radio blackout by use of raytracing

Investigate electromagnetic mitigation based on plasma flow control

Results from: "Blackout Analysis of Mars Reentry Missions" Sedeho Ranjbar and Andrea Lasti, Thierry Reig, Stefano Baccell, Bert Hov, Edgar Karsenti, and Jan Tholen, 2019, June 2019 (under review)
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**Magnetized plasma modeling**
CmPA core research: Space Weather modeling

Space weather events: from Sun to Earth, from CME to aurora borealis
Plasma is a mixture of **charged particles** (ions and electrons) and **neutrals** that is affected by **external magnetic fields**.
Multi-fluid magnetized plasma (PhD A. Alvarez Laguna)

Each species $\alpha$ (ions, electrons, neutrals) has its speed & temperature

### Fluid dynamics

$$\frac{\partial U}{\partial P} \frac{\partial P}{\partial t} + \nabla \cdot F^c = \nabla \cdot F^d + S$$

$$U = [\rho_\alpha \rho_\alpha u_\alpha \rho_\alpha E_\alpha]^T, \quad P = [\rho_\alpha u_\alpha T_\alpha]^T$$

$$F^c = \begin{pmatrix} \rho_\alpha u_\alpha \\ \rho_\alpha u_\alpha u_\alpha + p_\alpha \hat{I} \\ \rho_\alpha u_\alpha H_\alpha \end{pmatrix}, \quad F^d = \begin{pmatrix} 0 \\ \frac{\nabla T_\alpha}{T_\alpha} \\ (\frac{\nabla T_\alpha}{T_\alpha} \cdot u_\alpha)^T - q_\alpha \end{pmatrix}$$

$$S = \begin{pmatrix} \dot{m}_\alpha \\ Q_\alpha \vec{E} + \vec{j}_\alpha \times \vec{B} + \sum_{\beta \neq \alpha} \vec{R}_{\alpha\beta} \\ \vec{j}_\alpha \cdot \vec{E} + \sum_{\beta \neq \alpha} \vec{R}_{\alpha\beta} \cdot u_\alpha + \sum_{\beta \neq \alpha} H_{\alpha\beta} + \dot{Q}_\alpha \end{pmatrix}$$

### Maxwell + HDC

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times \vec{E} + \gamma \nabla \psi = 0$$

$$\frac{\partial \vec{E}}{\partial t} - c^2 \nabla \times \vec{B} + \chi c^2 \nabla \phi = -\frac{\vec{j}}{\epsilon_0}$$

$$\frac{\partial \psi}{\partial t} + \gamma c^2 \nabla \cdot \vec{B} = 0$$

$$\frac{\partial \phi}{\partial t} + \chi \nabla \cdot \vec{E} = \chi \frac{\rho_c}{\epsilon_0}$$

- Two scalar fields $\phi$ and $\psi$
- Artificial waves at $\chi c$ and $\gamma c$
- Clean divergence errors

A. A. Laguna et al, JCP, 2016

**Collisional terms**

**Maxwell-Fluid coupling terms**

**Chemical reactions terms** (e.g. ionization, recombination, charge exchange)
Solar wind/Earth magnetosphere interaction (unsteady)

06/04/00 magnetic storm, input based on the ACE satellite data

Movies: proton density, $B$ lines and physics-based mesh r-adaptation

Time-accurate parallel implicit FVM-MHD solver (also GPU-enabled)

Integrated into the ESA Virtual Space Weather Modeling Center

Ambitious long term goals (EU equivalent of US SWMF, NASA CCMC)

- integrate and couple together all European assets for real-time Sun-to-Earth SW forecasts
- mitigate impacts of SW events possibly affecting space operations, power systems, health...

European Space Weather models overview

Current components of the VSWMC system
Two-fluid: onset of chromospheric magnetic reconnection

- **Magnetic reconnection**: ubiquitous process by which the magnetic energy is transformed into thermal and kinetic energy
- **Two reacting fluid model**: considering charged particles + neutrals.

Drives explosions in astrophysics (e.g. CMEs)

Current density and B lines (w/o radiation)


Two-fluid: onset of chromospheric magnetic reconnection

- **Magnetic reconnection**: ubiquitous process by which the magnetic energy is transformed into thermal and kinetic energy.
- **Two reacting fluid model**: considering charged particles + neutrals.

Drives explosions in astrophysics (e.g. CMEs)

Current density and B lines (w/ radiation, plasmoids)


Courtesy from Shibata et al, Science 2007
Highly dynamical wave structures are identified in the chromosphere. Are they responsible for heating up the Sun atmosphere? Ours is a pioneer attempt to investigate weak ionization effects.

Chromospheric heating by slow magnetosonic waves

Geospace Environmental Modeling (GEM) challenge

by Dr. A. A. Laguna, Dr. N. Ozak, I. Alonso (University La Laguna)

- Benchmark case to validate space weather models
- Identifies essential physics in collisionless reconnection
- GPU-enabled two-fluid (ion-electron) FV solver

Time evolution of ionic momentum

A. A. Laguna et al, *Comp. Phys. Comm.*, 2018

Time evolution of electron momentum

Fusion: characterization of instabilities in screw pinch

by Dr. A. A. Laguna, N. Ozak, Prof. G. Lapenta

Screw pinch simulation in Tokamak (ion-electron): plasma column compressed by helical magnetic field

Electric current (red) showing kink instability
## Development status & perspectives

### COOLFluiD highlights
- Arguably the most advanced open source software platform for ATD and plasma modeling
- Thermochemical nonequilibrium models for characterizing ATD flows
- Pioneering multi-fluid/Maxwell models for characterizing space physics
- Advanced tools for radiation transport characterization
- Parallel solvers taking profit of massive heterogeneous HPC on multi-CPUs/GPUs

### ATD: ongoing/target research
- p-adaptive GPU-enabled FR solver for hypersonic transition (FWO PhD)
- r-adaptive FR solver for ATD in thermochemical nonequilibrium (master)
- Radio blackout analysis and mitigation via magnetic windowing (FWO PhD)

### Magnetized plasma: ongoing/target research
- Data-driven global coronal models starting from magnetogram data (AFOSR Postdoc)
- Multi-fluid modeling of wave propagation from photosphere to corona (FWO Postdoc)
- UQ of magnetic reconnection in magnetospheric conditions (FWO PhD)
- Multi-fluid FR solver for magnetic reconnection (master)
- Coupling multi-fluid and Particle-In-Cell models (KUL PhD)
- Exploiting heterogeneous HPC (CPU/GPU) towards exascale simulations
Thank you all for the attention!

https://github.com/andrealani/COOLFluiD/wiki