New Features and Applications

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Background

Objective

- Review **work in progress**: what is on my desk at the moment
- Provide details of code status, problems and future work beyond flashy slides and animations

Topics

1. Flash boiling model
2. Liquid film model
3. Naval hydrodynamics solver: steady-state flow and trim
4. Project status: development items and future work
    - Compressible flow solvers
    - Turbomachinery features: GGI update
    - OpenFOAM on Microsoft Windows
    - 1.6-dev development line

Flash-Boiling Simulations

Flash-Boiling Flows: **Shiva Gopalakrishnan, David P. Schmidt, UMass Amherst**

- The fundamental difference between flash boiling and cavitation is that the process has a higher saturation pressure and temperature: higher density
- Enthalpy required for phase change is provided by inter$-$phase heat transfer
- **Jakob number**: ratio of sensible heat available to amount of energy required for phase change

$$Ja = \frac{\rho_l c_p \Delta T}{\rho_v h_{fg}}$$

- Equilibrium models are successful for cavitation since Ja is large and timescale of heat transfer is small. Flash boiling represents a finite rate heat transfer process: **Homogeneous Relaxation Model (HRM)**

$$\frac{Dx}{Dt} = \frac{\bar{x} - x}{\Theta}; \qquad \Theta = \Theta_0 \epsilon^{-0.54} \phi^{1.76}$$

  x is the quality (mass fraction), relaxing to the equilibrium $\bar{x}$ over a time scale Θ

- The timescale Θ is obtained from empirical relationship: Downar–Zapolski [1996]. ϵ is the void fraction and ϕ is the non$-$dimensional pressure.

Flash-Boiling Simulations

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Flash-Boiling Flows: Numerical Method

- **Conservation of Mass**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\phi_v \rho) = 0$$

- **Conservation of Momentum**

$$\frac{(\partial \rho U^0)}{\partial t} + \nabla \cdot \left(\phi U^0\right) = -\nabla p^n + \nabla \cdot \left(\mu \nabla U^0\right)$$

- **Pressure Equation**

$$\frac{1}{\rho}\frac{\partial \rho}{\partial p}\Big|_{x,h}\left(\frac{\partial(\rho p^{k+1})}{\partial t} + \nabla \cdot (\rho U p^{k+1})\right) + \rho \nabla \cdot \phi^* - \rho \nabla \frac{1}{a_p} \nabla p^{k+1}$$
$$+ M\left(p^k\right) + \frac{\partial M}{\partial p}\left(p^{k+1} - p^k\right) = 0$$

The HRM model term is denoted as $M(=\frac{Dx}{Dt})$. The superscripts k and $k+1$ are the corrector steps for the pressure equation.

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Flash-Boiling Simulations

Conservation of Mass

```
solve
(
    fvm::ddt(rho) + fvm::div(phiv, rho)
);
```

Conservation of Momentum

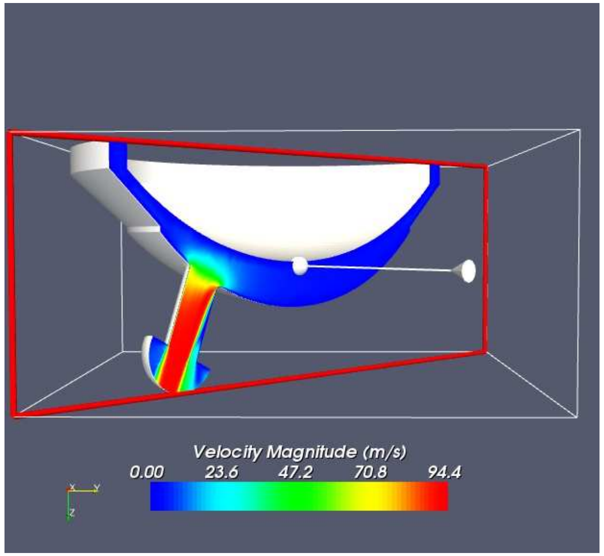
```
fvVectorMatrix UEqn
(
    fvm::ddt(rho, U) + fvm::div(phi, U) - fvm::laplacian(mu, U)
);
solve(UEqn == -fvc::grad(p));
```

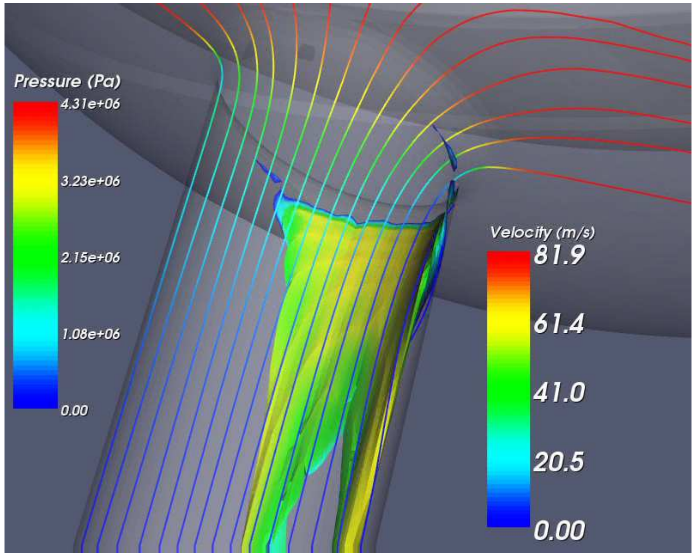
Pressure Equation

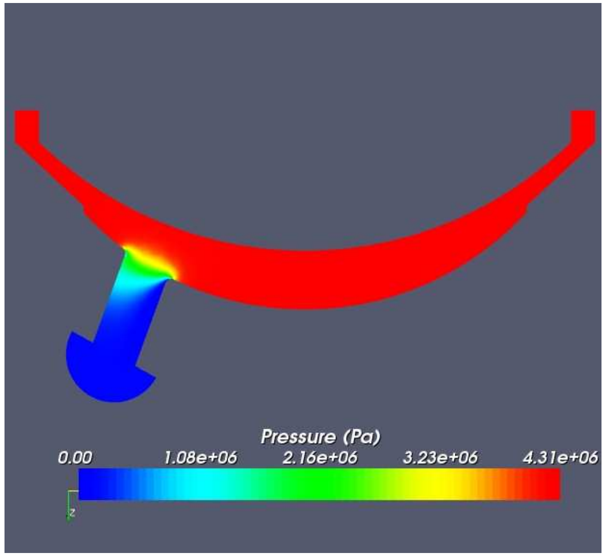
```
fvScalarMatrix pEqn(fvm::laplacian(rUA, p));

solve
(
    psi/sqr(rho)*(fvm::ddt(rho, p) + fvm::div(phi, p))
  + fvc::div(phivStar) - pEqn
  + MSave + fvm::SuSp(dMdp, p) - dMdp*pSave
);
```

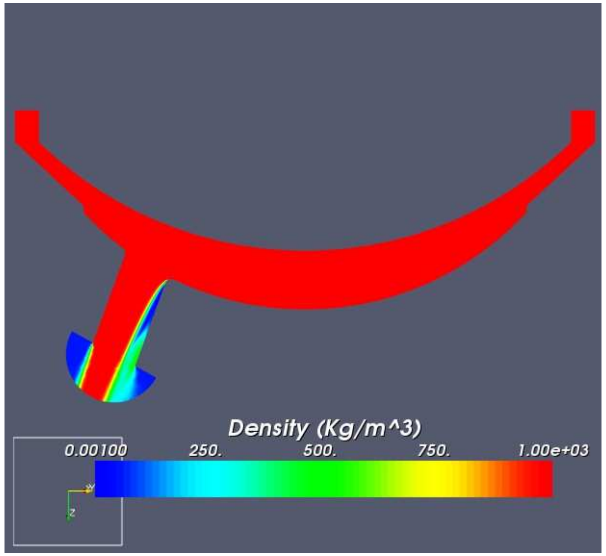
Flash-Boiling Simulations

Asymmetric Fuel Injector Nozzle-Design from Bosch GmbH.





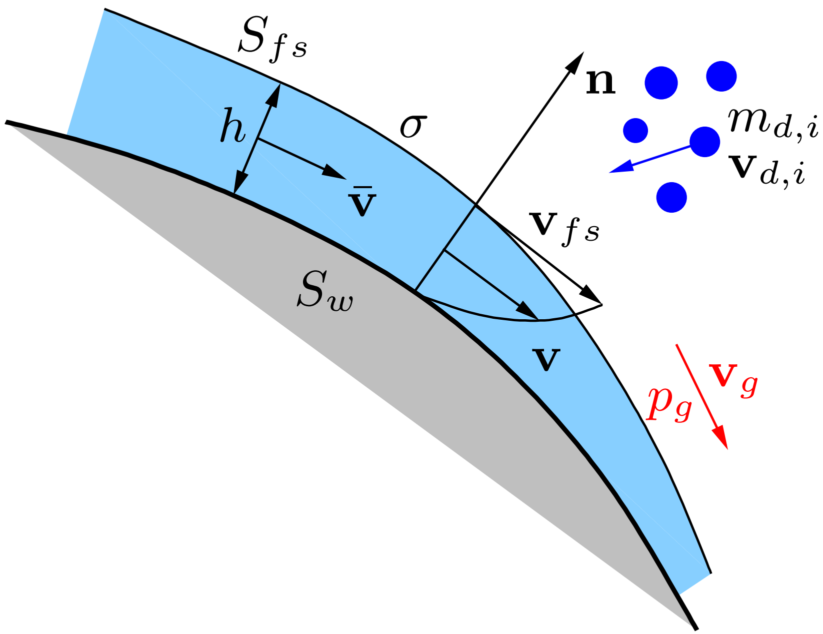




Thin Liquid Film Model

Modelling Assumptions: 2-D Approximation of a Free Surface Flow

- Isothermal incompressible laminar flow
- Boundary layer approximation:
  - Tangential derivatives are negligible compared to normal
  - Normal velocity component is negligible compared to tangential
  - Pressure is constant across the film depth
- Similitude of the flow variables in the direction normal to the substrate
  - Prescribed cubic velocity profile



Dependent variables: h and $\bar{\mathbf{v}}$

$$\bar{\mathbf{v}} = \frac{1}{h}\int_0^h \mathbf{v}\,\mathrm{d}h$$

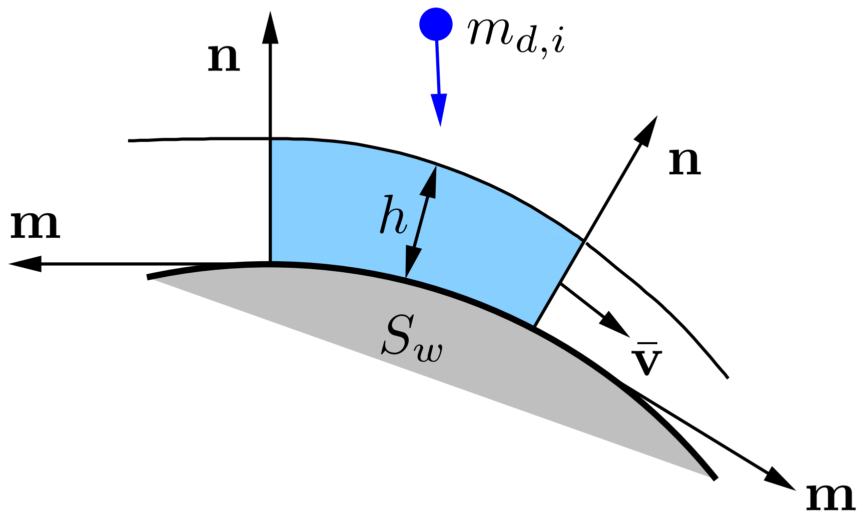
$$\mathbf{v}(\eta) = \mathbf{v}_{fs} \bullet \mathrm{diag}\left(\mathbf{a}\eta + \mathbf{b}\eta^2 + \mathbf{c}\eta^3\right)$$

$$\eta = \frac{n}{h},\;\; 0 \le n \le h$$

Thin Liquid Film Model

Liquid Film Continuity Equation

$$\int_{S_w} \frac{\partial h}{\partial t} \, \mathrm{d}S + \oint_{\partial S_w} \mathbf{m} \bullet \bar{\mathbf{v}} \, h \, \mathrm{d}L = \int_{S_w} \frac{\dot{m}_S}{\rho_L} \, \mathrm{d}S$$

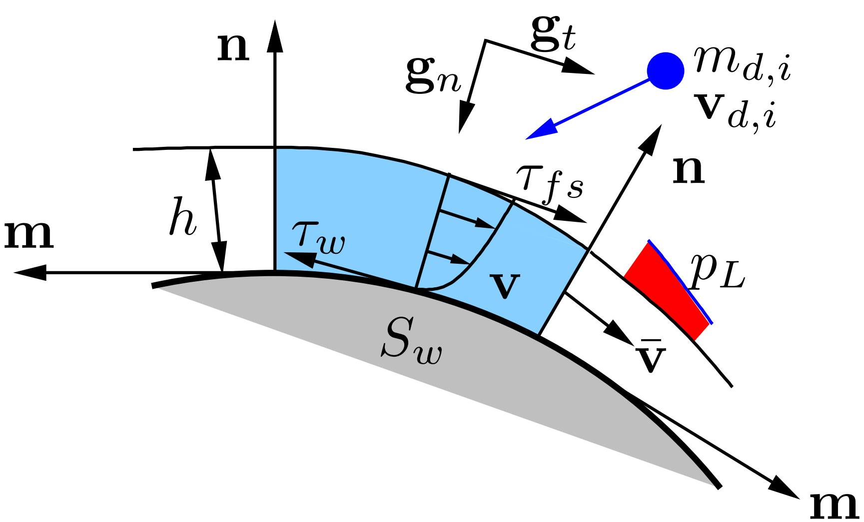


Thin Liquid Film Model

Liquid Film Momentum Equation

$$\int_{S_w} \frac{\partial h\bar{\mathbf{v}}}{\partial t}\,\mathrm{d}S + \oint_{\partial S_w} \mathbf{m}\bullet(h\bar{\mathbf{v}}\bar{\mathbf{v}} + \mathbf{C})\,\mathrm{d}L$$

$$= \frac{1}{\rho_L}\int_{S_w}(\boldsymbol{\tau}_{fs} - \boldsymbol{\tau}_w)\,\mathrm{d}S + \int_{S_w} h\mathbf{g}_t\,\mathrm{d}S - \frac{1}{\rho_L}\int_{S_w} h\nabla_s p_L\,\mathrm{d}S + \frac{1}{\rho_L}\int_{S_w}\bar{\mathbf{S}}_v\,\mathrm{d}S$$



$$p_L = p_g + p_d + p_\sigma + p_h$$

$$p_{d,i} = \frac{\rho(\mathbf{v}_{d,i})_n^2}{2}$$

$$p_\sigma = -\sigma\nabla_s\bullet(\nabla_s h)$$

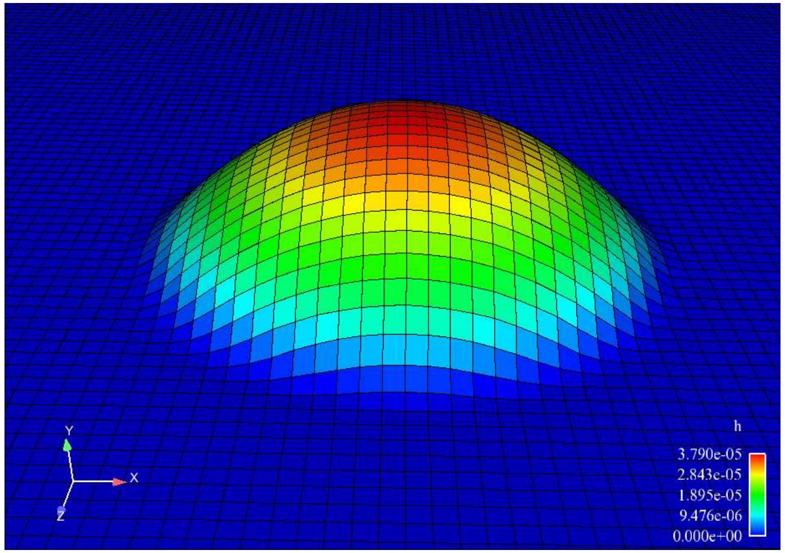
$$p_h = -\rho_L\mathbf{n}\bullet\mathbf{g}h$$

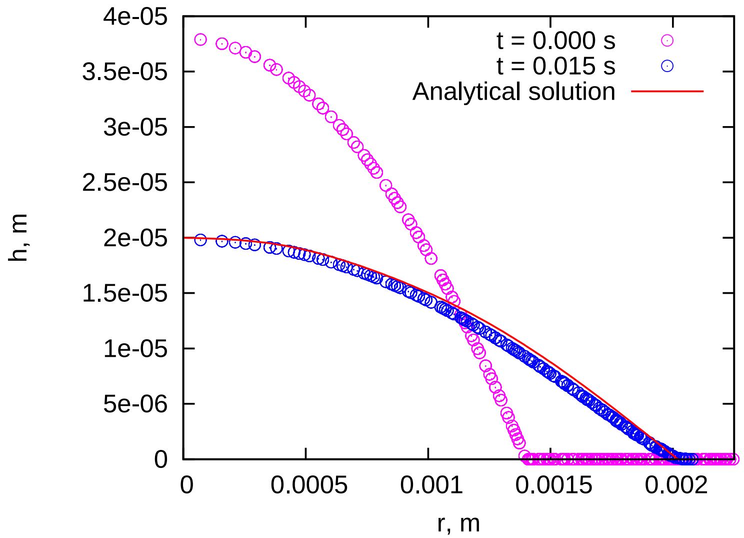
$$\bar{\mathbf{S}}_v = \frac{\sum_i m_{d,i}\,(\mathbf{v}_{d,i})_t}{\mathrm{d}t\ \mathrm{d}S}$$

Thin Liquid Film Model

Validation: Droplet Spreading Under Surface Tension

- Liquid film equations governing the flow; self-similar velocity profile
- Droplet spread driven by gravity and counteracted by surface tension
- Equation set possesses an (axi-symmetric) analytical solution



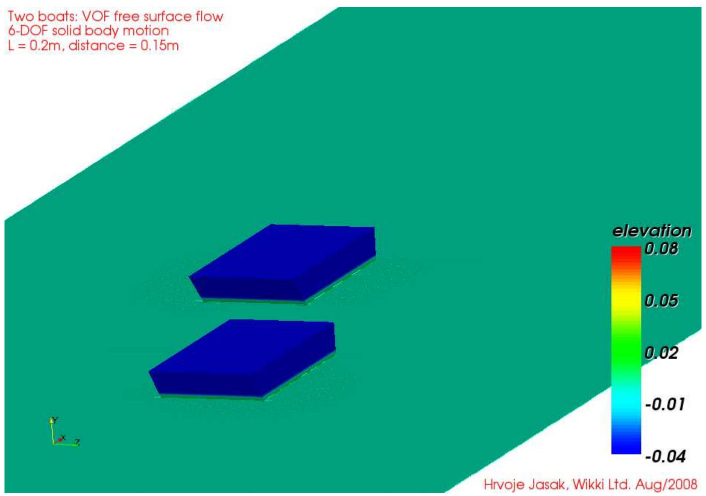


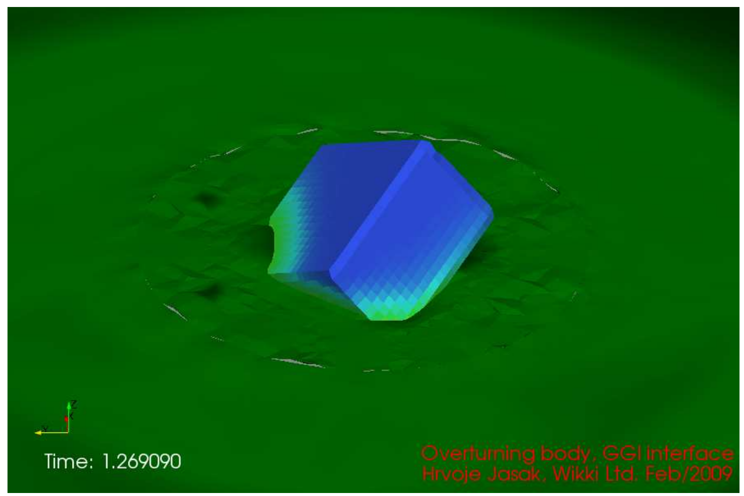
- Mesh handling, coupling and parallelisation: completed and validated
- Library contains tools for volume-to-surface and surface-to-volume mapping
- Liquid film model is ready for use!

Free Surface Flow: Examples

Floating Body in Free Surface Flow

- **Flow solver**: turbulent VOF free surface, with moving mesh support
- **Mesh motion** depends on the forces on the hull: 6-DOF solver
- **6-DOF solver**: `ODE + ODESolver` energy-conserving numerics implemented using quaternions, with optional elastic/damped support
- Variable diffusivity Laplacian motion solver with 6-DOF boundary motion as the boundary condition for the mesh motion equation
- Topological changes to preserve mesh quality on capsize
- Coupled transient solution of flow equations and 6-DOF motion, force calculation and automatic mesh motion: custom solver is built from library components

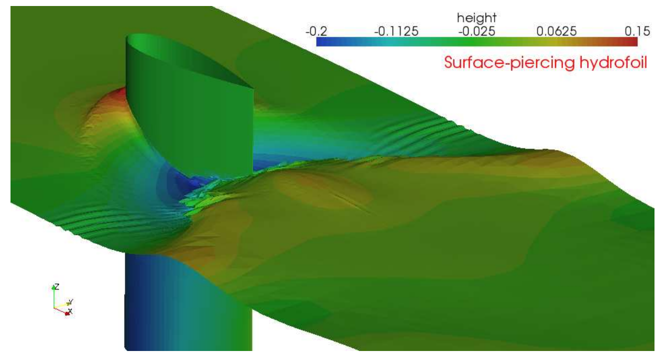


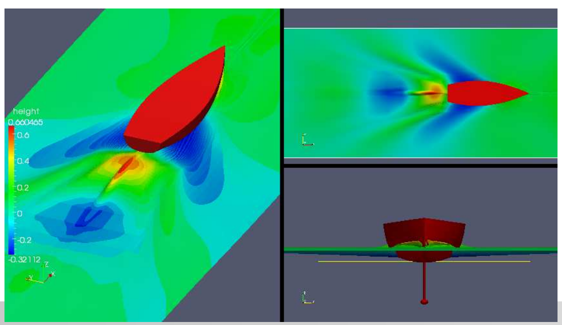


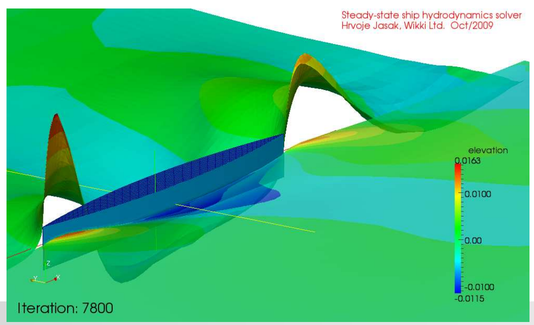
Free Surface Flow: Examples

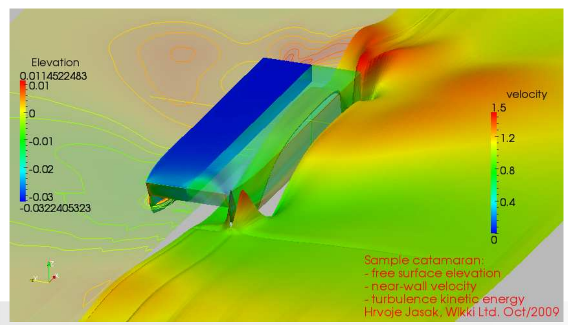
Naval Hydrodynamics Examples

- Ship resistance simulation in calm sea conditions requires a “steady-state” formulation for the free surface flow: **rewrite of basic numerics**
  - “Traditional” steady-state VOF solver with under-relaxation
  - Large Co-number tolerant transient solver
  - Validation pushed by BMW Oracle Team
- Steady trim: 6-DOF force balance with mesh motion with steady-state formulation
- **Level set method:** `foamedOver`
  - Alternative to VOF surface capturing
  - Resolves problem of VOF re-sharpening
  - Necessary for **overlapping grid solver**: with SUGGAR and DirtLib libraries (Eric Paterson, Ralph Noack, Penn State)









Project Status

Future Work and State of Development Items

- Work on **compressible flow solvers**: we need to do a better job
  - Steady-state solvers and improved convergence rates
  - Improvements in accuracy and shock resolution: `rhoCentralFoam`, `aeroFoam` are good attempts, but lacking in execution
  - **Block pressure-based solver** for turbomachinery applications
  - Implicit density-based shock-capturing solver of the Roe flux type. Help!
- GGI wrap-up: the code is complete, functional and validated
  - The implementation has lived up to expectation: accurate and stable
  - Derived forms working: current point of development is a **mixing plane** implementation (Martin Beaudoin, Hydro Quebec)
  - Large-scale simulation parallel performance issues: with 40M cells and 15 GGI pairs, the code slows down. The reason is known, but financial support is required for the project (resolve communication pattern)
  - Need to write a GGI numerics paper (in preparation)
- **Naval hydrodynamics solvers**: further work planned, limited to a consortium prepared to fund it. I will try and make the result publicly available
- Viscoelasticity: Jovani Favero to publish paper; free surface visco solver

Project Status

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Future Work and State of Development Items

- OpenFOAM on Microsoft Windows
  - I will be going to Redmond WA, to do the porting work
  - Objective: integrated Linux/Mac OS X/Windows (7?) source code with support for native builds (eg. Visual Studio, HPC environment)
  - Funded by the Microsoft HPC effort: looking for partners for validation and performance tuning and re-porting work
- OpenFOAM-1.6-dev line
  - In preparation, but progress slowed down due to project work
  - Some clean-up issues are interesting, but I'm scared of old-new bugs
  - Big worry: wall function re-implementation is wrong: needs to be fixed
  - To be hosted on GIT and SVN simultaneously as a part of side-by-side code management effort. Still no cooperation from OpenCFD
- Documentation project: **shut down!**, claiming Trademark infringement
- What are the consequences of Trademark wars by OpenCFD? Do we need to worry? Will this cause a change of name or attack on Stammtisch and Workshop?