A Massively Parallel Incompressible Smoothed Particle Hydrodynamics Simulator for Oilfield Applications

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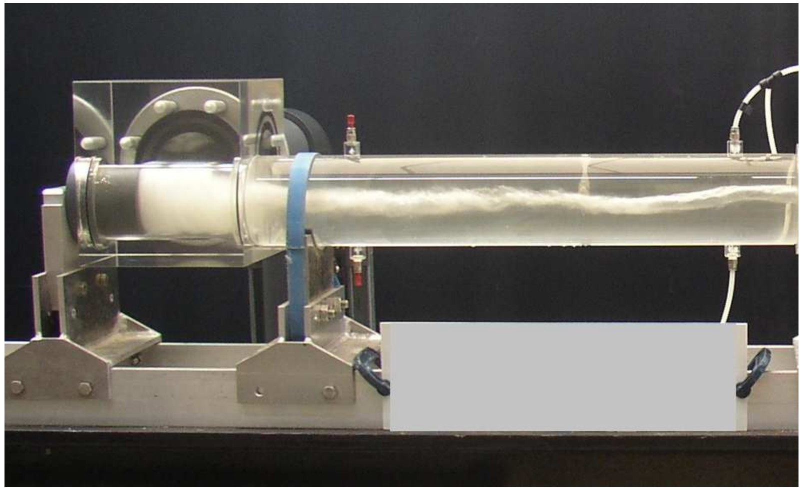
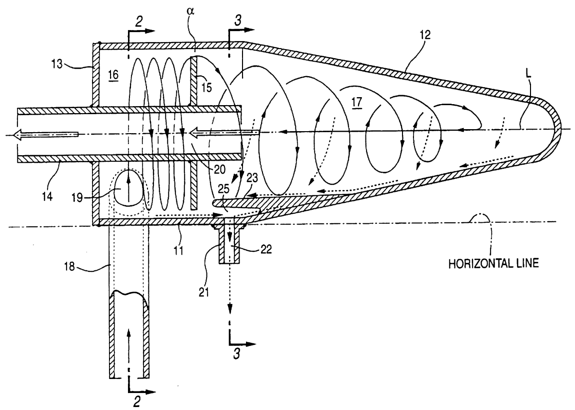
Introduction

- Multiphase flows are important to oil and gas industry
- Multiphase CFD can improve our understanding
- Multiphase CFD remains underdeveloped
- Smoothed Particle Hydrodynamics is good fit to many oilfield problems but significant scope for development
- Rotating gas-liquid flows of particular industrial importance





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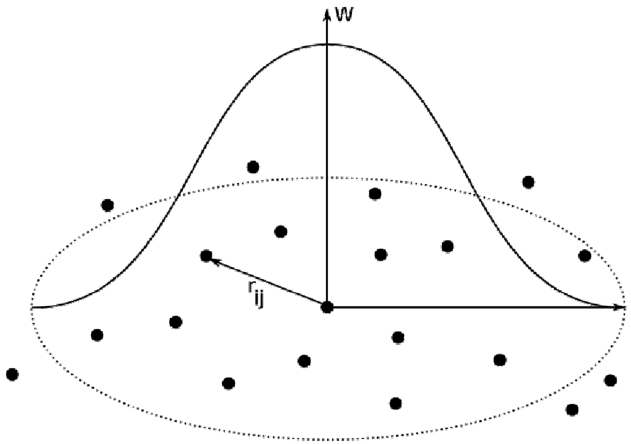
Smoothed Particle Hydrodynamics

- Fully Lagrangian meshless particle method
- Fluid properties distributed over points with kernel functions
- Topology changes and free surfaces
- Small volume of dominant fluid
- Particles can have history - eg shear history
- Expensive for simple problems, compares well for complex
- Immature method – restricted by computational cost
- Weakly Compressible and Incompressible Formulations

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right]$$



$$\nabla^2 p^{n+1} = \frac{\rho}{\Delta t}\nabla.\underline{u}*$$

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Resource Estimation

- Consider typical Rotating Flow Test Case
- Diameter 0.1m, length 1m
- 5mm resolution → 1-3 hours on single CPU
- 1mm resolution → 3-29 days on single CPU
- Parallel computing required
- ....and using incompressible formulation

Dickenson, P; 2009; "The Feasibility of Smoothed Particle Hydrodynamics for Multiphase Oilfield Systems";
Seventh International Conference on CFD in the Minerals and Process Industries; Melbourne 2009

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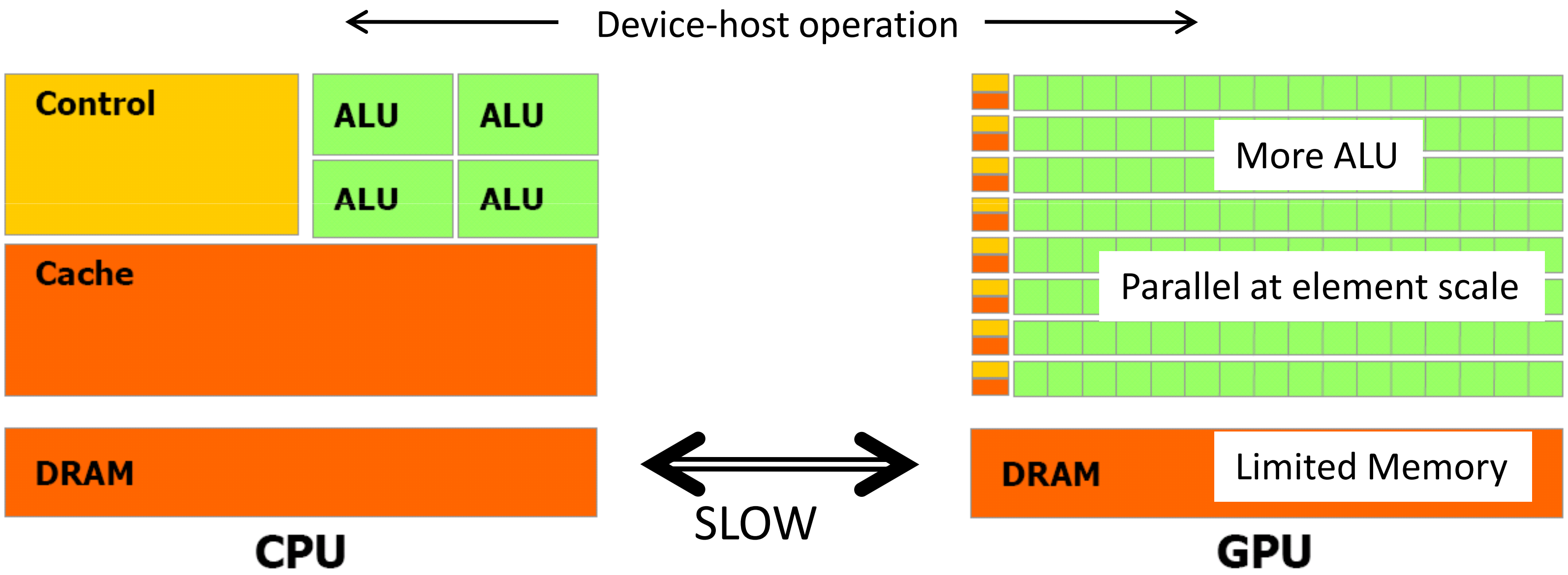
Massively Parallel Computing: GPU



- Good match to SPH EoM calculation
  - Simple data structures
  - High ratio of computation to memory
- Massively Parallel WCSPH exists ⟶ up to 50x speedup
- ISPH challenges ⟶ **set up and solve PPE matrix problem**

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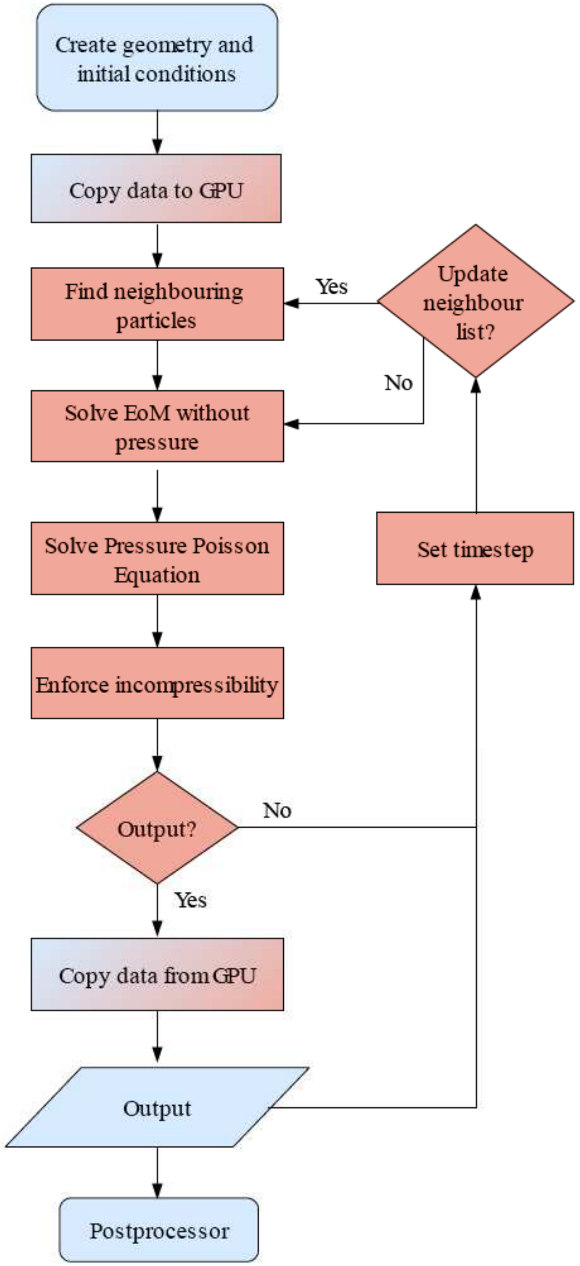
SPHIG Code Structure

- All significant computation on GPU
- Minimal data transfers



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Solving the PPE

- Pressure Poisson Equation
- Reduces to a matrix problem
- Matrix A is large but very sparse
- Need to solve on GPU ⟶ **minimise data transfers**
- Sparse matrix storage ⟶ **minimise memory use**
- BiCGSTAB Sparse matrix linear solver for GPU
  - Speed IT from vratis.com
- Input matrix in Compressed Sparse Row format

$$\nabla^2 p^{n+1} = \frac{\rho}{\Delta t} \nabla . \underline{u}^*$$

$$\underline{A}\underline{x} = \underline{b}$$

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PPE Set-up (1)

- Must generate matrix on GPU → **minimise data transfers**
- Generating matrix in CSR format is inherently serial

$$\begin{bmatrix} 1.0 & 1.4 & 0.0 & 3.0 \\ 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 5.2 \\ 7.1 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

vals = [1.0 1.4 3.0 1.0 1.0 5.2 7.1 1.0]
cidx = [0 1 3 1 2 3 0 3]
ridx = [0 3 4 6 8]

- Write entirely new solver or **create compatible parallel format**

PPE Set-up (2)

- New pCSR format developed for massively parallel matrix generation

$$\begin{bmatrix} 1.0 & 1.4 & 0.0 & 3.0 \\ 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 5.2 \\ 7.1 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

vals = [1.0 1.4 3.0 1.0 0.0 0.0 1.0 5.2 0.0 7.1 1.0 0.0]
cidx = [0 1 3 1 0 0 2 3 0 0 3 1]
ridx = [0 3 6 9 12]

- Fixed number of elements included per row
- Padded with existing zeros so back-compatible with CSR solvers
- Patent App GB1105576.1
- SPHIG: one thread per row

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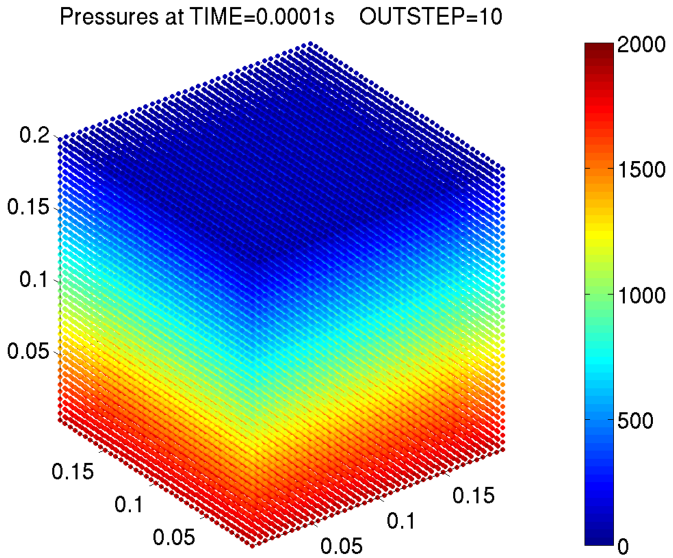
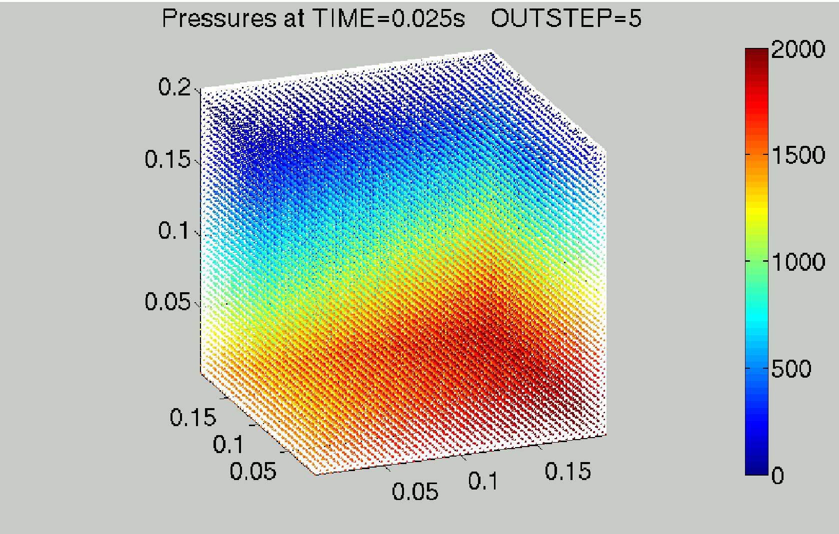
Results

Hydrostatic



Inclined Hydrostatic



- Correct pressure distributions obtained within 3 time steps
- Initial oscillation while particles move off grid
- Much shorter duration than acoustic waves seen in WCSPH
- Penetration of wall boundaries

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Other Issues.....

- Neighbour Searching
  - Massively parallel implementation
- Free surface boundary condition
  - Detect by kernel truncation
  - Set pressure to zero
- Wall boundary condition
  - Liquid particles fixed in space
  - Impose normal pressure gradient condition
  - Changes in progress.....

Conclusion

- All ISPH components implemented for GPU computing
- Pressure Poisson Equation generated and solved on the GPU
- Maximum number of particles limited by significant GPU memory required to store the PPE matrix
- Boundary conditions are challenging
- Massively parallel ISPH is achievable but more work is required before complex problems can be simulated

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