Performance Evaluation of SIMPLE Algorithm Using GPU Accelerated Sparse Matrix Multiplication

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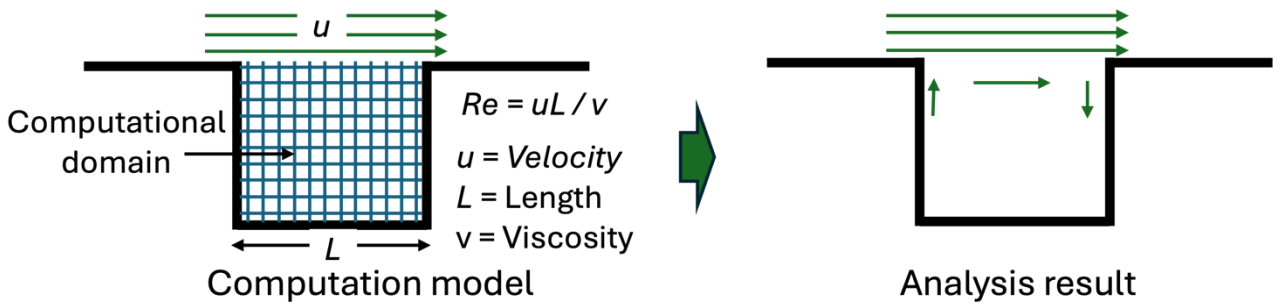
Abstract

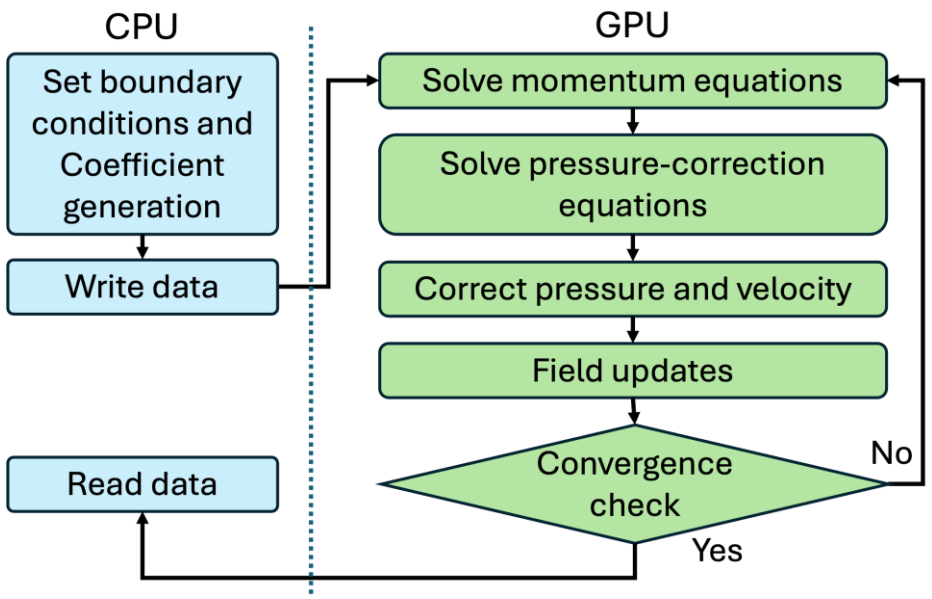
The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is one of the most widely used numerical methods for incompressible fluid-flow simulation in computational fluid dynamics. Previous GPU-based implementations of SIMPLE algorithm mainly focused on achieving speed-up for relatively small grids and employed simple iterative solvers such as Jacobi or Gauss-Seidel. Those methods require many iterations to converge, which limits their ability to process large grids. To address this problem, this work combines standard CUDA libraries with custom fused kernels to efficiently execute the solver, achieving up to a 13.58x speed-up compared to an optimized CPU implementation while maintaining identical convergence accuracy.

Background

- High computation amount
- Large number of iterations
- Difficult to converge



Proposed method



Computation	Implementation
Sparce matrix-vector product	cuSPARSE
Vector dot product	cuBLAS
X + αY + ωZ type computation	Custom kernels
Presure and velocity correction	Custom kernels
Field updates	Custom kernels
Convergence check	Custom kernels

- GPU concentrated computation with optimized libraries and custom kernels
- Custom fused kernels to reduce kernel launch latency
- Double precision computation for high accuracy

Performance Evaluation

Algorithm specifications

Parameter	Value
Reynolds number	100
Update rate for the velocity fields	0.7
Update rate for pressure correction equation	0.2
Convergence tolerance of bicgstab	10^{-6}

Hardware specifications

CPU	GPU
Intel Xeon Silver 4316	Nvidia A100 40GB HBM2e
Intel oneAPI Compiler 2024.1 Intel MKL	CUDA 12.8

Comparison against CPU computation

Grid size	CPU		GPU		Speedup
	Iterations	Time [ms]	Time [ms]	Iterations	t_{CPU}/t_{GPU}
101 x 101	3,320	94,008	3,320	121,870	0.77
151 x 151	7,057	728,995	7,057	411,776	1.78
201 x 201	12,127	2,881,745	12,127	876,587	3.29
251 x 251	18,397	8,483,358	18,397	1,548,517	5.48
301 x 301	25,836	18,332,652	25,836	2,289,413	8.01
351 x 351	34,413	38,412,786	34,413	3,464,037	11.09
401 x 401	44,101	62,151,324	44,100	4,580,483	13.57

References

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3. Kiril S. Shterev, GPU implementation of algorithm SIMPLE-TS for calculation of unsteady, viscous, compressible and heat-conductive gas flows, 2018