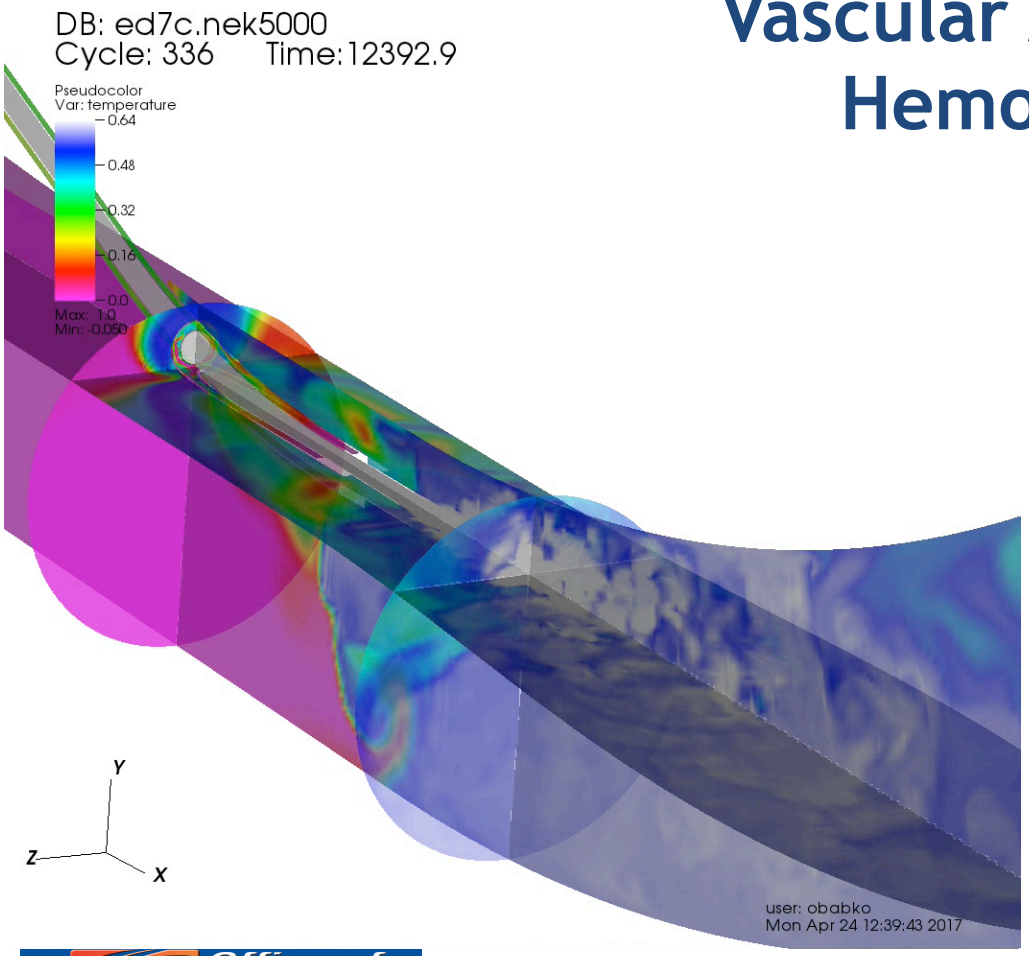
Large-Eddy Simulation of Flows Through a Novel Vascular Access Device for Hemodialysis Access



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Dual Lumen Novel Vascular Access Device (VAD)

- Novel combination of a relatively slender 18-gauge needle and a concentric, multilayer vascular dilator with funneled side orifices (US patent granted to Kenvelo LLC)

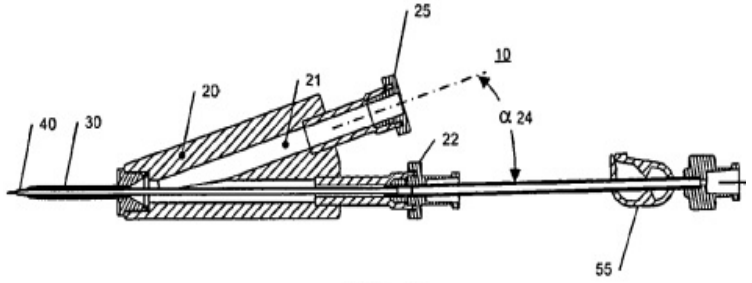
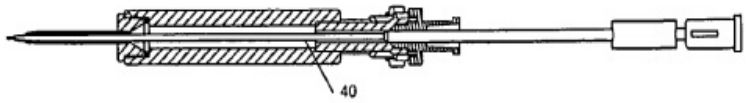


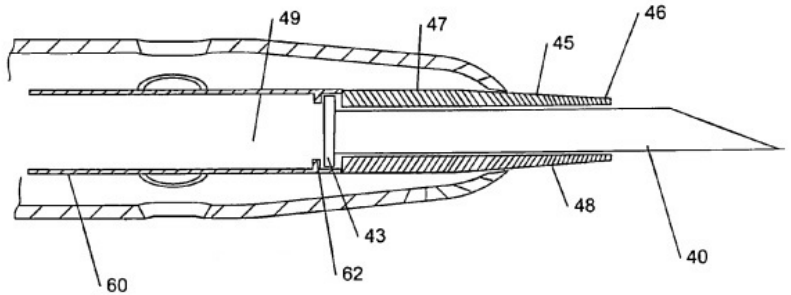
FIG. A

- Seems to provide a superior blood flow, lessened reported pain, and increased hemodynamic performance



SECTION VIEW A-A
FIG. B

- The goal is to further optimize geometry using CFD Solver Nek5000



Nek5000: Open-Source General Geometry Spectral-Element Method (SEM) CFD Solver

https://nek5000.mcs.anl.gov (& at github.com/Nek5000)

- Spectral Element Discretization: High accuracy at low cost
  - Also: even when it looks like there is no boundary layer, there actually is (beauty of the Gauss-Lobatto points).
  - R&D 100 Award (2016)
- Tailored to LES and DNS of incompressible turbulent heat transfer, but also supports
  - Low-Mach combustion, MHD, conjugate heat transfer, moving meshes
  - New features in progress: uRANS, compressible flow (U of Florida), low-Mach two-phase, Ensemble Averaging
- Chief Architect: Paul Fischer.

Scaling: 1999 Gordon Bell Prize; > 10^6 MPI processes.

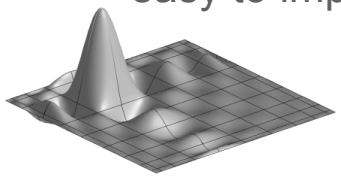
- Local Polynomial Nodal Basis:

$$u(x,y)|_{\Omega^e} = \sum_{i=0}^{N}\sum_{j=0}^{N} u_{ij}^e\, h_i(r)\, h_j(s)$$

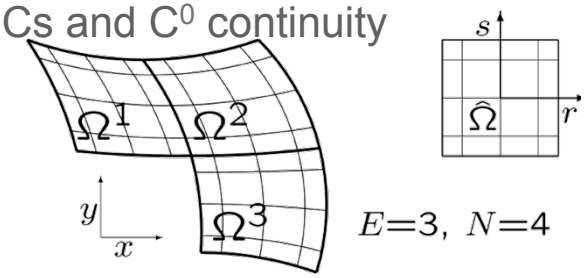
$$h_i(r) \in \mathcal{P}_N(r), \qquad h_i(\xi_j) = \delta_{ij}$$

- x_j = Gauss-Lobatto-Legendre quadrature points:

  - stability (*not* uniformly distributed points)
  - allows pointwise quadrature (for *most* operators…)
  - easy to implement BCs and C^0 continuity



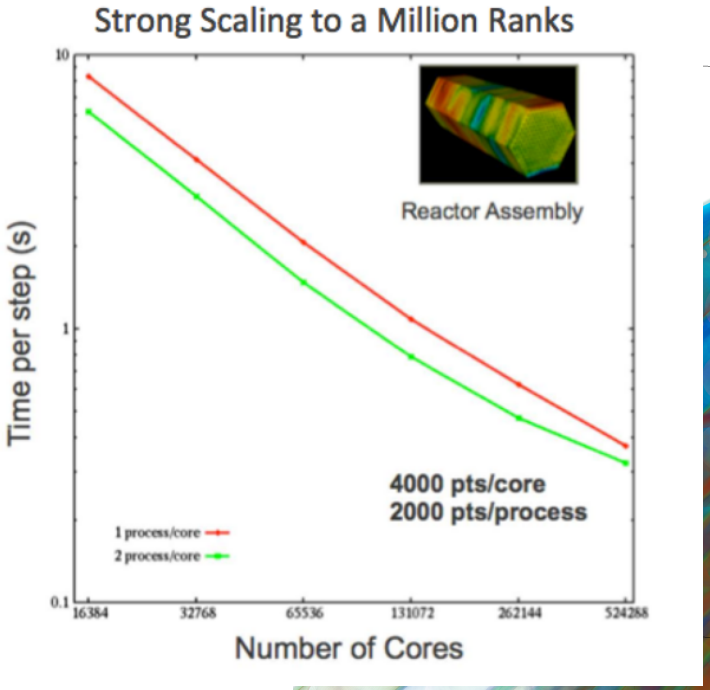
2D basis function, N=10



$E=3,\ N=4$

Why open-source SEM code Nek5000?

- High order => Exponential convergence (for continuous solutions) => min dof (and time) per accuracy
  - Dispersion errors accumulate linearly with time integration
    - Thus to maintain 1% accuracy at the end of 1e5 timesteps requires 1e-7 convergence tolerance per time step
  - Great transport properties even for marginally resolved flows



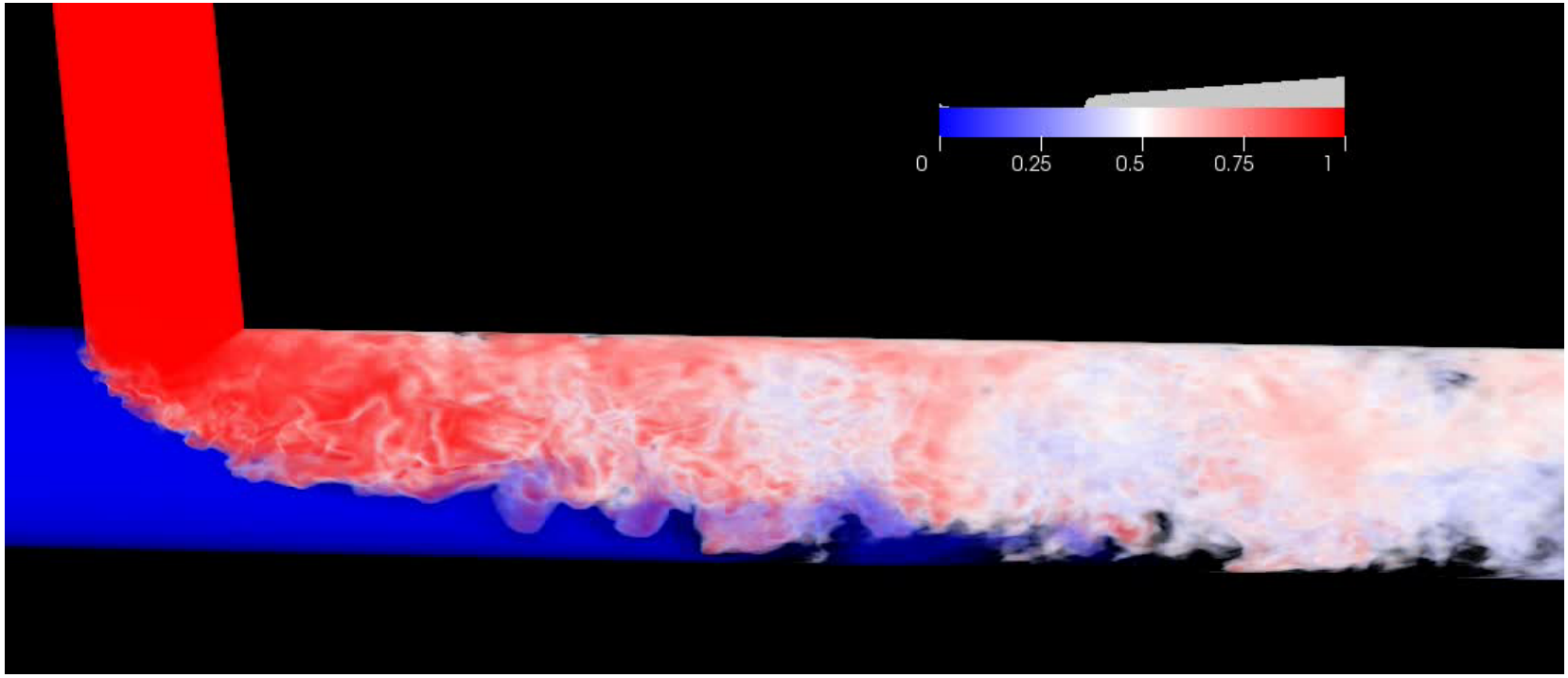
- Scalability (2k…10k grid points per MPI rank)
  - Gorden Bell Prize
  - Scales beyond 1 M MPI ranks on BG/Q

61-pin 7-wire-pitch conjugate heat transfer (E=15M, P=1M)

- Efficiency & Flexibility:
  - Exceptional pressure solvers
    - State-of-the-art preconditioners (8…15 pressure iterations per timestep)
    - Algebraic Multigrid (AMG) for large E>100,000

Why Nek5000? Validation…

T-junction Temperature

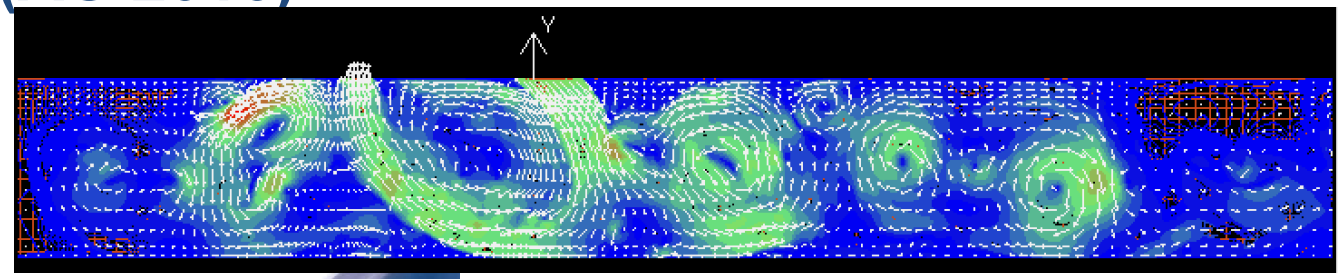


- Validation & Verification
  - Blind benchmarks:
    - 2012 OECD/NEA/IAEA Vattenfal T-junction benchmark (#1 in temperature predictions)
  - Other benchmarks show good performance also in flows with transition to turbulence

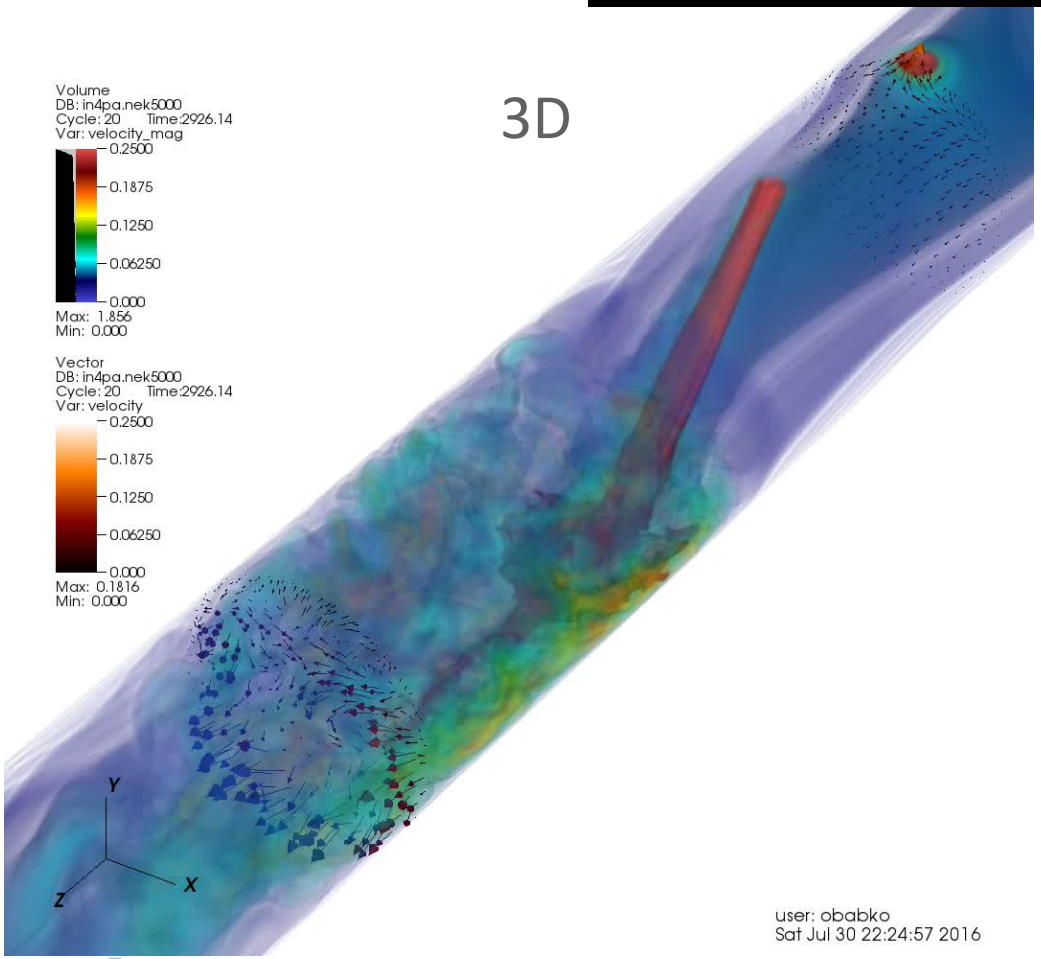
First Attempt (AO 2016)

2D

Velocity magnitude & vector field at Re~2,000

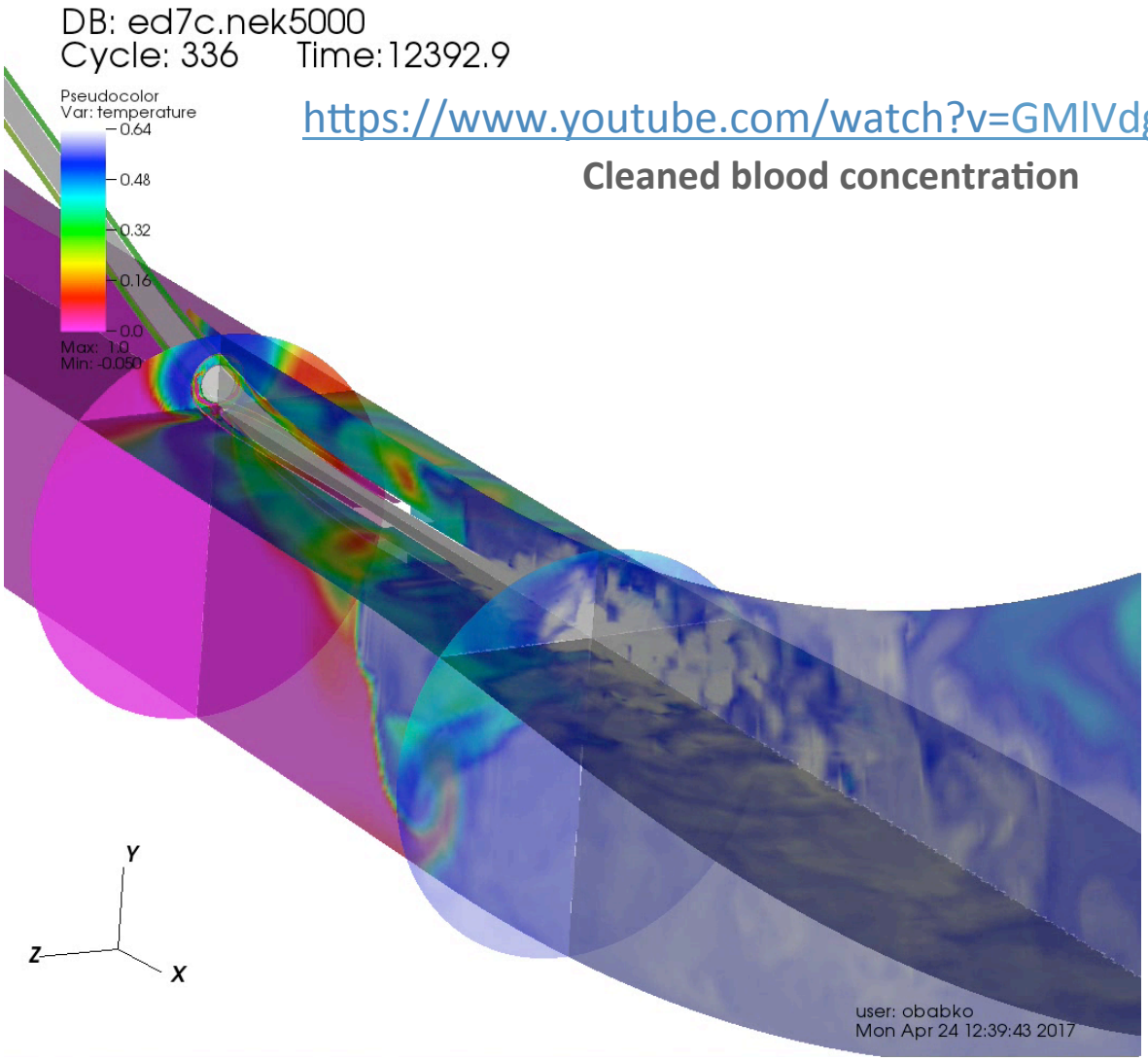


3D



- Preliminary idealized 2D & 3D simulation demonstrations for a baseline case of dialysis injection needle jet at 45 degrees and withdrawal port one diameter upstream
  - Estimates of simulation requirements and scales
  - Geometry effects with more complex meshing?

Worst case: Re=2,600

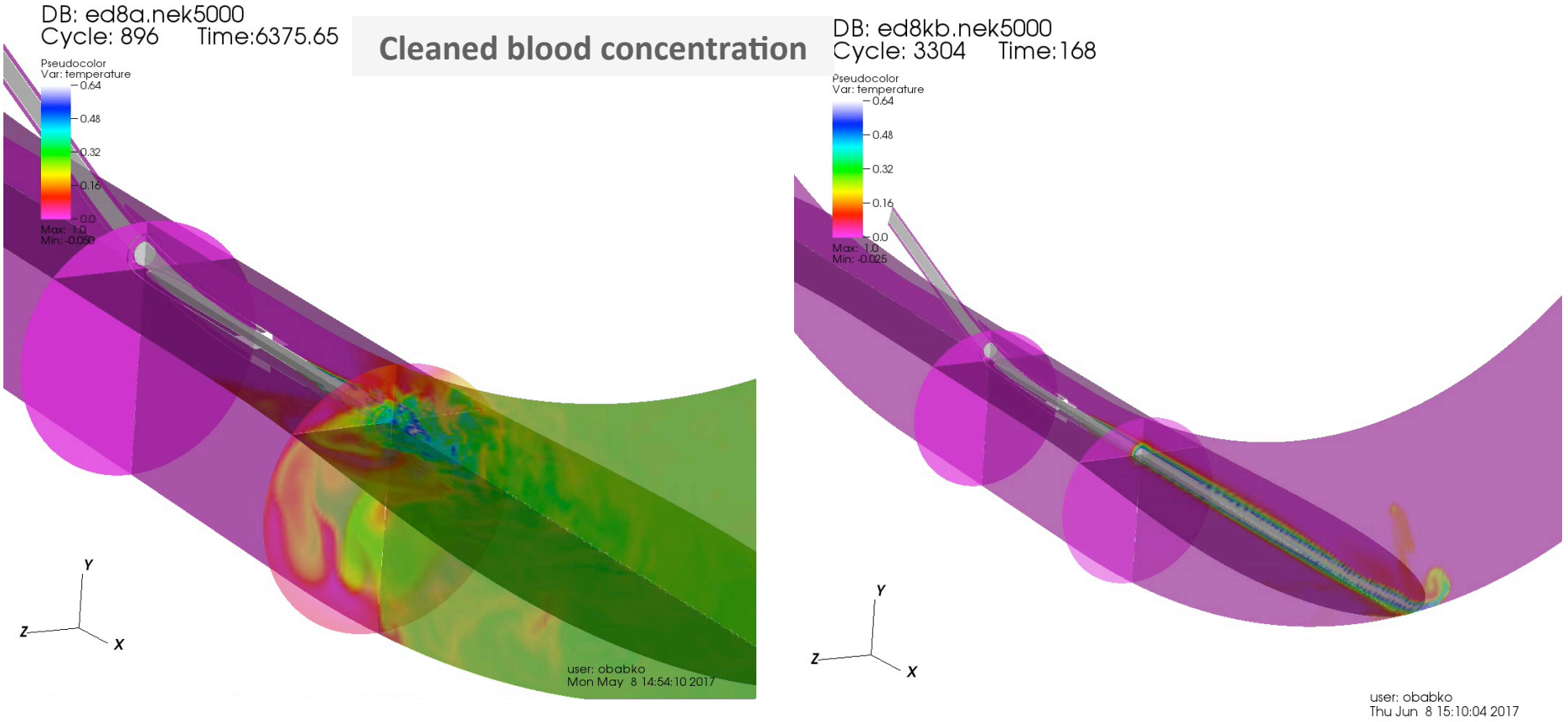


https://www.youtube.com/watch?v=GMlVdgtJdDk (& at Nek5000 Gallery)

Cleaned blood concentration

- 2 mm diameter w/ 595/600 ml/min blood flow rates
- All-hex compliant mesh generated with TrueGrid (R.R.) and exported directly in Nek5000 mesh format based on hex20
- Long transients
  - OIFS w/ CFL~10
- Recirculation rates of the cleaned blood are observed to be below 25%

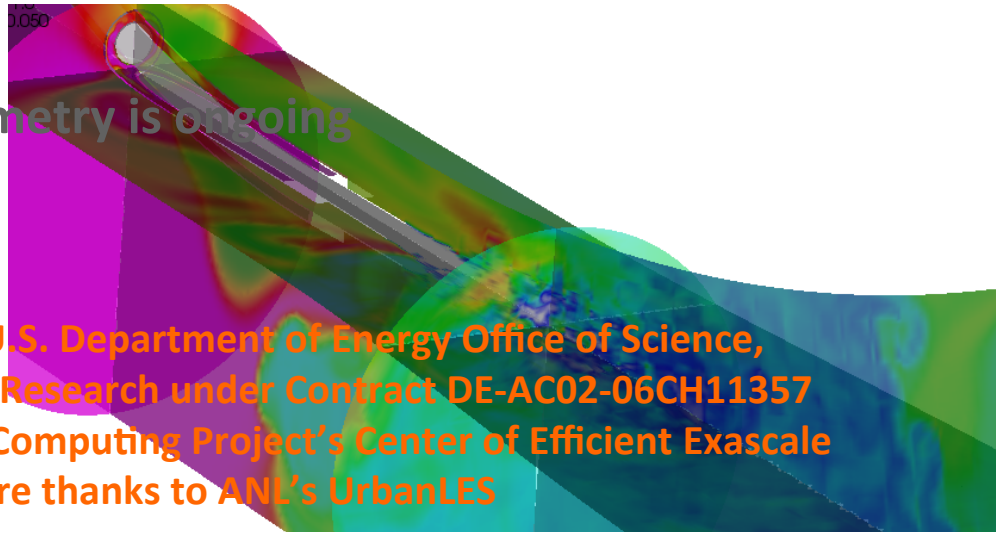
Change of Re



- Larger blood flow rate difference leads to zero recirculation rates
- Decrease of Re (e.g. down to ~650) reduces the unsteadiness toward relaminarization

Conclusions and Future Work

- Preliminary LES solutions with transition to turbulence in a novel vascular access device for hemodialysis access were computed with open-source SEM CFD solver Nek5000
  - Range of Reynolds numbers (/blood flow rates)
    - Near-worst-case scenario: recirculation rates of the cleaned blood ~<25%
    - Larger difference of inlet flow rate (lower Re) with respect to blood vessel reduces cleaned blood recirculation and flow unsteadiness
  - Most of the all-hex compliant meshes were generated with TrueGrid (R.R.) exported directly into the Nek5000 mesh file format (based on hex20)
- Further sensitivity to mesh, BC, geometry is ongoing



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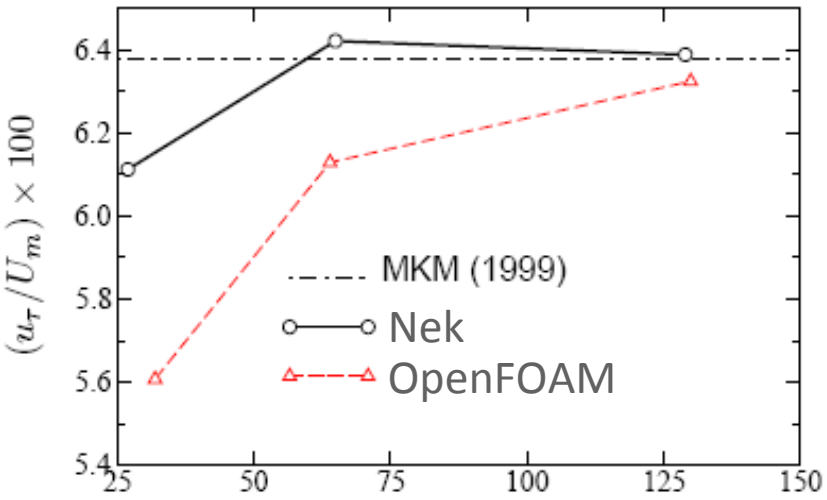
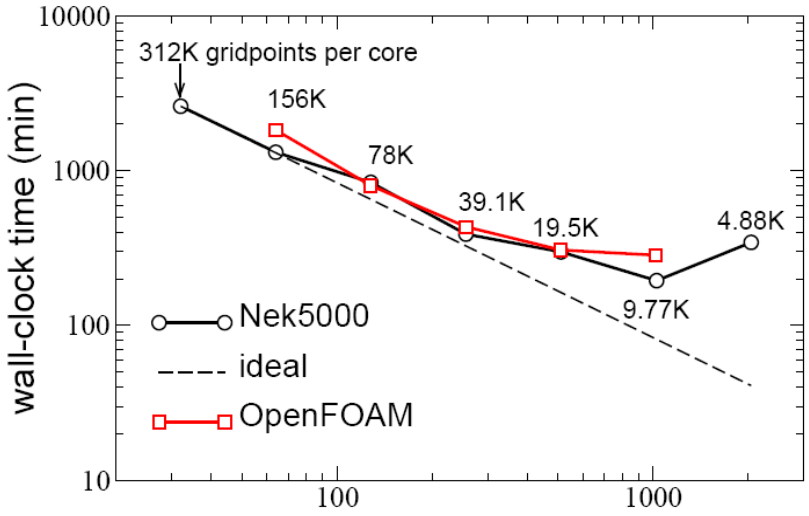
Scale Interaction Example: NREL Channel Flow Study *Sprague et al., 2010*



n_y: # of points in wall-normal direction



P: # of processors

- Test case: comparison to turbulent DNS results of Moser, Kim, Mansour ' 99.
- Results:
  - For fixed accuracy, FV needs 8 times as many points as 7th-order SEM
  - Nek5000 and OpenFOAM have the ***same*** cost per gridpoint
  - SEM-based Nek5000 is an ***order of magnitude faster***