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Analysis of fluidic-oscillator flow meters using high-fidelity CFD

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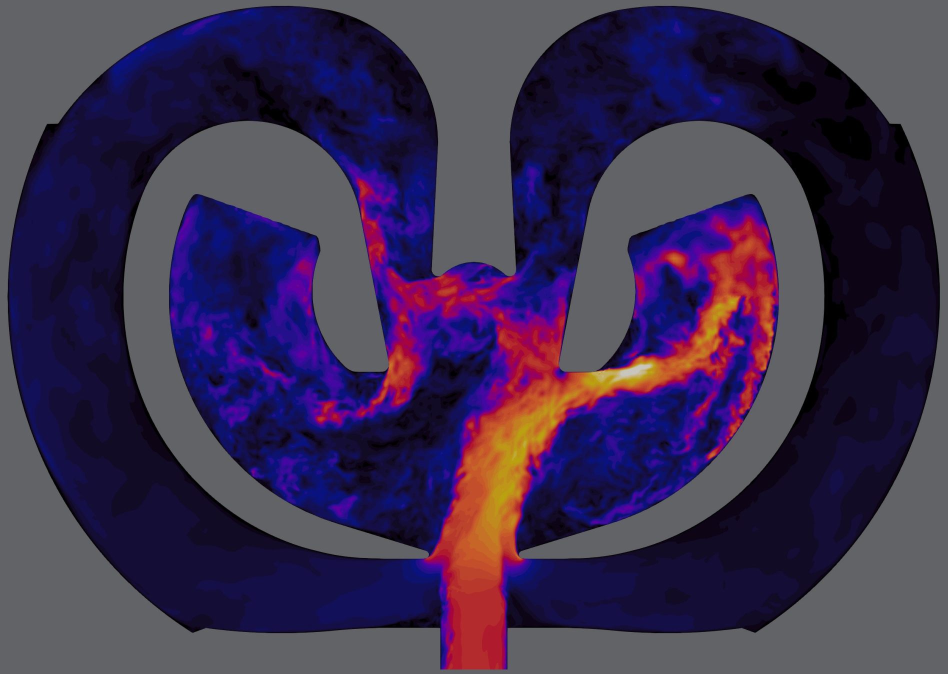
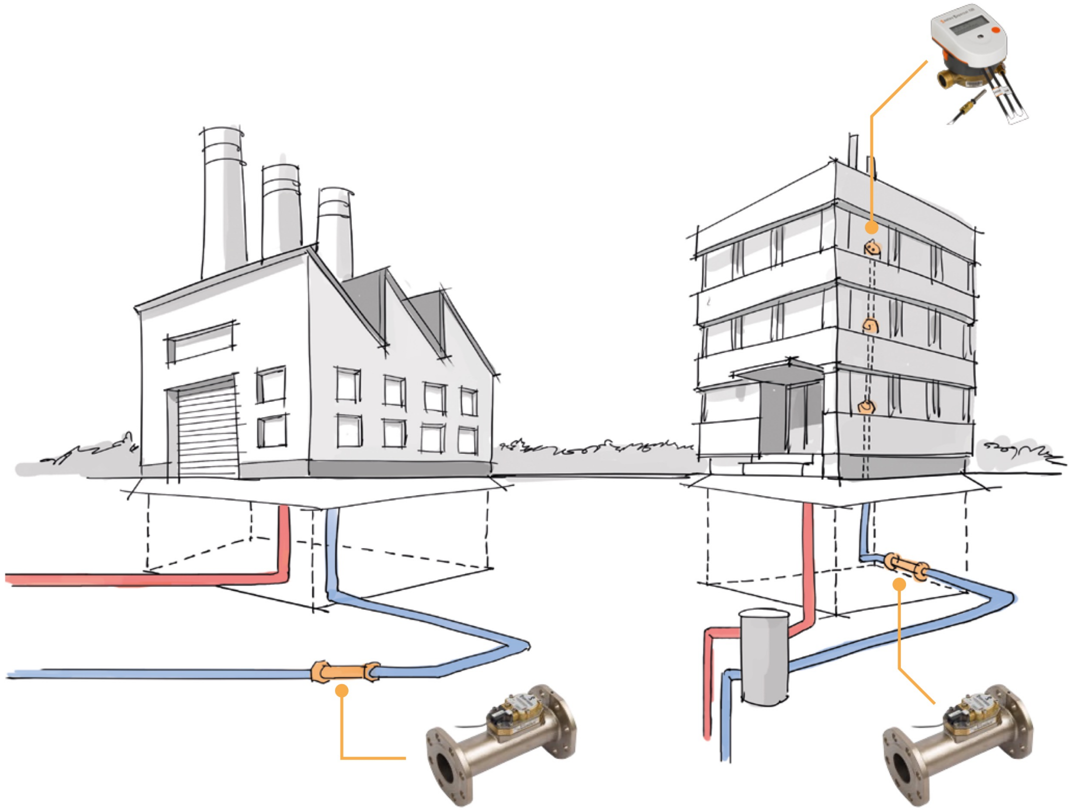


Flow meters based on the fluidic oscillator principle

- Applications e.g. in building technology, automation & heating networks
  - Hundreds of thousands in service, worldwide
- Advantages:
  - Reliable, maintenance-free, long lifespan, (no moving parts)
  - Unparalleled precision
  - Suitable for challenging applications (unaffected by deposits, small air bubbles)



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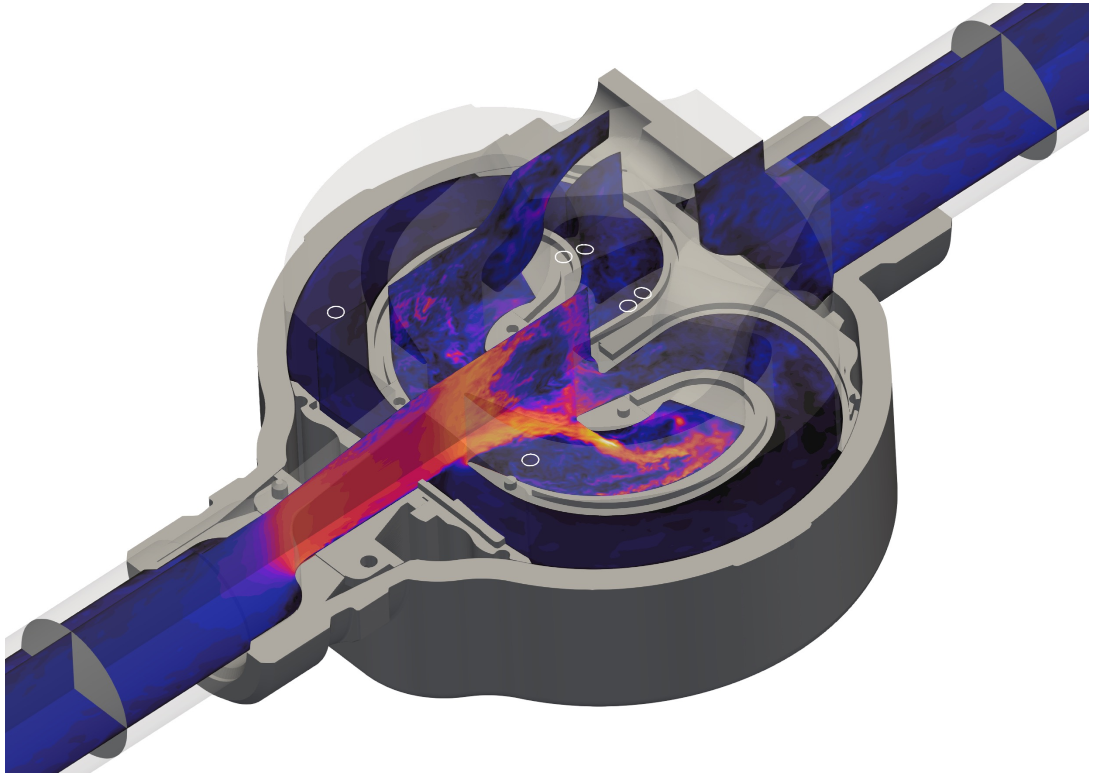
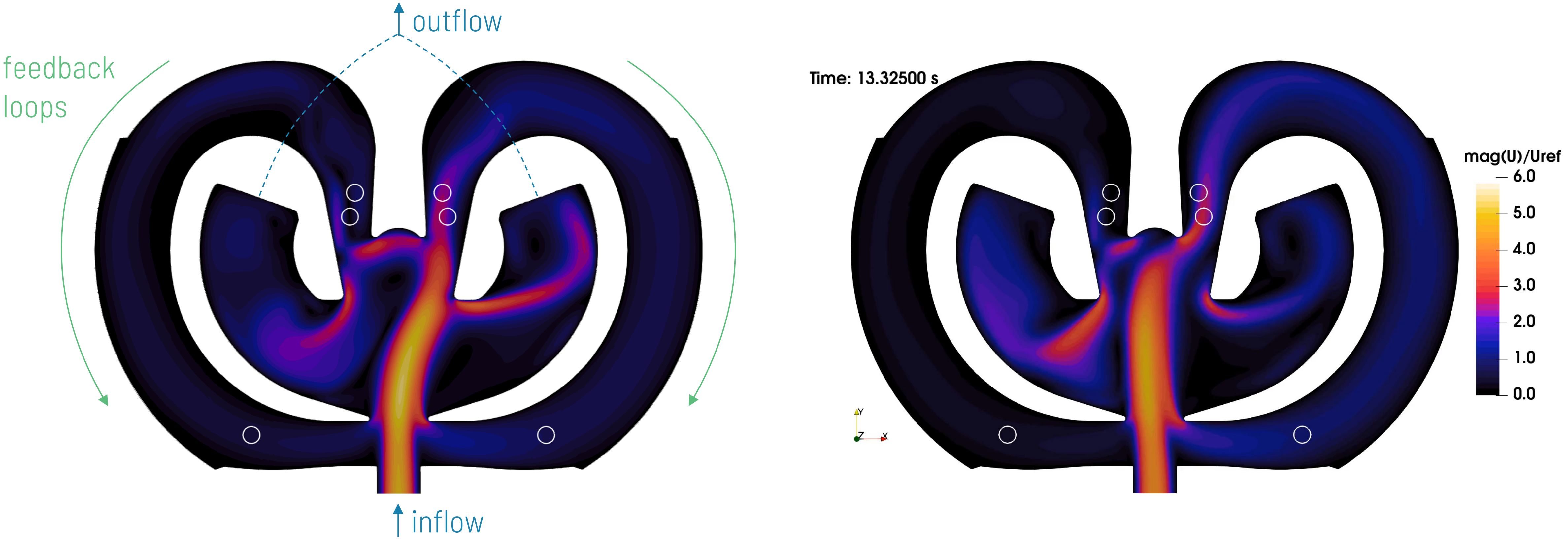


- How they work:
  - Self-sustaining oscillation in device, frequency proportional to flow rate
  - Frequency measured via fluctuating pressure difference across a piezoelectric sensor

Visualisation of fluidic oscillator

- Velocity magnitude at centre plane (laminar flow case visualised for clarity)
- Jet flow into one feedback loop causes jet to switch to opposite feedback loop
- 3D geometry: flow exits normal to visualised plane



Objective of investigation and challenges for simulation approach

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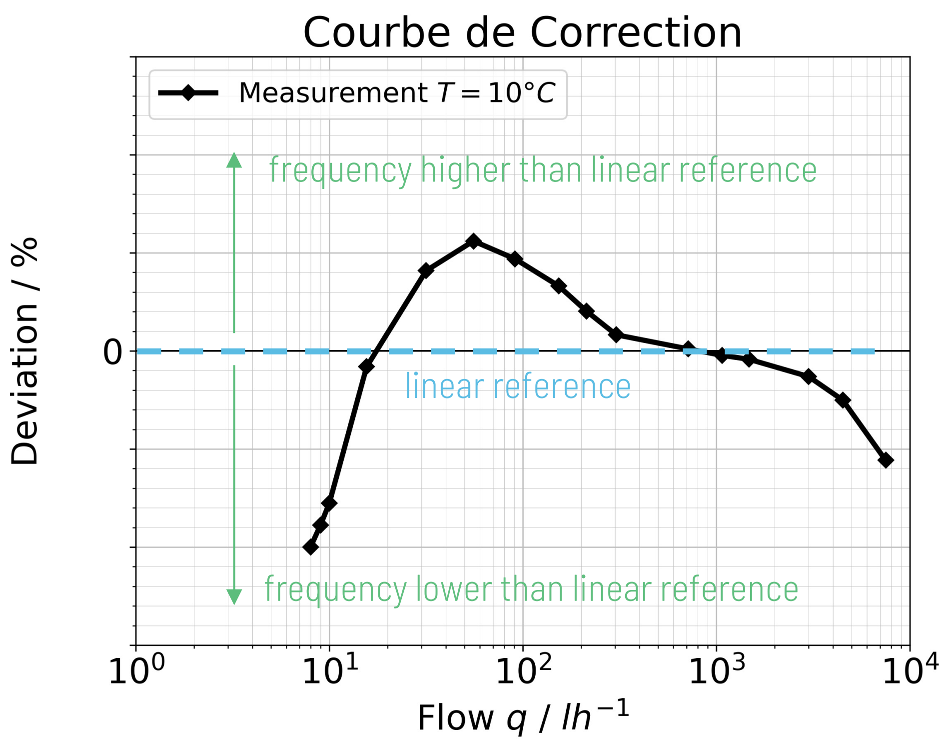
- Flow meters operate over a huge range of flow rates (2-3 orders of magnitude)
- Small deviations from perfect linearity occur (frequency vs. flow rate)
  - Characterised using *courbe de correction* diagram (CdC)
  - Once measured, CdC used to automatically correct reported flow rate

- Short-term objectives:
  - Provide insight into physical causes of CdC behaviour
- Long-term objectives:
  - Can design modifications reduce deviations from linearity (i.e. flatten the CdC)?
  - Can CFD compete with lab rig for oscillator design (cost, speed)?

- Simulation challenges:
  - Dominant influence of laminar-turbulent transition anticipated
    - Reynolds number of inlet pipe varies from about 200 to 20.000
  - Inherently unsteady application
  - Complex geometry

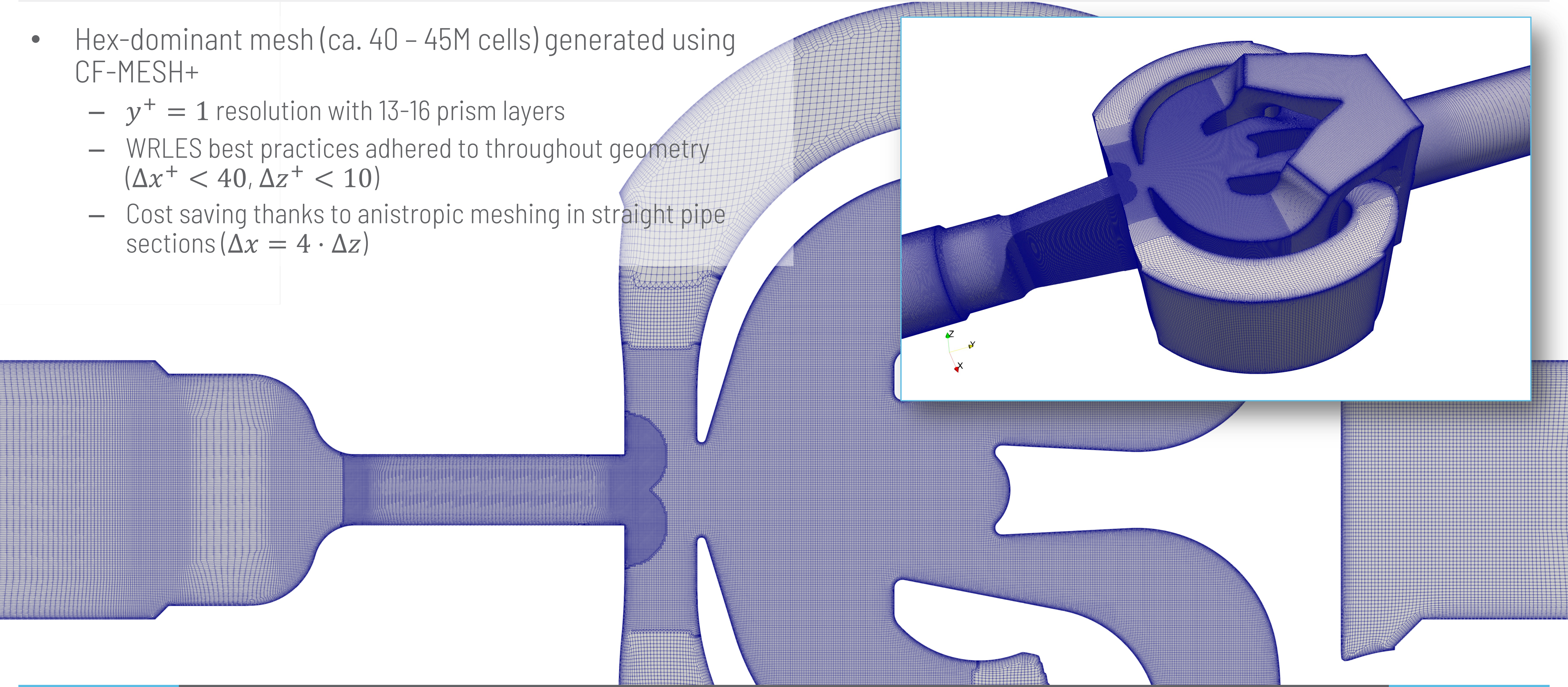


High-fidelity simulation approach

- Selected strategy: Wall-resolved LES (WRLES)
  - Properly executed, should resolve important transition phenomena directly
  - Minimises modelling heuristics
  - Estimated to be affordable at highest Re considered
- Subgrid scale model: σ model of Nicoud et al. (2011)
  - Regular SGS behaviour in fully-developed turbulence, deactivated in laminar flow regions
  - Computationally efficient algebraic formulation
  - (By the way: The σ model is a key ingredient of our grey-area enhanced DES approach)
- High-accuracy solver settings and minimal numerical dissipation required for WRLES:
  - Customised solver based on *pimpleFoam*
    - Reduces strength of dissipation from Rhie & Chow interpolation
    - See Montecchia et al. (2019)
  - *filteredLinear2V* convection scheme for velocity
    - Very low dissipation, more stable than pure *linear* scheme
- Time step size corresponds to $CFL_{max} \approx 1$ (approx. 10.000 time steps per oscillation cycle)

Mesh

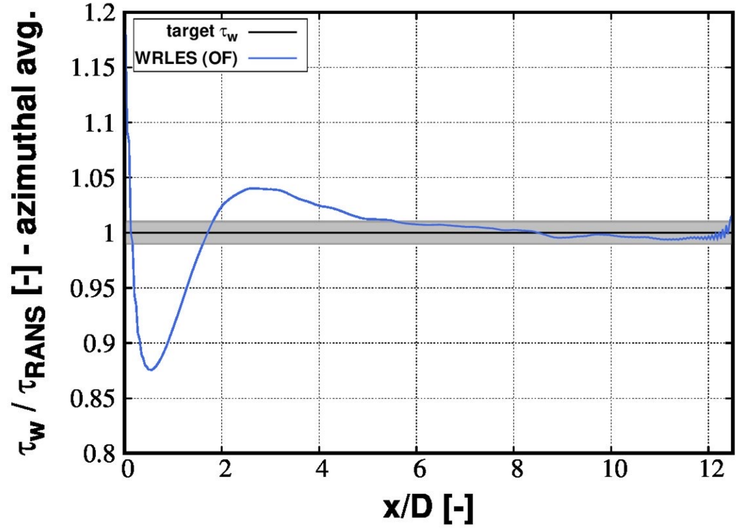
- Hex-dominant mesh (ca. 40 – 45M cells) generated using CF-MESH+
  - $y^+ = 1$ resolution with 13-16 prism layers
  - WRLES best practices adhered to throughout geometry ($\Delta x^+ < 40$, $\Delta z^+ < 10$)
  - Cost saving thanks to anistropic meshing in straight pipe sections ($\Delta x = 4 \cdot \Delta z$)



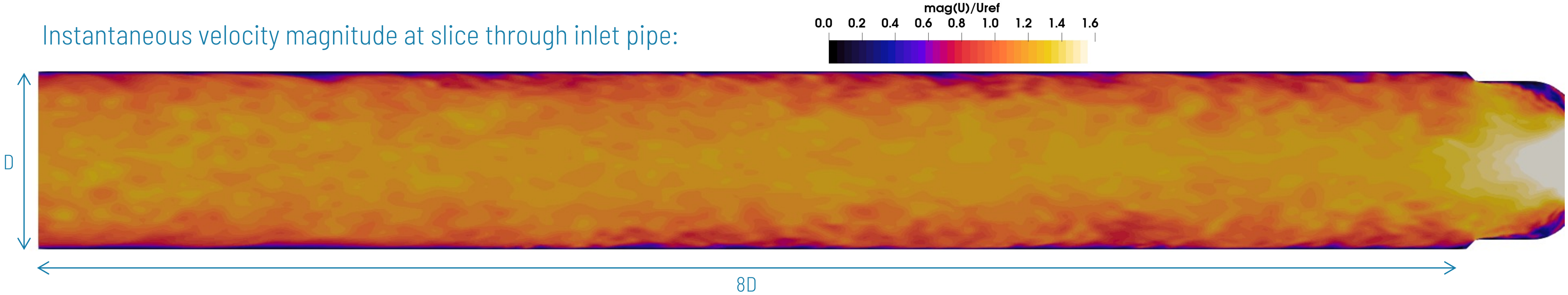
Inlet conditions

- Fully-developed pipe flow prescribed at domain inlet
- At low Re: Laminar profile from precursor simulation
- At high Re: Turbulent profile with synthetic fluctuations
  - Steady RANS input from precursor periodic pipe simulation
    - (Disturbed inlet from upstream components could also be imposed)
  - Corresponding resolved structures using divergence-free synthetic eddy method (DFSEM) of Poletto et al. (2013)

"Recovery length" for WRLES of pipe flow with DFSEM inlet:



Instantaneous velocity magnitude at slice through inlet pipe:



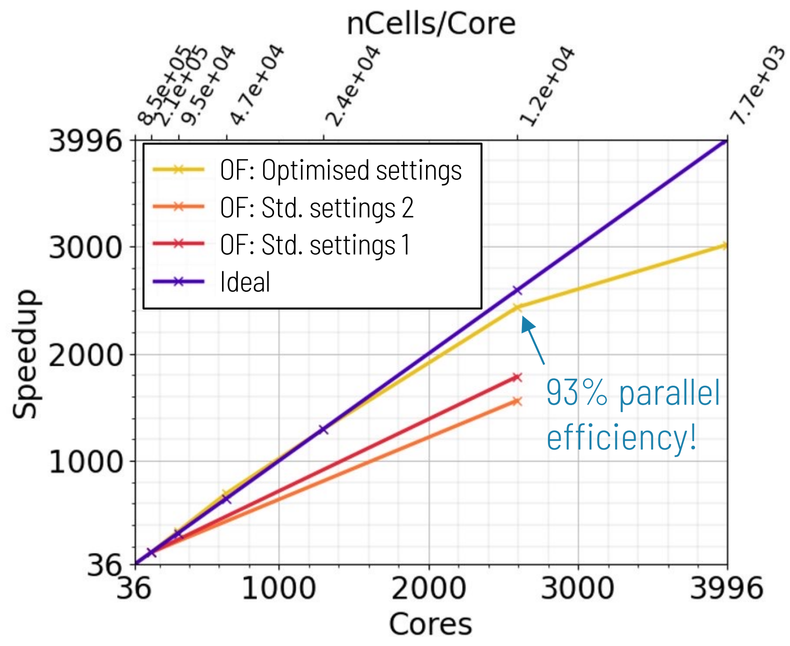
Parallel simulations on Amazon Web Services (AWS)

- Simulations carried out on AWS Elastic Compute Cloud (EC2):
  - Access to "effectively unlimited" computing resources
  - Only pay for actual usage, no capital expenditure
  - In prior testing, we have measured very impressive scalability (93% efficiency with only 12.000 grid cells per CPU core)
  - A game-changer for high-fidelity CFD

- Oscillator simulations: highly parallelised using 864 cores each
  - Ca. 50.000 cells per core
- Running multiple flow rates in parallel, a flow meter CdC can be characterised using wall-resolved LES in under 3 days

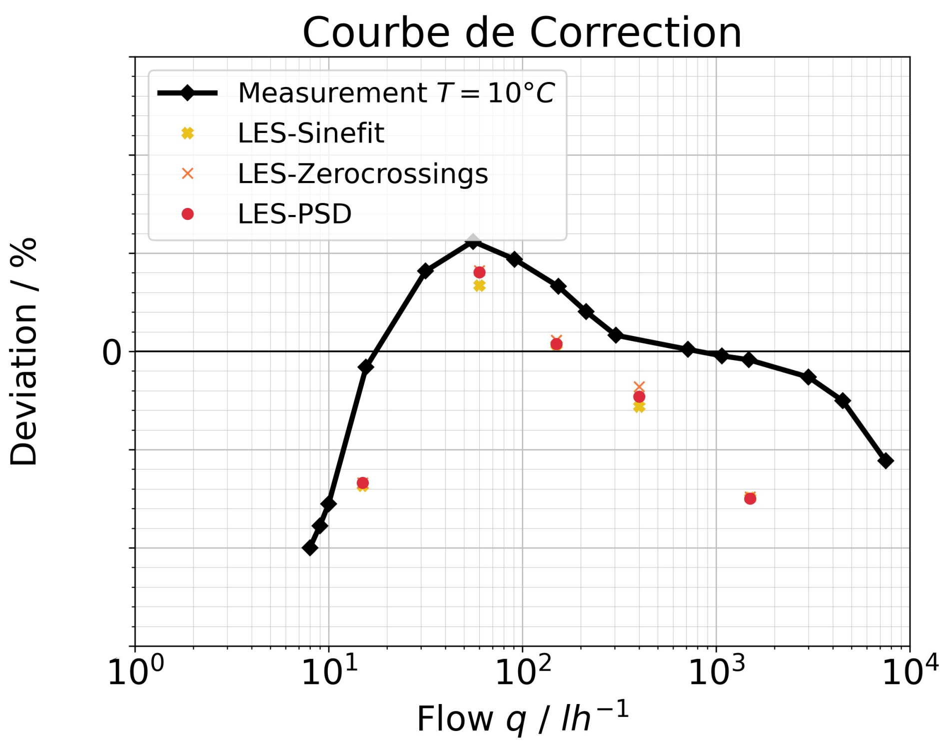
OpenFOAM scalability test on AWS

DES of generic car body (SAE Notchback), 30.6M grid cells



Results: Prediction of CdC

- Shape of CdC predicted very well by WRLES
  - Builds confidence that underlying physics is captured correctly
- Stronger deviation from measured CdC at higher flow rates
  - Cause may be mesh resolution: Although WRLES best practices are adhered to, the flow is inherently better resolved at lower flow rates (lower Re on same mesh)
- Can the LES results help us to understand and explain the CdC behaviour?



Animations of velocity magnitude at lowest two flow rates

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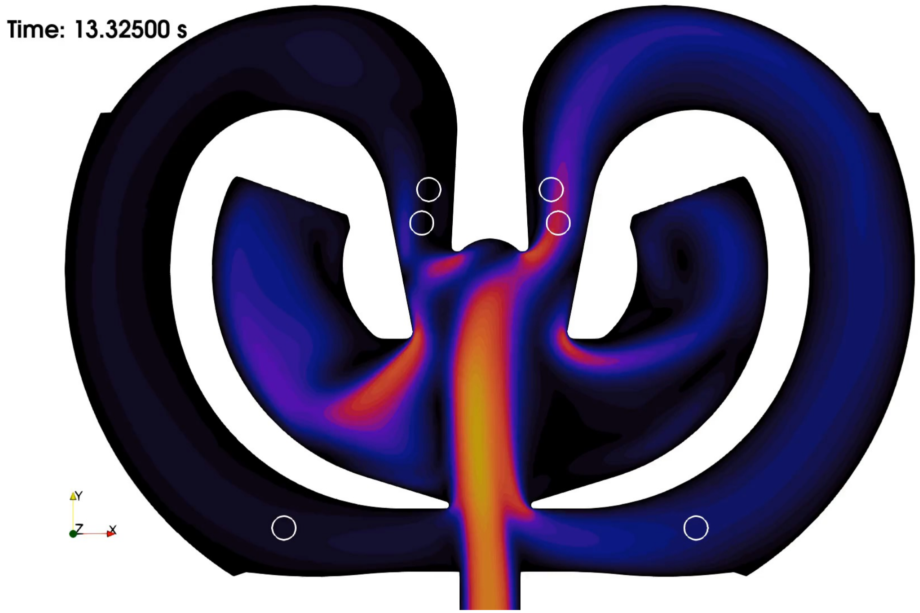
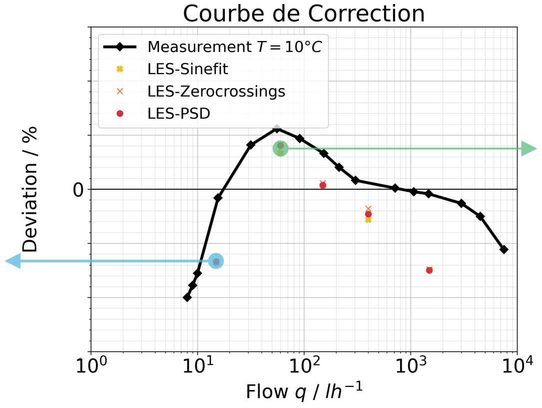
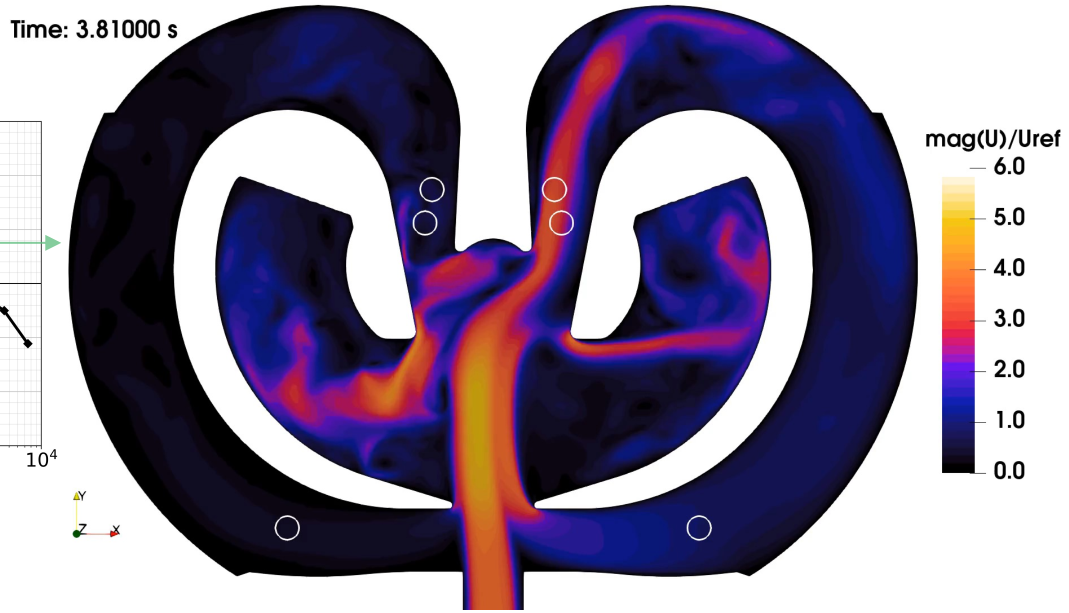
Playback speeds phase-locked for comparison







- Whole domain fully laminar
- Thick shear layers due to strong viscous effects

- Jet fully laminar, shear layers thinner
- Transition to coarse-grained turbulence after impingement and separation

Going faster…

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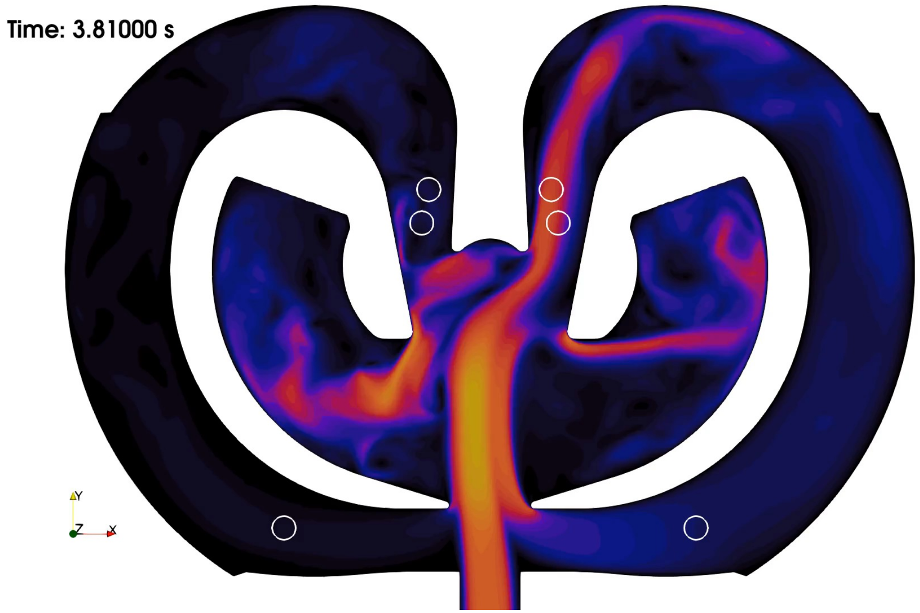
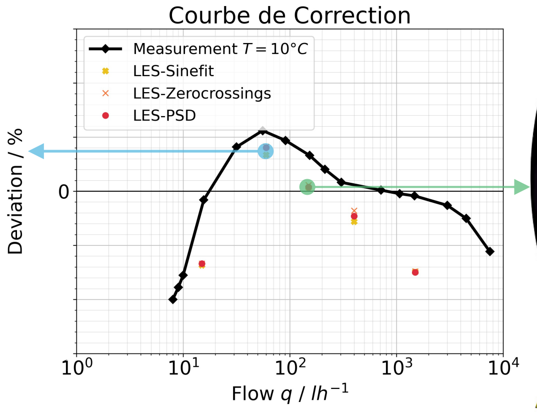
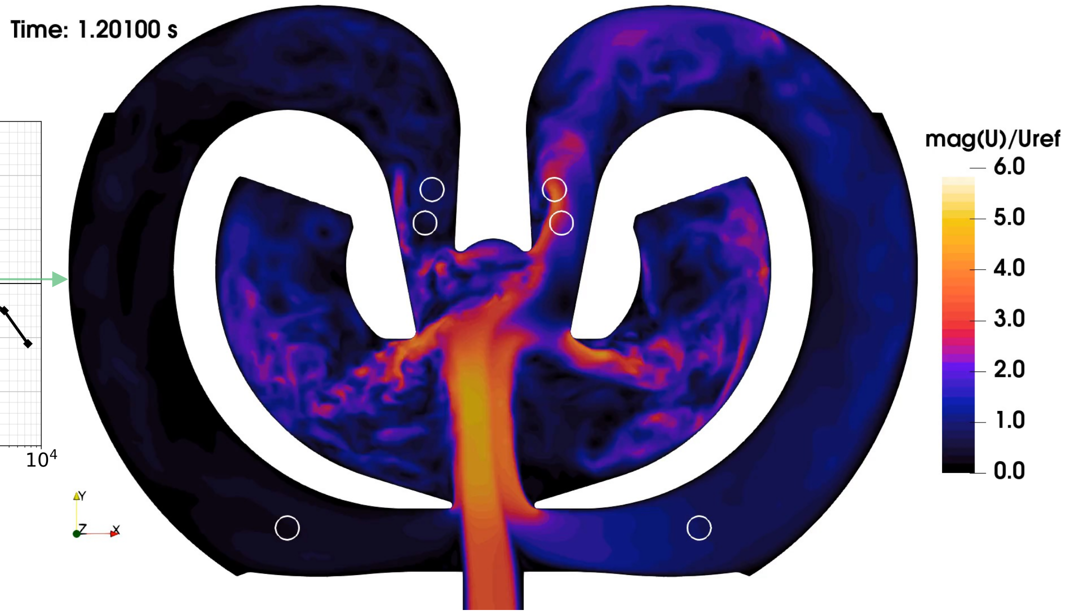
Playback speeds phase-locked for comparison





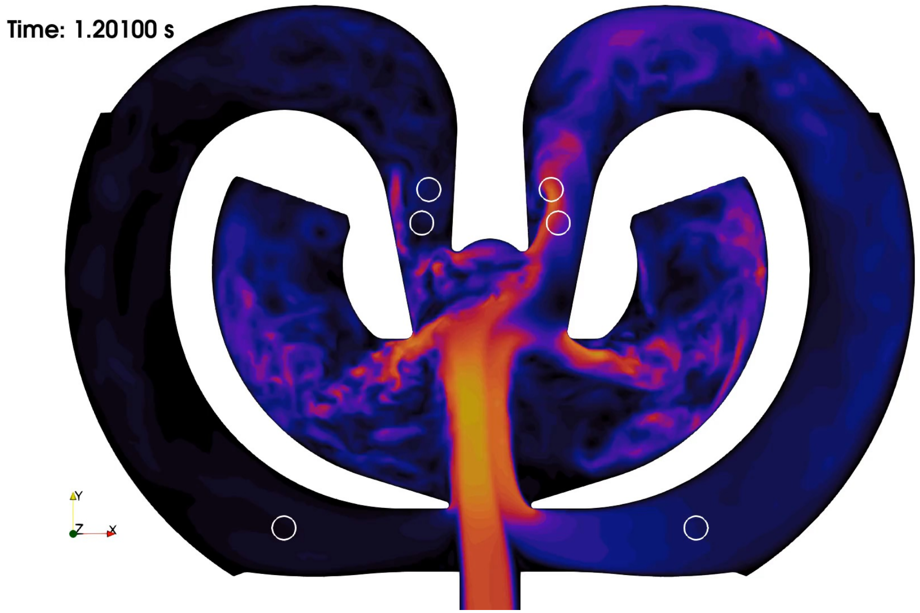


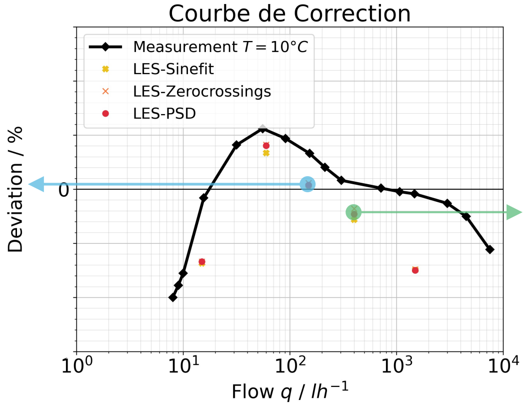
- Smoother (faster?) transition of jet between entrances to feedback loops

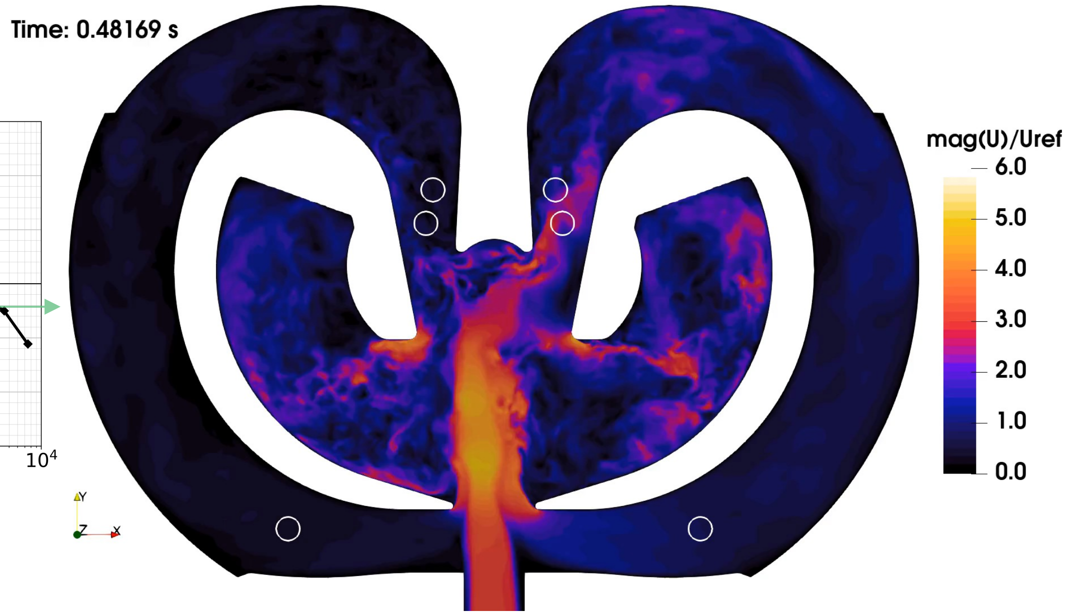
- Intermittent turbulence in jet
- Chaotic flow in impingement area: Does this hinder the switch between feedback loops?

Faster still...

Playback speeds phase-locked for comparison







- Intermittent turbulence in jet

- Jet fully turbulent after feedback junction
- Intermittent turbulence / transition waves in core jet (inflow)

Full speed

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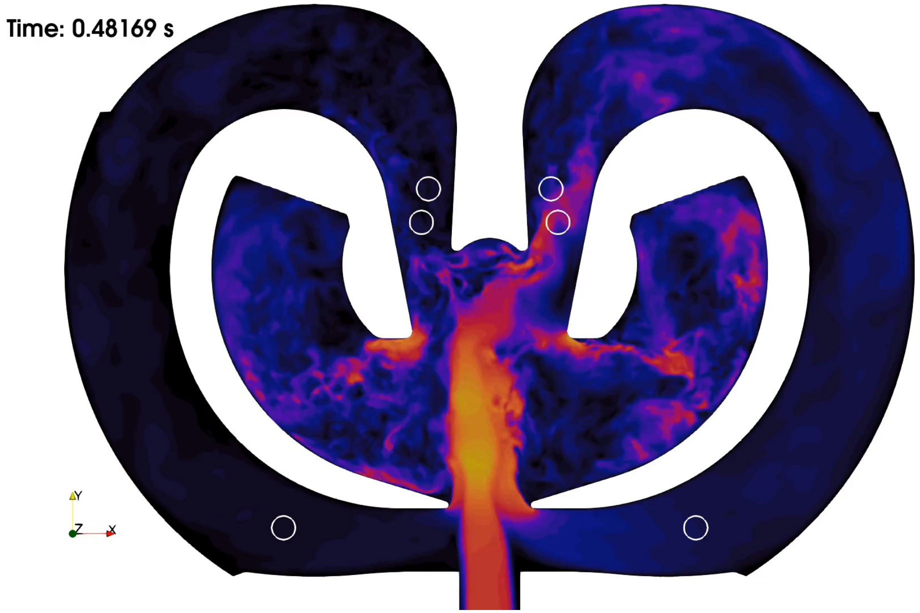
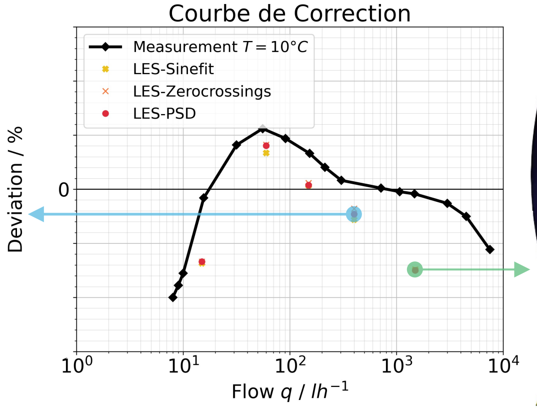
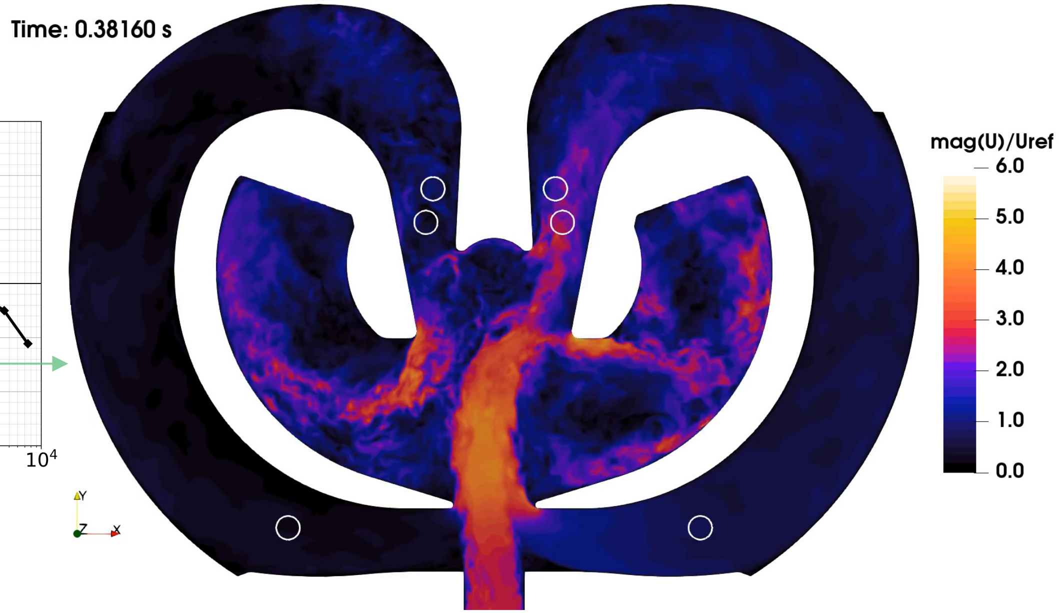
Playback speeds phase-locked for comparison





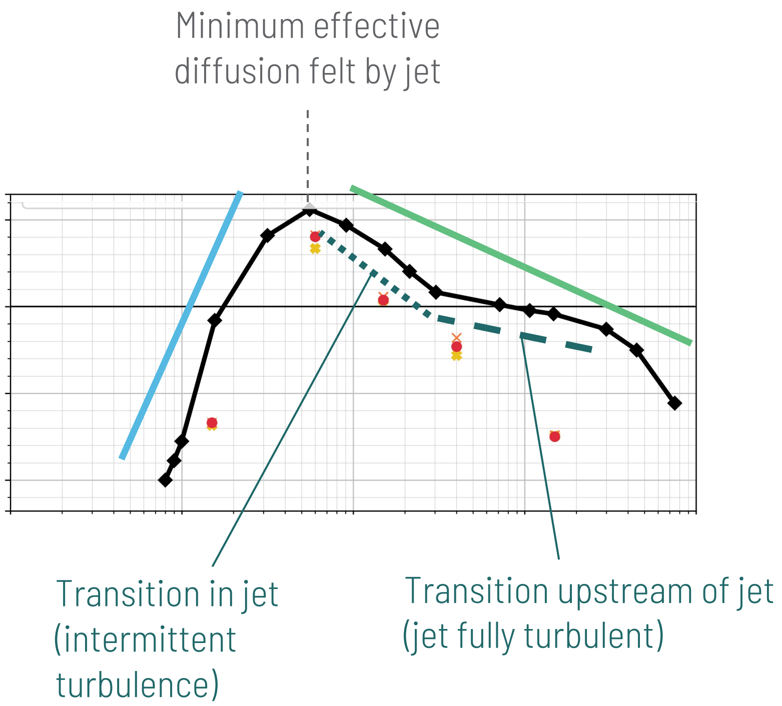


- Intermittent turbulence / transition waves in core jet (inflow)

- Turbulent core jet (inflow)
- Fine-grained turbulence in oscillator

Hypothesis for CdC behaviour

- Different regimes of CdC appear to be dominated by laminar/turbulent state of oscillating jet
  - Superlinear regime as long as jet is laminar
    - Increasing flow rate (Re) leads to reduced influence of viscous diffusion
  - Sublinear regime following onset of jet turbulence
    - Fluctuations / eddies in jet increase momentum exchange (turbulent diffusion)
  - Peak in CdC corresponds to minimum influence of effective (laminar + turbulent) diffusion in jet
- Can the turbulent regime be subdivided further?
  - This fits qualitatively to a wide range of CdC
  - (However, it isn't apparent from the current simulations!)



Conclusions and outlook

- High-fidelity simulation appears to capture underyling physics
- Offers insight into causes of deviation from linearity
  - Highest positive deviation of frequency occurs at the maximum Reynolds number when the jet is still laminar
  - Minimum influence of effective (laminar + turbulent) diffusion
- Highly parallel simulation in the cloud enables rapid turnaround time
  - On-demand access to huge computational resources a key enabler for high-fidelity CFD consulting
  - For this specific application, however, the overall cost is too high for regular use of LES as a design tool

Future work:

- Further analysis of high-fidelity flow fields to firm up hypothesis of CdC behaviour
- Development and assessment of low-cost methodology for CFD-based design
  - Use high-fidelity simulations to train/calibrate lower-order approach
  - Usefulness test: Can deltas between flow meter design variants be accurately predicted?
- If successful, a user-friendly automated workflow can be generated for use by product designers

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Thank you for your attention

2nd Automotive CFD Prediction Workshop

- Berlin, 26th-27th August 2021
  - Decision on face-to-face / online / hybrid event will be announced end of March
- Two test cases planned: Windsor model & DrivAer Notchback
- AutoCFD 2 web site: https://autocfd.eng.ox.ac.uk
  - Interested?
    - Sign up to the mailing list (via web site)
    - Email a (non-binding) notice of participation by 31st March
    - Take part in kick-off meeting (online) on 12th April
- Event co-located with the AEROVEHICLES 4 conference
  - https://aerovehicles4.sciencesconf.org