WALL RESOLVED LARGE EDDY SIMULATION OF A FLOW THROUGH A SQUARE-EDGED ORIFICE IN A ROUND PIPE AT RE=25000

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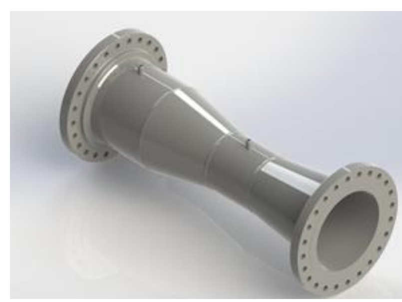
“80 PERCENT OF FLOW MEASUREMENT IN FRENCH NPP USE DIFFERENTIAL PRESSURE DEVICES … AND A BIG PART OF THEM ARE ORIFICE PLATES”

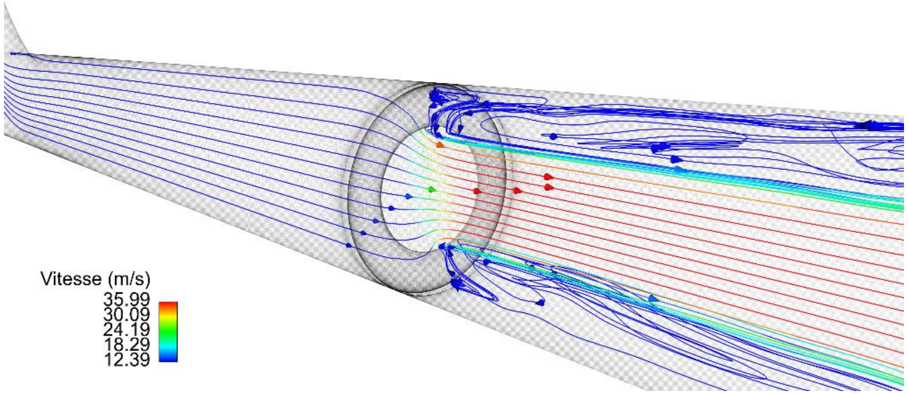
Orifice plates (≈70%)



Venturi (≈ 20%)

Nozzles (≈ 10%)

OUTLOOK



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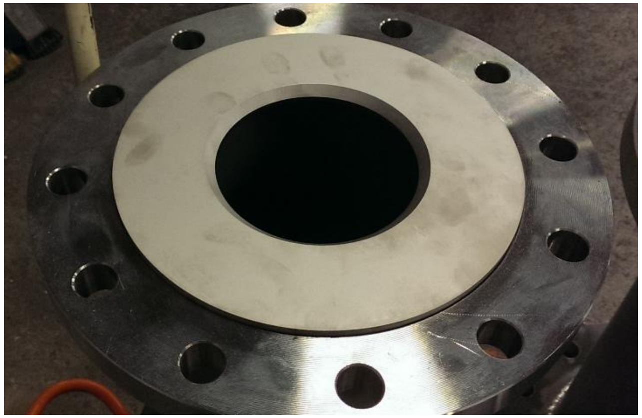


CONTEXT (1/2)

Orifice plate is a commonly used instrument for flow measurements in pipes, thanks to:

- Simplicity → Relationship between ***ΔP*** and q_m
- Standardized → ISO 5167 /ISO TR12767
- Installation and operation not expensive → Easily installed between flanges, fabrication simple, no limitations on the materials, line size and flowrate

Mass flowrate equation

$$\boxed{q_m = \frac{\pi}{4} C E d^2 \sqrt{2 \Delta P \rho}}$$

Where:

C : discharge coefficient (calculated by ISO)
E: velocity of approach factor (known)
d : diameter of orifice (known)
ΔP: differential pressure (measured)
ρ : density of the fluid (known)

CONTEXT (2/2)

$$C_{ISO\_5167}(\pm\sigma)$$

ISO 5167-2

Reader-Harris/Gallagher equation

$$C = 0{,}596\,1 + 0{,}026\,1\beta^2 - 0{,}216\beta^8 + 0{,}000\,521\left(\frac{10^6\beta}{Re_D}\right)^{0{,}7} + (0{,}018\,8 + 0{,}006\,3A)\beta^{3{,}5}\left(\frac{10^6}{Re_D}\right)^{0{,}3}$$

$$+ (0{,}043 + 0{,}080\mathrm{e}^{-10L_1} - 0{,}123\mathrm{e}^{-7L_1})(1 - 0{,}11A)\frac{\beta^4}{1-\beta^4} - 0{,}031(M'_2 - 0{,}8M'^{1{,}1}_2)\beta^{1{,}3}$$

$+$ *Uncertainty of the discharge coefficient C*

The discharge coefficient (and its uncertainty) can be calculated if you know:

- Geometry
- Reynolds number
- Placement of pressure taps
- Fluids properties
- Straight lengths between orifice plates and fittings (bend, tee, reducer, etc.)

…but in some cases straight lengths are shorter than required and ISO 5167 cannot be used to predict the coefficient and the uncertainty.

What to do then?

STRATEGY (1/2)

Experimental solution

The solution is performing experiments to calculate discharge coefficient and its uncertainty by reproducing real geometry and fluid conditions in our lab

…performing experiments for all the configurations we have would be very ***expensive (time and money) !***

ex. Single 90° bend with no minimum straight lengths in the upstream side

$$C_{EXP}(\pm\sigma_C) = \frac{4\boxed{q_m}_{EXP}}{\pi \boxed{E d^2} \sqrt{2\boxed{\Delta P}_{EXP}\boxed{\rho}}}$$

Unknown

Fluid properties and geometry:
ρ, μ, D, d, β

Known or measured in our water loop

$q_m + \sigma_{qm}$

Reference flow meter

- Coriolis
- Electromagnetic

$\Delta P + \sigma_{\Delta P}$

DP transmitter

Orifice plate

ex. Tee with no minimum straight lengths in the upstream and downstream sides

STRATEGY (2/2)

Hybrid solution (exp. / CFD)

From the lab to the industry…

Validate the CFD calculations
- Experiment of simple cases
- PIV, LDV (velocity)
- Multipoint pressure measurements
- CFD simulations (RANS)

Apply the methodology to an industrial problem
- Experiment data for Velocity and pressure
- CFD simulations (RANS)
- Sensitivity tests

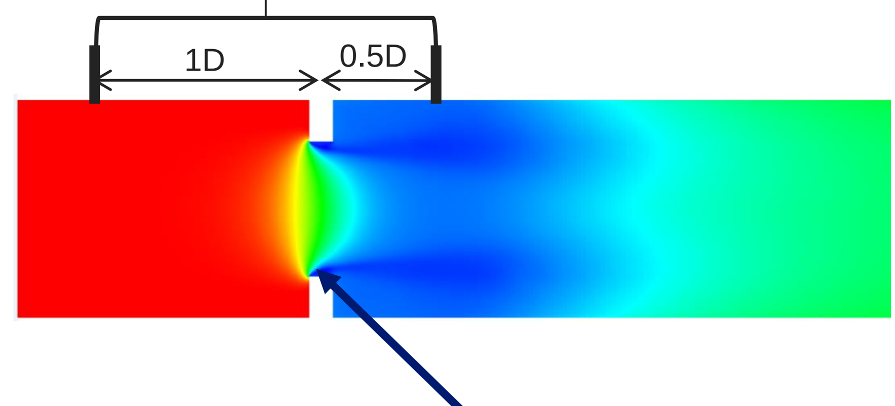
Apply the obtained methodology for all such configurations
- In the scope of ISO
- Beyond the scope of ISO

Apply the obtained methodology for all such devices
- Nozzles
- Venturi tubes
- Multi-hole orifice plate

We're here

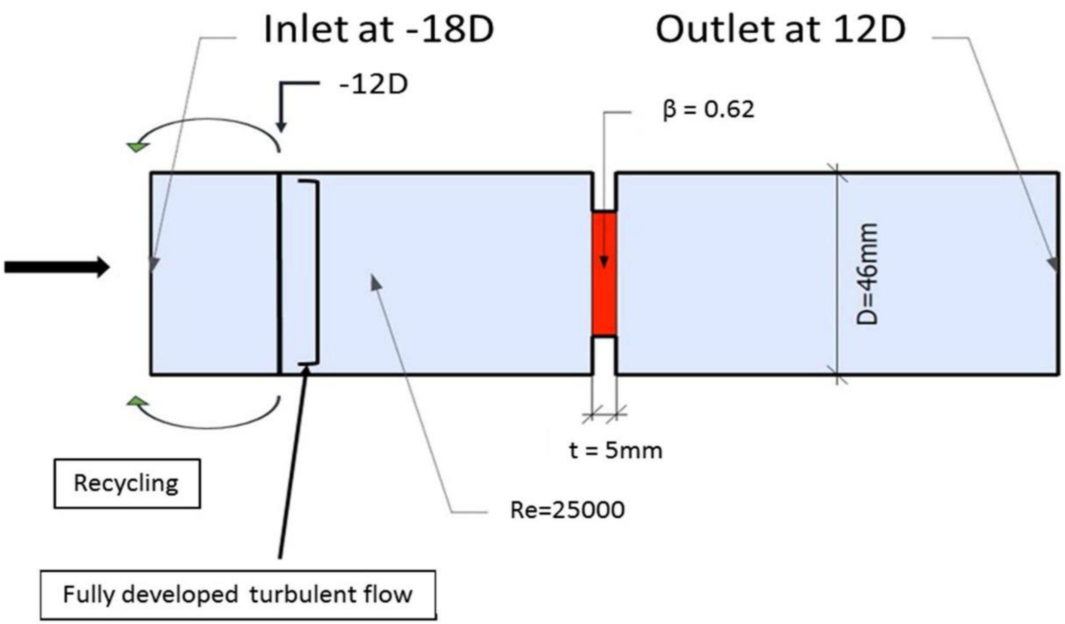
$$C_{CFD} = \frac{4q_{m\_CFD}}{\pi \boxed{Ed}^2 \sqrt{2 \boxed{\Delta P}_{CFD} \boxed{\rho}}}$$

Fluid properties and geometry:
ρ, μ, D, d, β



Orifice plate

TEST CASE



Features of Shan et al. case

- Square-edged orifice
- Round pipe
- Standard water
- Smooth pipe wall
- Re = 25000
- Velocity fields measurement (PIV)

$$q_m = \frac{\pi}{4} C E d^2 \sqrt{2 \Delta P \rho}$$

$$C_{CFD} = \frac{4 q_{m\_CFD}}{\pi E d^2 \sqrt{2 \Delta P_{CFD} \rho}}$$

$$E = 1/\sqrt{1-\beta^4}$$

…**but** a doubt arose about experimental data uncertainties…

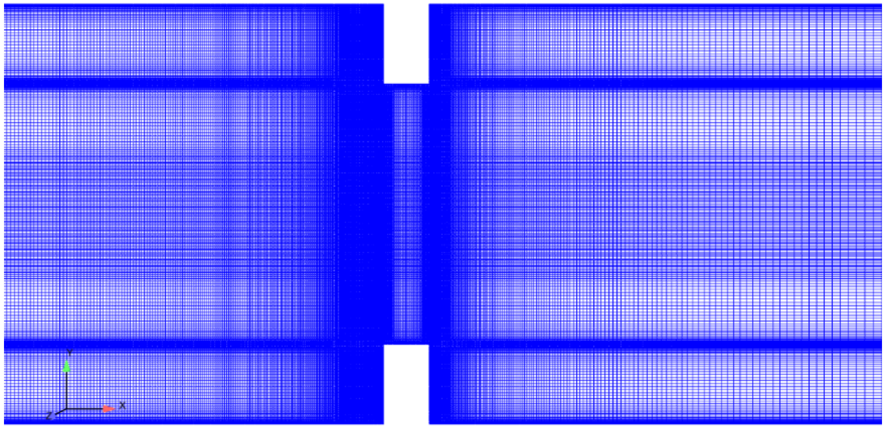
Solution

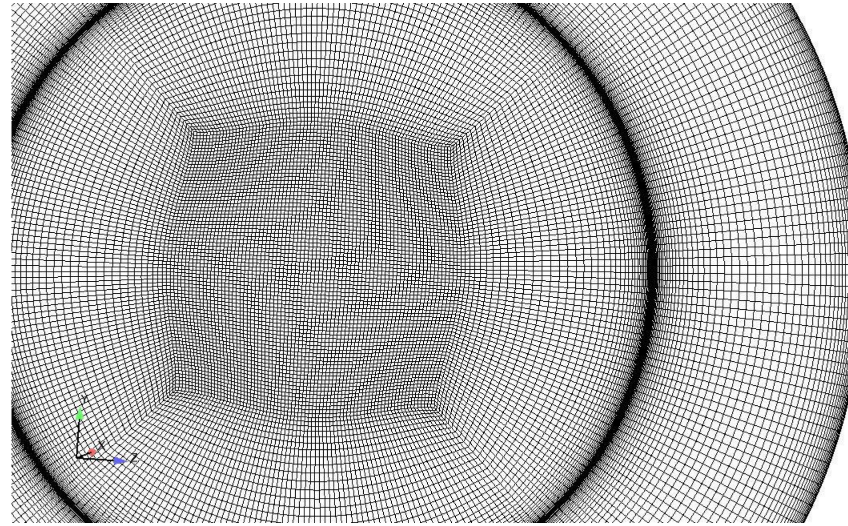
Using Large Eddy Simulations to:

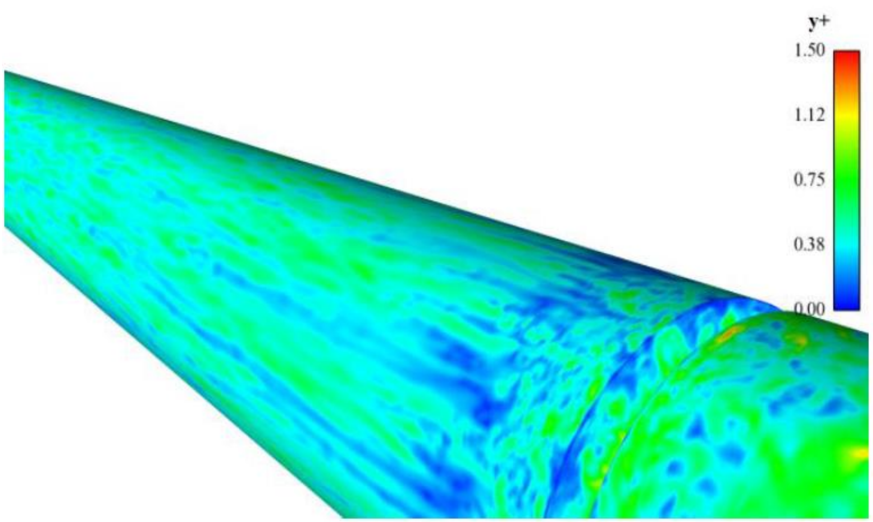
- Better understand flow
- Predictions of pressure losses and C

NUMERICAL SETUP (1/3)

Mesh generation







Features of mesh

- ICEM CFD v14.0
- 55 million cells
- Structured and refined near the orifice
- Conformal throughout the domain
- Solution is resolved beyond the Taylor micro-scale

  (using a RANS computation, on uses $\sqrt{15\nu k/\ }$)
- Wall shear velocity u_* = 0.025 m/s
- Distance y+ is kept below 1 almost everywhere
- $\Delta x+_{max}$=40, $\Delta r+_{max}$=10, $r\Delta\theta+_{max}$=12

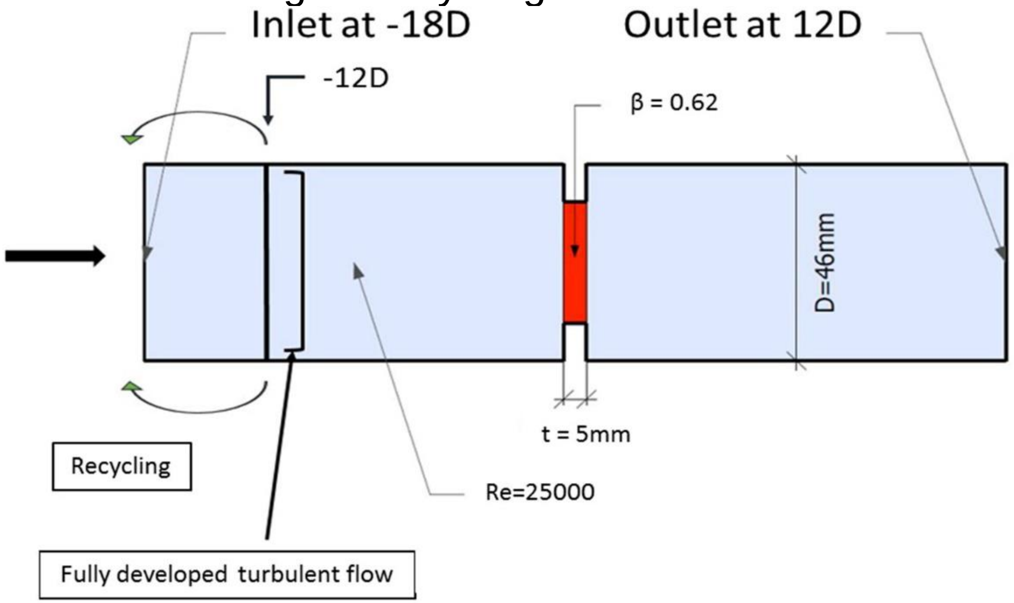
NUMERICAL SETUP (2/3)

- **In-house** open-source **EDF CFD** tool (www.code-saturne.org)
- The LES capabilities of Code_Saturne have been validated on various academic and industrial cases
- Temporal discretization for the LES is second order in time with linearized convection (Crank Nicolson and Adams Bashforth), CFL<1 almost everyt
- Spatial discretization is a pure second order central difference scheme
- Sub-grid scale models used are the Dynamic Smagorinsky (no negative values, Cs_{max}=0.065), the standard Smagorinsky (Cs=0.065) and no SGS model
- High Performance Computing (HPC): Blue Gene/Q supercomputer, using a total of 256 nodes (4,096 processors - Power BQC 16C 1.6GHz), 2.2 s per time step
- Post-processing: Ensight, Matlab

NUMERICAL SETUP (3/3)

Inlet boundary condition

- The inlet is located 18D upstream
- The inlet profile is simulated through a recycling method

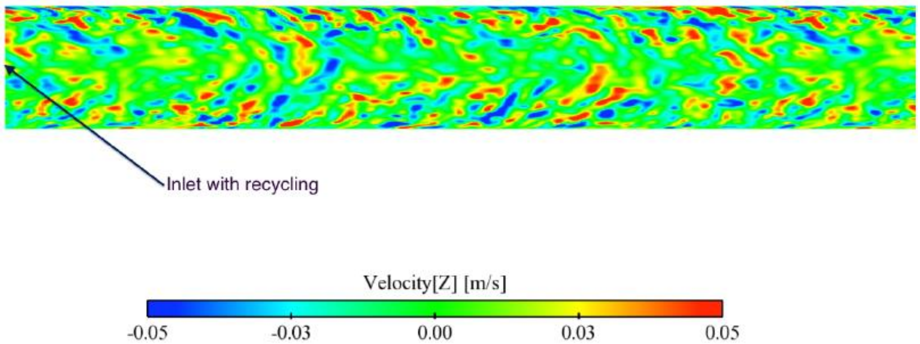


Pressure Loss and discharge coefficients

- Discharge: Δp 1D upstream of the orifice and 0.5D downstream (from the upstream face of the contraction)
- Pressure Loss: Δp 2D upstream of the orifice and 6D downstream

SENSITIVITY STUDIES (1/2)

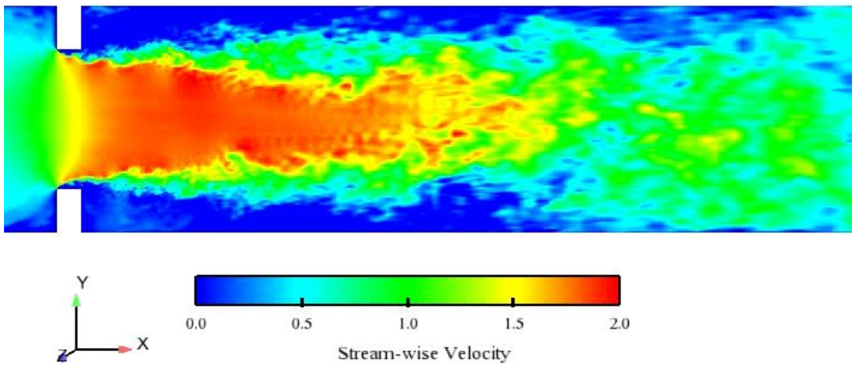
Statistics

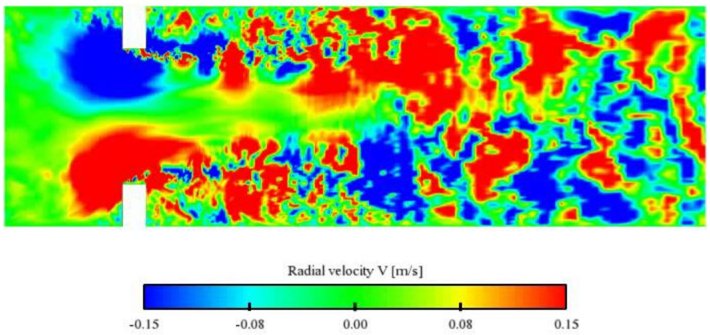


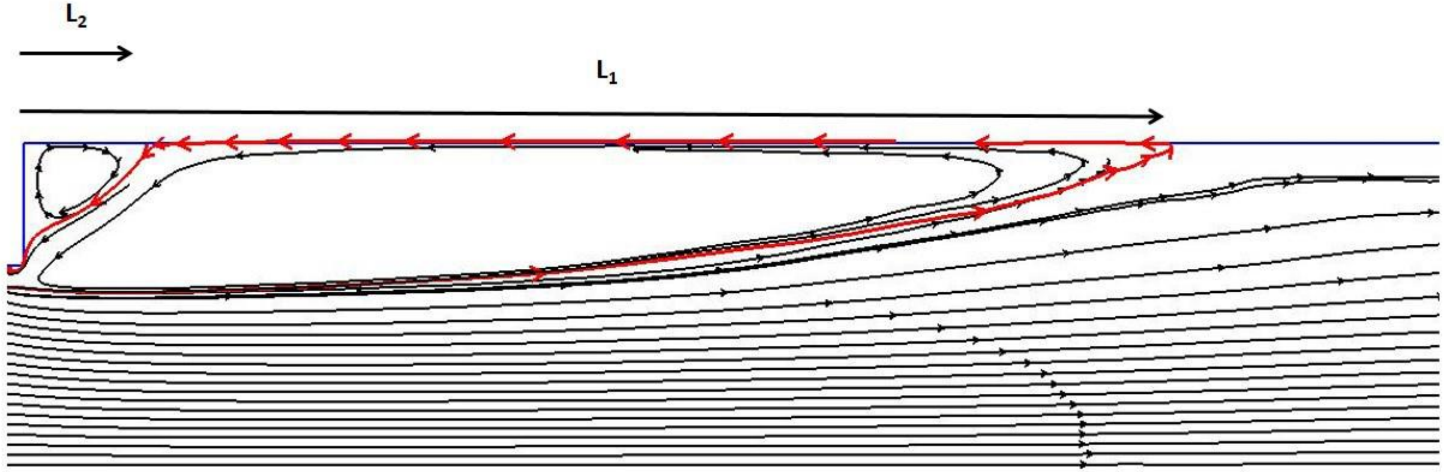
Instantaneous azimuthal velocity field: the structures are characteristic of a fully developed turbulent flow in a pipe

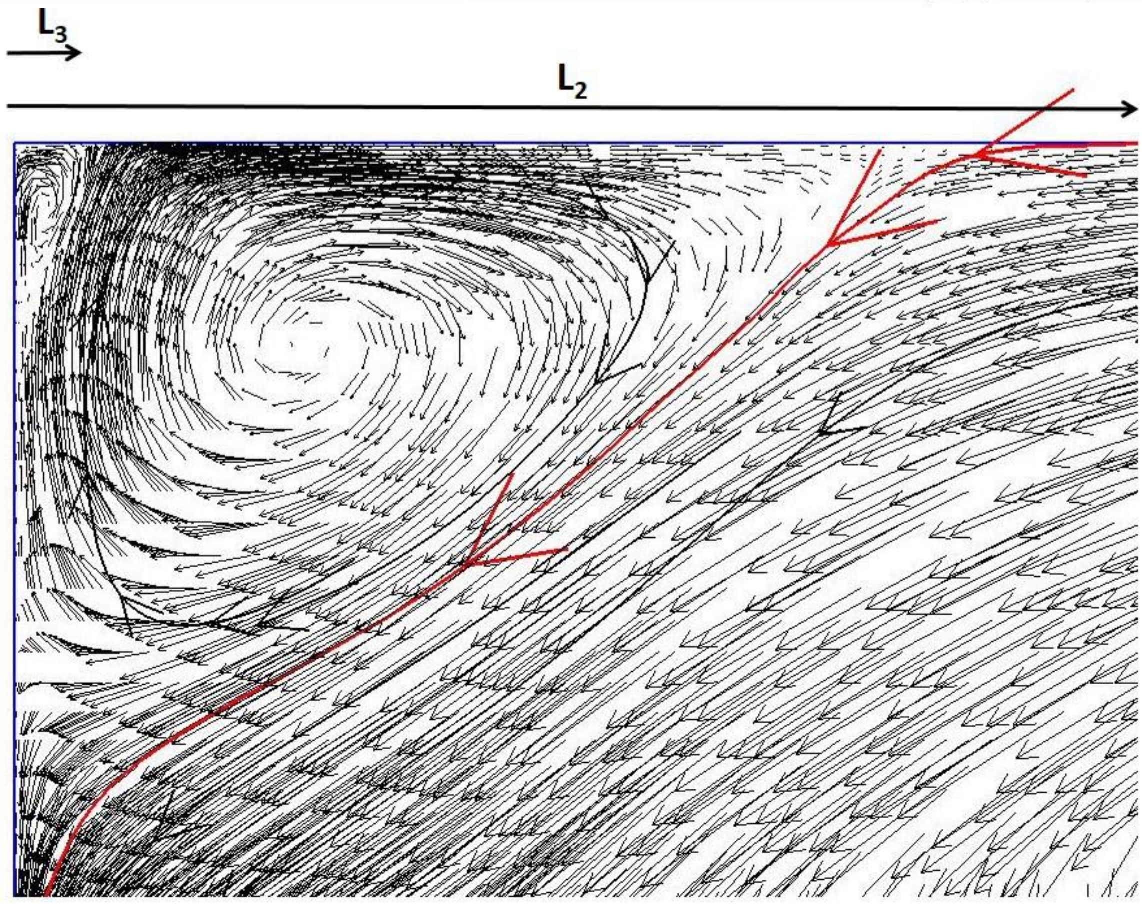
The velocity, pressure and Reynolds stresses are averaged in time:

- 8 flow-passes for dynamic Smagorinsky (1.2 million time steps)
- 4.5 flow-passes for the other SGS models

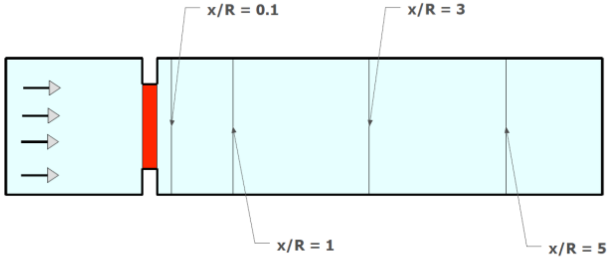




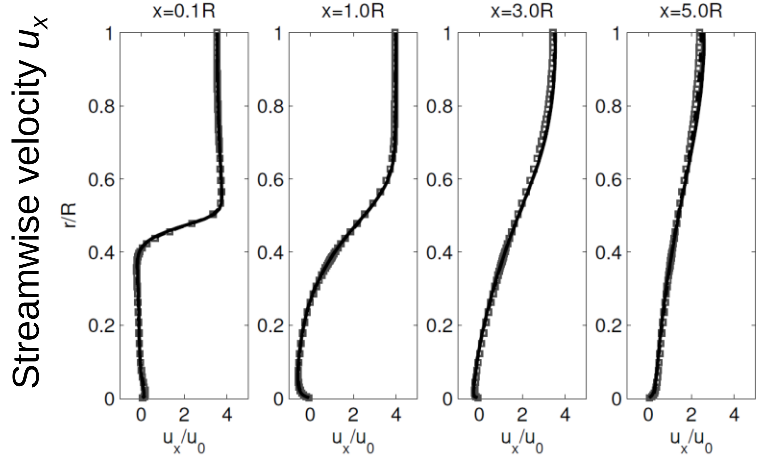

L_2
L_1

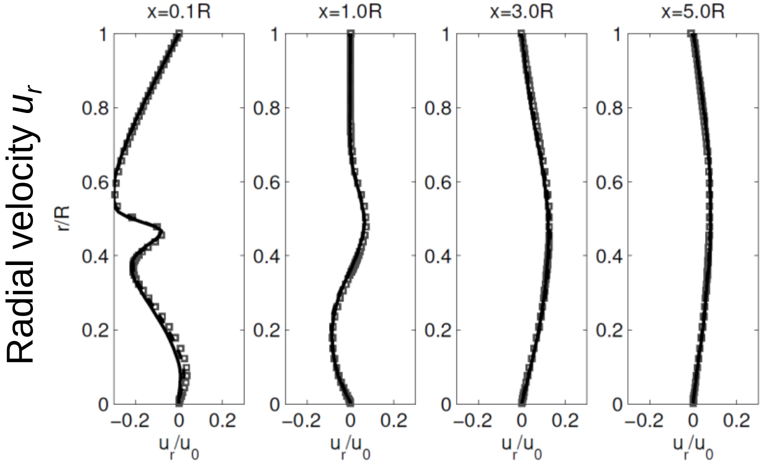

L_3
L_2

SENSITIVITY STUDIES (2/2)



Sub-grid scale model





	Dynamic Smagorinsky	Constant Smagorinksy	No Sub-grid Scale Model
Pressure loss coefficient	8.64	8.79	8.71
Primary reattachment [x/R]	3.92	4.25	4.11
Secondary reattachment [x/R]	0.42	0.37	0.40
Tertiary reattachment [x/R]	0.025	0.020	0.023

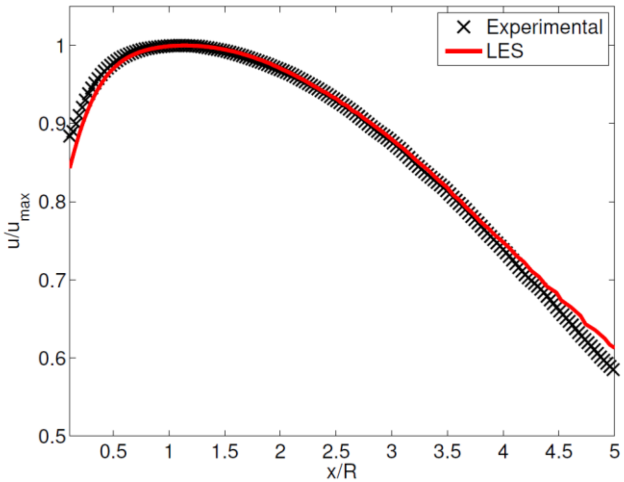
The downstream recirculation reattachment points are determined as the point at which the wall shear stress, τ_{wall} changes direction

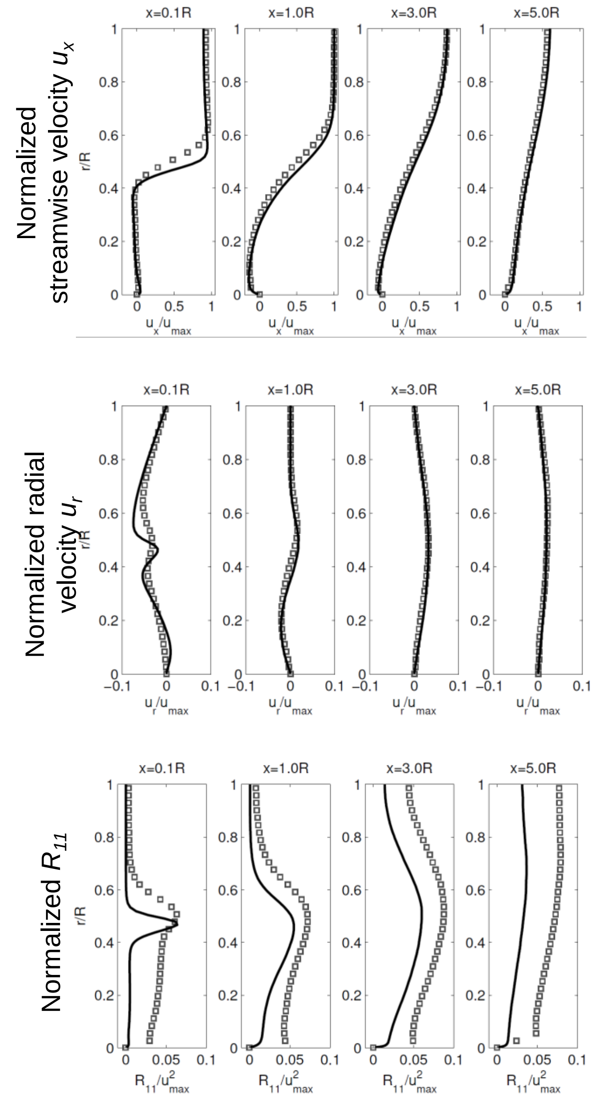
- No significant differences between the three different SGS models and similar results for R_{ii} profiles
- The close resemblance between all three models demonstrates that the LES is well resolved beyond the Taylor micro-scale, as the influence of the SGS model is almost negligible

□, dynamic Smagorinsky, —, Smagorinsky, - -, no SGS

COMPARISONS WITH EXPERIMENTAL DATA (1/3)

Local statistics





- The centerline stream-wise velocity normalized by the average velocity shows very similar behavior between the PIV observations and LES
- The shapes of both the LES and PIV stream-wise and radial velocity profiles provide a close match
- The results differ in two important zones: high gradients of the velocity and near wall region

COMPARISONS WITH EXPERIMENTAL DATA (2/3)

Recirculation zones

	FFP method (Forward Flow Probability, 0.056R from the wall)			Stream-wise velocity zero-crossing method (0.028R from the wall)		
	PIV	LES (zero τ_w)	Δ%	PIV	LES (D-S)	Δ%
Primary reattachment	3.64R	3.92R	+7.7	3.62R	3.60R	-0.55
Secondary reattachment	-	-		0.27R	0.34R	26

It is clear that the predicted reattachment points calculated with the same methodology using PIV data and the LES are similar

COMPARISONS WITH EXPERIMENTAL DATA (3/3)

Pressure loss and discharge coefficients

$$C_{PIV\_ISO}\ (\pm\sigma_C)$$

$$C_{LES} = \frac{4q_{m\_LES}}{\pi E d^2 \sqrt{2\Delta P_{LES}\rho}}$$

The discharge coefficient, $C_{D,ISO}$ = 0.628 ± 0.005 (0.8%) and the pressure loss coefficient K_{iso} = 8.71 ± 0.07 (0.8%)

The discharge coefficient, $C_{D,LES}$ = 0.632 and the pressure loss coefficient K_{LES} = 8.64 (Idel'cik gives 8.61)

- The results between the ISO standards and the LES are in very close agreement which serves as further validation of the LES results

CONCLUSIONS AND PERSPECTIVES (3/3)

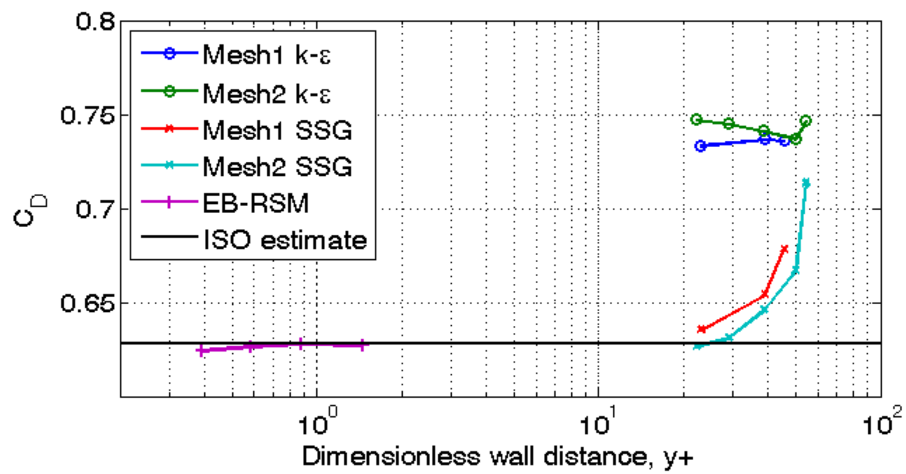
- This study demonstrates that a very fine wall-resolved LES with a dynamic Smagorinsky SGS can accurately and precisely simulate a single phase flow through a square-edged orifice plate.
- A sensitivity study shows that the effect of the SGS model and pressure-velocity coupling is negligible
- The LES shows excellent agreement with the velocity from the experimental data
- The pressure loss coefficient and discharge coefficient are also shown to be in agreement with the predictions of ISO 5167-2
- The results from this simulation can be used to validate other simulation techniques such as RANS approaches

Next step…

Validation of RANS results by LES ones seems to be possible when no experimental data are available

And then…

Apply the methodology to an industrial problem (second step of hybrid strategy)



What's the best turbulence model?

Thanks