Nonintrusive determination of aerodynamic pressure and loads from PIV velocity data (Invited)

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Publication date
2019

Document Version
Final published version

Citation (APA)
van Oudheusden, B. (2019). *Nonintrusive determination of aerodynamic pressure and loads from PIV velocity data (Invited)*. 10th Ankara International Aerospace Conference, Ankara, Turkey.

Nonintrusive determination of aerodynamic pressure and loads from PIV velocity data

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10th ANKARA INTERNATIONAL AEROSPACE CONFERENCE

September 18-20, 2019 @ METU, Ankara - TURKEY

TU Delft

Delft University of Technology

Acknowledgements

People (colleagues, MSc and PhD students, collaborators, etc.)

Anand Ashok, Steve Brust, Eric Casimiri, Paul van Gent, Roeland de Kat, Valeria Gentile, Marco Klein Heerenbrink, Kyle Lynch, Remco van de Meerendonk, Matteo Novara, Qais Payanda, Mustafa Percin, Daniele Ragni, Eric Roosenboom, Fulvio Scarano, Jan Schneiders, Ferry Schrijer, Louis Souverein, Daniele Violato, Pierre-Elie Weiss (ONERA), and others...

Support funding (grants)

STW (Dutch National Science Foundation): grants 7645 (2006-2011) and 11023 (2010-2016)

EU grants: **FP7-NIOPLEX** (2013-2016) and **H2020-HOMER** (2018-2021)

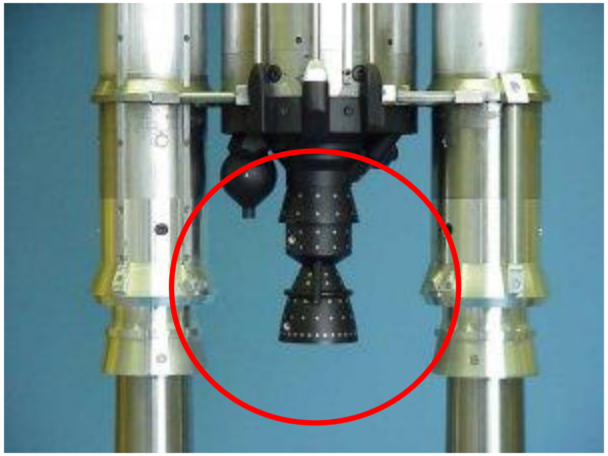
Background: Classical procedures for pressure and load measurement

Pressure: surface pressure sensors and flow probes

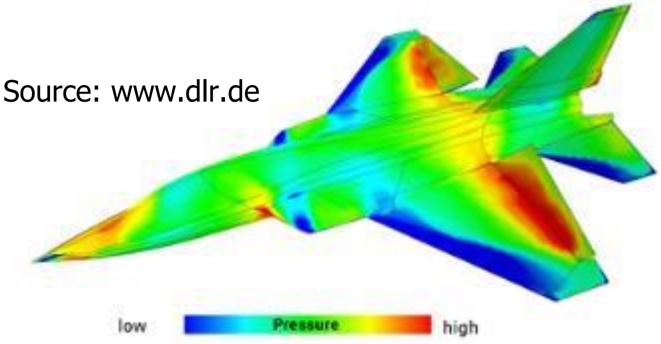
Loads: mechanical balance systems

Features:

- Reliable & established
- Expensive (system complexity)
- Intrusive
- Either localized or global
- Low spatial resolution
- High temporal resolution



Non-intrusive optical pressure/load measurement



Source: www.dlr.de

Pressure Sensitive Paint (PSP)

- Surface pressure

PIV/PTV-based pressure measurement: "pressure from velocity"

PIV = Particle Image Velocimetry

PTV = Particle Tracking Velocimetry

Attractive Features:

- Flow-field (+surface) pressure
- Tuneable sensitivity
- Non-intrusive
- No (model or probe) instrumentation required
- Flow + pressure: FSI & aeroelasticity; aeroacoustics

Outline

1. **Working Principles**

2. **Applications (aerospace domain)**

Part 1

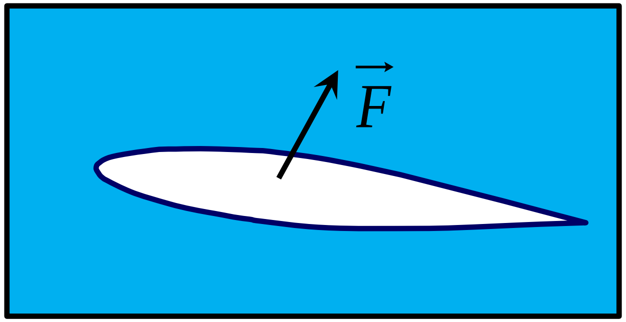
Working Principles

Velocimetry-based pressure measurement

Pressure/loads from velocity: basic operating principle

1. **Pressure gradient from momentum equation:** $$\nabla p = -\rho \frac{D\mathbf{u}}{Dt} + \mu \nabla^2 \mathbf{u}$$
2. **Pressure field from spatial integration:** $$p = \iint \nabla p \, dA$$
3. **Integral loads from control volume formulation:**

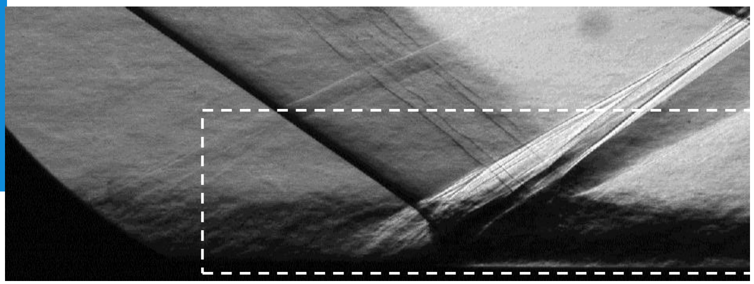
$$\mathbf{F}(t) \approx -\underbrace{\iiint_V \frac{\partial \rho \mathbf{u}}{\partial t} dV}_{\text{Acceleration term}} - \underbrace{\iint_S \rho \mathbf{u}\mathbf{u} \cdot \mathbf{n} \, dS}_{\text{Momentum flux term}} - \underbrace{\iint_S p \, \mathbf{n} \, dS}_{\text{Pressure term}}$$

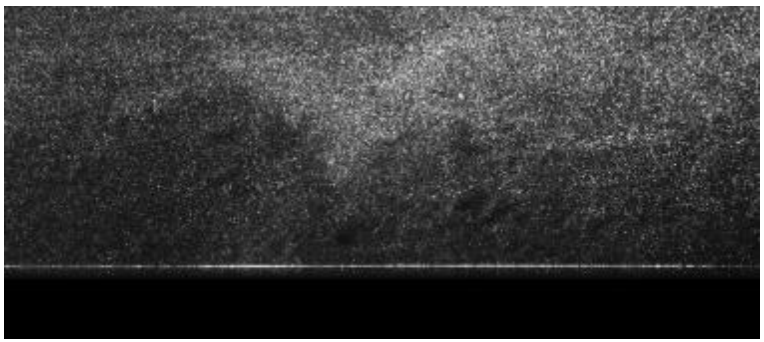


Review publications:

- Van Oudheusden (Meas.Sci.Technol. 2013) - pressure
- Rival & Van Oudheusden (Exp.Fluids 2017) - loads

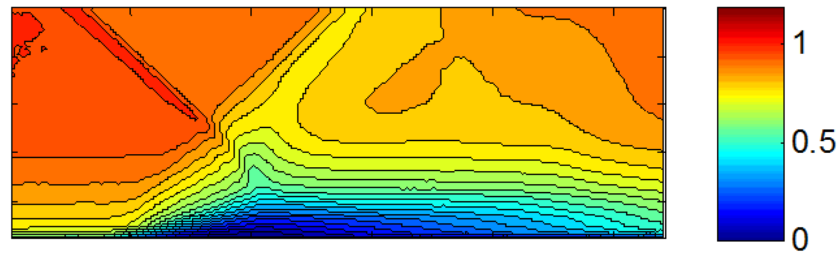
PIV-based pressure procedure



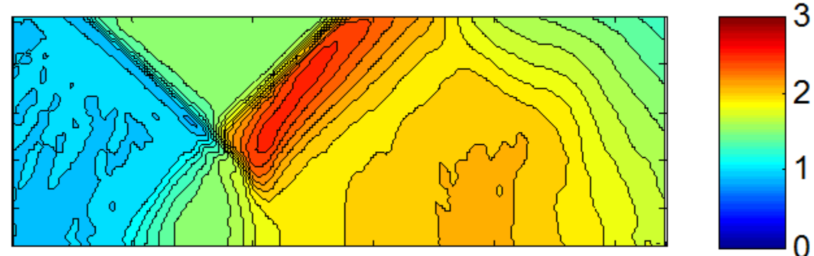


Mach = 1.6 shock-wave boundary-layer interaction
(Van Oudheusden and Souverein 2007)

velocity U/U_∞



static pressure p/p_∞



1. **PIV image recording**
2. **image interrogation**
3. **pressure integration**

Visualisation-based pressure determination

A (pre-)historical example: Schwabe 1935 (!)

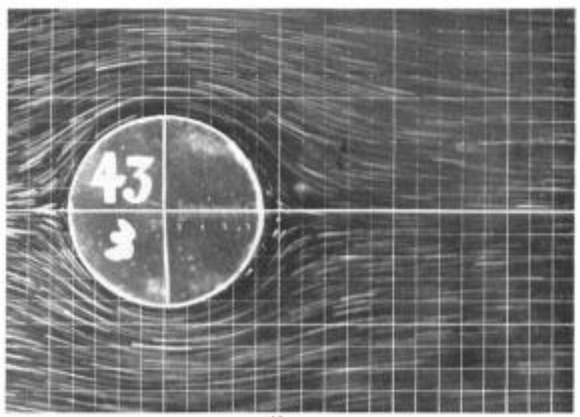


Abb. 5a.

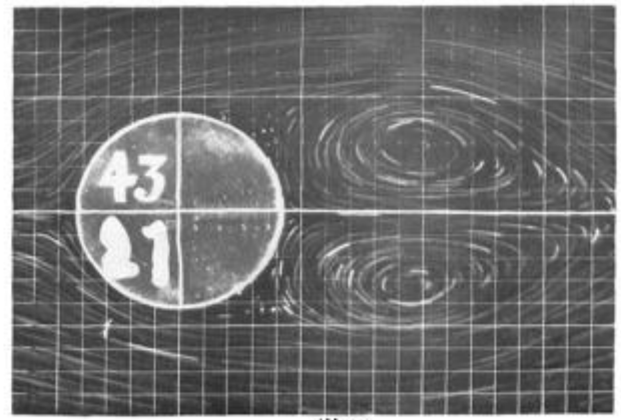


Abb. 5e.

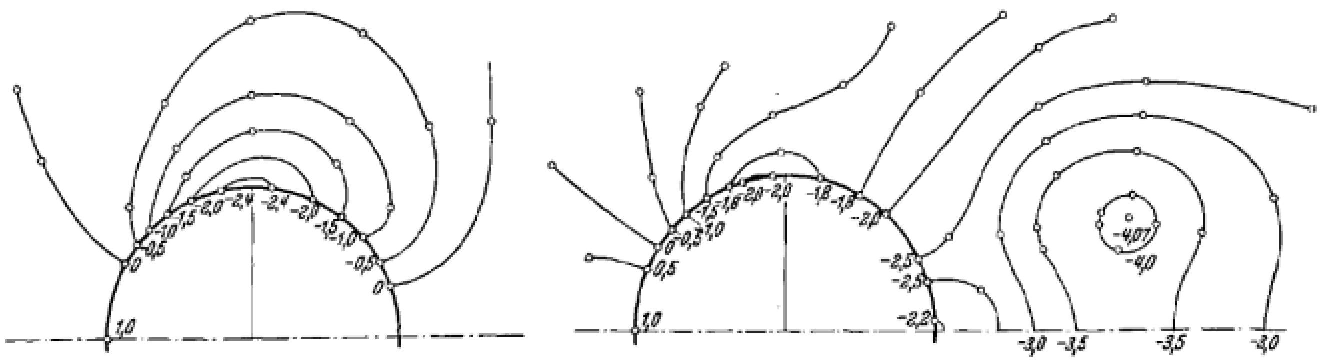


Abb. 7a. Abb. 7b.

Abb. 7a, 7b. Linien gleichen Druckes. *a* nach Abb. 5a, *b* nach Abb. 5e.

Schwabe M (1935) Über die Druckermittlung in der nichtstationären ebenen Strömung - *Ing. Archiv*

Visualisation-based pressure determination

Developments towards a digital implementation

Progress is enabled by advances in digital camera hardware, image processing tools and numerical algorithms

Early steps:

- Imaichi and Ohmi (1983) applied a numerical processing of photographic flow-visualization data of two-dimensional cylinder flows

Real progress after the introduction of Digital PIV (DPIV, Willert & Gharib, 1991):

- Jakobsen et al (1997) and Jensen et al. (2001) used PIV to determine acceleration and pressure in water wave phenomena
- Baur and Köngeter (1999) investigated pressure variations in vortical structures
- Gurka et al. (1999): time-average pressure in a nozzle flow and an air jet

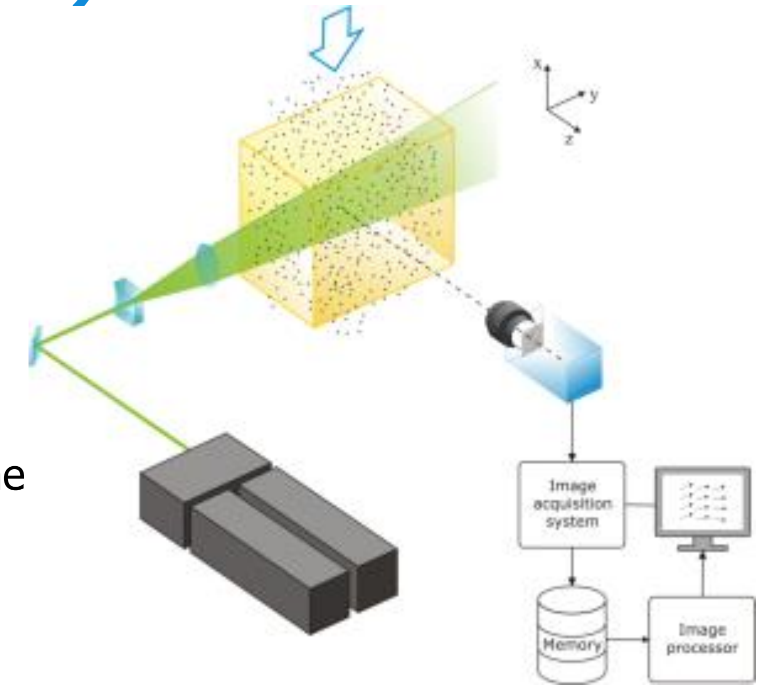
So, basically the technique is about 20 years old

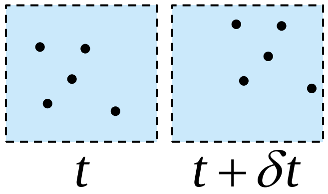
Particle Image Velocimetry (PIV)

Planar PIV (2C or 3C-stereo)

Basic working principle:

1. Flow is seeded with small particles
2. Illumination by thin laser sheet (pulsed)
3. Two image frames are captured at small time interval (= pulse separation δt)
4. Image interrogation: cross-correlation of frame sections (“interrogation windows”) provides local average particle displacement
5. local flow velocity = part.displacement / δt





an “interrogation window”

Typical current PIV system capabilities:

- pulse separation δt down to 1 μs
- Repetition rate up to 10 kHz

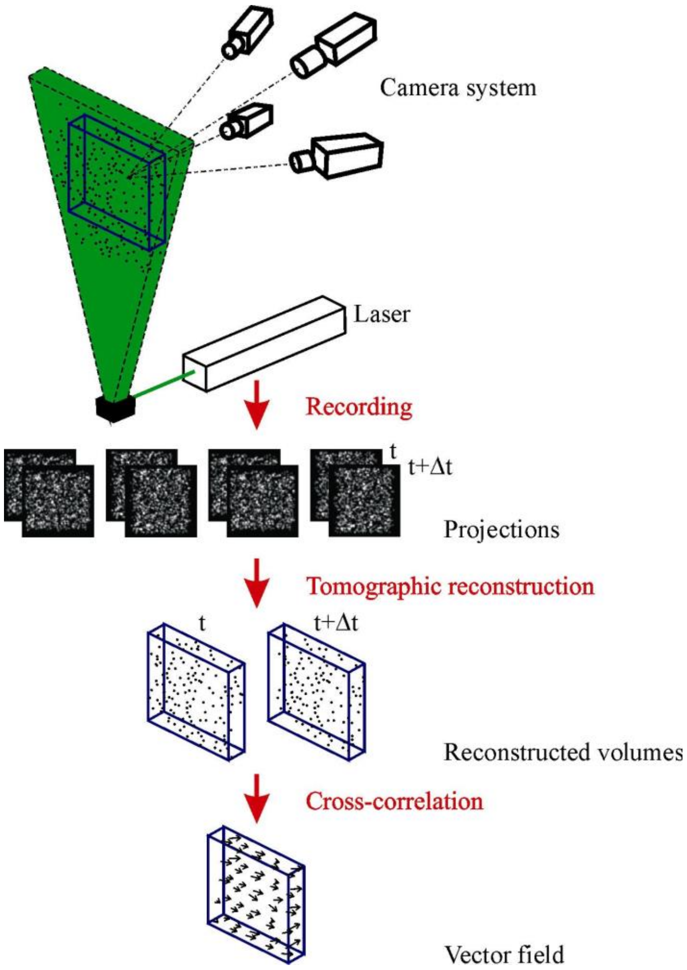
Volumetric PIV

Tomographic PIV

Extension of stereoscopic PIV:

1. Volumetric illumination
2. Simultaneous recording from multiple views → "projections" (typical 4)
3. Tomographic reconstruction of volumetric "particle" distribution
4. 3D cross-correlation → **3D-3C** velocity data

- Tomo-PIV has severe volumetric limitations (~100 cm^3 in air) + large processing time
- Recent improvements by using volumetric particle tracking methods



(Elsinga et al, Exp. in Fluids, 2006)

PIV-based "pressure measurement"

$$\nabla p = -\rho \frac{D\mathbf{u}}{Dt} + \mu \nabla^2 \mathbf{u}$$

viscous term (negligible)

with: $$\frac{D\mathbf{u}}{Dt} = \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}$$

material derivative = flow acceleration

Requirements on velocity measurement

- **Instantaneous pressure determination** in unsteady flows: requires acceleration data (time-resolved or "multiple-pulse" PIV)
  - pulse separation δt governs velocity measurement
  - time separation Δt (~repetition rate) governs acceleration measurement
- **Mean pressure** (or steady flow): velocity mean/statistics sufficient
- **Pressure in 2D flow**: planar velocity data sufficient (2C-PIV)
- **Pressure in 3D flow**: volumetric velocity data needed (3D-3C-data)

Accuracy of material derivative determination

Effect of time separation Δt

$$\frac{du}{dt}(t) \approx \frac{u(t+\Delta t) - u(t)}{\Delta t}$$

Error sources:

1. Truncation error

(result of discretization)

NB: τ and U are typical time and velocity scales of the flow

$$\varepsilon_{trunc} \sim \Delta t \frac{U}{\tau^2}$$

opposite effects of time separation

2. Precision error

propagation of velocity measurement uncertainty ε_u

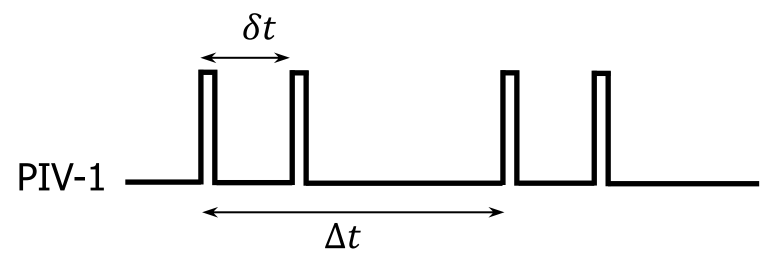
$$\varepsilon_{pr} \sim \frac{\varepsilon_u}{\Delta t}$$

typically $\Delta t / \delta t$ of the order 5 to 10

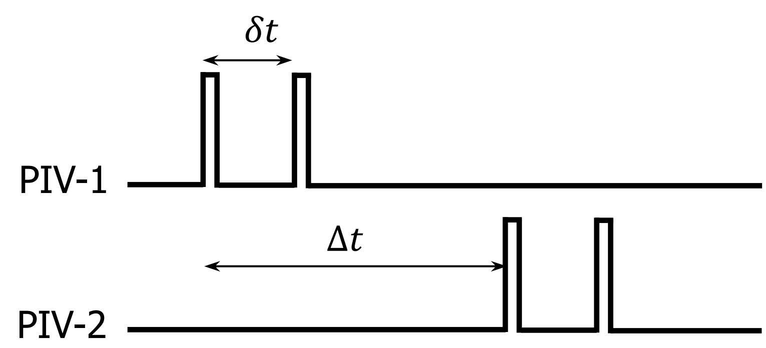
NB: error can be further reduced by using time-series data

Timing strategies (hardware implementation):

- **Time-resolved double-pulse:**
  - Allows independent tuning of pulse separation δt and time separation Δt
  - Requires high repetition rate (~ kHz)
  - Minimum time separation sets limit on flow speed (~ 25 - 50 m/s)



- **Multiple-pulse (or dual PIV):**
  - Suitable for high speed flow
  - Small time separation achieved by delay between two independent PIV systems; no high repetition rate required!
  - Optical separation of the PIV systems (e.g. by wavelength or polarization)

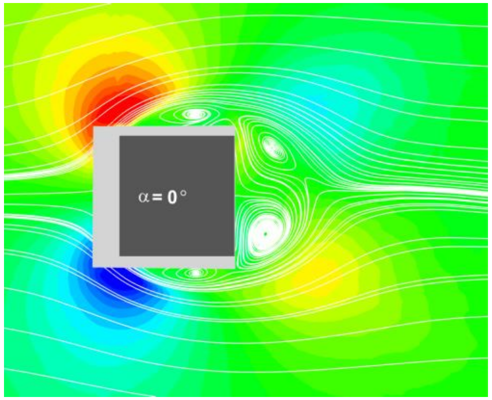


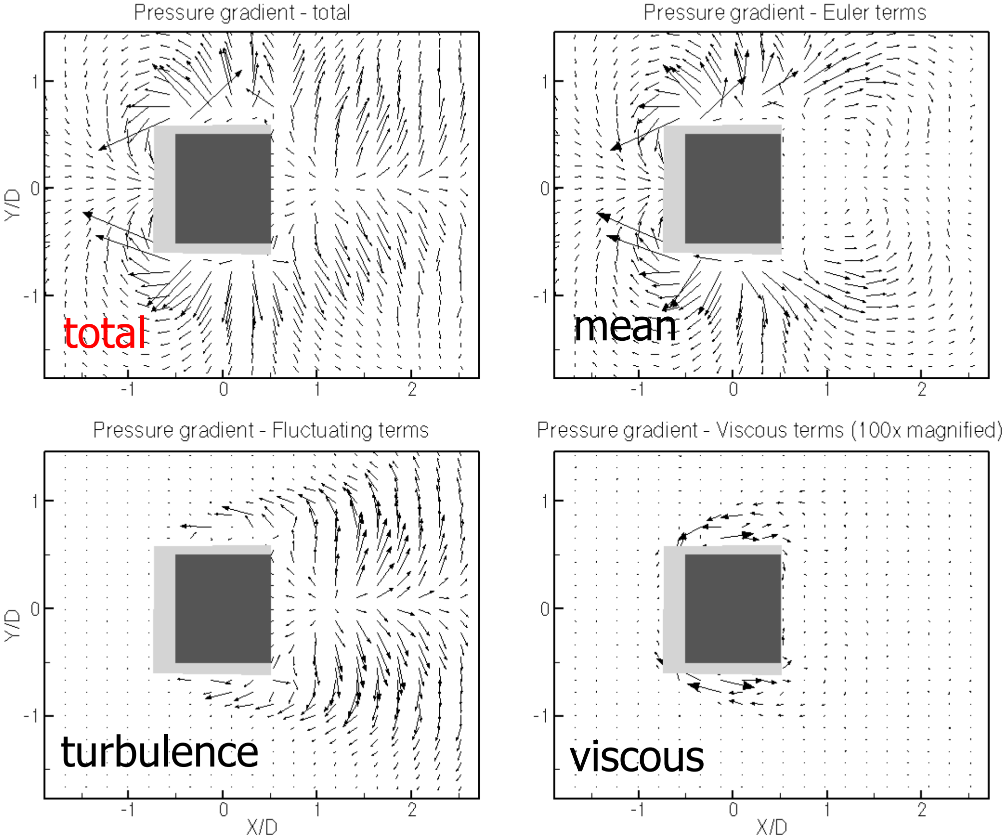
Reynolds-averaging for mean pressure

Mean pressure gradient from Reynolds-averaged momentum equation:

$$\nabla \overline{p} = -\rho(\overline{\mathbf{u}} \cdot \nabla \overline{\mathbf{u}} + \nabla \cdot \overline{\mathbf{u}'\mathbf{u}'}) + \mu \nabla^2 \overline{\mathbf{u}}$$

contributions from: mean flow turbulence viscous





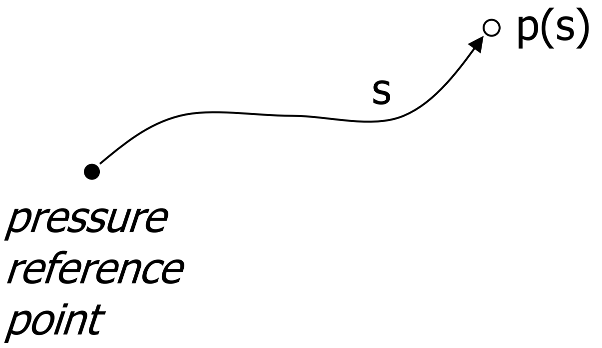
Contributions to the mean pressure gradient for the flow around a square-section prism (Re_D = 20,000)

Note: viscous terms negligible

Pressure-gradient integration approaches

Spatial integration:

$$p(\mathbf{s}) = p(\mathbf{s}_{\mathrm{ref}}) + \int_{\mathbf{s}_{\mathrm{ref}}}^{\mathbf{s}} \nabla p \cdot d\mathbf{s}$$



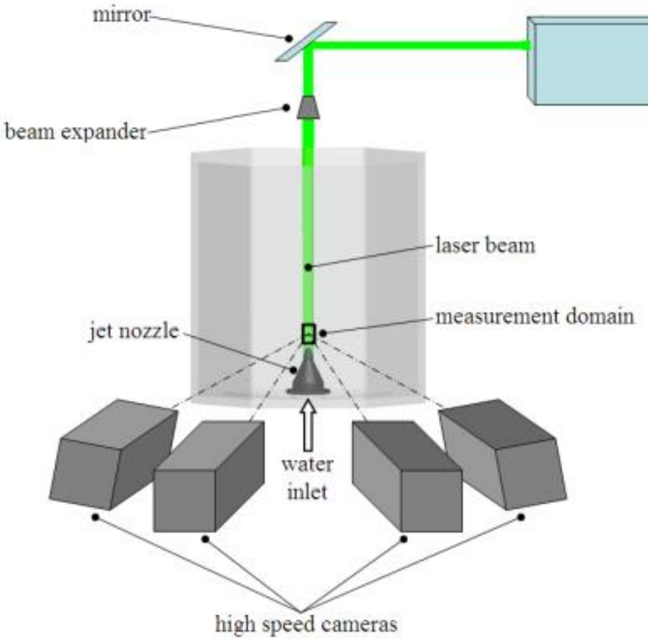
Uniqueness:

- Pressure value can be path-dependent due to pressure-gradient inconsistencies (measurement errors or incomplete velocity information)
- Multi-path integration or marching-schemes with weighted averages
- Poisson-equation approach (equivalent to global error minimization)

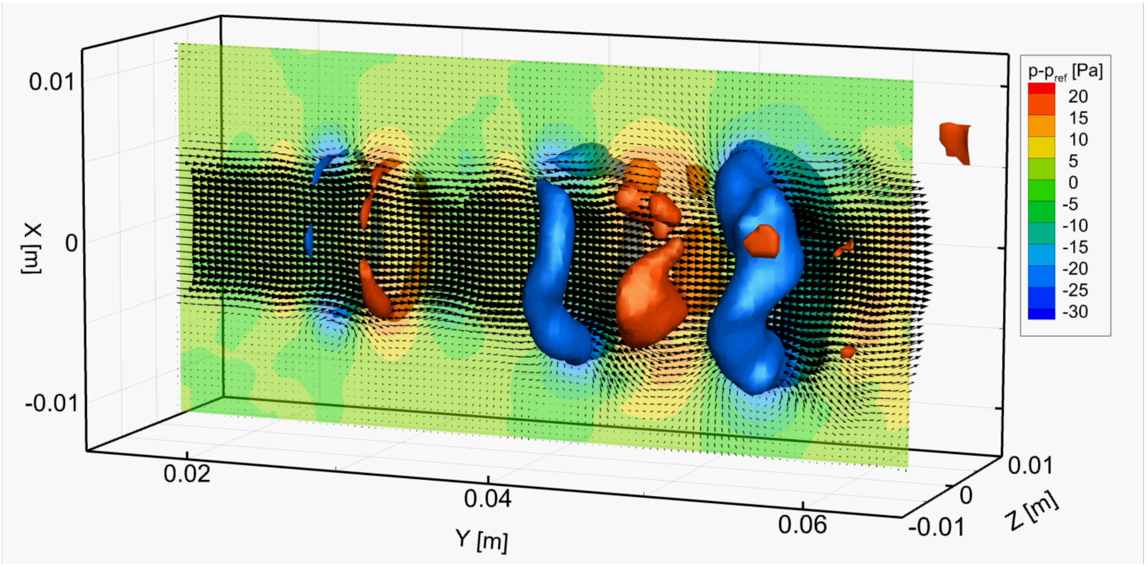
$$\nabla^2 p = \nabla \cdot f(\mathbf{x},t) \quad \Leftrightarrow \quad \min_p \int_S \left\| \nabla p - f(\mathbf{x},t) \right\|^2 dS$$

Example: 3D pressure field of low-Re jet in water

3D characterization of a transitional jet using time-resolved tomo-PIV



Formation and breakup of ring vortices pressure field animation (courtesy of: Matteo Novara)



Nozzle exit diameter: 10 mm
Exit velocity: 0.1 – 2.5 m/s
Meas. domain size: 3 x 3 x 5 cm^3
Acquisition rate: 1 kHz

(Violato et al. 2011)

Part 2

Applications in high speed flows

Extension to compressible flows

Axisymmetric base flows

Extension to compressible flow

Governing relation: (with viscous term neglected)

- momentum equation: $\nabla p = -\rho \frac{D\mathbf{u}}{Dt}$ but with variable density!

Closure procedure: (Van Oudheusden et al. 2006)

- equation of state: $\rho = \frac{p}{RT}$
- constant total temperature: $c_p T + \frac{1}{2}\|\mathbf{u}\|^2 = \text{cst.}$

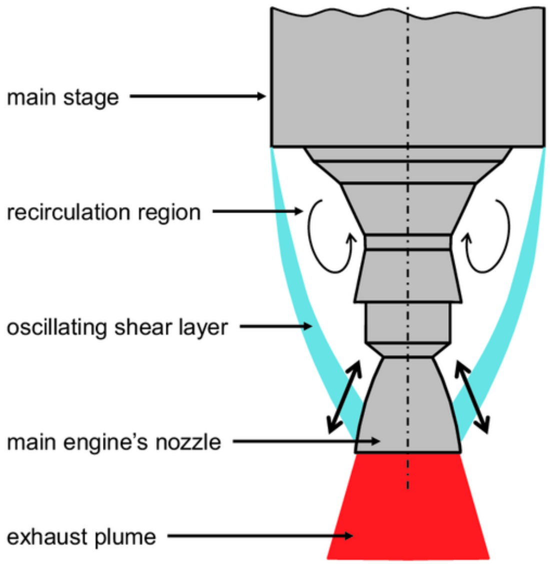
$$\left.\begin{array}{l} \rho = \frac{p}{RT} \\ c_p T + \frac{1}{2}\|\mathbf{u}\|^2 = \text{cst.} \end{array}\right\} \rho = \frac{p}{R \cdot T(\|\mathbf{u}\|)}$$

Explicit formulation for the pressure gradient: $$\frac{\nabla p}{p} = \nabla(\ln\, p) = \frac{1}{R \cdot T(\|\mathbf{u}\|)} \cdot \frac{D\mathbf{u}}{Dt}$$

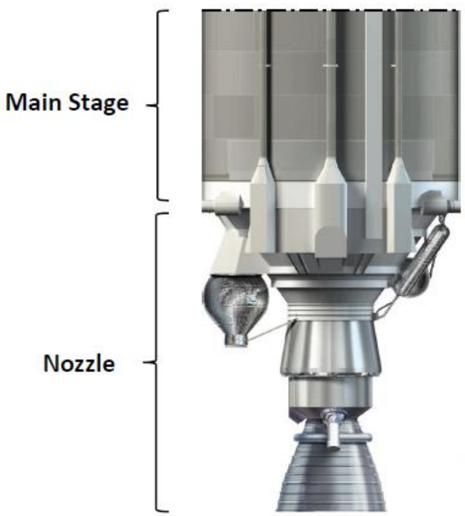
Axisymmetric base flows

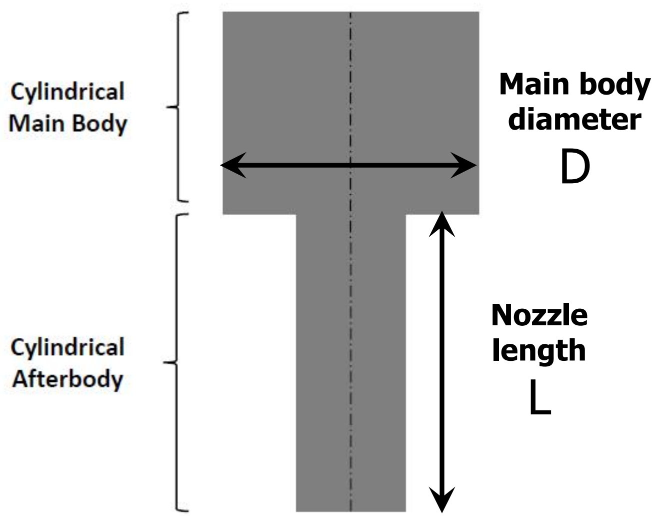
Relevance:

- Background: transonic buffet in launchers
- Unsteady shear layer reattachment
- Simplification: generic (axisymmetric) test geometries



(Scharnowski, 2014)



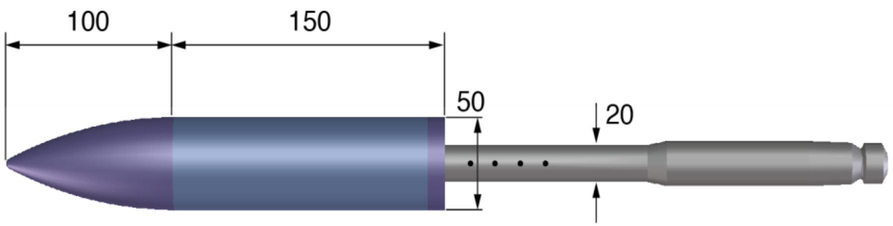


(Van Gent, 2018)

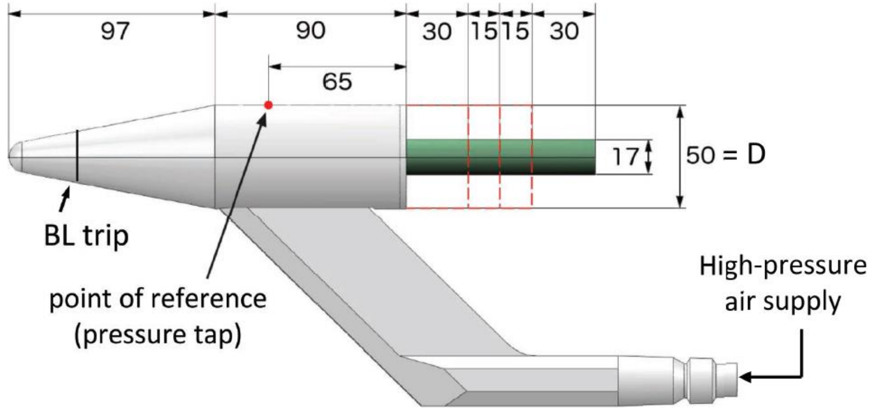
Base flow investigations

Experimental models:

- Rear-sting mounted model

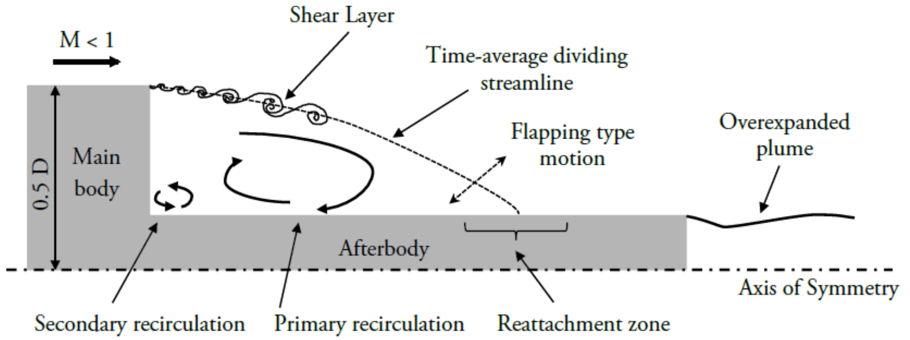


- Side-sting mounted model with exhaust plume simulation (1990's FESTIP program)



Objectives:

- Unsteady flow behaviour
- Particular interest: pressure on base and afterbody
- Influence of afterbody length and plume presence



Base flow investigations

1. Potential for instantaneous pressure:

- Synthetic test case: method assessment (numerical simulation)
- Instantaneous pressure in low-speed (experimental)
- Idem in high-speed

2. Determination of mean pressure:

- Re-averaged approach for mean pressure
- 2D vs 3D data (is tomo necessary?)
- Application study: base flow with simulated exhaust plume

SEVENTH FRAMEWORK PROGRAMME

PhD of Paul van Gent (various publications; 2015-2018)

Partly funded by FP7 project "NIOPLEX" (2013-2016)

NIOPLEX

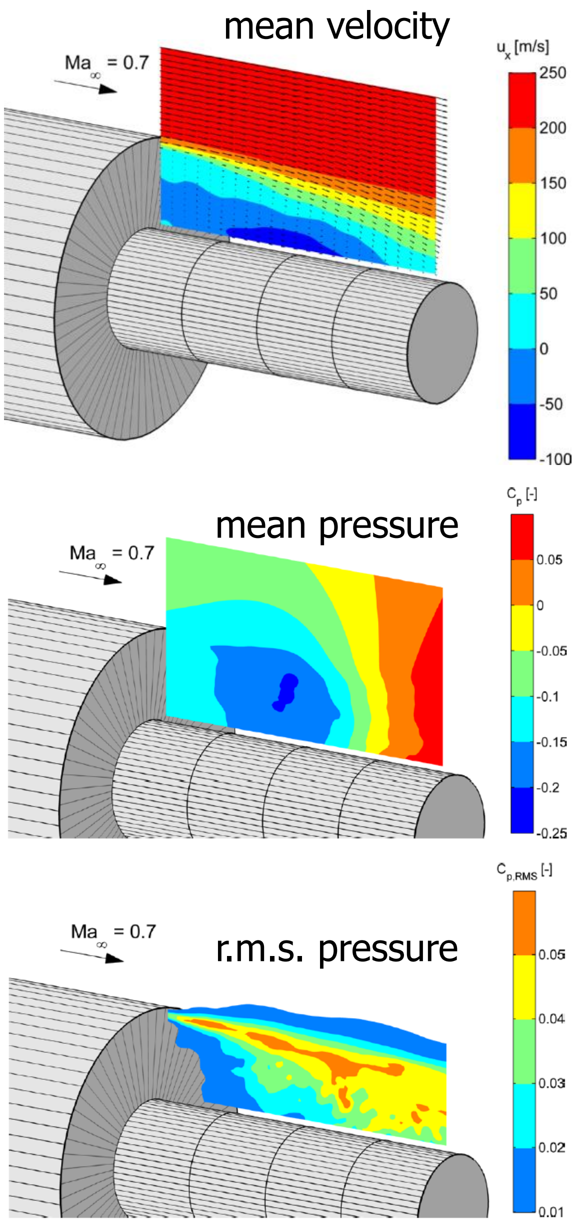
Comparative test case

Methodology:

- Reference data: Zonal Detached Eddy (ZDES) simulation (ONERA) of a transonic base flow (Mach = 0.7)
- The CFD data is processed to construct a "synthetic PIV experiment"
- This comprises sequences of quasi-PIV/PTV data in either time-resolved or multi-pulse (4 pulses) mode

Objectives:

- Assessment of modeling assumptions
- Comparison of different methods (PIV/PTV, time-resolved/multi-pulse, processing schemes)
- Effect of data noise, etc..

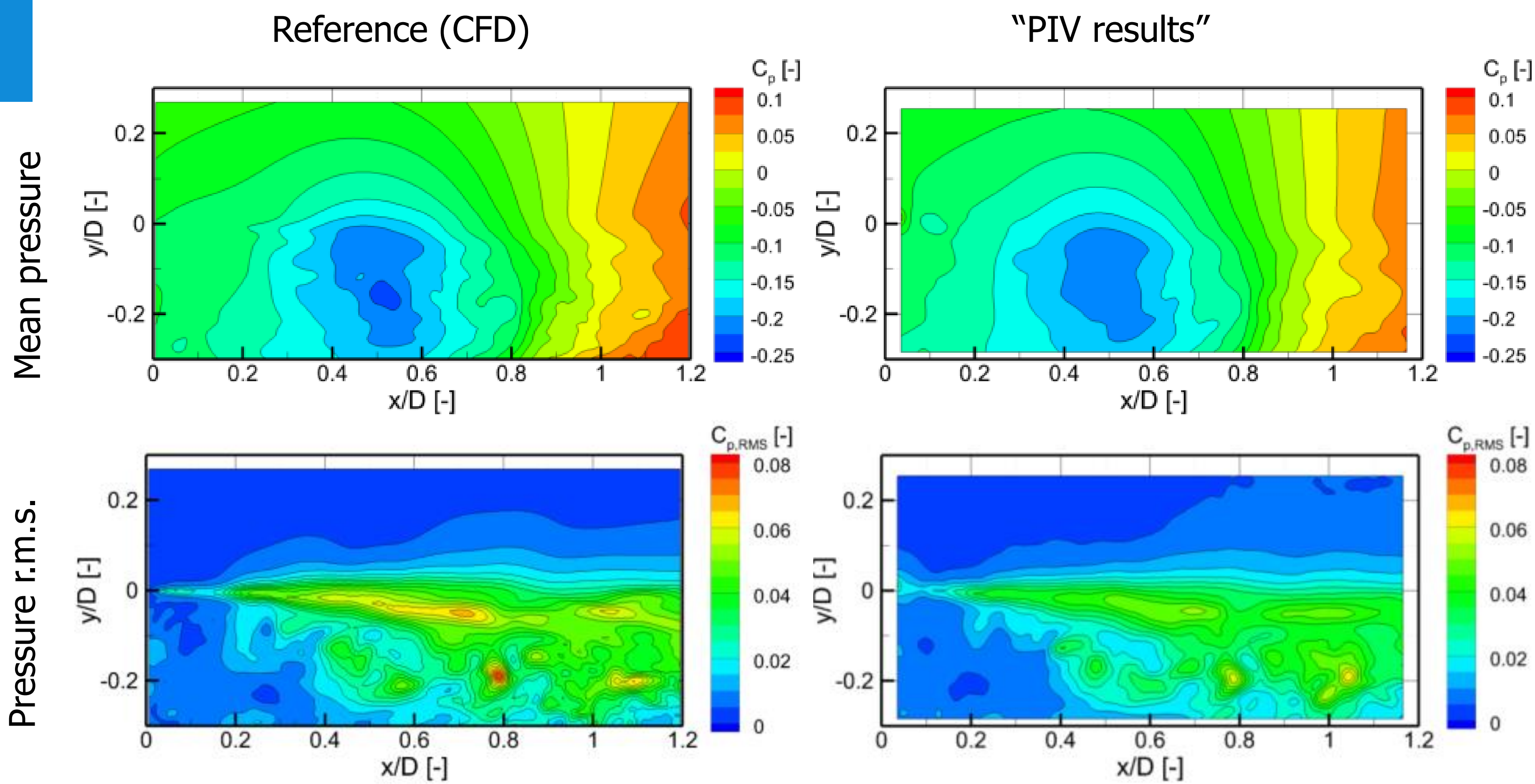


(Schneiders et al., 2014)

(Van Gent et al., Experiments in Fluids, 2017)

Comparative test case – results

Illustrative results from an earlier study



(Van Gent et al., Lisbon Laser Conf, 2014)

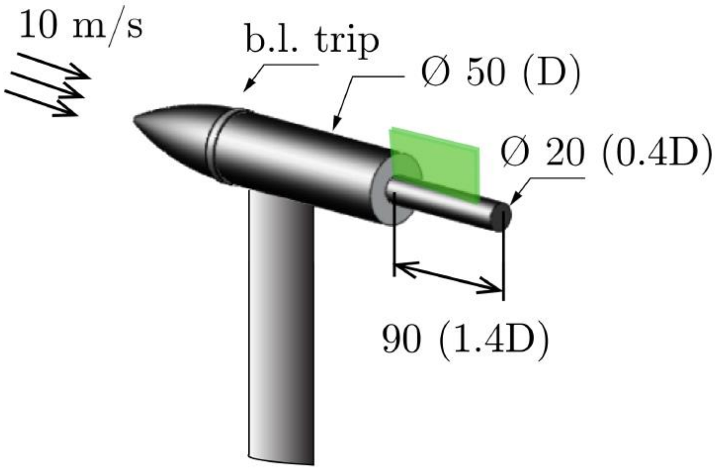
Comparative test case - conclusions

- Modeling assumptions are less relevant than the accuracy of the flow acceleration determination
- All different processing methods allow a good to accurate reconstruction of the pressure (r.m.s. errors <1-2%)
- PTV-based methods can give higher accuracy than PIV-based, due to higher spatial resolution
- Time-resolved data provides the best results, but meaningful pressure can be obtained from multi-pulse (or even single-snapshot) approaches
- Adding (realistic) image noise levels is not prohibitive

Low-speed base flow experiment

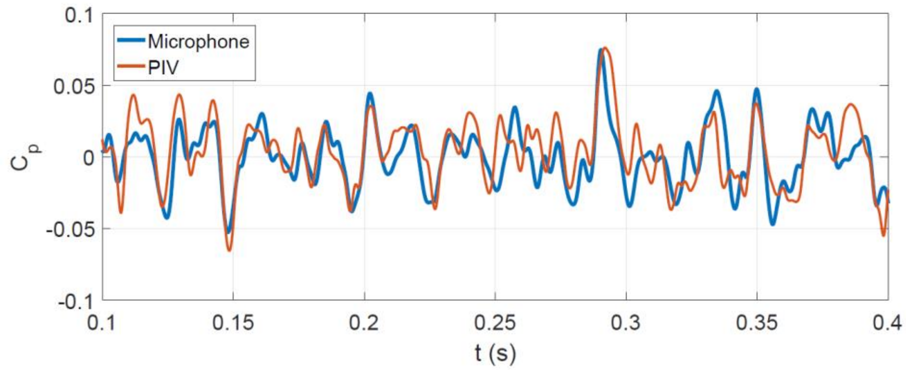
Experimental set-up:

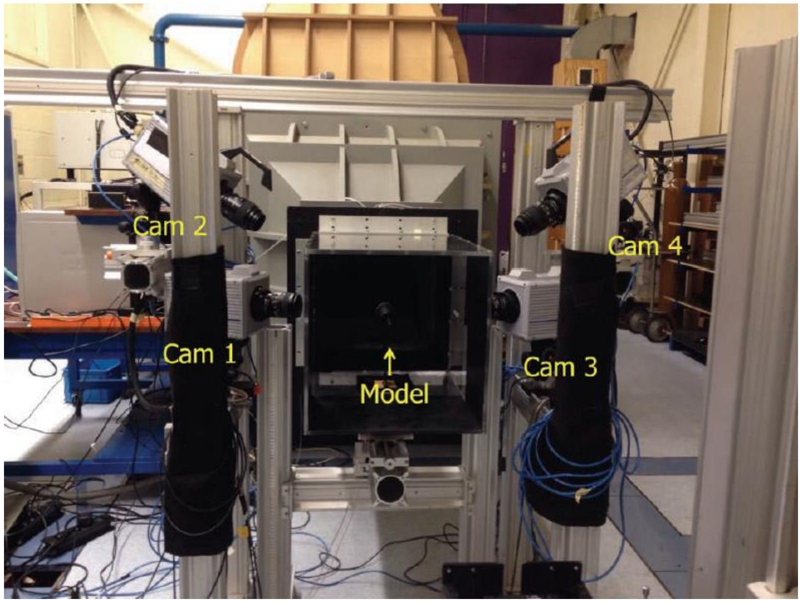
- Flow speed: 10 m/s
- PIV: 4-camera thin-tomo volume (75 mm x 35 mm x 3.5 mm)
- Acquisition rate 10 kHz (**time-resolved**)
- Reference pressure: microphones (6)



Data processing:

- Flow acceleration is computed from tracks of 25 subsequent PIV fields

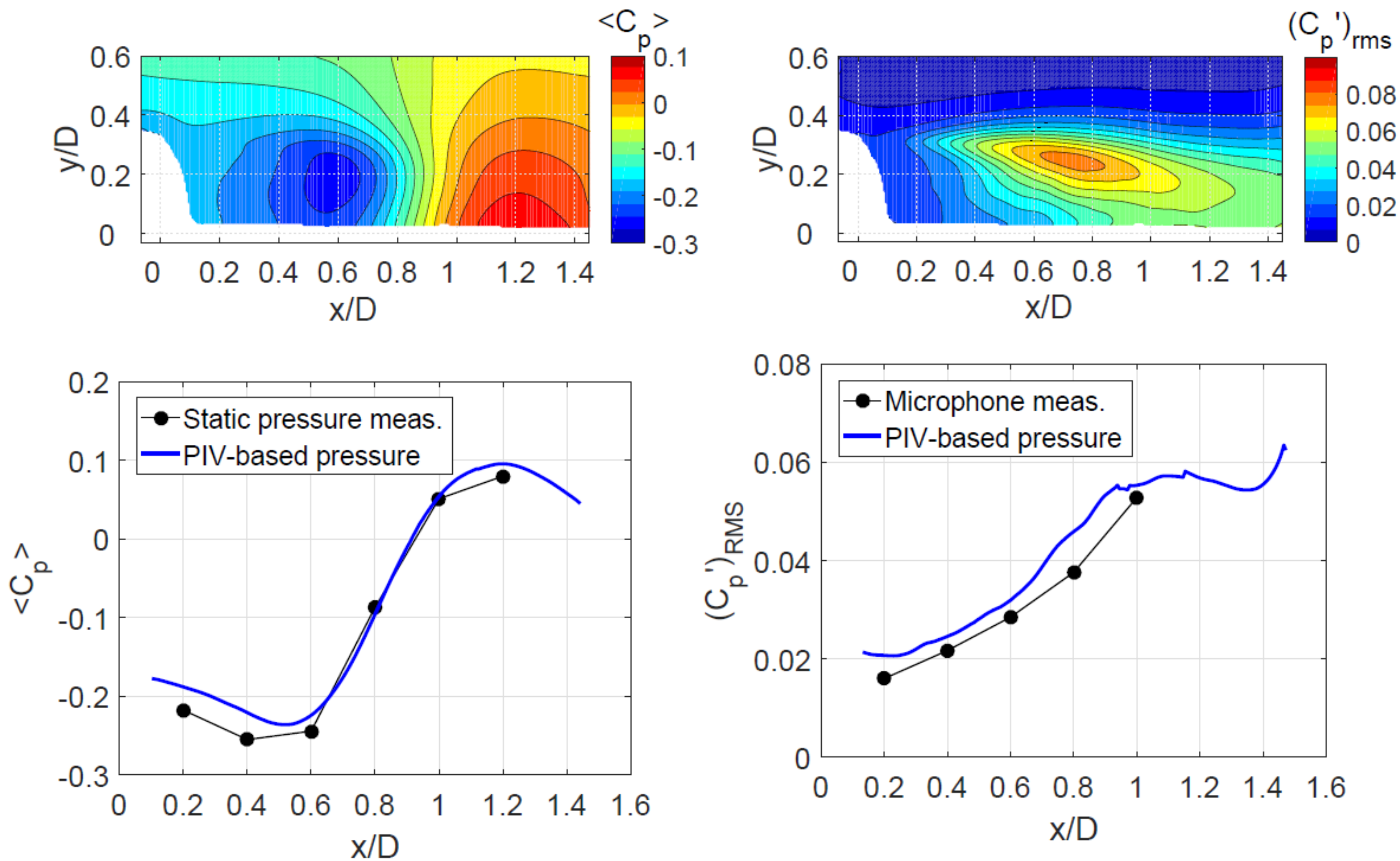




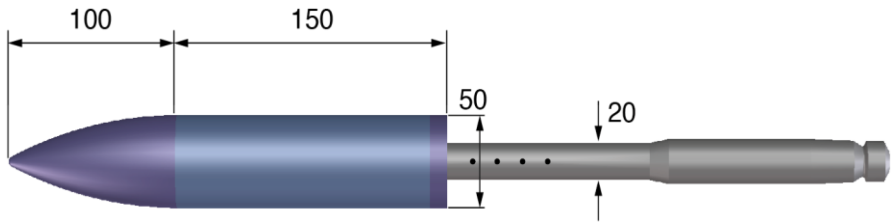
Low-speed base flow experiment

Results:

- Good agreement between PIV-based and reference (microphone) pressure



High-speed base flow experiment

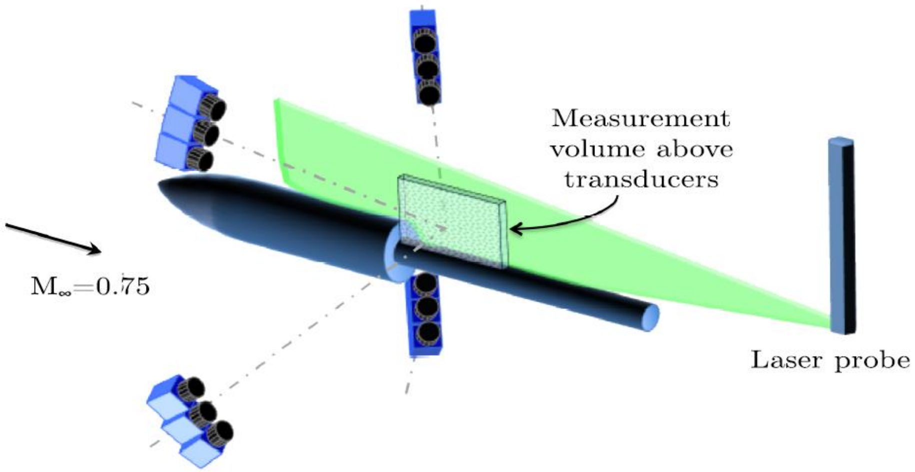


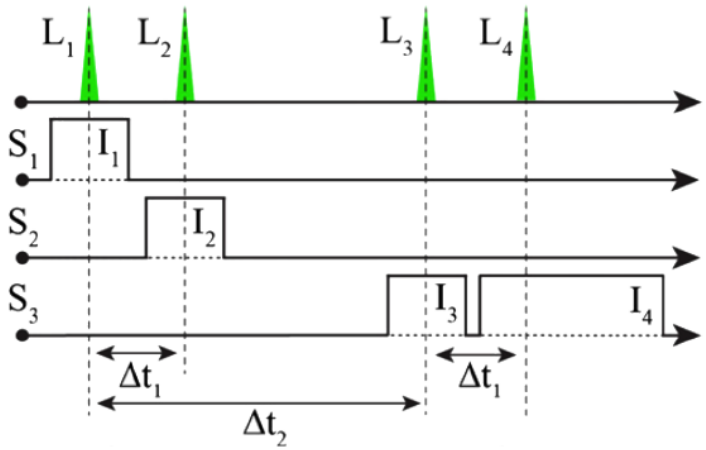
Model:

- Rear-sting-mounted model
- Flow speed: Mach = 0.75
- Pressure: 4 Endevco transducers

PIV set-up:

- PIV strategy: **four-pulse tomographic**
- 3 independent tomographic PIV systems
  (2-laser, 12-camera system, Lynch & Scarano 2014)
- PIV volume: 65 mm x 45 mm x 3.5 mm





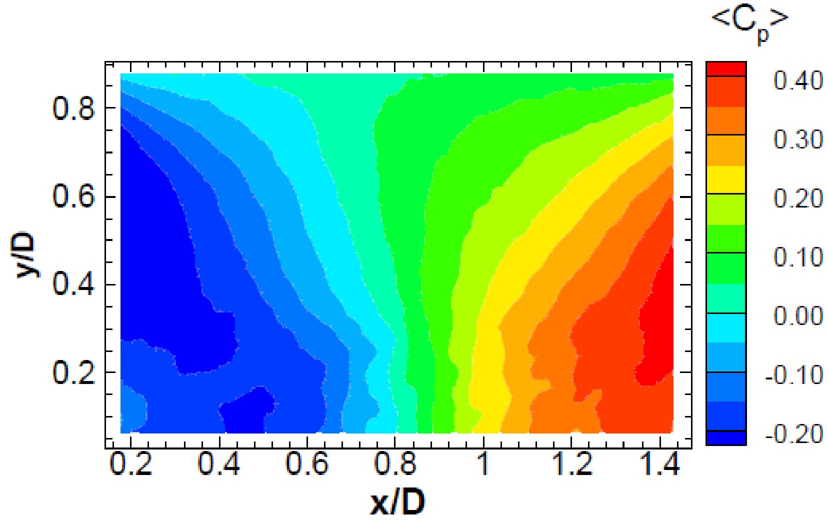
Δt_1 = 2.5 μs; Δt_2 = 5-10 μs

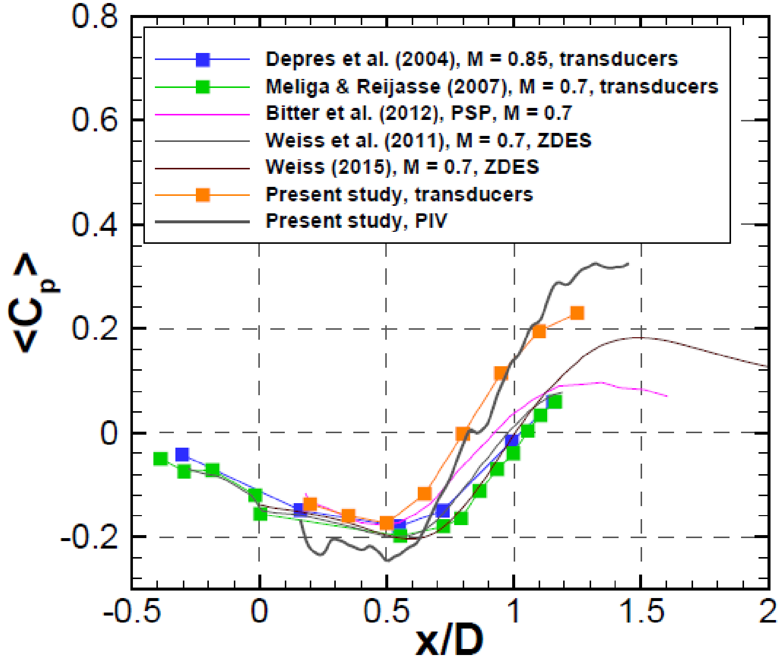
(Van Gent, PhD thesis, 2018)

High-speed base flow experiment

Results for the mean pressure:

- Good agreement between transducer and PIV-based pressure
- Reasonable agreement with other experiments and numerical simulations (differences in exact configuration, flow conditions, blockage, etc.)





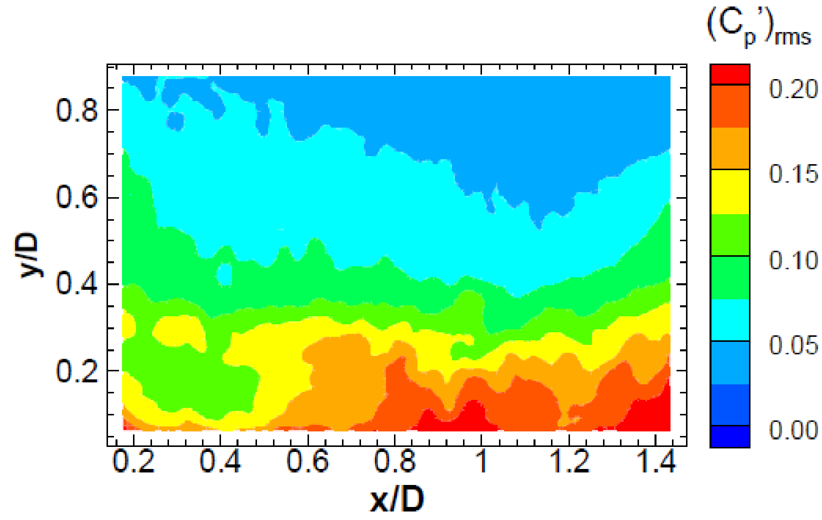
High-speed base flow experiment

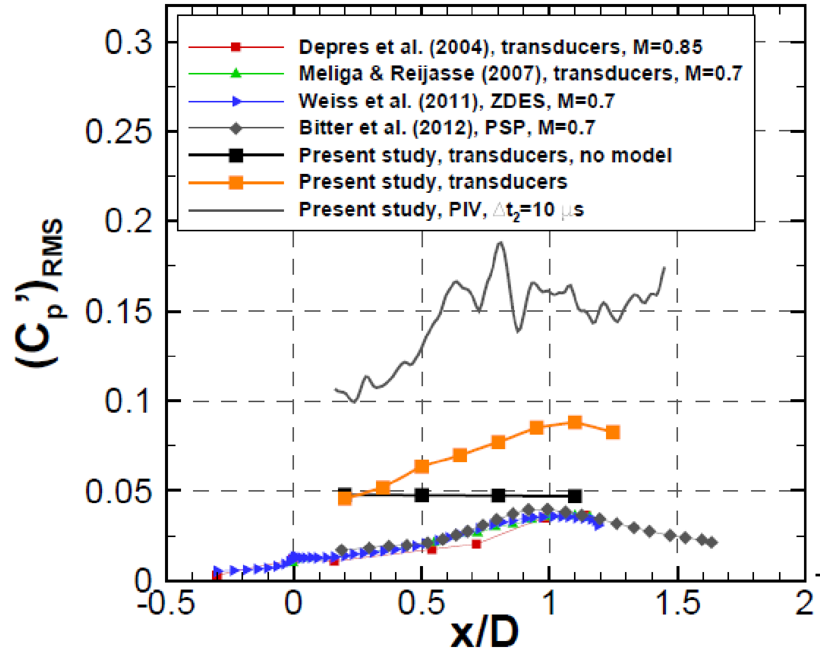
Results for the r.m.s. pressure:

- Poor agreement between PIV and transducers
- Pressure levels higher than for reference studies (both exp & num)

Possible causes:

- High wind tunnel noise level
- Detrimental effect of discrepancies between the different PIV systems





Mean pressure determination in compressible flow

Reynolds averaging approach

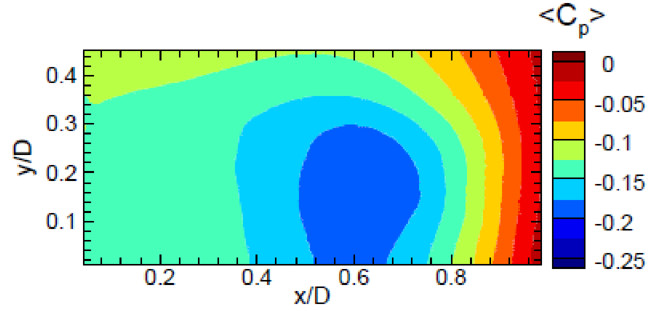
- (Mean) pressure from velocity data using (Re-avg.) momentum equation:

$$\nabla \bar{p} = -\rho[\overline{\boldsymbol{u}} \cdot \nabla \overline{\boldsymbol{u}} + \nabla \overline{\boldsymbol{u}'\boldsymbol{u}'}] + h.o.t.$$

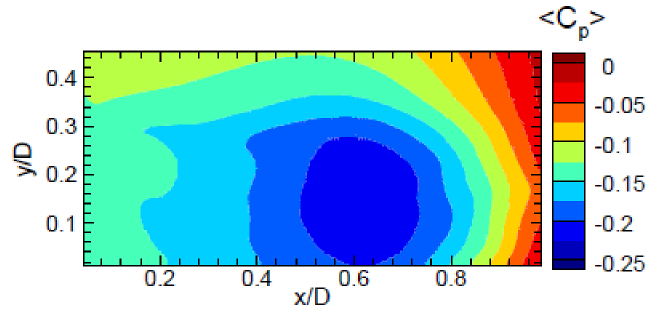
- $h.o.t.$: fluctuations and gradients of density -> are negligible (Van Gent et al. 2018)

Assesment with synthetic PIV exp. data:

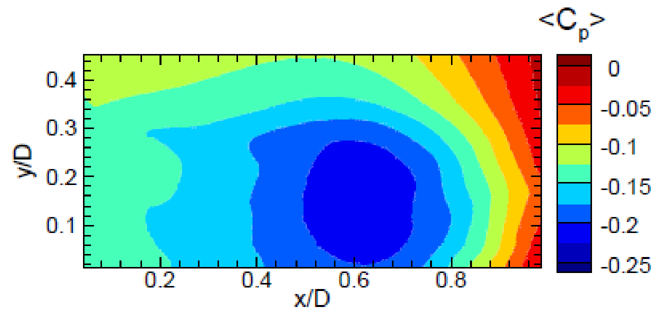
- Contribution of the Reynolds-stresses: ~ 20%
- Contribution of $h.o.t.$: ~ 1 %
- Including Re-stresses reduces r.m.s. error from 17% to 5%
- Tomo vs. planar PIV: 2D-2C and 3D-3C results differ by less than 1%!
- -> planar PIV is "sufficient" in this case (NB: axisymmetric geometry)



(b) Pressure field reconstructed using mean-flow terms



(d) idem + Reynolds-stresses terms



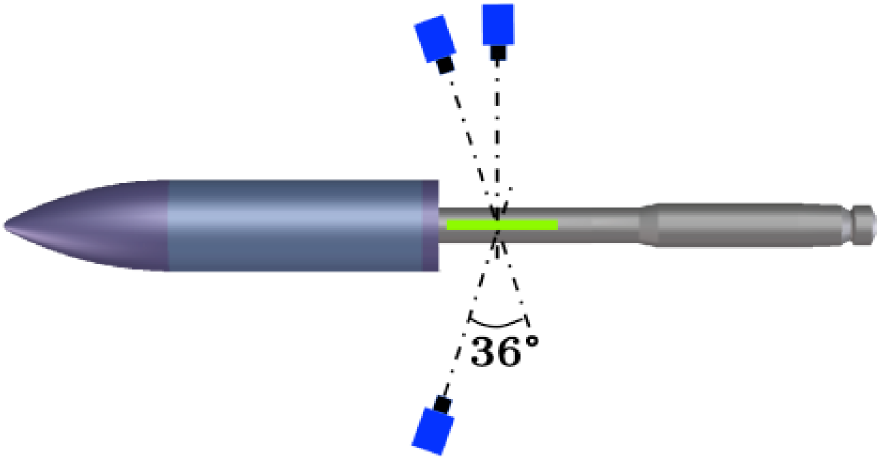
(f) idem + density-gradient terms

(Van Gent et al., Experiments in Fluids, 2018)

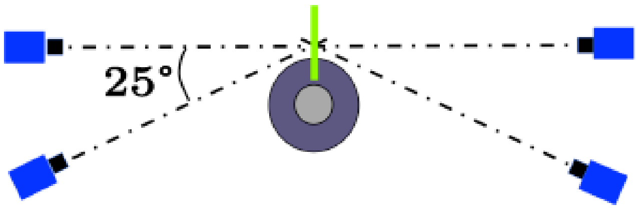
Mean pressure: compressible base flow experiments

Experimental set-up

- Rear-sting-mounted model
- Single tomographic PIV system (5 cameras, one in planar configuration)
- Standard **double-pulse** strategy @ 5 Hz repetition rate)
- PIV volume: 85 mm x 50 mm x 5 mm
- Mach number: M = 0.75 (transonic) and M = 1.5 (supersonic)



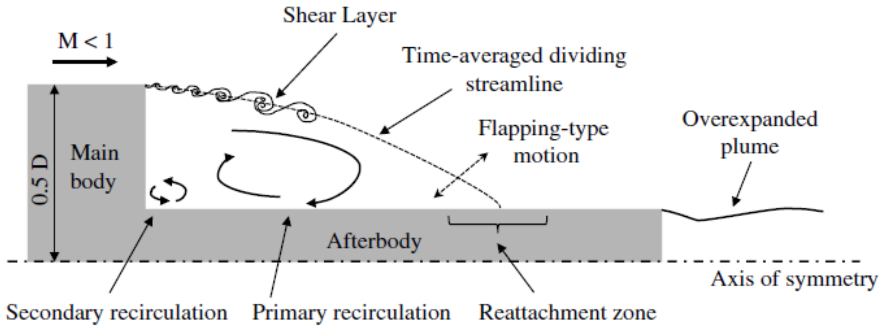
(a) Top-view

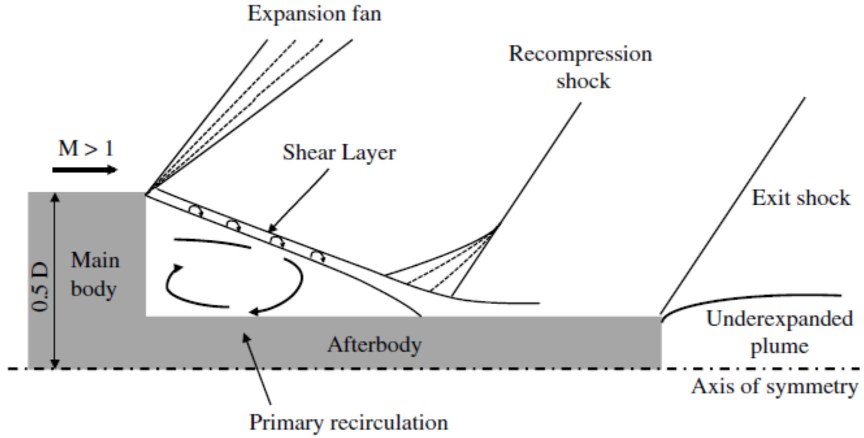


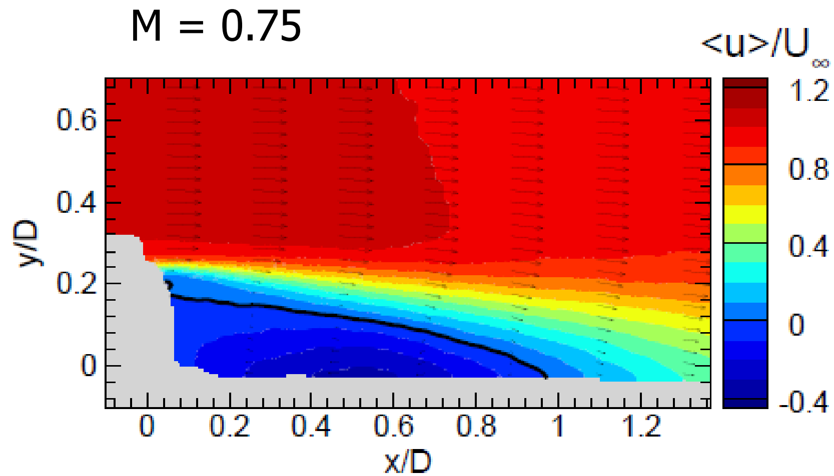
(b) Back-view

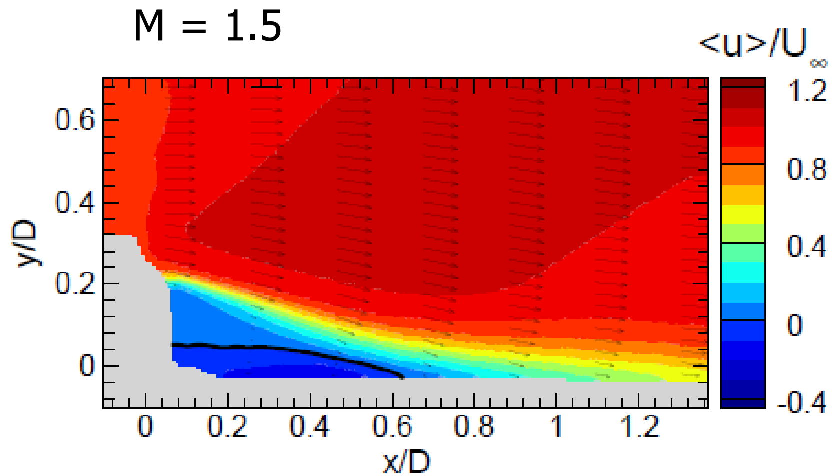
Mean pressure: compressible base flow experiments

Time-average velocity flow fields







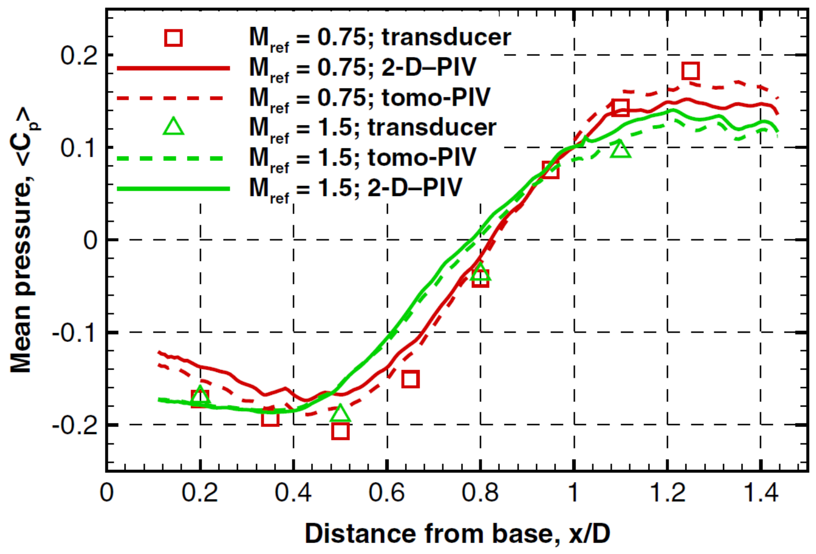


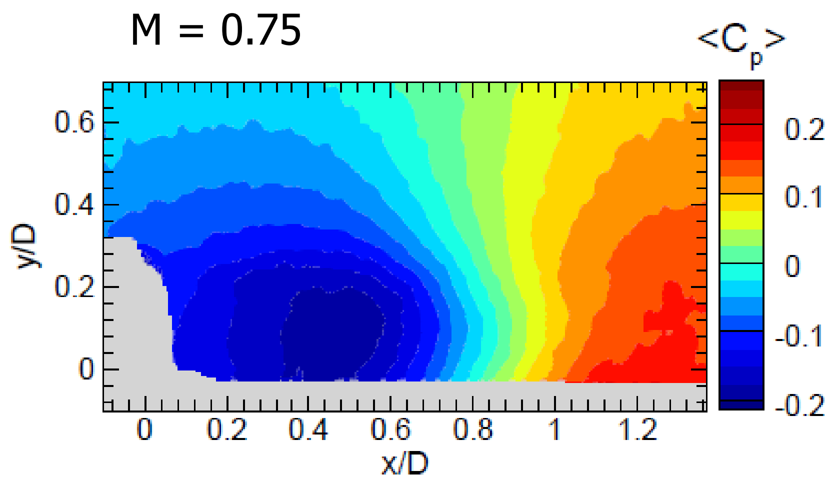
Mean pressure: compressible base flow experiments

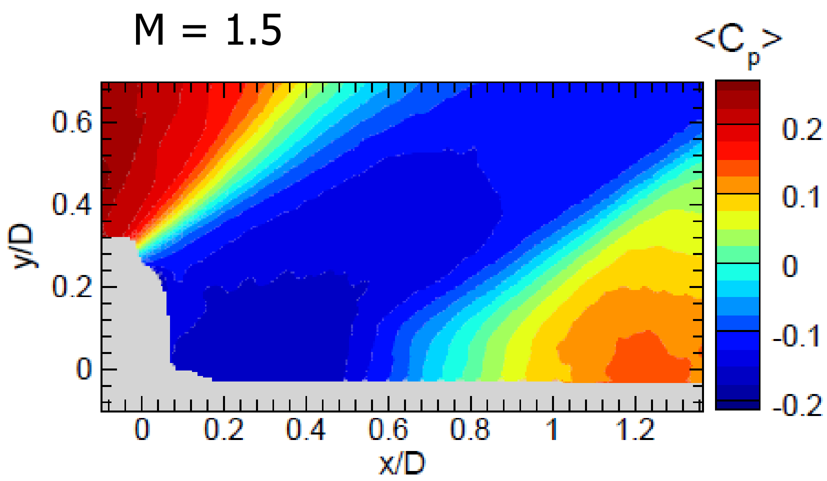
Pressure results

- Good agreement between PIV and transducer data, for transonic and supersonic flow
- Close agreement between 2D and tomo PIV data!

  -> planar PIV is “sufficient” in this case



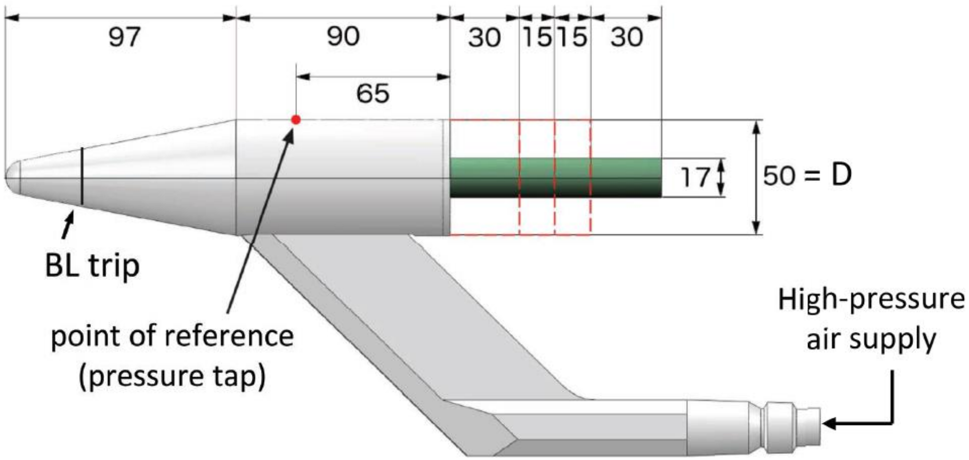




Base flow with simulated exhaust plume

Experimental set-up

- Side-sting-mounted model
- Effect of jet plume is simulated by compressed air supply
- Variable nozzle length (collars)
  L/D = 0.6, 0.9, 1.2, 1.8



Flow conditions

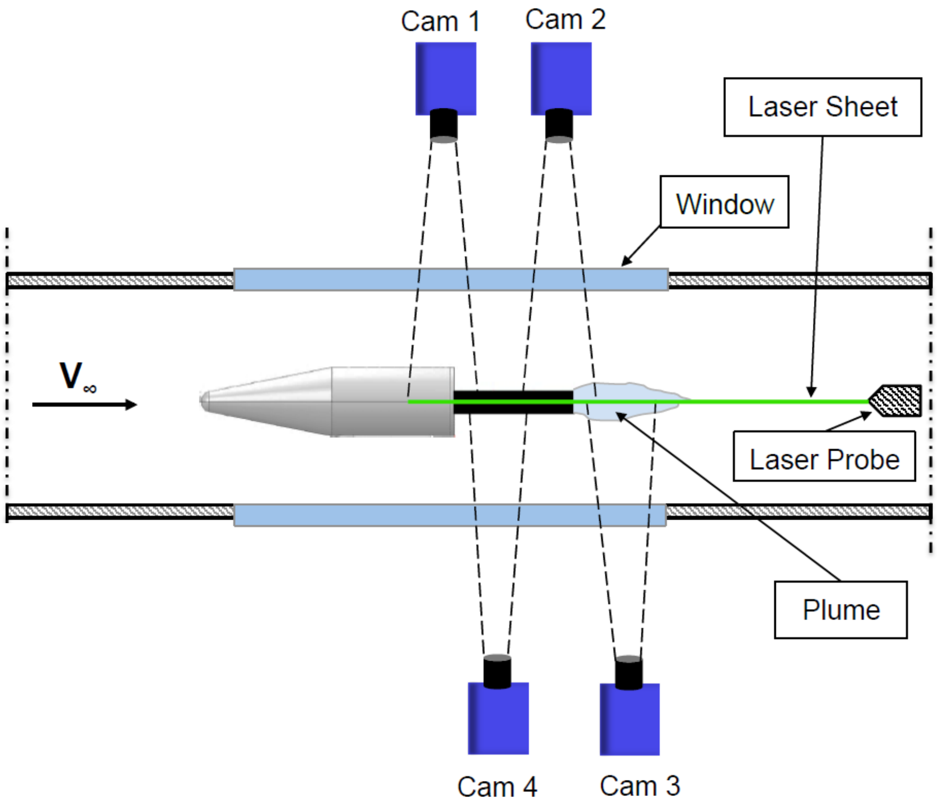
- Free-stream Mach number: M = 0.76 (transonic) and M = 2.2 (supersonic)
- Jet exit Mach number 3.5
- Jet (pressure) conditions are modelled after Ariane 5 Vulcain 2 operation
- In terms of jet pressure ratio: $\mathrm{JPR} = \mathrm{p_j}/\mathrm{p_{amb}}$
  - Transonic: $\mathrm{JPR} = 0.21$ (over-expanded)
  - Supersonic: $\mathrm{JPR} = 1.57$ (under-expanded)

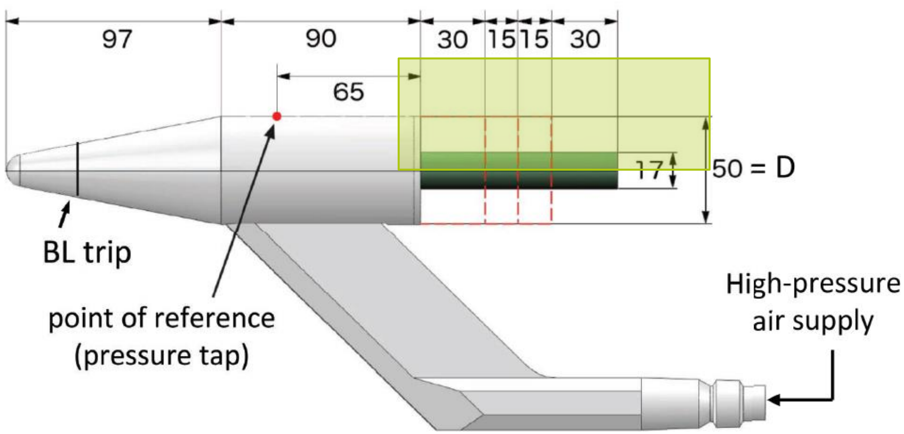
(Van Gent et al., AIAA Journal, 2019)

Base flow with simulated exhaust plume

PIV configuration

- Planar (2C) PIV
- Recording: 5 Hz in double-frame mode
- 4 cameras to extend field of view
- FOV size: 140 mm x 50 mm
- NB: only free stream flow is seeded





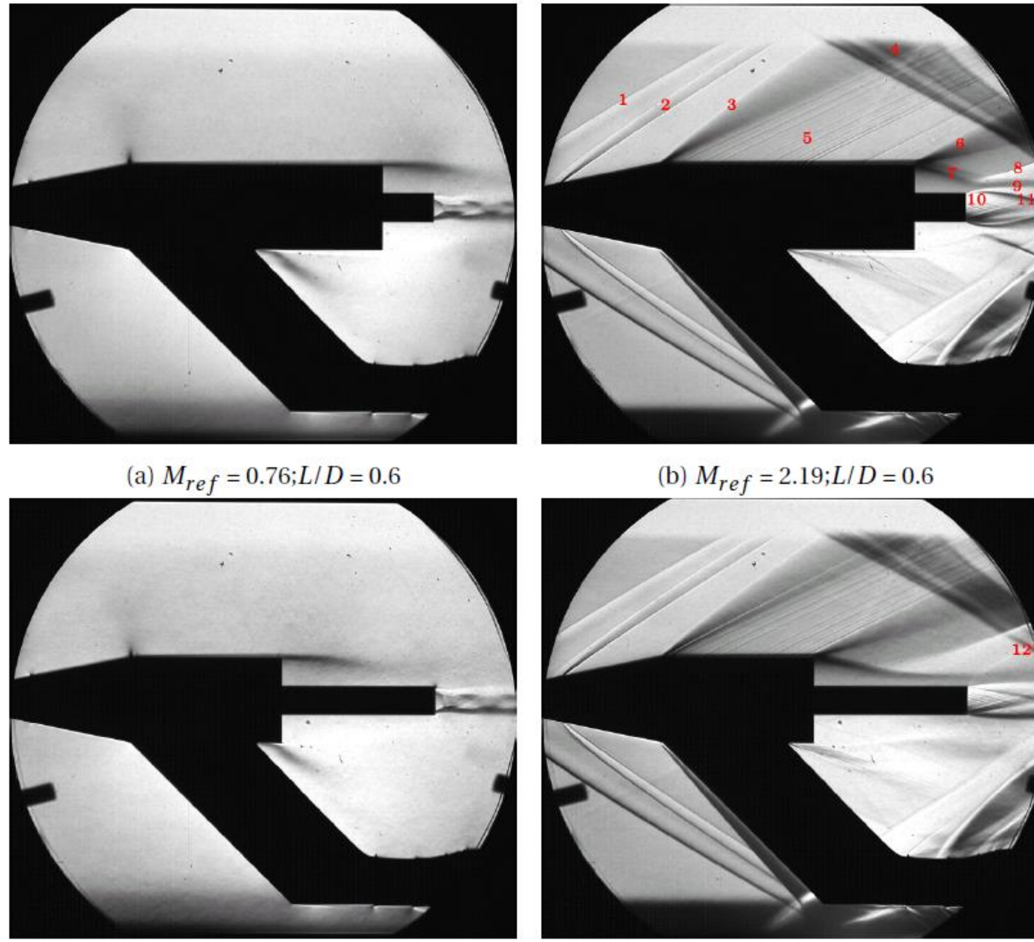
Base flow with simulated exhaust plume

Schlieren visualization

(with jet operative)

Shortest nozzle (L/D = 0.6)

Longest nozzle (L/D = 1.8)



(a) $M_{ref} = 0.76; L/D = 0.6$

(b) $M_{ref} = 2.19; L/D = 0.6$

(c) $M_{ref} = 0.76; L/D = 1.8$

(d) $M_{ref} = 2.19; L/D = 1.8$

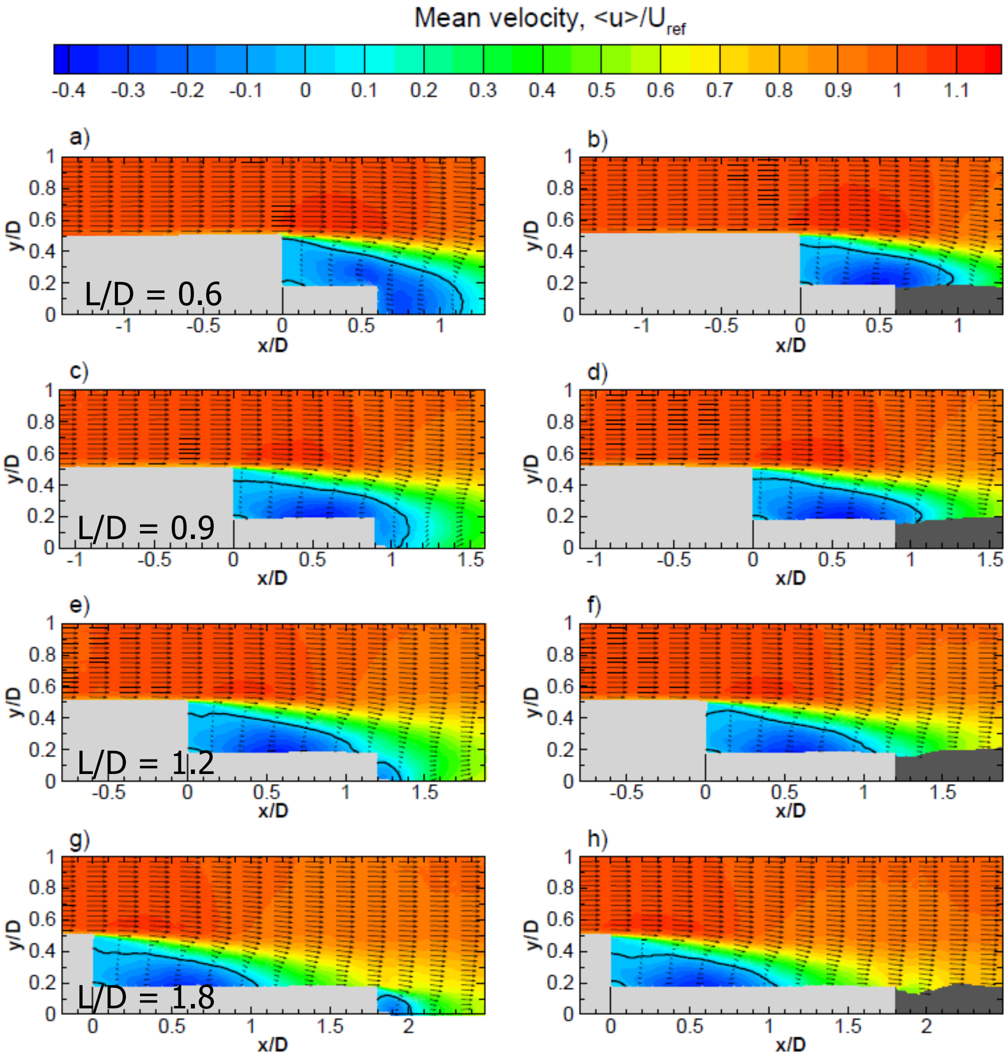
Transonic case M = 0.76 (over-expanded jet)

Supersonic case M = 2.19 (under-expanded jet)

Base flow with simulated exhaust plume

Transonic case

- Effect of nozzle length and jet on flow reattachment
- For L/D > 1.1 reattachment on after-body surface
- Flow unsteadiness reduces for longer afterbodies



(no jet) (with jet)

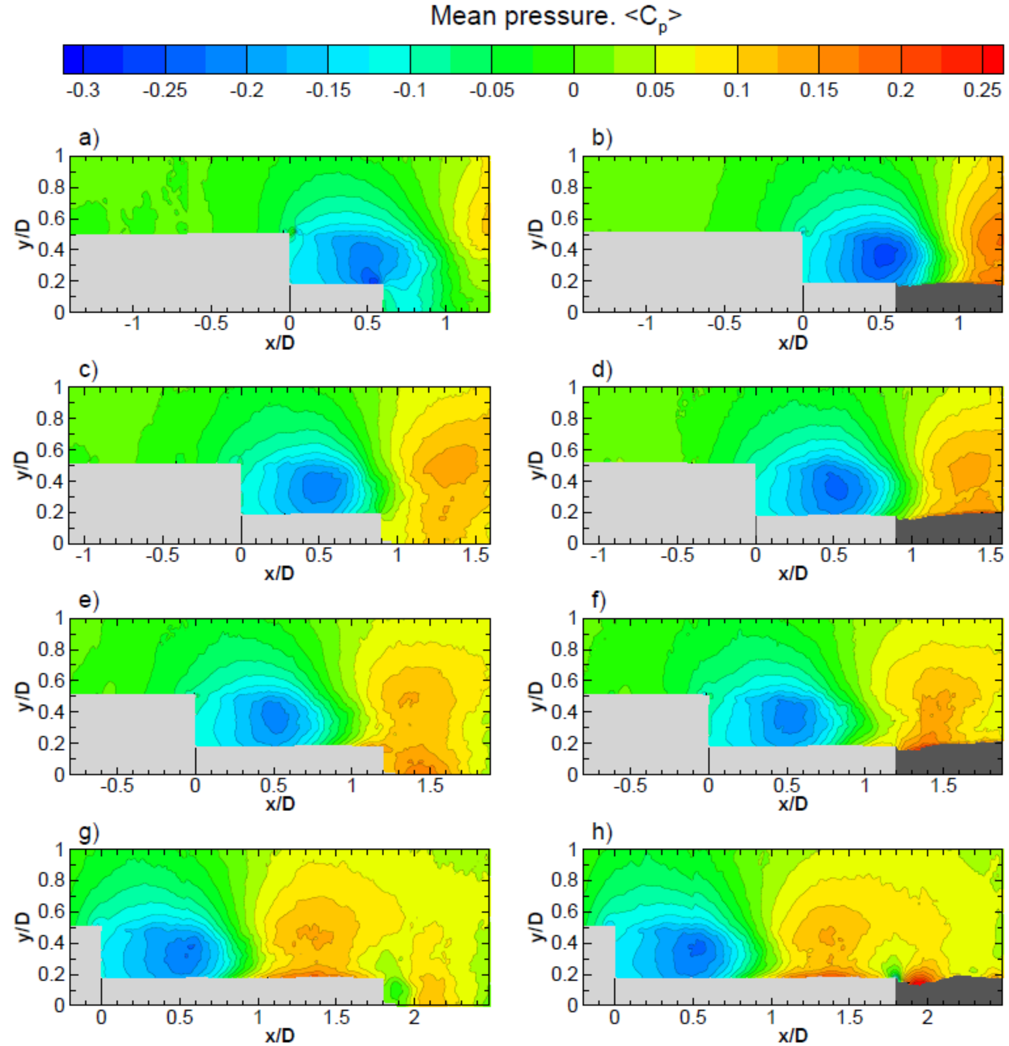
Base flow with simulated exhaust plume

Transonic case

- Effect of nozzle length and jet on flow reattachment
- For L/D > 1.1 reattachment on after-body surface
- Flow unsteadiness reduces for longer afterbodies

Pressure fields:

- Largest jet effect for the shortest nozzle



(no jet) (with jet)

Conclusions

Operating principles

- Pressure (fluctuations) can be "measured" non-intrusively with PIV

Implementation:

- For (predominantly) 2D flows planar PIV is sufficient
- Volumetric data required for 3D flows
- Instantaneous pressure requires time information: time-resolved (low flow speed) or multi-pulse (high flow speed)
- Multi-pulse approach challenging due to system complexity and synchronization issues
- Mean pressure requires no time information (velocity data statistics only)

Applications:

- Transonic base flows (many others can be found in literature)