# High-Fidelity Aerothermal Simulations Using a Lattice Boltzmann Approach for Turbine Clearance Control Systems

Thèse CIFRE – Safran AE – CERFACS – M2P2

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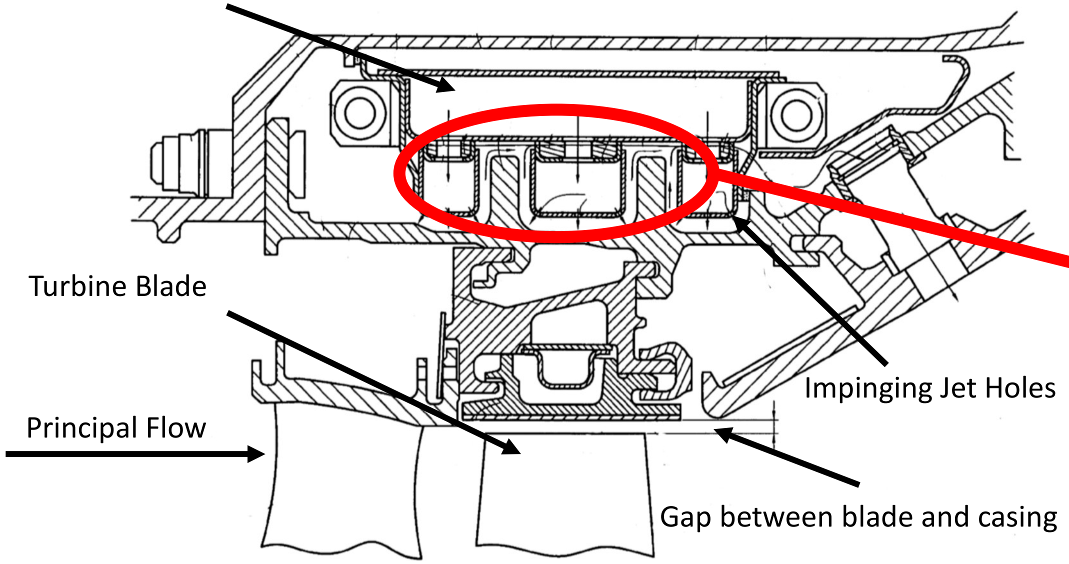
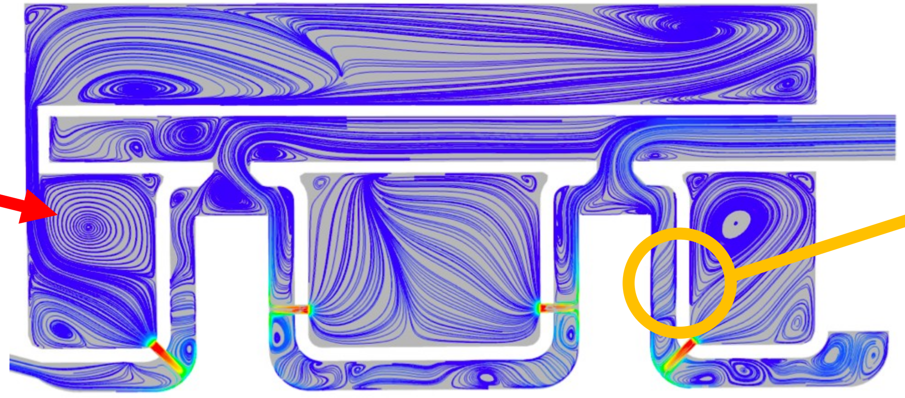
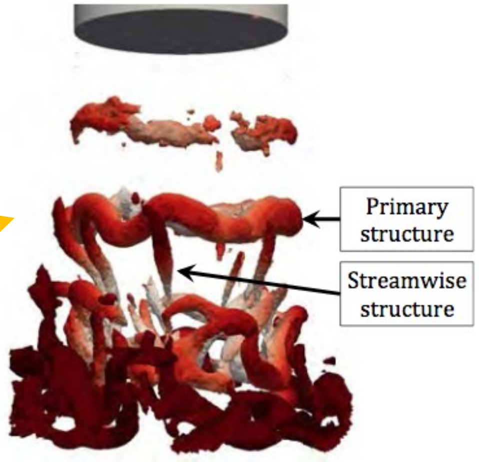
# Industrial Context




High Pressure Turbine[2a]



**H**igh **P**ressure **T**urbine **A**daptive **C**learance **C**ontrol (HPTACC) System



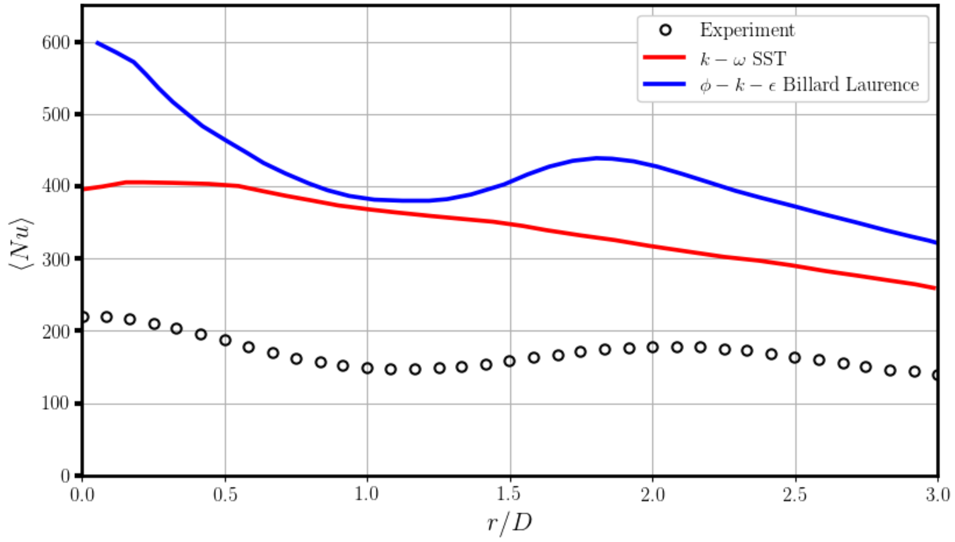

Impinging Jet Flow[2b]

[2a] A. Gendraud et al., "Device for Controlling Clearance in a Gas Turbine". U.S. Patent 7,114,914. (2006)
[2b] P. Aillaud et al., Simulations aux grandes échelles pour le refroidissement d'aubages de turbine haute pression. PhD Thesis, 2017

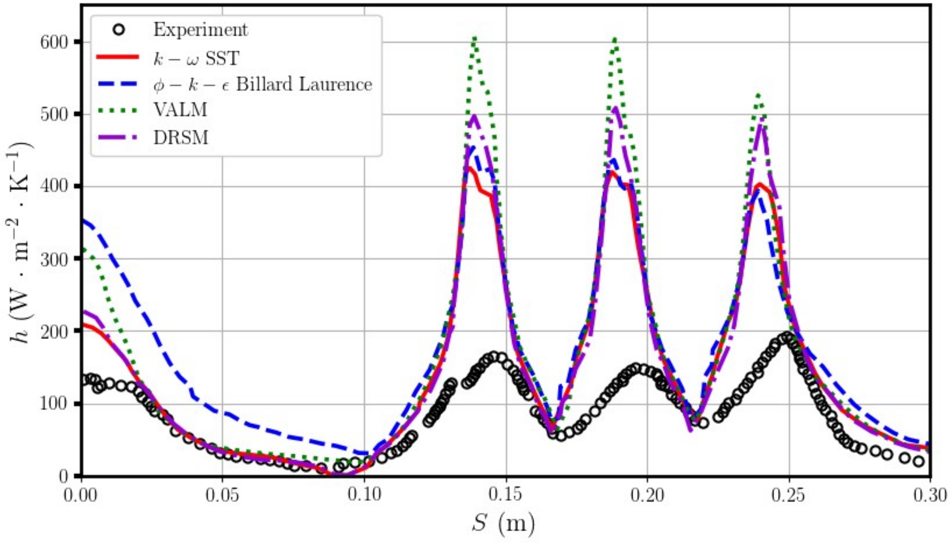
# Limitations of Traditional RANS Approaches

- Traditional CFD methods, using RANS (Reynolds-Averaged Navier Stokes) models, have significant difficulty in predicting accurate heat transfer distributions.

- The models that are deemed best suited for jet impingement heat transfer, the  and  models (along with its variants, such as  or )[3a], produce mixed results.




*Single impinging jet test case, ,* [3b]




*Multi-impinging jet test case for turbine vane cooling*[3c]


[3a] N. Zuckerman, N. Lior, "Jet Impingement Heat Transfer: Physics, Correlations, and Numerical Modeling", Advances in Heat Transfer, 39, P. 565-631 (2006)
[3b] P. Grenson. "Caractérisation expérimentale et simulations numériques d'un jet chaud impactant. Modélisation et simulation". PhD Thesis. INSTITUT SUPERIEUR DE L'AERONAUTIQUE ET DE L'ESPACE (ISAE), (2016)
[3c] E. Laroche, et al., "A Combined Experimental and Numerical Investigation of the Flow and Heat Transfer Inside a Turbine Vane Cooled by Jet Impingement", Journal of Turbomachinery 140(30), P. 031002 (2018)

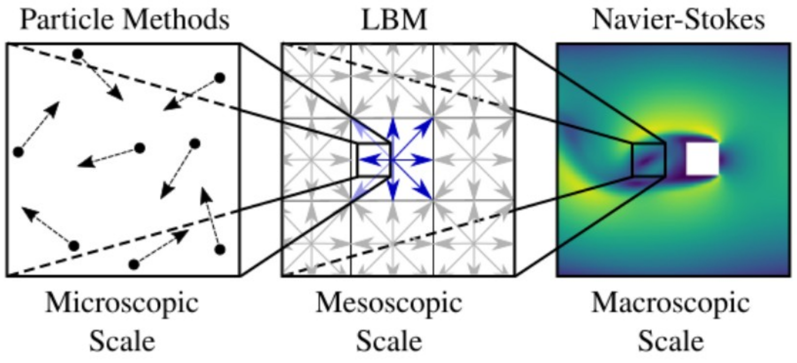
# Traditional LES vs LBM-LES

- Traditional Large Eddy Simulation (LES) approaches are highly computationally expensive, and meshing a test case can involve a very large amount of time spent by a highly trained specialist[4a], rendering it costly in both CPU and human hours.

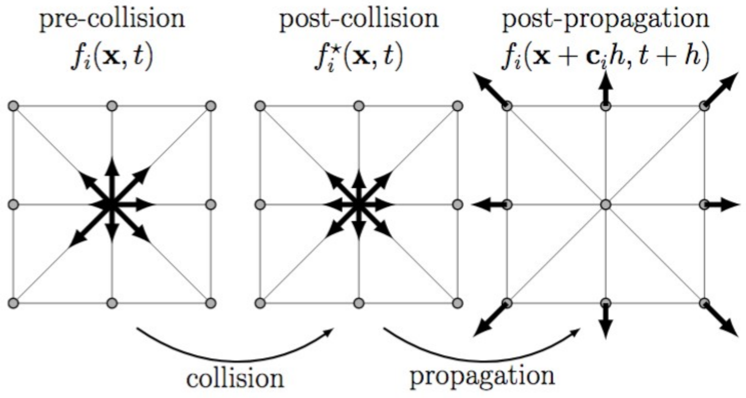
- The Lattice Boltzmann Method (LBM), which uses a mesoscopic approach, is based on the propagation of distribution functions , which reproduces the physics of the Navier-Stokes Equations. It can produce high quality turbulence resolving simulations, with computational time that can be significantly faster than traditional approaches[4b].

- The use of octree meshes enable rapid mesh generation, significantly reducing the human-hours needed to set up a test cases.

- However, LBM approaches have historically been limited to weakly compressible, non-thermal flows.




*Different scales for viewing fluid flow*[4c]




*The collide-and-stream algorithm*[4d]

[4a] R. Löhner, "Towards overcoming the les crisis," *International Journal of Computational Fluid Dynamics* 33, 87–97 (2019).
[4b] Y. Hou et al., "Lattice-Boltzmann and Navier-Stokes simulations of the partially dressed, cavity-closed nose landing gear benchmark case," in *25th AIAA/CEAS Aeroacoustics Conference (2019*) pp. 1–20
[4c] A, Bravo, Wind Flow Simulation around Buildings using the Lattice Boltzmann Method, *Master Thesis (*2019)
[4d] U. D. Schiller et al., Mesoscopic Modelling and Simulation of Soft Matter, *Soft Matter Journal,* (2018)

# PhD Overview

- ProLB is a parallel lattice Boltzmann Solver developed by a consortium of French companies and research institutions. It has been successfully used for aeroacoustic and automotive applications.

- Recently, a series of new developments[5e][5f][5g][5h][5i] have made it practical to use an LBM approach for compressible and thermal flows, but there has been little extension to complex industrial aerothermal test cases.

- The objective of this PhD thesis is to develop ProLB to make it a tool appropriate for high fidelity aerothermal simulations, and to valide the solver on thermal impinging jet simulations of increasing complexity.

[5e] Y. Feng et al., Hybrid recursive regularized thermal lattice boltzmann model for high subsonic compressible flows. *Journal of Computational Physics*, 394:82–99, (2019)
[5f] S. Guo et al., An efficient lattice boltzmann method for compressible aerodynamics on d3q19 lattice. *Journal of Computational Physics,* 418:109570, (2020)
[5g] G. Farag et al., A pressure-based regularized lattice-boltzmann method for the simulation of compressible flows. *Physics of Fluids*, 32:066106, (2020)
[5h] S. Guo et al., Improved standard thermal lattice boltzmann model with hybrid recursive regularization for commpressible laminar and turbulent flows. *Physics of Fluids*, 32:126108, (2020)
[5i] F. Renard et al., "Improved compressible hybrid lattice boltzmann method on standard lattice for subsonic and supersonic flows," *Computers and Fluids 219,* 104867 (2021)

# Outline

1. Context and Introduction
2. **Developments in ProLB**
3. Single Impinging Jet Test Case
4. Multi-impinging Jet Test Case
5. Conclusion

# Key Implementations into Thermal ProLB

## Turbulence Injection, with Navier-Stokes Boundary Conditions (NSCBC)

- The flow-field and heat transfer of an impinging jet issuing from a pipe are heavily reliant on the conditions at the nozzle, as the jet shear layer is immediately downstream of the pipe boundary layer.

- Properly simulating fully developed pipe flow is thus crucial to producing an accurate jet simulation

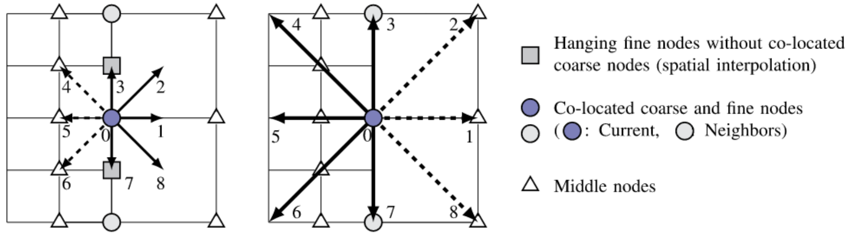
- The synthetic turbulence generation implemented is similar to the one described by Shur et al.[7a]. It is a synthetic Fourier method with turbulence anisotropy. This approach was implemented into ProLB using a Navier-Stokes Boundary Condition (NSCBC) formalism[7b][7c]

## Advanced Transition Algorithms

- ProLB uses an octree mesh system, allowing for grid refinement at zones of interest.

- The Direct-Coupling transition algorithm of Astoul et al.[7d], developed for the athermal version of the code, allows for smooth transitions of flow structures and waves through grid refinement zones.

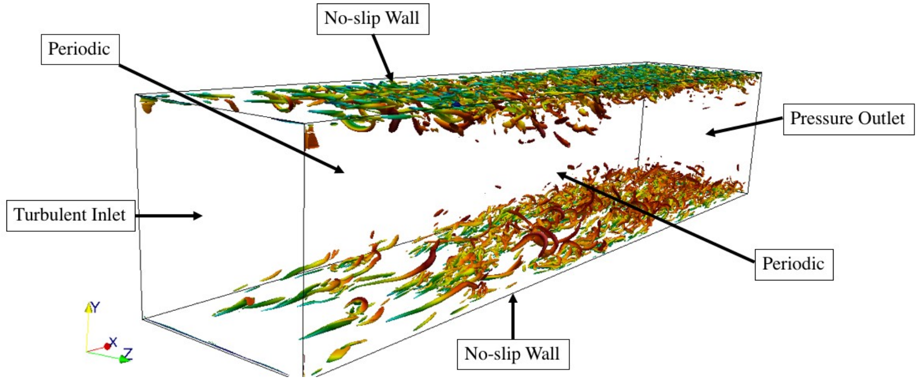
- This was adapted and implemented into the compressible thermal version,

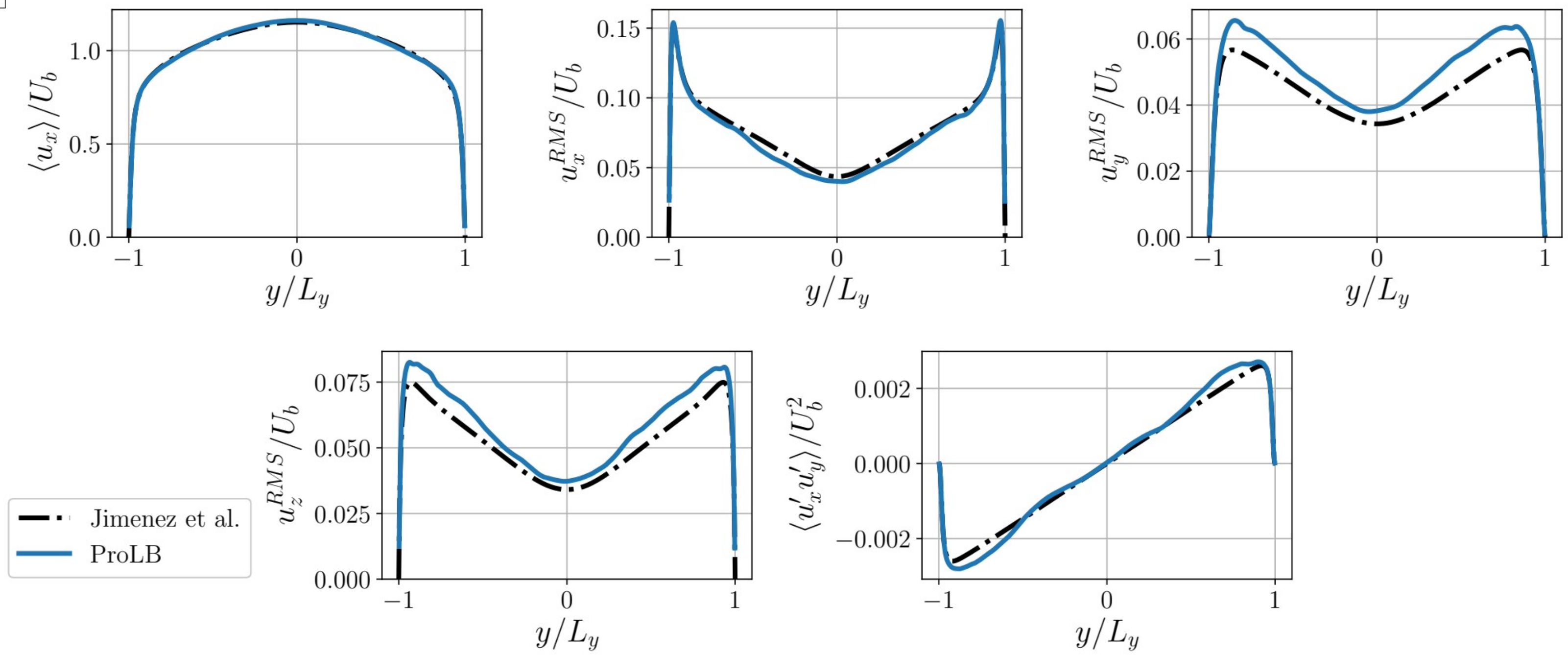



*Mesh transition [7d]*

[7a] M. Shur et al. « *Synthetic turbulence generators for RANS-LES interfaces in zonal simulations of aerodynamic and aeroacoustic problems* » *Flow, Turbulence, and Combustion*, 93:63-92 (2014)
[7b] Y. Feng et al., "Solid wall and open boundary conditions in hybrid recursive regularized lattice Boltzmann method for compressible flows," *Phys. Fluids* 31, 126103 (2019)
[7c] T. J. Poinsot et al., "Boundary conditions for direct simulations of compressible viscous flows," *J. Comput. Phys.* 101, 104–129 (1992).
[7d] T. Astoul et al., "Lattice Boltzmann method for computational aeroacoustics on non-uniform meshes: A direct grid coupling approach", Journal of Computational Physics 447, 110667 (2021)

# Validation of the Turbulence Injection




- Turbulence injection validated on a planar channel test case[8a]

- These results are shown at , or eight boundary layers downstream of the inlet

- The mean and axial fluctuations are well shown, while there are some noticeable overestimations for the other fluctuations. This is likely due to the length-scales chosen.

[8a] J. Jiménez and Sergio Hoyas. « Turbulent fluctuations above the buffer layer of wall-bounded flows ». *Journal of Fluid Mechanics*, 611:215–236, 2008

# LBM-LES of a single round impinging jet

, Low Mach, Fully developed pipe injection

**Good Benchmark for a solver, as many RANS approaches fail to produce the well-known secondary Nusselt number peak**

**Large wealth of experimental and numerical data**

**Experiments:**

Tummers et al.[9a] (Re = 23 000)

Fenot et al.[9b] (Re = 23 000)

Baughn and Shimizu[9c] (Re = 23 750)

Katti and Prabhu[9d] (Re = 23 000)

**DNS:**

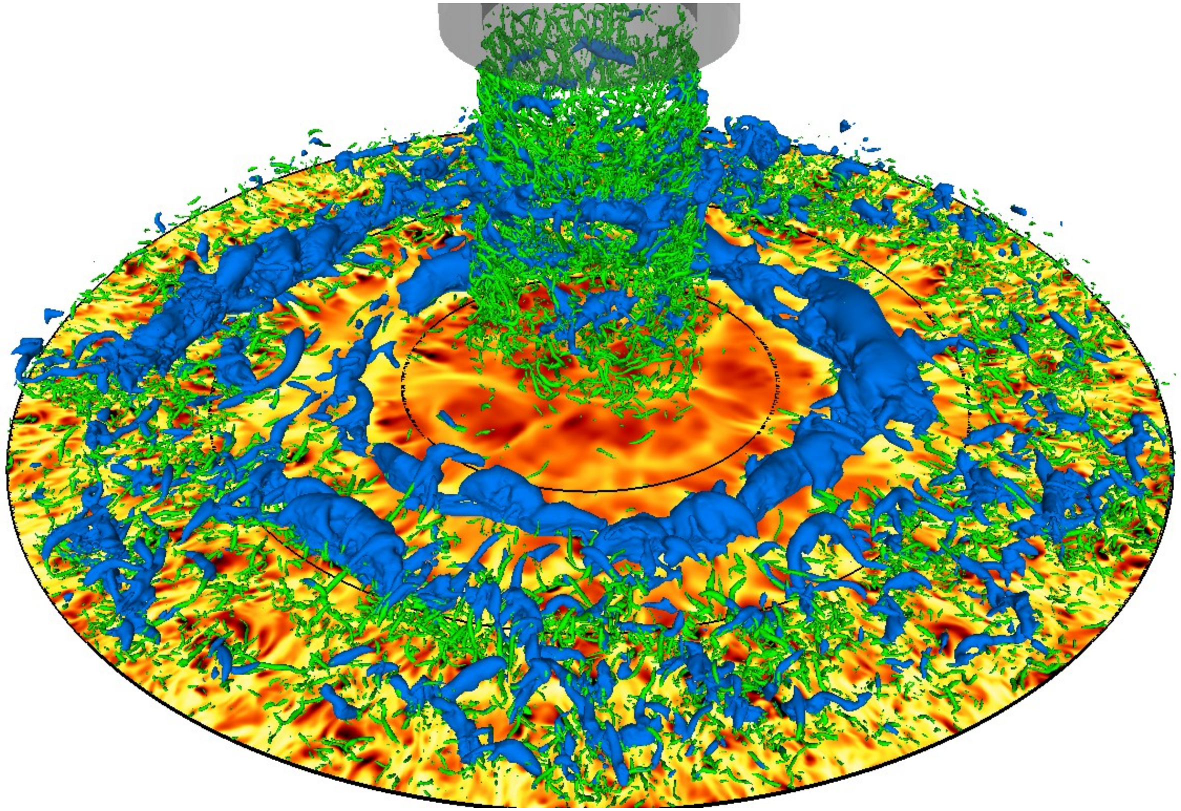
Wu et al.[9e] (pipe-flow only, Re = 24 580)

**LES:**

Hadžiabdić and Hanjalić[9f] (Re = 20 000,  mesh)

Uddin et al.[9g] (Re = 23 000)

Aillaud et al.[9h] (Re = 23 000)



[9a] M. Tummers et al., « Turbulent flow in the near field of a round impinging jet », *International Journal of Heat and Mass Transfer* 54, p. 4939-4948 (2011)

[9b] M. Fenot et al., «  Local heat transfer due to several configurations of circular air jets impinging on a flat plate with and without semi-confinement », *International Journal of Thermal Sciences* 44, p. 665-675, (2005)

[9c] J. W. Baughn, S. Shimizu, « Heat transfer measurements from a surface with uniform heat flux and an impinging jet », *Journal of Heat Transfer* 111, p. 1096-1098, (1989)

[9d] V. Katti, S. V. Prabhu, « Experimental study and theoretical analysis of local heat transfer distribution between smooth flat surface and impinging air jet... »,  *Int Jnl of Heat and Mass Transfer* 51:17-18, p. 4480-4495, (2008)

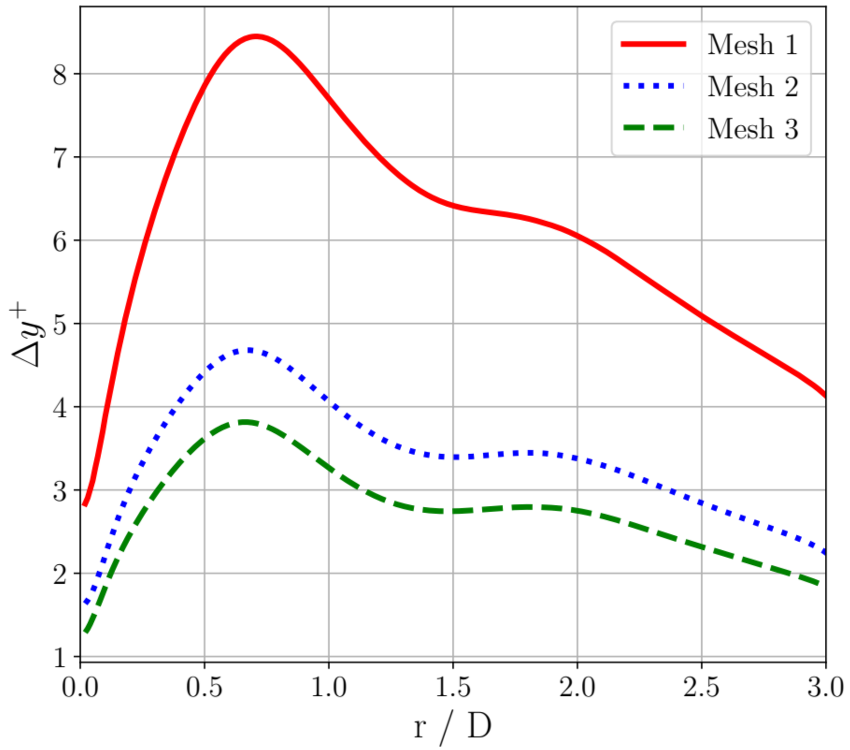
[9e] X. Wu et al., « Direct numerical simulation of a 30R long turbulent pipe flow at R+ = 685: large and very large-scale motions »,  *Journal of Fluid Mechanics* 698, p. 235-281, (2012)

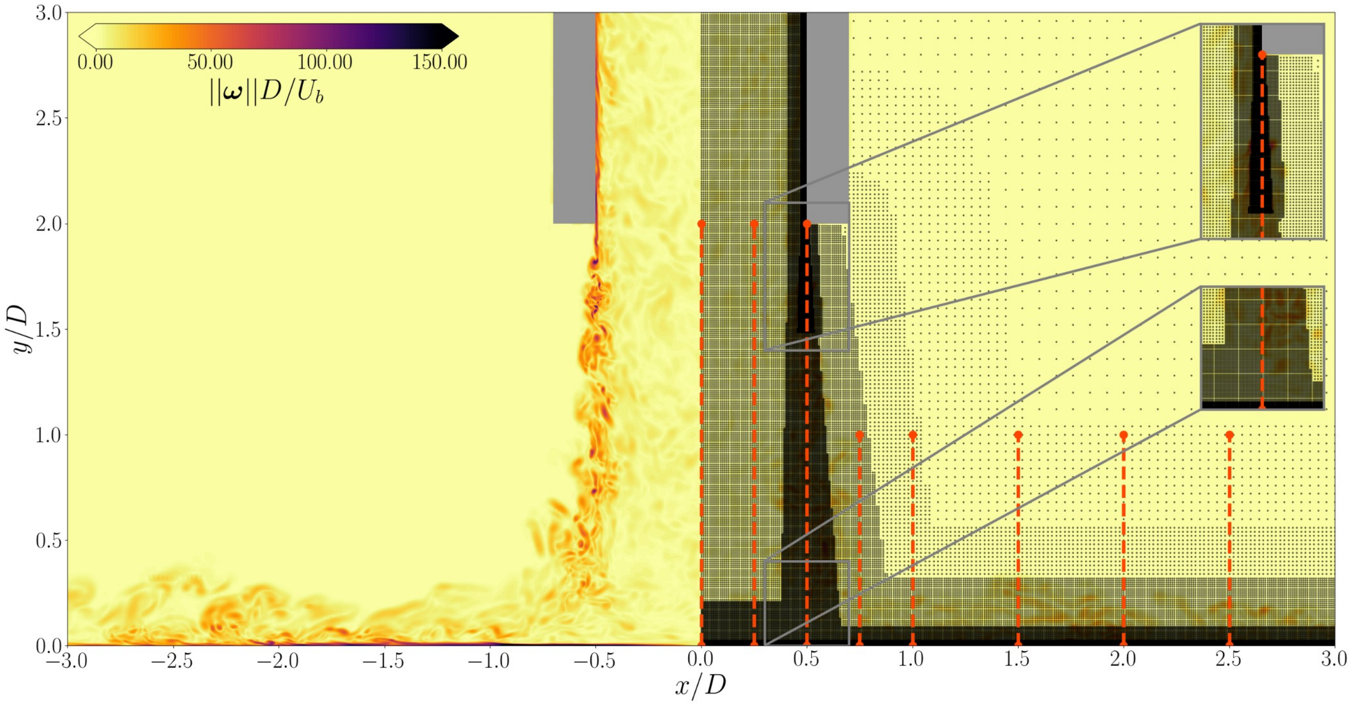
[9f] M. Hadžiabdić, K. Hanjalić, « Vortical structures and heat transfer in a round impinging jet », *Journal of Fluid Mechanics*, 596, p. 221-260, (2008)

[9g] N. Uddin et al., « LES simulations of an impinging jet: On the origin of the second peak in the Nusselt number distribution », *International Journal of Heat and Mass Transfer* 57, p. 356-368, (2013)

[9h] P. Aillaud et al., « Secondary peak in the Nusselt number distribution of impinging jet flows: A phenomenological analysis »,  *Physics of Fluids* 28, p. 095110, (2016)

# Meshing Strategy




| | Mesh 1 | Mesh 2 | Mesh 3 |
|---|---|---|---|
| hCPU / | 302 | 936 | 2000 |
| hCPU / | 6040 | 18720 | 40000 |

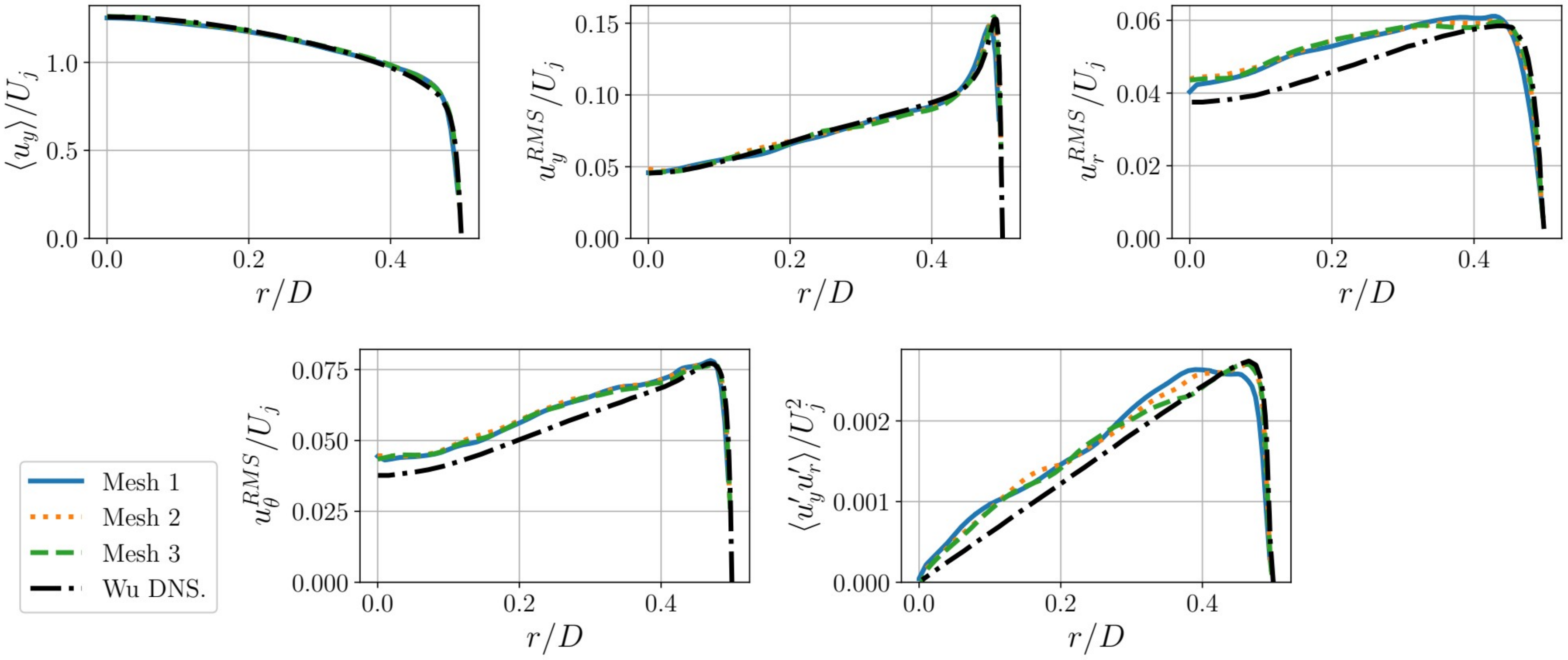
- The finest mesh refinement zones are reserved for the pipe boundary layer, free-jet shear layer, and impacted plate boundary layer. Mesh 1 is identical to Mesh 2 but does not have the finest refinement zones

- Since the mesh is Cartesian, resolution in the radial and azimuthal direction is superior for cardinal directions than in diagonal directions

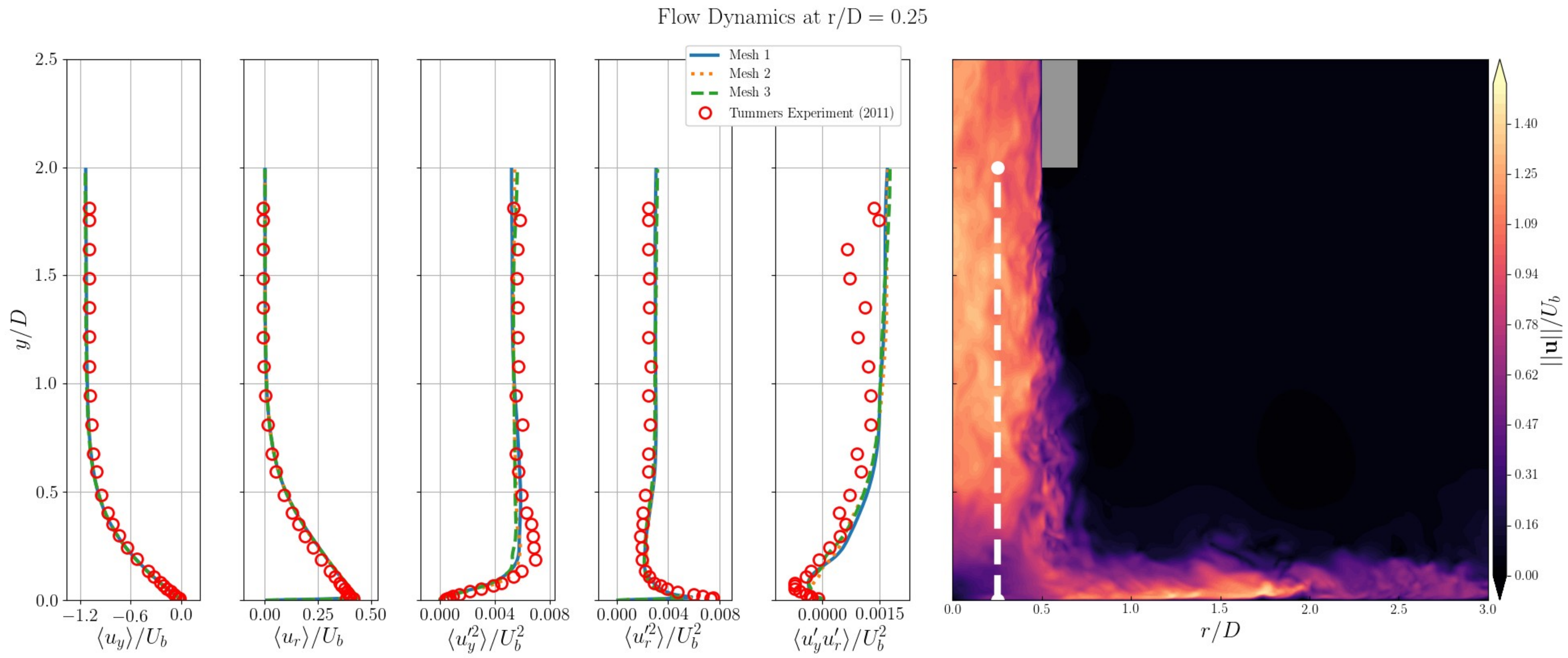
# Pipe Flow Results

- While the mean flow profile and axial fluctuations are both very well captured, the radial and azimutha fluctuations, as well as the Reynolds shear stress, are over-represented in the pipe core.

- We attribute these discrepancies to the pipe entrance length of , and the use of homogeneous and isotropic turbulent *length-scales* (even if the *intensities* are non-homogeneous and anisotropic)



# Jet Flow Field Statistics

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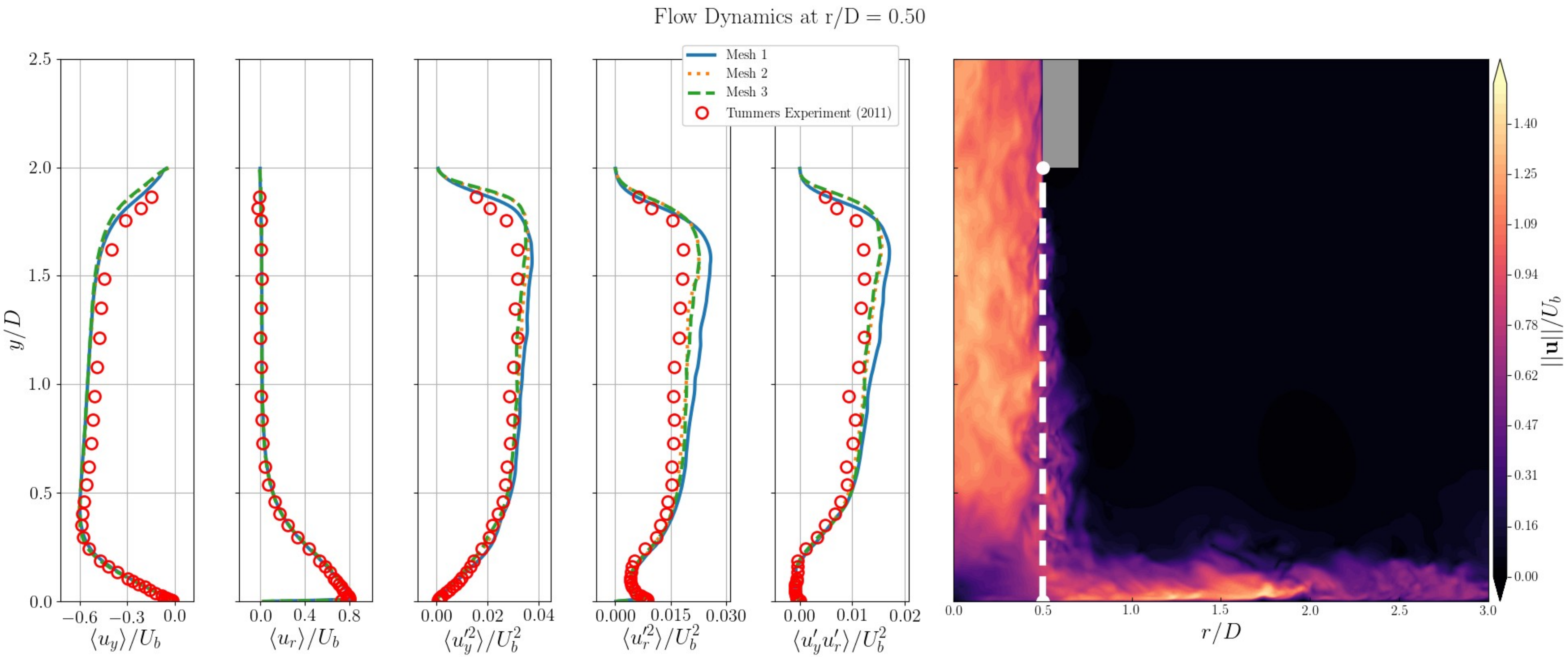
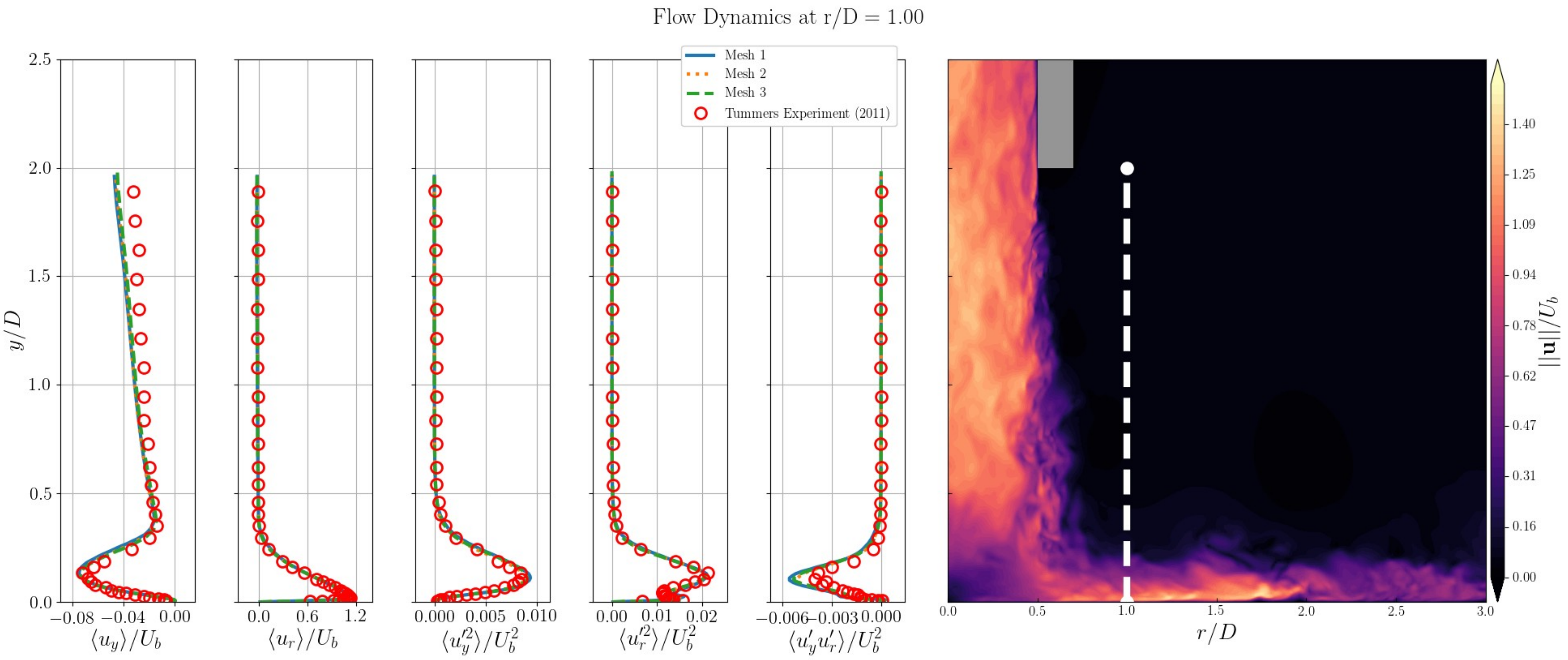
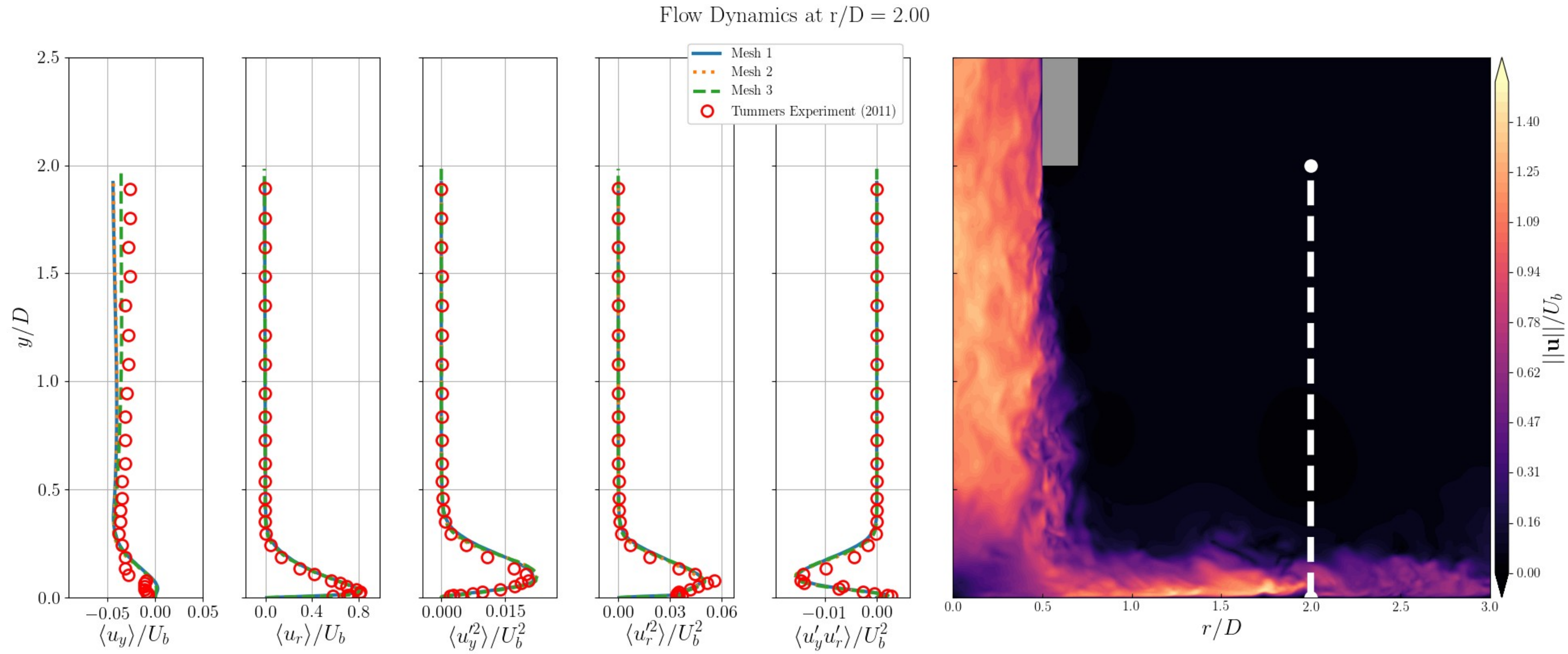
# Jet Flow Field Statistics



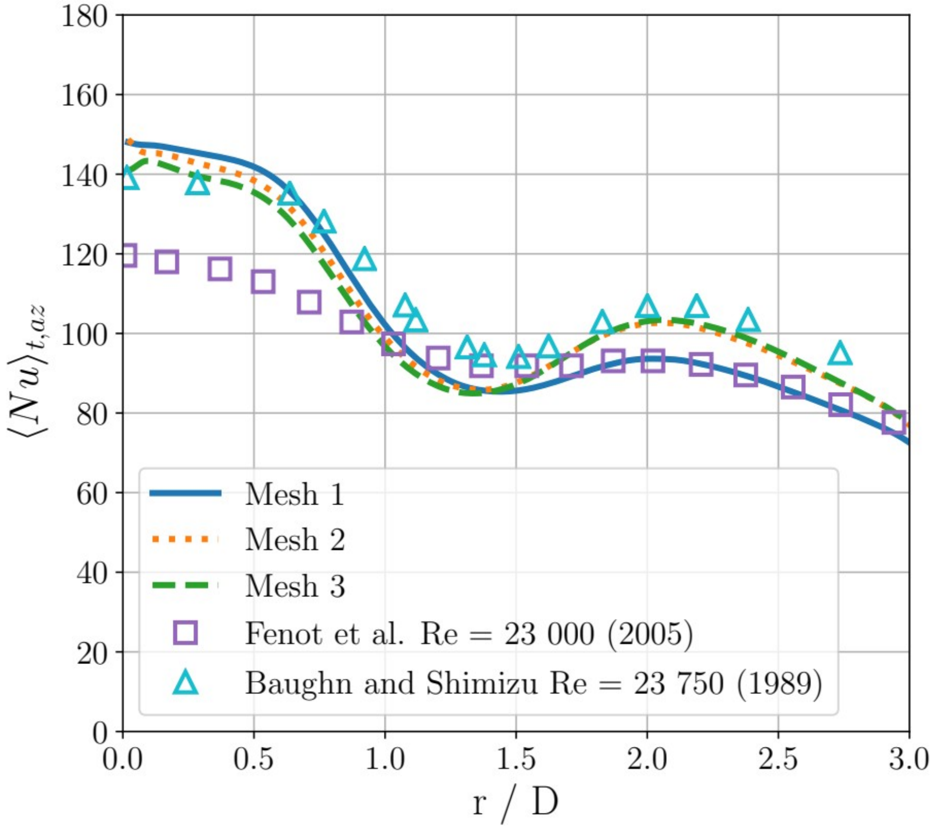
# Jet Flow Field Statistics

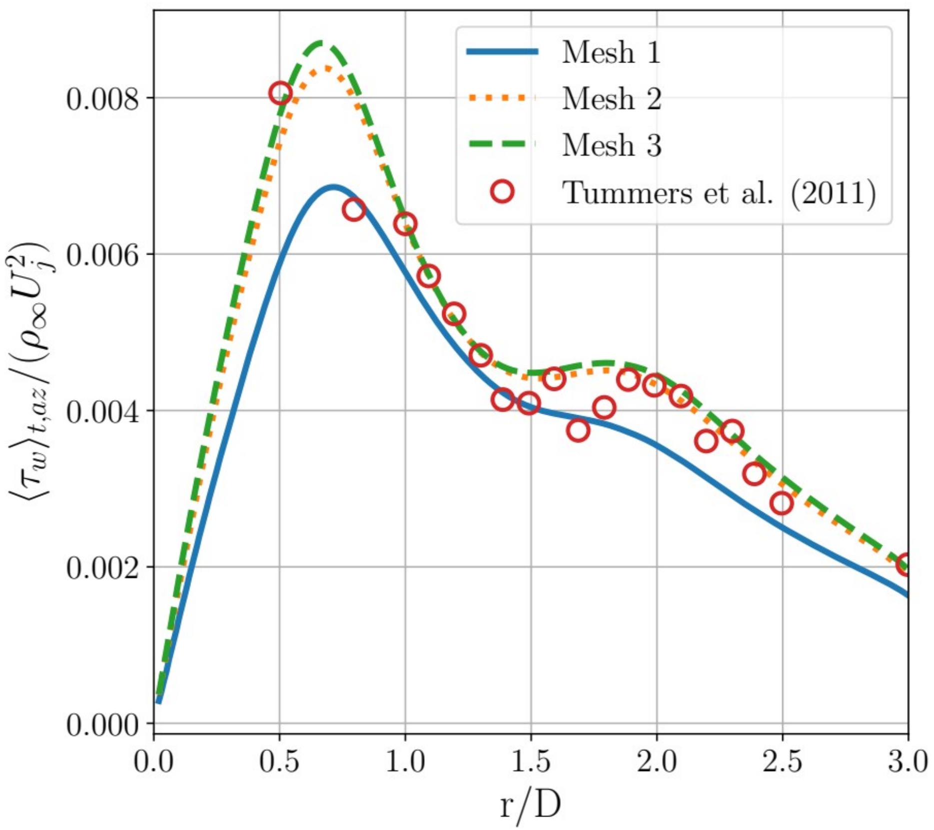


# Jet Flow Field Statistics



# Surface Quantities





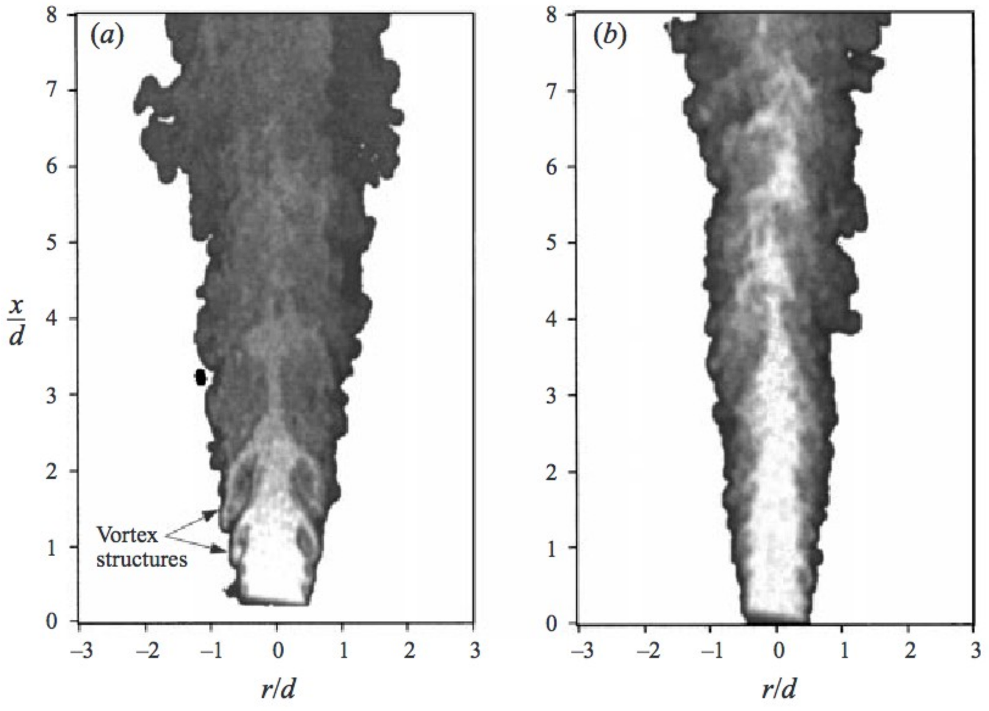
[17a] M. Tummers et al., «Turbulent flow in the near field of a round impinging jet », *International Journal of Heat and Mass Transfer* 54 (2011) 4939-4948
[17b] M. Fenot et al., « Local heat transfer due to several configurations of circular air jets impinging on a flat plate with and without semi-confinement », *International Journal of Thermal Sciences* 44 (2005), 665-675
[17c] J. W. Baughn, S. Shimizu, « Heat transfer measurements from a surface with uniform heat flux and an impinging jet. » *Journal of Heat Transfer* 111 (1989) 1096-1098

# Coherent Structures in the Free Jet

- Within the literature, the presence of coherent Kelvin-Helmholtz structures forming a ring vortex is not universally attested for fully developed pipe flow jets.

- Mi et al.[18a] found that no such structures in their experiments, whereas Grenson et al.[18b] did.

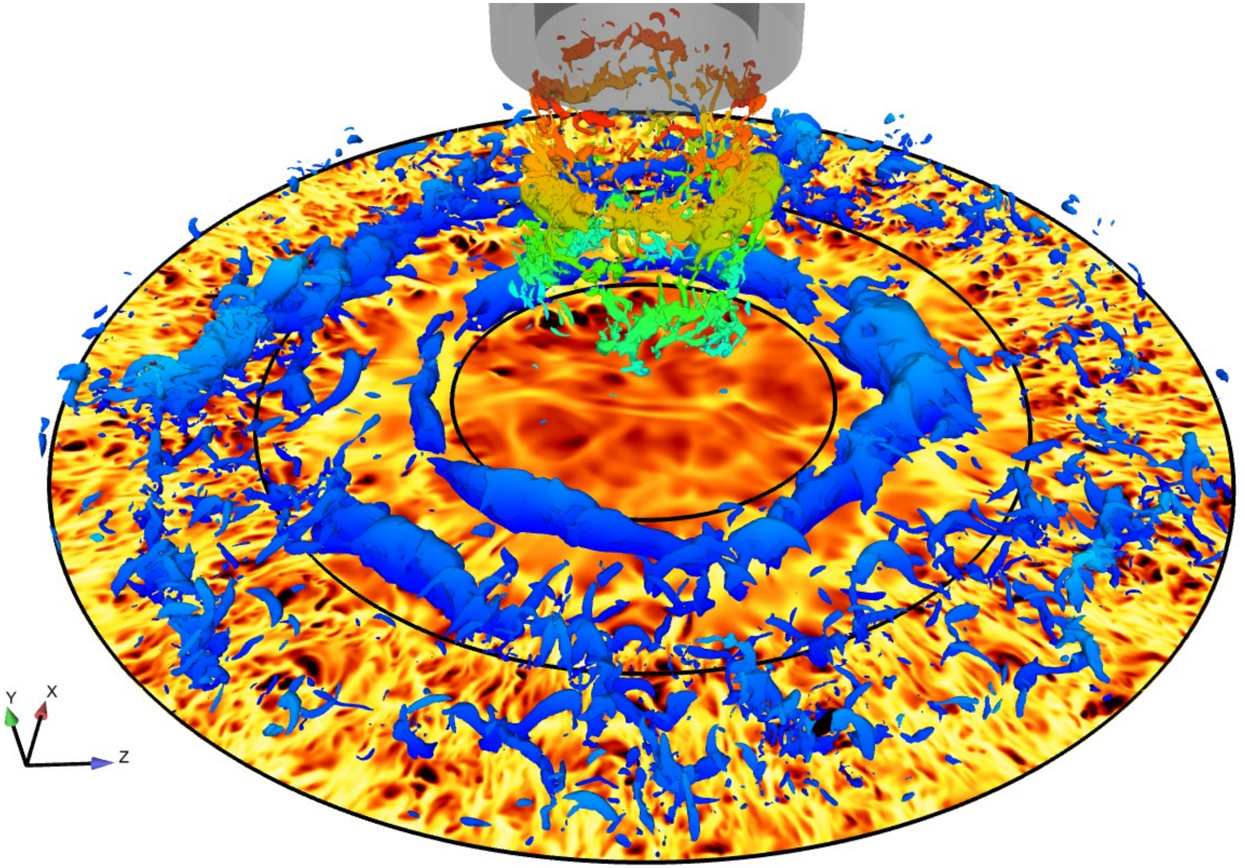
- The LES of Uddin et al.[18c] saw no coherent structures in the free-jet, while Aillaud et al.[18d] and Hadžiabdić and Hanjalić[18e] did



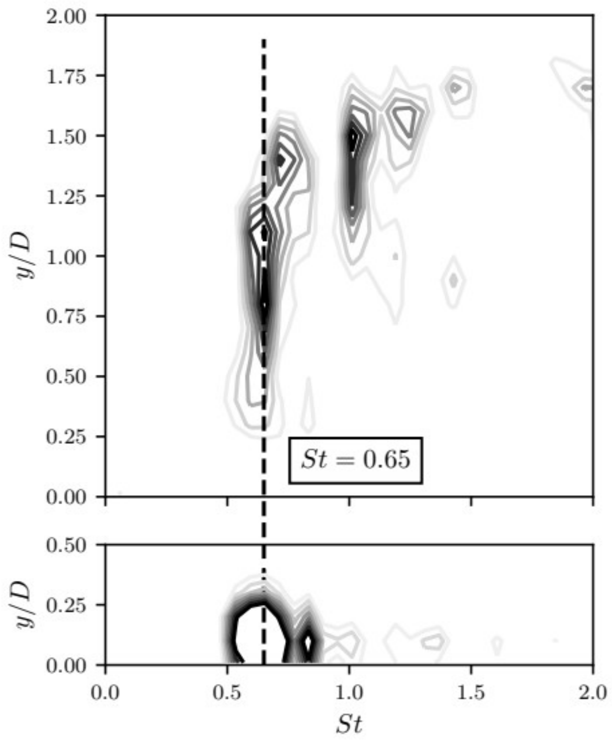

*Experiment of Mi et al.[18a]. Coherent vortical structures are found for a converging nozzle (left) but not for a fully developed pipe flow (right)*


[18a] J. Mi et al., "Influence of jet exit conditions on the passive scalar field of an axisymmetric free jet," *Journal of Fluid Mechanics* 432, 91–125 (2001).
[18b] P. Grenson et al., "Investigation of an impinging heated jet for a small nozzle-to-plate distance and high reynolds number: An extensive experimental approach," *International Journal of Heat and Mass Transfer* 102, 801–815 (2016)
[18c] N. Uddin et al., « LES simulations of an impinging jet: On the origin of the second peak in the Nusselt number distribution », *International Journal of Heat and Mass Transfer* 57, p. 356-368, (2013)
[18d] P. Aillaud et al., « Secondary peak in the Nusselt number distribution of impinging jet flows: A phenomenological analysis », *Physics of Fluids* 28, p. 095110, (2016)
[18f] M. Hadžiabdić, K. Hanjalić, « Vortical structures and heat transfer in a round impinging jet », *Journal of Fluid Mechanics*, 596, p. 221-260, (2008)

# Coherent Structures in the Free Jet




*Iso-surfaces of static pressure showing a ring vortex of only weak coherence in the free-jet, as well as a ring vortex in the wall*

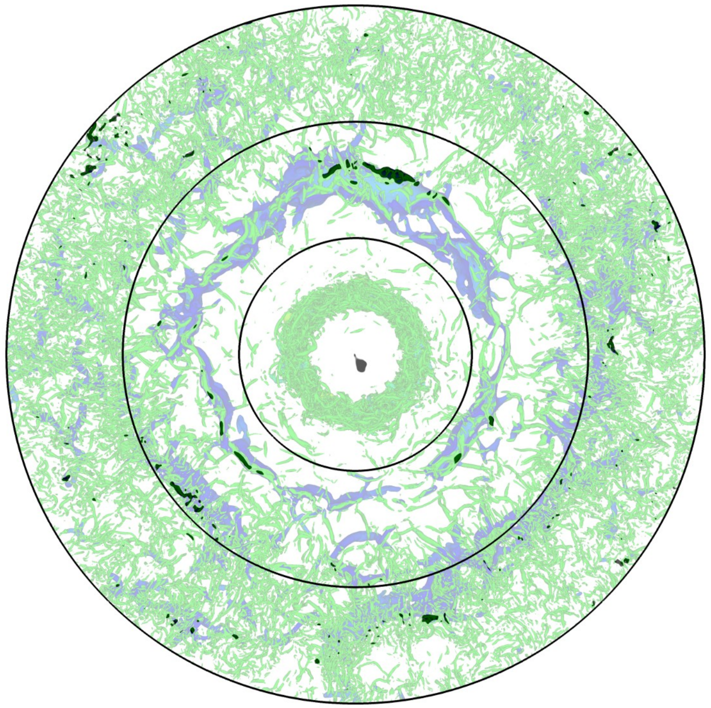



*PSD results of azimuthally averaged probes at  (top) as well as at  (bottom), showing that vortical structures in the shear-layer have roughly the same frequency as the structures in the wall jet*

# Coherent Structures Near the Wall

Dairay et al.[20a] and Aillaud et al.[20b] describe a ring of near-wall flow separation beneath the vortex ring, whereas Uddin et al.[20c] do not show any separation at all. Grenson and Deniau[20c] showed patches of flow-separation rather than a ring.

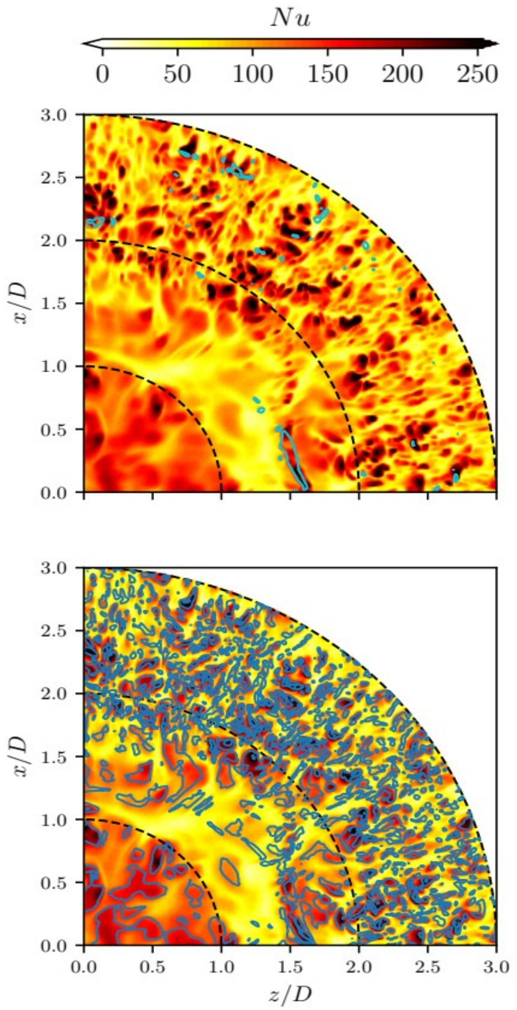
Zones of negative radial shear stress, indicating flow separation, are colored in black here. The results are similar to those of Grenson and Deniau[20c], with "patches" of flow separation rather than a ring



*View from "beneath" the impacted plate, showing the ring vortex (blue), iso-surfaces of the Q-criterion (green), and zones of flow-separation (black)*


[20a] T. Dairay et al., « Direct numerical simulation of a turbulent jet impinging on a heated wall », *Journal of Fluid Mechanics* 764, p. 362-394 (2015)
[20b] P. Grenson and H. Deniau, "Large-eddy simualtion of an impinging heated jet for a small nozzle to-plate distance and high reynolds number," International Journal of Heat and Fluid Flow 68, 348–363 (2017)
[20c] N. Uddin et al., « LES simulations of an impinging jet: On the origin of the second peak in the Nusselt number distribution », *International Journal of Heat and Mass Transfer* 57, p. 356-368, (2013)
[20d] P. Aillaud et al., « Secondary peak in the Nusselt number distribution of impinging jet flows: A phenomenological analysis », *Physics of Fluids* 28, p. 095110, (2016)
[20f] M. Hadžiabdić, K. Hanjalić, « Vortical structures and heat transfer in a round impinging jet », *Journal of Fluid Mechanics*, 596, p. 221-260, (2008)

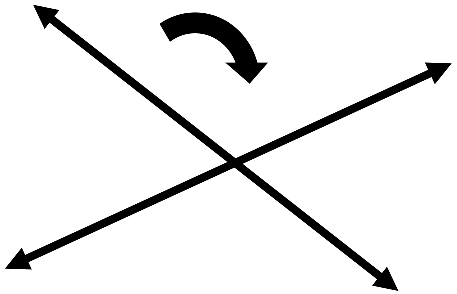
# Near-Wall Thermal Spots




*Instantaneous distribution of the Nusselt number highlighted by zones of flow separation (top) and zones of friction line divergence (bottom)*

- Highlighting the zones of flow separation relative to the Nusselt number shows that there are far more thermal spots than there are zones of flow separation – it is thus, not the primary cause of the secondary peak, as affirmed by Grenson and Deniau[21a]

- Instead, essentially all of the thermal spots correspond to zones where the 2D divergence of the shear stress  is positive and large. Since this flow is considered to be incompressible, any 2D divergence of the flow vectors near the wall indicates "downwash" of (colder) flow from above, enhancing heat transfer



*Divergence of the 2D streamlines indicates flow coming from « above »*

[21a] P. Grenson and H. Deniau, "Large-eddy simualtion of an impinging heated jet for a small nozzle to-plate distance and high reynolds number," International Journal of Heat and Fluid Flow 68, 348–363 (2017)

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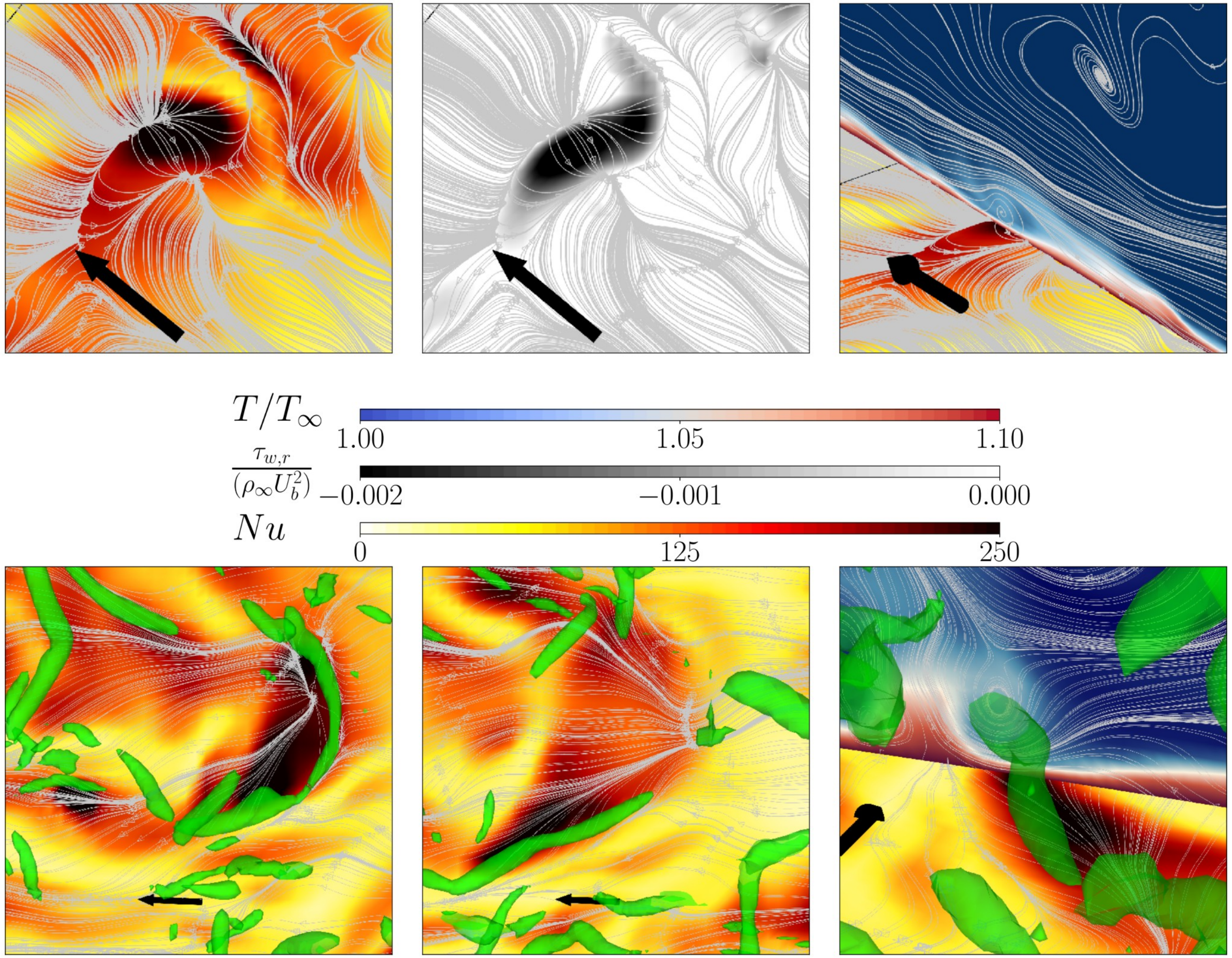
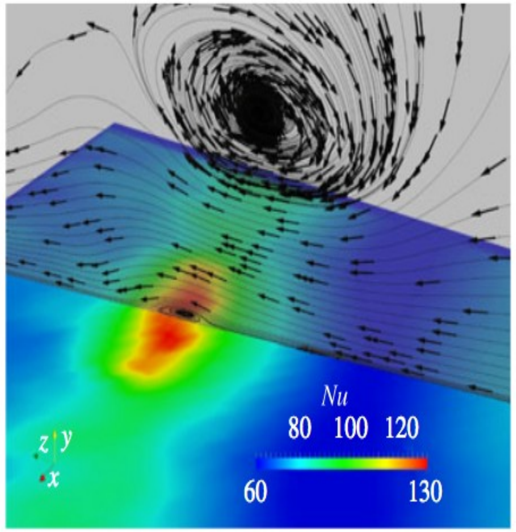
# Near-Wall Thermal Spots




*Both flow separation and streamwise structures contribute to the formation of thermal spots*




*"Patch" of local flow separation showing friction lines compared to the image of Dairay, et al.[22a]*

[22a] T. Dairay et al.i, « Direct numerical simulation of a turbulent jet impinging on a heated wall », *Journal of Fluid Mechanics* 764, p. 362-394 (2015)

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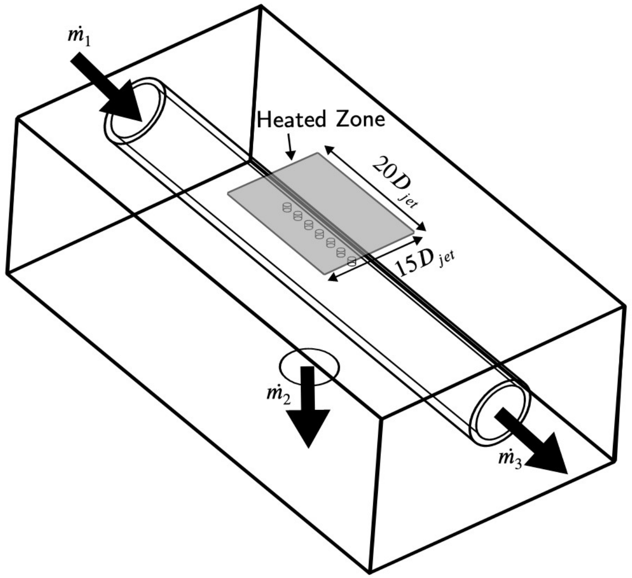
# Adaptive Clearance Control Test Case

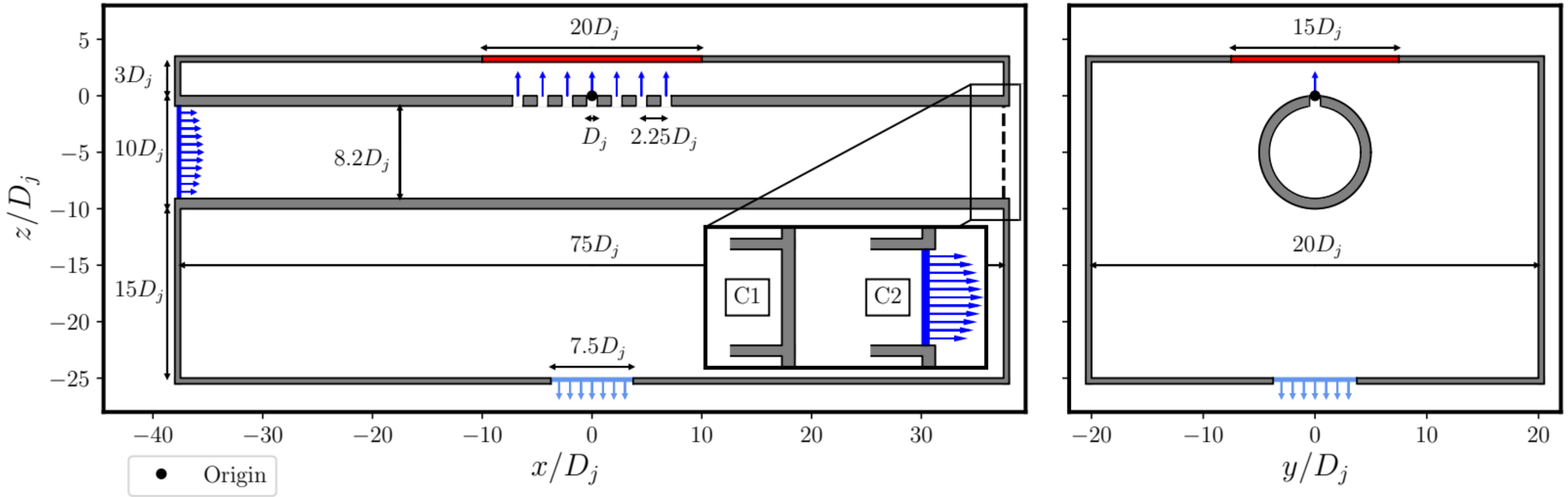
A series of multi-jet configurations representing a simplified ACC geometry was studied experimentally during the PhD thesis of Y. Ahmimache at Safran A.E./Pprime[24a][24b]. Here we study two configurations:

Case 1 (C1): closed pipe, weak upstream crossflow

Case 2 (C2): open pipe, strong upstream crossflow

All cases have a nominal Reynolds number . Furthermore, three Mach numbers are tested to examine compressibility effects:



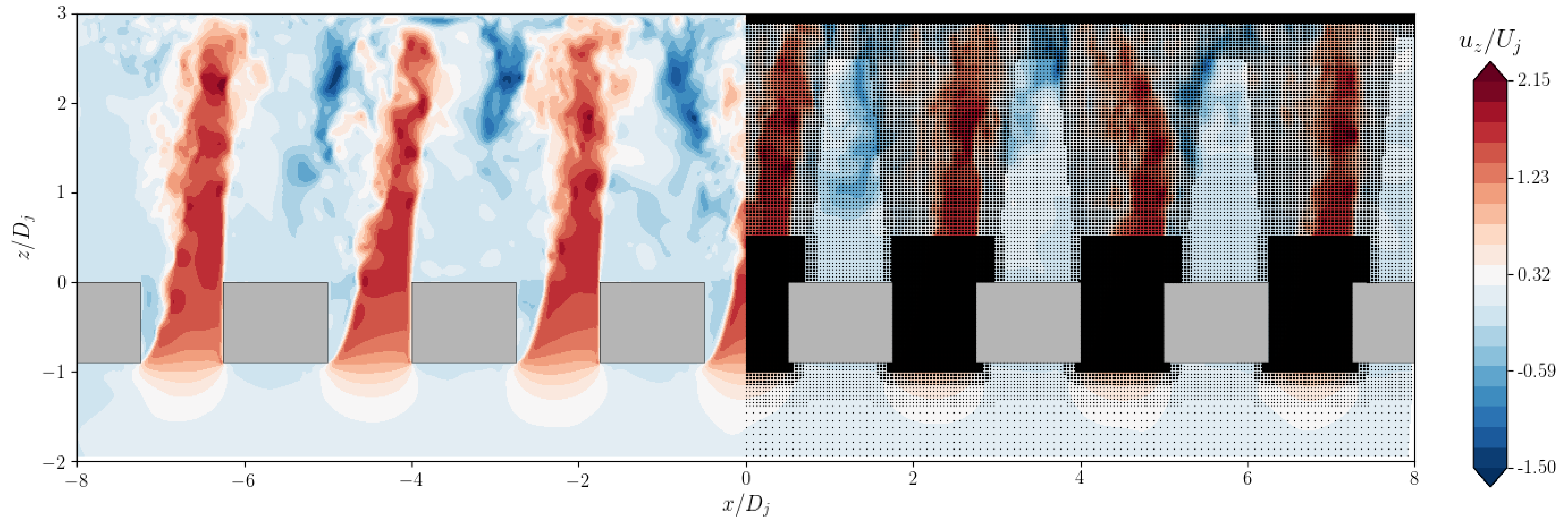





[24a] Y. Ahmimache et al. , « Heat transfer and flow velocity study of a row of jets emerging from a perforated pipe at low Reynolds number ». *International Journal of Heat and Mass Transfer* 183, 122067 (2022)

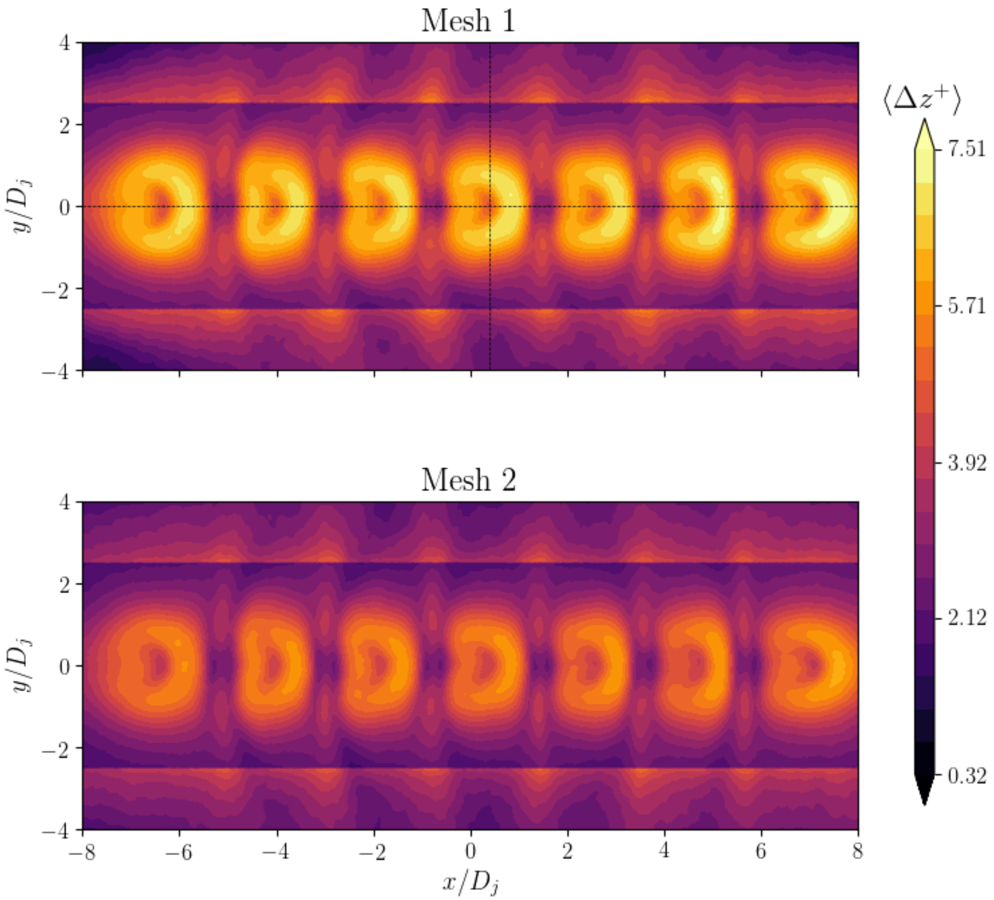
[24b] Y. Ahmimache « Caractérisation expérimentale et numérique des transferts thermiques par impact de jets à faible nombre de Reynolds : application au refroidissement du carter de turbine basse pression d'un turboréacteur » PhD Thesis, Université de Poitiers (2022)

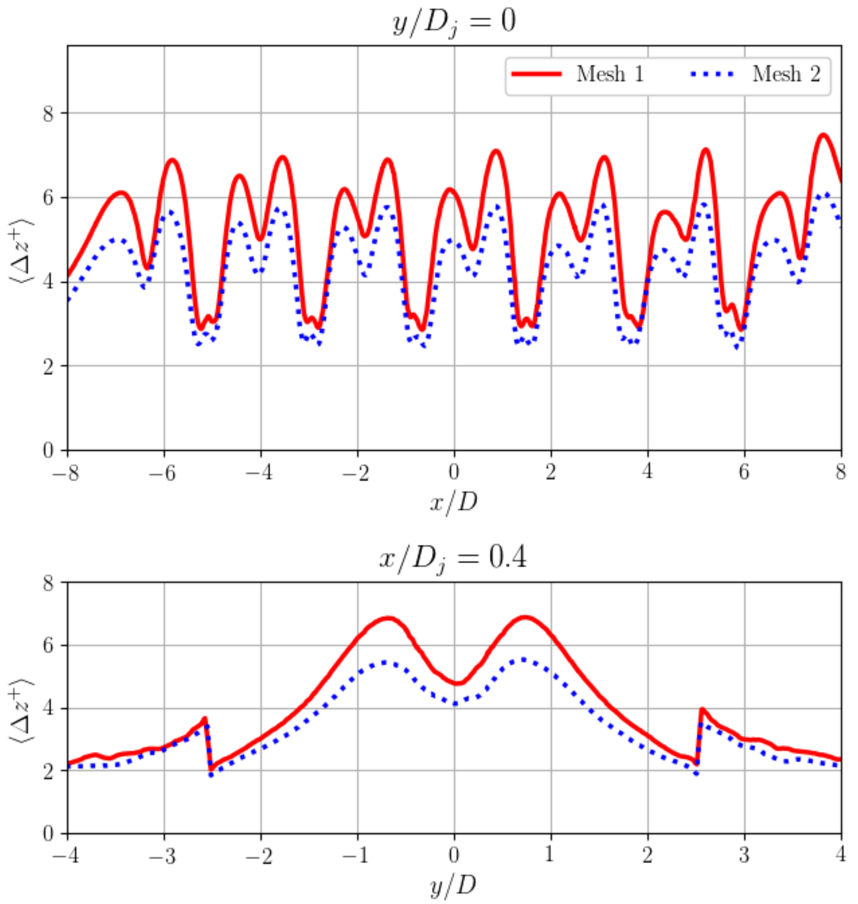
# Instantaneous Flow Field and Mesh (Case 2, Mesh 2)



# Mesh (Case 2)

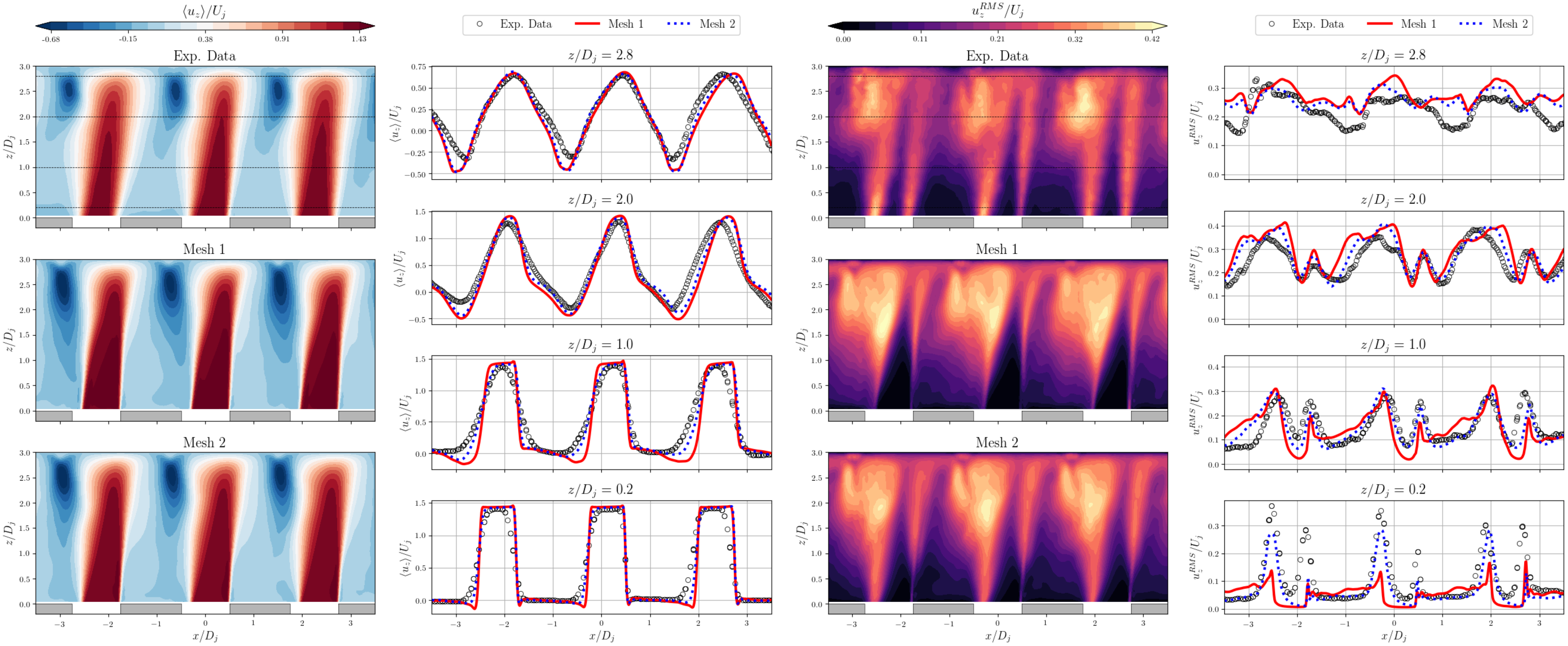
- RD1 is reserved for the central portion of the plate.
- Refinement reduced to RD2 fo



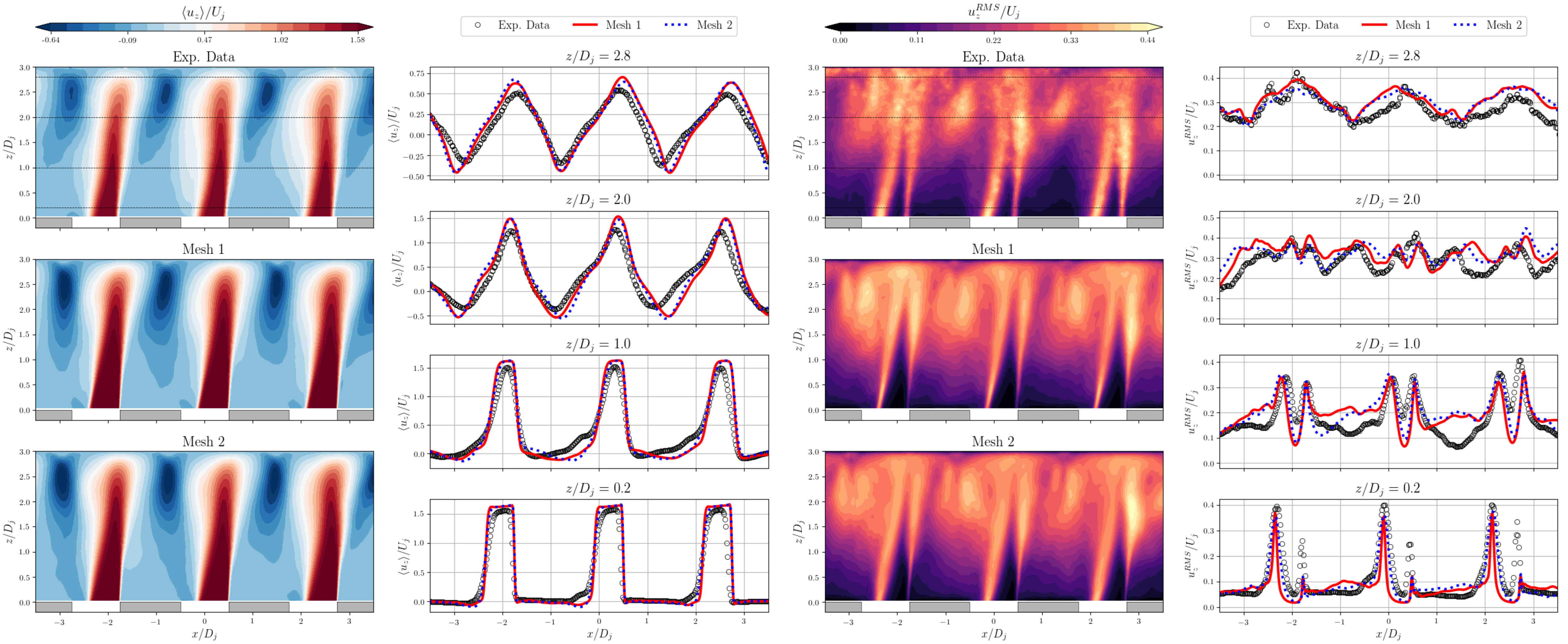




| | Mesh 1 | Mesh 2 |
|---|---|---|
| hCPU / | 82.6 | 177 |
| hCPU / | 9165 | 19672 |

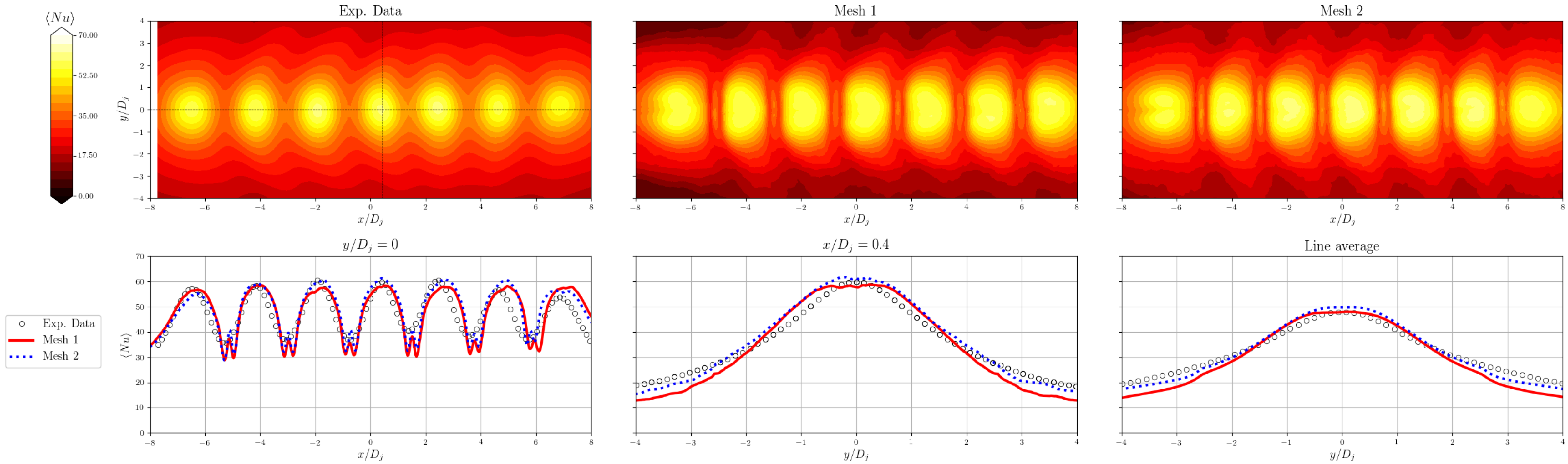
# Case 1 Flow Field



# Case 2 Flow Field



# Case 1 Heat Transfer




Calculating the space average for

Exp: 32.42

Mesh 1: 30.32 (6.48% error)

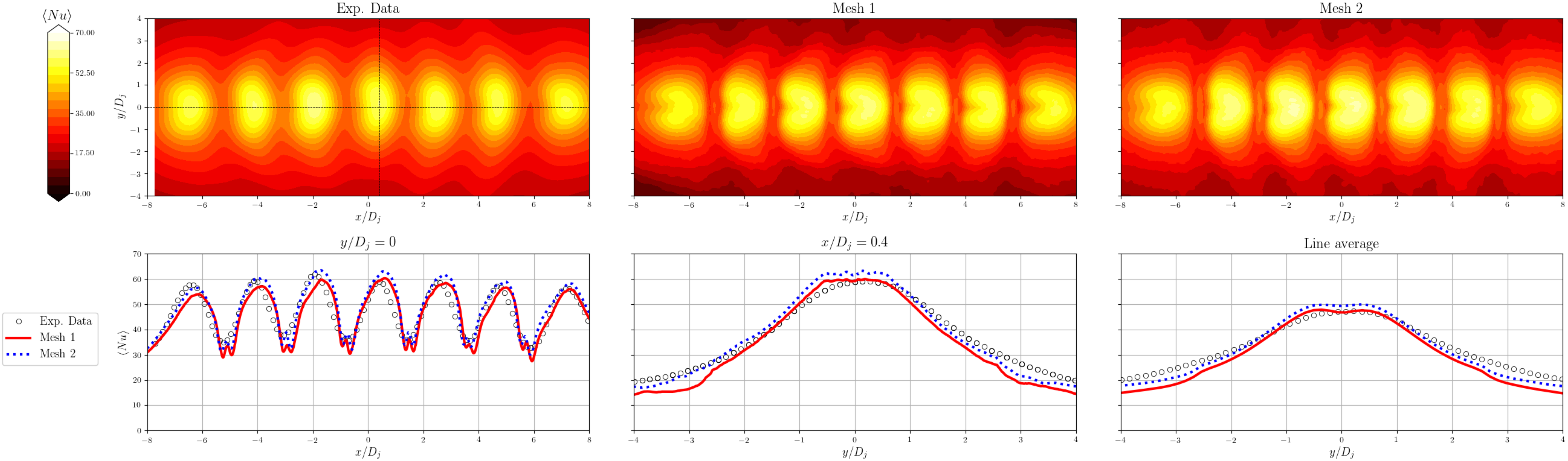
Mesh 2: 32.20 (0.679% error)

Exp. uncertainties estimated to be between 6-12%[29a]

CERFACS SAFRAN M2P2

[29a] Ahmimache, et al., « Heat transfer and flow velocity study of a row of jets emerging from a perforated pipe at low Reynolds number ». *International Journal of Heat and Mass Transfer* 183, 122067 (2022)

# Case 2 Heat Transfer




Calculating the space average for

Exp: 33.46

Mesh 1: 30.36 (9.26% error)

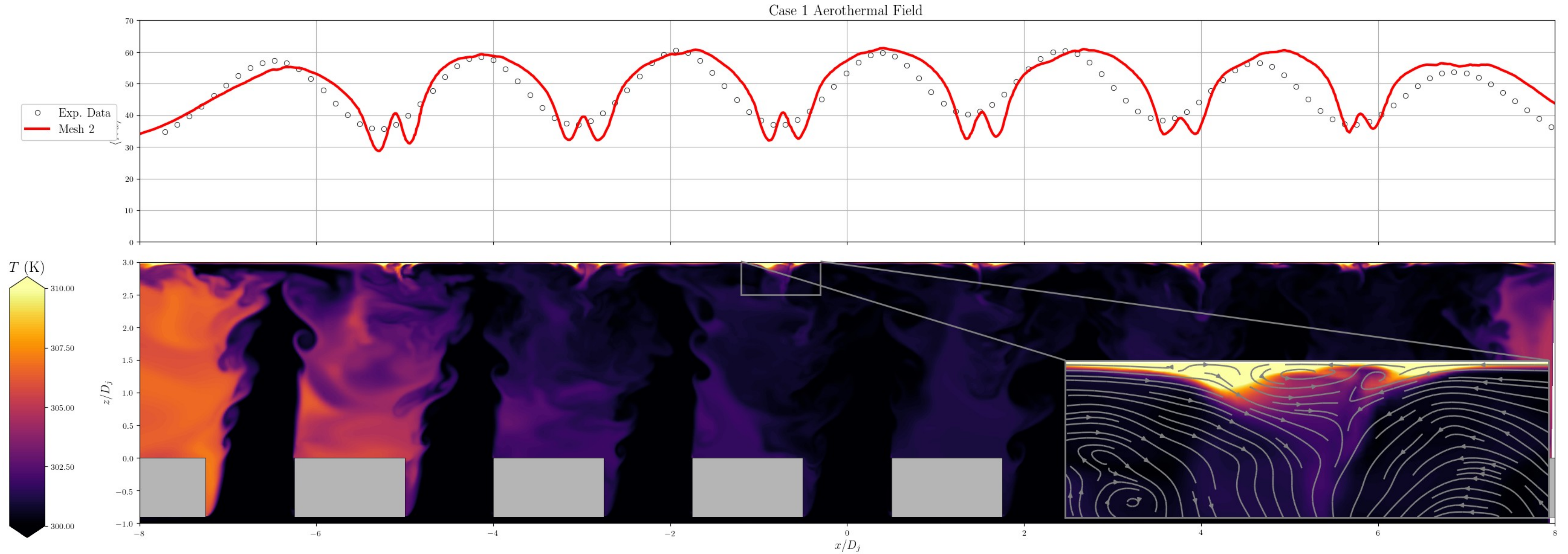
Mesh 2: 32.56 (2.69% error)

Exp. uncertainties estimated to be between 6-12%[30a]

CERFACS SAFRAN M2P2

[30a] Ahmimache, et al., « Heat transfer and flow velocity study of a row of jets emerging from a perforated pipe at low Reynolds number ». *International Journal of Heat and Mass Transfer* 183, 122067 (2022)

# Near Wall Aerothermal Behavior




- Presence of a secondary vortex induced by flow separation.
- Identical aerothermal behavior and secondary peaks found in the LES study of Ahmimache (2022)[31a], it is possible that the corresponding PIV and IR study does not have enough resolution to capture such small-scale aerothermal phenomena

[31a] Y. Ahmimache « Caractérisation expérimentale et numérique des transferts thermiques par impact de jets à faible nombre de Reynolds : application au refroidissement du carter de turbine basse pression d'un turboréacteur » PhD Thesis, Université de Poitiers (2022)

# Mach Number Effects

**For multi-jet cases**

Ben Ahmed et al. (2010)[32a], One row multijet, RANS:

- *Negative correlation*

Goodro et al. (2010)[32b] , Multi-row multijet, Experiment:

- *Positive correlation*

**For single jet test cases, we have:**

Fénot et al. (2019)[32c], Experiment:

- *Almost no influence*

Wilke and Sesterhenn. (2017)[32d], DNS:

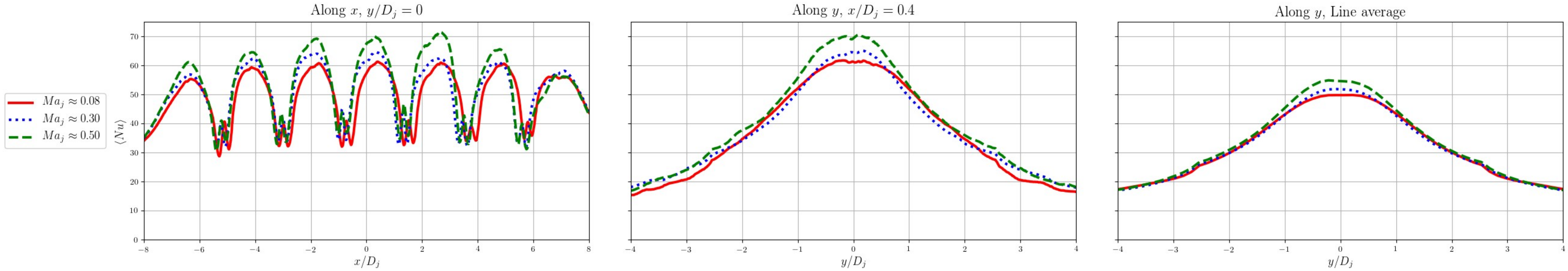
- *Positive Correlation*

Otero Pérez et al. (2020)[32e], LES:

- *Positive Correlation*

**Present:**

*Positive correlation*





[32a] Ben Ahmed et al., « Heat Transfer and Pressure Drop Characteristics for a Turbine Casing Impingement Cooling System ». *Proceedings of the 14th International Heat Transfer Conference 49408, p. 199-212* (2010)

[32b] Goodro et al., « Mach number, Reynolds number, jet spacing variations: full array of impinging jets. » *Journal of thermophysics and heat transfer* 24(1) p. 133-144 (2010)

[32c] Fénot et al., « Flow and heat transfer of a compressible impinging jet » *International Journal of Thermal Sciences* 136, p. 357-369 (2019)

[32d] R. Wilke, J. Sesterhenn, « Statistics of fully turbulent impinging jets » *Journal of Fluid Mechanics* 825 p. 795-823 (2017)

[32e] J. J. Otero-Pérez, R. D. Sandberg, « Compressibility and variable inertia effects on heat transfer in turbulent impinging jets » *Journal of Fluid Mechanics* 887 A15 (2020)

# Conclusions (1)

- Developments were made in a thermal version of the LBM solver ProLB to make it capable of performing aerothermal jet simulations. These include NSCBC turbulence injection conditions,  the adaptation of grid-refinement algorithms, and mass flow control boundary conditions.

- The turbulence injection methodology was validated on a planar channel test case

- The impinging jet LES was performed with three mesh configurations. All three simulations produced excellent flow-field results, as well as a good Nusselt number distribution, including the well-known secondary peak. The coarsest grid failed only to retrieve an adequate wall shear stress profile.

- The fine structures of turbulence found in the literature were also reproduced, supporting the theory in which both radial and azimuthal vortical structures produced thermal spots leading to the well-known secondary maximum.

The single jet study was the subject of a journal article:

M. Nguyen, J. F. Boussuge, P. Sagaut, J.C. Larroya-Huguet, *Large eddy simulation of a thermal impinging jet using the lattice Boltzmann method.* Physics of Fluids 34, 0551155 (2022); https://doi.org/10.1063/5.0088410

and one conference participation:

M. Nguyen, J. F. Boussuge, P. Sagaut, J.C. Larroya-Huguet, *Aerothermal Jet Simulations Using the Lattice Boltzmann Method.* 56th Edition of the 3AF International Conference on Applied Aerodynamics, Toulouse, France, March 2022

# Conclusions (2)

- The LBM solver was next tested on a multi-jet configuration meant to represent a simplified aircraft engine cooling apparatus.

- Generally good agreement was found for the flow field statistics and heat transfer profiles.

- A secondary maximum was found where the wall jets collide. This was not found in the corresponding experiment, but was found elsewhere in a separate LES. The physical realism of this phenomenon should be further investigated.

- Test involving a higher Mach number flow resulted in an increase in wall heat transfer.

- An article is currently being written for the multi-jet test case, with the intention of submitting it to a journal

# Thank you for your attention

Questions?

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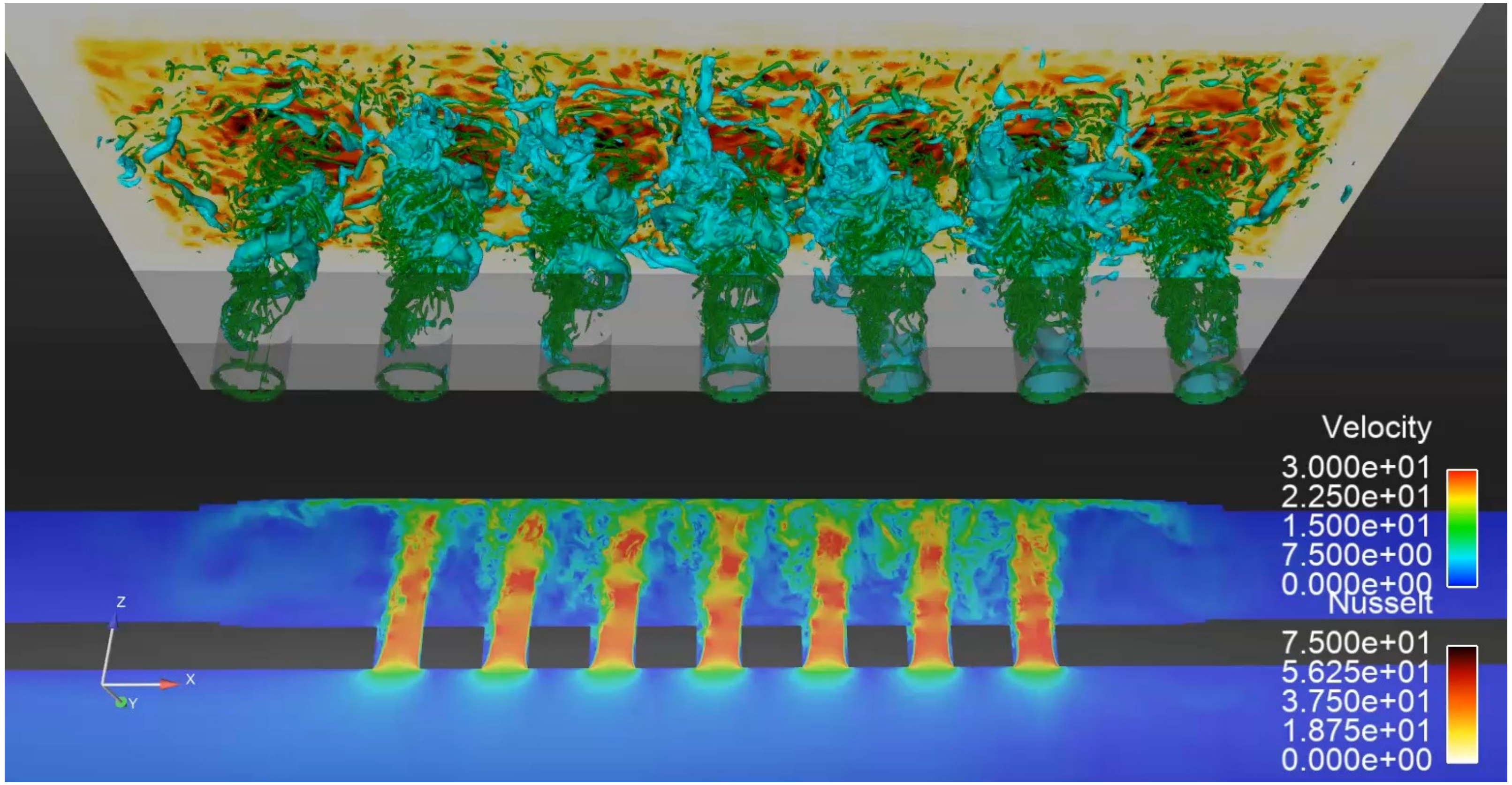

# Appendix: Effect of Temperature Choice on Nusselt Number Distribution

Erratum on the legend

Red, green,

Blue, purple,