DNS of a turbulent jet impinging on a heated wall

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24/04/2014
Impinging jet

- A fluid issuing from a nozzle impinging on a solid wall
- Efficient tool to optimize flow/wall heat transfer
- Widely used in industrial applications requiring high transfer rates (cooling, drying...)

![Diagram of impinging jet]

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Some applications

Cooling of electronic components

- Increase of computing resource requirements
- Efficient and simple solution

Chang et al., ETFS, 2007

Vertical Take-Off and Landing aircraft

- Vertical force generated by impinging jets
- Control the jets: improve the aircraft stability
Some applications

### Cooling of electronic components

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_Chang et al., ETFS, 2007_

### Vertical Take-Off and Landing aircraft

- **Vertical force** generated by impinging jets
- Control the jets: improve the aircraft stability

_Take-off of an AV8B-Harrier ©2013 ForWallpaper.com_

_T. Dairay et al. (ICL/Institute PPRIME) Incompact3d meeting 24/04/2014_
 Cooling of turbine blades

**Industrial challenge**

Improve aircraft engine’s cooling is a major challenge for the manufacturers

- Optimize the engine **efficiency**
- Increase its **life duration**
- Decrease the maintenance **cost**

**Different cooling techniques**

- Forced internal convection cooling
- Film cooling
- Impinging jet cooling

Fénot, PhD Thesis, 2004
Cooling of turbine blades

At the lab

- Many experimental research at the Institute PPRIME
- Industrial collaboration: DGA, Snecma Moteurs, Turboméca, ONERA


Industrial system

Physical analysis: single jet
Cooling of turbine blades

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Industrial system

Physical analysis: single jet
Single impinging jet

- A boundary-free shear flow region
- A **wall-bounded** flow region
- A **stagnation region**
- Accelerated/decelerated **wall jet**

Adapted from

*Gauntner et al., TR-NASA, 1970*
Single impinging jet: multiple parameters

A lot of possible configurations depending on the choice of geometrical, aerodynamical or thermal parameters:

- Jet type, nozzle-to-plate distance...
- Inflow velocity, Reynolds number...
- Plate heating, temperature difference between the plate, the jet and the surrounding fluid...

Experimental studies

- Review papers of Jambunathan et al., IJHFF, 1992; Webb and Ma, AHT, 1995

Numerical studies

- Hadziabdic and Hanjalic, JFM, 2008;
- Dewan et al., HTE, 2012;
- Uddin et al., IJHMT, 2013
Today’s motivations

- **Secondary maximum** in the radial distribution of the mean Nusselt number
- **Measurement technics limitations**: synchronized temporal evolution of the 3D fields is extremely difficult to obtain, measurement of the near-wall dynamics
- **Unsteady numerical studies** \( (Re \geq 10000) \): exclusively Large Eddy Simulation (LES)
Today’s study

DNS of a circular confined jet impinging on a flat plate in a realistic flow regime

\[ Re = \frac{U_d D}{\nu} = 10000 \]
\[ \frac{H}{D} = 2 \]

What is the role of unsteady processes to explain the spatial distribution of the mean heat transfer at the wall?

For experimental validation (PIV, IR Thermography) and comparisons with different LES methodologies, see

Dairay et al. under review, IJHFF 2014
1. Numerical methods
2. Main turbulent statistics
3. Unsteady processes and heat transfer distribution at the wall
4. Conclusion
Contents

1 Numerical methods
   - Numerical tool
   - Flow configuration

2 Main turbulent statistics

3 Unsteady processes and heat transfer distribution at the wall
   - Instantaneous visualisations
   - Temperature distribution analysis
   - Conditional averaging of temperature and velocity

4 Conclusion
Incompressible Navier-Stokes equations
\[
\frac{\partial \mathbf{u}}{\partial t} + \frac{1}{2} (\nabla \cdot (\mathbf{u} \otimes \mathbf{u})) + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u}
\]
\[
\nabla \cdot \mathbf{u} = 0
\]

Reynolds number : \(Re = \frac{U_d D}{\nu}\)

Temperature equation (passive scalar)
\[
\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{1}{Re Pr} \nabla^2 T
\]

Prandtl number : \(Pr = \frac{\nu}{\kappa}\)
Incompact3d

Solve the **incompressible Navier-Stokes equations** on a Cartesian mesh.

- **Spatial discretization**: High-order compact schemes $O(\Delta x^6)$
- **Time advancement**: Explicit Adams-Bashforth scheme coupled with an implicit Crank-Nicolson scheme $O(\Delta t^2)$
- Pressure treatment in the *spectral space* with the help of the modified wave number concept
- **Parallel version** (MPI implementation and pencil domain decomposition)

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S. Laizet and E. Lamballais, JCP, 2009

S. Laizet et al., CF, 2010

S. Laizet and N. Li, IJNMF, 2011
Computational domain and boundary conditions

- **Physical parameters**: $Re = 10000$, $H/D = 2$, $Pr = 1$
- **Numerical parameters**:
  - $n_x = n_z = 1541 \Rightarrow \Delta x^+ \approx 10$
  - $n_y = 401 \Rightarrow 0.9 \lesssim \Delta y^+ \lesssim 40$
  - $\Delta t = 2.10^{-4}$

**Velocity**
- Inflow: Mean velocity prescribed (power law) + synthetic perturbations
- Outflow: Buffer zone
- Top and bottom plates: No-slip condition

**Temperature**
- Inflow: Constant temperature $T_j$
- Outflow: Convective condition
- Top plate: Constant temperature $T_j$
- Bottom plate: Constant heat flux $\varphi_p$

T. Dairay et al., ETC14, 2013
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Main turbulent statistics

Velocity statistics

- **Free jet region** ($0.5 < y/D < 2$): Potential core, low turbulence intensity on the jet axis ($u_y = U_{max}$), shear layer $r/D \approx 0.5$

- **Stagnation region** ($0 < y/D < 0.5$ and $r/D < 1.8$): Axial to radial flow, boundary layer from the stagnation point, $u_r$ increase, $k$ maximum

- **Wall jet region** ($r/D > 1.8$): radial velocity, $u_r$ and $k$ decrease
Local minimum at the stagnation point: low turbulence level on the jet axis (potential core)

Primary maximum at $r/D \approx 0.7$: structures issuing from the jet shear layer

Secondary maximum at $r/D \approx 2$: linked with the region $1 \leq r/D \leq 2$ of high $k$
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Flow animation: $Q$ criterion colored by $y/D$
Large-scale organisation

2D toroidal structures:

- Primary vortex
  \[ \omega_\theta > 0 \]
  \[ \omega_\theta < 0 \]

- Near-wall secondary vortex
  \[ \omega_\theta < 0 \]

Heat transfer:

\[ Q = 70 \]
Small-scale organisation

- **Cold spots**: extremely high heat transfer
- **Radial stretching**: filament propagation of cold spots

Hadziabdic et Hanjalic, JFM, 2008; Uddin et al., IJHMT, 2013
Small-scale organisation

Isosurface $Q = 50$ and temperature map in the plane $r/D = 1.5$
Small-scale organisation

Isosurface $Q = 50$ and temperature map in the plane $r/D = 1.5$
Instantaneous fields in the vicinity of a cold spot

Isolated cold spot

Point froid
Unsteady processes and heat transfer distribution at the wall

Instantaneous visualisations

Instantaneous fields in the vicinity of a cold spot

\[ T \text{ in the plane } \theta = \text{Cste} \]

2D toroidal

Isolated cold spot

Azimuthal distortion

Point froid

Incompact3d meeting
Instantaneous fields in the vicinity of a cold spot

$T$ in the plane $\theta = \text{Cste}$

Isosurface $Q = 10$

2D toroidal
Instantaneous fields in the vicinity of a cold spot

\[ T \text{ in the plane } \theta = Cste \]

**Isolated cold spot**

Isosurface \( Q = 10 \)

Radial structures
Instantaneous fields in the vicinity of a cold spot

Unsteady processes and heat transfer distribution at the wall

Isolated cold spot

$T$ in the plane $\theta = \text{Cste}$

Isosurface $Q = 10$

$T$ in the plane $r/D = 1.77$

2D toroidal

Radial structures

Azimuthal distortion
Unsteady processes and heat transfer distribution at the wall

Instantaneous visualisations

Spatio-temporal maps

\[ \tau_w = \mu \frac{\partial u_r}{\partial y} \]

For \( r/D < 0.5 \): steady evolution \( \implies \) local minimum of \( \bar{Nu} \)

For \( 0.5 < r/D < 1 \): periodical appearance of high heat transfer values \( \implies \) primary maximum of \( \bar{Nu} \)

For \( 1 < r/D < 2.5 \): secondary vortex and cold fronts convected at \( U_c \approx 0.45 U_d \) \( \implies \) increase of \( \bar{Nu} \)
Unsteady processes and heat transfer distribution at the wall

Instantaneous visualisations

Spatio-temporal maps

\[ \tau_w = \mu \frac{\partial u_r}{\partial y} \]

Time

\( \frac{r}{D} \)

\( \frac{r}{D} \)

For \( \frac{r}{D} < 0.5 \) : steady evolution \( \Rightarrow \) local minimum of \( \bar{Nu} \)

For \( 0.5 < \frac{r}{D} < 1 \) : periodical appearance of high heat transfer values \( \Rightarrow \) primary maximum of \( \bar{Nu} \)

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Spatio-temporal maps

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- For \( 0.5 < r/D < 1 \): periodical appearance of high heat transfer values \( \rightarrow \) primary maximum of \( \overline{Nu} \)
- For \( 1 < r/D < 2.5 \): secondary vortex and cold fronts convected at \( U_c \approx 0.45 U_d \) \( \rightarrow \) increase of \( \overline{Nu} \)
For $1.5 \leq r/D \leq 2.5$ (blue and black curves): highly skewed PDF with $Nu > 200 \iff$ rare but extremely intense thermal events

- Most probable location of $\tau_w \leq 0$ in the range $1.5 \leq r/D \leq 2$
- Extreme events localised in the range $1.5 \leq r/D \leq 2.5$ with a maximum probability at $r/D \approx 2$
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Most probable location of $\tau_w \leq 0$ in the range $1.5 \leq r/D \leq 2$

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Extreme events localised in the range $1.5 \leq r/D \leq 2.5$ with a maximum probability at $r/D \approx 2$
Cold spots detection and conditional averaging

Intermediate radial location $r/D = 1.75$

1. Selection of comparable instants
2. Detection of the azimuthal angles corresponding to a cold spot (threshold $S = 110$)
3. Conditional averaging operator $\langle f(r, \xi, y, t_0) \rangle_{Nu} = \frac{1}{N} \sum_{j=1}^{N} f(r, \theta_j + \xi, y, t_0)$
4. Temporal averaging of each conditionally averaged field

Temporal evolution of the azimuthally averaged Nusselt number at $r/D = 1.75$

![Graph showing temporal evolution of the azimuthally averaged Nusselt number at $r/D = 1.75$.]
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Unsteady processes and heat transfer distribution at the wall

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Temporal evolution of the azimuthally averaged Nusselt number at \( r/D = 1.75 \)

Nusselt number at \( r/D = 1.75 \)

![Graph showing the temporal evolution of the azimuthally averaged Nusselt number with marked instants and moving average.](image)
Unsteady processes and heat transfer distribution at the wall

Cold spots detection and conditional averaging

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Temporal evolution of the azimuthally averaged Nusselt number at $r/D = 1.75$
Aerothermal fields in the vicinity of a cold spot

Unsteady processes and heat transfer distribution at the wall
Conditional averaging of temperature and velocity

\[ \langle \text{Nu}(r, \theta, y) \rangle \text{Nu} \]

Cold fluid flux
Conditional mean streamlines
Primary and secondary vortices
Conditional mean streamlines projected in the near-wall plane \( y/D = \Delta y \)
Unsteady processes and heat transfer distribution at the wall

Conditional averaging of temperature and velocity

Aerothermal fields in the vicinity of a cold spot

\[ \langle Nu(r, \theta, y) \rangle_{Nu} \quad \text{and} \quad \langle T(r, \theta, y) \rangle_{Nu} \]

in a plane \( \theta = \text{cste} \)

Cold fluid flux
Aerothermal fields in the vicinity of a cold spot

\[ \langle Nu(r, \theta, y) \rangle_{Nu} \text{ and } \langle T(r, \theta, y) \rangle_{Nu} \]

in a plane \( \theta = \text{cste} \)

Conditional mean streamlines

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\[ \langle \text{Nu}(r, \theta, y) \rangle \text{Nu} \] and \[ \langle \text{T}(r, \theta, y) \rangle \text{Nu} \]
in a plane \( \theta = \text{cste} \)

Conditional mean streamlines

Projected in the near-wall plane

\[ y/D = \Delta y_{\text{min}} \]

Cold fluid flux

Primary and secondary vortices
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Unsteady processes and heat transfer distribution at the wall

- **Instantaneous visualisations**
  - Large-scale toroidal organisation
  - Azimuthal distortion → cold spots
  - Radial stretching

- Spatio-temporal maps: cold fronts convected at the same velocity as the secondary vortex

- PDF: extremely high heat transfer linked with cold spots occurrence in the vicinity of the secondary maximum ($1.5 \leq r/D \leq 2.5$)

- Conditional averaging: cold fluid flux directed toward the impingement plate
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Instantaneous visualisations
- **Large-scale** toroidal organisation
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Spatio-temporal maps: cold fronts convected at the same velocity as the secondary vortex

PDF: extremely high heat transfer linked with cold spots occurrence in the vicinity of the secondary maximum ($1.5 \leq r/D \leq 2.5$)

Conditional averaging: cold fluid flux directed toward the impingement plate
The secondary maximum amplitude is reduced when using LES approaches → confirm the importance of the small-scale contribution to the mean heat transfer
Thank you