Turbulent kinetic energy transfers in low-Mach wall bounded flows
Flows inside solar processes

- The vast majority of flows inside solar systems are very **anisothermal and turbulent**.

- The understanding of the **coupling between velocity and temperature** is a fruitful approach for the optimization of solar processes.
Very anisothermal flow

A simple illustration of velocity and temperature coupling

Bi-periodic channel flow submitted to a high temperature gradient
Isosurfaces: Q-criterion (in blue and green)
Isotherm 480 K (in red)
Global strategy

One of the difficulties:
Size difference between
small turbulent structures (~ μm) and
the solar receiver geometry (~ m)

Multi-scale approach

- **Local scale**: study of velocity/temperature coupling
- **Modular scale**: heat transfer characterization
- **Industrial scale**: design and sizing

Numerical and experimental tools
dedicated to each scale

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Outline

1. Concentrated solar power plant
2. Resolution of low-Mach equations
3. Velocity/temperature coupling
4. Turbulent kinetic energy
Conclusions and outlook
Choice of a high temperature thermodynamic cycle: Brayton cycle at 1000°C

Solar receiver: a key component that transfers the concentrated solar energy to the working fluid
Plate pressurized solar receiver

Goal
Transfer of the concentrated solar energy to the working fluid
• Maximize the heat exchange between the gas and the wall,
• Minimize the pressure drop

Characteristics
• High temperature 1000°C
• Turbulent flow
• Asymmetric heating
• Velocity/temperature coupling
Main characteristics of HT SR:
- Turbulent flow
- Asymmetric heating

Bi or mono periodic channel flow

Study of the coupling between velocity and temperature
Resolution of Low-Mach equations: numerical tools

- Trio_U software developed by CEA

- Realized improvement
  - Time and convection schemes
  - Parallel multigrid methods
  - Post processing for spectral analysis
  - New algorithm for Low Mach number equations (incompressible):
    - Acoustic is not solve
    - Dilatation is taken into account
Resolution of Low-Mach equations: new algorithm

New algorithm advantages:
- Mass and energy conservation
- Coupling between temperature and velocity

Density

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \]

- Thermodynamic pressure
  (Global energy conservation)
- Temperature
  (Ideal gas law)

\[ \frac{\partial P_{th}}{\partial t} = \frac{\gamma - 1}{V} \int_s \lambda(T) \nabla T dS \]
\[ T = \frac{P_{th}}{\rho r} \]

- Velocity
  (Navier-Stokes equation)
- Dynamic pressure
  (Local energy conservation)

\[ \nabla \cdot (U) = \frac{1}{\gamma P_{th}} \left( (\gamma - 1) \nabla \cdot (\lambda(T) \nabla T) - \frac{\partial P_{th}}{\partial t} \right) \]
Resolution of Low-Mach equations:

- Accurate numerical tools:
  - Conservation properties
  - Channel flow in agreement with literature

- Fine Simulations: DNS and LES

- Reference data for the study of the coupling between temperature and velocity
Goal: Model development for RANS

Contribution: understanding of velocity/temperature coupling

Effect of the temperature gradient on turbulence properties:
- Mean and fluctuation velocities
- Mean and fluctuation temperatures
- Study in the space and frequency domains

DNS $Re_{\tau}=395$ and $T_2/T_1=2$
- $L_x=4\pi h$, $L_y=2h$, and $L_z=2\pi h$
- 1536x896x1536 (2.1 billion) cells and $y^+=0.125$
Simplified geometry: bi-periodic channel flow

Statistics:
- Average in the homogeneous directions (x and z),
- Average in time,
- Functions of the distance to the wall (y).
Local scale:
DNS $Re_\tau=395$ and $T2/T1=2$

Mean velocity in the streamwise direction
Classical nondimensionalization

- Hot: $u^+ = 2.5 \ln(y^+) + 4.5$
- Cold: $u^+ = 2.8 \ln(y^+) + 5.5$

Isothermal case
$u^+ = 2.5 \ln(y^+) + 5.5$

$u^+ = y^+$

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Mean velocity in the streamwise direction
Van Driest nondimensionalization

\[ u^+ = \frac{2}{PrT/T_w} \left( 1 - \sqrt{1 - PrT/T_w \frac{u}{u_\tau}} \right) \]

By analogy with effusion, an injection speed is identified:

\[ V_{inj} = PrT/T_w u_\tau \]

Isothermal case
\[ u^+ = 2.5 \ln(y^+) + 5.5 \]
Local scale:
DNS $Re_\tau = 395$ and $T2/T1 = 2$

Mean velocity perpendicular to the wall
Classical nondimensionalization

Injection velocity used in the Van Driest nondimensionalization

Hot
Cold

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Velocity/temperature coupling

- **Mean velocity** perpendicular to the wall = 0 in the isothermal case.

- This velocity is **due to the temperature gradient** that creates a density gradient that generates the mean velocity perpendicular to the wall.

- The **Van Driest nondimensionalization** can be understood as the **taking into account of the mean velocity** perpendicular to the wall created by the temperature gradient.

- This velocity **modifies the turbulence properties**. Because it is negative (from the hot side to the cold one):
  - it pushes back the turbulent structures from the hot side
  - it brings the turbulent structures closer to the cold side
Velocity/temperature coupling: DNS $Re_\tau = 395$ and $T2/T1 = 2$

Root mean square velocity in the spanwise direction

Classical nondimensionalization

Semi local nondimensionalization
Velocity/temperature coupling

- Taking into account the mean variations of fluid properties (semi local nondimensionalization) does not remove the dissymmetry.

- The velocity/temperature coupling is more complex.

- It is the first time that it is shown by DNS in a fully turbulent case (without low Reynolds effect).

- Is the dissymmetry due to the turbulence levels of the hot and cold sides?
Velocity/temperature coupling

- Viscous effect: comparisons of anisothermal profiles with isothermal profiles at equivalent Reynolds number.

- The temperature gradient effect is bigger than the viscous effect.

- Study in the frequency domain.
Turbulent kinetic energy: Study in the frequency domain

- Evolution equation
- Spectral model
Turbulent kinetic energy: Evolution equation

\[
\frac{\partial E_c(k, y)}{\partial t} = \Pi(k, y) + \sum T_n(k, y) + D(k, y)
\]

Production   Transfer   Dissipation

Terms specific to anisothermal case:

\[
\int_{k} -2 \Re \left[ \sum_{i} \left[ \tilde{v}_{i}^* U_{y} \frac{\partial v_{i}'}{\partial y} + \frac{1}{2} \tilde{v}_{i}^* \tilde{v}_{i}' \frac{\partial U_{y}}{\partial y} - \sum_{j} \frac{1}{2} \tilde{v}_{i}^* \left( v_{i}' \frac{\partial u_{j}'}{\partial x_{j}} \right) + \sum_{j} \tilde{v}_{i}^* V_{i} \frac{\partial u_{j}'}{\partial x_{j}} \right] \right] d\bar{k}
\]

Non zero velocity normal to the wall

Non zero velocity divergence

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Turbulent kinetic energy: terms specific to anisoothermal case

Explanation of the turbulent fluctuation levels

Real geometry should avoid this transfer
Simulation results show that, according to the Reynolds number, the temperature gradient and the side of the channel, the slope of the inertial range of turbulent kinetic energy spectra is equal to $-5/3$ or $-7/3$.  

<table>
<thead>
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<th>Probe</th>
<th>$Re_{τm} = 180$</th>
<th>$Re_{τm} = 395$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$T_R = 2$</td>
<td>$T_R = 2$</td>
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<tr>
<td></td>
<td>$T_R = 5$</td>
<td>$T_R = 5$</td>
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<tr>
<td>$S_H$</td>
<td>Slope $k^{-\sigma}$</td>
<td>Slope $k^{-\sigma}$</td>
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<tr>
<td>$S_C$</td>
<td>$\sigma \approx 7/3$</td>
<td>$\sigma \approx 5/3$</td>
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<td>$\sigma \approx 7/3$</td>
<td>$\sigma = 7/3$</td>
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</table>
Turbulent kinetic energy: spectral model

Introduction of a time scale that depends on temperature gradient

- No temperature gradients, \( f \to \infty, \ E \sim k^{-5/3} \)
- Big temperature gradients, \( f \to 0, \ E \sim k^{-7/3} \)

**Kolmogorov model**

\[
E(k) = C_K \varepsilon^{2/3} k^{-5/3} \left(1 + \frac{1}{fkh}\right)^{2/3}
\]

Correction for very anisothermal case
The model finds again the good behaviour.

The best situation corresponds to 5/3 slope at the hot side.
Vortex generators:
Create longitudinal vortices that enhance turbulence and heat transfer
Remove the velocity perpendicular to the wall

Riblets:
Increase surface exchange
Lead vortices
Conclusions

- Development of numerical tools: new algorithm
- Velocity/temperature coupling
  - The temperature gradient modifies the turbulence characteristics
  - A dissymmetry between the hot and cold side appears
  - This dissymmetry is not only due to the mean variation of the fluid properties or to the turbulent intensity
  - A turbulent kinetic energy transfer from the hot side to the cold side exists
  - We propose a model of the inertial zone of the turbulent kinetic energy spectrum

- Acknowledgement:
  - Trio_U, open source developed by CEA
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Development of numerical tools
- Kinetic energy conservation
- Large Eddy Simulation modelling

Velocity/temperature coupling
- Study of the turbulent kinetic energy equation

High temperature solar receiver
- Tests under high solar flux at the Themis power plant
Thank you

Isotherm at 520 K