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# Influence of high temperature gradient on turbulence spectra

LABORATOIRE
PROCÉDÉS, MATÉRIAUX
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PROCESSES,MATERIALS
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LABORATORY

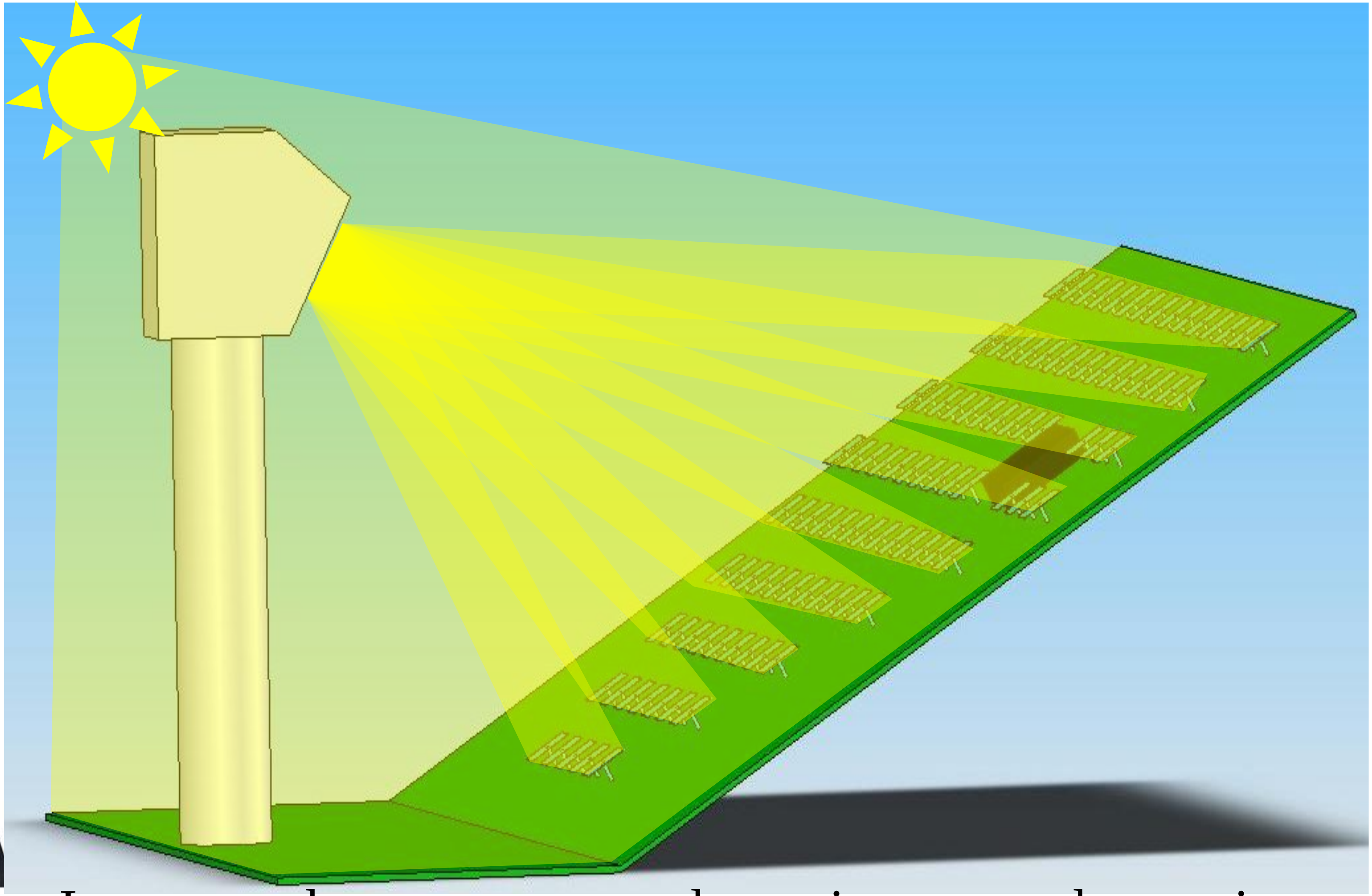
**Adrien Toutant**
Sylvain Serra
Françoise Bataille
Ye Zhou

**Adrien.Toutant@univ-perp.fr**

cnrs
PROMES
UPVD
Université de Perpignan Via Domitia
Lawrence Livermore National Laboratory

# Motivation

Concentrated solar thermal power plant: production of electricity using solar energy.



Improve solar power tower plant = improve solar receiver

# The numerical study

The receivers of concentrated solar thermal power plant have two main characteristics:

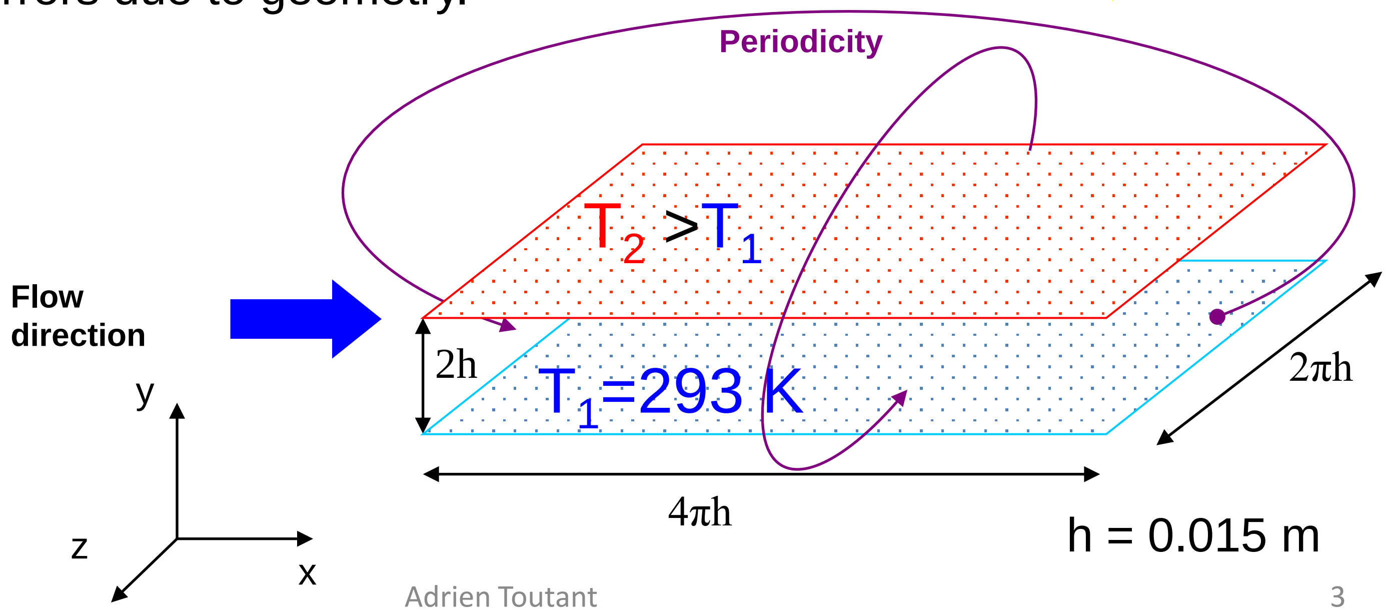
- **Asymmetric heating**,
- **Turbulent flow**.

Study of the **coupling** between a high **temperature gradient** and the **turbulence**.

Choice of an academic geometry in order to:

- Compare with the literature,
- Reduce the computation time,
- Avoid errors due to geometry.





# Studies of the literature

Turbulence intensity →

Thermal gradient ↓

| $T_2/T_1$ \ Reτ | 180 (Rec = 3300) | 395 (Rec = 6400) |
|---|---|---|
| 1 | **Kim, Moin & Moser (1987)** | • **Moser, Kim & Mansour (1999)**<br>• **Kawamura (1999,2000)** |
| 1.01 | • **Debusschere (2004)**<br>• **Nicoud (1998)** | LES realized |
| 2 | **Nicoud (1998)**<br>LES realized | DNS and LES realized |
| 5 | LES realized | LES realized |

Reτ : Reynolds number based on the wall friction velocity

Rec : Reynolds number based on the centre velocity

**Literature** data (validation of the simulations)

LES: large eddy simulation
DNS: direct numerical simulation

# Objectives

- **Illustrations of the complex coupling between turbulence and temperature gradient.**

- **Improvement of the understanding of the turbulence/temperature gradient interaction mechanisms.**

## <u>Outline</u>

1. The numerical tool
2. Effects of the temperature gradient
3. “Temperature gradient" time scale
4. Extended inertial range energy spectra model

# 1. The numerical tool

**Solved equations**:

- Approximation of **low Mach number** for an **ideal gas**
- Allow to take into account the **dilatational effect due to temperature without solving acoustic**.

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \left(\overline{\rho}\widetilde{U_j}\right)}{\partial x_j} = 0$$

$$\frac{\partial \overline{\rho}\tilde{U}_i}{\partial t} + \frac{\partial(\overline{\rho}\tilde{U}_i\tilde{U}_j)}{\partial x_j} = -\frac{\partial \overline{P'}}{\partial x_i} + \frac{1}{Re}\left[\frac{\partial}{\partial x_j}\left[\overline{\mu}\left(\frac{\partial \tilde{U}_i}{\partial x_j} + \frac{\partial \tilde{U}_j}{\partial x_i}\right)\right] - \frac{2}{3}\frac{\partial}{\partial x_i}\left(\overline{\mu}\frac{\partial \tilde{U}_j}{\partial x_j}\right) - \frac{\partial \overline{\rho}\tau_{ij}}{\partial x_j}\right]$$

$$Cp\left(\frac{\partial(\overline{\rho}\tilde{T})}{\partial t} + \frac{\partial(\overline{\rho}\tilde{U}_j\tilde{T})}{\partial x_j}\right) = \frac{\gamma - 1}{\gamma}\frac{\partial \overline{P_{thermo}}}{\partial t} + \frac{1}{RePr}\left[\frac{\partial}{\partial x_j}\left(\overline{\lambda}\frac{\partial \tilde{T}}{\partial x_j}\right) - \frac{\partial \overline{\rho} Cp \Im_j}{\partial x_j}\right]$$

$$\overline{P_{thermo}} = R\overline{\rho}\tilde{T}$$

$$\frac{\partial \overline{P_{thermo}}}{\partial x_i} = 0$$

Fluid properties in function of the temperature (Sutherland laws)

$$\mu(T) = 1.461.10^{-6}\frac{T^{1.5}}{T + 111}$$

$$\lambda(T) = \frac{\mu Cp}{Pr} = \frac{1.468.10^{-3}}{Pr}\frac{T^{1.5}}{T + 111}$$

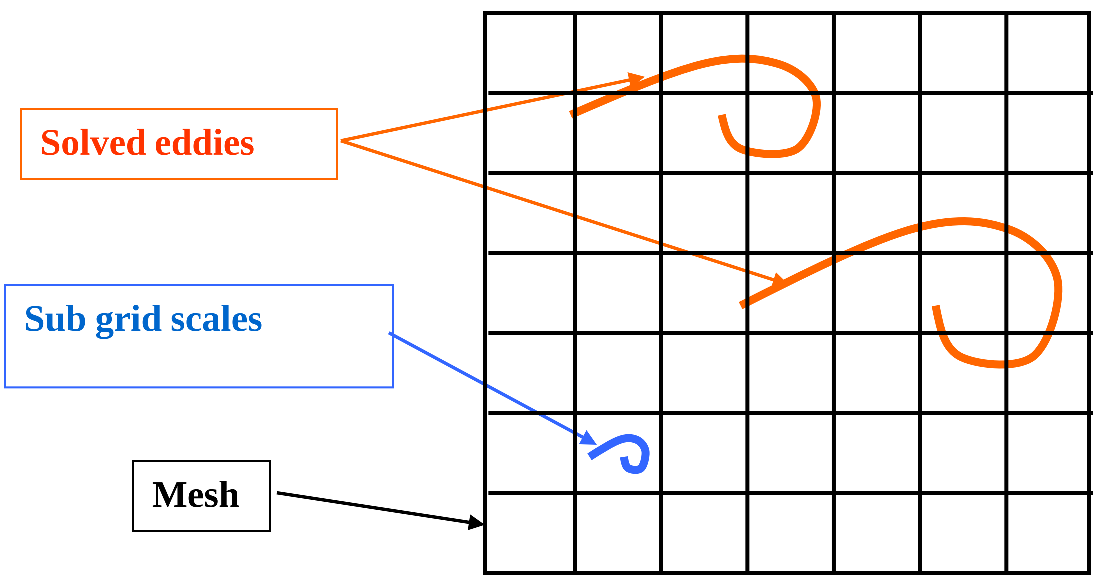
# 1. The numerical tool

## <u>Solved equations</u>: Large Eddy Simulation

$\overline{\phantom{x}}$ is the volume average

$\tilde{U}_i = \dfrac{\overline{\rho U_i}}{\overline{\rho}}$ is the Favre average

- Momentum equation: WALE model
- Energy equation: dynamic subgrid scale Prandtl number



# 1. The numerical tool

**CFD software** ***Trio_U*** developed by CEA-Grenoble (CEA: French Atomic Agency)

***Trio_U***: object oriented programming (**C++**)
adapted to massively **parallel computation**

Staggered grid discretization (pressure at the center of cells, pressure gradient and momentum at the faces of the cells).

Time integration: third order Runge-Kutta scheme

Convection scheme:

- second order centered scheme for velocity
- third order quick scheme for temperature

Non uniform mesh in the normal direction
At the wall, $\Delta y^{+} < 1$

# 1. The numerical tool

2 Reynolds numbers:
180 and 395

3 temperature ratios:
1, 2 and 5

Very different
Reynolds numbers
at the hot and cold walls

| Name | $T_H$ / $T_R = \frac{T_H}{T_C}$ / $T_C$ | $Re_{\tau H}$ / $Re_{\tau m}$ / $Re_{\tau C}$ | $U_{\tau H}$ / $U_{\tau C}$ | $\rho_H$ / $\rho_C$ | $\mu_H$ / $\mu_C$ | $\lambda_H$ / $\lambda_C$ |
|---|---|---|---|---|---|---|
| | | $Re_{\tau m} = 180$ | | | | |
| | 293 | 180 | $0,183$ | $1,19$ | $1,81e^{-5}$ | $\emptyset$ |
| 180-1 | 1 | 180 | | | | |
| | 293 | 180 | $0,183$ | $1,19$ | $1,81e^{-5}$ | $\emptyset$ |
| | 586 | 106 | $0,355$ | $0,595$ | $2,97e^{-5}$ | $0,0393$ |
| 180-2 | 2 | 184 | | | | |
| | 293 | 262 | $0,268$ | $1,19$ | $1,81e^{-5}$ | $0.0240$ |
| | 1465 | 44 | $0,644$ | $0,238$ | $5,2e^{-5}$ | $0,0687$ |
| 180-5 | 5 | 178 | | | | |
| | 293 | 312 | $0,319$ | $1,19$ | $1,81e^{-5}$ | $0,0240$ |
| | | $Re_{\tau m} = 395$ | | | | |
| | 293 | 392 | $0,400$ | $1,19$ | $1,81e^{-5}$ | $\emptyset$ |
| 395-1 | 1 | 393 | | | | |
| | 293 | 393 | $0,400$ | $1,19$ | $1,81e^{-5}$ | $\emptyset$ |
| | 586 | 241 | $0,809$ | $0,595$ | $2,97e^{-5}$ | $0,0421$ |
| 395-2 | 2 | 396 | | | | |
| | 293 | 551 | $0,563$ | $1,19$ | $1,81e^{-5}$ | $0,0257$ |
| | 1465 | 101 | $1,472$ | $0,238$ | $5,2e^{-5}$ | $0,0736$ |
| 395-5 | 5 | 390 | | | | |
| | 293 | 680 | $0,695$ | $1,19$ | $1,81e^{-5}$ | $0,0257$ |

# 2. Effects of the temperature gradient

Objective: characterization of the coupling between the turbulence and the temperature gradient

Statistics: average in time and space along the homogeneous directions (x and z)
=> profile along y (the direction normal to the walls)

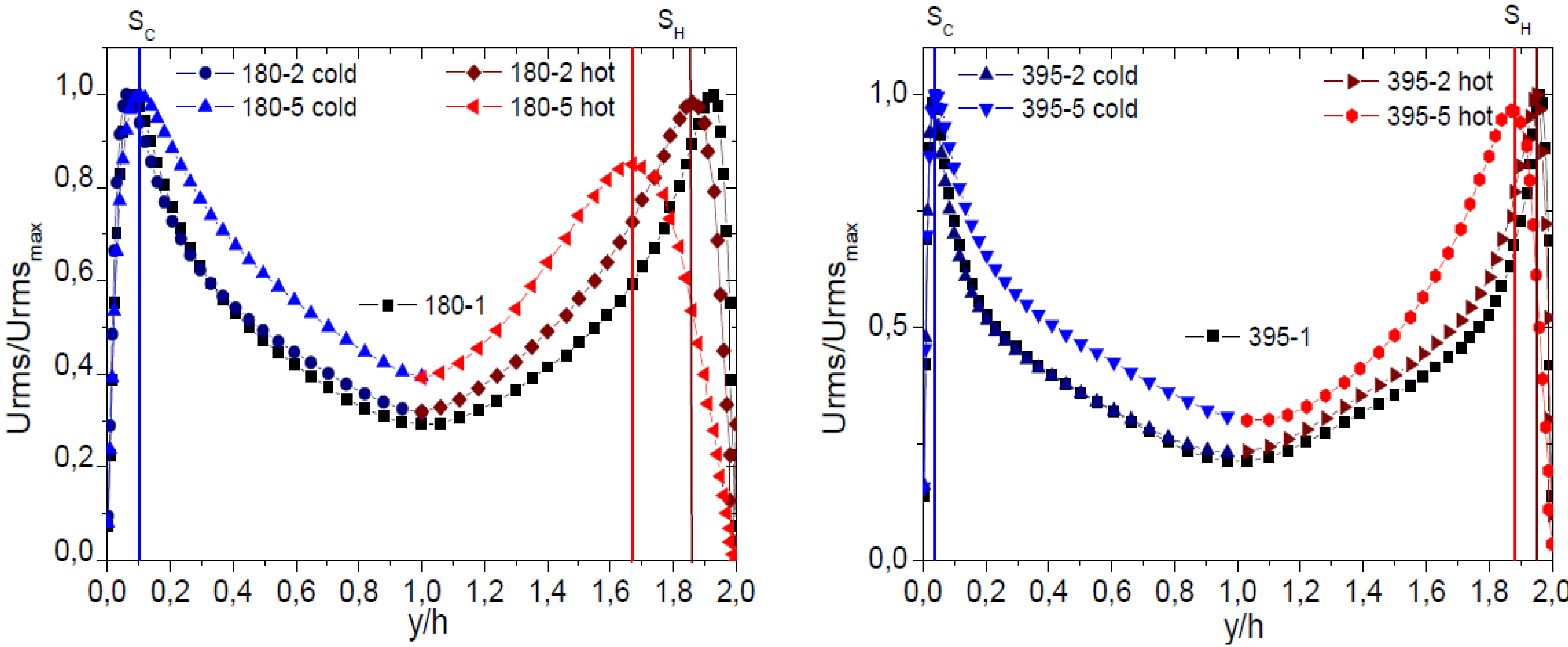
Comparison of the non-dimensionalized profiles obtained at the hot and cold sides.

Fluctuation profiles for velocity.

Localization of the fluctuation maximum.

Study of the kinetic energy spectra at this location.

# 2. Effects of the temperature gradient



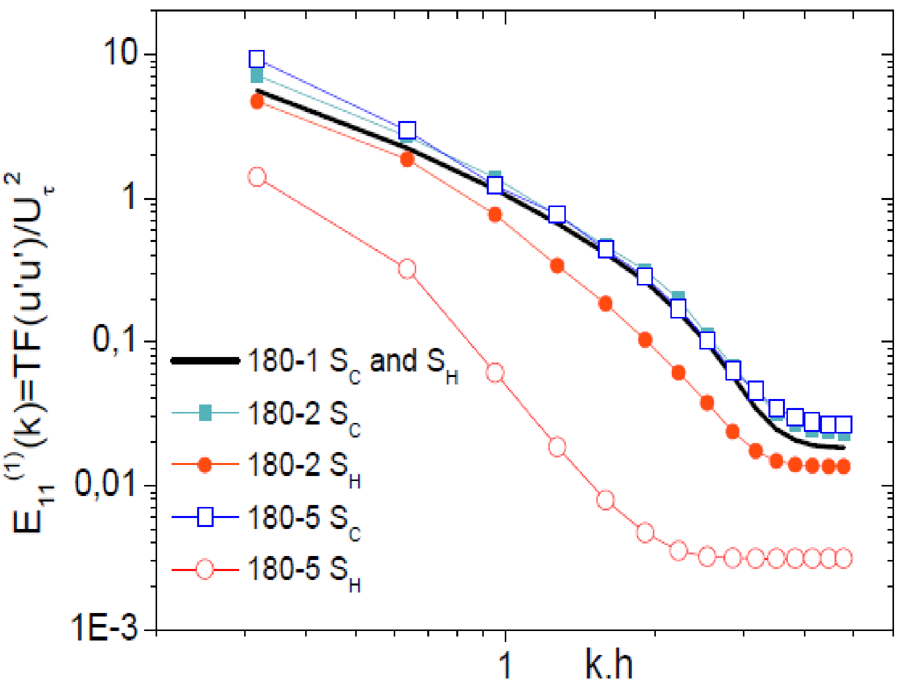

(a) $Re_{\tau m} = 180.$ (b) $Re_{\tau m} = 395.$

The profiles become asymmetric with temperature ratio.

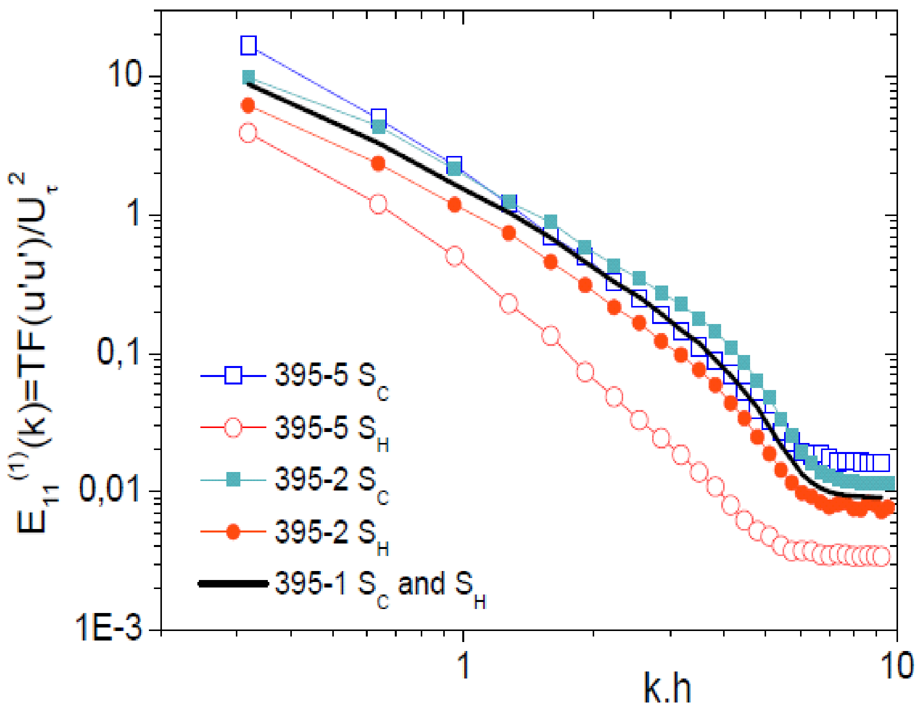
Fluctuations increase at the cold side and decrease at the hot side.

It is not a pure vicous effect (not shown here).

# 2. Effects of the temperature gradient




(a) $Re_{\tau m} = 180.$




(b) $Re_{\tau m} = 395.$

The profiles become asymmetric with temperature ratio.
Fluctuations increase at the cold side and decrease at the hot side.

# 2. Effects of the temperature gradient

Temperature ratio of 1:
Kolmogorov slope 5/3

Temperature ratios of 2 and 5:

| | $Re_{\tau m} = 180$ | | $Re_{\tau m} = 395$ | |
|---|---|---|---|---|
| | $T_R = 2$ | $T_R = 5$ | $T_R = 2$ | $T_R = 5$ |
| Probe | Slope $k^{-\sigma}$ | Slope $k^{-\sigma}$ | Slope $k^{-\sigma}$ | Slope $k^{-\sigma}$ |
| $S_H$ | N/A | N/A | $\sigma \approx 7/3$ | N/A |
| $S_C$ | $\sigma \approx 7/3$ | $\sigma \approx 7/3$ | $\sigma \approx 5/3$ | $\sigma = 7/3$ |

The slope evolves with the temperature gradient

# 3. "Temperature gradients" time scale

Considering the energy balance, the dissipation is

$$\epsilon = C\tau_3(k)E^2(k)k^4$$

$\tau_3$ the time scale for the decay of the triple correlation

The eddy turn-over or the non-linear time scale is

$$\tau_{NL}(k) = \left(k^{3/2}E^{1/2}(k)\right)^{-1}$$

$$\Rightarrow \quad \epsilon = C\tau_3(k)\tau_{NL}^{-1}(k)E^{3/2}(k)k^{5/2}$$

In the classical case,

$$\tau_3(k) = \tau_{NL}(k)$$

$$\Rightarrow \quad E(k) = C_K\epsilon^{2/3}k^{-5/3}$$

Kolmogorov spectrum

# 3. “Temperature gradients” time scale

In our case, life time of triple decorelations depends on

- non linear triadic interactions,
- external agency here the temperature gradients.

Simple choice
$$\frac{1}{\tau_3(k)} = \frac{1}{\tau_{NL}(k)} + \frac{1}{\tau_{\Delta T}(k)}$$

$$\tau_3(k)\tau_{NL}^{-1}(k) = \frac{1}{1 + \frac{\tau_{NL}(k)}{\tau_{\Delta T}(k)}}$$

Assuming temperature gradient applies to largest length scales, we assume $\tau_{\Delta T}(k) = \tau_{NL}(k) f k h$

$f$ is a function.
Its parameters have to be determined according to LES results.

If $f \rightarrow 0$, $\tau_{\Delta T}$ is the dominant time scale.
If $f \rightarrow \infty$, $\tau_{NL}$ is the dominant time scale.

# 3. "Temperature gradients" time scale

According to simulation results, $f$ should depend on the following parameters:

$$f = f(Re_{\tau L}, Re_{\tau H}, Re_{\tau m}, T_R)$$

$Re_{\tau L}$ : local turbulent Reynolds number

$Re_{\tau H}$ : turbulent Reynolds number of the hot side

$Re_{\tau m}$ : mean turbulent Reynolds number

$T_R$ : temperature ratio

and should have the following behaviours:

1. $T_R \to 1$ implies $f \to \infty$, $\quad f \cong \dfrac{1}{T_R^{\alpha} - 1}$ OK
2. $Re_{\tau H} \to 0$ implies $f \to 0$,
   $$f \cong tanh\left(\beta\left(Re_{\tau H} - Re_{\tau c}\right)\right) + 1$$ OK
3. $Re_{\tau H} << Re_{\tau C}$ implies $f \to 0$ hot side and
   $f \to \infty$ cold side
   $$f \cong \left(\frac{Re_{\tau L}}{Re_{\tau m}}\right)^{\gamma}$$ OK

# 3. "Temperature gradients" time scale

Finally, we assume that

$$f(Re_{\tau L}, Re_{\tau H}, Re_{\tau m}, T_R) =$$

$$C_1 \frac{1}{T_R^{\alpha} - 1} \left(tanh\left(\beta\left(Re_{\tau H} - Re_{\tau c}\right)\right) + 1\right) \left(\frac{Re_{\tau L}}{Re_{\tau m}}\right)^{\gamma}$$

$$\Rightarrow \quad \epsilon = C \frac{1}{1 + \frac{1}{fkh}} k^{5/2} E^{3/2}(k)$$

$$\Rightarrow \quad \boxed{E(k) = C_K \epsilon \, k^{-5/3} \left(1 + \frac{1}{fkh}\right)^{2/3}}$$

No temperature gradients, $f \to \infty$, $\tau_3 \to \tau_{NL}$ $\quad E \sim k^{-5/3}$

Big temperature gradients, $f \to 0$, $\tau_3 \to \tau_{\Delta T}$ $\quad E \sim k^{-7/3}$

# 4. Extended inertial energy spectra

$$f(Re_{\tau L}, Re_{\tau H}, Re_{\tau m}, T_R) = C_1 \frac{1}{T_R^{\alpha} - 1} \left(tanh\left(\beta\left(Re_{\tau H} - Re_{\tau c}\right)\right) + 1\right) \left(\frac{Re_{\tau L}}{Re_{\tau m}}\right)^{\gamma}$$

$$E(k) = C_K \epsilon\, k^{-5/3} \left(1 + \frac{1}{fkh}\right)^{2/3}$$

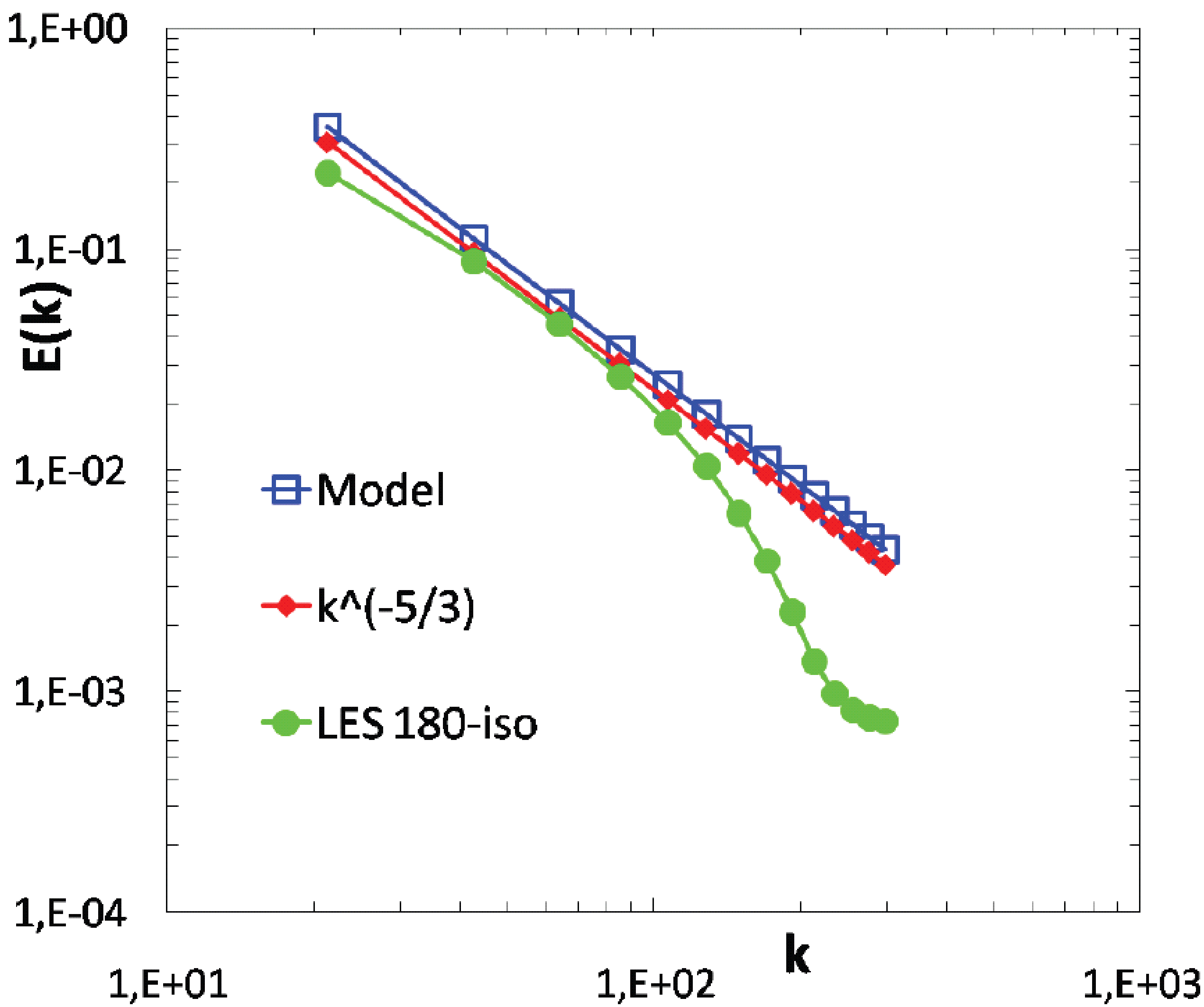
Fit with LES results

| $\alpha$ | $\beta$ | $\gamma$ | $Re_{\tau c}$ | $C_1$ |
|---|---|---|---|---|
| 2 | 1 | 10 | 135 | 2 |

# 4. Extended inertial energy spectra

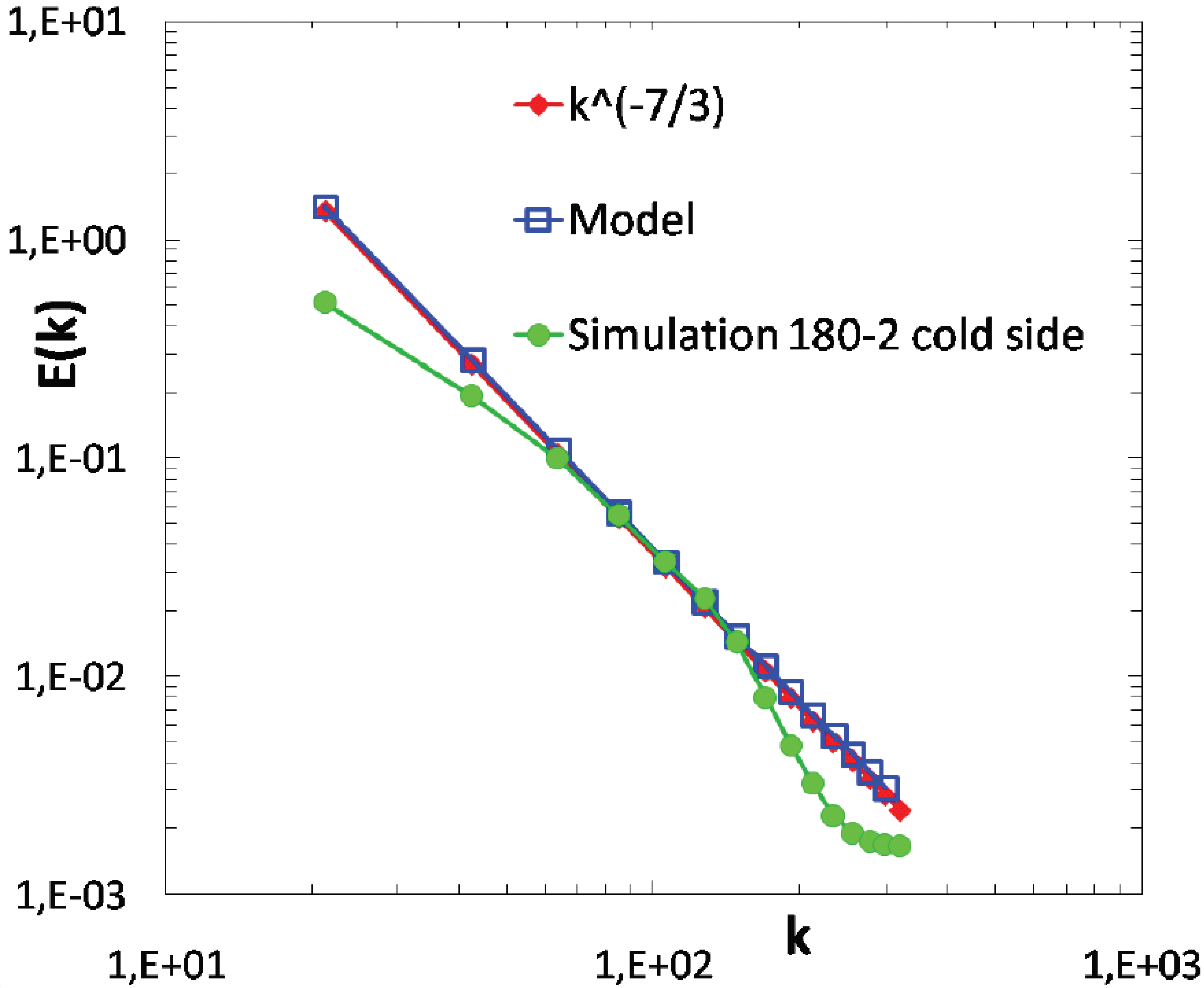
$Re_{\tau m} = 180$

Isothermal



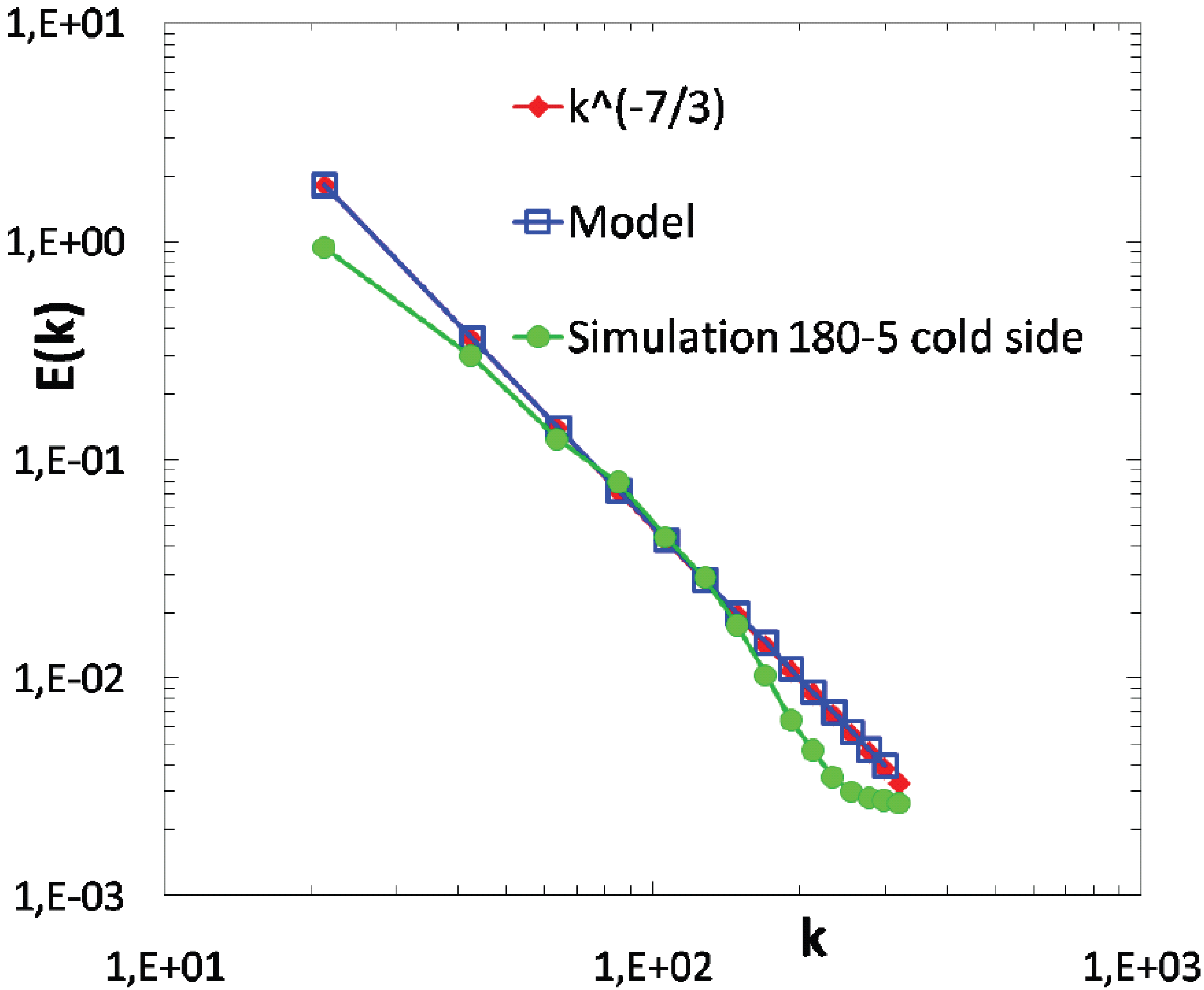
# 4. Extended inertial energy spectra

$$Re_{\tau m} = 180$$
$$T_R = 2$$



# 4. Extended inertial energy spectra

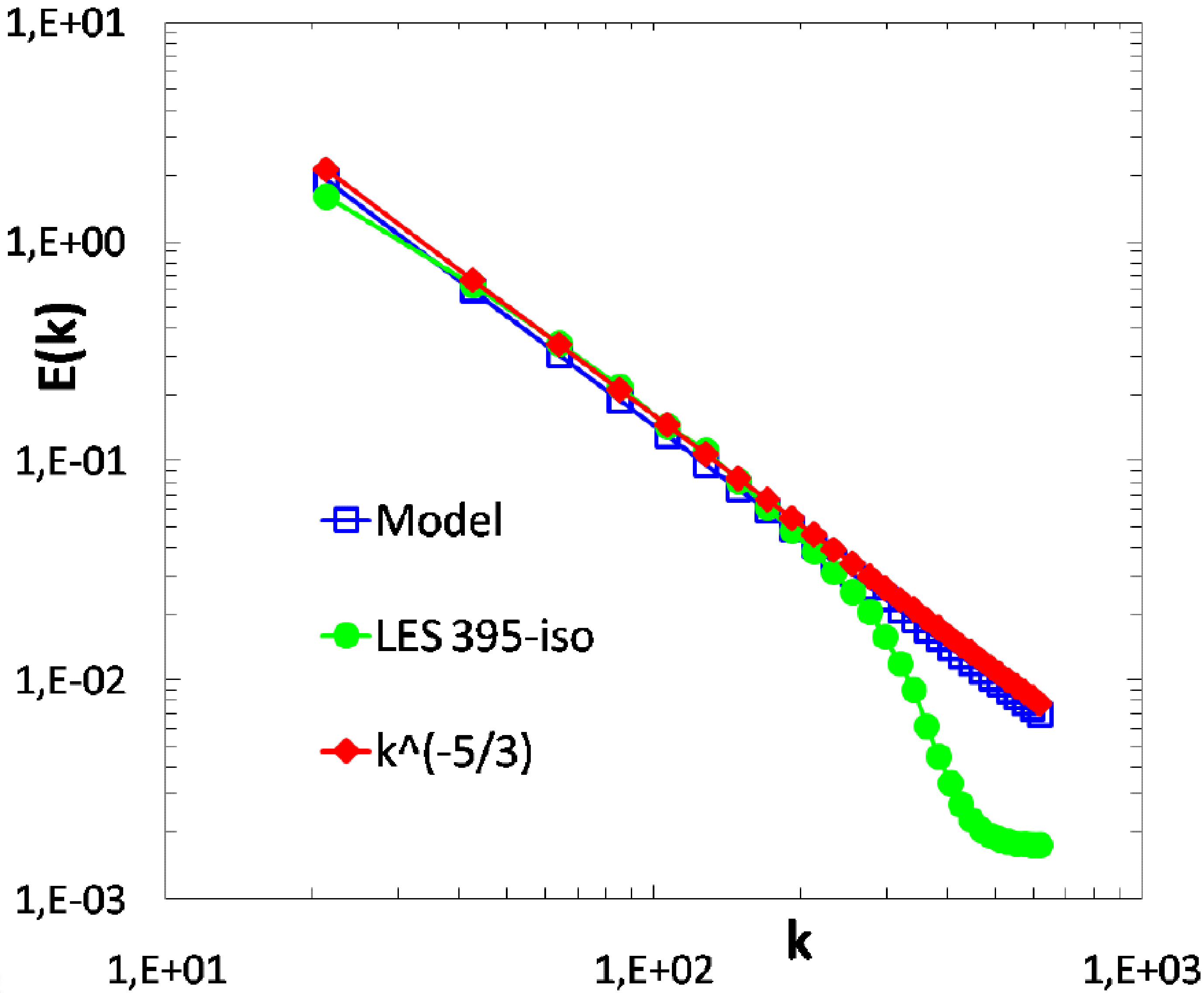
$$Re_{\tau m} = 180$$
$$T_R = 5$$



# 4. Extended inertial energy spectra

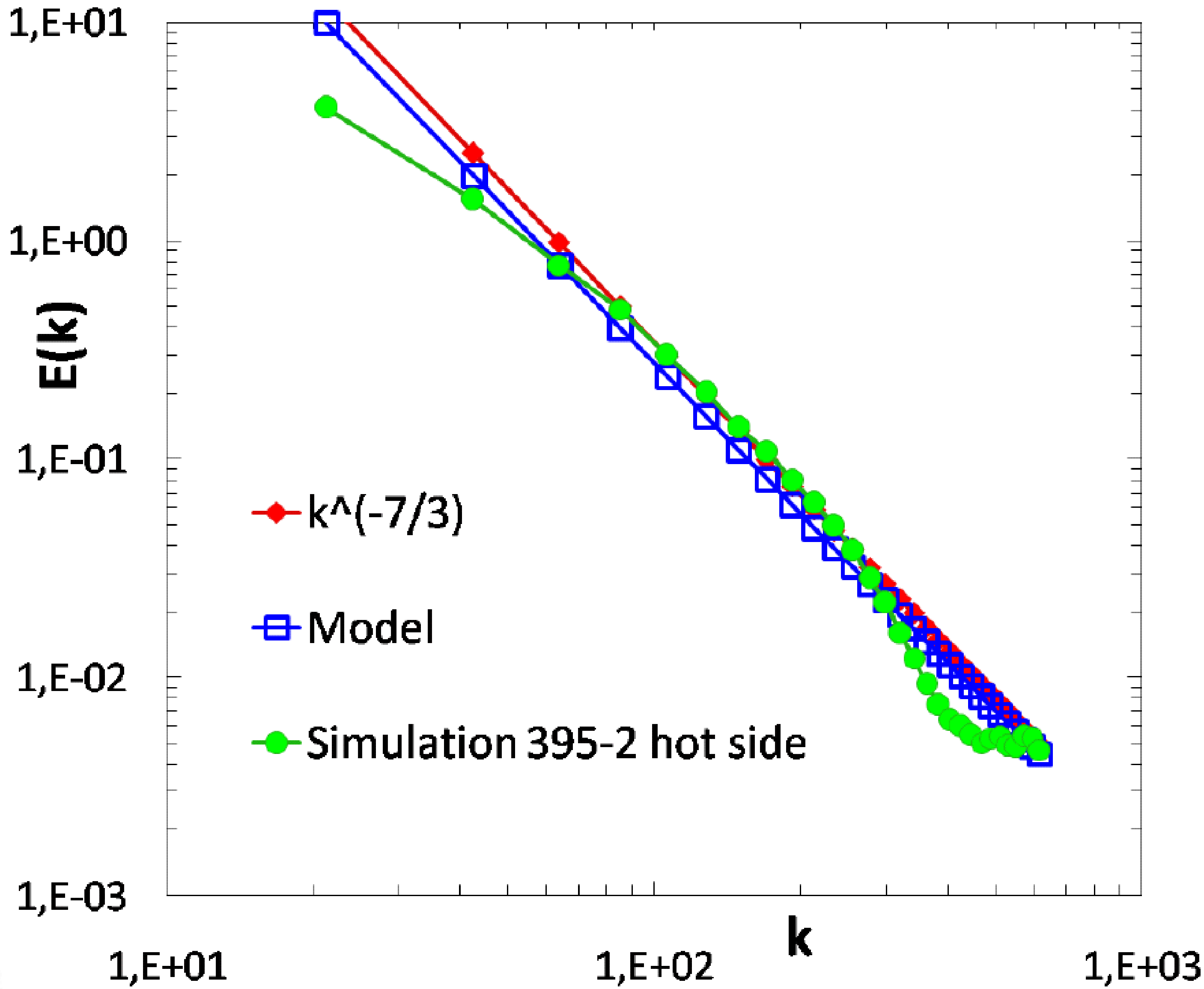
$Re_{\tau m} = 395$

Isothermal



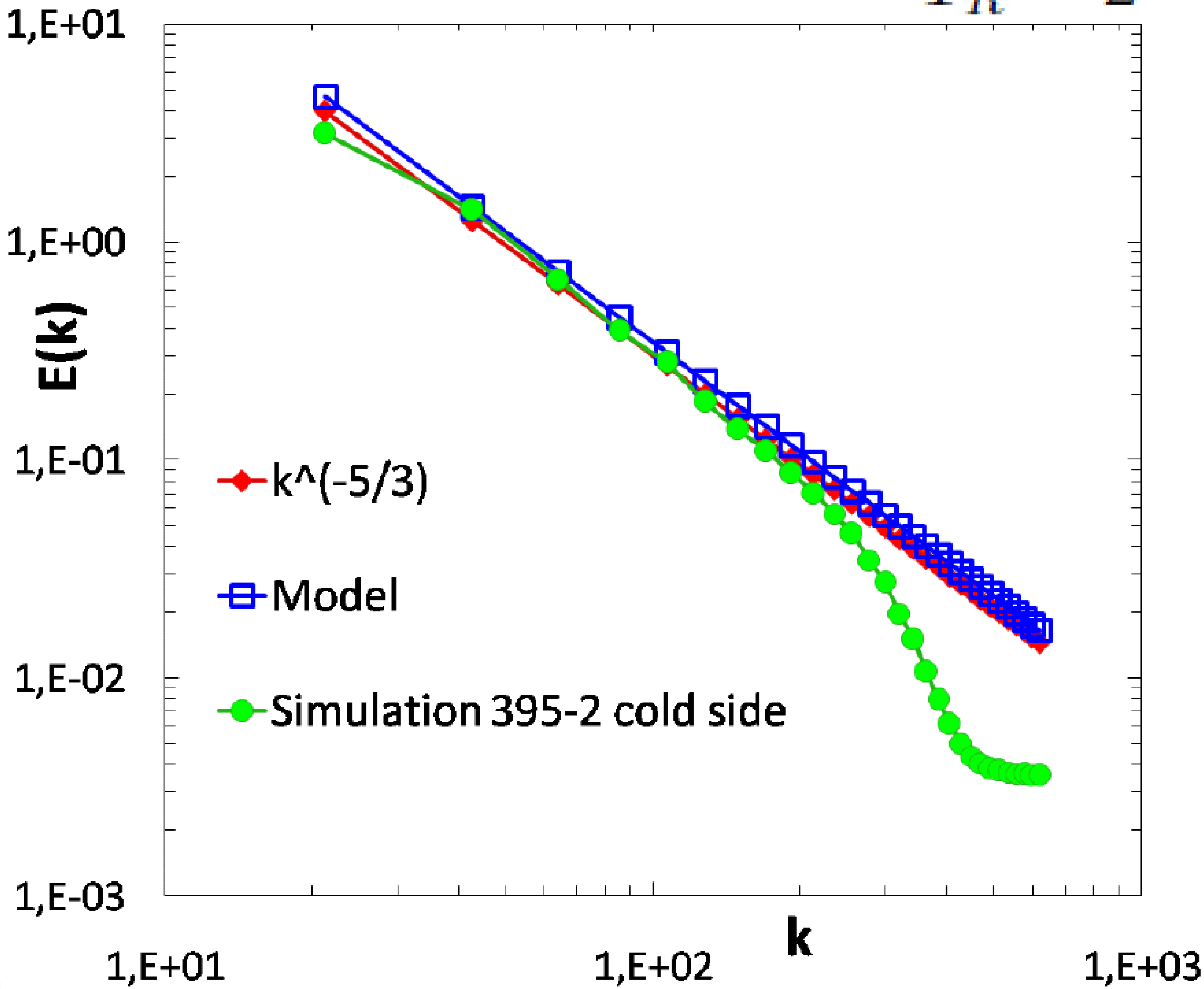
# 4. Extended inertial energy spectra

$$Re_{\tau m} = 395$$
$$T_R = 2$$



# 4. Extended inertial energy spectra

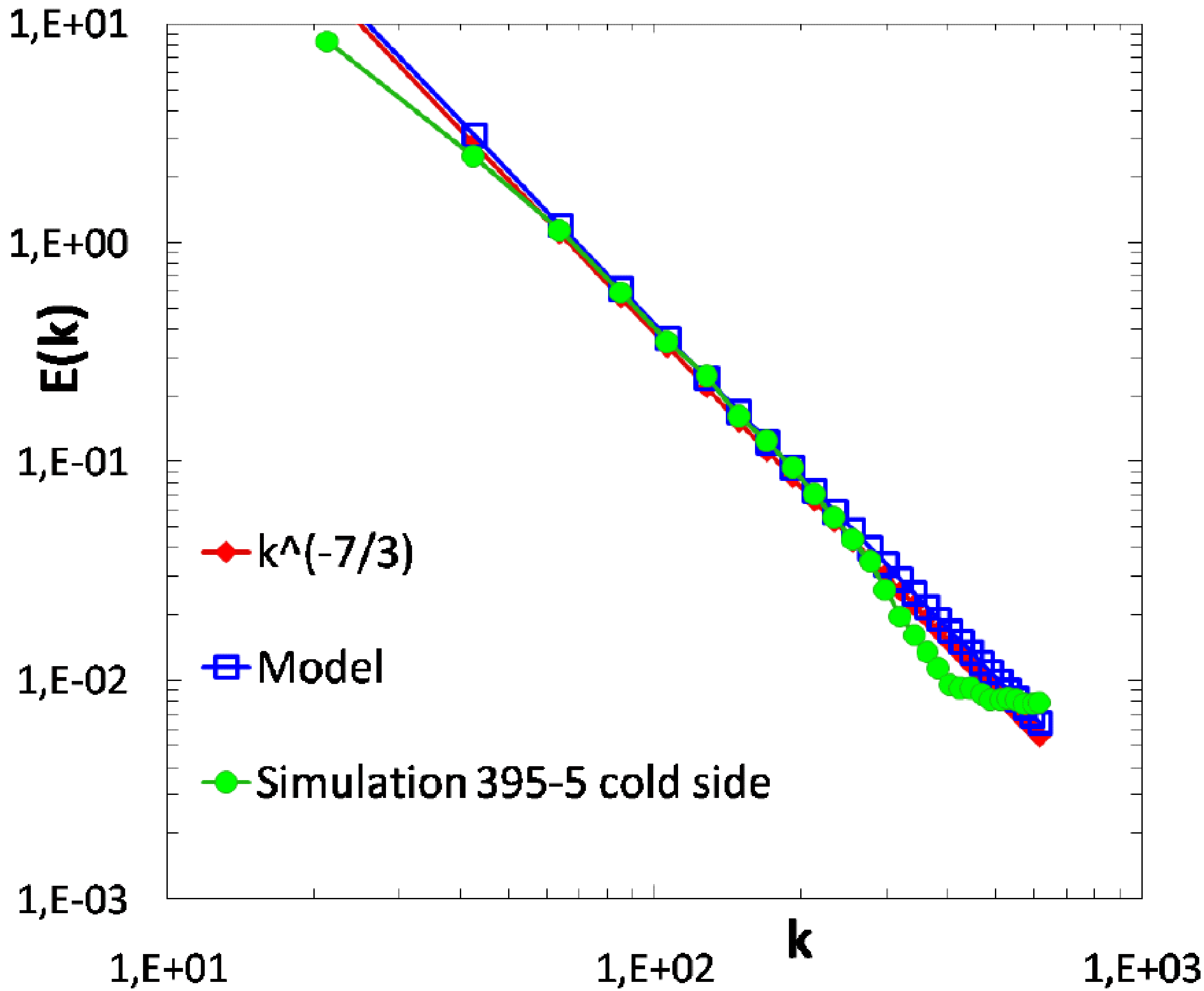
$$Re_{\tau m} = 395$$
$$T_R = 2$$



# 4. Extended inertial energy spectra

$Re_{\tau m} = 395$

$T_R = 5$



# Conclusions and outlook

**Conclusions:**

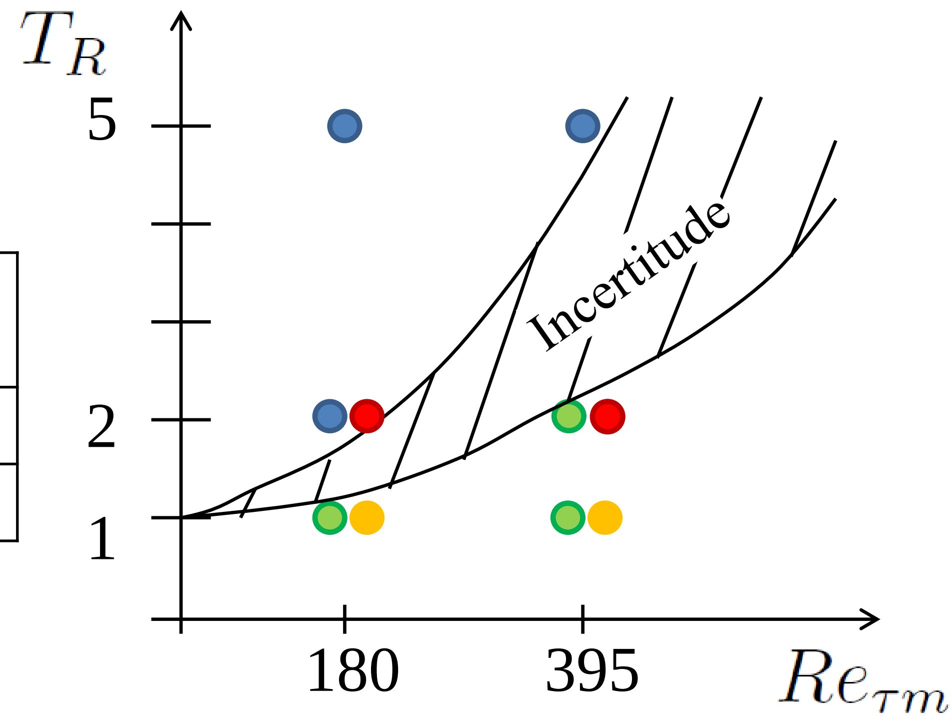
1. Effect of temperature gradient
2. Determination of a new temperature gradient time scale
3. Development of generalized inertial range energy spectrum
4. Validation of the behavior compared with LES results:
   - 5/3 slope
   - 7/3 slope

# Conclusions and outlook

**Outlook:**

1. Add points

| Slope / Side | -5/3 | -7/3 |
|---|---|---|
| Cold | | |
| Hot | | |




2. Increase the precision of the simulations (DNS)
3. Improve the generalized inertial range energy spectrum (more coupling? New parameter values?)
4. Realize spectral studies

**Acknowledgments**:

CINES for the calculation resources,

CEA –Grenoble for the Trio_U software.

## General conclusion:

- very important to study the coupling between turbulence and heat transfers,
- understand the interactions
- model theses interactions