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Modeling of turbulent heat transfer in liquid metals and molten salts

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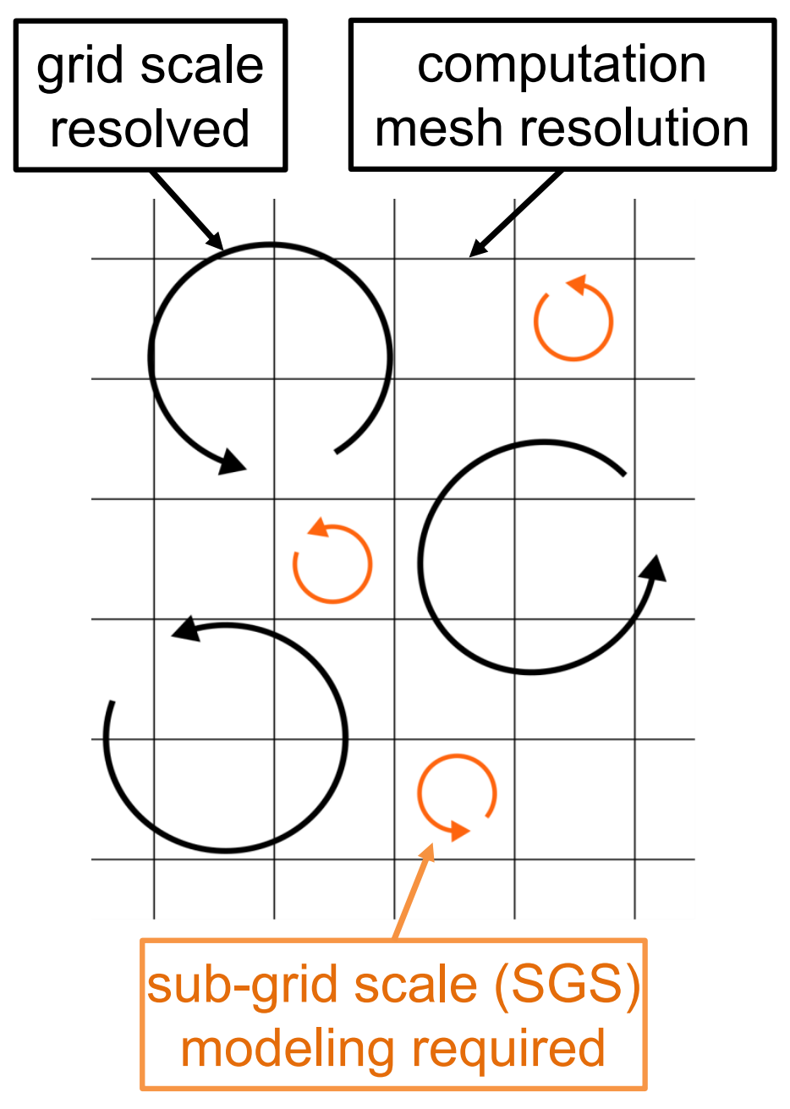
Introduction

Background:

- In Generation IV reactor concepts such as the Lead-Cooled Fast Reactor or the Molten Salt Reactor, liquid metals (e.g. Pb) or molten salts (e.g. LiF-BeF$_2$) are utilized as coolants

Motivation:

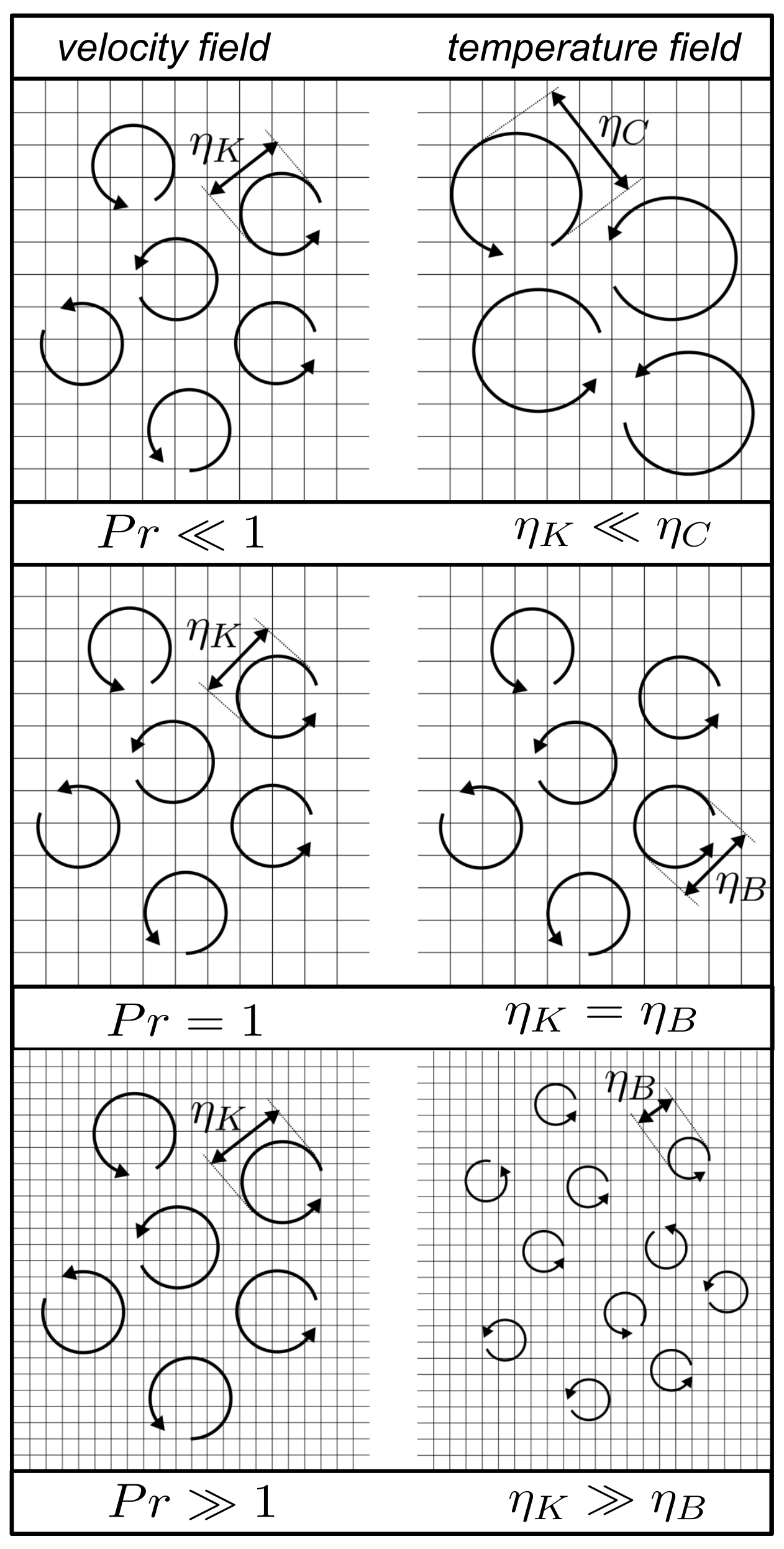
- The computational effort $\left(\sim L_x^2 L_y Re_\tau^4 Pr^{3/4}\right)$ for the calculation of the entire cooling circuit with turbulence-resolving direct numerical simulations (DNS) is prohibitively high
- Large eddy simulation (LES) resolves only large turbulent structures, while small turbulent structures are modeled



- Common modeling approaches for the SGS heat flux are based on the Reynolds analogy
- The Reynolds analogy uses the similarity between the velocity and temperature fields for $Pr = 1$ to approximate the SGS heat flux via the turbulent momentum transport
- For coolants where $Pr \neq 1\,(\delta_m \neq \delta_t)$, the Reynolds analogy is no longer valid, therefore alternative modeling approaches are required

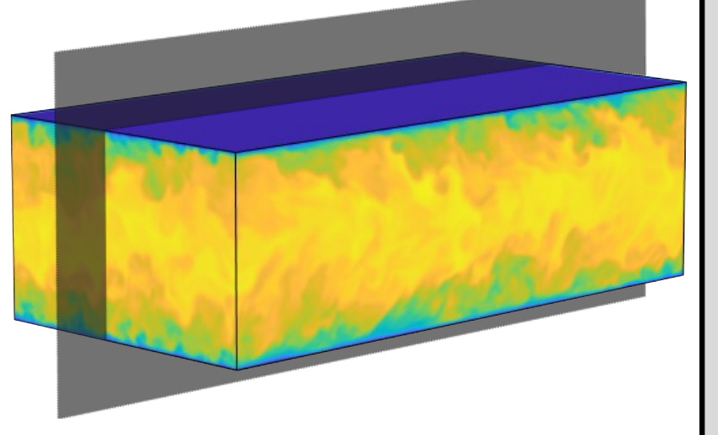
	liquid metal: *Pb*	**molten salt: *LiF-BeF$_2$***
Prandtl number	0.02 (at $450°C, 1\,bar$)	13 (at $700°C, 1\,bar$)

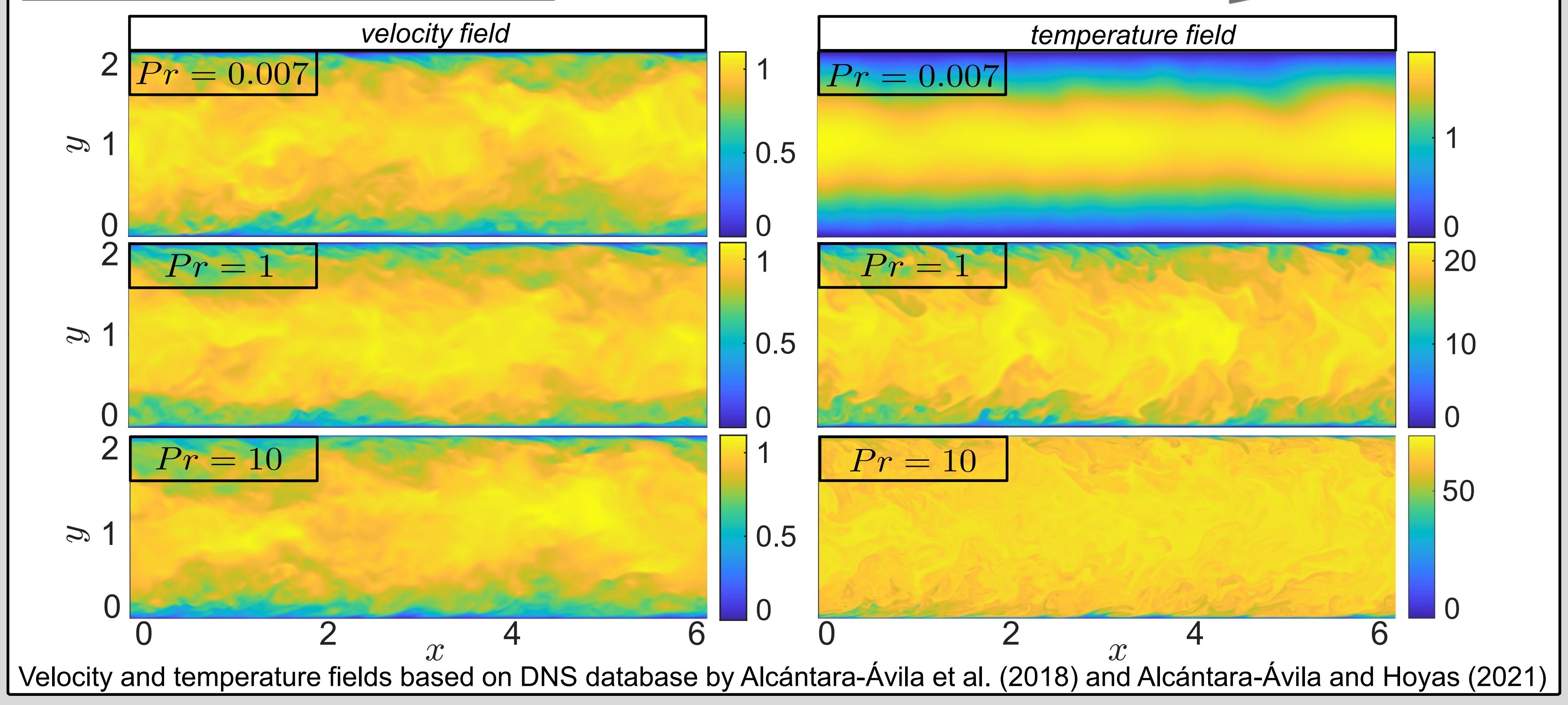
Turbulent scales for varying Prandtl numbers



- The Prandtl number describes the ratio between the momentum diffusivity and the thermal diffusivity
- $Pr = 1$: Temperature fluctuations extend to scales as small as the smallest turbulent length scales of the velocity field
- $Pr \neq 1$: A separation occurs between the smallest turbulent length scales of the temperature and velocity fields
- $Pr > 1$: Temperature fluctuations reach smaller scales than the smallest turbulent length scales of the velocity field
- The size of the smallest turbulent length scales is decisive for the required mesh resolution

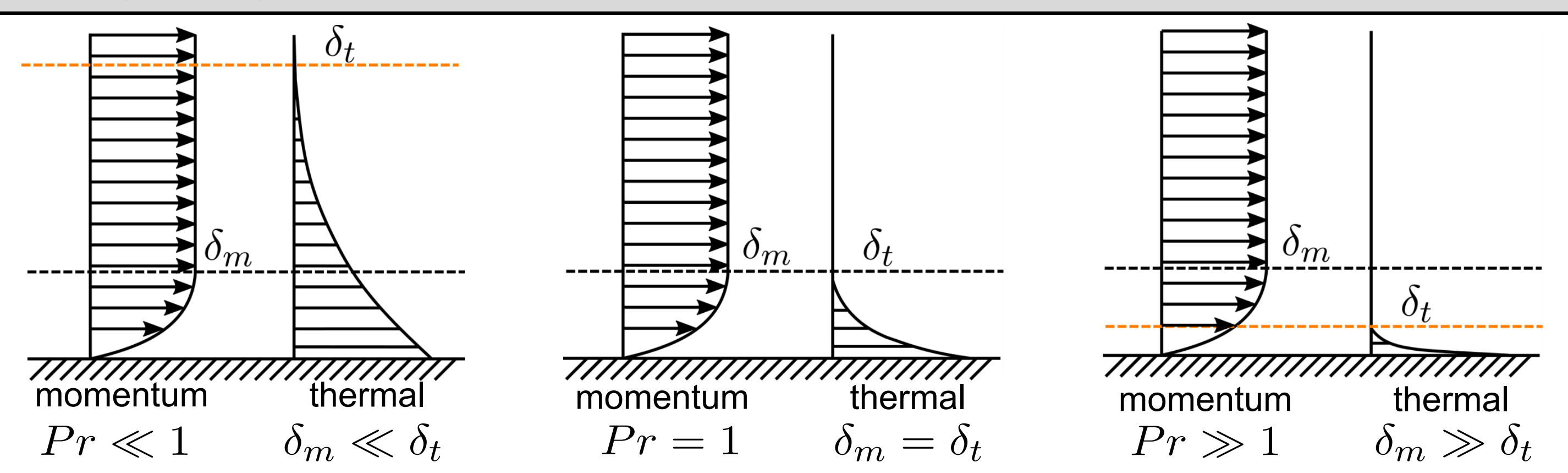
$$\boxed{Pr = \frac{\nu}{a}} \quad \boxed{\frac{\eta_C}{\eta_K} = Pr^{-\frac{3}{4}}} \quad \boxed{\frac{\eta_B}{\eta_K} = Pr^{-\frac{1}{2}}}$$



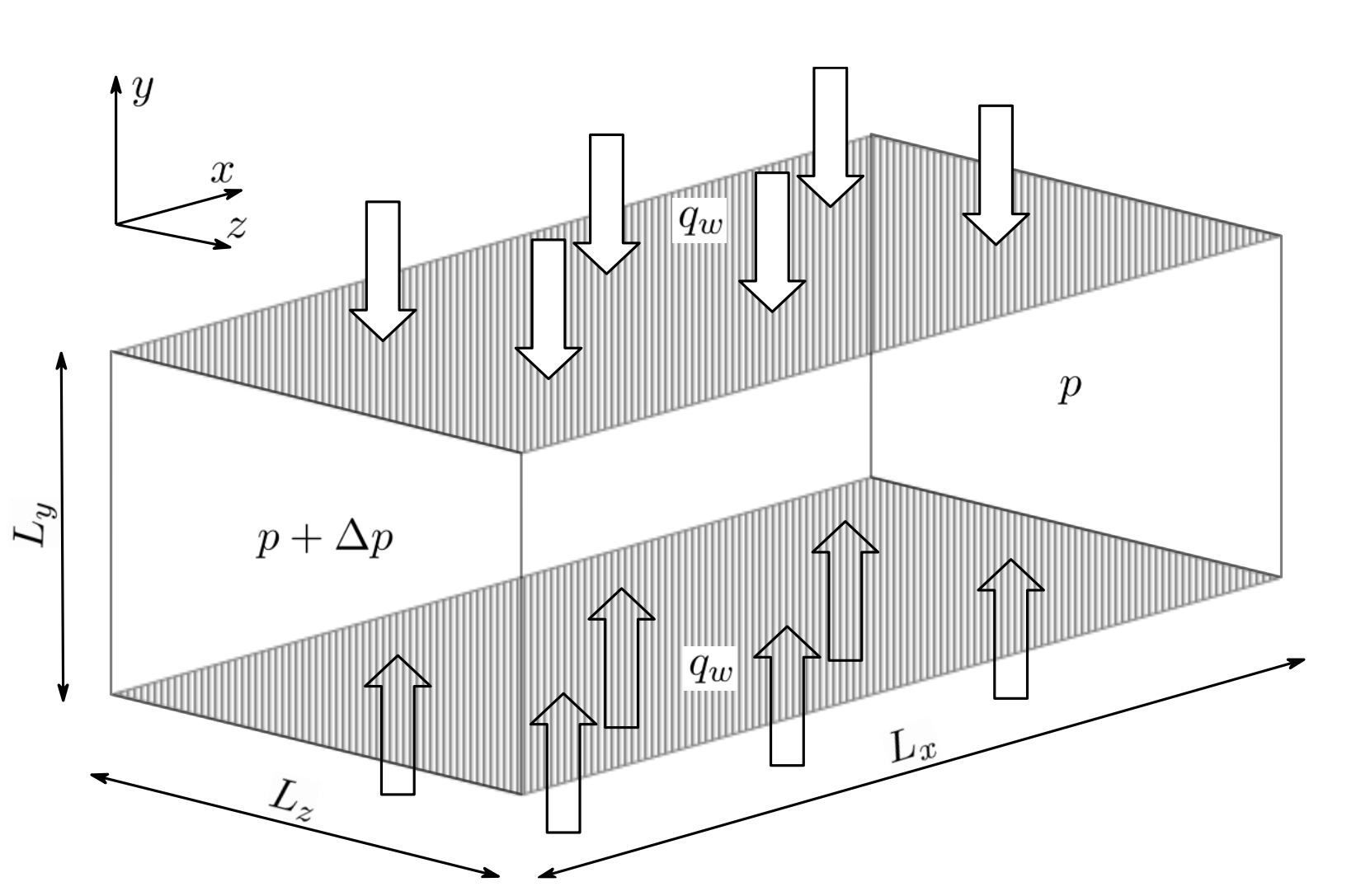


Velocity and temperature fields based on DNS database by Alcántara-Ávila et al. (2018) and Alcántara-Ávila and Hoyas (2021)

Boundary layer



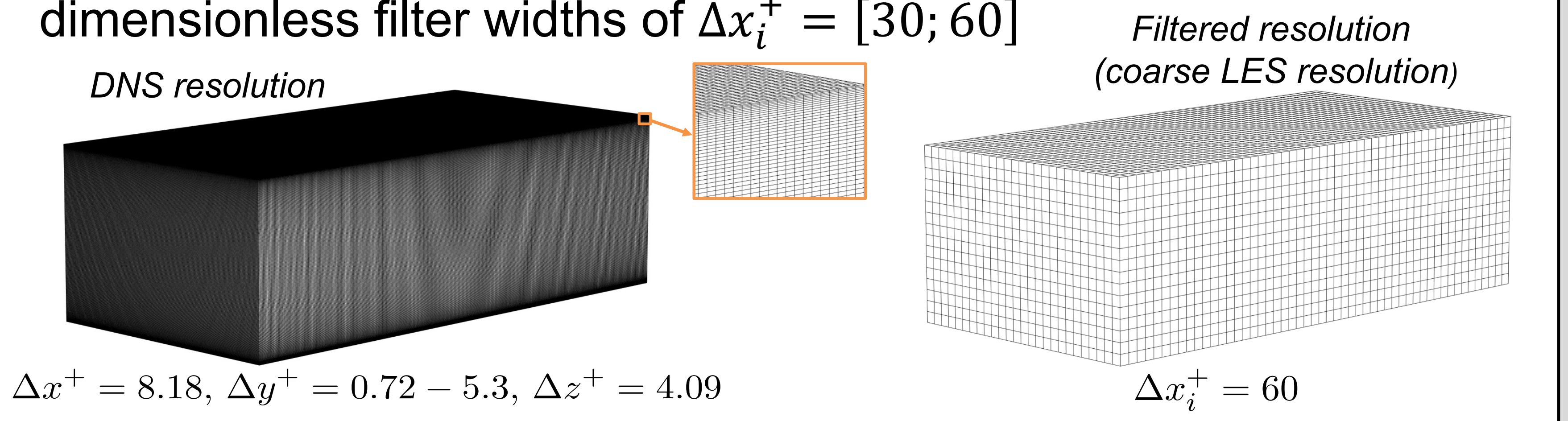
Methodology: a-priori analysis



Computational Setup:

- Rectangular thermal channel flow
- Channel size of $2\pi H \times 2H \times \pi H$
- Periodic in x- and z-directions
- Flow controlled by a constant pressure gradient, considered as incompressible, and subjected to a uniform wall heat flux

- Determination of the SGS heat flux by explicit filtering of DNS data
- DNS database by Alcántara-Ávila et al. (2018) and Alcántara-Ávila and Hoyas (2021) for various Prandtl numbers
- Diffusion-based filter method similar to a Gaussian filter with the dimensionless filter widths of $\Delta x_i^+ = [30; 60]$

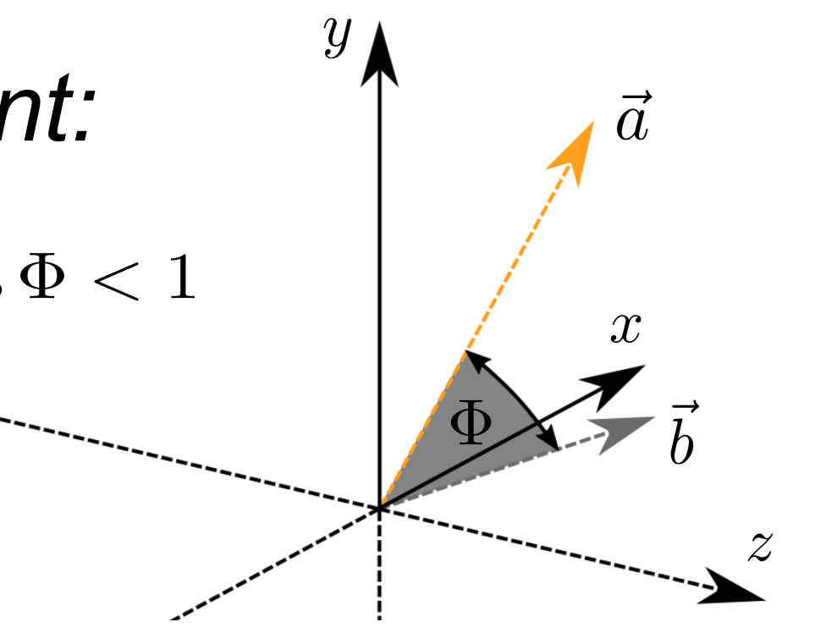


- Assessment of two different turbulence models:
  - Gradient diffusion hypothesis model (functional LES model)
  - Clark's gradient model (structural LES model)

by determination of the alignment and the correlation coefficient between the SGS heat flux and turbulence models

Alignment:

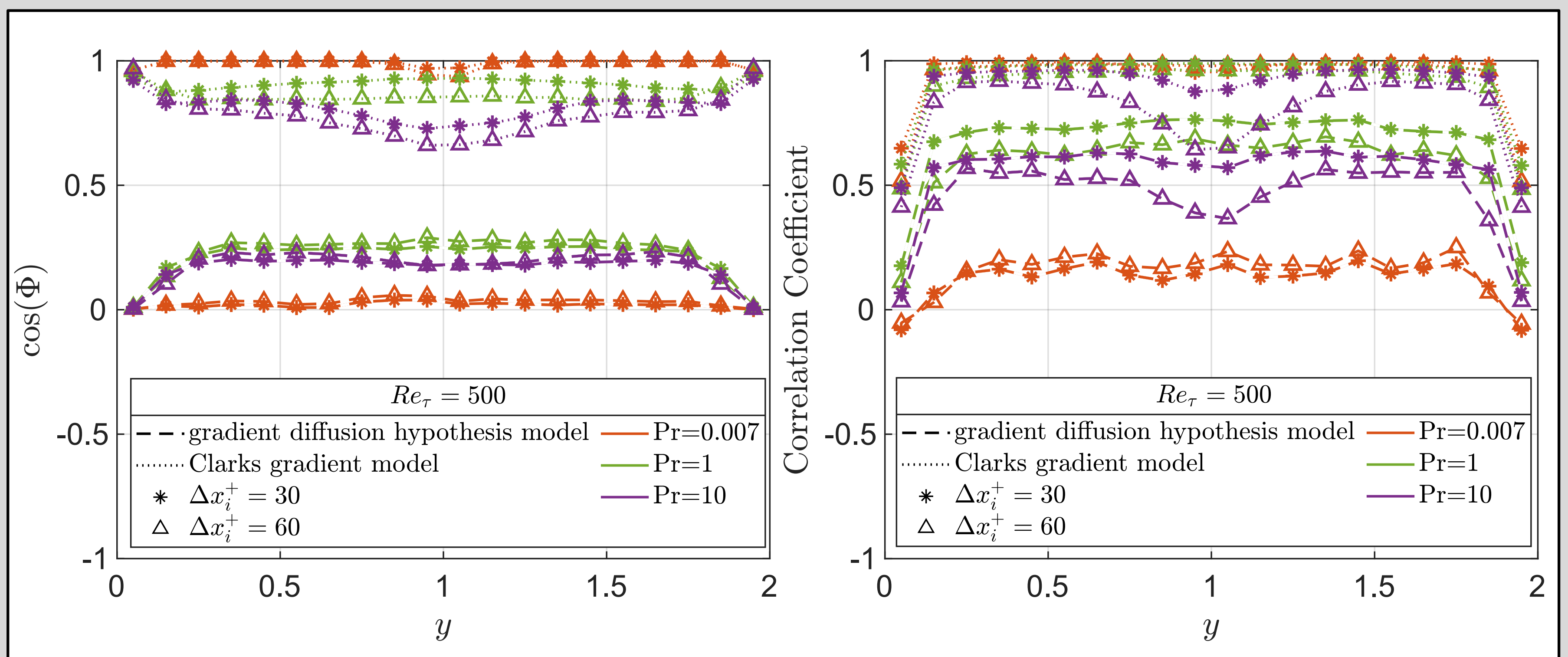
$-1 < \cos\Phi < 1$



Correlation coefficient:

$+1$	perfect linear relationship
0	no linear relationship
-1	negative linear relationship

Results and discussion



- For $Pr = 0.007$ the alignment for the structural model is nearly one, this means the SGS heat flux is colinear to the structural model
- For $Pr = 0.007$ and $Pr = 1$ there is a strong linear relationship between the SGS heat flux and the structural model
- The alignment and correlation coefficient of the structural model decreases with increasing Prandtl number and filter width
- The functional model achieves the highest values for the alignment and the correlation coefficient for $Pr = 1$, where the Reynolds analogy is valid, for $Pr \neq 1$ the alignment and the correlation coefficient of the functional model decrease
- The structural model performs significantly better than the functional model and is promising for further a-posteriori analysis

References

Alcántara-Ávila et al. (2018), *Int. J. Heat Mass Transfer,* 127, 349-361.

Alcántara-Ávila and Hoyas (2021), *Int. J. Heat Mass Transfer,* 176, 121412.

R.A. Clark et al. (1979), *J. Fluid Mech.,* 91(1), 1-16.