The influence of heterogeneous surfaces on forced and mixed convection

Bettina Frohnapfel

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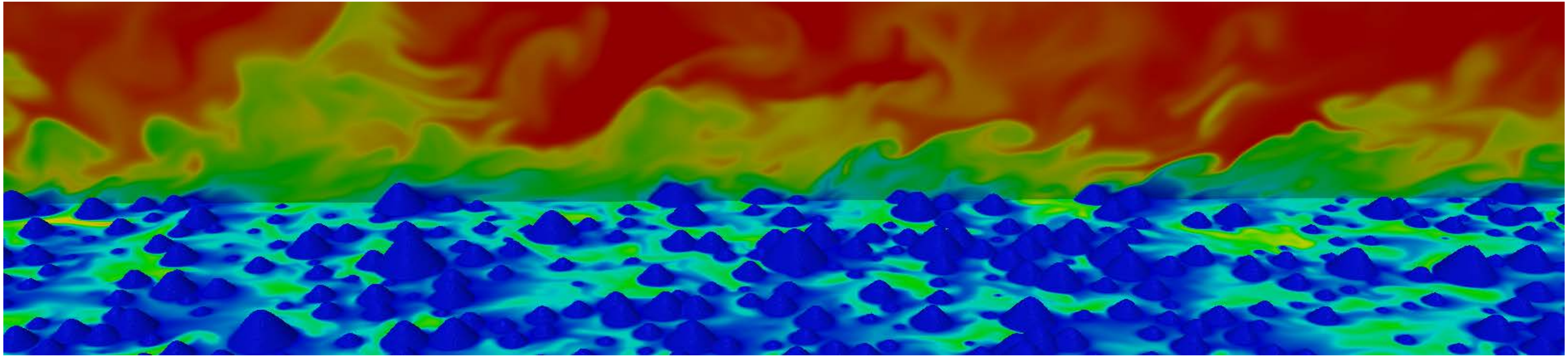

Thanks to

Karlsruhe Institute of Technology

@ istm Institute of Fluid Mechanics

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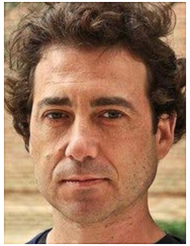


DFG
Deutsche Forschungsgemeinschaft

Overview

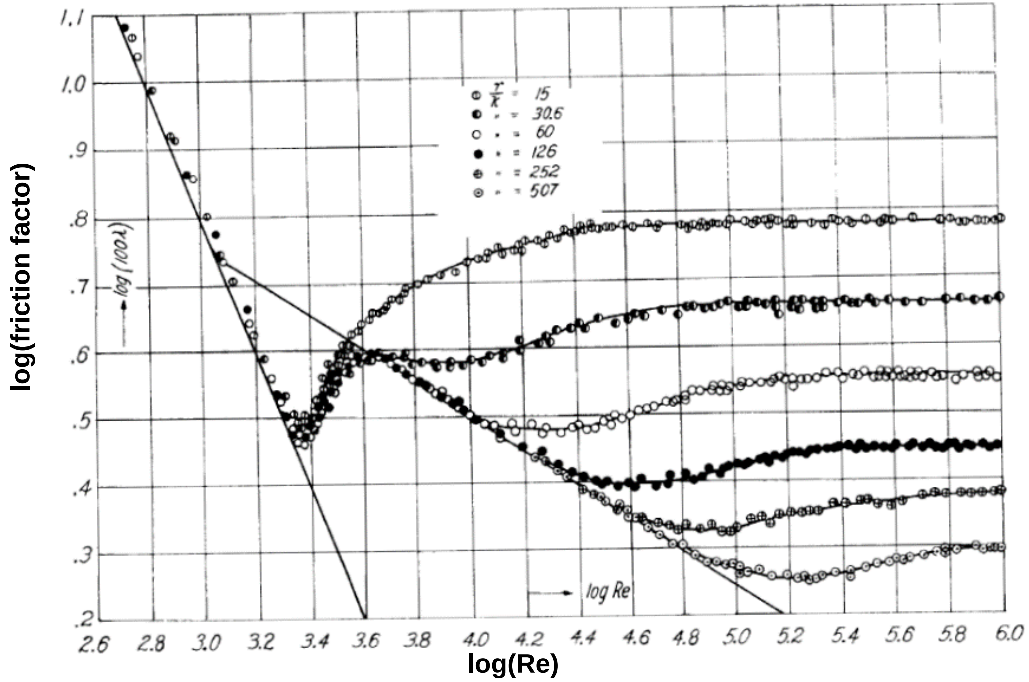
- Forced convective flow
  - over homogeneously rough surfaces
  - over heterogeneous surfaces
- Mixed convective flow
  - flow structures over homogeneous (smooth) surfaces
  - flow structures over heterogeneous surfaces
- Roughness modelling for flows with large scale separation

Heterogeneous surfaces

Hajo Dietz, www.nuernberluftbild.de

www.bnn.de

Nikuradse Diagram for homogeneous roughness in internal flows



K. Nikuradse (1933) Strömungsgesetze in rauen Rohren, VDI-Forschungsheft 361

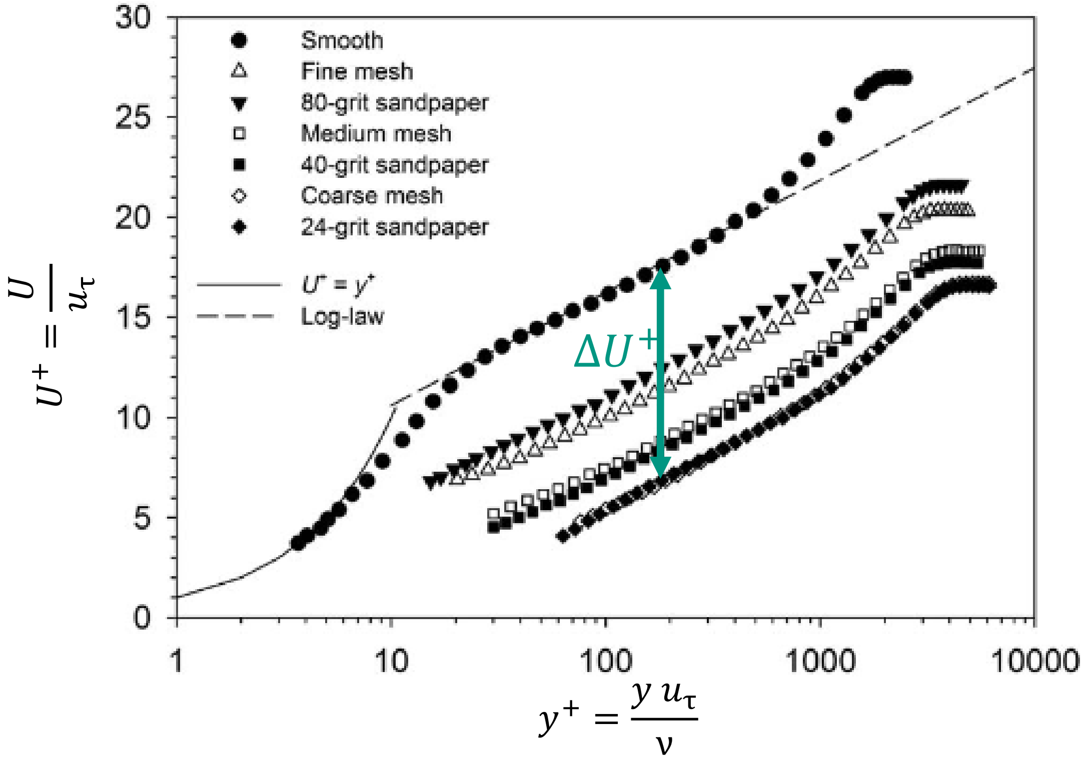
Nikuradse sand-grain roughness

equivalent sand grain roughness

$k_s = ?$ $(\Delta U^+ = ?)$

roughness does not lead to drag increase in laminar flows

Influence of roughness on TBL velocity profile



in logartithmic region

$$U^+ = \frac{1}{\kappa} \ln y^+ + B \quad - \Delta U^+$$

roughness function

for fully rough flow conditions

$$\Delta U^+ = \frac{1}{\kappa} \ln k_s^+ + B$$

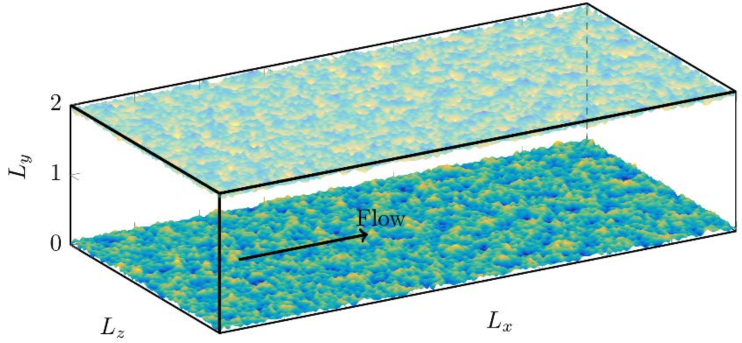
Flack, K. A., & Schultz, M. P. (2014). Roughness effects on wall-bounded turbulent flows. *Physics of Fluids*, *26*(10), 101305.

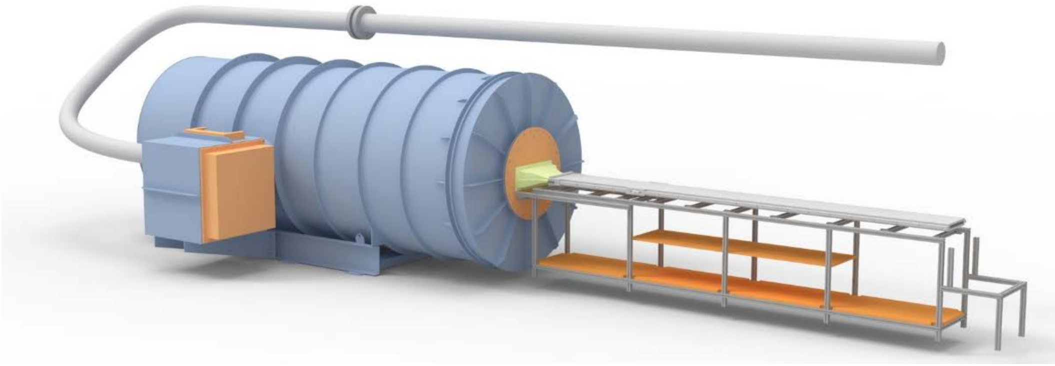
Data Generation

the flow property k_s (or ΔU^+) has to be determined for different rough surfaces

DNS (IBM based)

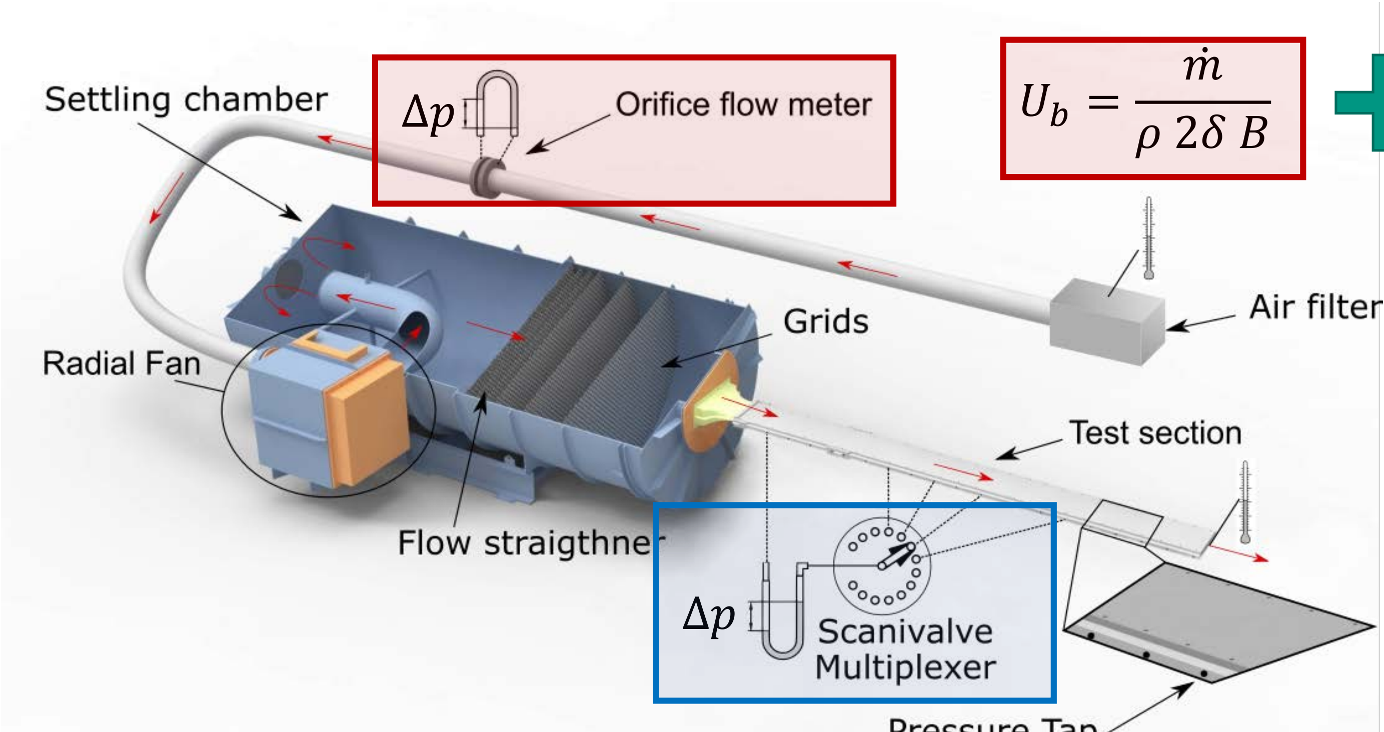
experiments





pressure drop „measurement“ at prescribed flow rate

High precision blower wind tunnel



$$U_b = \frac{\dot{m}}{\rho\, 2\delta\, B}$$

+

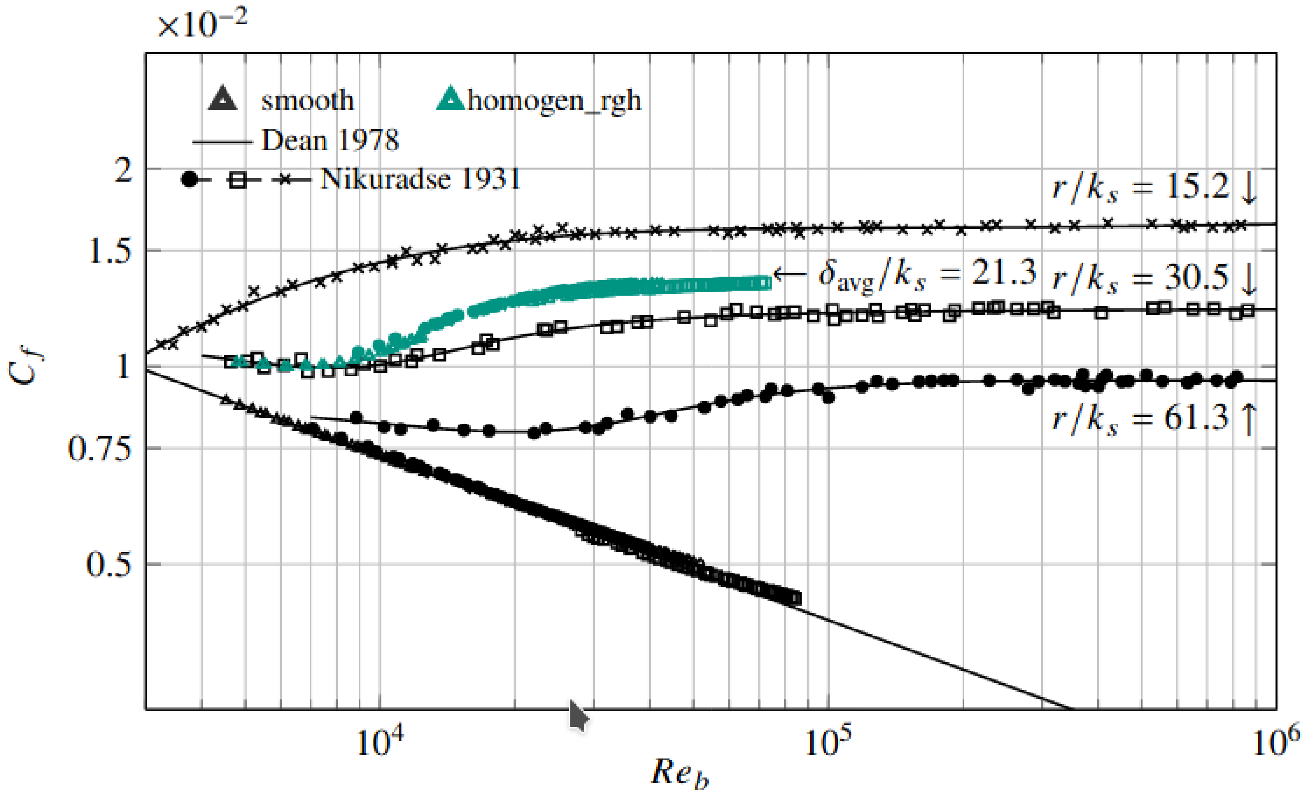
$$\tau_w = \frac{\Delta p}{\Delta x}\,\delta$$

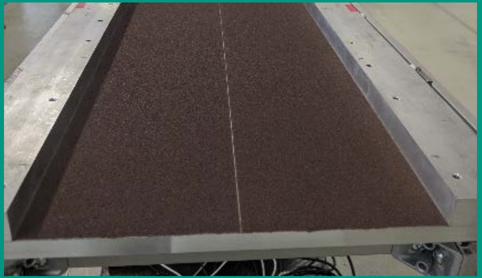
$$C_f = \frac{\tau_w}{\frac{\rho}{2}\,U_b^2}$$

$$Re_b = 2\,\frac{\delta\, U_b\, \rho}{\eta}$$

$$(3000)\ 4500 < Re_b < 85000$$

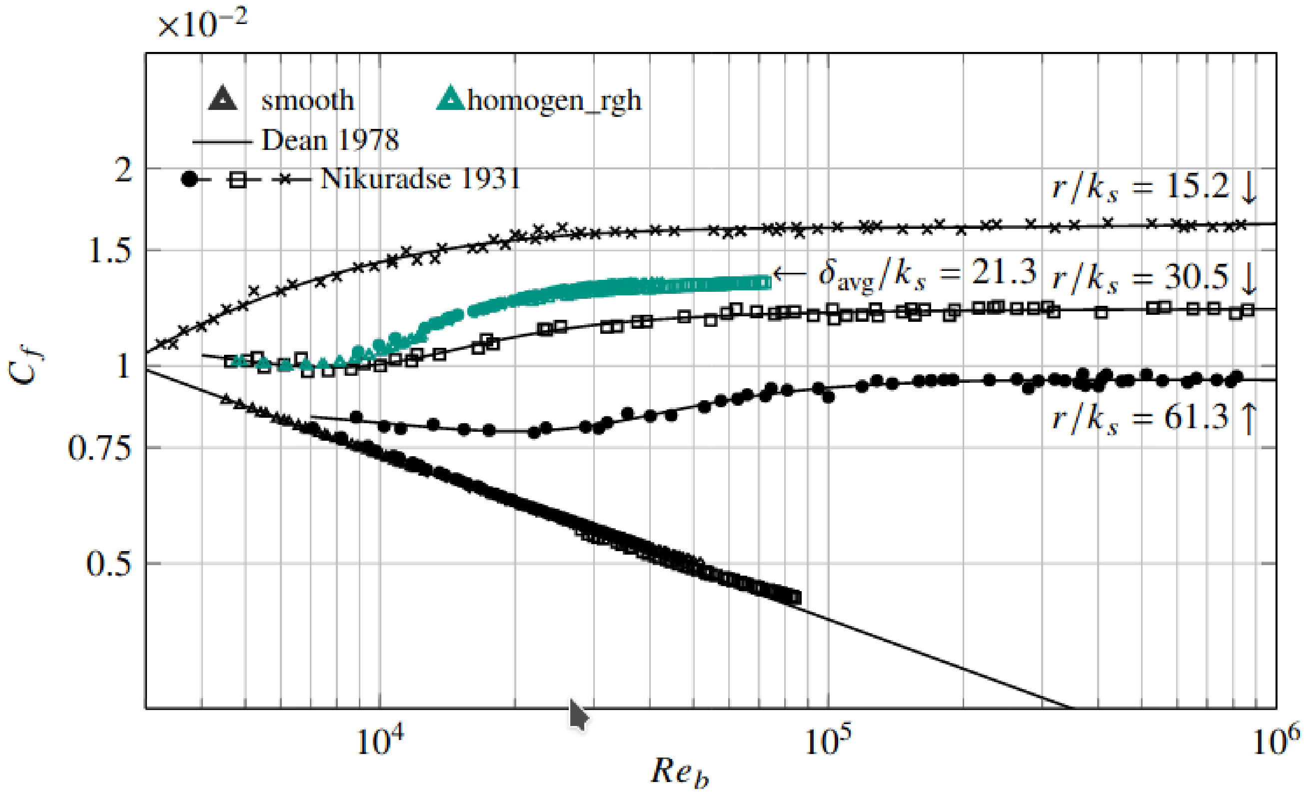
Friction factor for roughness strips





fully rough regime is basis for roughness predictions

What is the drag behavior of a heterogeneous surface?

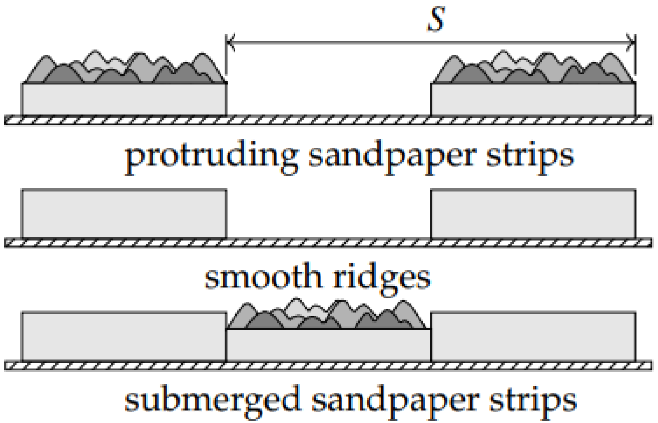


homogeneous roughness

heterogeneous roughness

Roughness strips in forced convection

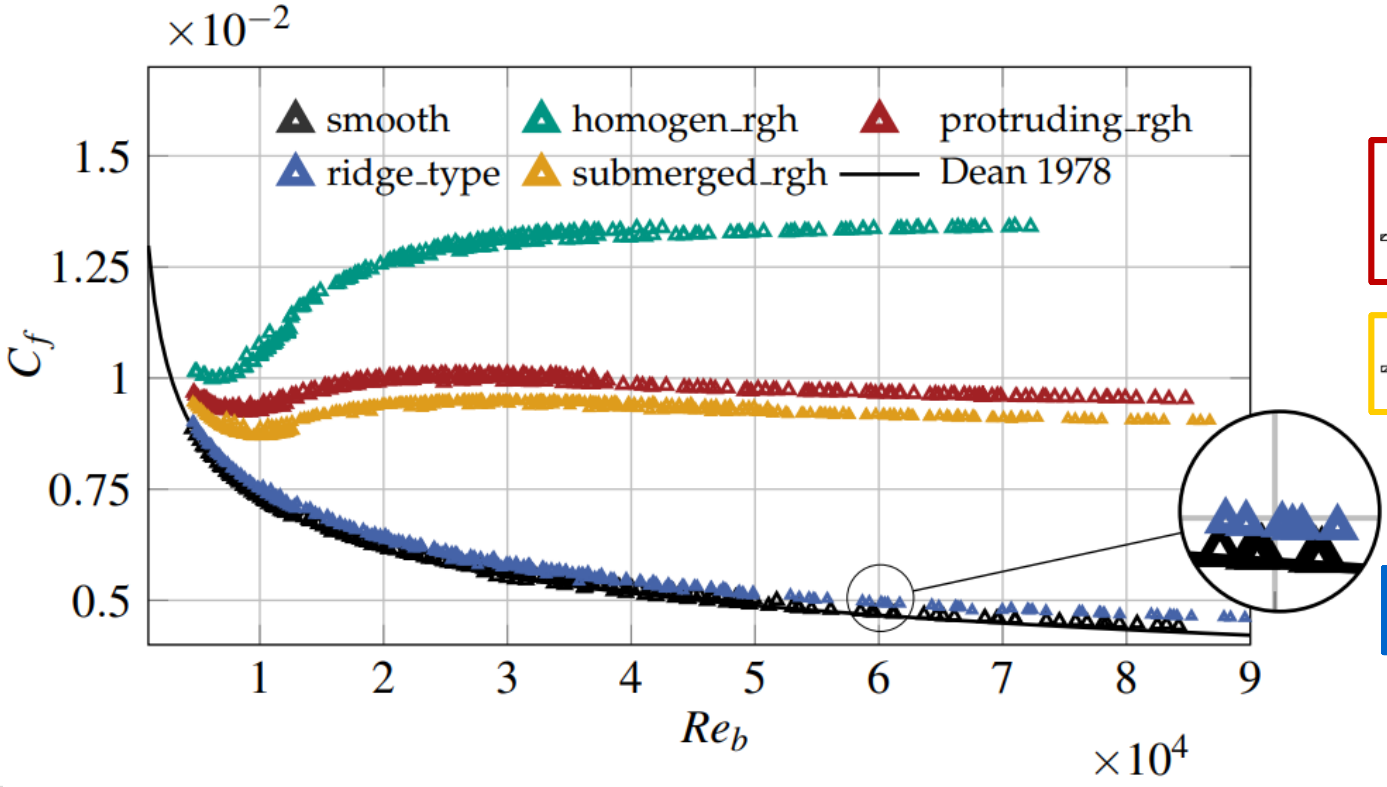
Experimental set-up does not allow large scale separation beween roughness height and boundary layer thickness

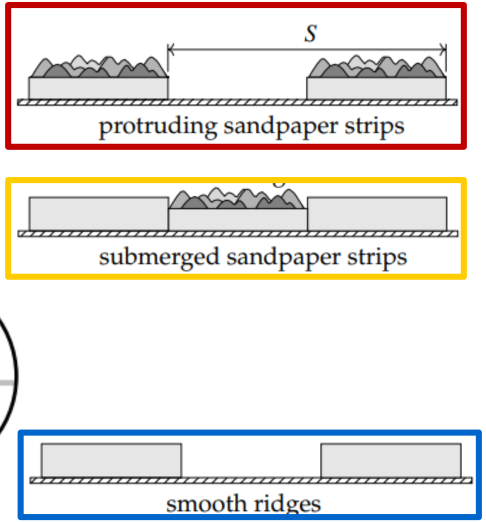


$$h = 0.05\delta$$

$$\frac{s}{\delta} = 2$$

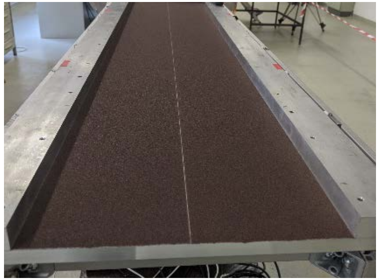
Drag of roughness strips





unpublished results

Spanwise inhomogenous roughness



homogeneous roughness

heterogeneous roughness

counter-intuitive flow rate distribution

EXPERIMENTAL INVESTIGATION
ON SECONDARY CURRENTS
IN THE TURBULENT FLOW
THROUGH A STRAIGHT CONDUIT*

J. O. HINZE

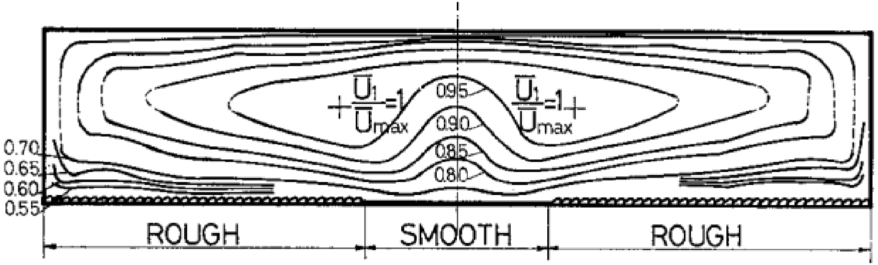
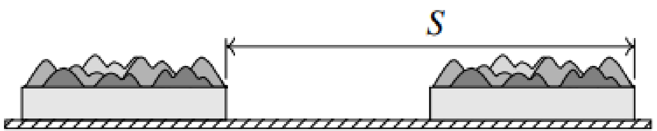


Fig. 1. Distribution of isovels.

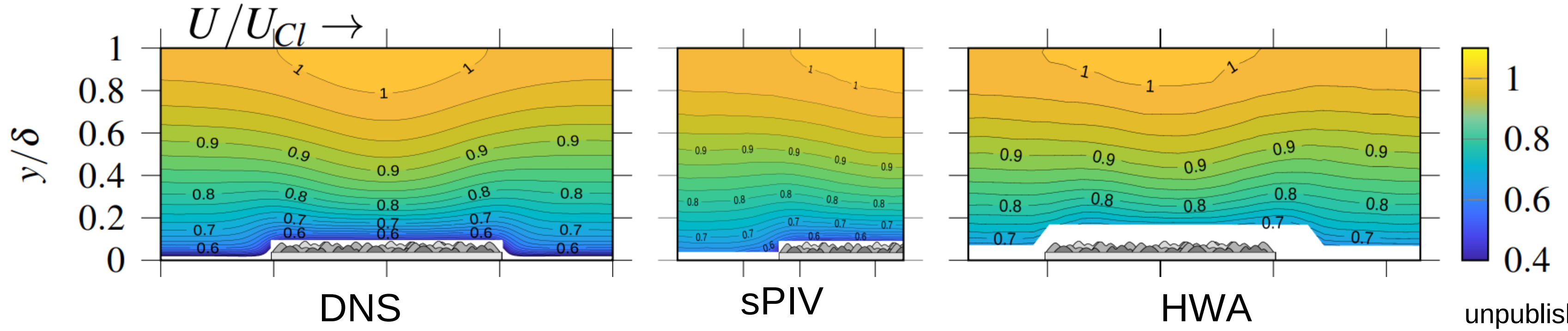
Hinze Appl. Sci. Res. 1973

Mean flow field above roughness strips



$h = 0.05\delta$

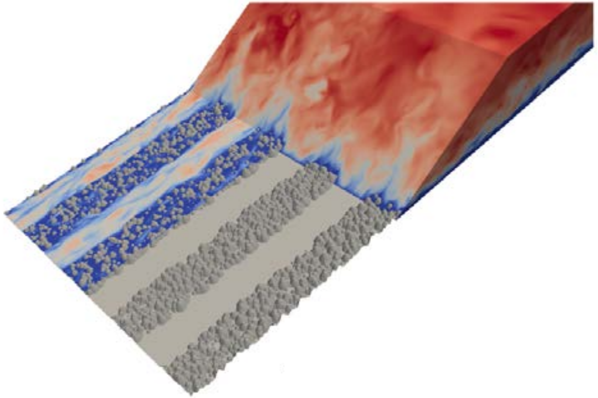
$\frac{s}{\delta} = 2$



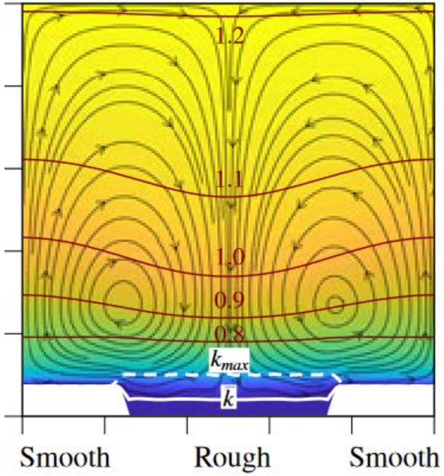
unpublished results

Turbulent Secondary Motions

secondary flow of Prandtl's second kind in forced convection



instantaneous flow field

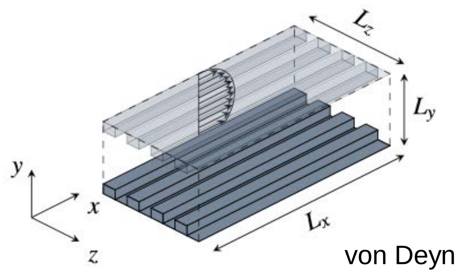


time-averaged flow field

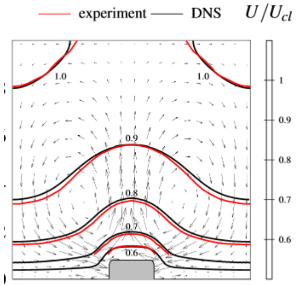
Stroh et al. JFM 2020; Schäfer et al. JFM 2022

Simplified scenario in literature: ridge type „roughness“

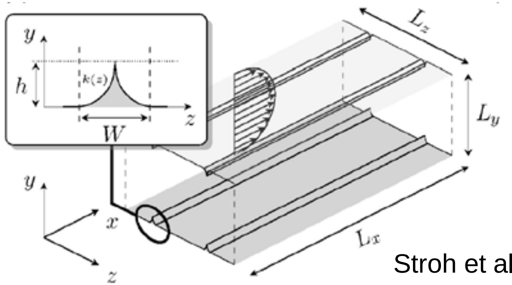
streamwise aligned ridges induce turbulent secondary motions similar to the flow phenomena above roughness strips



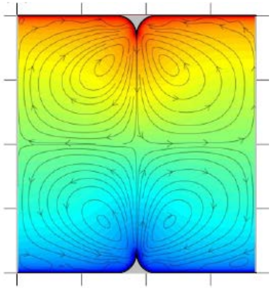
von Deyn et al. ExiF 2022



velocity field
in channel cross section



Stroh et al. IJHFF 2020

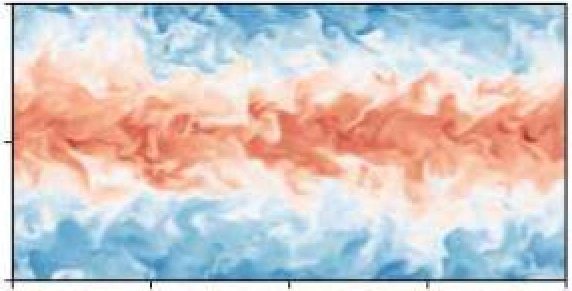


temperature field
in channel cross section

Relevance in convective boundary layers?

mixed convection over smooth surfaces (unstable thermal stratification)

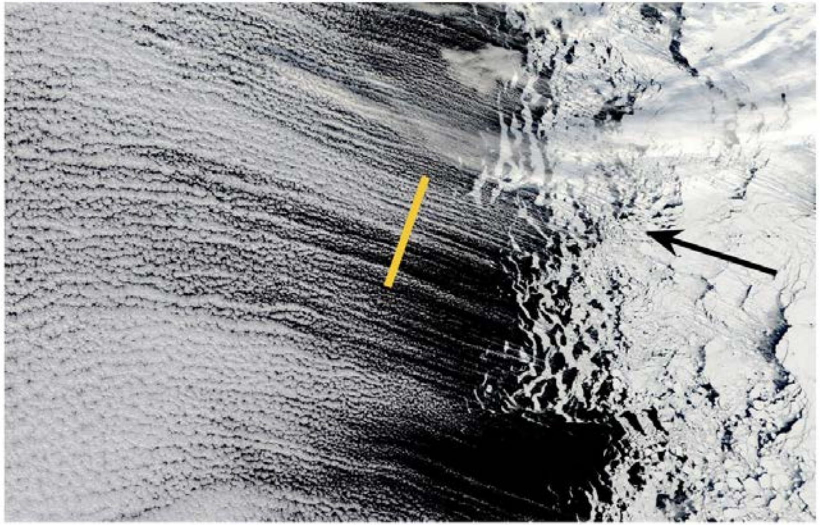
NASA earth observatory



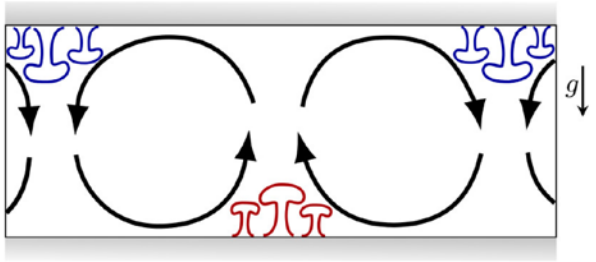
temperature field

Relevance in convective boundary layers?

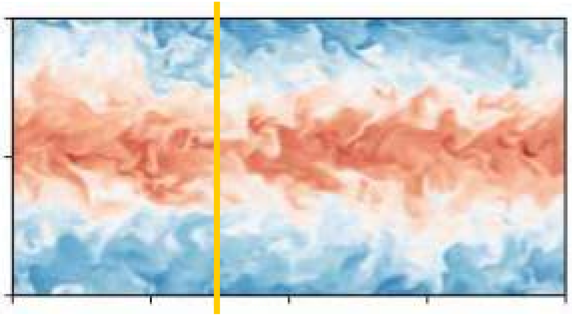
mixed convection over smooth surfaces (unstable thermal stratification)



NASA earth observatory



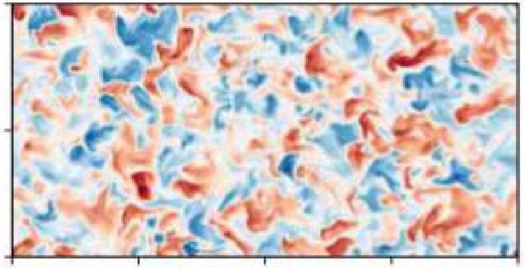
convective rolls



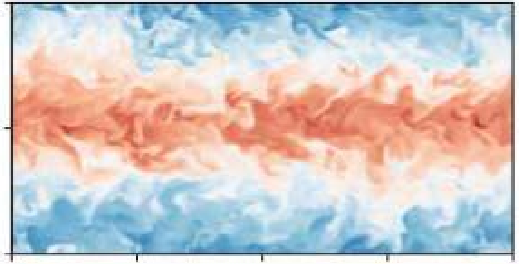
temperature field

Mixed convection in turbulent channel flow with smooth walls

instantaneous temperature fluctuations in channel center plane (view from top)

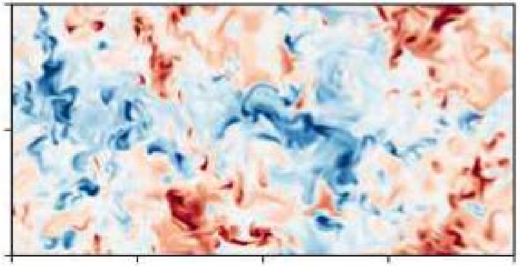


forced convection
$Ri = 0$



mixed convection
small Ri *or* $\delta/_L$

roll to cell transition

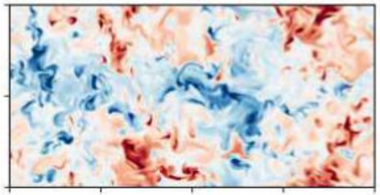


natural convection
large Ri *or* $\delta/_L$

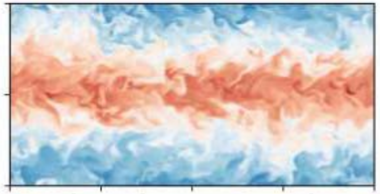
δ – boundary layer thickness
L – Obukhov length scale

Schäfer et al, JFM 2022, accepted

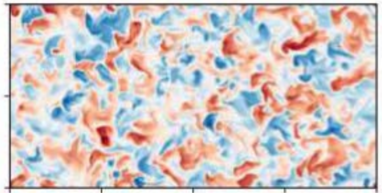
Mixed convection in turbulent channel flow with smooth walls



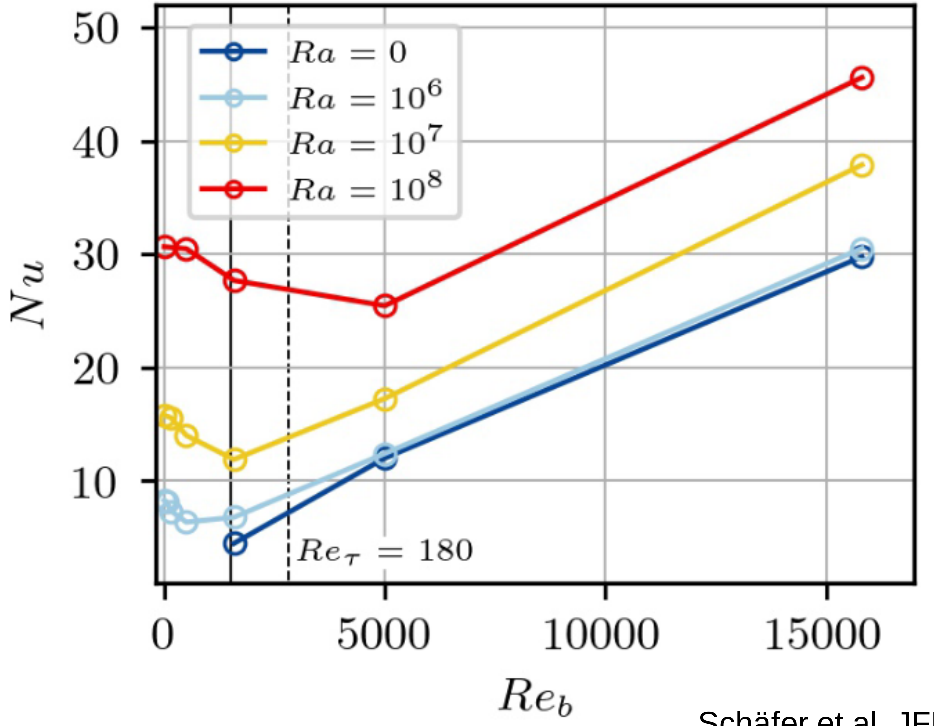
natural convection



mixed convection

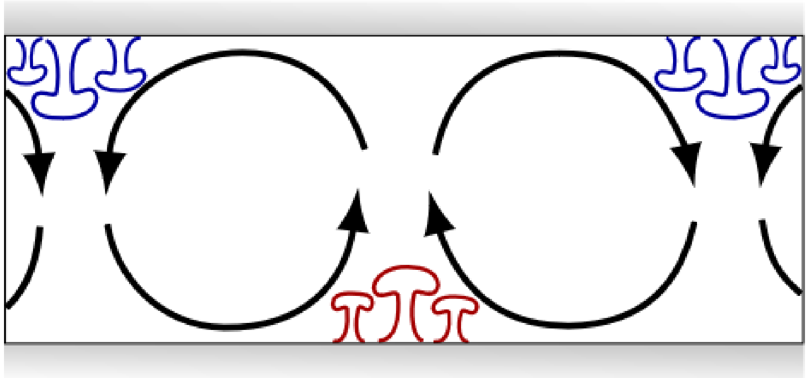


forced convection

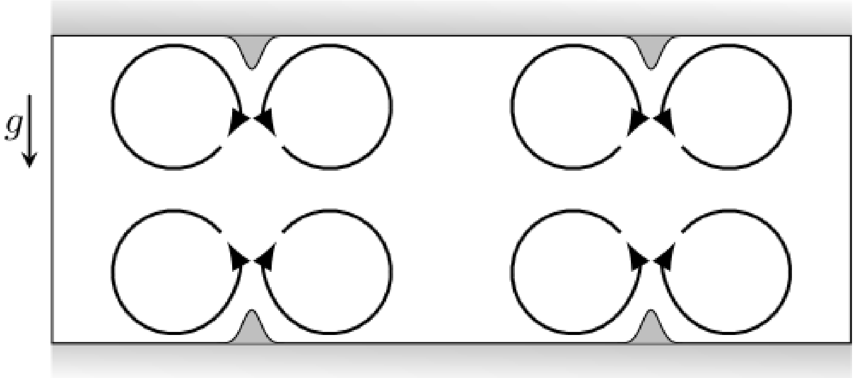


Schäfer et al, JFM 2022, accepted

Convective rolls vs turbulent secondary motion



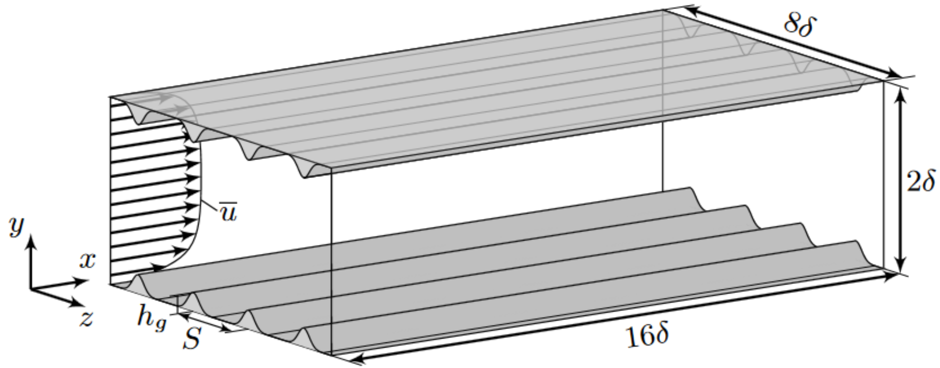
convection rolls
smooth channel walls
mixed convection

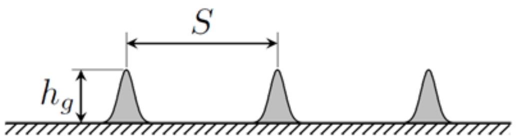


turbulent secondary flows
structured channel walls
forced convection

What is the influence of structured surfaces in mixed convection? (DNS study)

Investigated Parameter Space





$$h_g = 0.1\delta$$

$$S/\delta = 0.5, 1, 2, 4, (8), \infty$$

Schäfer et al, JFM 2022, accepted

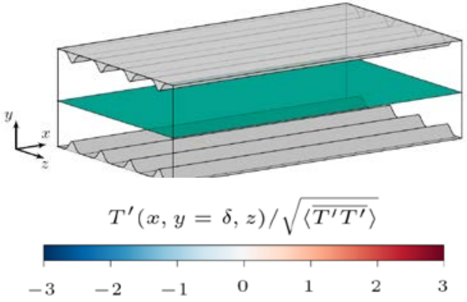
$$Re_b = \frac{u_b\,\delta_{\text{eff}}}{\nu}, \qquad Ra = \frac{(2\delta_{\text{eff}})^3\,\beta g\,\Delta T}{\alpha\nu}, \qquad Pr = \frac{\nu}{\alpha} = 1$$

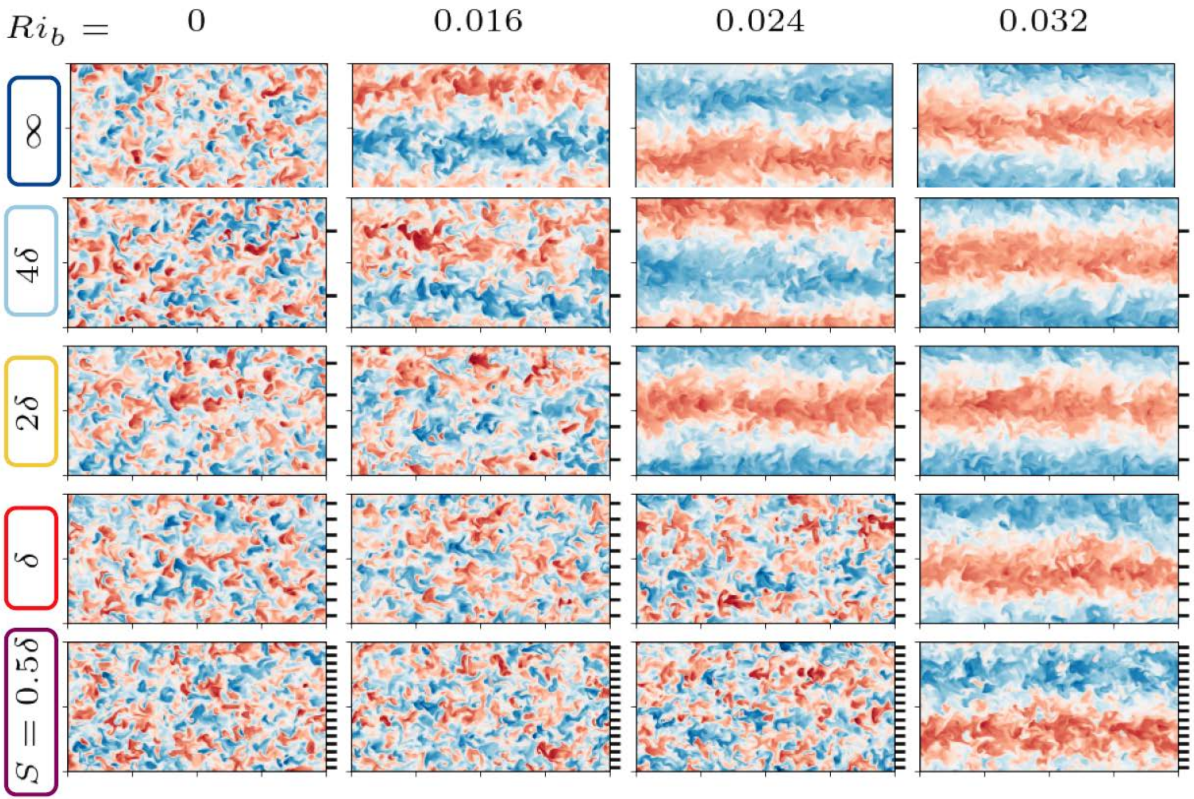
$$\Rightarrow Ri_b = \frac{Ra}{4Re_b^2\,Pr}$$

- $Ri \ll 1$: forced
- $Ri \approx 1$: mixed
- $Ri \gg 1$: natural convection

Impact of ridges on convection rolls

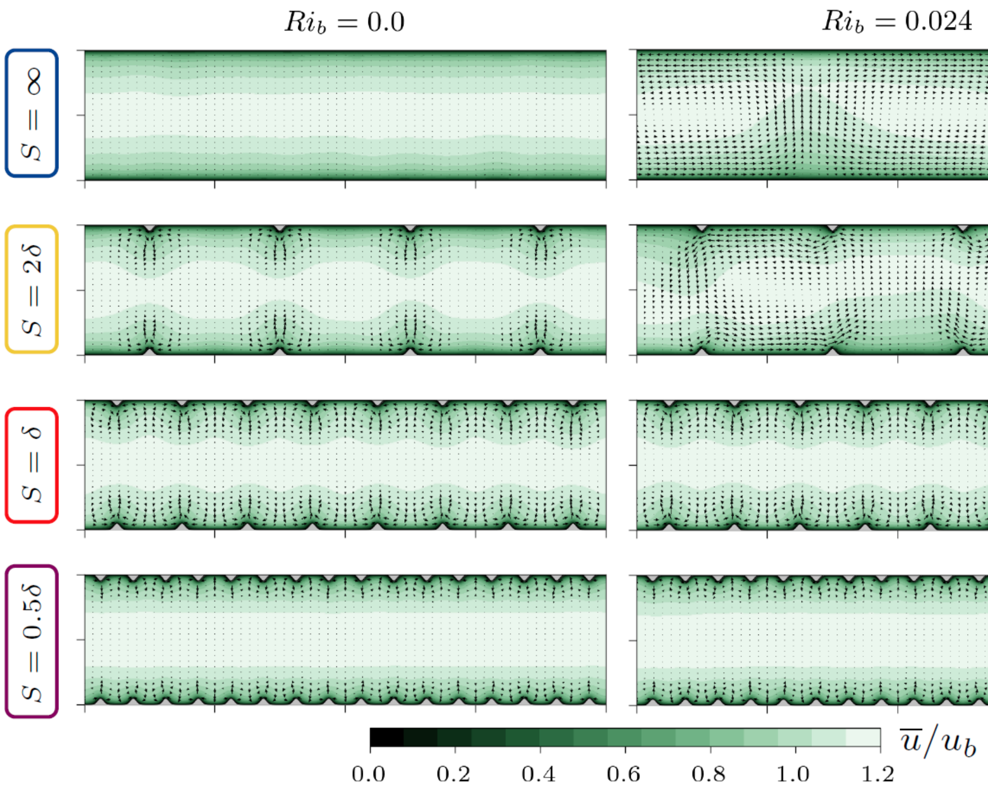
instantaneous temperature fluctuations in channel center plane





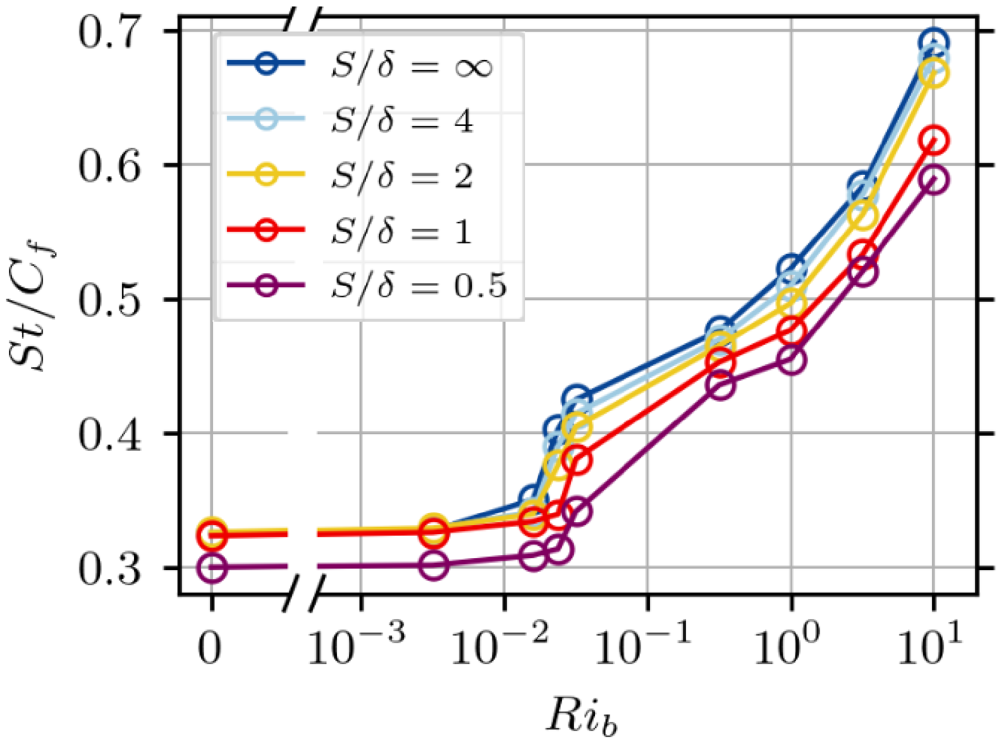
surface ridges delay emergence of rolls

In-plane motion and streamwise velocity distribution



Schäfer et al, JFM 2022, accepted

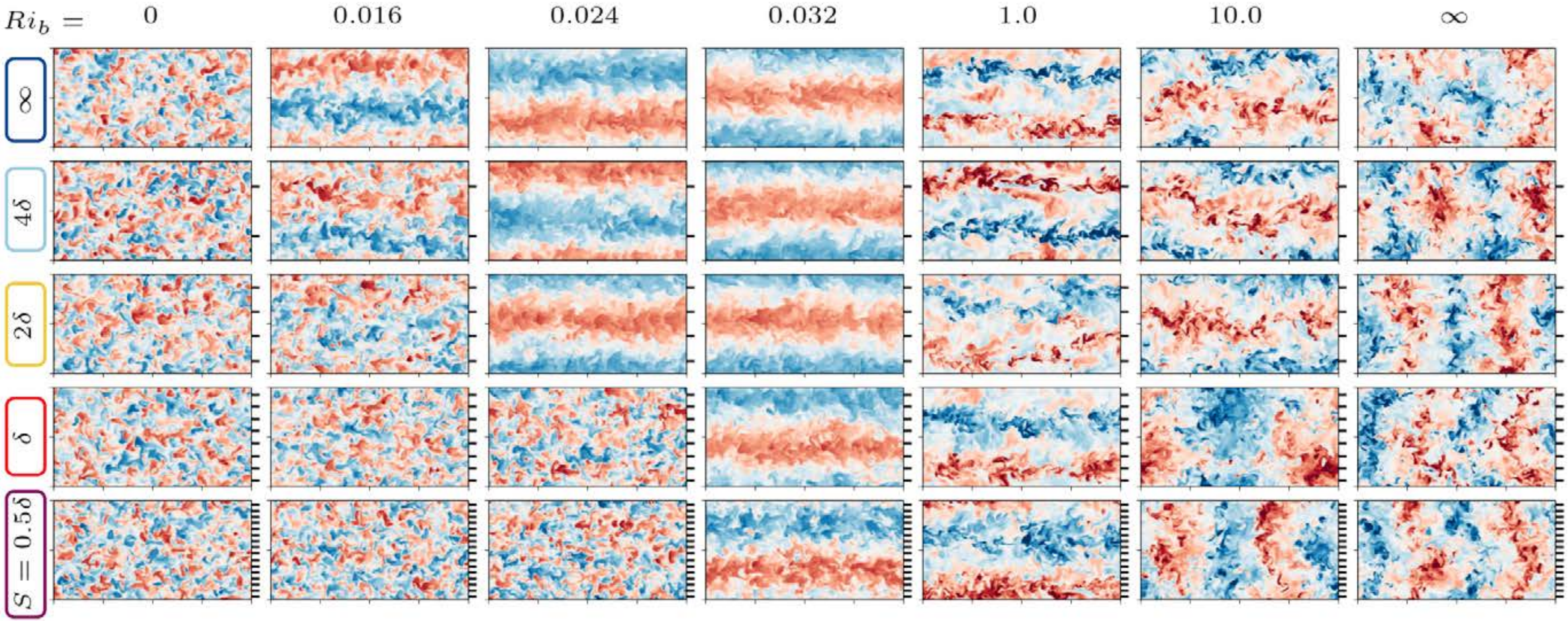
Global flow properties over ridges



- buoyancy induces larger increase of heat transfer than of momentum transfer
- more ridges → relative importance of momentum transport increases
- formation of rolls (indicated by increase in St/c_f) is delayed by ridges
- additional drag by ridges is important feature

Schäfer et al, JFM 2022, accepted

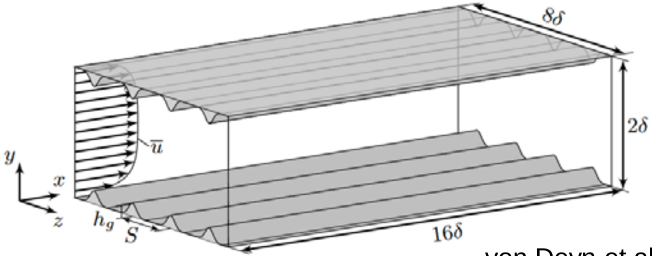
From convection rolls to convection cells?



convection cells occur earlier and have a preferred orientation on anisotropic structured surface

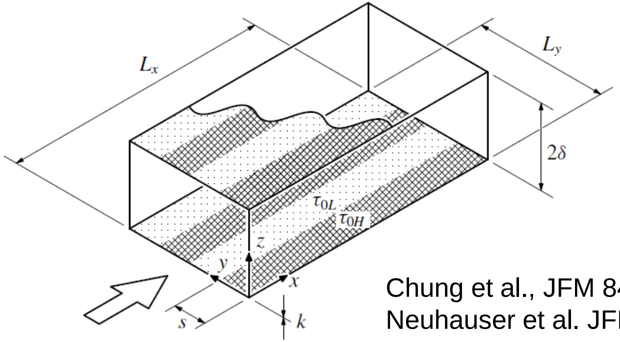
The challenge of scale separation

Ridges have non-negible height compared to boundary layer thickness
→ Is the height critical?
→ How to run DNS with „large“ scale separation?



von Deyn et al. ExiF 2022
Stroh et al. IJHFF 2020

„ridge type“ roughness

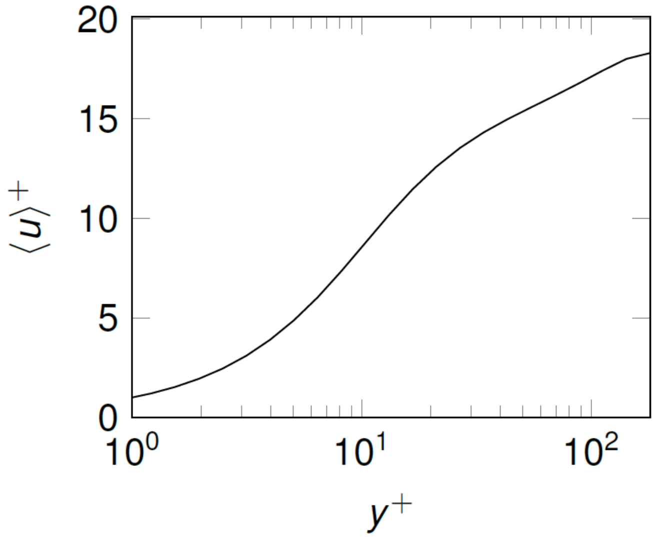


Chung et al., JFM 847, 2018
Neuhauser et al. JFM 2022

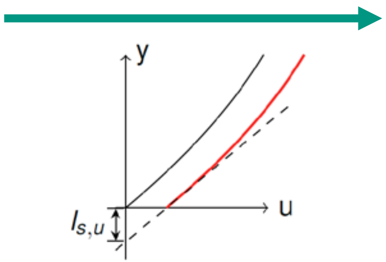
„strip type“ roughness

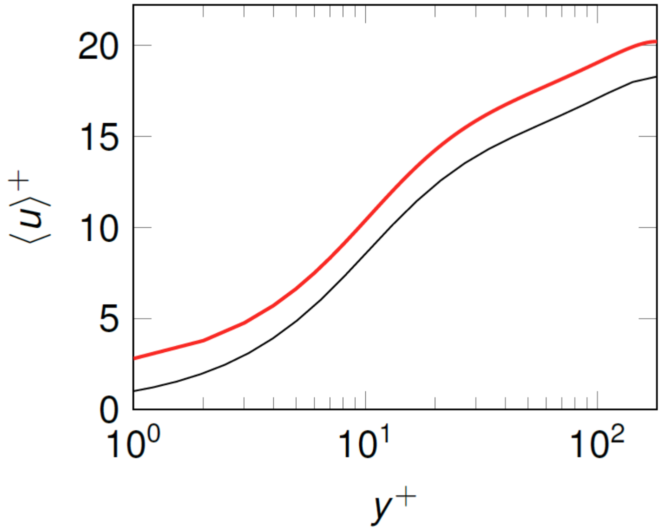
Slip length model

turbulent velocity profile



streamwise
slip length

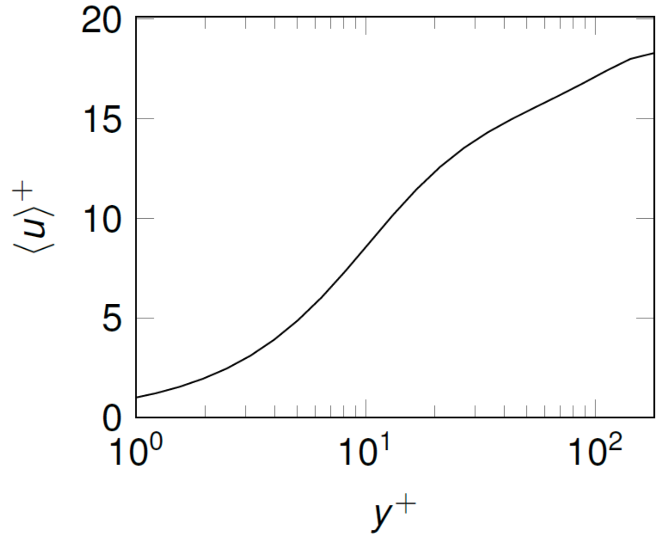




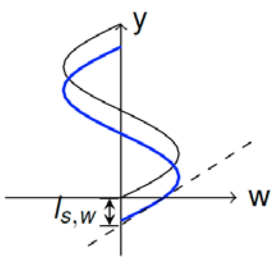
Slip-length boundary condition: $u_i\big|_{y=0} = l_{s,i}\,\frac{\partial u_i}{\partial y}\Big|_{y=0}$

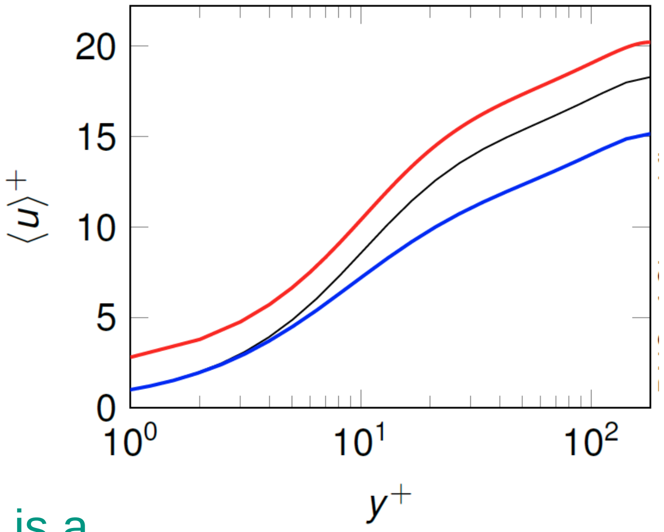
Slip length model

turbulent velocity profile



spanwise
slip length

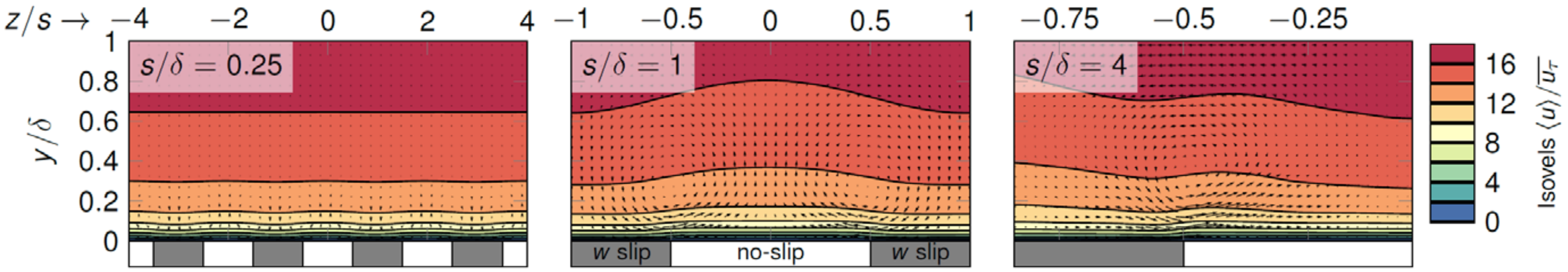




spanwise slip length is a
simple model for rough surface

Neuhauser et al. JFM 2022

Turbulent secondary flow over rough strips

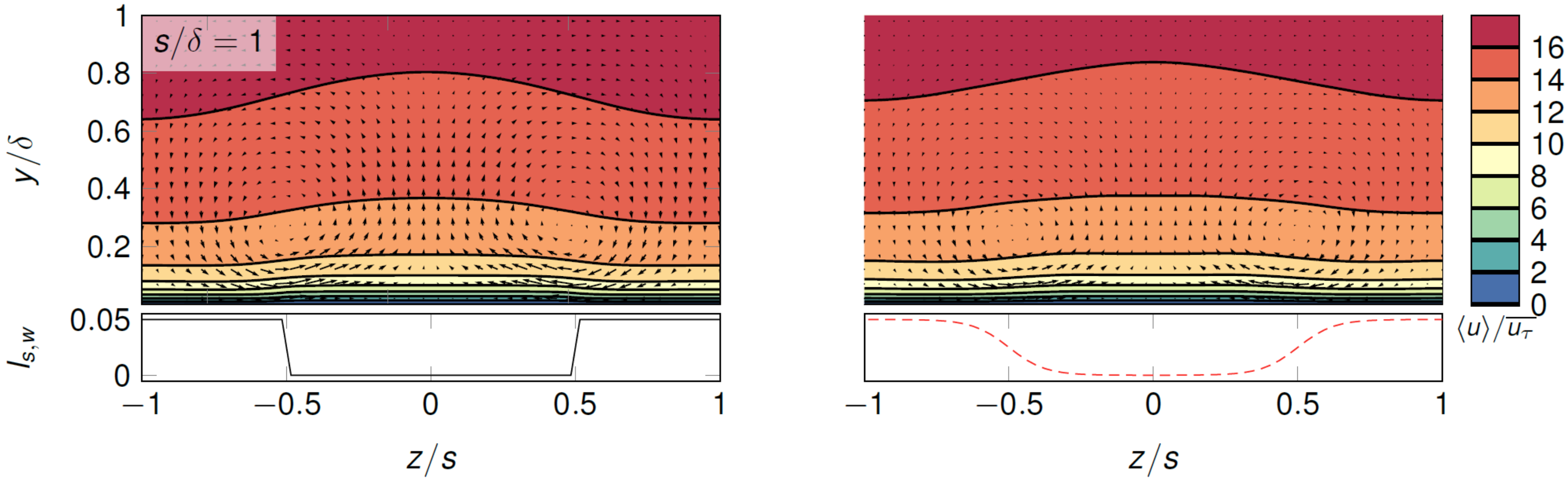


spanwise slip length roughness model

- easy to implement, captures laminar behavior correctly
- reproduces flow phenomena of rough strips
- model is too simplistic to model fully rough flow state (same holds true for ridge type roughness model)
- enables parameter studies

Neuhauser et al. JFM 2022

Effect of transition between smooth and rough domains



formation of turbulent secondary flow does not depend on gradient in boundary condition

Neuhauser et al. JFM 2022

Final remarks

Karlsruhe Institute of Technology

- today‘s state of the art for roughness predictions rely on fully rough flow state known for homogeneous roughness
- drag prediction for inhomogeneous surfaces is one of the great challenges in roughness research
- lateral (spanwise) heterogeneity can induce large scale turbulent secondary motions visible in the mean (!) flow field, resemblence of convective rolls to some extend
- two literature models for roughness strips: ridge type and slip type
- ridges in mixed convection: convective rolls occur later and convective cells occur earlier (smaller Ri or δ/L)

Institute of Fluid Mechanics

Future points

- Is the impact of strip type roughness onto mixed convection comparable to ridge type roughness?
- Relevance of scale separation in general
- What happens if different surface textures have different heat emissions?
- To which extend is the symmetric set-up of the channel flow DNS comparative to (atmospheric) boundary layer conditions?

Related publications @ ISTM

- **The effect of spanwise heterogeneous surfaces on mixed convection in turbulent channels**
  Schäfer, K.; Frohnapfel, B.; Mellado, J.P.
  2022. Journal of Fluid Mechanics, accepted
- **From drag reducing riblets to drag increasing ridges**
  Deyn, L. H. von; Gatti, D.; Frohnapfel, B.
  2022. Journal of Fluid Mechanics, accepted
- **Simulation of turbulent flow over roughness strips**
  Neuhauser, J.; Schäfer, K.; Gatti, D.; Frohnapfel, B.
  2022. Journal of Fluid Mechanics, 945, Art.-Nr.: A14. doi:10.1017/jfm.2022.536
- **Modelling spanwise heterogeneous roughness through a parametric forcing approach**
  Schäfer, K.; Stroh, A.; Forooghi, P.; Frohnapfel, B.
  2022. Journal of Fluid Mechanics, 930, A7. doi:10.1017/jfm.2021.850
- **Ridge-type roughness: from turbulent channel flow to internal combustion engine**
  Deyn, L. H. von; Schmidt, M.; Örlü, R.; Stroh, A.; Kriegseis, J.; Böhm, B.; Frohnapfel, B.
  2022. Experiments in Fluids, 63 (1), 18. doi:10.1007/s00348-021-03353-x
- **Rearrangement of secondary flow over spanwise heterogeneous roughness**
  Stroh, A.; Schäfer, K.; Frohnapfel, B.; Forooghi, P.
  2020. Journal of Fluid Mechanics, 885, R5. doi:10.1017/jfm.2019.1030
- **Secondary flow and heat transfer in turbulent flow over streamwise ridges**
  Stroh, A.; Schäfer, K.; Forooghi, P.; Frohnapfel, B.
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Thank you!