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Flow stratification of supercritical CO_2 in a heated pipe

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Thermo-Fluid Dynamics

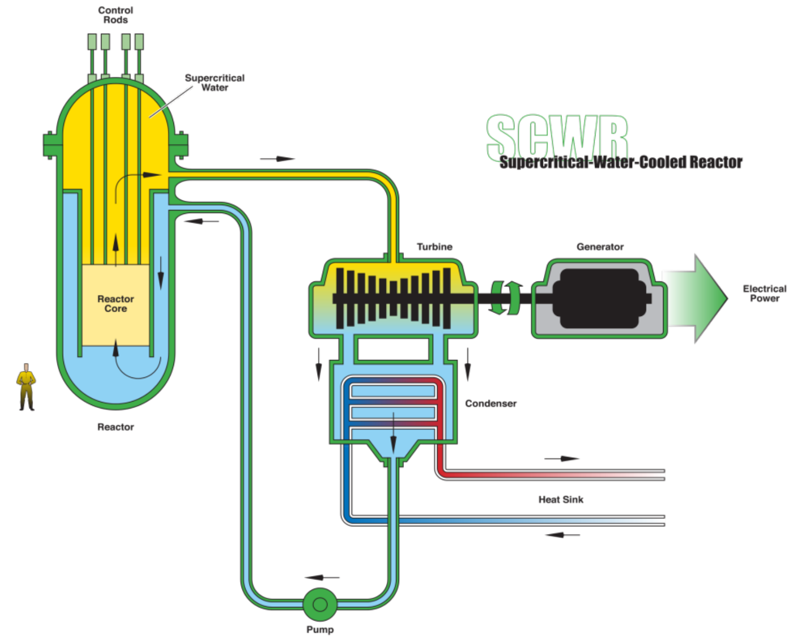
Agenda

- **Introduction**
  - Motivation
  - Previous work
  - Aim of study
- **Numerical method**
  - Governing equations
  - Simulation conditions
- **Results and discussion**
  - Bulk properties
  - Flow stratification
  - Secondary flow
  - Turbulence statistics
- **Conclusions**

Motivation

Supercritical water reactor (SCWR, HPLWR):

- ❑ High efficiency
- ❑ Compact and simpler system design
- ❑ Water is cheap, non-toxic and transparent
- ❑ Gen IV reactor concept

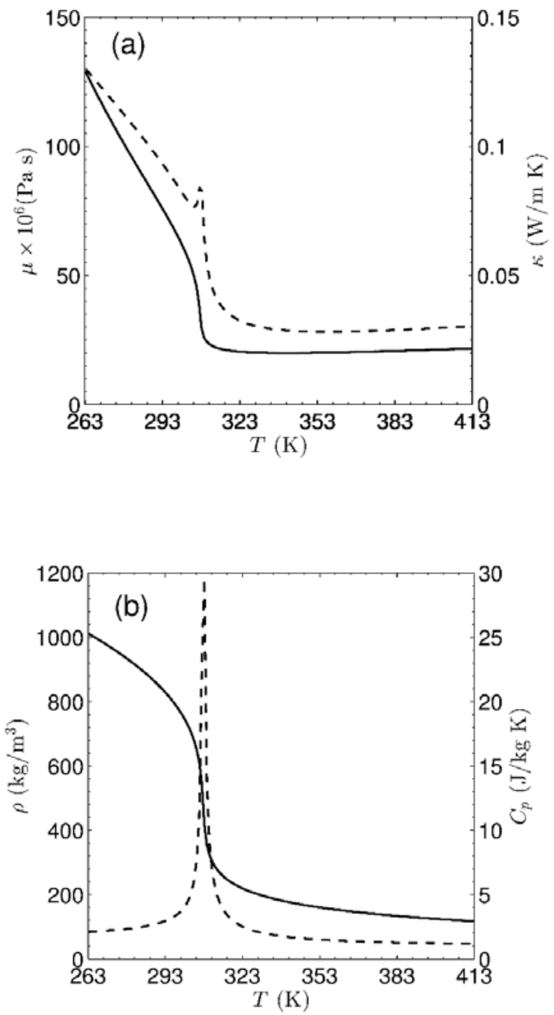


sCO_2 facility (SCARLETT) at IKE, University of Stuttgart

- ❑ Max. mass flux $\dot{m} = 0.1$ (Kg/s), $P_{max} =$ 120 bar
- ❑ Followed by development of PCHE (sCO2-HeRo Project in EU)

Motivation

CFD of heat transfer with supercritical fluid



- ❑ **RANS-Application oriented**
  - ❑ Various attempt with different models and solvers
  - ❑ modelling (classical/advanced) proved to be unreliable
  - ❑ DNS is needed for further understanding and model imporvement
- ❑ **DNS-A powerful tool for turbulence research**
  - ❑ Details resolved without turbulence modeling
  - ❑ Limited to simple geometry
  - ❑ Very rare, extremly high computational cost
  - ❑ Bae *et al.*, 2005, Nemati/Pecnik,2015: vertical pipe, CO_2, Re_0=5400, P_0=8 MPa, house code

Previous work

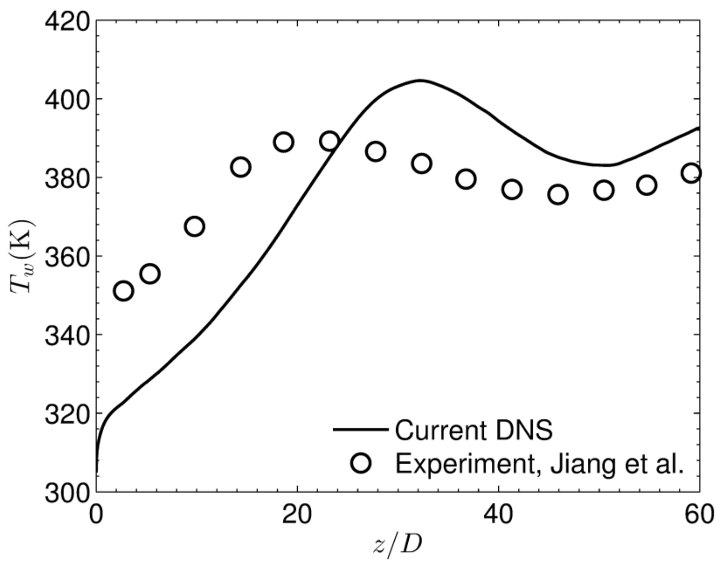
DNS of vertical pipe

DNS vs. DNS (Bae *et al.*, 2005, Nemati/Pecnik,2015)

- Re_0=5400, P_0=8 MPa/8.8 MPa, *D*=1 mm/2 mm, variable q_w, T_0
- Up to 80 Mio. cells
- DNS data base (10 cases) with average field, tuburlence field, budget, spectrum

DNS vs. Experiments

- Experiments from Jiang *et al.* (U Tsinghua, China), Re_0=9000, P_0=8.8 MPa, *D*=2 mm
- Well resolved DNS with 150 Mio. cells



Aim of Study

- Using DNS to investigate heat transfer of sCO_2 under different conditions including vertical/horizontal pipe, complex geometry and conditions in the future

- Data serves for model improvement/development (see companion paper by Laurien, Pandey and McEligot)

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Numerical method

Governing equation

- **Variation of thermo-physical properties:**

  Low-Mach N-S equations based on Cartesian Coordinates

$$\frac{\partial(\rho)}{\partial t}+\frac{\partial(\rho U_j)}{\partial x_j}=0$$

$$\frac{\partial(\rho U_i)}{\partial t}+\frac{\partial(\rho U_i U_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}(\mu(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}))\pm\rho g\delta_{i1}$$

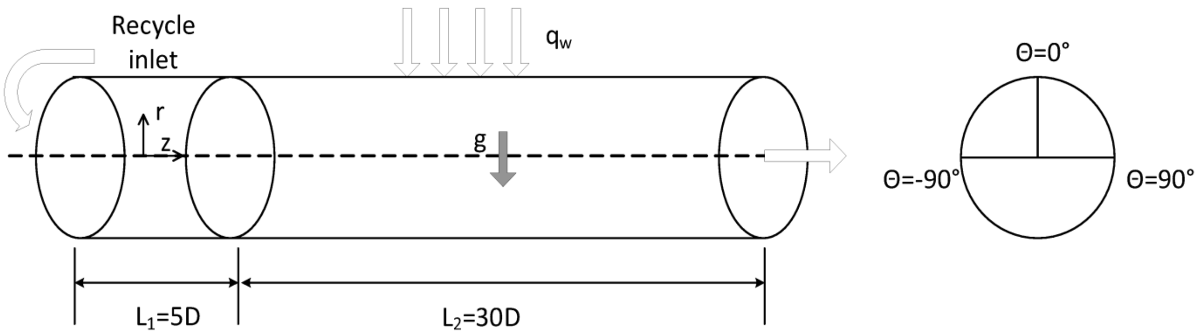
$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho U_j h)}{\partial x_j}=\frac{\partial}{\partial x_j}(k\frac{\partial T}{\partial x_j})$$

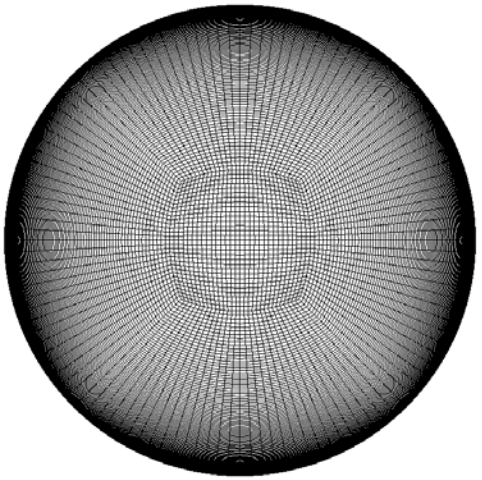
$$h=h(P_0,T),T=T(P_0,h),\rho=\rho(P_0,h),\mu=\mu(P_0,h),k=k(P_0,h),C_p=C_p(P_0,h)$$

- OpenFOAM V2.4 as solver, FVM
- PISO as the algorithm for P-U coupling, 2-Order spatial/temporal
- Implementation of properties library: NIST

Numerical method

Computational details





Resolution	r	θ	z	Δr_1^+	$(R\Delta\theta)^+$ (wall)	Δz^+	Δt^+
	168	172	2800	0.11	6.5	4.6	1.1×10^{-4}

- Structured Mesh based on Cartesian Coordinate, 80 Mio. cells
- Fully developed turbulent flow at inlet (Recycle/Rescale BC)
- Used and validated on experiments with heated air (Shehata and McEligot, 1998)

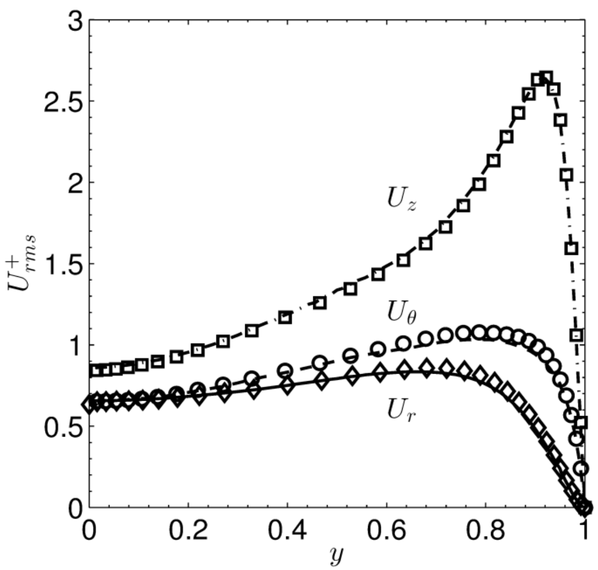
Numerical method

Computational details

- Parallel computation on 1400 CPU cores, 4 days for 10 FTT
- C_f at inlet 0.15% difference as Blasius estimation → numerical quality
- Inflow turbulence quality, validated with Wu and Moin,2008

Simulation conditions, P_0= 8 MPa

Case	Type	D (mm)	q_w (kW/m²)	T_0 (K)
SC160	Mixed	1	61.74	301.15
SC230F	Forced (g=0)	2	30.87	301.15
SC230	Mixed	2	30.87	301.15
SC260	Mixed	2	61.74	301.15



T_{pc}=307.8 K

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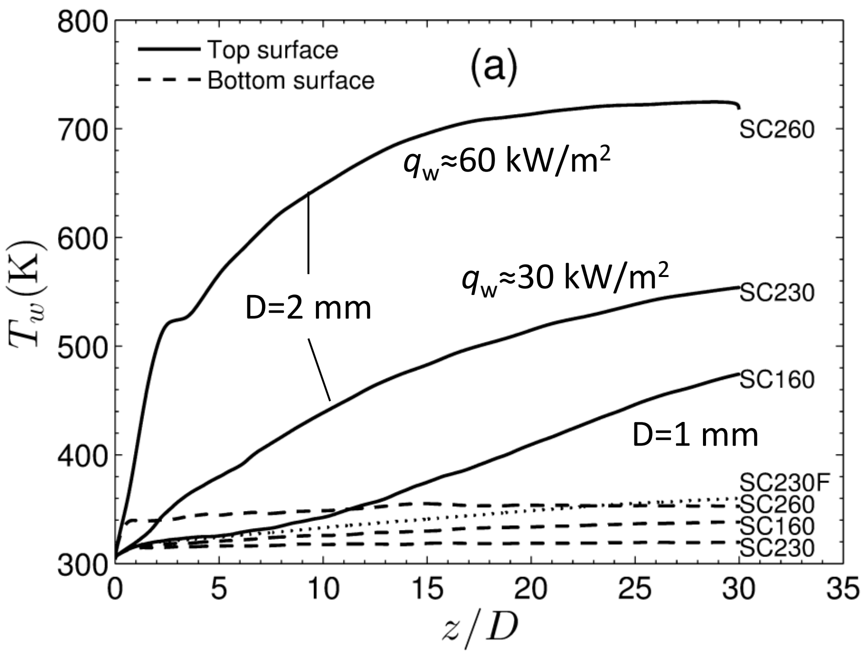
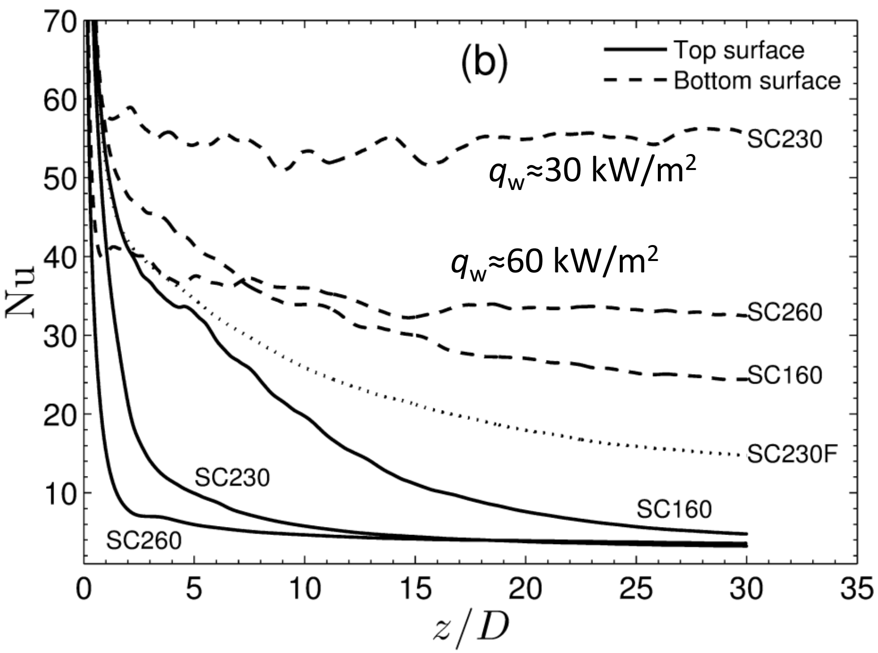
Results and discussion

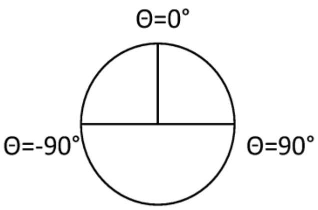
Bulk properties

Mean wall temperature T_w



Nusselt number Nu

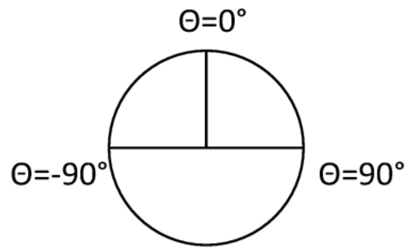




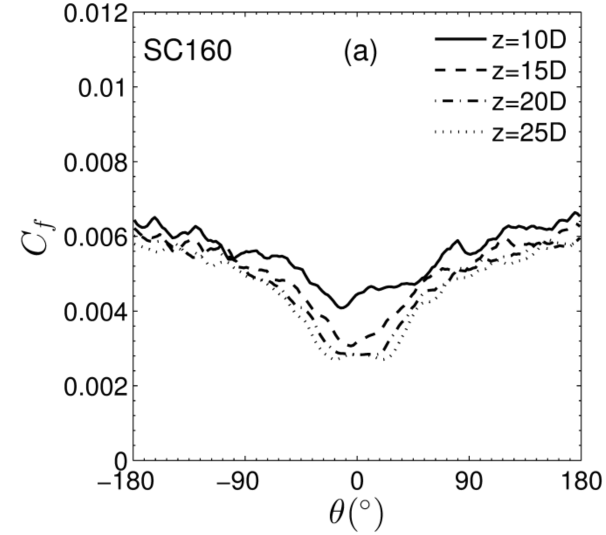
Results and discussion

Bulk properties

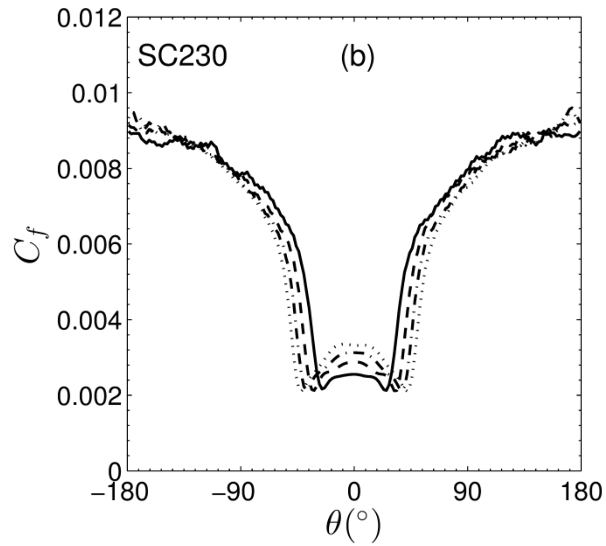
- C_f strongly inhomogenous
- Non-monotonical tendency



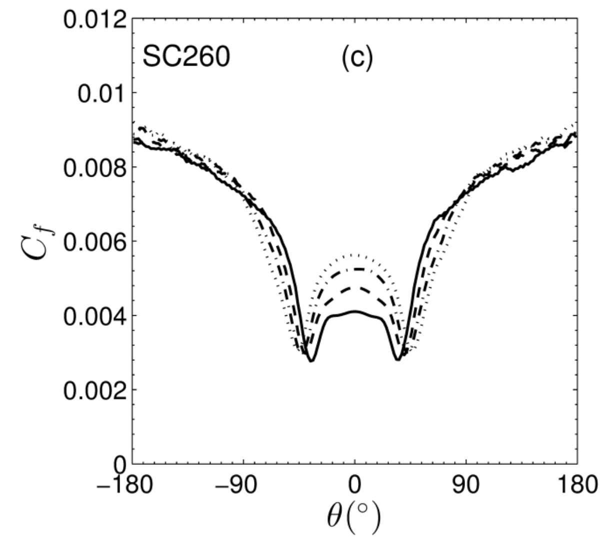
D=1mm



D=2mm, q_w≈30 kW/m²

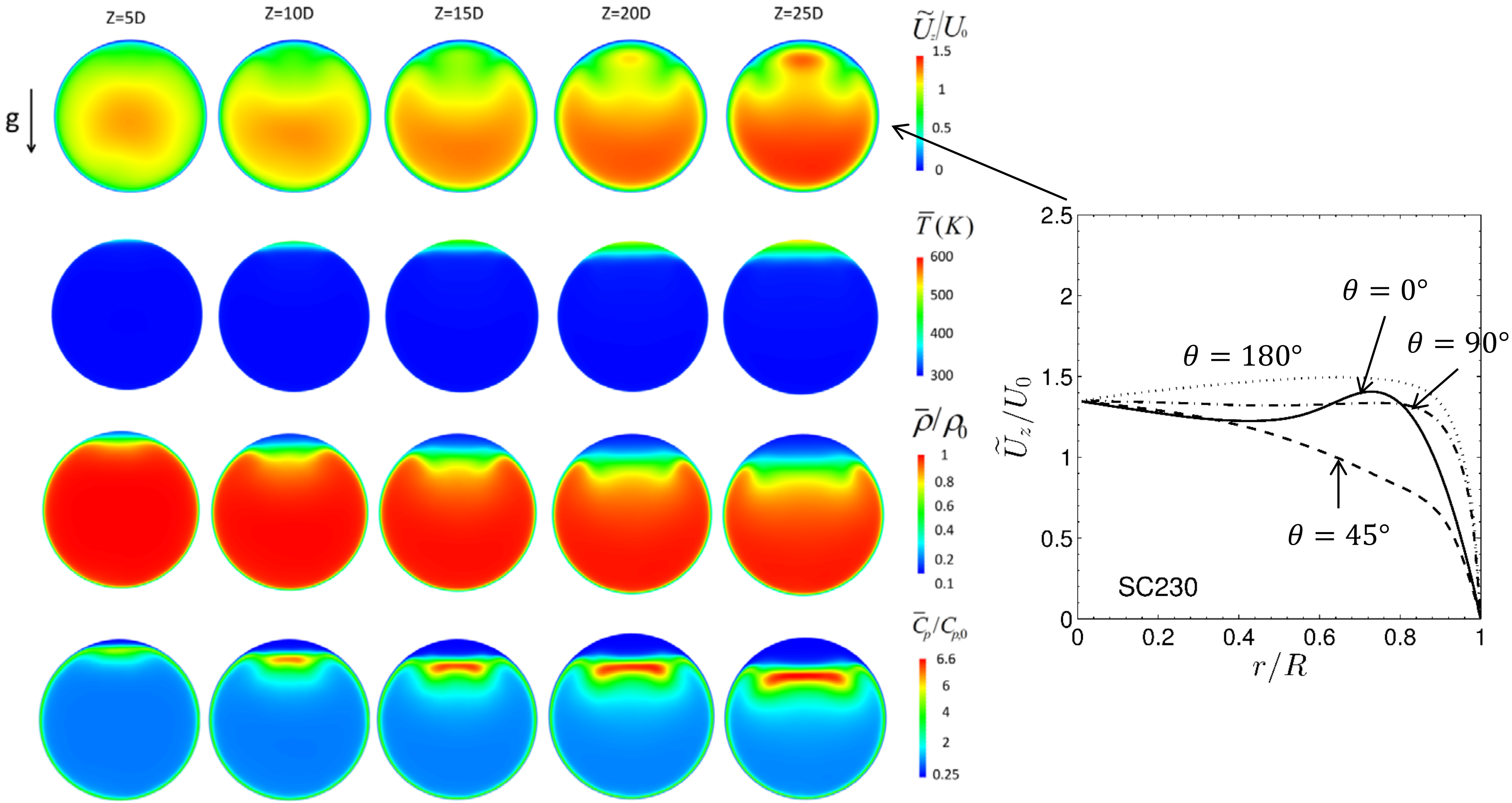


D=2mm, q_w≈60 kW/m²



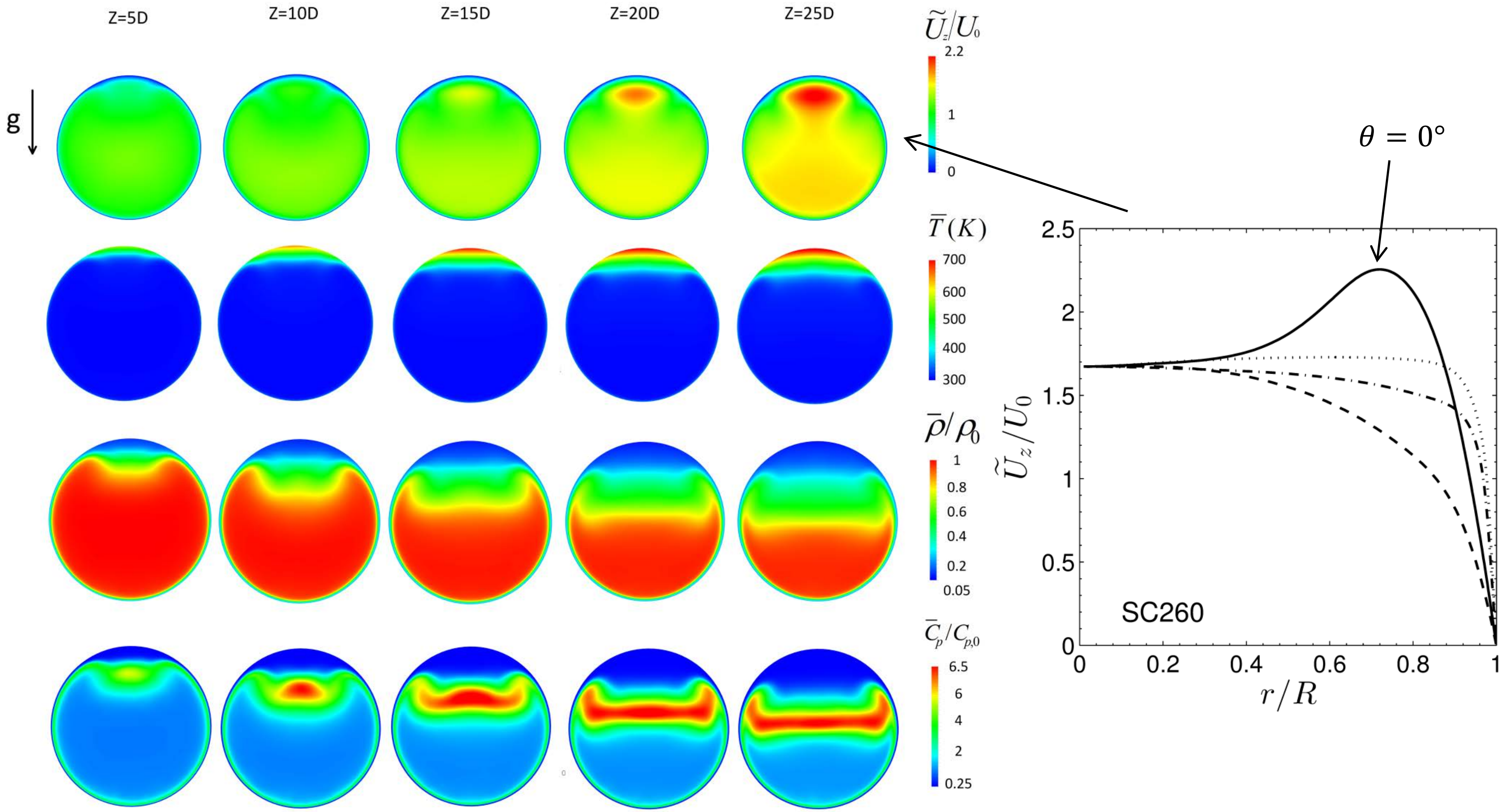
Results and discussion

Flow stratification, SC230, q_w≈30 kW/m^2



Results and discussion

Flow stratification, SC260, q_w≈60 kW/m^2

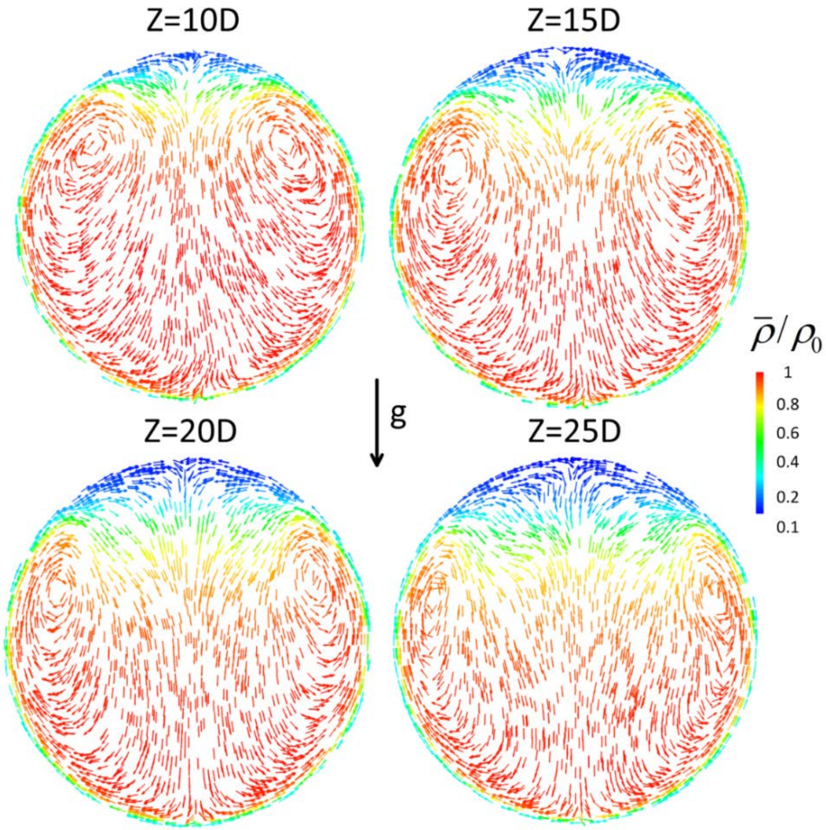


Results and discussion

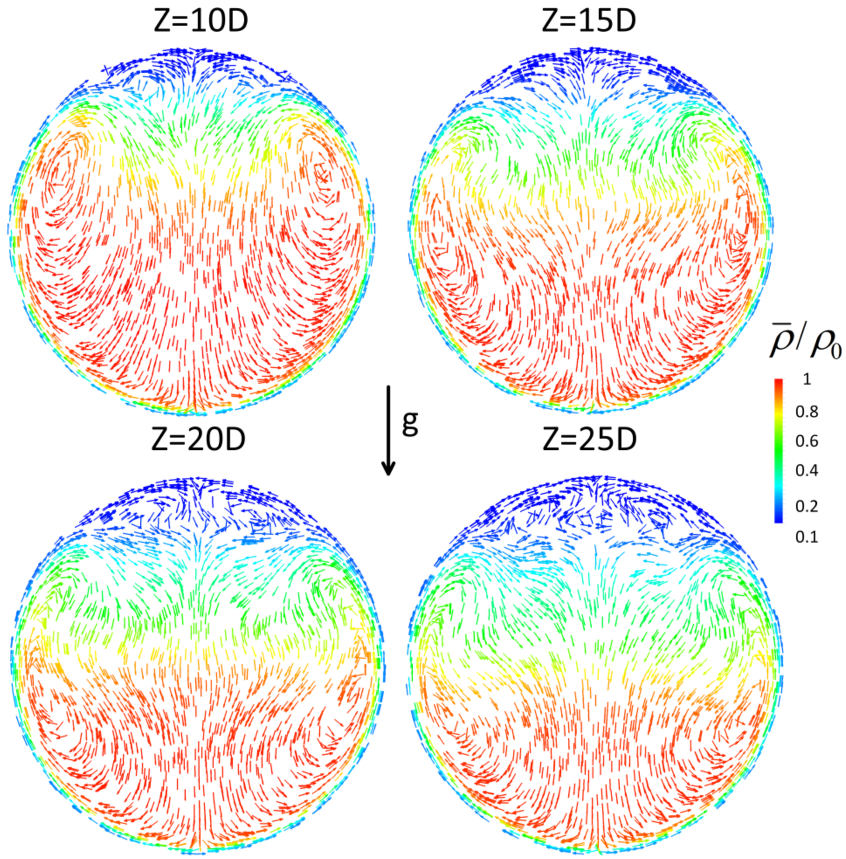
Secondary flow

Vector plot of $\widetilde{U_r}$ and $\widetilde{U_\theta}$

SC230



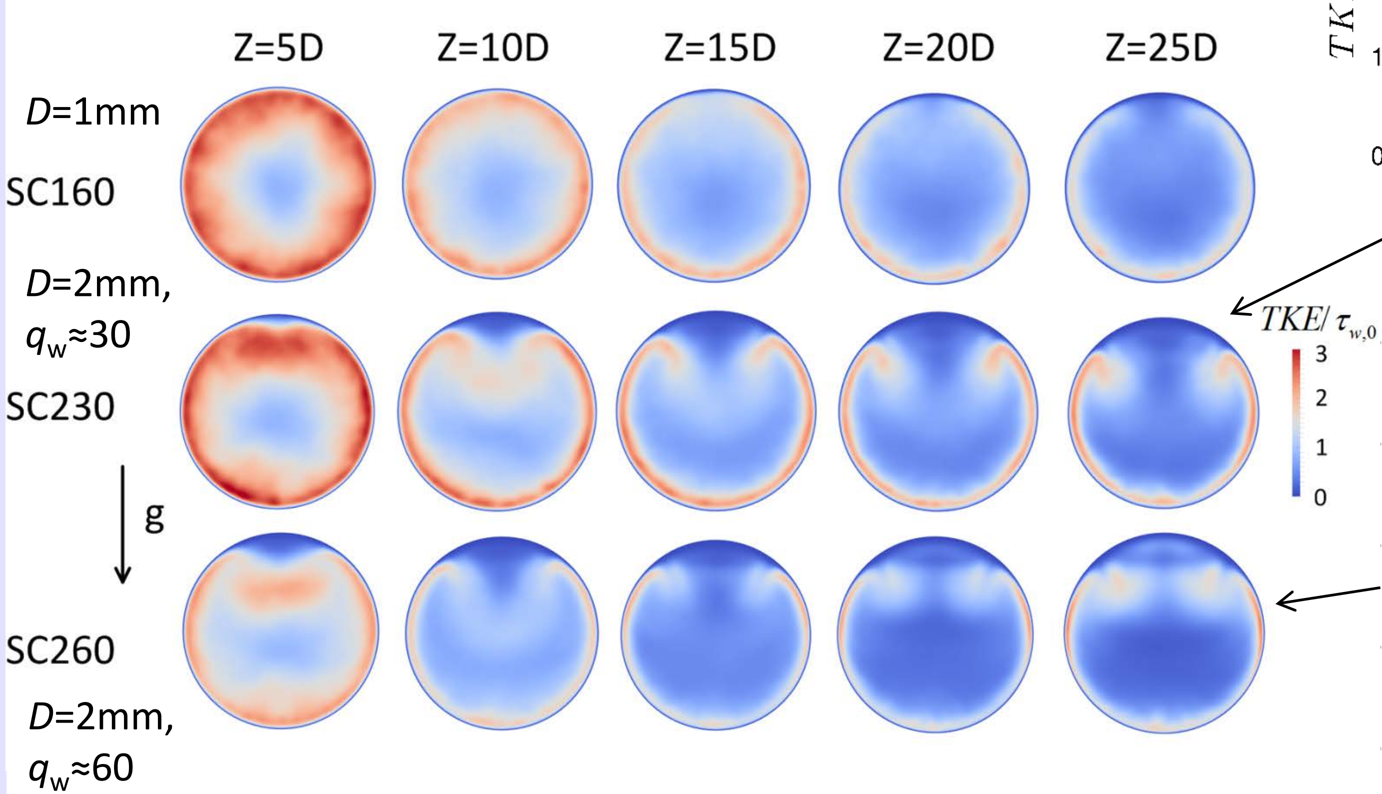
SC260

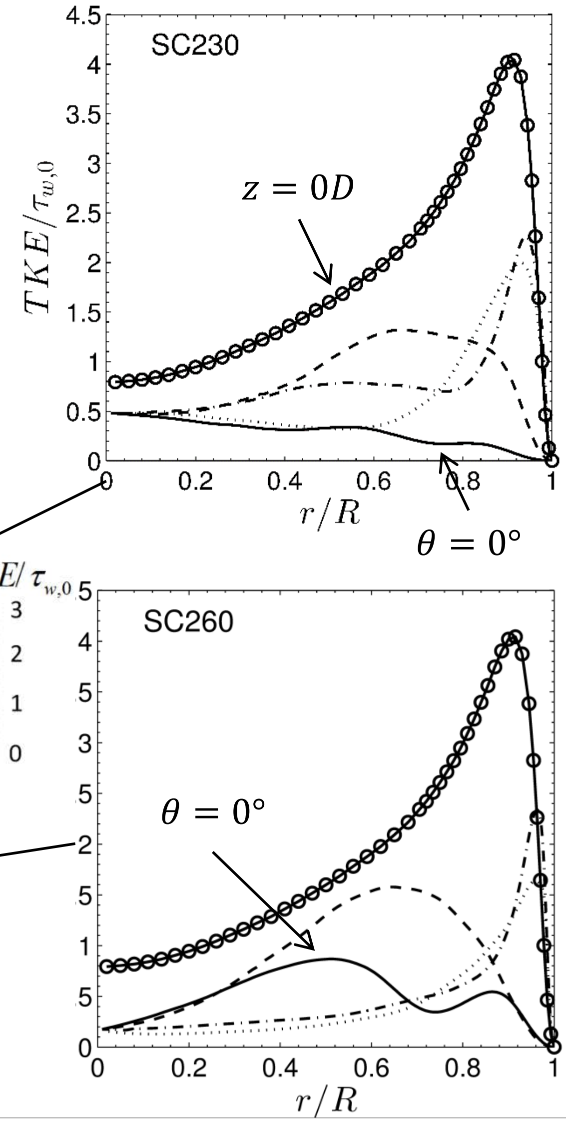


Results and discussion

Turbulence statistics

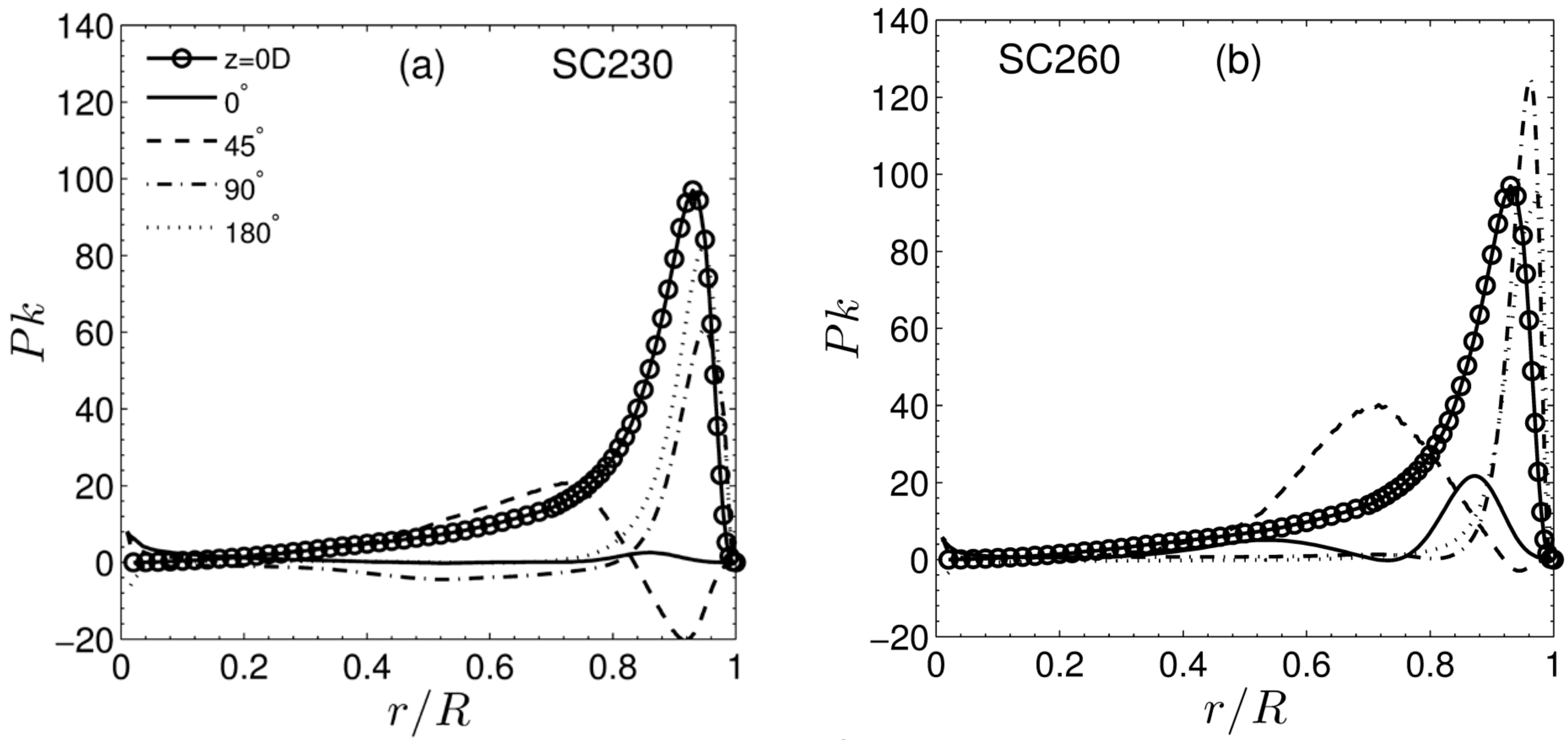
$$TKE = \frac{1}{2}\overline{\rho U_i'' U_i''}$$

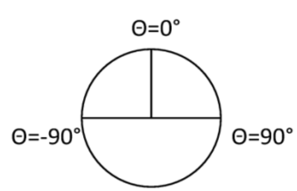




Results and discussion

Turbulence statistics





Conclusions

- Effect of buoyancy to the heat transfer of sCO2 in a horizontal pipe using DNS
- Wall temperature T_w and skin friction coefficient strongly inhomogeneous in the circumferential direction
- Secondary flow is built up due to density difference and it transports the heated fluid to the top surface
- Modified mean velocity field and turbulence field

Thank you for your attention.