Universität Stuttgart
Institut für Kernenergetik
und Energiesysteme

Direct Numercal Simulation of Flow and Heat Transfer within Channels of a Supercritical CO_2 Cooler

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IKE

sCO2 Europe, Sept. 18-19, 2019, Paris

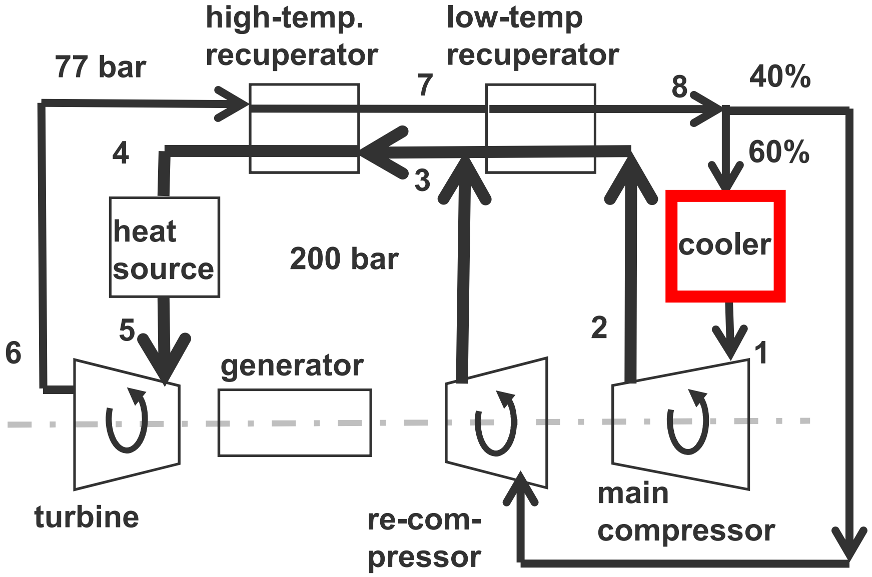
Outline

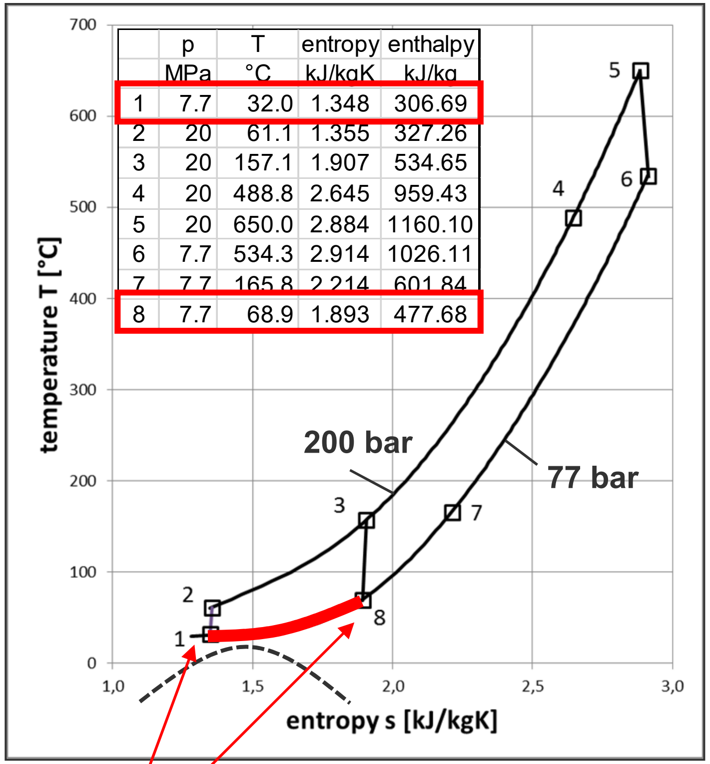
1. Introduction
2. Direct Numerical Simulation
3. Development of a Practical Calculation Method
4. Application to the sCO_2 Cooler
5. Conclusions

Introduction

sCO_2-Recuperative Brayton-Cycle

'Advanced Design' of the MIT-Study by Dostal et al. (2004)



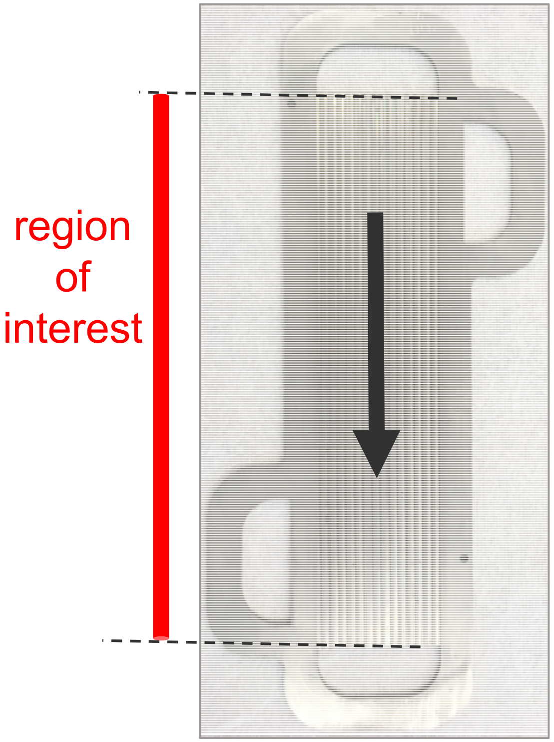


	p	T	entropy	enthalpy
	MPa	°C	kJ/kgK	kJ/kg
1	7.7	32.0	1.348	306.69
2	20	61.1	1.355	327.26
3	20	157.1	1.907	534.65
4	20	488.8	2.645	959.43
5	20	650.0	2.884	1160.10
6	7.7	534.3	2.914	1026.11
7	7.7	165.8	2.214	601.84
8	7.7	68.9	1.893	477.68

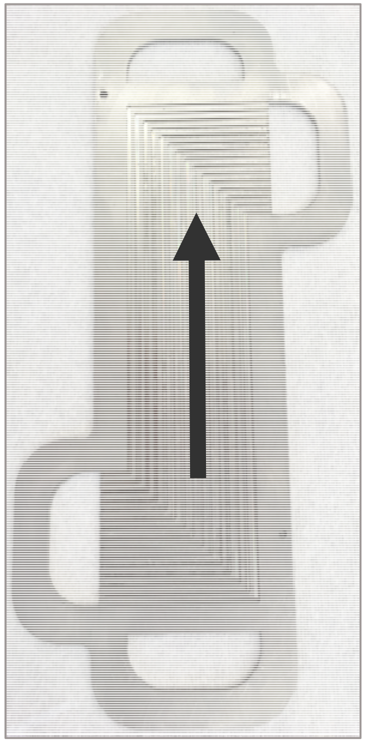
region of interest (cooler)

Compact Heat Exchanger (sCO_2-Cooler of a Brayton Cycle)

Consisting of a stack of plates with machined 1x2 mm channels



primary side
sCO_2

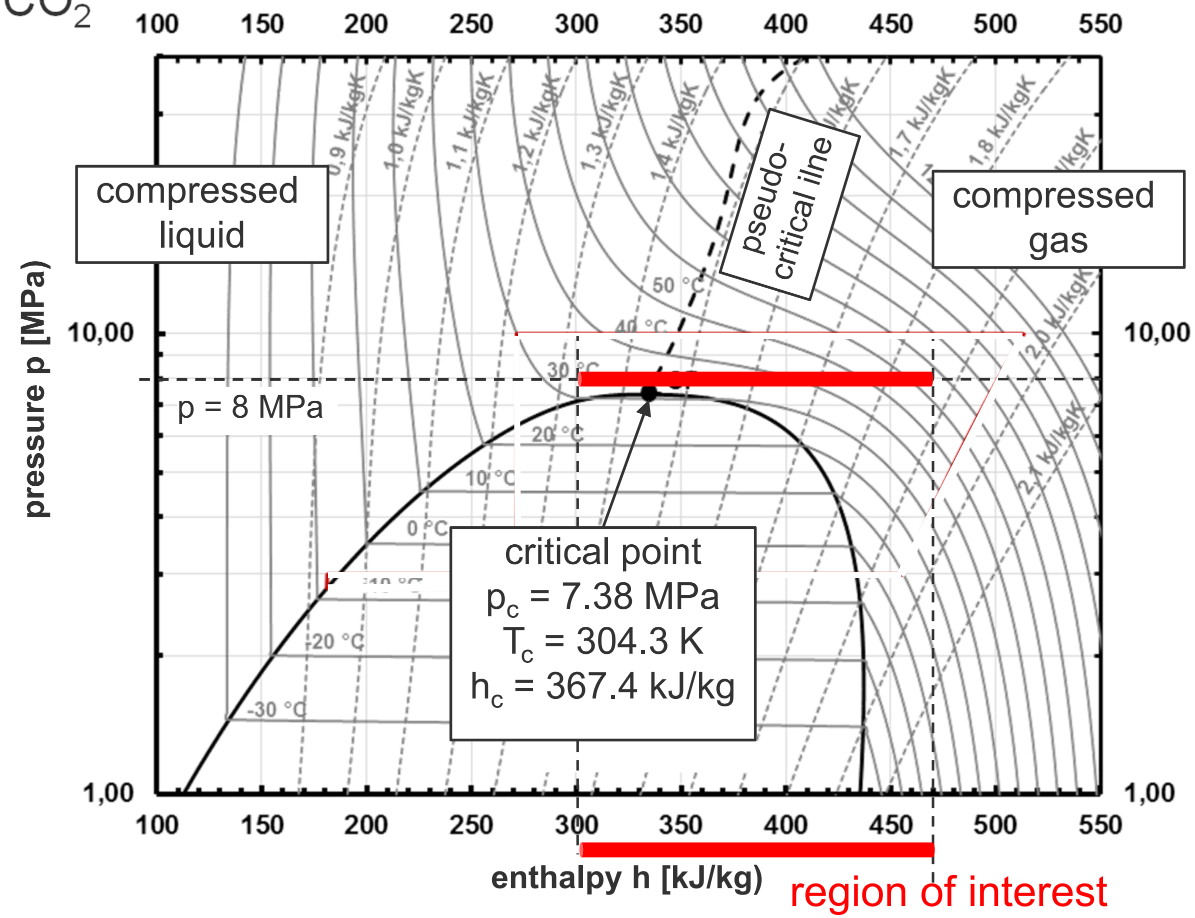


secondary side
e.g. water

manufactured in the Framework
of the European Reseach Project
sCO_2-HeRo (heat removal)

Thermodynamic Definitions

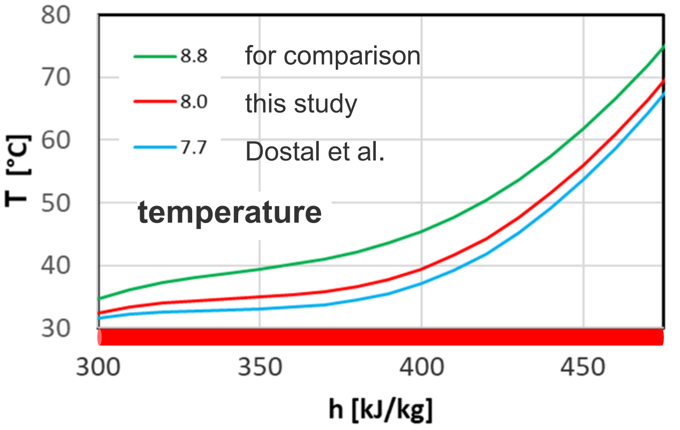
Fluid: CO_2

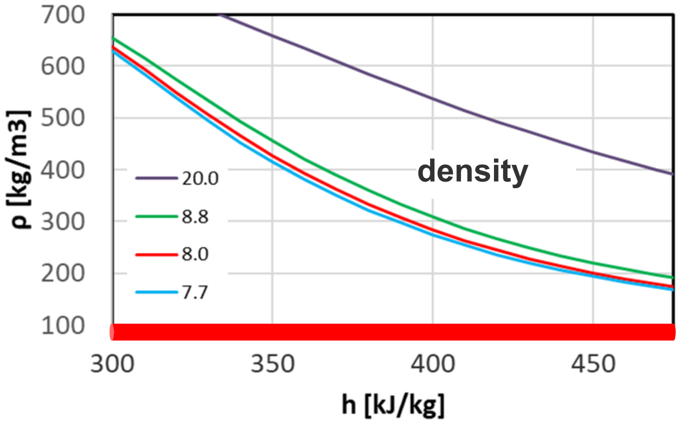


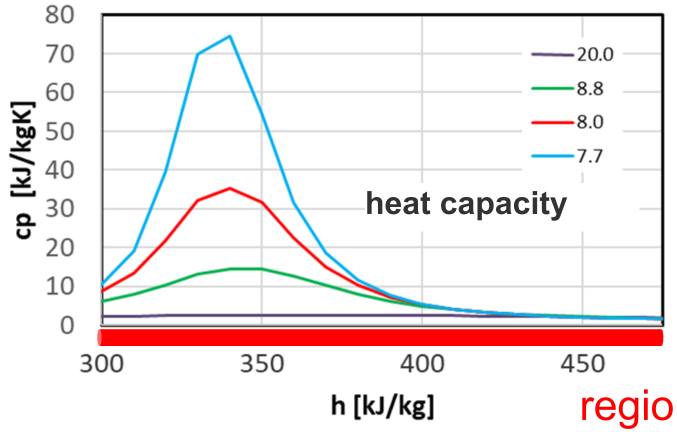
critical point
p_c = 7.38 MPa
T_c = 304.3 K
h_c = 367.4 kJ/kg

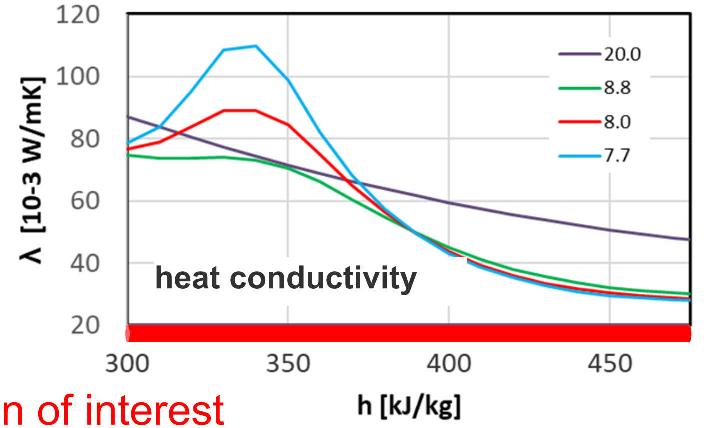
Properties of supercritical CO_2 vs. enthalpy h

at various pressures in MPa (after NIST)









region of interest

Empirical Nusselt-Correlatios

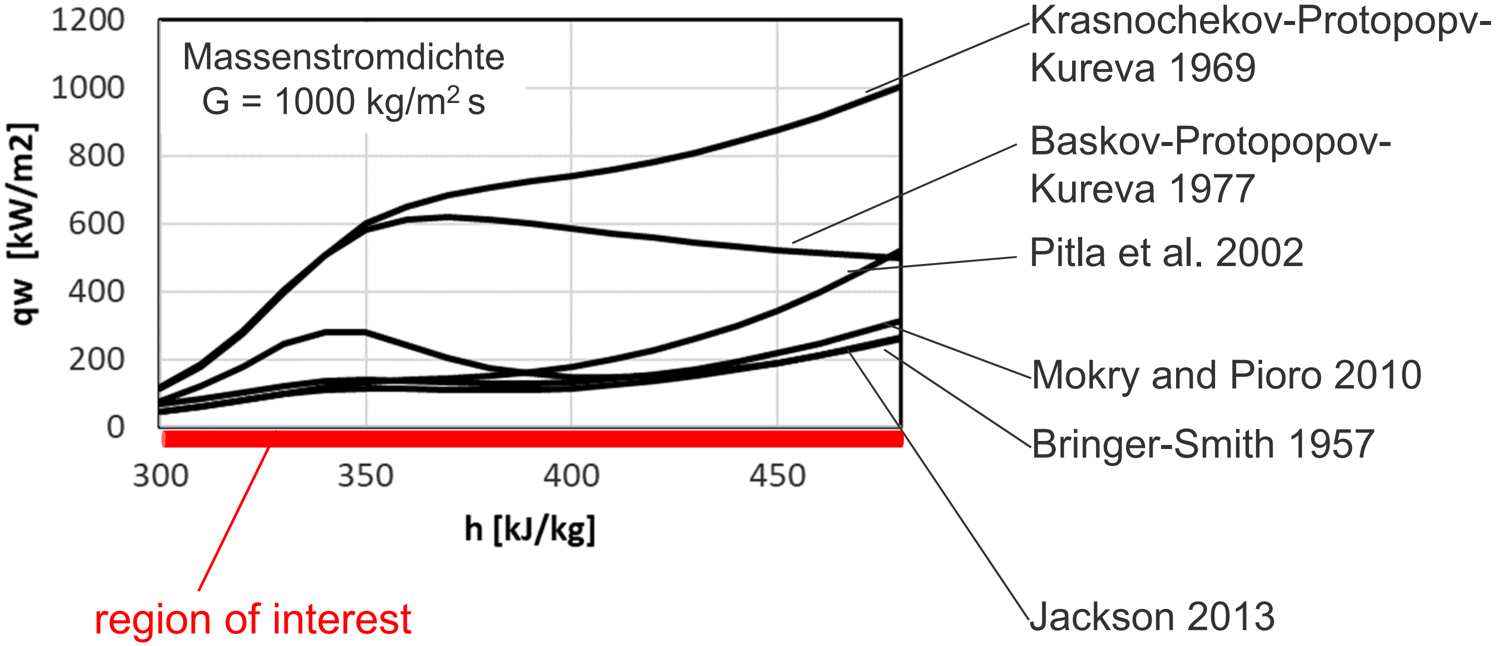
for Pipe Flow with variable properties, no boyancy

Name	Math. Expression
Krasnoshchekov, Protopopov, Kureva (1969)*	$Nu_w = \dfrac{f/8\,\mathrm{Re}_b\,\mathrm{Pr}_b}{1.07+12.7\sqrt{f/8}\left(\mathrm{Pr}_b^{2/3}-1\right)}\left(\dfrac{\rho_w}{\rho_b}\right)^n\left(\dfrac{\bar{c}_p}{c_{p,w}}\right)^m \quad ;n=0.38 \quad ;m=0.75\left(\dfrac{\bar{c}_p}{c_{p,w}}\right)^{0.18}$
Baskov-Protopopov-Kureva (1977)*	$Nu_w = \dfrac{f/8\,\mathrm{Re}_b\,\mathrm{Pr}_b}{1.07+12.7\sqrt{f/8}\left(\mathrm{Pr}_b^{2/3}-1\right)}\left(\dfrac{\rho_w}{\rho_b}\right)^n\left(\dfrac{\bar{c}_p}{c_{p,w}}\right)^m \quad ;n=0.15 \quad ;m=1.4$
Pitla et al.(2002)*	$Nu_b = \left(\dfrac{Nu'_w+Nu'_b}{2}\right)\dfrac{\lambda_w}{\lambda_b}; Nu'_{w,b} = \dfrac{\left(f_{w,b}/8\right)\left(\mathrm{Re}_{w,b}-1000\right)\mathrm{Pr}_{w,b}}{1+12.7\sqrt{f_{w,b}/8}\left(\mathrm{Pr}_{w,b}^{2/3}-1\right)}; f_{w,b} = \left(1.82\log\mathrm{Re}_{w,b}-1.64\right)^{-2}$
Mokry and Pioro (2010)	$Nu_b = 0.0121\,\mathrm{Re}_b^{0.86}\,\overline{\mathrm{Pr}}^{0.23}\left(\dfrac{\rho_w}{\rho_b}\right)^{0.59}$
Bringer-Smith (1957)*	$Nu_b = 0.0375\,\mathrm{Re}_b^{0.77}\,\mathrm{Pr}_w^{0.55}$
Jackson (2013)	$Nu_b = 0.023\,\mathrm{Re}_b^{0.8}\,\mathrm{Pr}_b^{0.3}\left(\dfrac{\rho_w}{\rho_b}\right)^{0.3}$

*L.F. Cabeza, A. de Garcia, A. I. Fernandez, M.M. Farid: Supercritical CO_2 a Heat Transfer Fluid: A Review, Applied Thermal Engineering 125, 799-810 (2017)

Appliocatio of epirical Nusselt-correlations to the cooler

Annahme: 8 MPa, T_w = 25°C



L.F. Cabeza, A. de Garcia, A. I. Fernandez, M.M. Farid: Supercritical CO_2 a heat transfer fluid: A review, Applied Thermal Engineering 125, 799-810 (2017)

Aim of this Work

- Perform DNS for Cooled Pipes
- Understand the Physical Behaviour of Flow Turbulence
- Derive a Practical Heat-Transfer Prediction Method
- Compare to Nusselt Correlations

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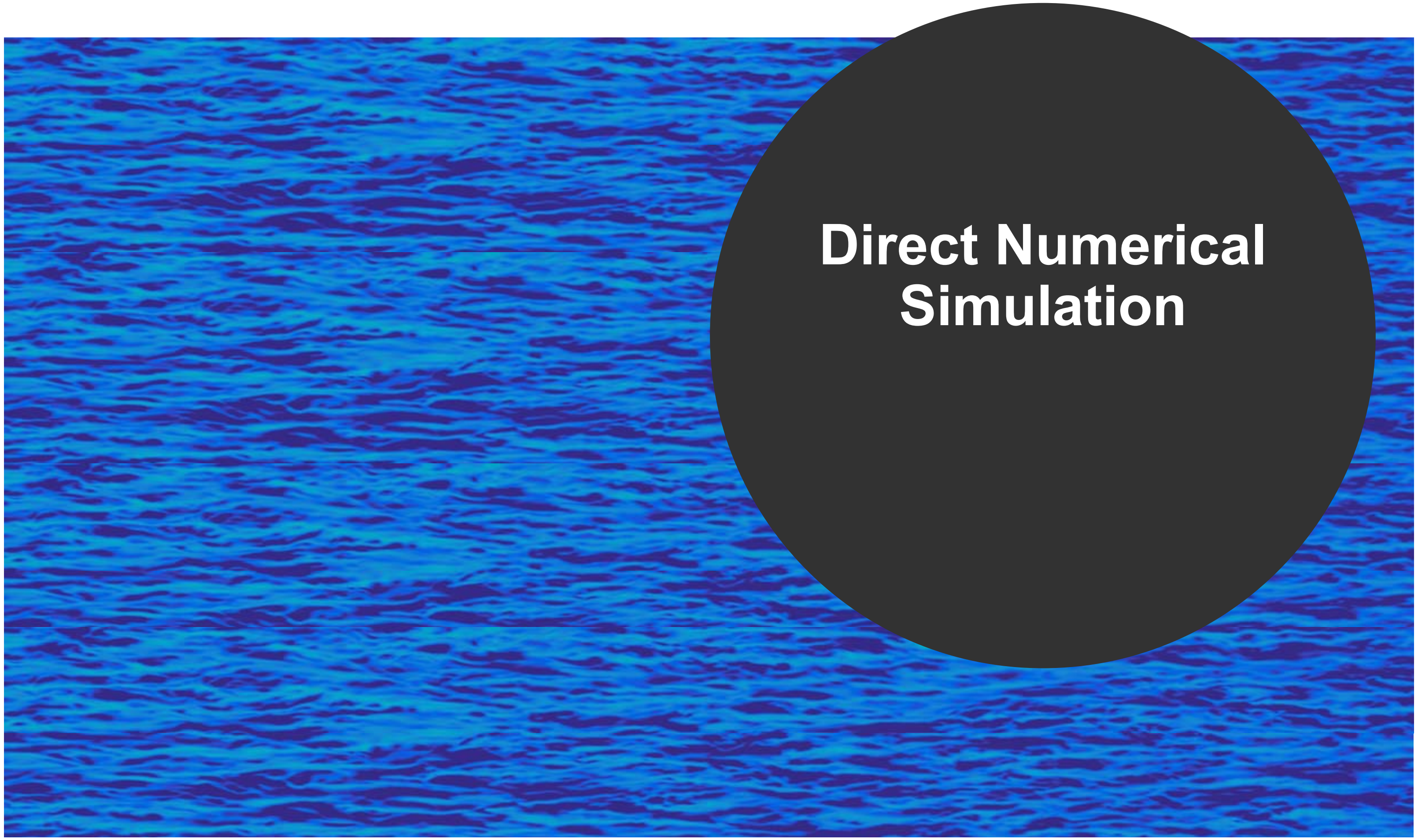
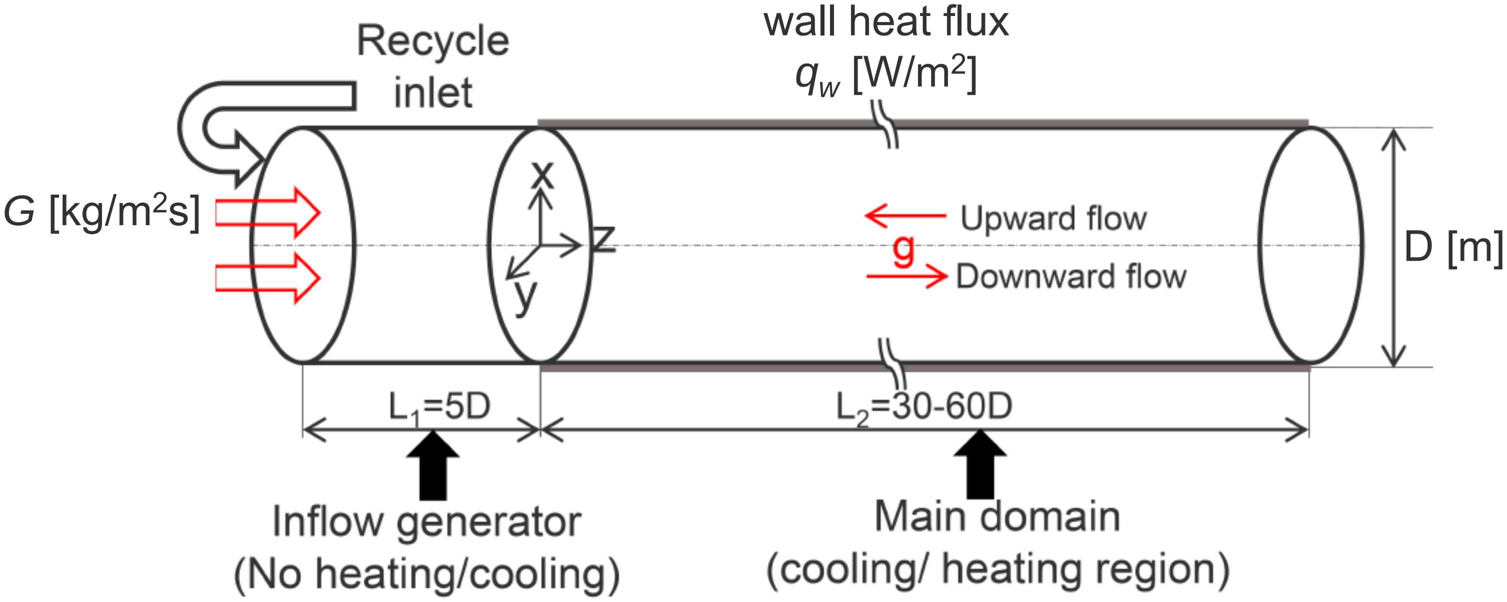


Direct Numerical Simulation

Direct Numerical Simulation (DNS)

Integration of the fundamental Navier-Stokes Equations



Limitation of a DNS: Reynolds Number

$$\boxed{\mathrm{Re} = \frac{G\,D}{\mu} < 6000}$$

Numerical Method : OpenFOAM v 5.0

Low-Mach Number Navier-Stokes Equations
(no disadvantage compared to fully compressible flow*)

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

$$\frac{\partial\left(\rho u_i\right)}{\partial t}+\frac{\partial\left(\rho u_i u_j\right)}{\partial x_j}=\rho g_i e_{ax}-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)$$

$$e_{ax}=\left\langle\begin{array}{ll}1 & \textit{upward}\\ -1 & \textit{downward}\\ 0 & \textit{gravity off}\end{array}\right.$$

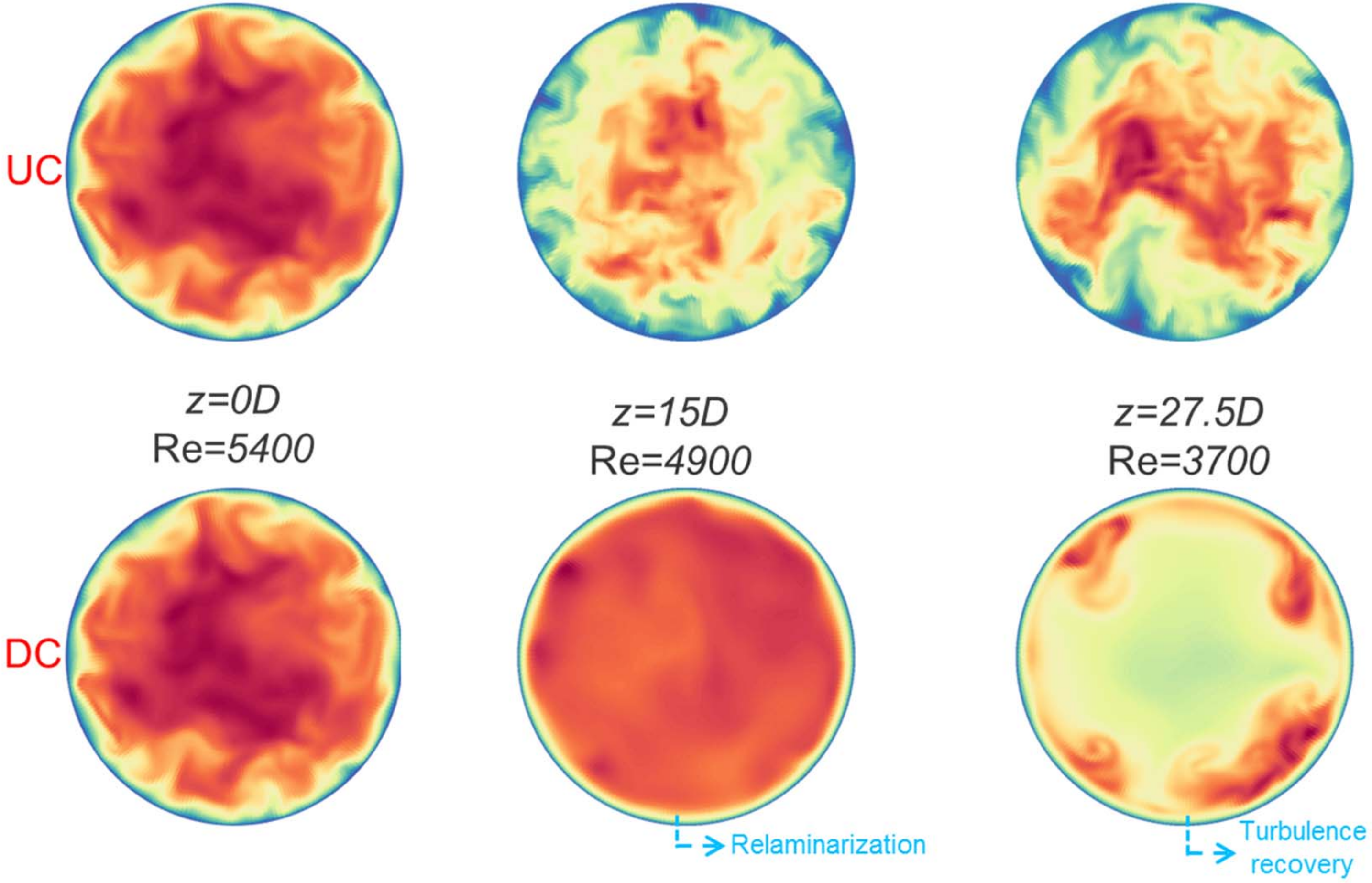
$$\frac{\partial\left(\rho h\right)}{\partial t}+\frac{\partial\left(\rho u_j h\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\lambda\frac{\partial T}{\partial x_j}$$

$$\rho=\rho(h);\ \lambda=\lambda(h);\ \mu=\mu(h);\ T=T(h)$$

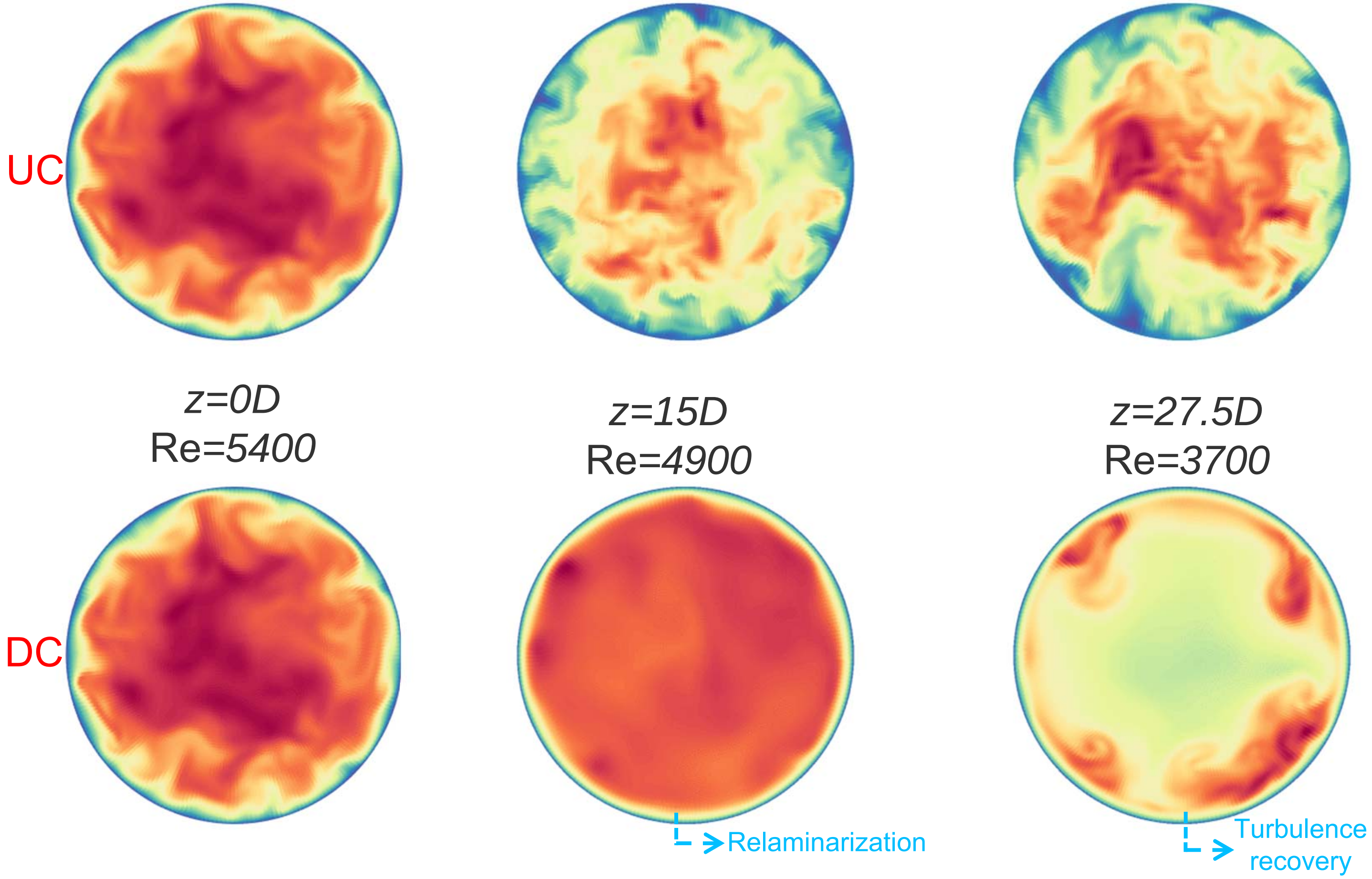
- properties fitted by spline functions to NIST
- Semi-implicit coupling of pressure and velocity (PISO)
- 2nd order accuracy in space and time

*F. Föll, S. Pandey, X. Chu, C.-D. Munz, E. Laurien, B. Weigand, "High-fidelity direct numerical simulation of supercritical channel flow using discontinuous Galerkin spectral element method", Transactions of the High Performance Computing Center, Stuttgart (HLRS) 2018, **Springer International Publishing**, 2018

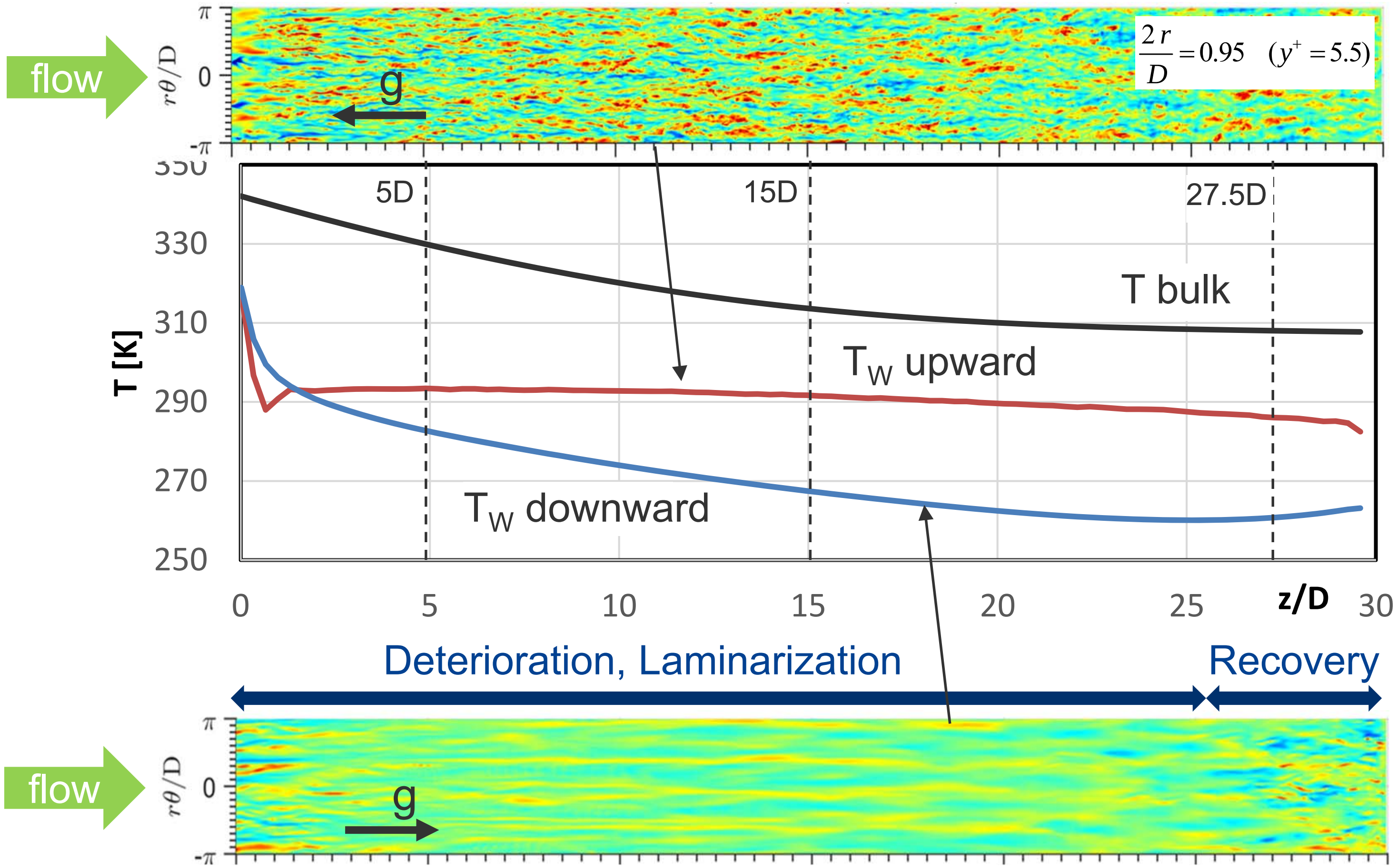
Instantaneous velocity field, wall heated



Instantaneous velocity field, wall heated



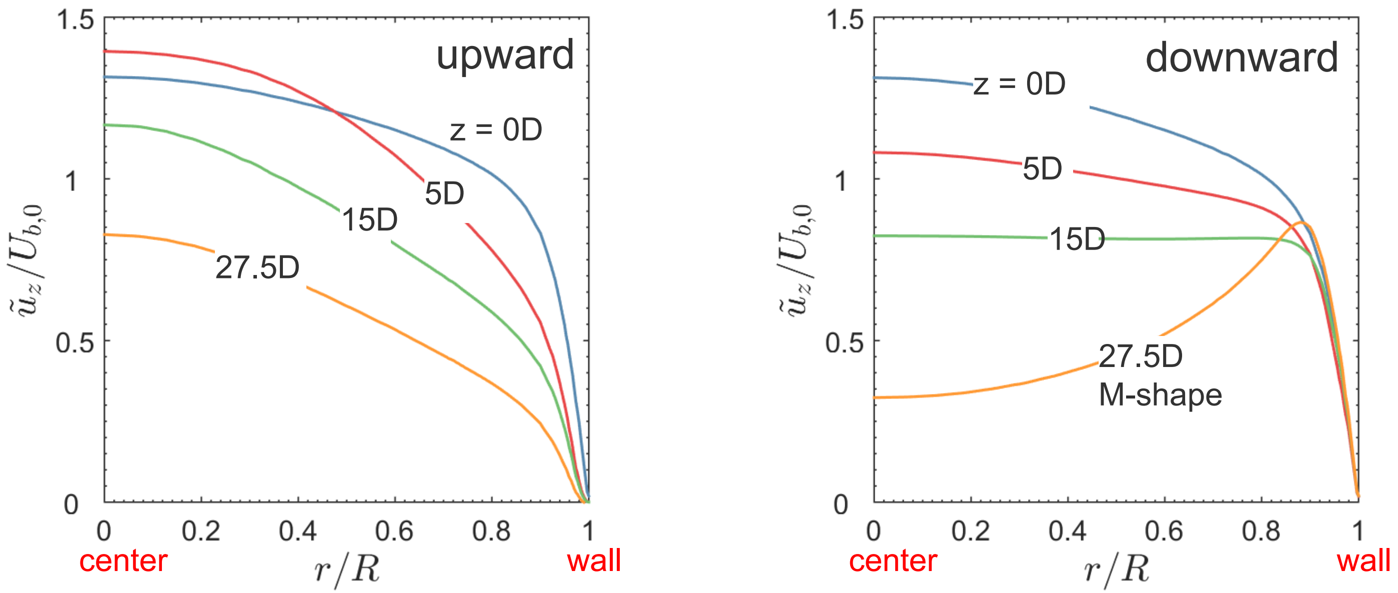
Near-Wall Turbulence Structures



near-wall longitudinal streaks

breakup of streaks

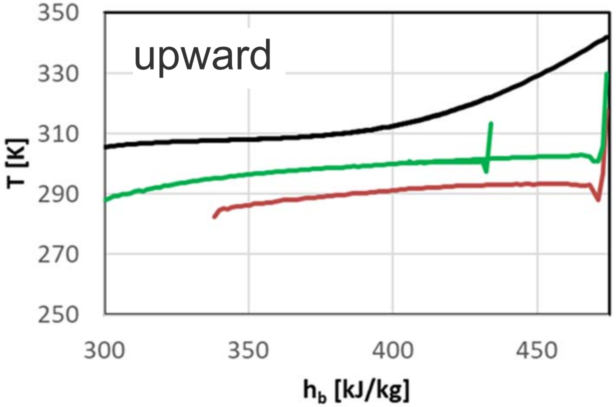
Radial Velocity Profile u_z, Wall Cooling

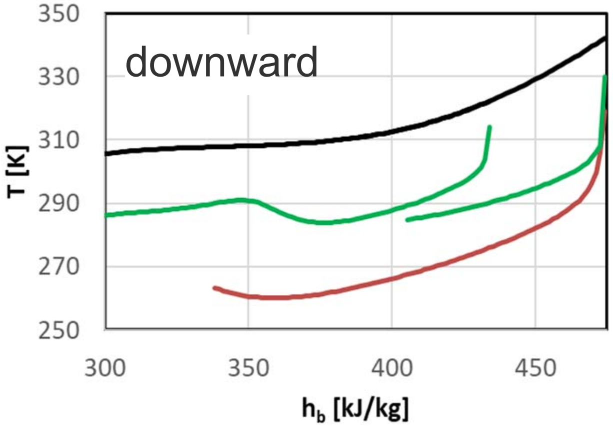


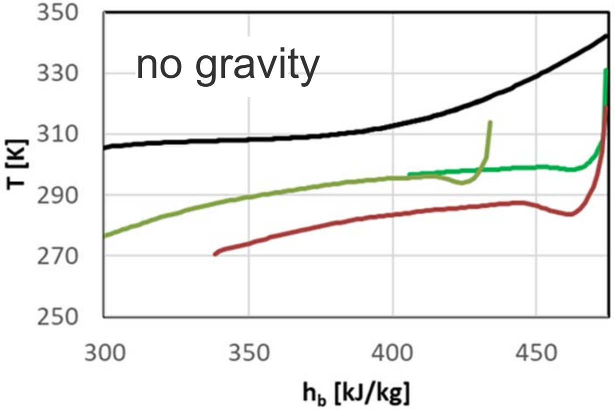
- Overall flow deceleration along the streamwise direction
- Transformation into ‘M’ shape velocity profile for downward flow

Presentation of the Computes Wall Temperature

two cooling rates: -30.87 kW/m^2 and -61.74 kW/m^2







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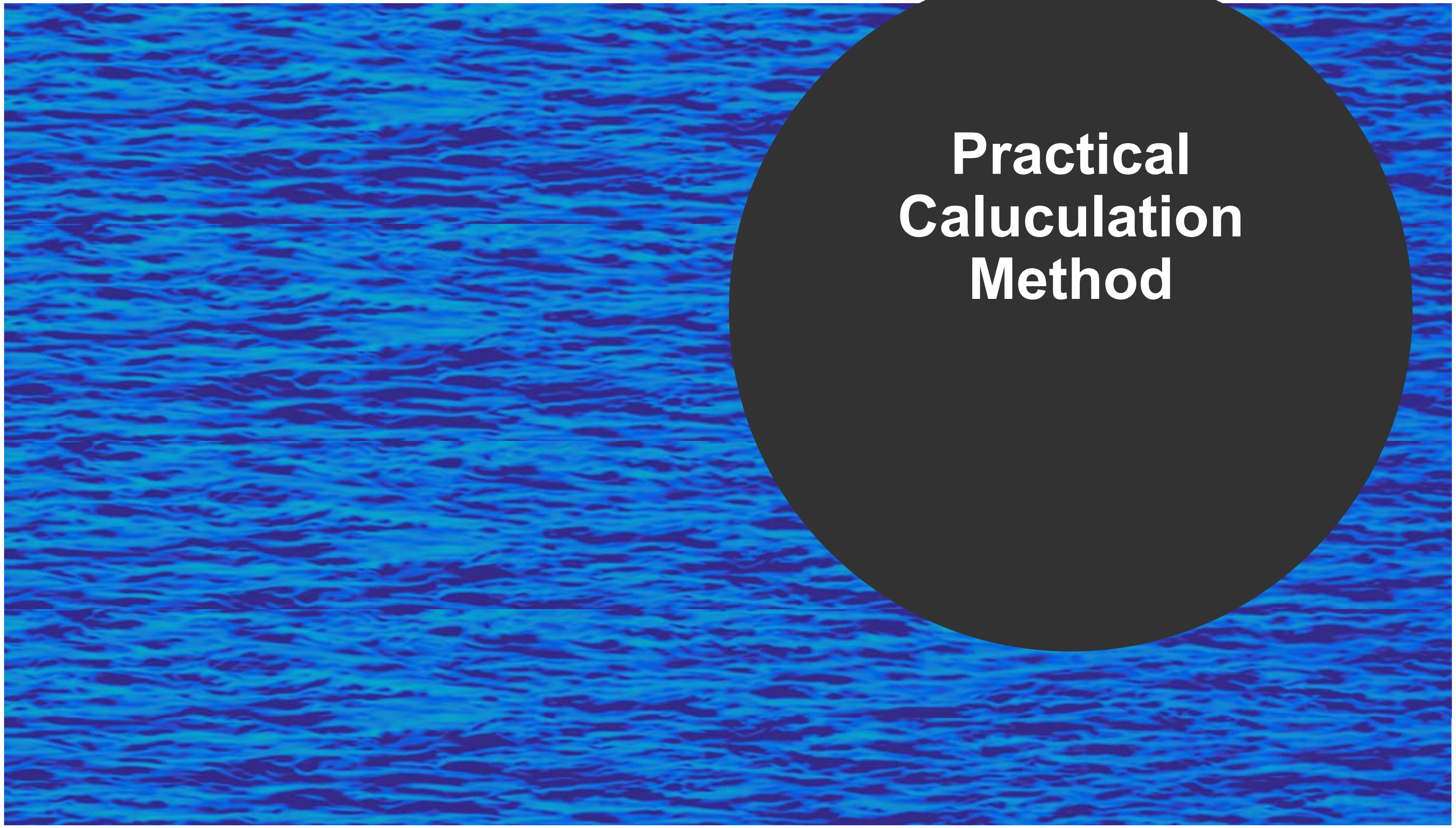
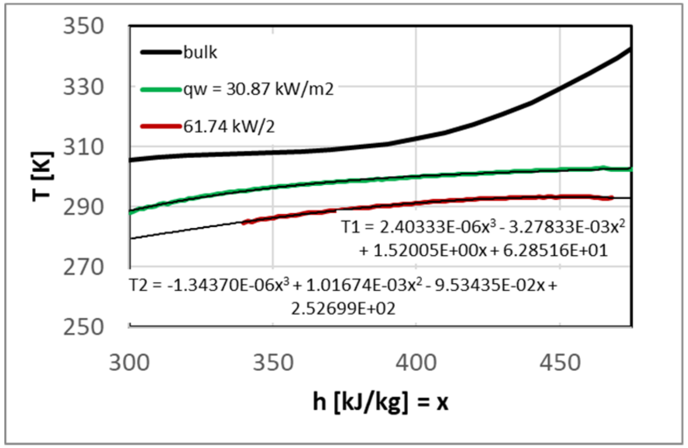
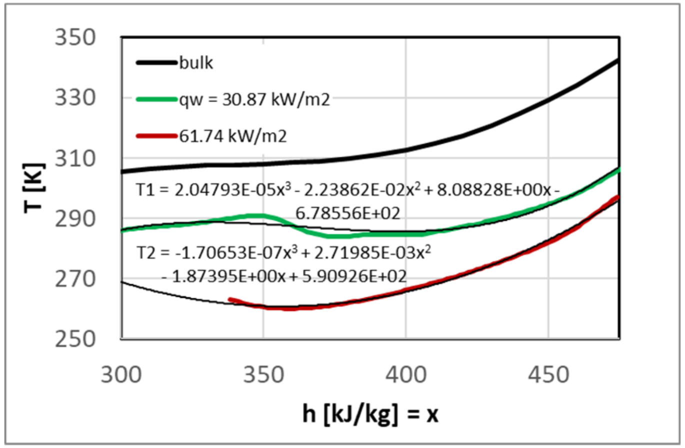


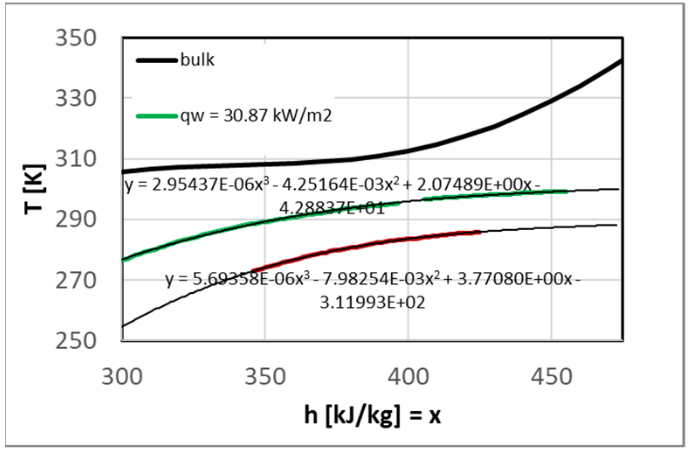
Practical Caluculation Method

Approximation by Polynomials

G = 53.7 kg/m^2s, p = 8 MPa, D = 2 mm

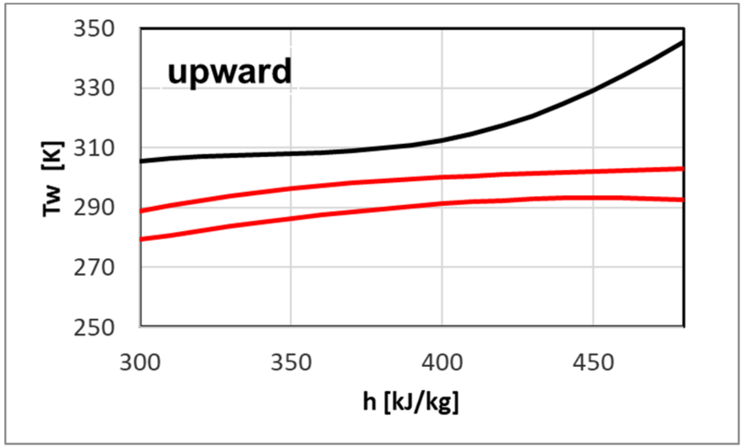


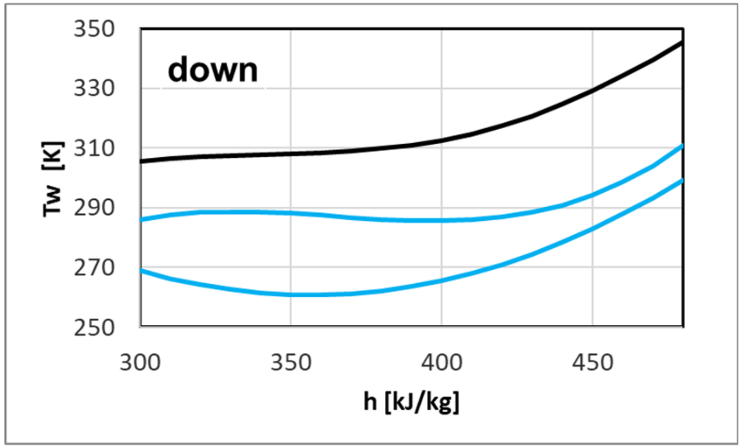


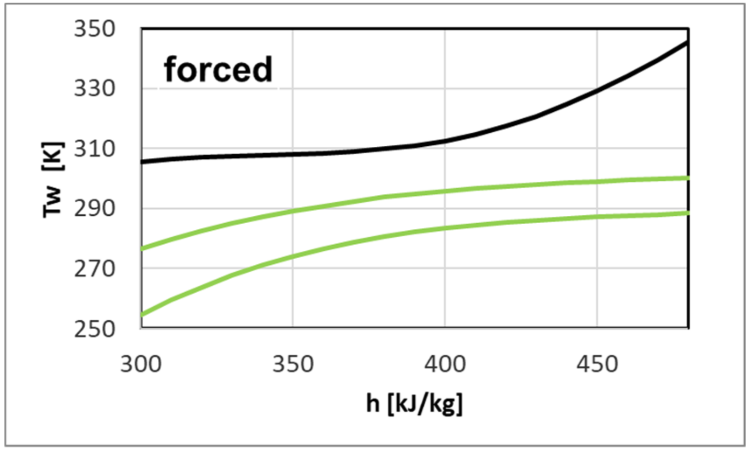


Polynomial Curve Fit

Wall Cooling, G = 53.7 kg/sm^2, p = 8 MPa, D = 2 mm







Piecewise Linear Interpolation Formulas for q_w

at h = const

From given

$$T_0 = T(q_0 = 0) = T_b$$
$$T_1 = T_w(q_1)$$
$$T_2 = T_w(q_2)$$

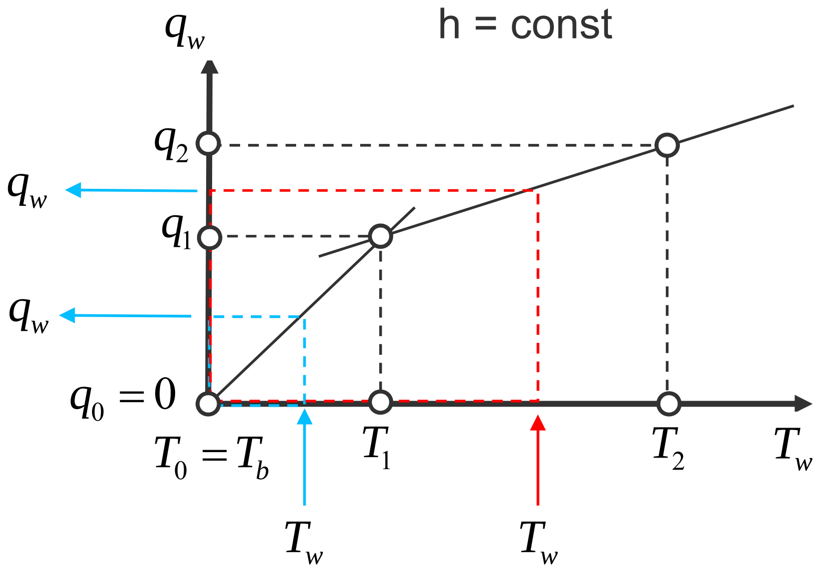
we get

$$q_w(T_w) = q_1$$
$$+L_{01}\left(q_0 - q_1\right)$$
$$+L_{12}\left(q_2 - q_1\right)$$

with

$$L_{01} = \max\left(\frac{T_w - T_1}{T_0 - T_1}, 0\right)$$

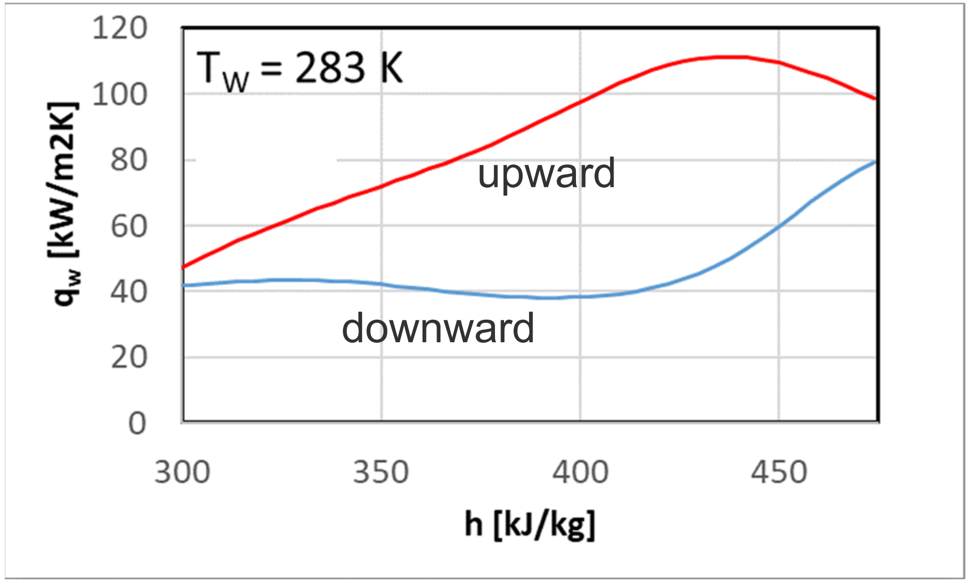
$$L_{12} = \max\left(\frac{T_w - T_1}{T_2 - T_1}, 0\right)$$



Interpolation of DNS Results for Wall Cooling

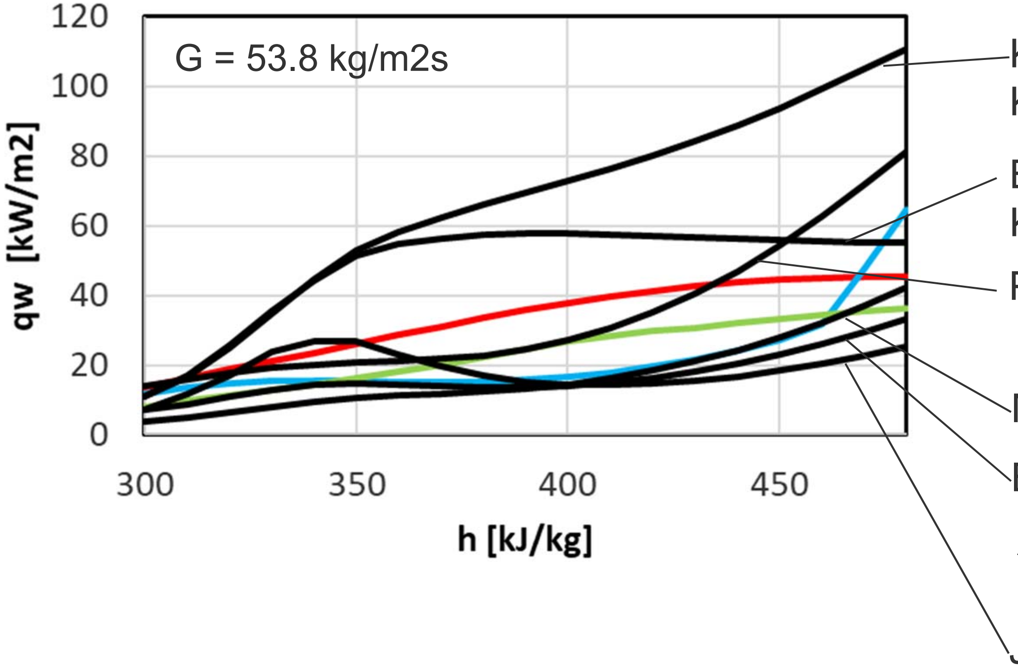
80 bar, D = 2 mm

Distribution of the wall heat flux with given wall temperature T_w



Vergleich: DNS Ergebnisse mit empirischen Nusselt Korrelationen

Kühler-Bereich, 8 MPa, T_w = 25°C



Krasnochekov-Protopopv-Kureva 1969

Baskov-Protopopov-Kureva 1977

Pitla et al. 2002

Mokry and Pioro

Bringer-Smith 1957

$$Nu = 0.0375\,\mathrm{Re}_b^{0.77}\,\mathrm{Pr}_w^{0.55}$$

Jackson 2013

Nusselt-Korrelationen aus:

L.F. Cabeza, A. de Garcia, A. I. Fernandez, M.M. Farid: Supercritical CO_2 a heat transfer fluid: A review, Applied Thermal Engineering 125, 799-810 (2017)

DNS aufwärts

DNS abwärts

DNS ohne Schwerkraft

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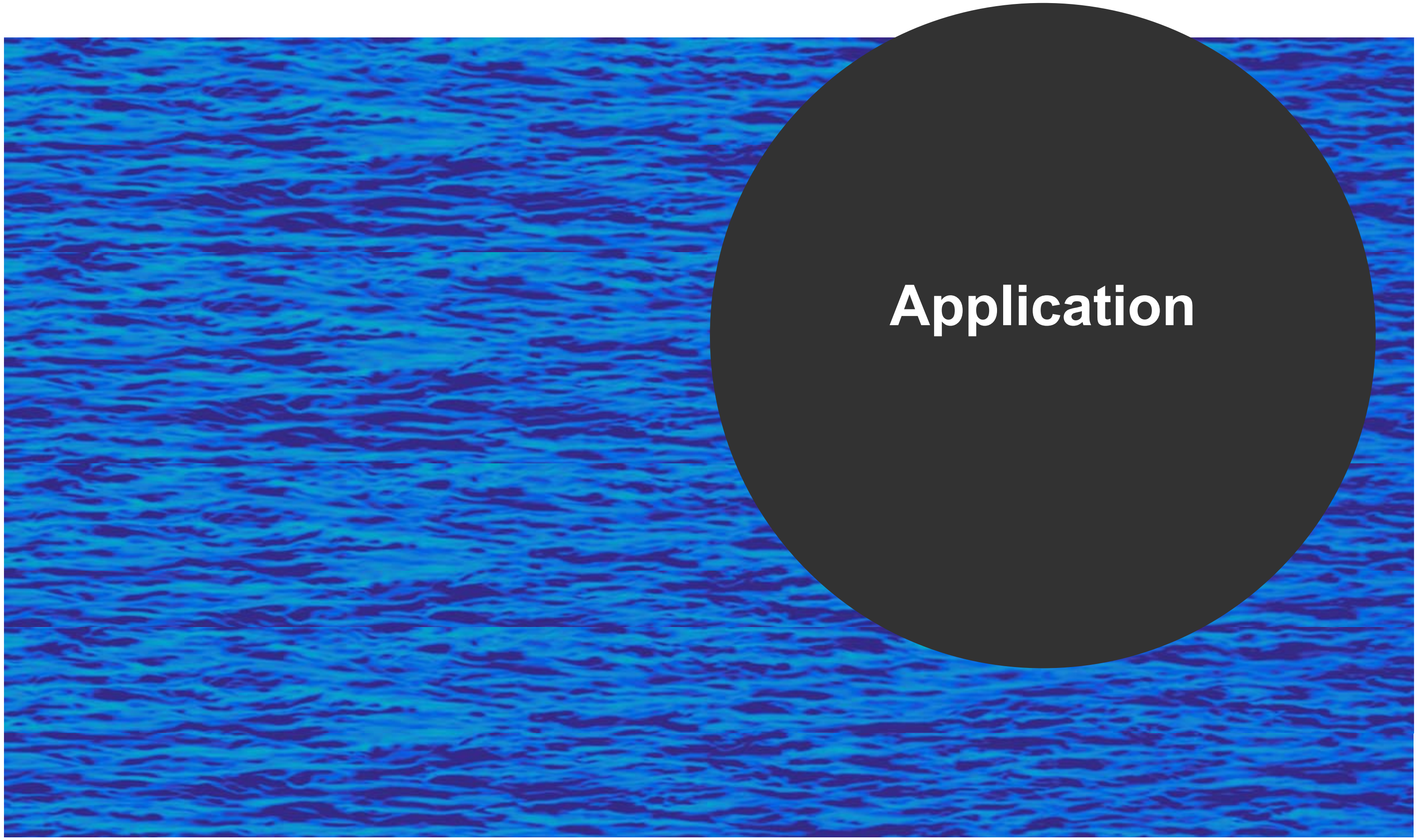
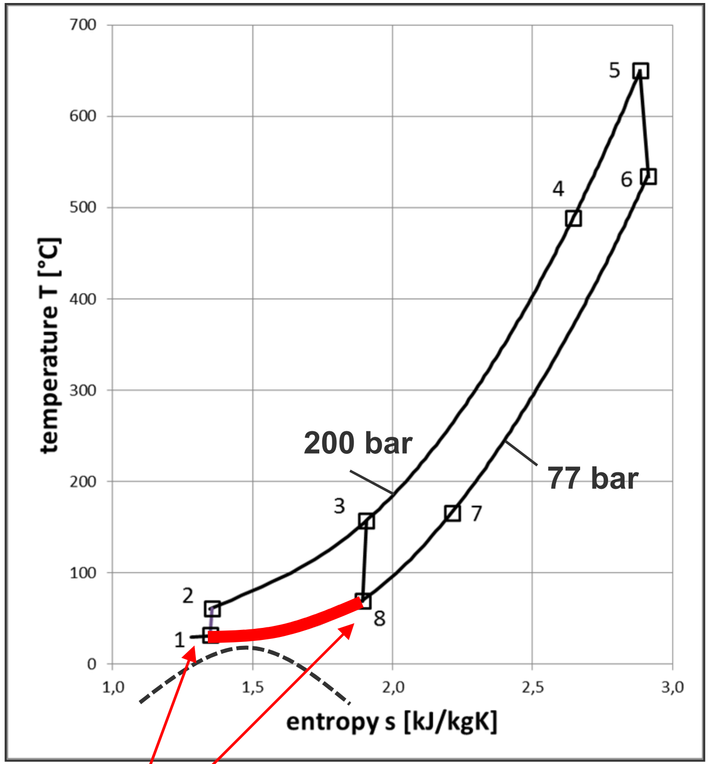


Application

sCO$_2$-Recuperativer Joule(Brayton)-Zyklus

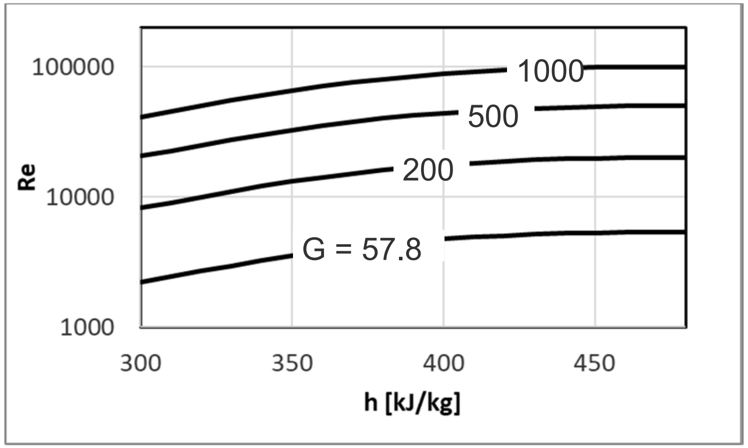
'Advanced Design' of the MIT-Studie by Dostal et al. (2004)



region of interest (cooler)

Wann spielt Auftrieb eine Rolle ?

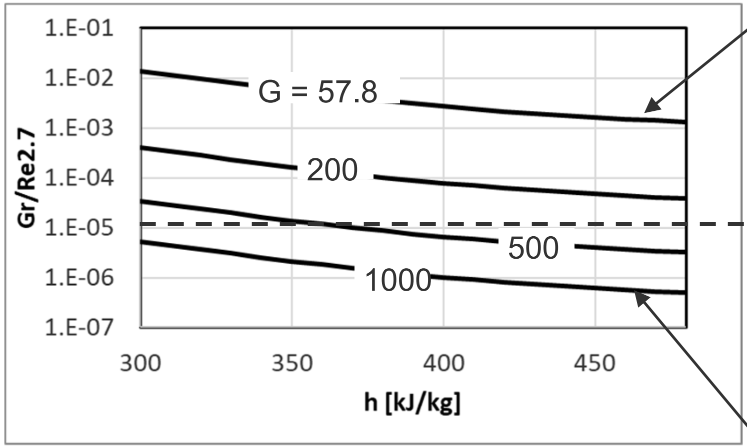
bei unterschiedlichen Massenstömen G [kg/m^{2}s]



Jackson-Kriterium:
Auftrieb spielt nur dann
eine Rolle, wenn

$$\boxed{\frac{\mathrm{Gr}}{\mathrm{Re}^{2.7}} > 10^{-5}}$$

Gr: Grashofzahl
Re: Reynoldszahl



unsere
DNS-Rechnungen
G = 57.8 kg/m^{2}s

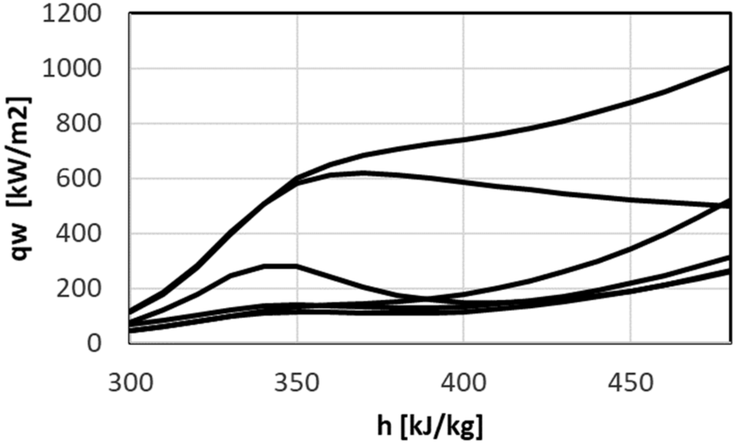
Auftrieb spielt
<u>keine</u> Rolle
(aber: Beschleunigung
bzw. Verzögerung und Variation
der Stoffeigenschaften)

Anwendung

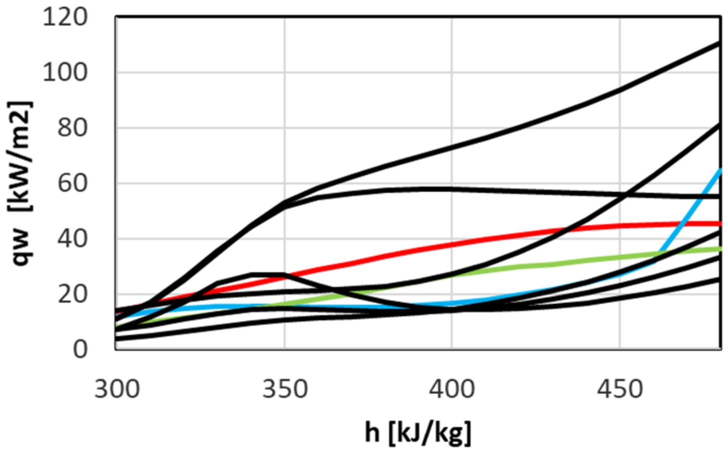
Vergleich der Korrelationen und der DNS mit unterschiedlichen Massenstromdichten G

Kühler, 8 MPa

G = 1000 kg/m^2 s



G = 53.8 kg/m^2 s



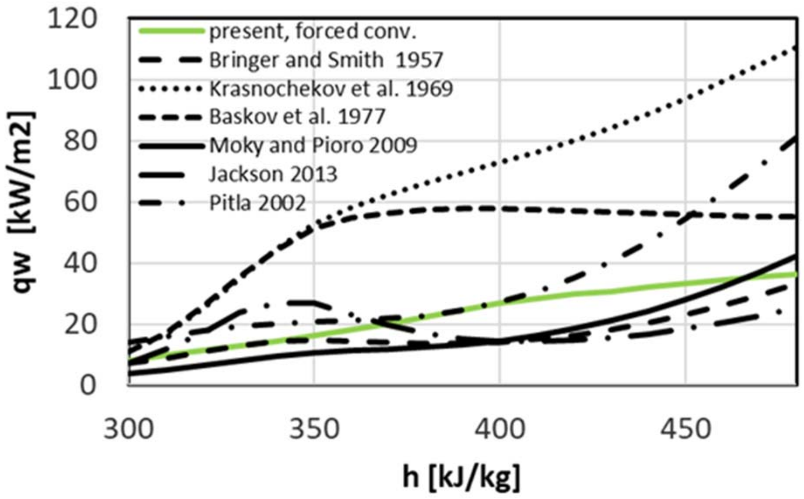
nächster Schritt: Aufstellung eines Skalierungsgesetzes

q_w (G)   oder   Nu (Re)

DNS aufwärts
DNS abwärts
DNS ohne Schwerkraft

Compare Directly to Correlations

here: forced convection (no gravity), cooling



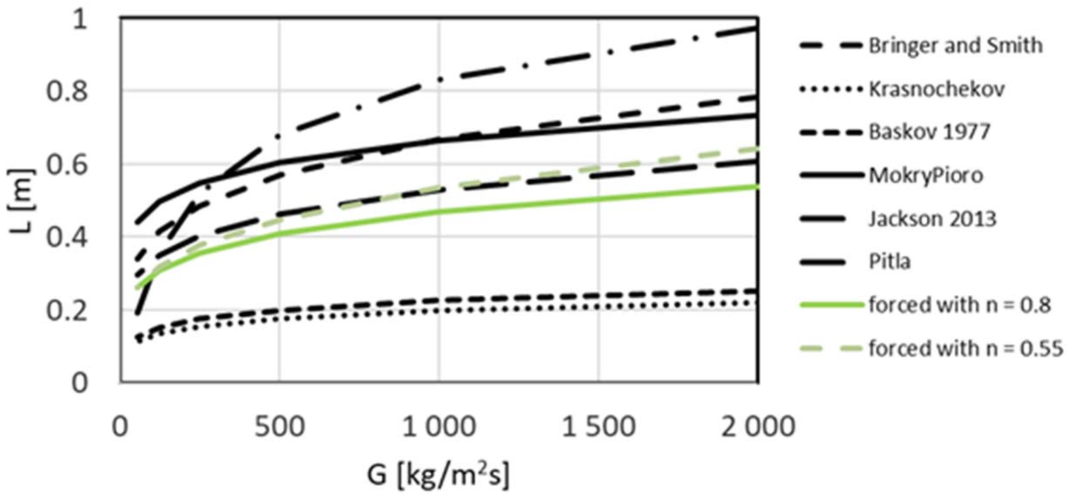
Authors	year	n
Bringer & Smith	1957	**0.77**
Yoon et al.	2003	**0.69**
Son and Park	2006	**0.55**
Oh and Son	2010	**0.7**
Jackson	2002	**0.82**
Huai and Koyama	2007	**0.8**
Lee et al.	2013	**0.56**
Saltanov	2015	**0.823**
Simoes et al.	2008	**0.8**

$$\mathrm{Nu}_b = \frac{q_w\, D}{\left(T_b - T_w\right)\lambda_b} = C\,\mathrm{Re}_b^n\,\mathrm{Pr}_b^m \left(\frac{\rho_b}{\rho_w}\right)^p \left(\frac{\mu_b}{\mu_w}\right)^s$$

Minimum Cooler Length L

8 MPa T_w = 283 K

$$L = \frac{G \cdot D}{4} \int_{h_{in}}^{h_{out}} \frac{1}{q_w} dh \quad .$$



Conclusions

- new DNS data for the enthalpy-region of the cooler available
- physical mechanisms of turbulence identified
- correlation method for G = 53.8 kg/m2s derived (up, down, forced)
- first attempt for scaling to larger G for forced convection
- work is important to reduce scatter in prediction methods (e.g. for the minimum cooler length)

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Thank you for your attention!

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