The Dominant Thermal Resistance Approach for Heat Transfer to Supercritical-Pressure Fluids

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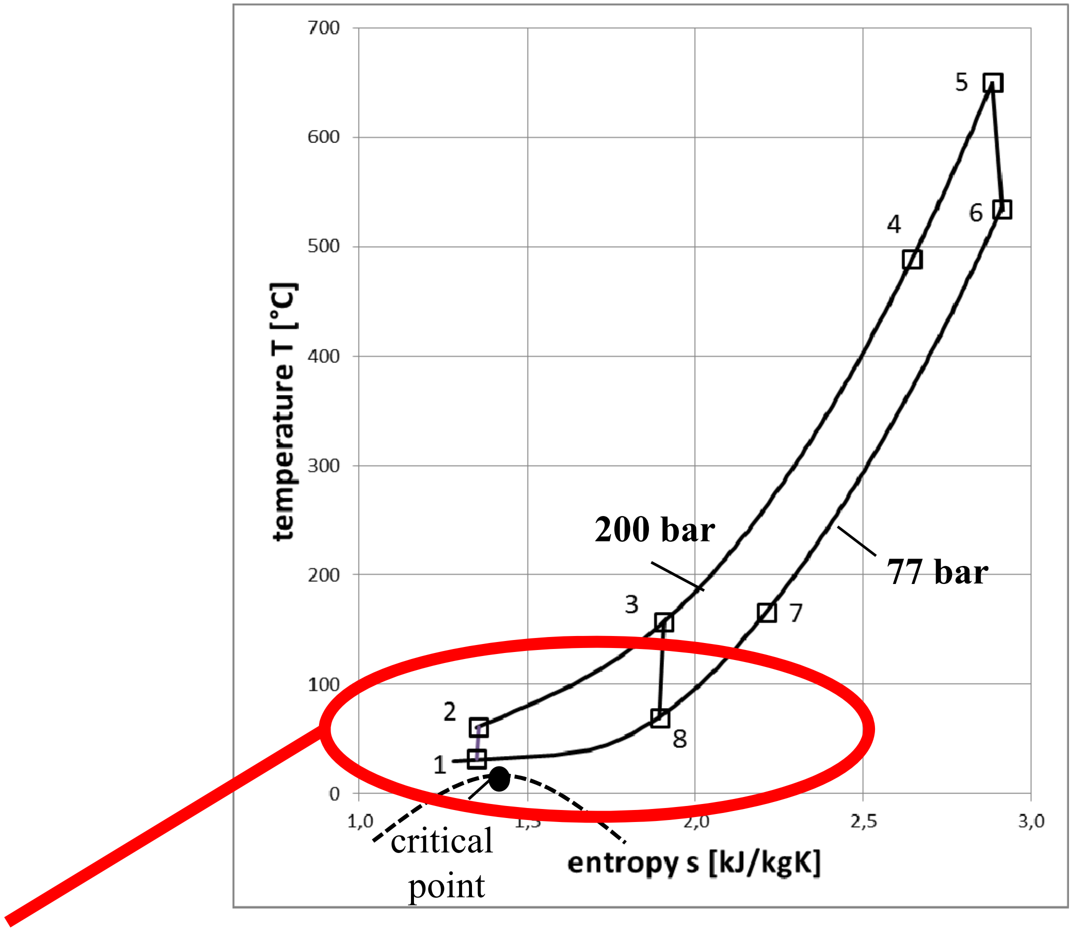
sCO_2 Recuperative Recompression Brayton Cycle

'Advanced Design' of the MIT-Study



region of interest

Outline

Introduction

Test Case : Direct Numerical Simulation (Wang, He)

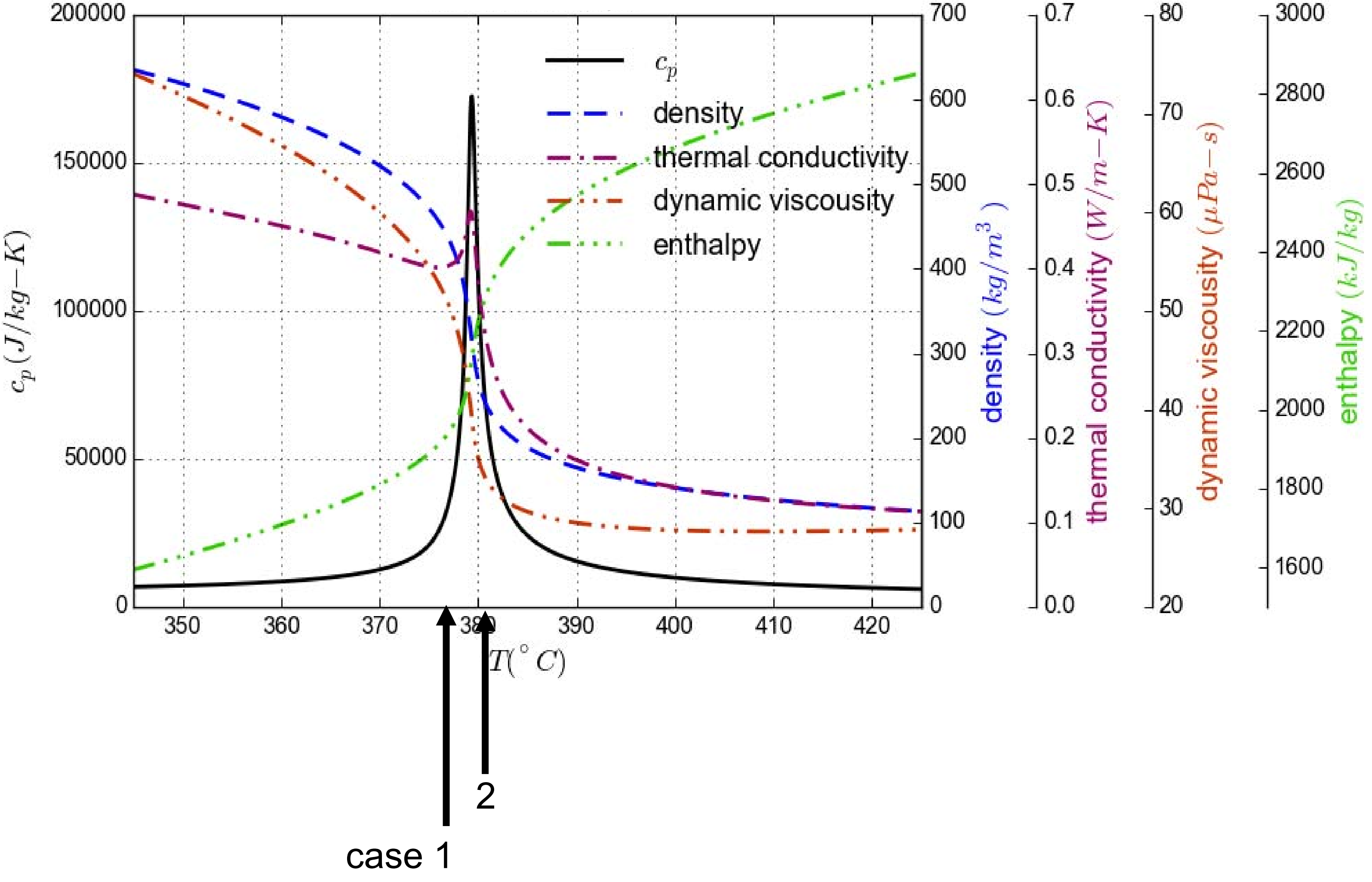
Dominant Thermal Resistance Approach

Results

Conclusions and Outlook

Physical Properties of Supercritical Water

pressure : 23.5 MPa



Why Develop an Approximate Method ?

Approach to provide approximate predictions and improved analyses with varying fluid properties

Possibly a useful basis for extending constant property correlations to variable properties

A reasonable, sensible, simple analysis will (may) provide better predictions than empirical correlations for fluids with significant property variation

Improved treatment for wall functions in CFD

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DNS of Supercritical Pipe or Channel Flows (Water or CO_2)

DNS : Direct Numerical Simulation

Computational Fluid Dynamics (CFD) without turbulence model, all scales resolved

Rynolds Number Re must below (typically: Re < 6000)

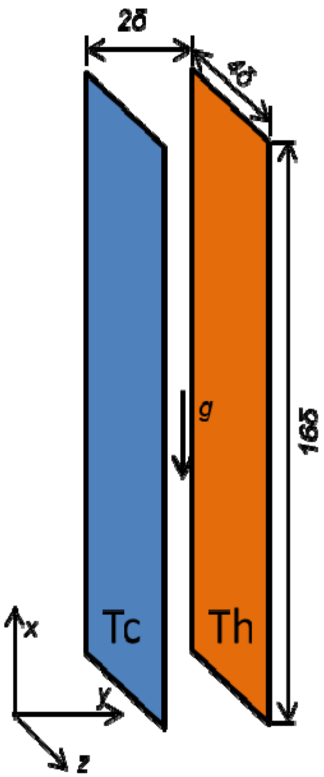
used
in the
present
work

authors	case	HT mode	published	year
Bae, Yoo, Choi (Korea)	upward vertical pipe	wall heating	Phys Fluids	2006
Nemati et al. (Delft)	vertical pipe whith/no buoyancy	wall heating	IJHMT	2015
Chu and Laurien (Stuttgart)	horizontal pipe	wall heating	J. Supercritical Fluids	2016
Wang and He (Sheffield, UK)	plane channel whith/no buoyancy	constant T at the walls	NURETH-16	2015
Pandey and Laurien (Stuttgart)	vertical pipe	wall heating or cooling	this conference	2018

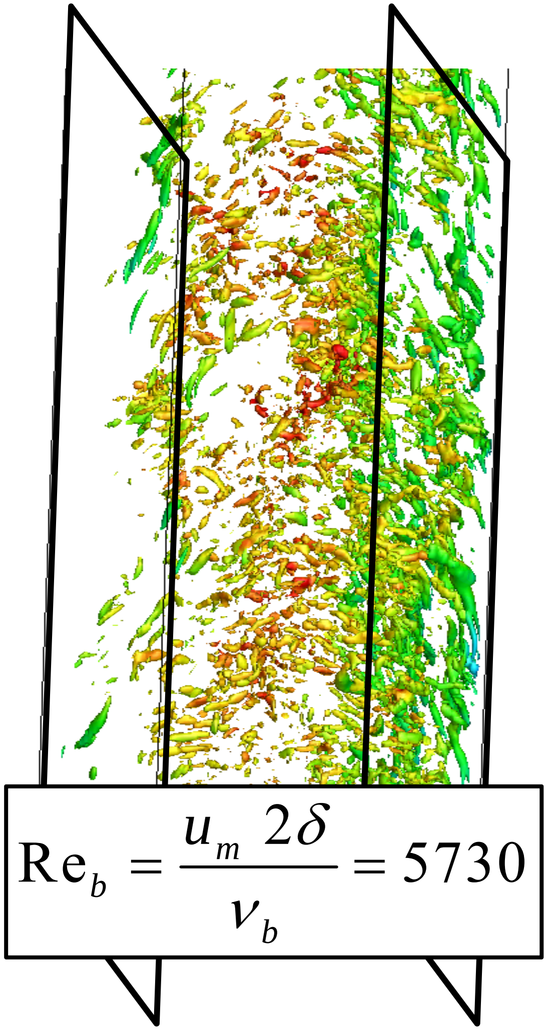
Description of the ‘Wang-DNS’ (no accelation, no buoyancy)

p = 23.5 MPa, G = 108.6 kg/m2s, T_c = 367 °C

Geometry

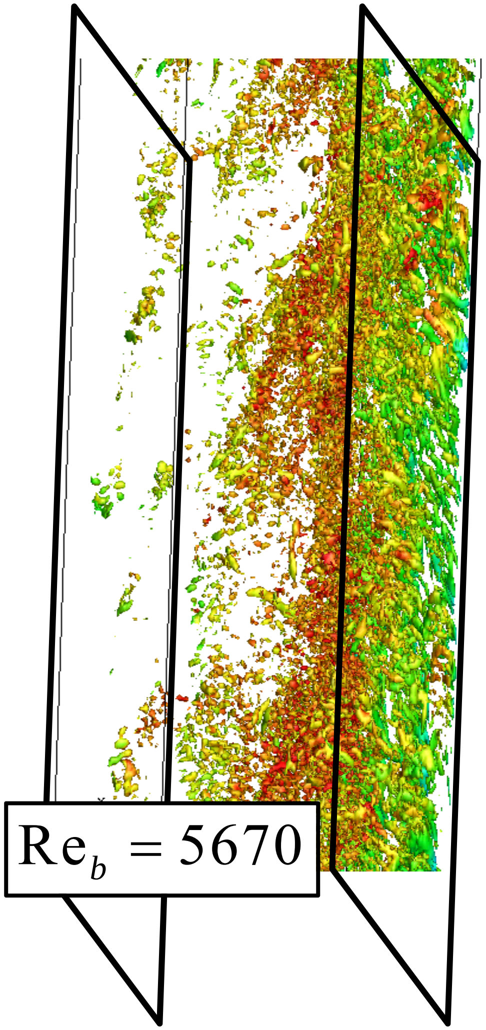


case: 1, T_h = 367 °C



$$\mathrm{Re}_b = \frac{u_m\, 2\delta}{\nu_b} = 5730$$

case 2, T_h = 380 °C



$$\mathrm{Re}_b = 5670$$

Turbulence structures visualized by the second-largest eigenvalue of the stress tensor

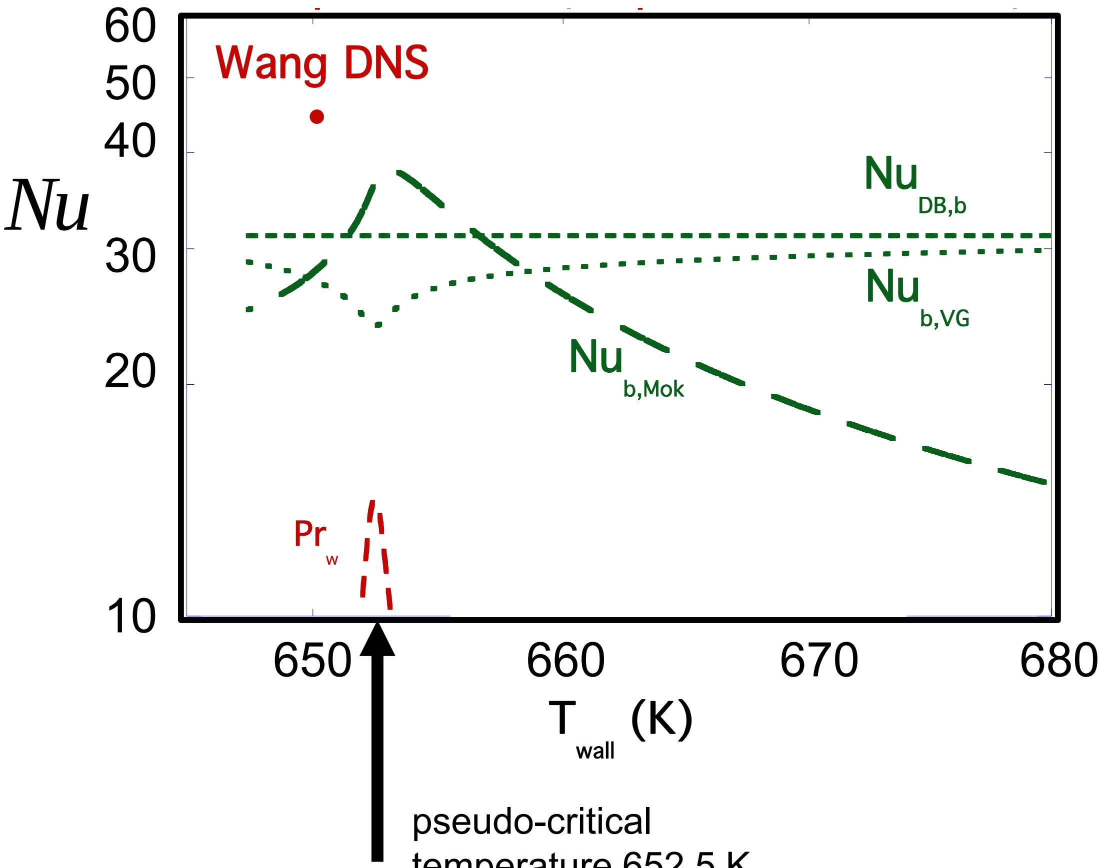
W. Wang & S. He, NURETH-16, 2015

Forced-Convection Correlations for Nu

Dittus Boelter (DB), Gnielinski (VG), Mokry and Pioro (Mok)

$$Nu = \frac{q''_w}{(T_w - T_b)} \frac{2\delta}{k_b}$$

case 1



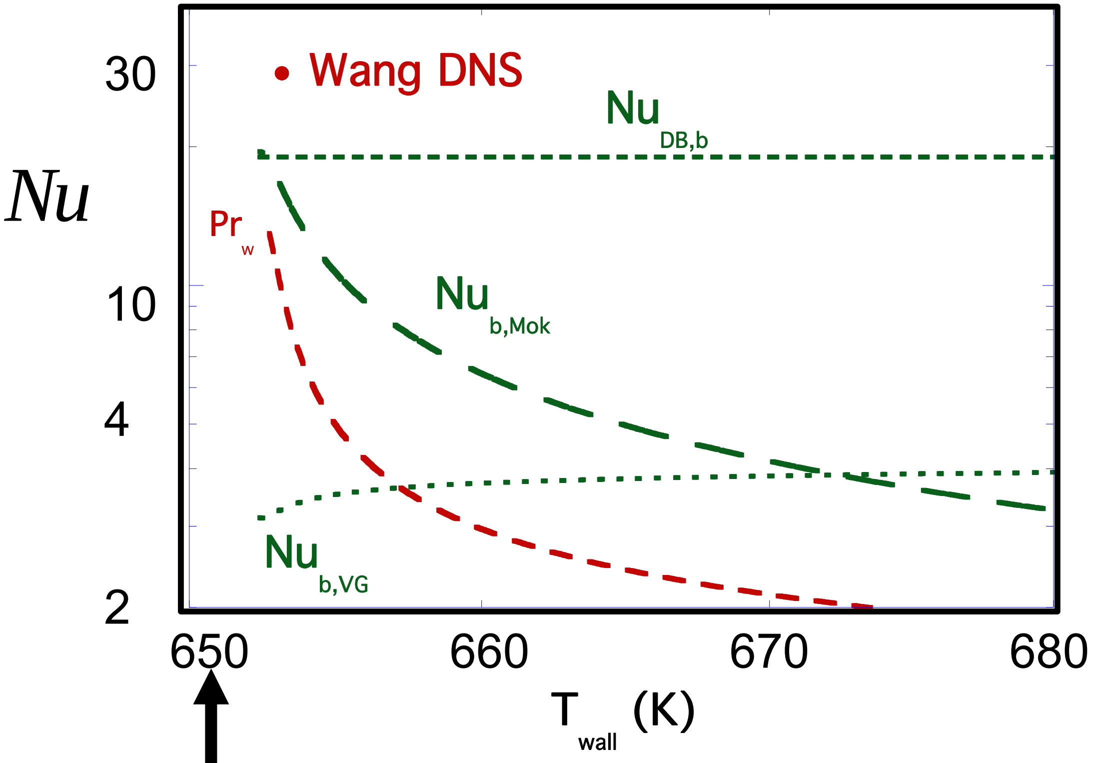
pseudo-critical
temperature 652.5 K
at the wall

Forced-Convection Correlations for Nu

Dittus Boelter (DB), Gnielinski (VG), Mokry and Pioro (Mok)

$$Nu = \frac{q''_w}{(T_w - T_b)} \frac{2\delta}{k_b}$$

case 2



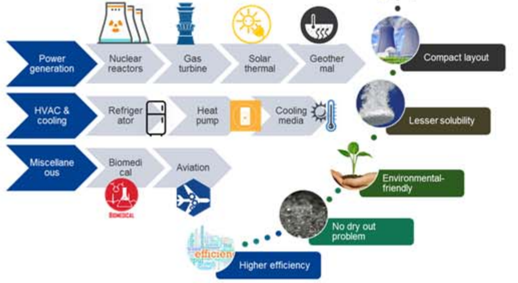
pseudo-critical
temperature 652.5 K
at the wall

Development of direct numerical simulation database for supercritical carbon dioxide

S. Pandey, E. Laurien (Institute of Nuclear Technology and Energy Systems, University of Stuttgart)
X. Chu (Institute of Aerospace Thermodynamics, University of Stuttgart)

Motivation and Aim

- Supercritical carbon dioxide (sCO_2) is a promising working fluid for heat transfer applications.



- Heat transfer peculiarity creates a problem in prior prediction, therefore a database of mean statistics is delivered, which is generated by direct numerical simulations.

Numerical and computational details

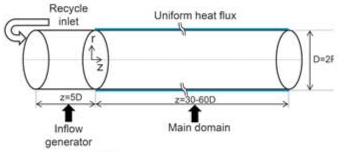
- Low-Mach Navier-Stokes equations are used instead of the fully compressible N-S equations and finite volume based solver was employed for the DNS.

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho U_j)}{\partial x_j}=0 \qquad (1)$$

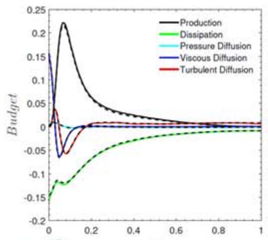
$$\frac{\partial \rho U_i}{\partial t}+\frac{\partial(\rho U_i U_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})\right)\mp\rho g\delta_{i1} \qquad (2)$$

$$\frac{\partial \rho h}{\partial t}+\frac{\partial(\rho U_j h)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\kappa\frac{\partial T}{\partial x_j}\right) \qquad (3)$$

- The simulation domain consists of a tube with a total length of 35-65 diameters. Tube diameter ranges from 2-10 mm.



Geometry of the tube



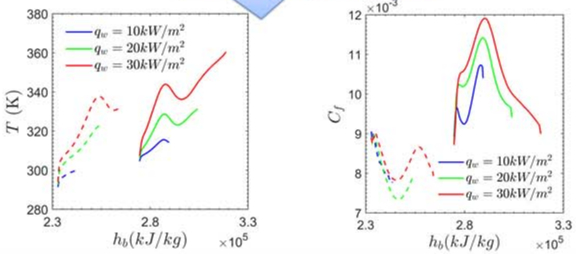
Validation of inflow turbulence with ‘KTH FLOW’ database

- Total 47 cases were simulated by means of DNS. This includes heating and cooling in the vertical orientation of tube. For heating, we conducted DNS only for upward flow with combinations of inlet temperature, pressure, diameter, and heat flux. For cooling, all three possibilities (upward, downward and forced) were simulated for 2 mm diameter.

Results

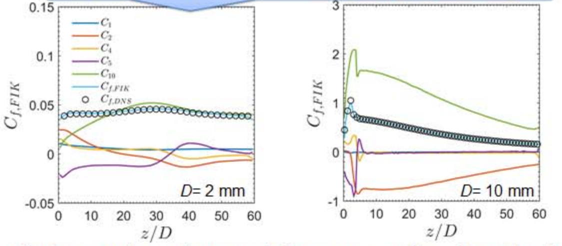
- During heating, a local peak in temperature can be seen in upward flow, which is a characteristic of heat transfer deterioration.

D= 2 mm, P_0= 8 MPa, Heating, Upward flow

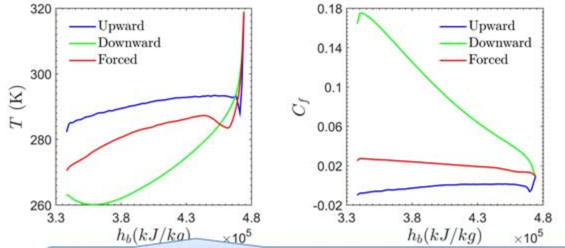


- The decomposition of skin friction coefficient (FIK identity) shows that C_{10}, which is buoyancy contribution to skin friction, has the largest contribution.

P_0= 8 MPa, q= 20 kW/m² Heating, Upward flow

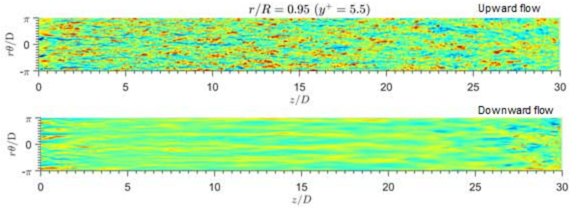


- During cooling, downward flow case suffers from the heat transfer deterioration. The ejection and sweep events reduced in the downward flow case which attenuate the turbulence, thereby, the heat transfer.



D= 2 mm, P_0 = 8 MPa, q= -61.74 kW/m², Cooling

- Streak stretching in the downward flow (in cooling) leads to impaired heat transfer.



- This database can be used in benchmarking of turbulence models, empirical fitting of the coefficient in correlations, and training of machine learning algorithm.

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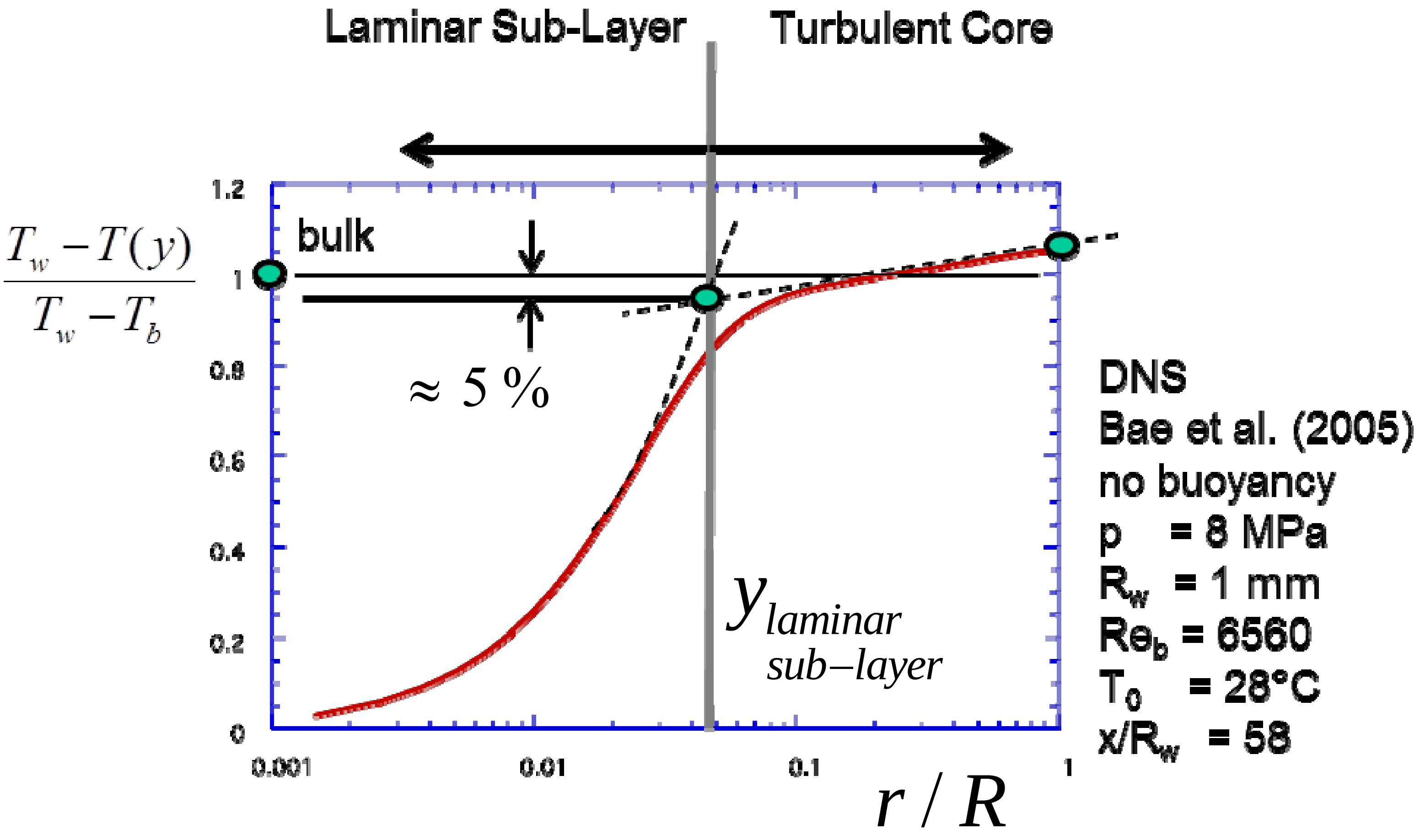
STUTTGART

HLRS
High-Performance Computing Center | Stuttgart

Scan code to download data

Importance of the Turbulent Core

DNS data from Bae, Yoo and Choi, Phys. Fluids 2005



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Dominant Thermal Resistance Approach

assumptions

Steady state,

Quasi-established velocity and temperature profiles

Constant shear layer and heat flux layer approximations

Negligible buoyancy, negligible acceleration

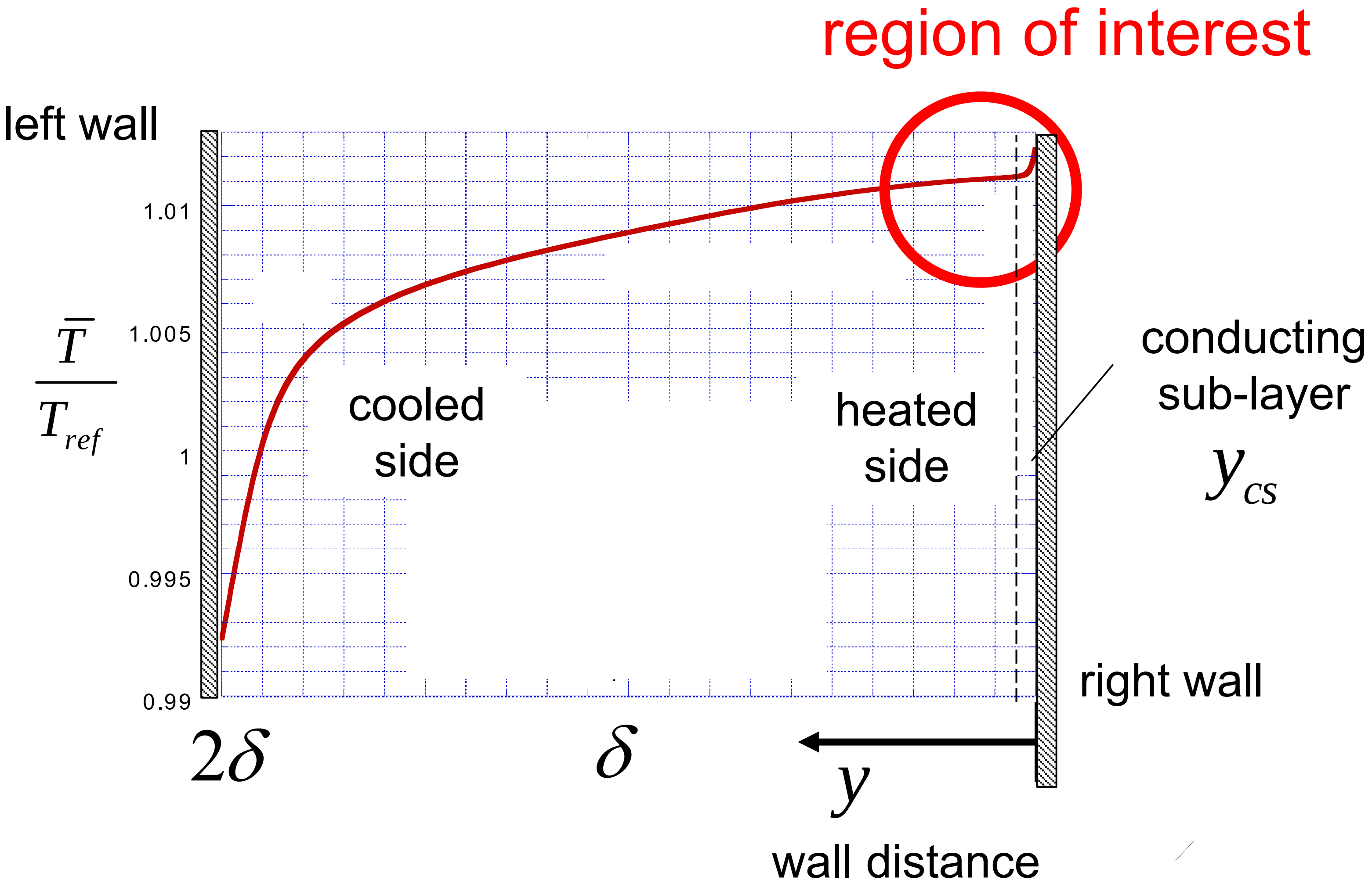
Turbulent core - high turbulence,

high ρ, high c_p ---->

$$T_b \approx T_{\text{centerline}} \approx T_{\substack{\text{laminar}\\\text{sublayer}}} = T_{\substack{\text{conducting}\\\text{sublayer}}}$$

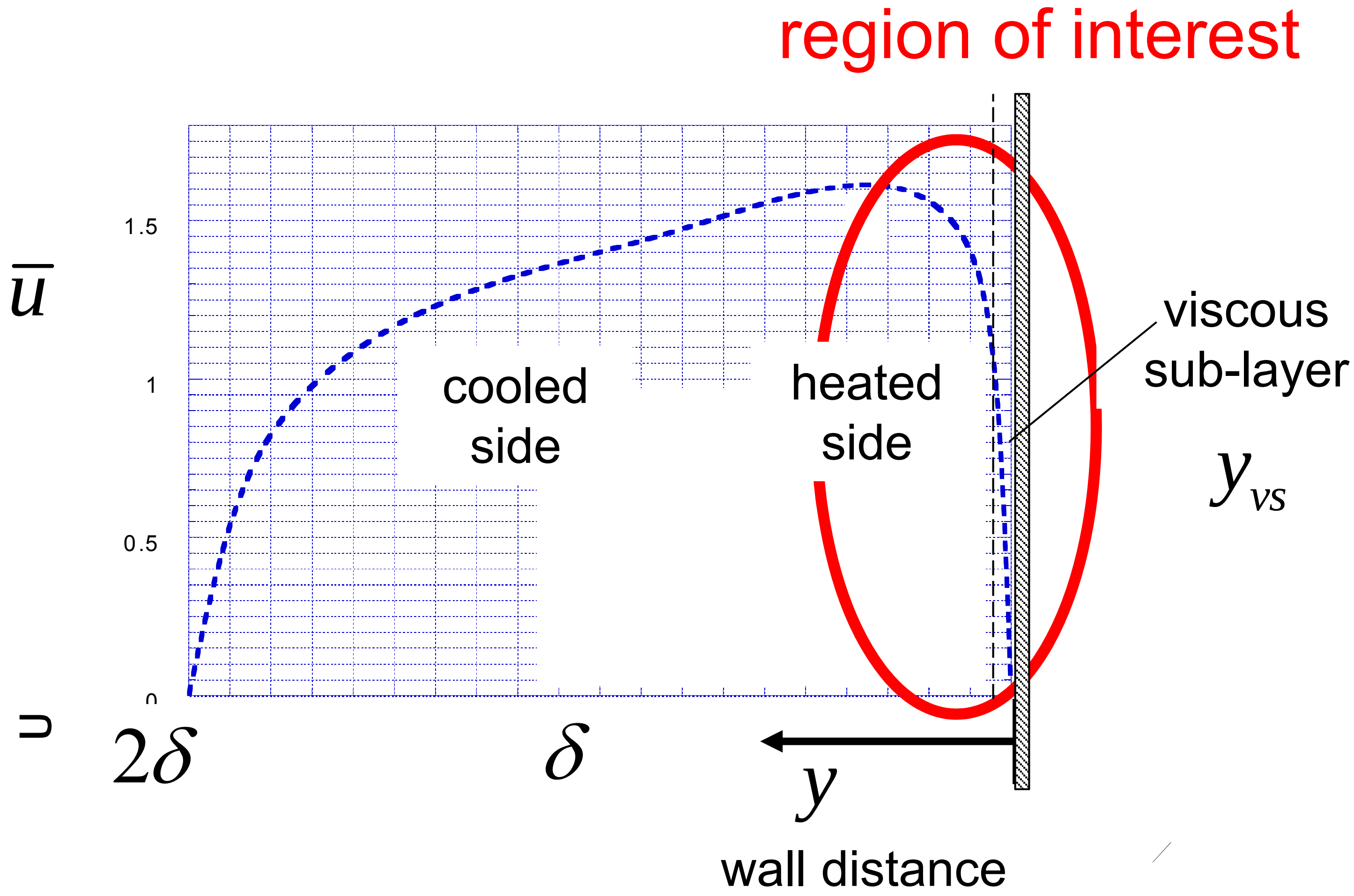
Wang-DNS Mean Temperature Profile

Case 1



Wang-DNS Mean Velocity Profile

Case 1



Integration of the Thermal Energy Equation

in the laminar, conducting sub-layer: the region of dominant thermal resistance

$$0 = \rho\, c_p U \frac{\partial T}{\partial x} \approx \frac{\partial q''}{\partial y} \quad \Rightarrow \quad q''(y) \approx const. \approx q''_w$$

Near the wall we have Fourier's law:

$$q''(y) \approx -k(T)\frac{\partial T}{\partial y}$$ Integrate: $$q''(y)\int_0^y d\, y \approx -\int_{T_w}^{T(y)} k(T)\, d\, T$$

Define

$$\omega(T) = -\int_{T_{ref}}^{T} k(T)\, d\, T$$ a property

then

$$q''_w\, y = -\left[\omega(T) - \omega(T_w)\right]$$

At $y = y_{cs}$

$$q''_w = -\frac{\omega(T_b) - \omega(T_w)}{y_{cs}}$$

May be a good approximation
If one has a good estimate
of y_{cs}

How to get good Estimates for y_{cs}

using the universal wall units

Prandtl [1910] approach $y_{cs}^{+} \approx y_{vs}^{+}$

Two-layer approximation $y_{vs}^{+} \approx 11.6$

where $y^{+} = y (\tau_w/\rho)^{1/2}/\nu$ **or**

$$y^{+} = (y/D_h)\, Re_{Dh}\, (C_f/2)^{1/2}$$

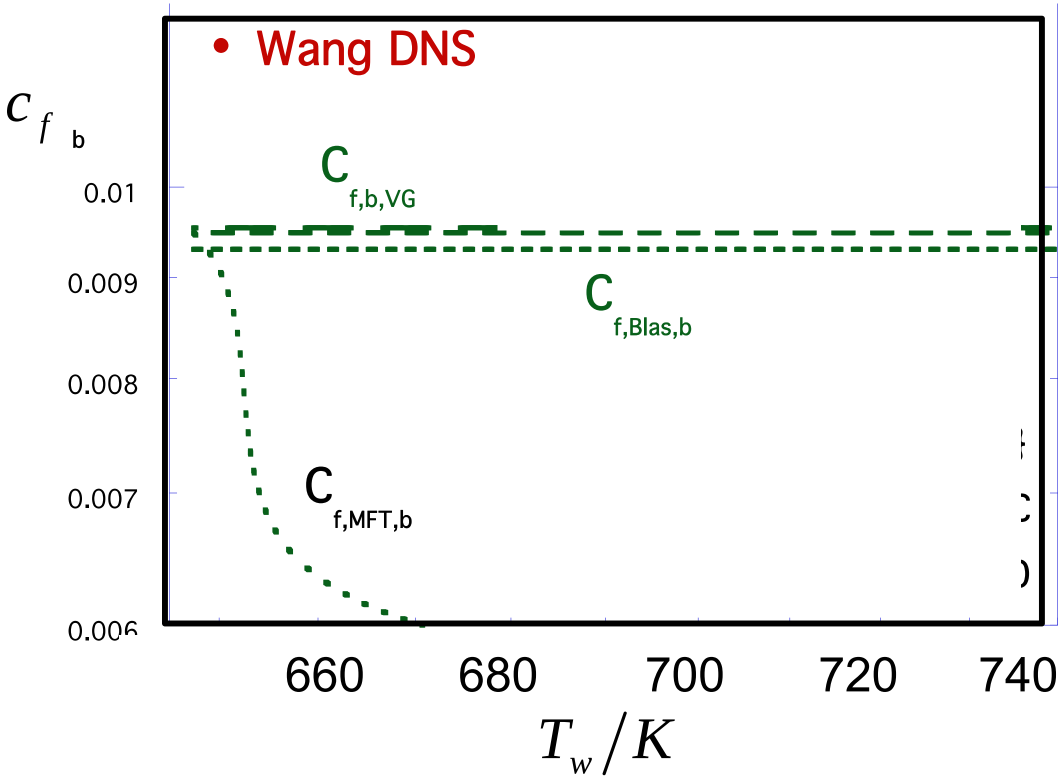
DO WE HAVE A GOOD ESTIMATE OF C_f ***?***

Forced-Convection Correlations for wall friction c_f

used in Gnielinski (VG), Drew, Koo, McAdams (DKM), M.F. Taylor (MFT), Blasius (Blas)

$$c_f = \frac{\tau_w}{0.5\,\rho_w\,u_m^2}$$

case 1

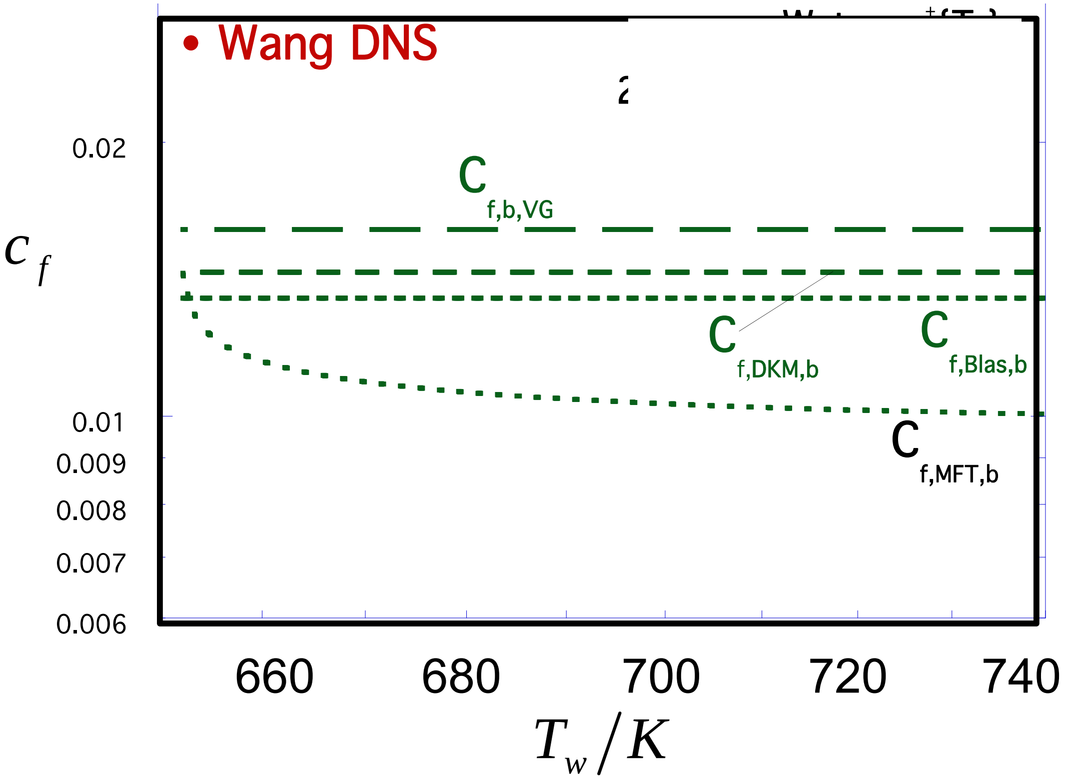


Forced-Convection Correlations for Nu

used in Gnielinski (VG), Drew, Koo, McAdams (DKM), M.F. Taylor (MFT), Blasius (Blas)

$$c_f = \frac{\tau_w}{0.5\,\rho_w\,u_m^2}$$

Case 2



Integration of the Momentum Equation

in the laminar, conducting sub-layer: the region of dominant flow resistance

$$\tau(y) \approx \mu \frac{\partial U}{\partial y} \quad \Rightarrow \quad \tau(y) \approx const. \approx \tau_w$$

Near the wall we have Newton‘s law and Fourier‘s law:

$$\tau_w \, dy = \mu(T)\, dU \qquad q''_w \, dy = -k(T)\, dT$$

$$dU = \frac{\tau_w \, dy}{\mu(T)}$$ and $$dy = -\frac{k(T)\, dT}{q''} \quad \Rightarrow \quad dU = -\frac{\tau_w \, k(T)\, d\,T}{\mu(T)\, q''_w}$$

Define

$$\Phi(T) = -\int_{T_{ref}}^{T} \frac{k(T)}{\mu(T)} \, d\,T$$ a property

Integrate

$$\int_0^{U_b} d\,U \approx -\frac{\tau_w}{q''_w} \int_{T_w}^{T_b} \frac{k(T)}{\mu(T)} \, d\,T \quad \Rightarrow \quad U_b = -\frac{\tau_w}{q''_w} \left[\Phi(T_b) - \Phi(T_w) \right]$$

Solve for

$$\tau_w = -\frac{U_b \, q''_w}{\Phi(T_b) - \Phi(T_w)}$$

Integration of the Momentum Equation (contd.)

in the laminar, conducting sub-layer: the region of dominant flow resistance

Substitute into

$$q''_w \, y_{cs} = -\left[\omega(T_{cs}) - \omega(T_w)\right] \quad \text{with} \quad y_{cs} = \frac{y^+_{cs} \, \nu}{\sqrt{\tau_w / \rho}}$$

i.e. into

$$q''_w \frac{y^+_{cs} \, \nu}{\sqrt{\tau_w / \rho}} = -\left[\omega(T_{cs}) - \omega(T_w)\right]$$

to give

$$q''_w \frac{y^+_{cs} \, \nu}{\sqrt{\dfrac{U_b \, q''_w}{\Phi(T_w) - \Phi(T_b)} \Big/ \rho}} = -\left[\omega(T_{cs}) - \omega(T_w)\right]$$

and solve for

$$q''_w = \frac{U_b}{\rho \, (y^+_{cs} \nu)^2} \frac{\left[\omega(T_b) - \omega(T_w)\right]^2}{\left[\Phi(T_w) - \Phi(T_b)\right]}$$

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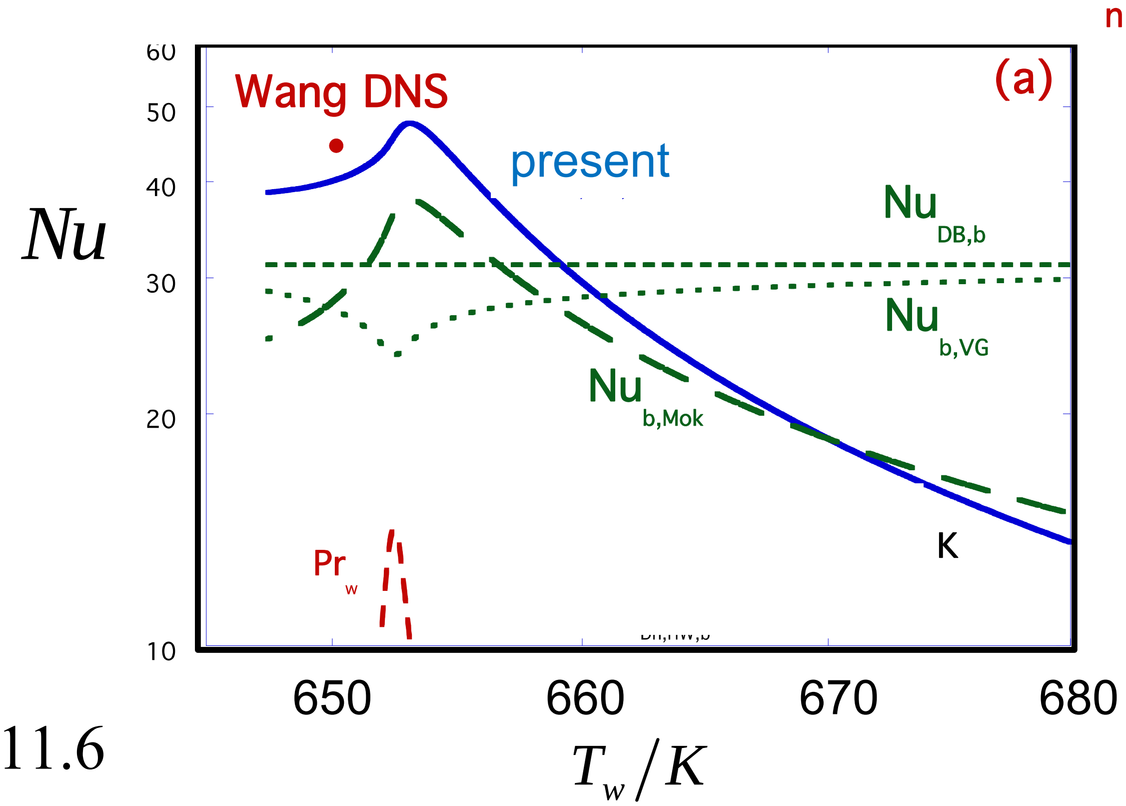
Result

Heat Transfer

$$Nu = \frac{q''_w}{(T_w - T_b)} \frac{2\delta}{k_b}$$

case 1



$$y^+_{vs} = y^+_{cs} = 11.6$$

$$y^+ = \frac{y}{\nu_w}\sqrt{\frac{\tau_w}{\rho_w}}$$

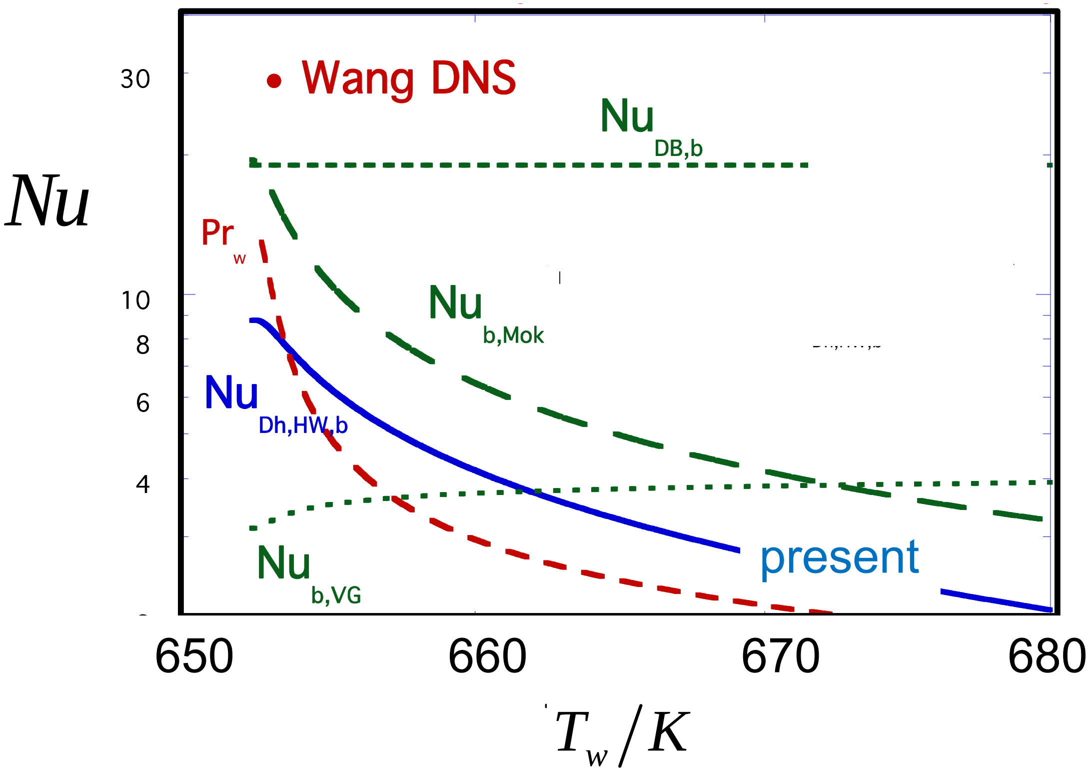
upper index +
in „wall units“

Result

Heat Transfer

$$Nu = \frac{q''_w}{(T_w - T_b)} \frac{2\delta}{k_b}$$

<u>case 2</u>

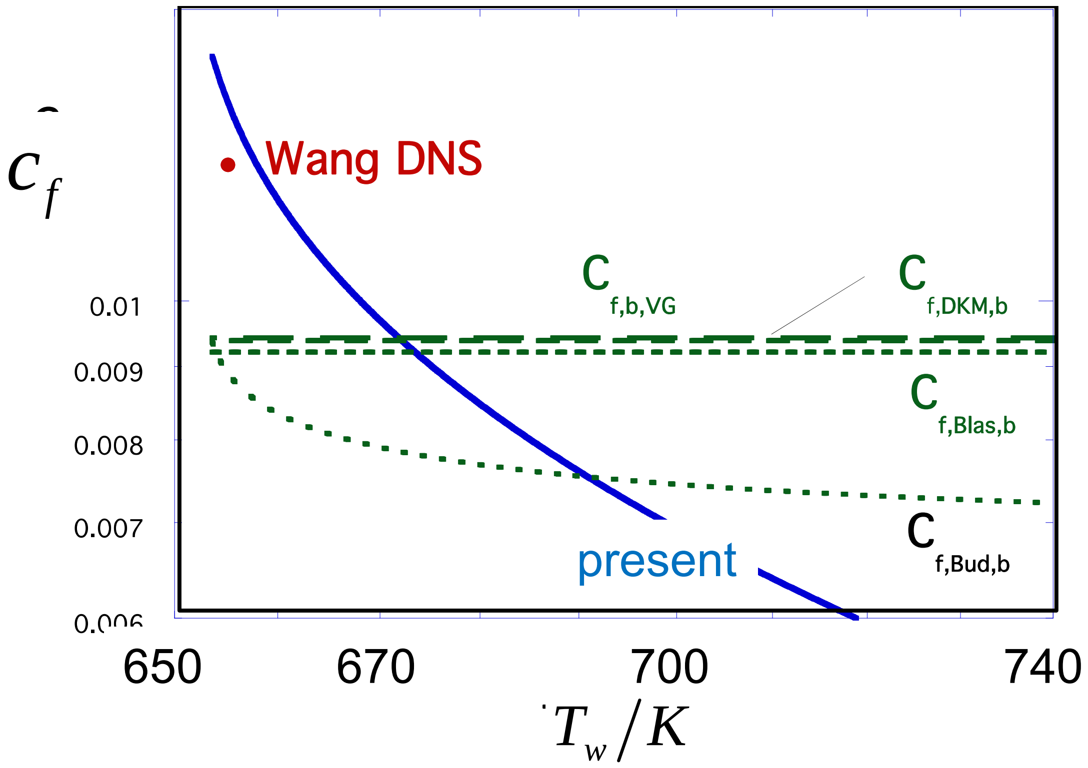


Result

Friction

$$c_f = \frac{\tau_w}{0.5\,\rho_w\,u_m^2}$$

<u>case 3</u>



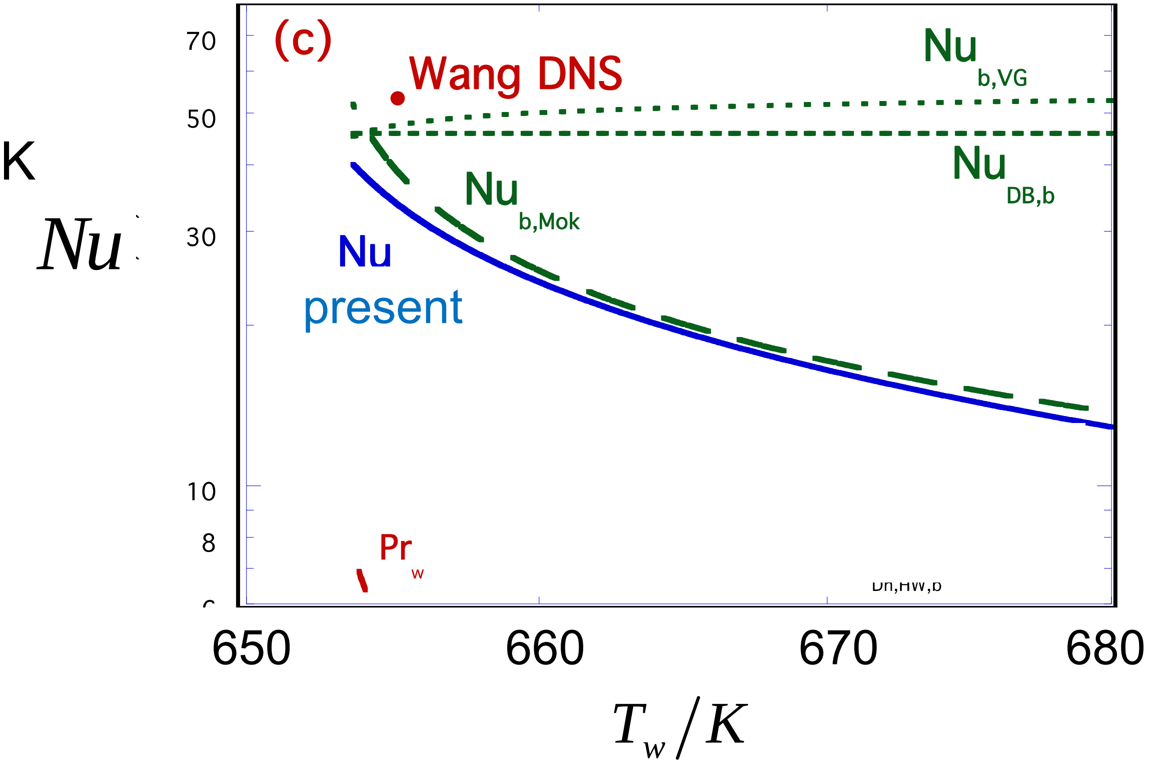
Result

Heat Transfer

$$Nu = \frac{q''_w}{(T_w - T_b)} \frac{2\delta}{k_b}$$

<u>case 3</u>

T_h = 655 K



Concluding Remarks

Demonstrated a closed-form, approximate, coupled analysis for Nu for ScPF (with negligible buoyancy and acceleration)

Some reasonable agreement with DNS of Wang+He

Nu is sensitive to choice of y_{vs}^+

Useful approach to provide approximate predictions and improved analyses

Improved treatment for wall functions in CFD

Can provide a first estimate for interative processes in "more sophisticated" analyses

Outlook

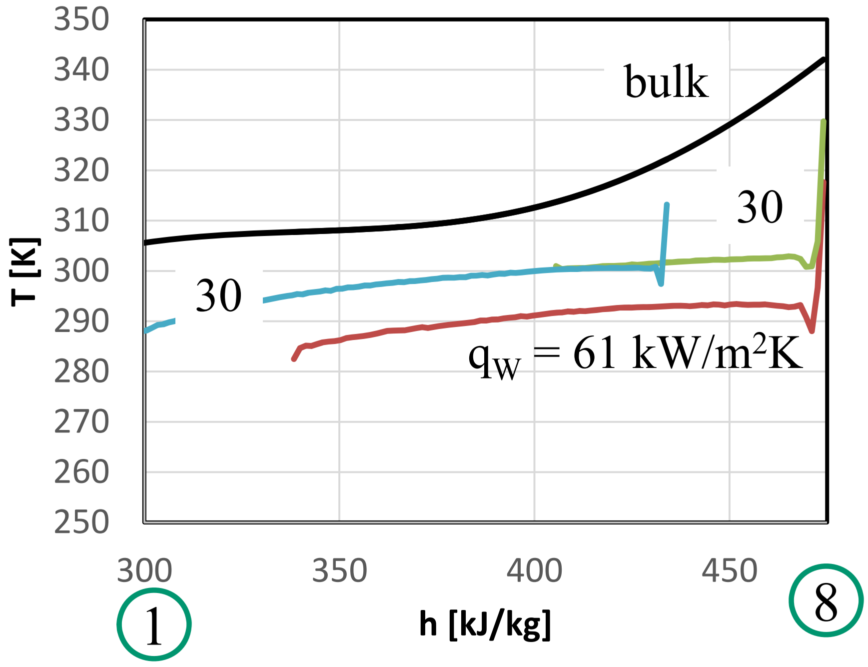
Extend to significant buoyancy and acceleration

Revise analysis to treat differing y_{cs}^+ and y_{vs}^+

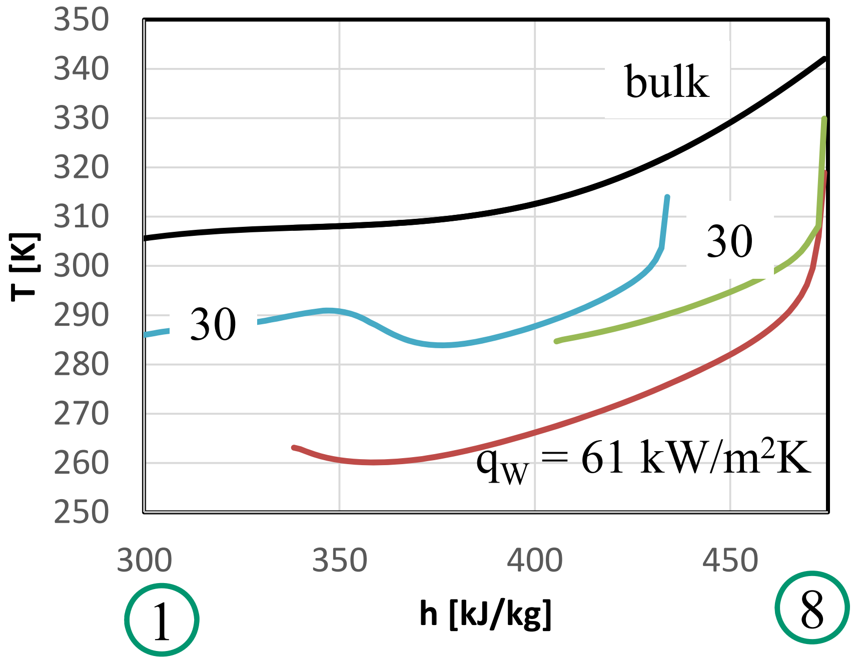
Add thermal resistance for turbulent core?

DNS data: 80 bar, CO_2, D = 2 mm

upward



downward



Backup Slides

State-of-the-Art Correlations for Narrow Channels (2 mm)

$G = 60\ \mathrm{kg/m^2s}$, $q_w = -30\ \mathrm{kW/m^2}$ (cooled wall)

Forced convection

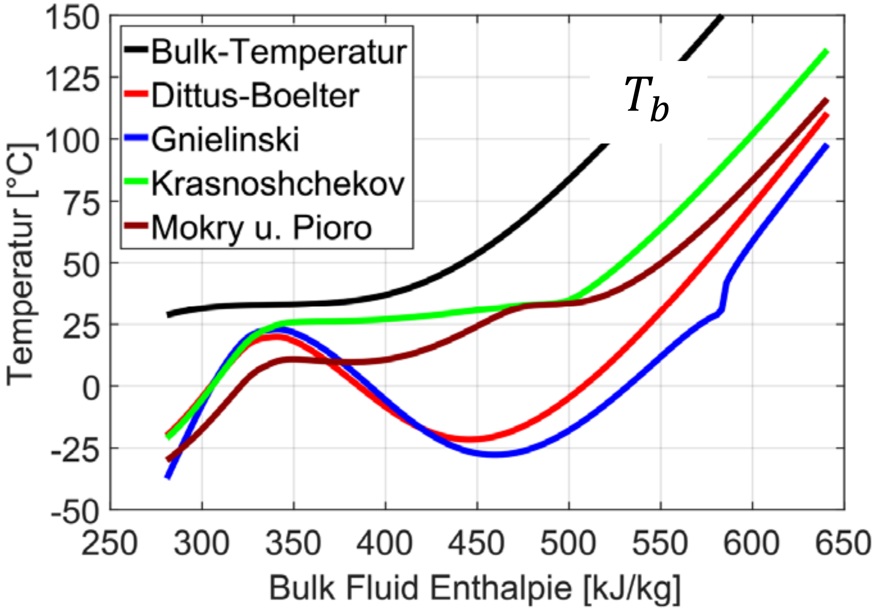
$$\mathrm{Nu}_0 = \mathrm{Nu}_{0b} \left(\frac{\rho_w}{\rho_b}\right)^{n_1} \left(\frac{c_{pw}}{c_{pb}}\right)^{n_2} \cdots$$

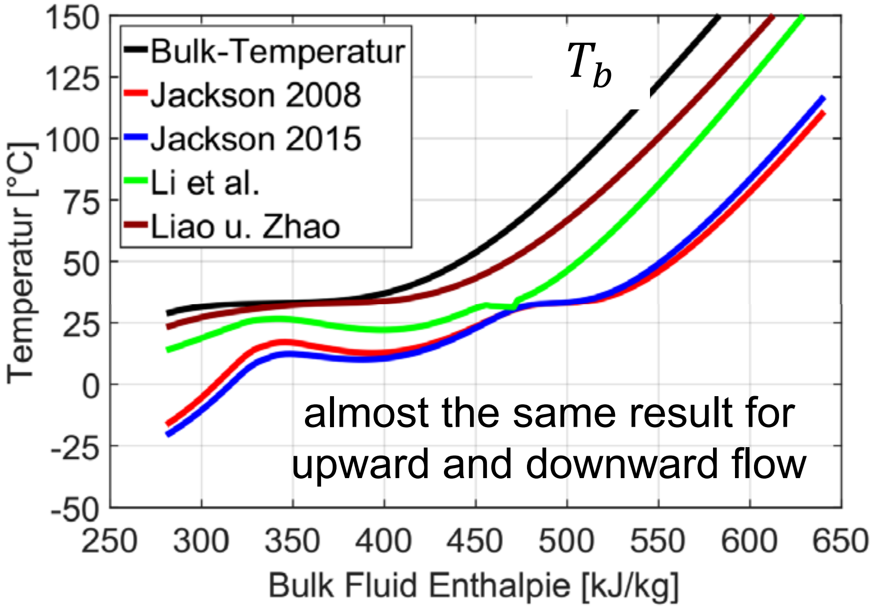
index 0 : constant properties
w : wall
b : bulk

Mixed convection (w/ gravity influence)

$$\mathrm{Nu} = \mathrm{Nu}_0 \left[1 \pm C_1 \times \left(\frac{\mathrm{Gr}_m}{\mathrm{Re}^{2,7}}\right)^{n_1} \ldots\right]$$

Nu : Nusselt number
Gr : Grashof number
Re : Reynolds number
+ upward, - downward flow



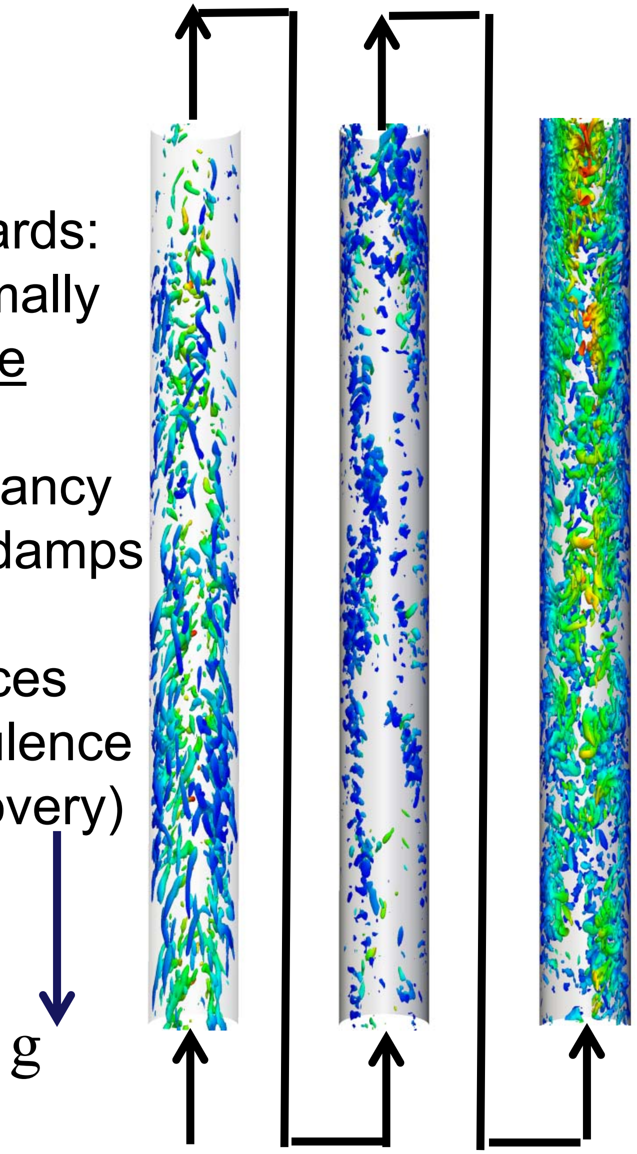


almost the same result for upward and downward flow

DNS-Results of a Heated PipeFlow at Re = 5400

upwards:
thermally
stable

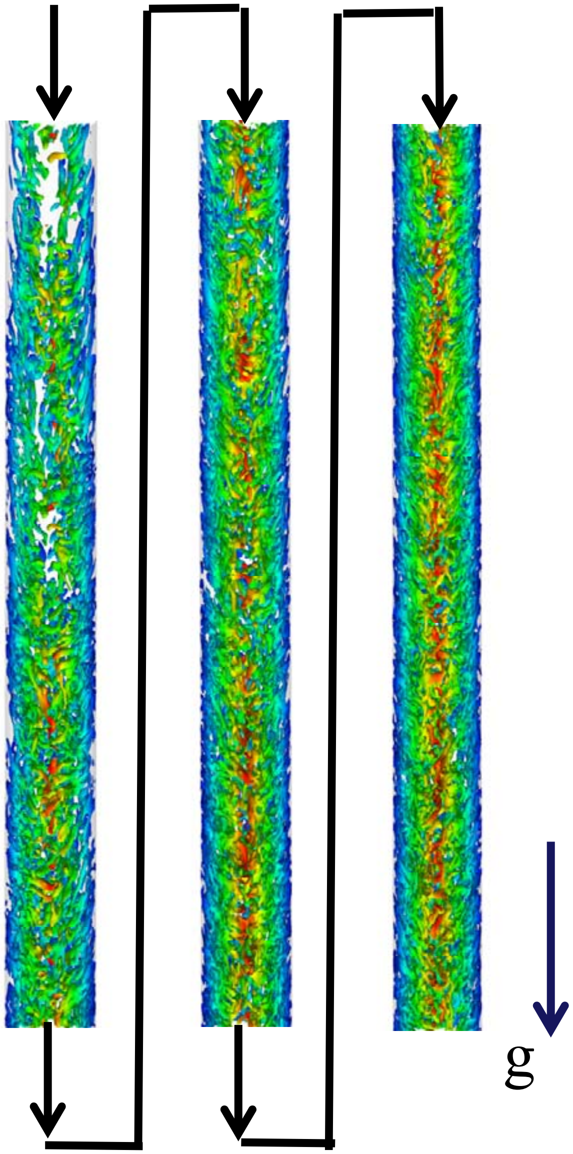
buoyancy
first damps
later
induces
turbulence
(recovery)



downwards:
thermally
unstable

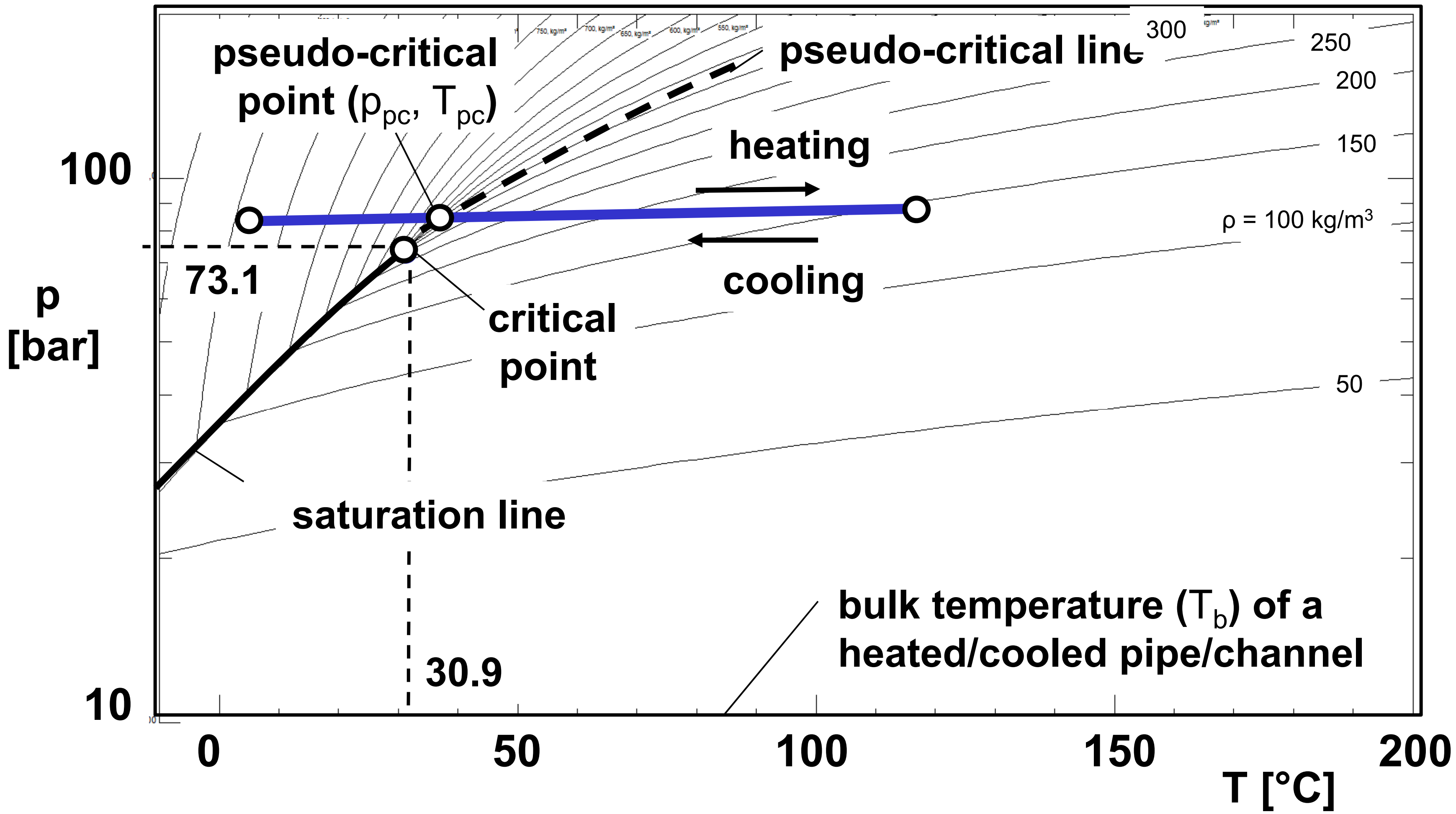
buoyancy
induces
turbulence

Visualization of
turbulence structures
using the λ_2 criterium



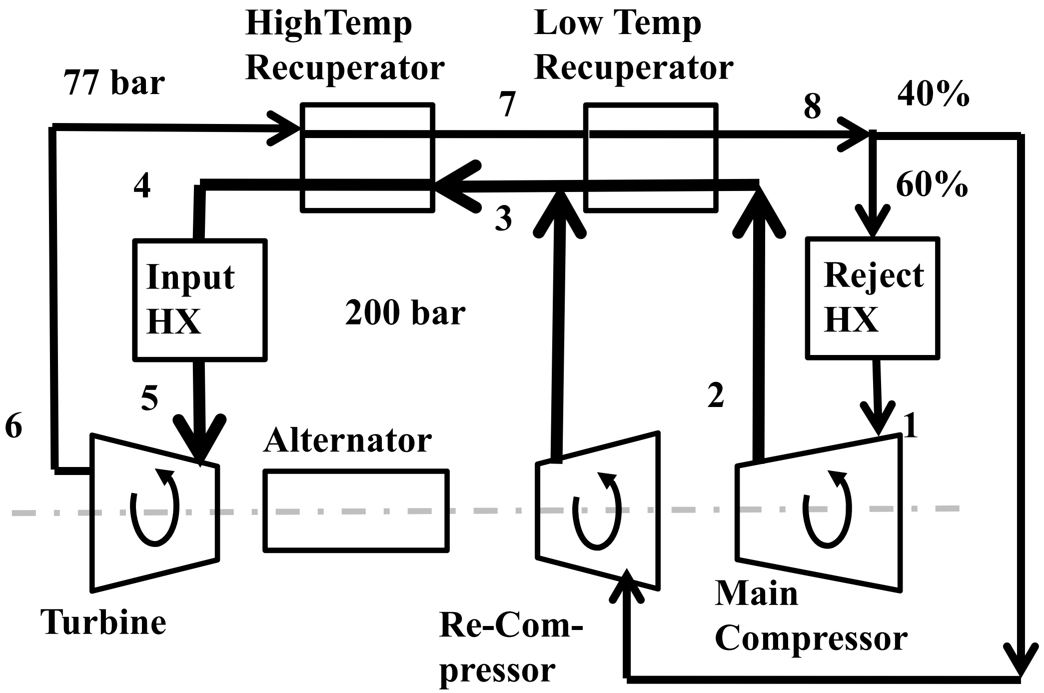
Terminology

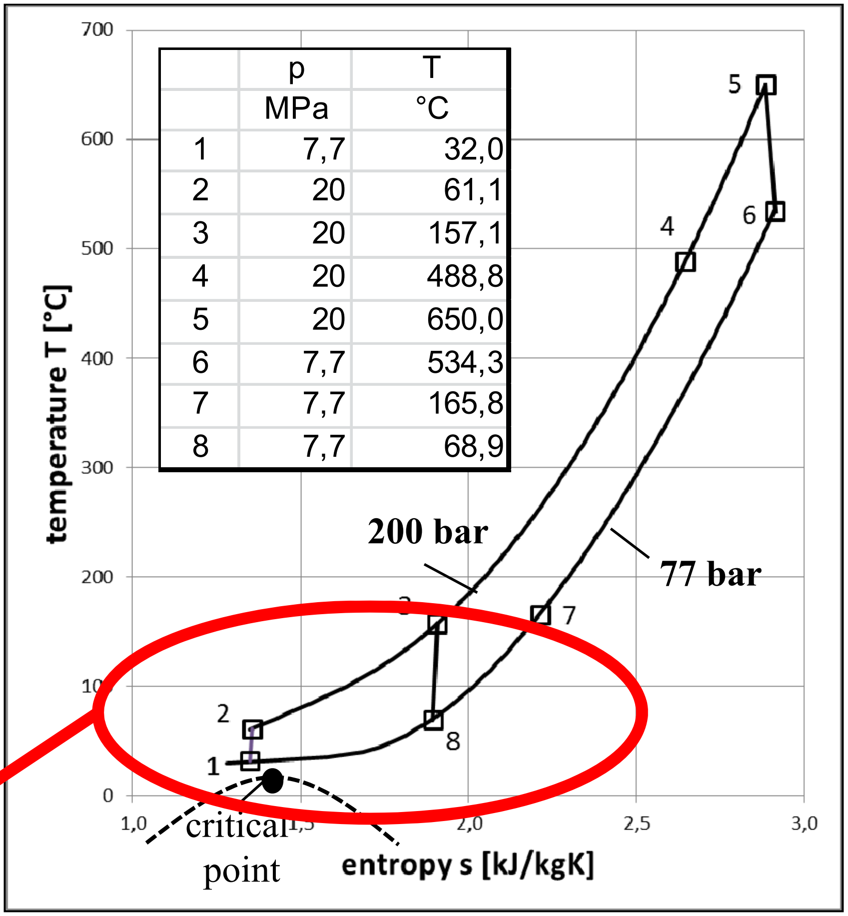
of Single-Pipe or Channel Experiments at Super-Critical Pressure



sCO_2 Recuperative Recompression Brayton Cycle

'Advanced Design' of the MIT-Study: Net Efficiency ~47 %



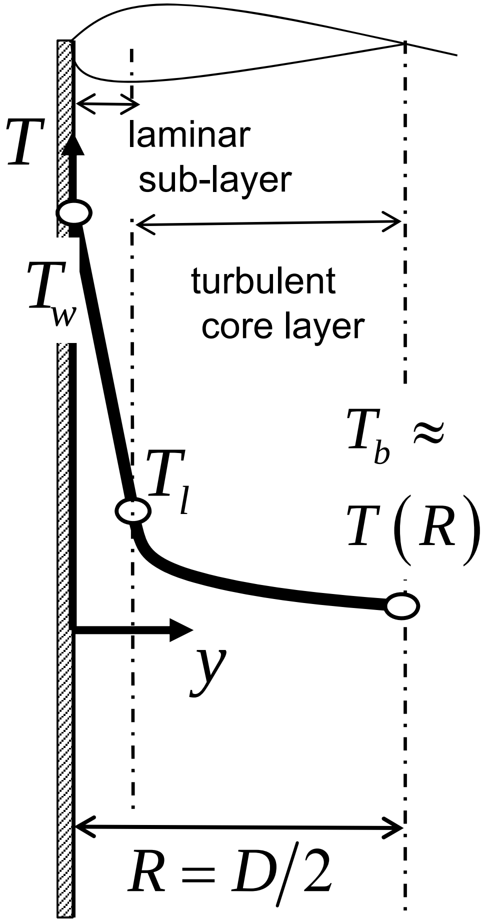


	p MPa	T °C
1	7,7	32,0
2	20	61,1
3	20	157,1
4	20	488,8
5	20	650,0
6	7,7	534,3
7	7,7	165,8
8	7,7	68,9

region of interest

Example: Two-Layer Model for Turbulent Boundary Layers

Prandtl 1910, Kays and Crawford 1980, constant properties



The temperature in wall units

$$T^+(y) = \frac{\rho\, c_p\, u_\tau}{q''_w}\left(T_w - T(y)\right) = \rho\, c_p\, u_\tau R$$

Can be considered a non-dimensional thermal resistance. Expand to

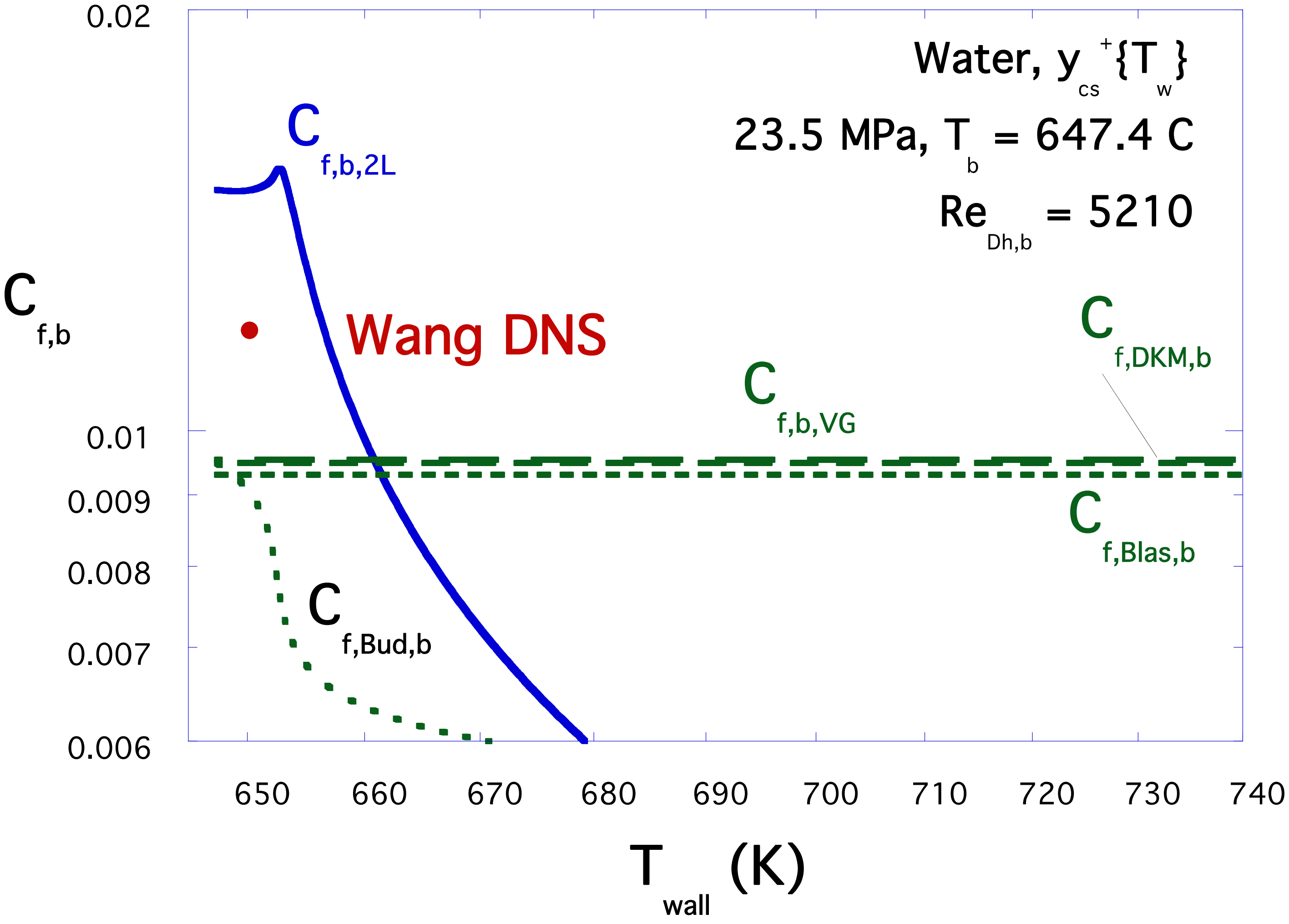
$$T^+(y) = \rho\, c_p\, u_\tau\left(R_{lam} + R_{turb}\right)$$

And compare to the Kays and Crawford relation

$$T^+(R) = \Pr y^+_{lam} + \frac{\Pr_t}{\kappa}\left(\ln R^+ - \ln y_{lam}\right) \approx T^+_b$$

The total resistance is the sum of two individual resistances fore the two layers

WangF650-2L,Cf,b,HW.qpc



WangF653-2L,Cf,bHW.qpc