CFD studies of heat tansfer at structured surfaces

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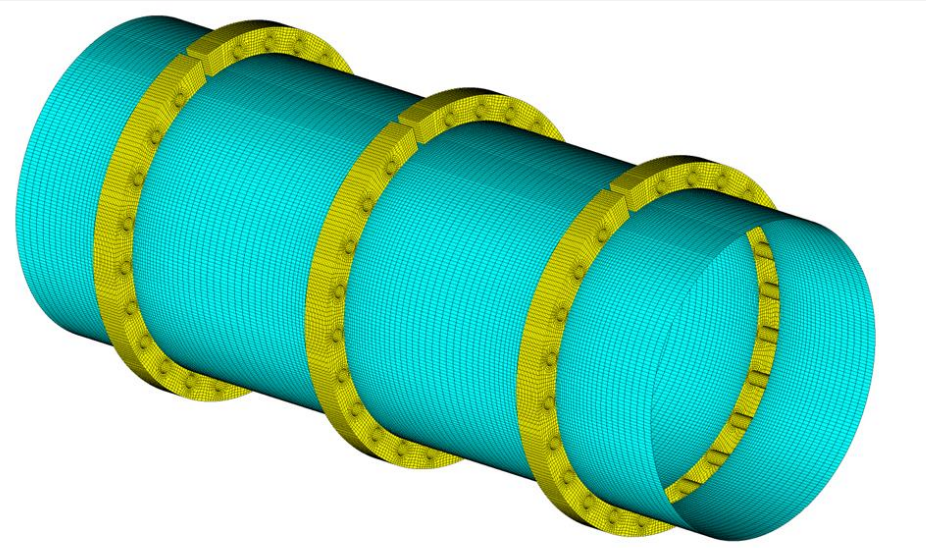
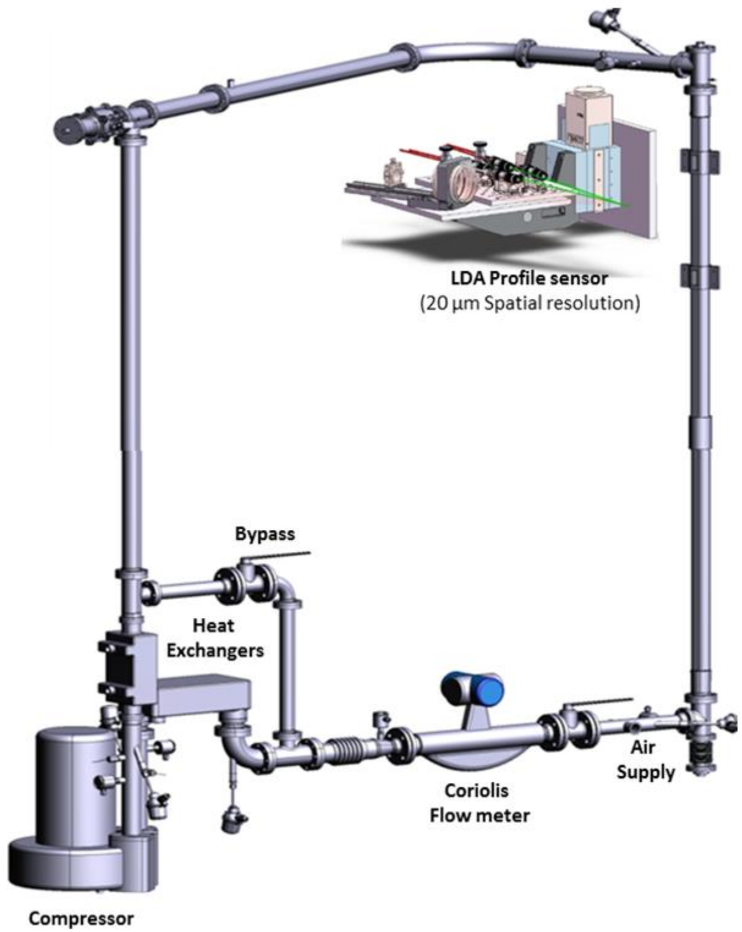


Content

- Facts about the L-Star test facility
- CFD models
  - RANS simulations (entire test section)
  - LES (parts of test section)
- Results
  - Smooth heater rod
  - Heater rod with solid rings ⟵
  - Heater rod with perforated rings ⟵
- Summary and outlook

L-Star test facility



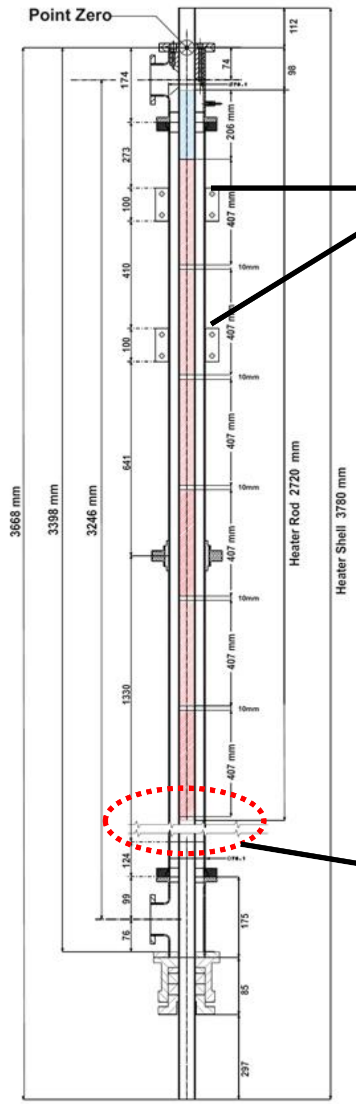
Luft-**St**ab-**A**bstandshalter-**R**auhigkeiten

Experiments related to GEN IV Gas Cooled nuclear reactors
Coolant: air

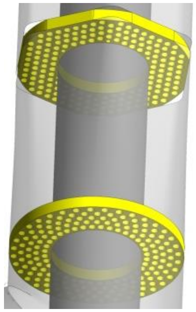
Intentions:
Improvement of heat transfer by surface roughness
Qualification and improvement of turbulence models

Parameter	Value
Test section length	**3.7 m**
Design electrical power	**24 kW (750°C)**
Gas temperature range	**RT to 250 °C**
Maximum operating pressure	**3 bar (abs)**
Maximum mass flow rate	**0.33 kg/s**
Maximum operating Re	**$2 \cdot 10^5$**

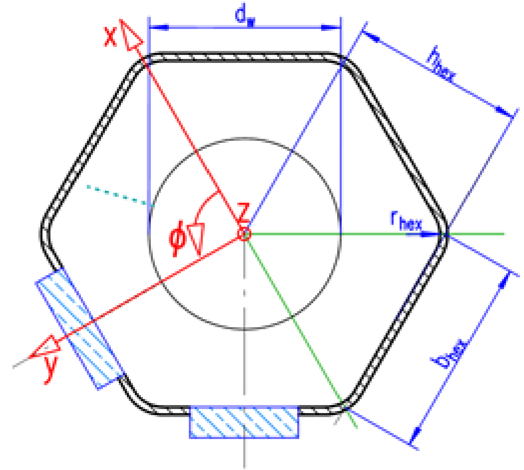
L-Star test section composition



Optical windows



Flow straightener for surface rough-ness experiments



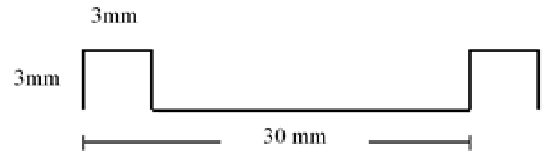
Measurement equipment:

48 thermocouples

4 pressure sensors

LDA system at optical window

Rings as surface roughness:



or

Experiments - overview

Without flow straightener:

Smooth heater rod:

P_0 = 1.5 bar / 6.32 – 50.5 g/s / Re=6000 … 35000 / 0.339 – 2.031 KW

Pressure and temperature measurements only

Flow straightener installed:

Heater rod with solid rings:

P_0 = 1.5 bar / 6.32-50 g/s / Re=6000 … 35000 / 0.58 – 1.5 KW

Fluctuations by LDA for heated and unheated standard case

Heater rod with perforated rings:

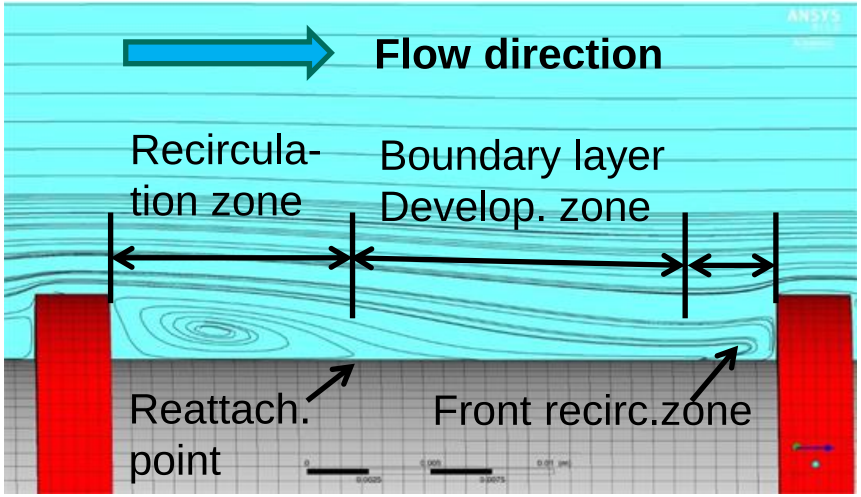
P_0 = 1.5 bar /6.32-50 g/s / unheated experiments

Fluctuations by LDA (*in progress*)

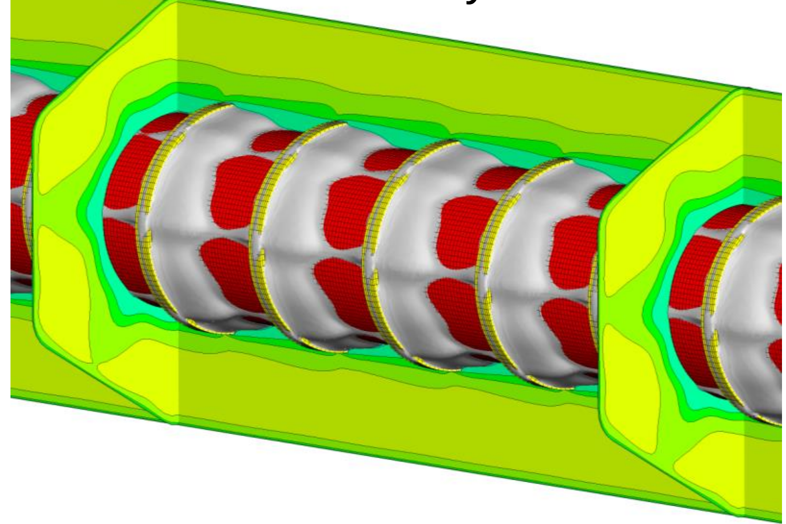
Standard case:

P_0 = 1.5 bar 26.15 g/s / Re=16500 / 1KW

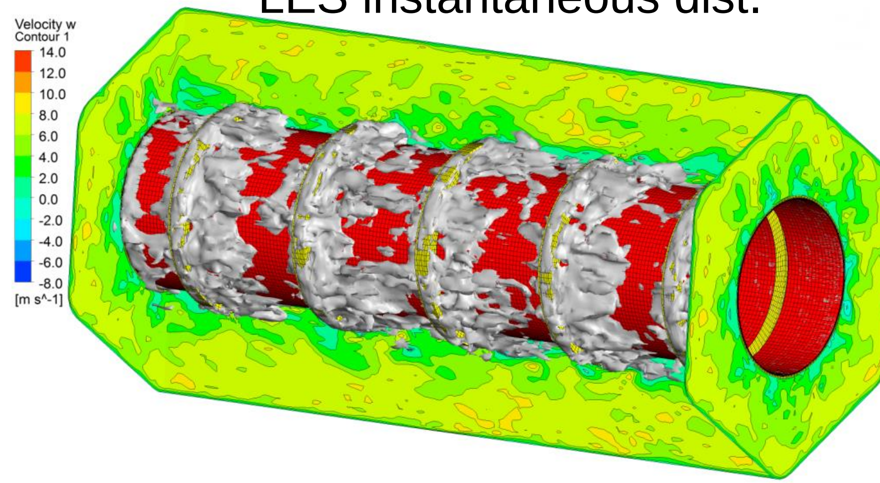
Flow configuration at solid rod surface structures



RANS steady state solution



LES instantaneous dist.



Flow Phenomena:

Separation and reattaching

Secondary flow in corners

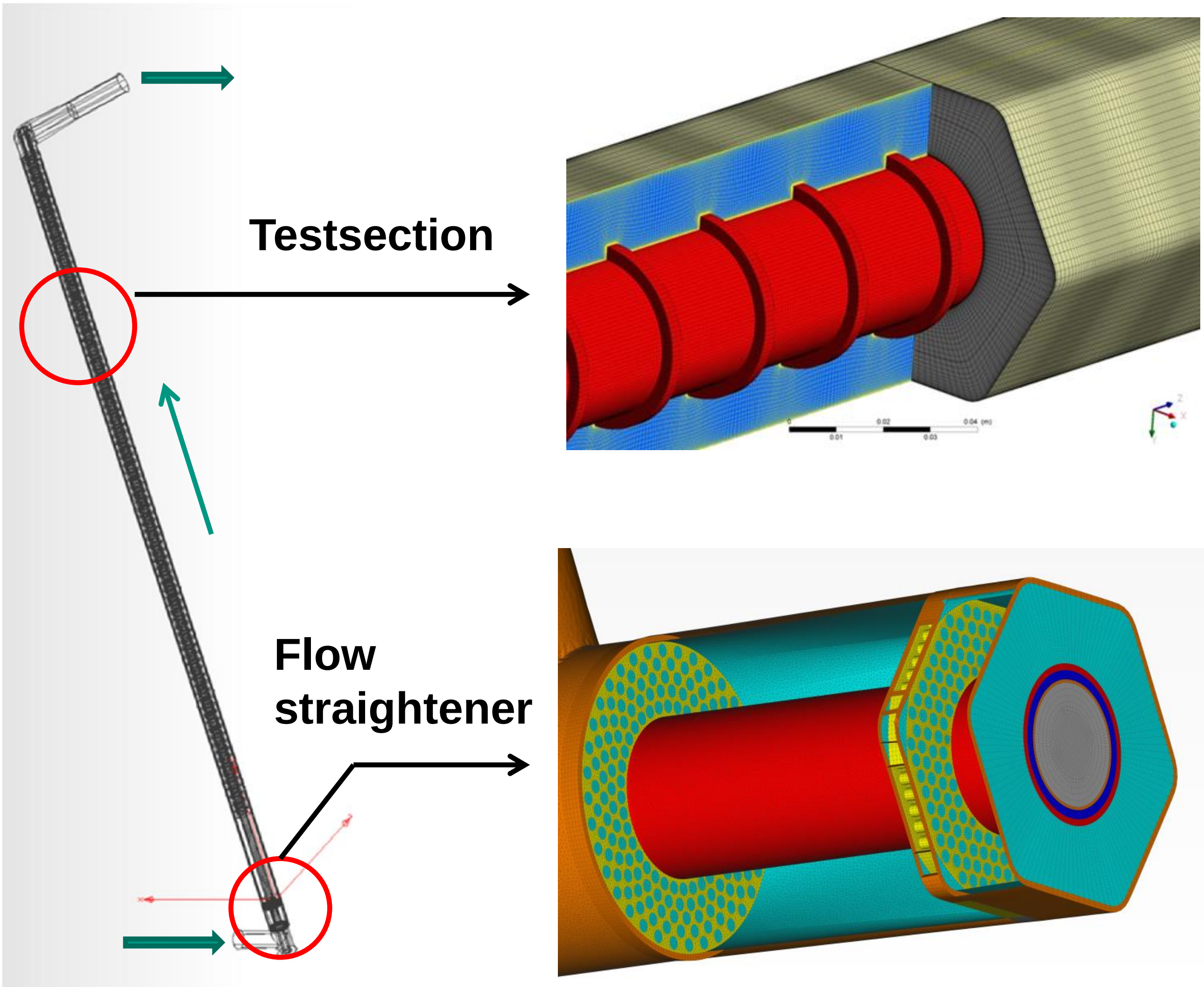
Local Jets (perforated rings)

stagnation regions

Conjugate heat transfer+radiation

difficult to predict by RANS methods and Re analogy!!

L-Star : the solid ring case



33.6 mio hex
38 mio total

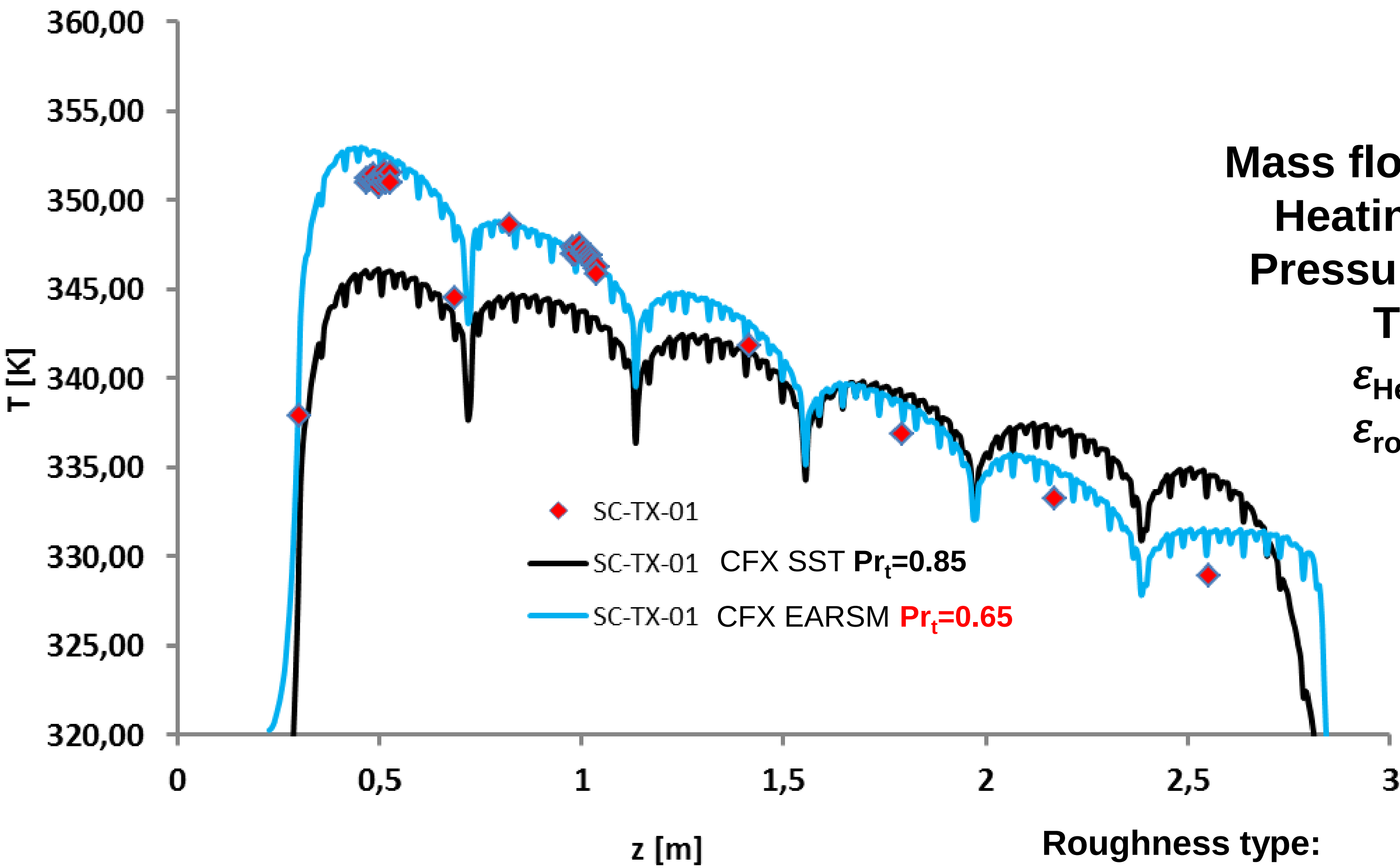
$Y^+<1$ (heater rod)
$Y^+<80$ (flow straight)

BSL EARSM (SST)
Turb. Model

Monte Carlo
Radiation Model

Heat conduction in channel wall, heater rod and flow straight. components

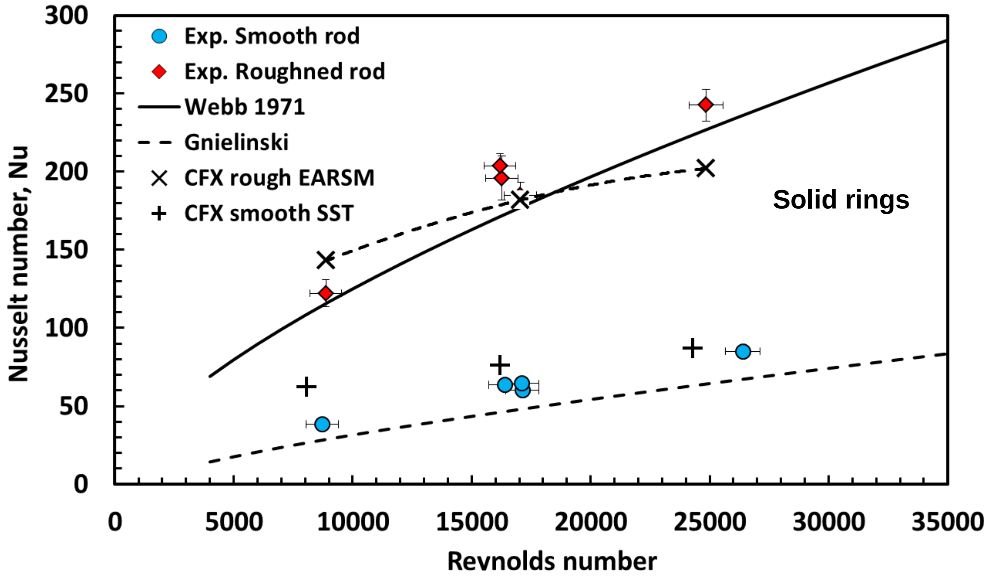
Axial rod surface temperature profile

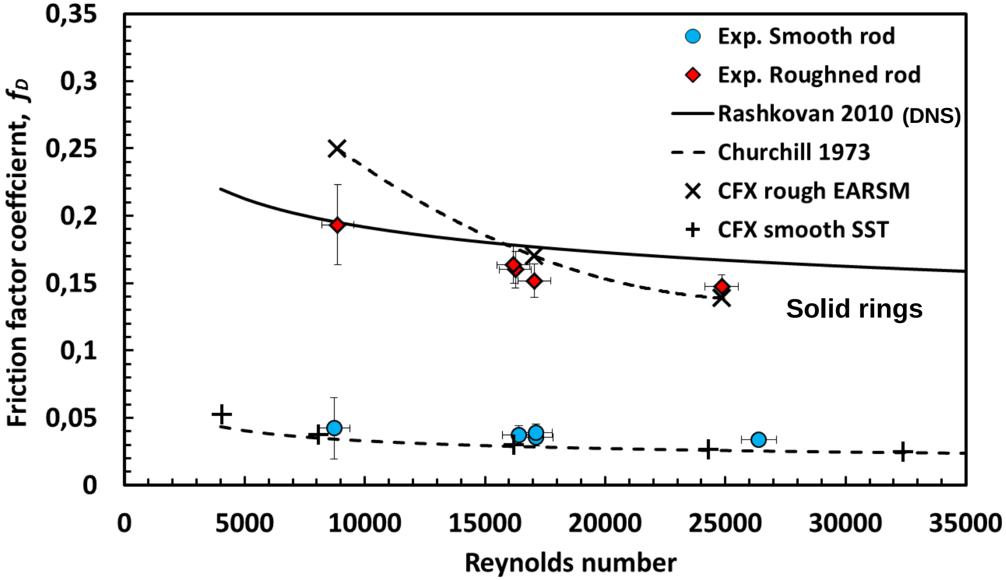


Mass flow	26.1 g/s
Heating	1018.9 W
Pressure	1.51 bar
T_{in}	16.6° C
ε_{Hex}	0.25
ε_{rod}	0.63

Roughness type:
Solid rings

Comparison of smooth and structured rod





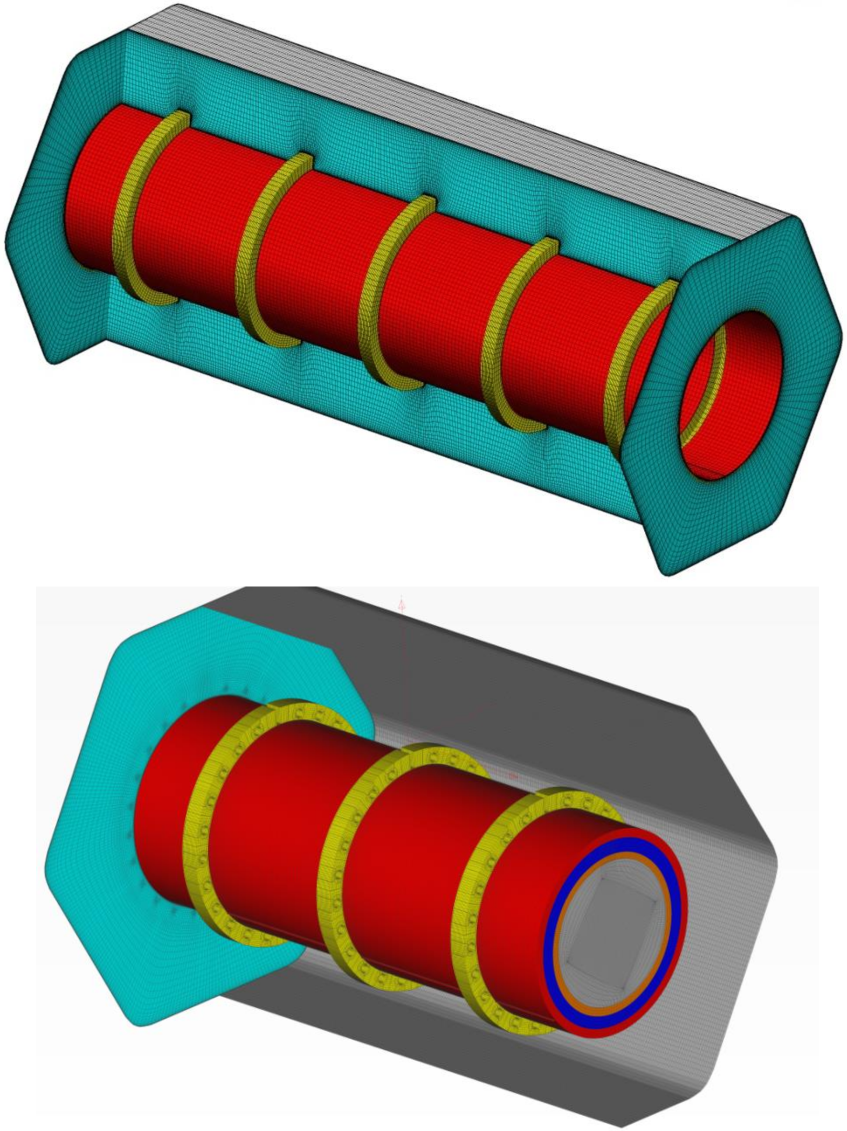
Rough case:
Parameters obtained for the base case at Re~16000 are used for the calculation of other experiments (Pr_t=0.65)

Smooth case:
SST (instead of EARSM)
Pr_t=0.85

The advantage of a better heat transfer is paid by increased pressure loss:

Nu: +200%
Δp: +300%

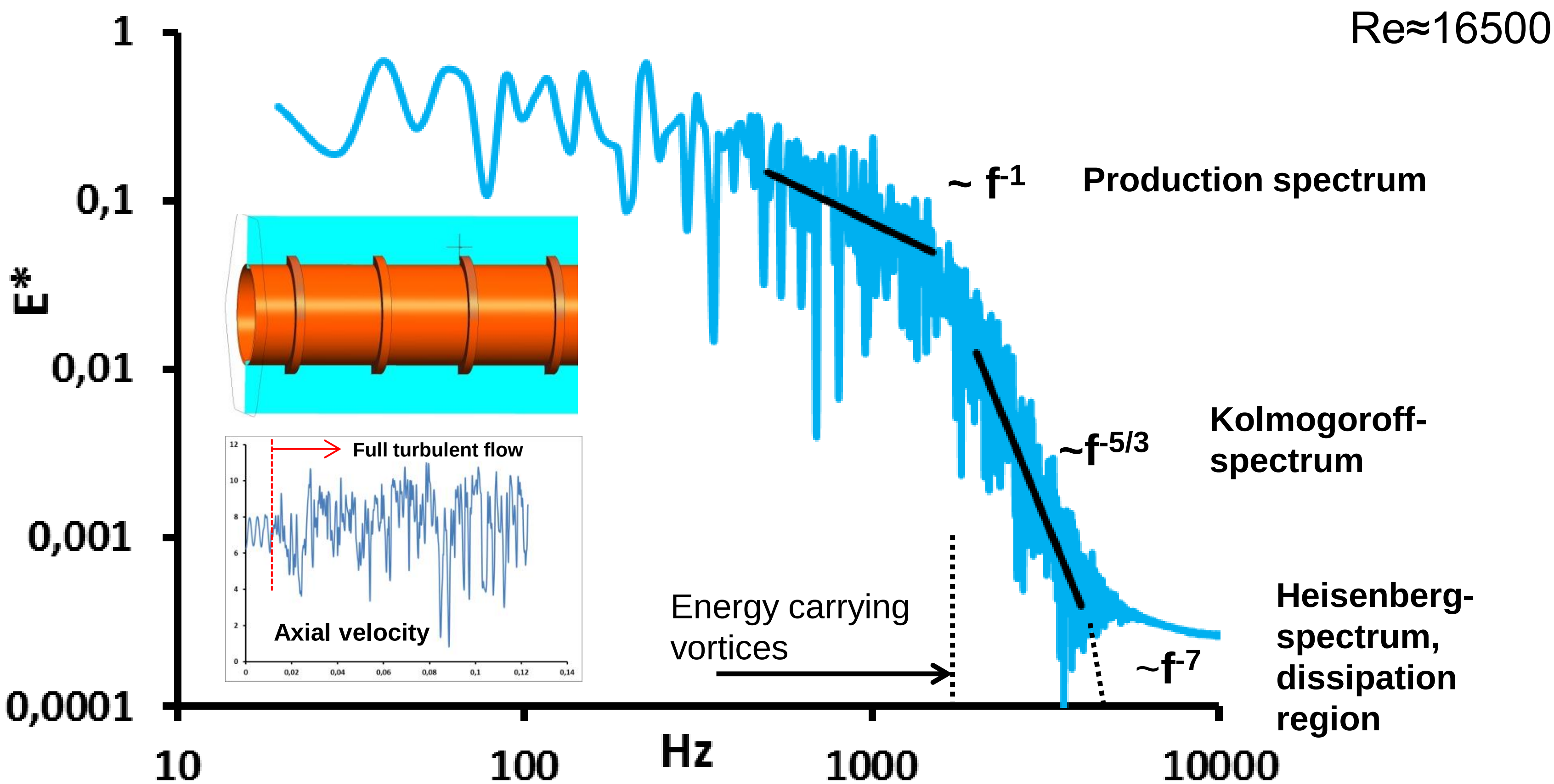
LES Models for solid and perforated rings



	solid rings	Perforated rings
Mesh size [mio]	1.44 (5 rings)	8.92 (3 rings)
Mesh type	structured	structured
Aspect ratio	<50	<80
Angle min.	42°	20°
Y^+	<1	<1
Δt	$5*10^{-5}$s	$2.5*10^{-5}$s
Cou av./max	0.9 / 10	0.7 /10
Comp. time [d]	4 (14 CPU´s)	19 (30CPU´s)
Simulated time	0.2s /4000 steps	0.25s 10000 steps

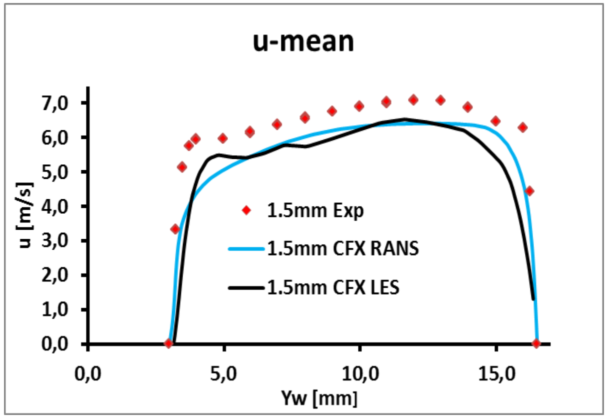
LES Smagorinsky
periodic boundary conditions
Isothermal flow

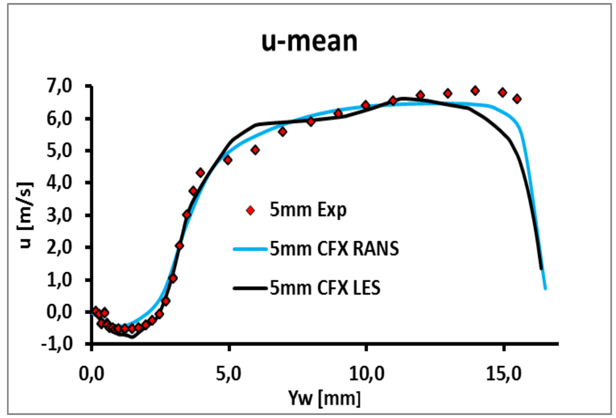
Spectral analysis of LES model data

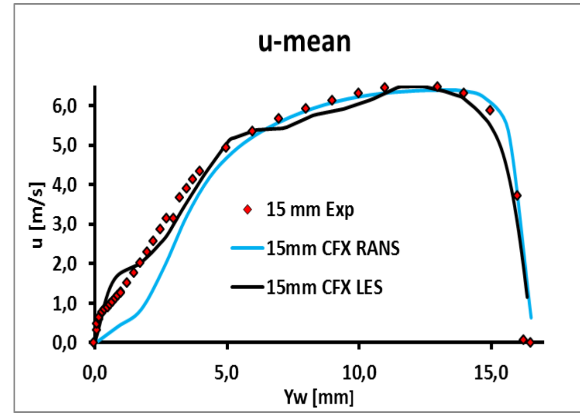


The spectral analysis indicates a complete coverage of the energy carrying region. Furthermore, the noise indicates a rather short physical integration time.

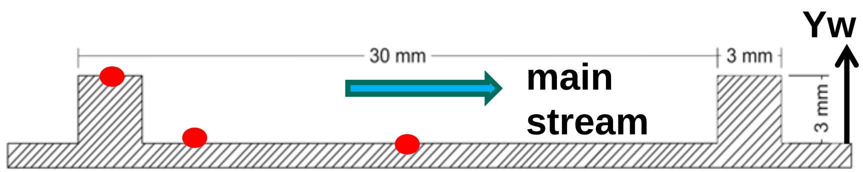
Unheated case – solid rings



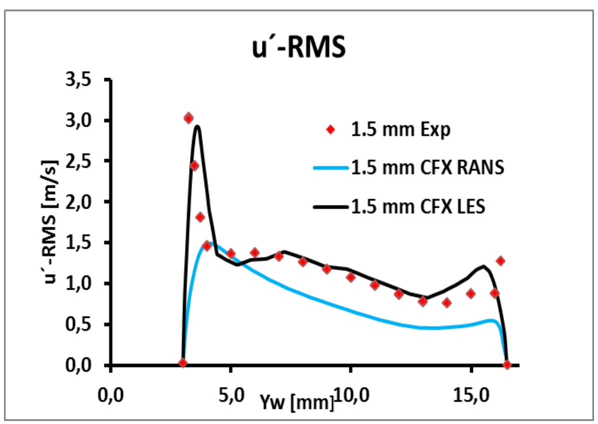


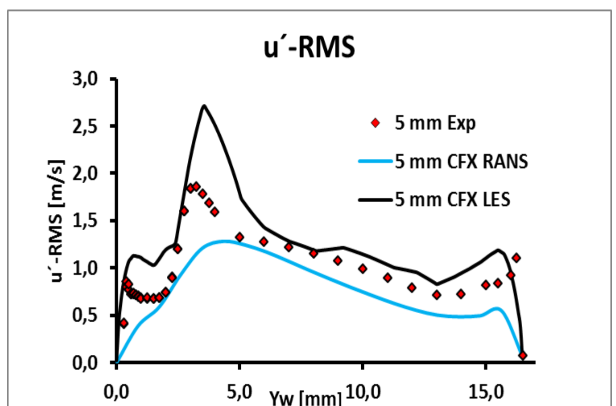


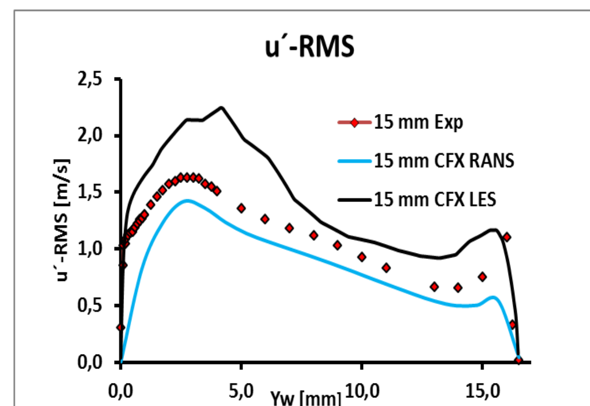
26.15 g/s
1.5 bar
20°C



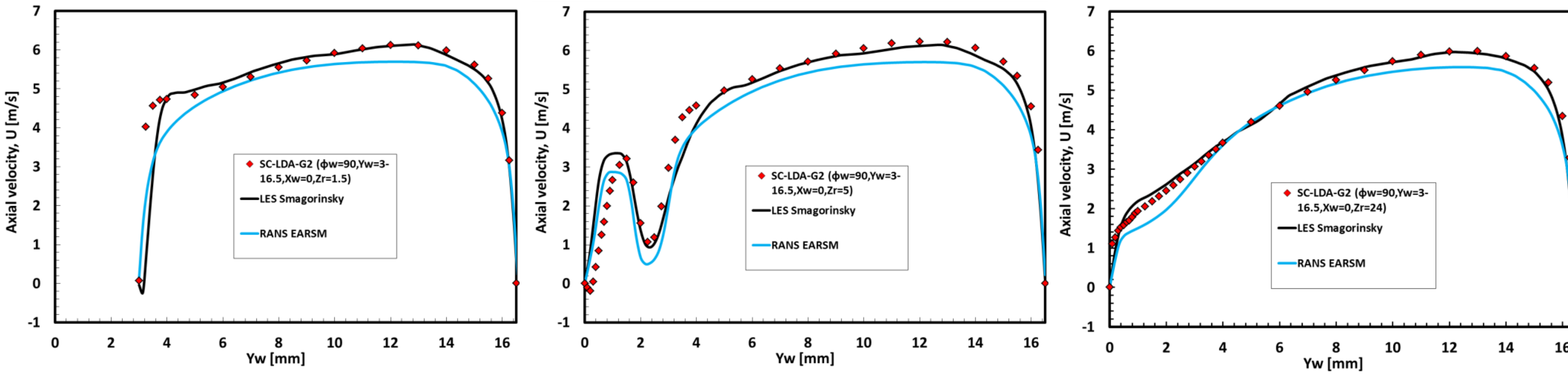
0.15 s av. time
Perhaps not enough !



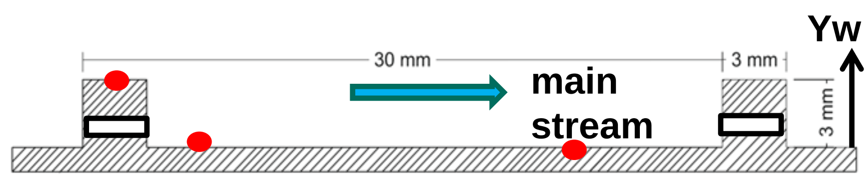


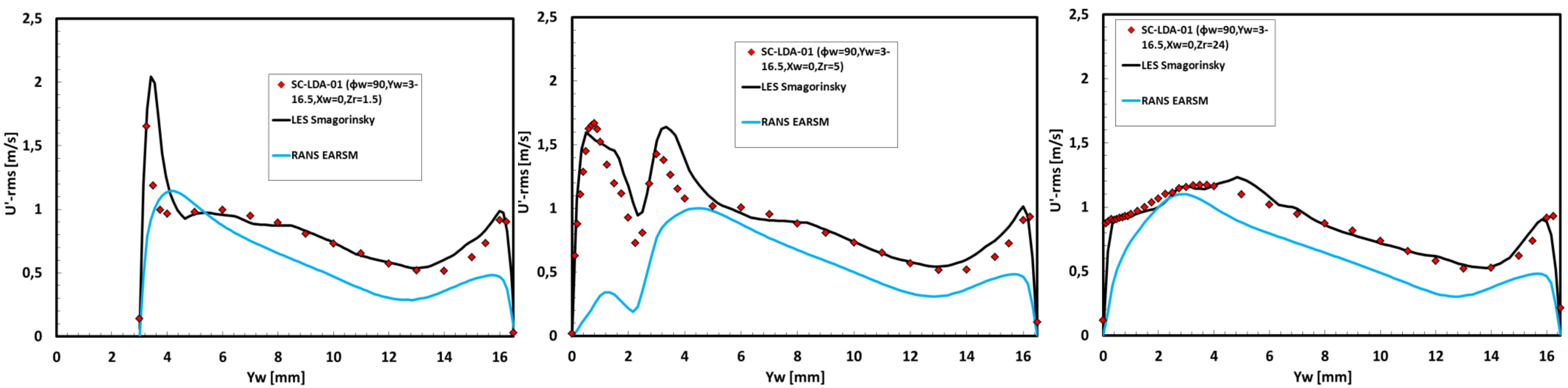


Unheated case – perforated rings

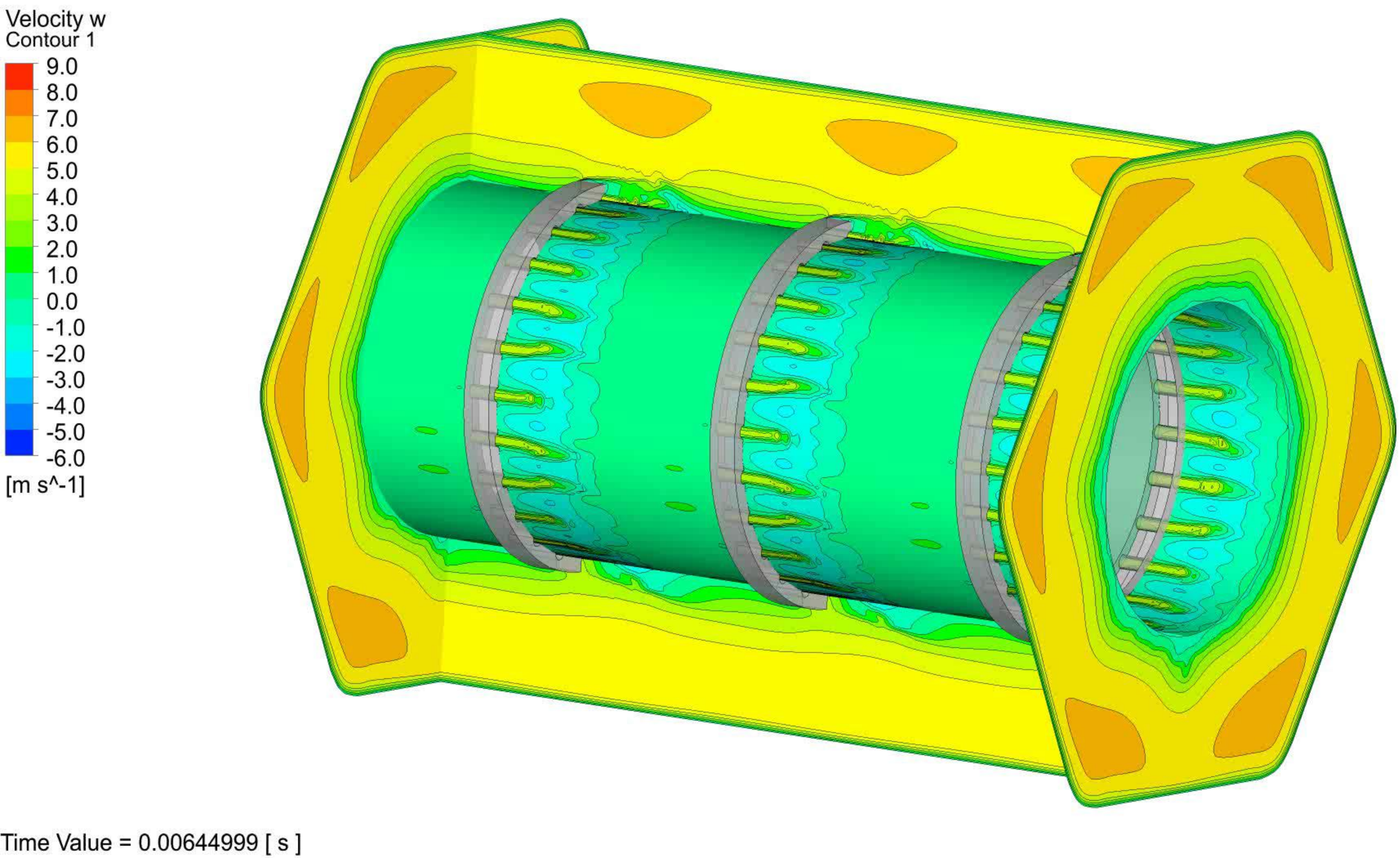


26.15 g/s
1.5 bar
20°C





Perforated rings – LES simulation



Summary and Conclusions and Outlook

For the L-STAR experiments CFD RANS models for the entire test section as well as LES models for unheated experiments and smaller parts of the test section were developed.

By surface structures the heat transfer can be improved significantly, but this is paid by increased pressure loss .

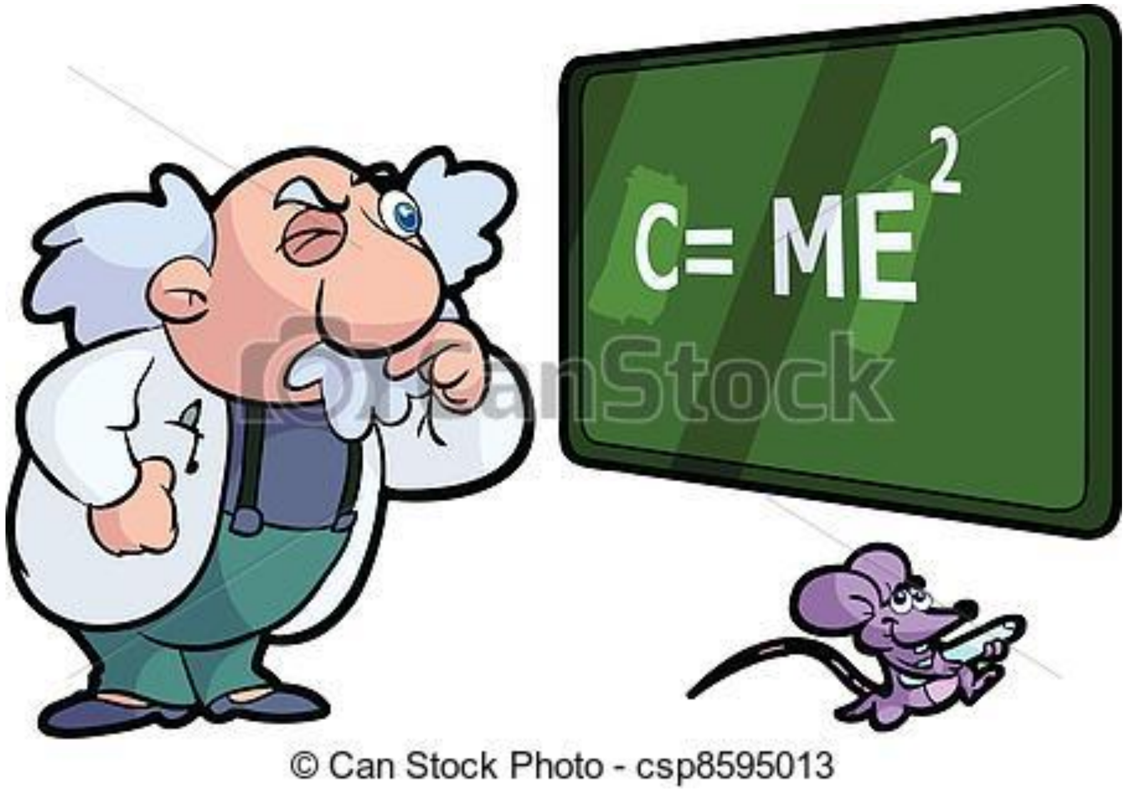
The comparison with experimental heat transfer data for structured surfaces was successfull, but only by modification of the turbulent Prandtl number, which obviously is Re dependent.

A comparison of turbulent quantities for isothermal flow obtained by LDA measurements demonstrated the inaccuracies of presently available RANS models such as SST, RS or EARSM. LES fits better but is more expensive (up to 500 times) and grid dependent. Furthermore, boundary conditions are a problem !

The consequence for RANS turbulence models should be the modification of model coefficients with dependency of Re, Pr and the local pressure gradient,
which should be the topics of future investigations .

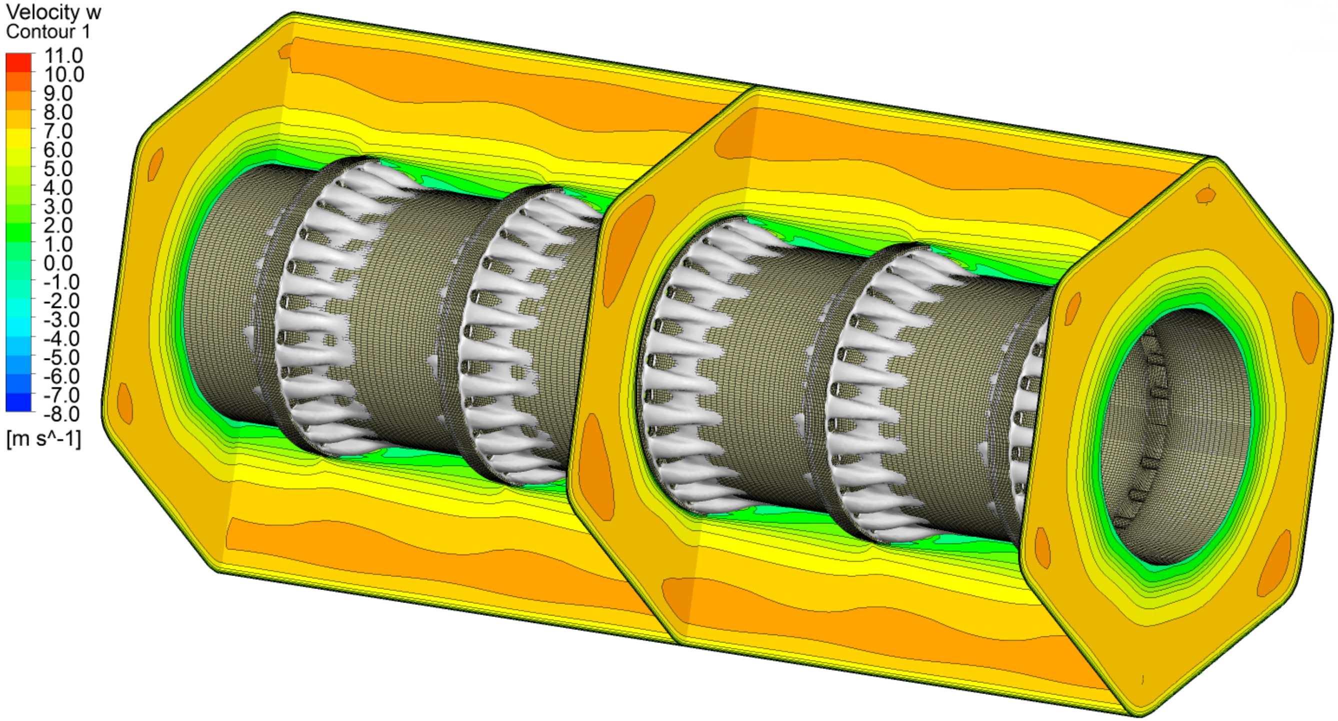
The experimental work was supported within the framework of the European THINS project.

Acknowledgements to Rodrigo Gomez, who provided the experimental data basis, and to all members of the L-Star team !



Are there any questions ?

Solid rings or perforated rings ?



25.3 g/s
1.0 bar
T_0 = 20°C
isothermal

Idea:
smaller separation region
improvement of heat transfer
reduced pressure loss ?

First results:
See next slights !

Reynolds analogy concept

Karlsruher Institut für Technologie

By time averaged momentum equation:

$$\overline{v_k' v_j'} = -\nu_t \frac{\partial \overline{v}_j}{\partial x_k}$$

Reynolds stress tensor
Eddy viscosity approach

ν_t solved by turbulence models (k-ε, RS, etc)

By time averaged energy equation:

$$\overline{T' v_k'} = -a_t \frac{\partial \overline{T}}{\partial x_k}$$

Reynolds heat flux

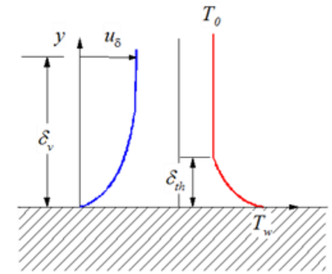
a_t solved by Re analogy
turbulent Prandtl number

$$\boldsymbol{Pr_t = \frac{\nu_t}{a_t} = \rho c_p \frac{\nu_t}{\lambda_t}}$$

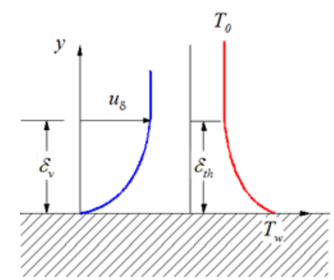
= 0.9 ??

Not valid for stagnation and separation regions, liquid metal flow !

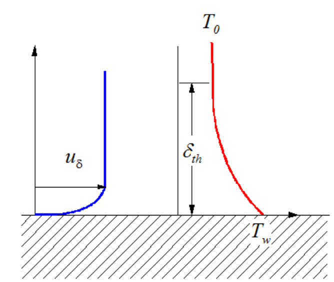
Momentum and thermal boundary layers:



Pr>>1
Oils



Pr=1
Gases



Pr<<1
Liquid metals

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Karlsruher Institut für Technologie

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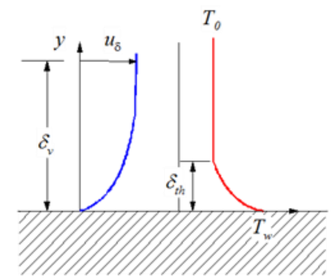
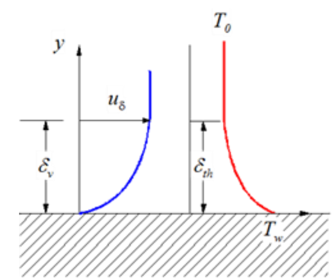
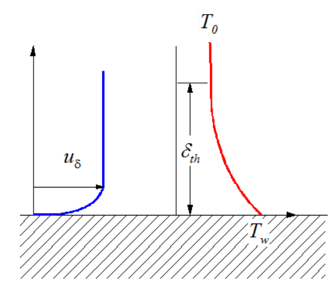


Pr>>1
Oils

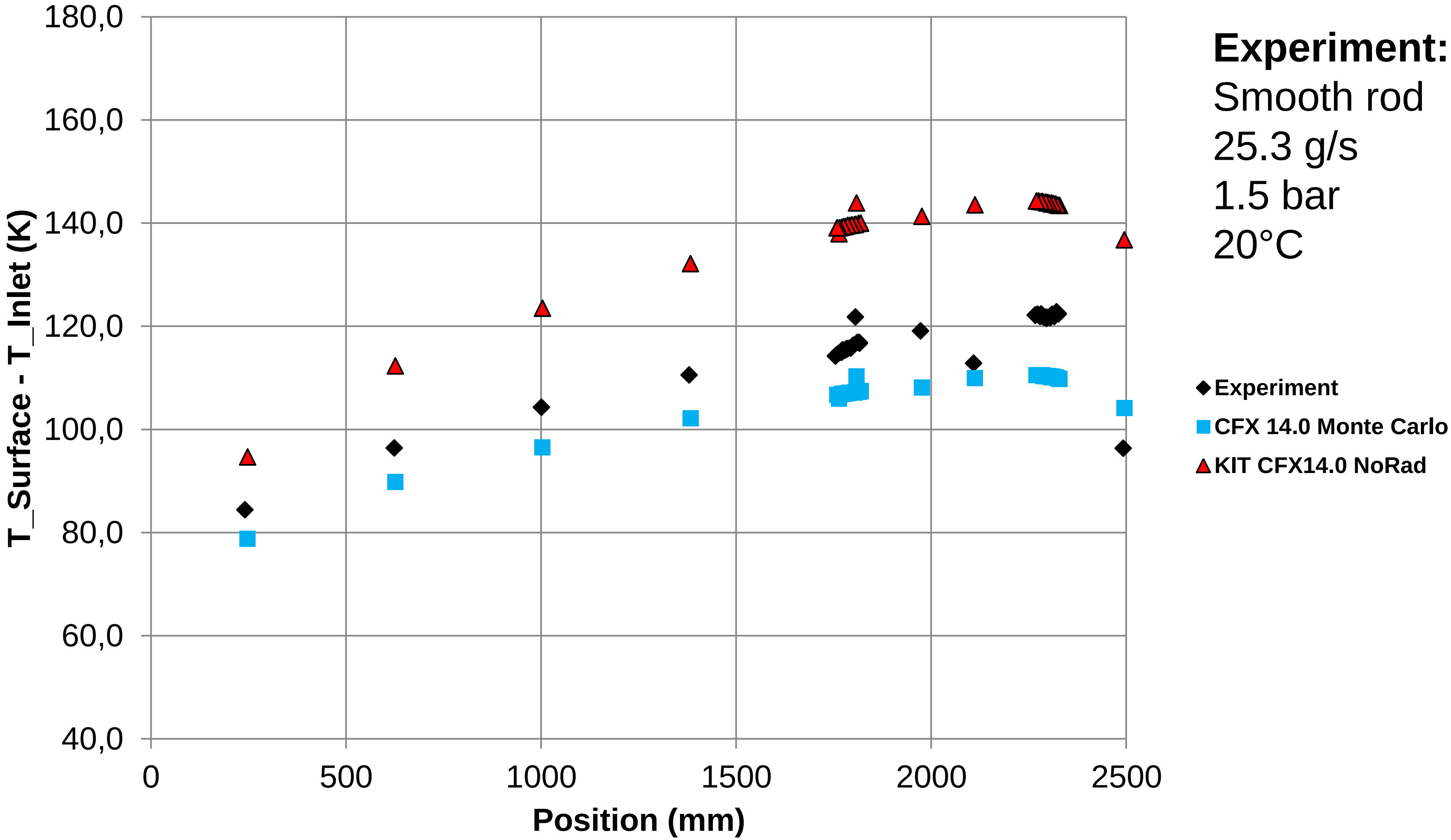


Pr=1
Gases



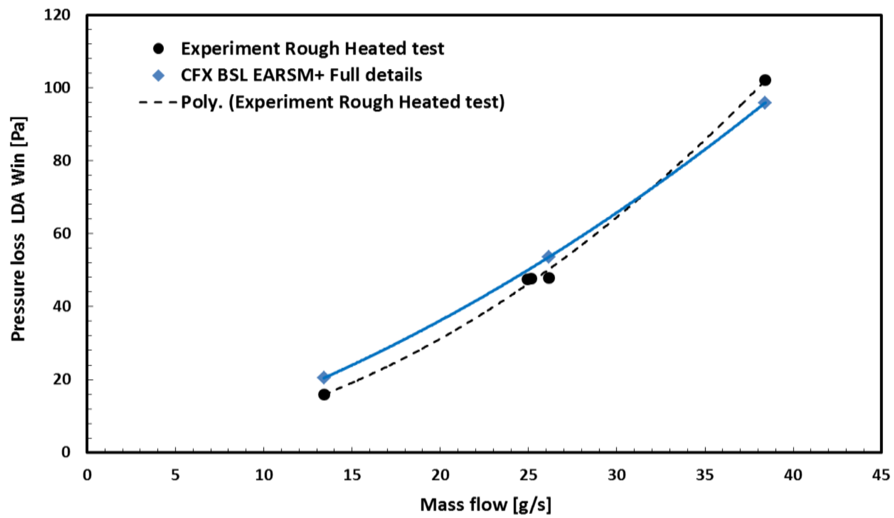
Pr<<1
Liquid metals

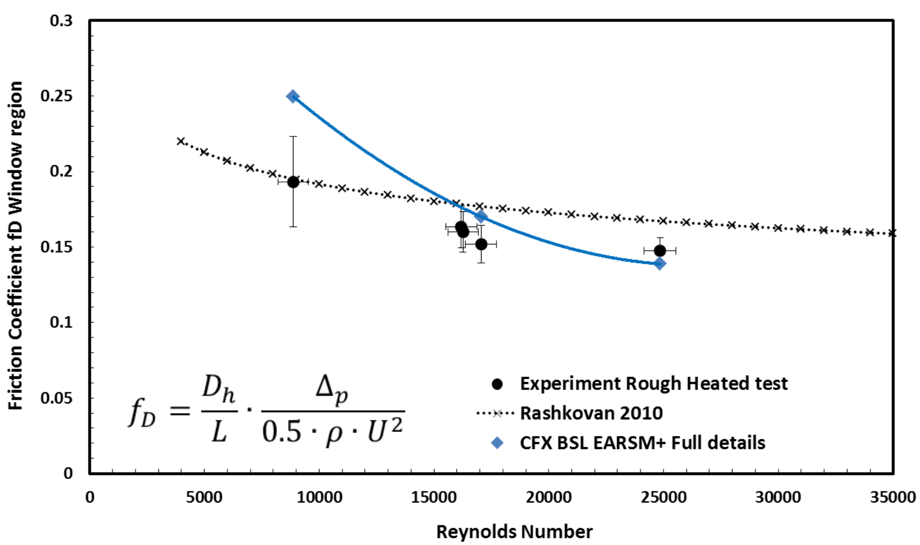
Why to use radiation radiation ?

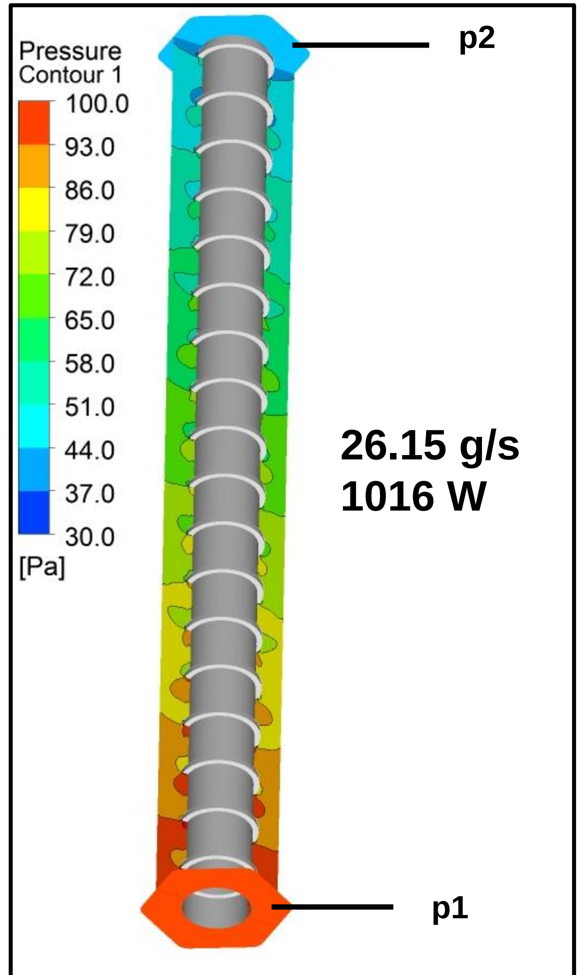


Experiment:
Smooth rod
25.3 g/s
1.5 bar
20°C

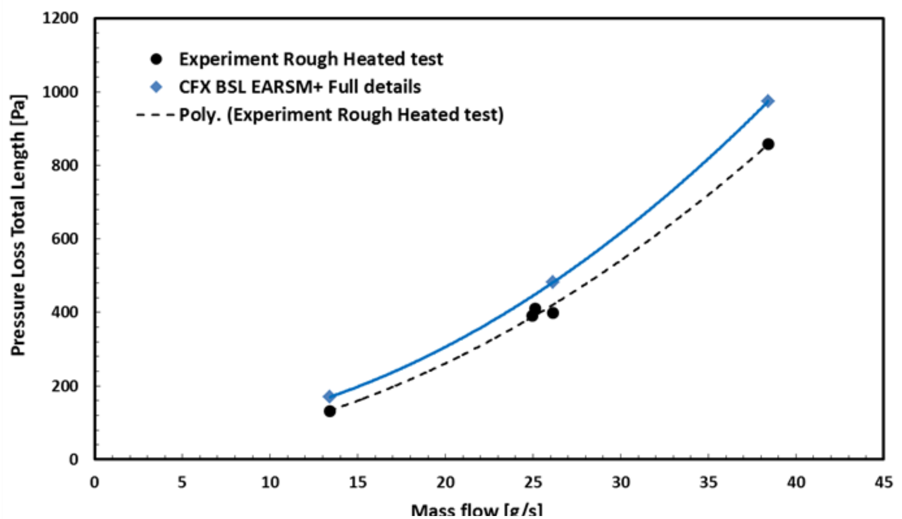
Pressure losses in test section

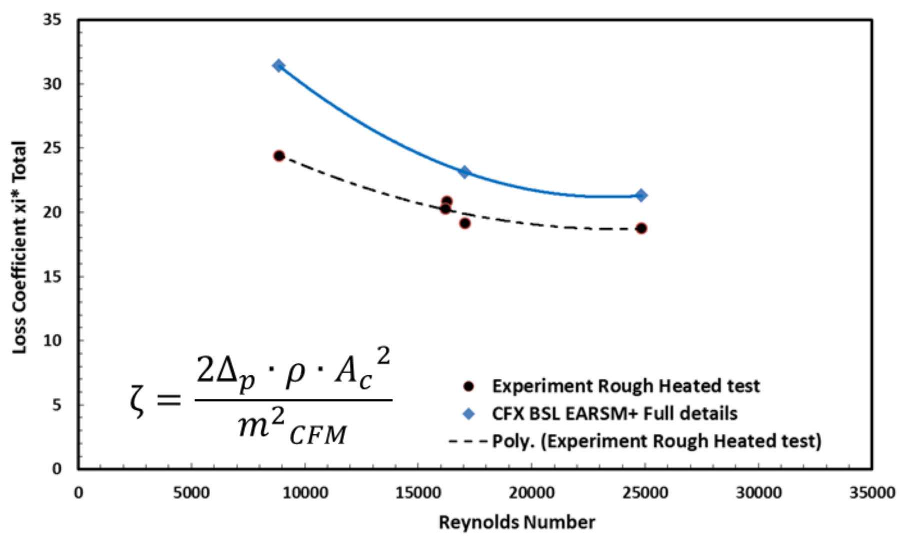


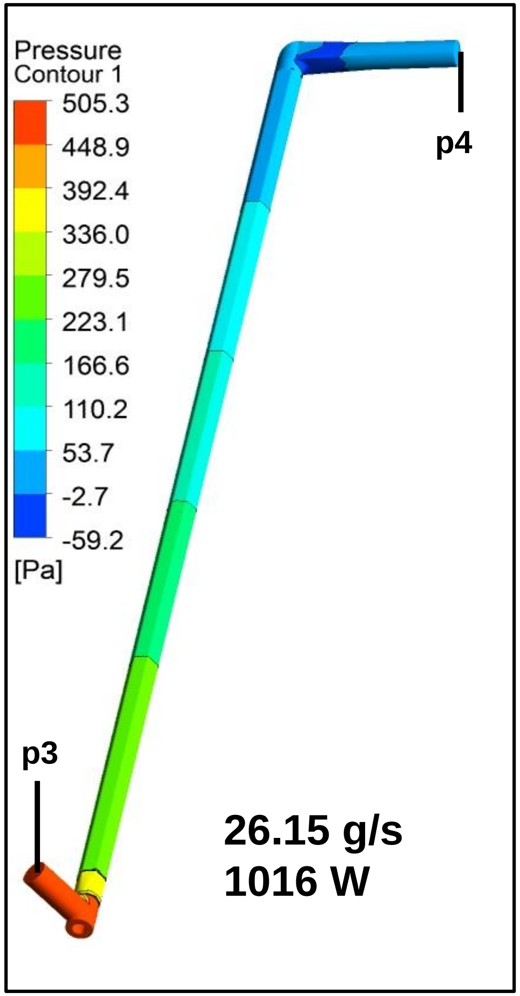




Pressure loss for the entire section







Turbulenzmodelle

- Explizites algebraisches Reynolds Stress Modell

  numerisch Aufwand zwischen 2-Gleichungsmodellen und RS-Modell

  keine zusätzlichen Transportgleichungen für RS Komponenten

  $$\overline{u_i u_j} = F[(\frac{\partial \overline{u}_i}{\partial xj} + \frac{\partial \overline{u}_j}{\partial xi}), (\frac{\partial \overline{u}_i}{\partial xj} - \frac{\partial \overline{u}_j}{\partial xi})]$$

  als Kombination mit k-ε oder k-ω

  anisotrope Strömungen

  Korrektur für stark gekrümmte Stromlinien

  höhere numerische Stabilität als RS Modell

- SST Shear Stress Transport Modell

  2-Gleichungsmodell, Kombination von k-ε und k-ω

  Blendingfunktionen: k-ω in Wandnähe und k-ε im Aussenbereich

  hat k-ε als Standardmodell abgelöst

Re analogy concept in CFD

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Turbulent energy equation:

$$\rho c_p\left(\bar{u}\frac{\partial \bar{T}}{\partial x}+\bar{v}\frac{\partial \bar{T}}{\partial y}\right)=-\frac{\partial}{\partial y}\left(-\lambda\frac{\partial \bar{T}}{\partial y}+\rho c_p\overline{v'T'}\right)=-\frac{\partial}{\partial y}\left(-(\lambda+\lambda_t)\frac{\partial \bar{T}}{\partial y}\right)$$

In analogy with the turbulent viscosity a turbulent heat flux appears and thus a turbulent eddy heat diffusivity $\varepsilon_H=\lambda_t/(\rho\, c_p)$ can be defined, the ratio is called the turbulent Prandt number Pr_t:

$$Pr_t=\frac{\varepsilon_M}{\varepsilon_H}=f\left(Re, Pr, Gr, {}^{y}\!/\!_{R}\right)=\frac{\overline{u'v'}}{\overline{v'T'}}\frac{\dfrac{\partial T}{\partial y}}{\dfrac{\partial u}{\partial y}}=const.??$$

Consequences:

Pr_t is a tensor depending on a couple of variables and difficult to measure directly, especially in liquid metals. Re analogy can be applied only if $Pr_t=o(1)$!!

Gittergenerierung und Modellierung

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Kriterien Nicht erfüllt

Geometrie und Physik CAD Modell

Verwendbares CAD Modell
Größe, Gaps, Mehrfachbe-legung

Lokale Auflösung, y^+ ?
Unstrukturiert, strukturiert oder hybrid ?
RANS, LES oder DNS

Kriterien Nicht erfüllt

Memory PC und Rechner
Voraussichtliche Rechenzeit
Best Practice Guidelines
Arbeitszeit (Gitterqualität)

Auswahl physikalischer Modelle und Parameter

Kriterien Nicht erfüllt

Optimierter Ablauf:
Konvergenzkriterien abschwächen (falls möglich)

Simulationsläufe
Konvergenz, physi-kalische Plausibilität

Postprocessing
Publikation der Ergebnisse

INR Seminar
8.12.2014

The k-ε turbulence model

Equation 2–14.

The k -ε model, like the zero equation model, is based on the eddy viscosity concept, so that:

$$\mu_{\text{eff}} = \mu + \mu_t \qquad (2\text{–}21)$$

where μ_t is the turbulence viscosity. The k -ε model assumes that the turbulence viscosity is linked to the turbulence kinetic energy and dissipation via the relation:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \qquad (2\text{–}22)$$

where C_μ is a constant. For details, see List of Symbols.

C_μ=0.09

Proposal for modification !!

The values of k and ε come directly from the differential transport equations for the turbulence kinetic energy and turbulence dissipation rate:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j k\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon + P_{kb} \qquad (2\text{–}23)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j \varepsilon\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}\left(C_{\varepsilon 1} P_k - C_{\varepsilon 2}\rho\varepsilon + C_{\varepsilon 1} P_{\varepsilon b}\right) \qquad (2\text{–}24)$$

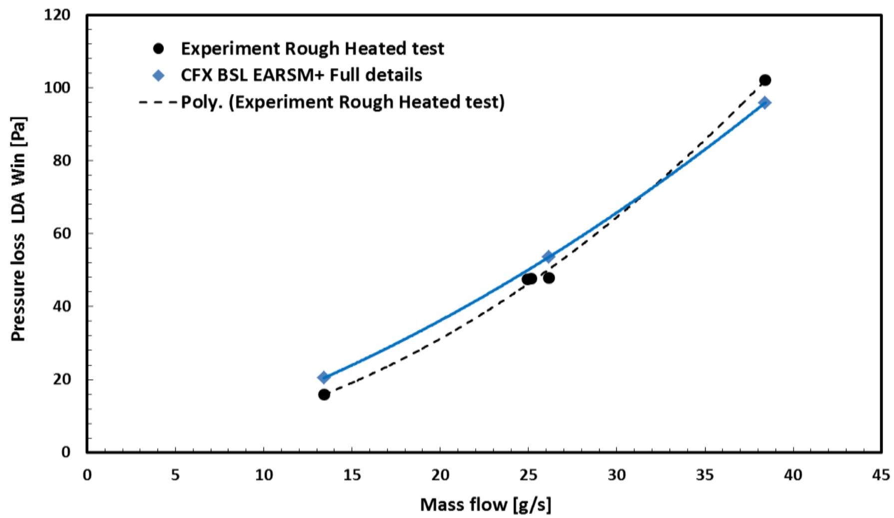
where $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k and σ_ε are constants. For details, see List of Symbols.

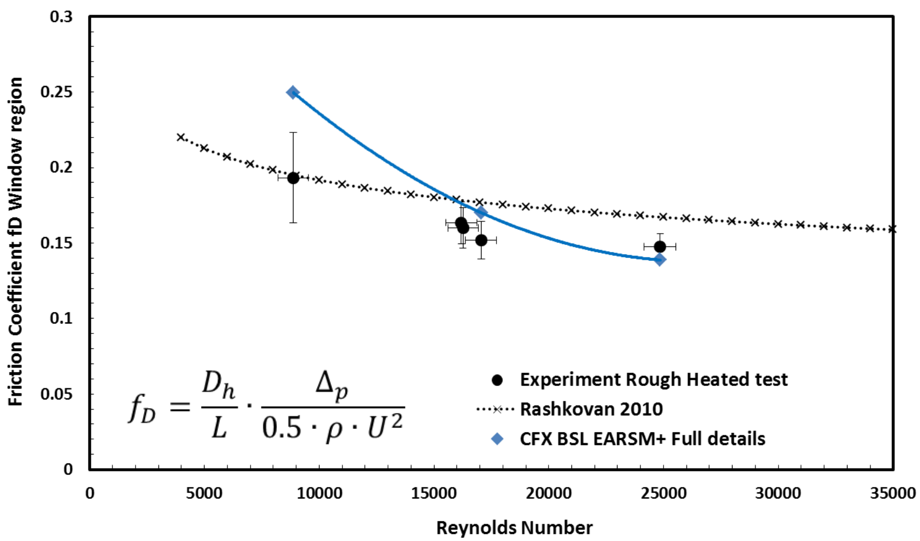
P_{kb} and $P_{\varepsilon b}$ represent the influence of the buoyancy forces, which are described below. P_k is the turbulence production due to viscous forces, which is modeled using:

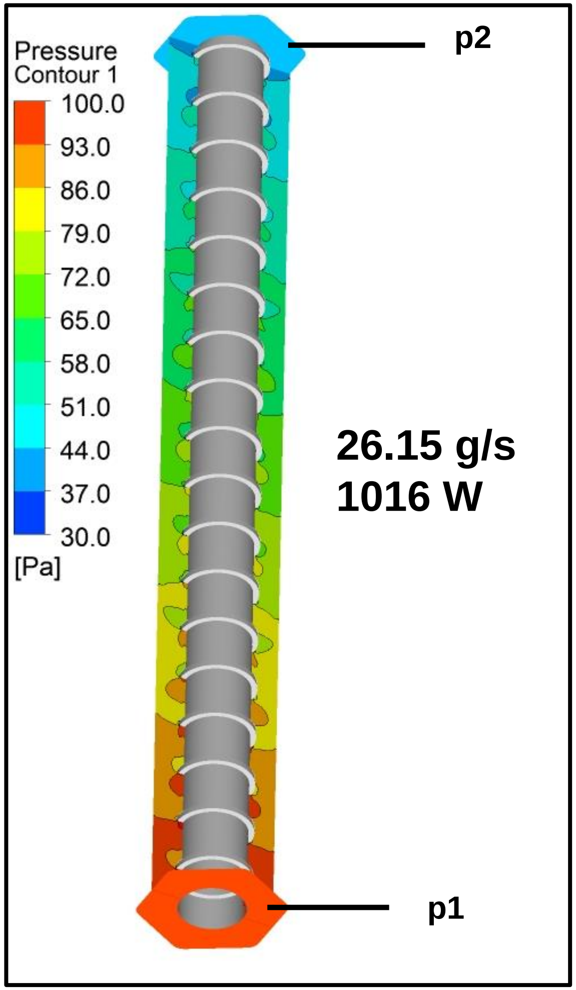
$$P_k = \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} - \frac{2}{3}\frac{\partial U_k}{\partial x_k}\left(3\mu_t\frac{\partial U_k}{\partial x_k} + \rho k\right) \qquad (2\text{–}25)$$

Source: ANSYS 15.0 CFX solver manual

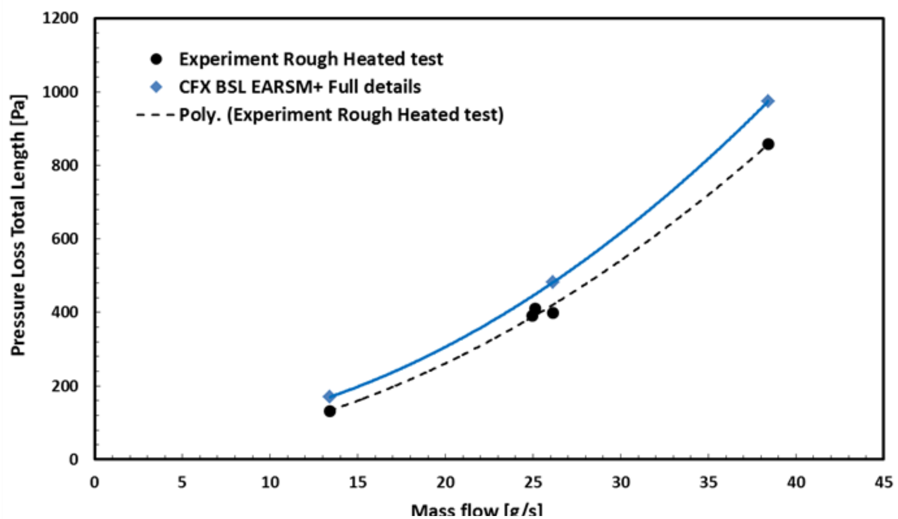
Pressure losses in test section

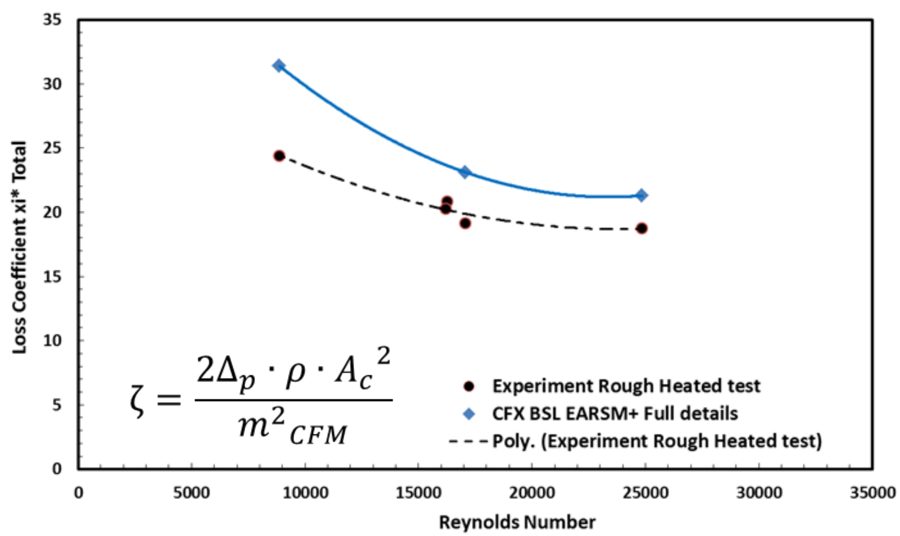


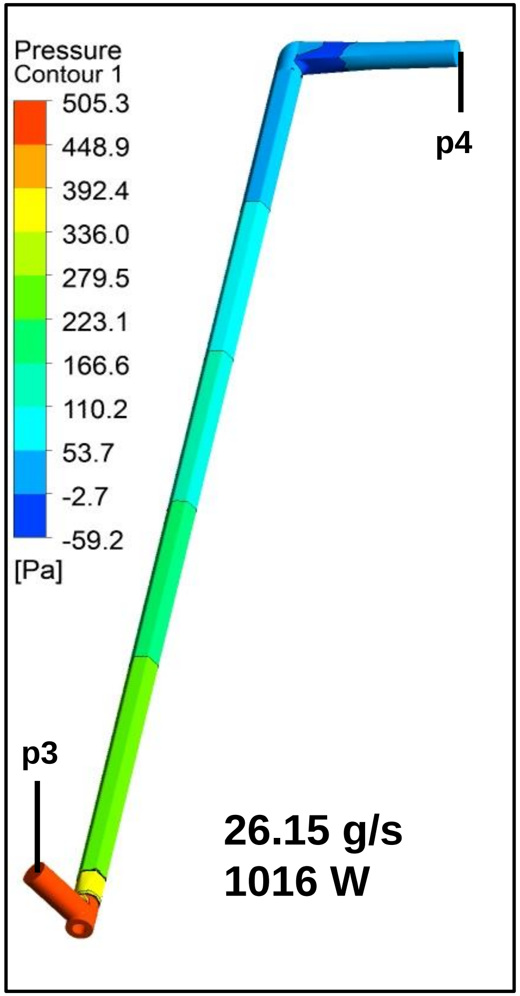




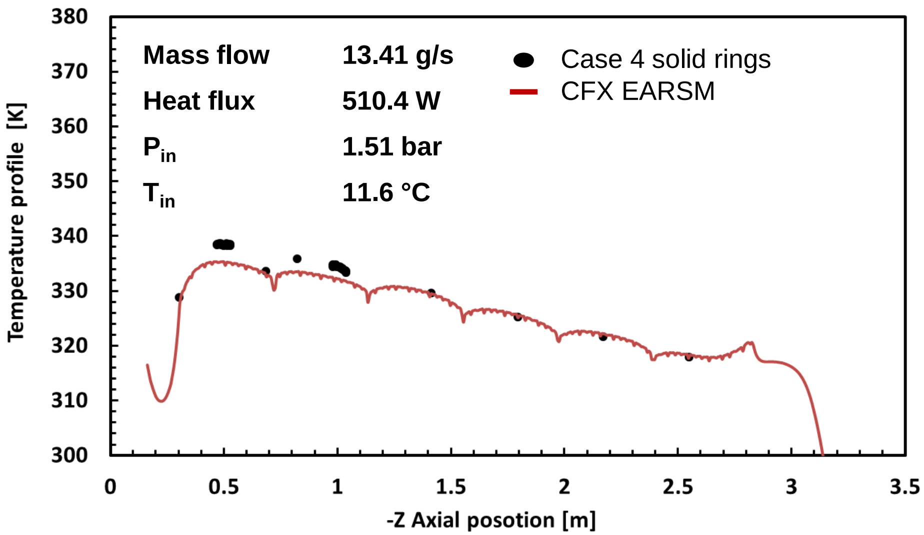
Pressure loss for the entire section

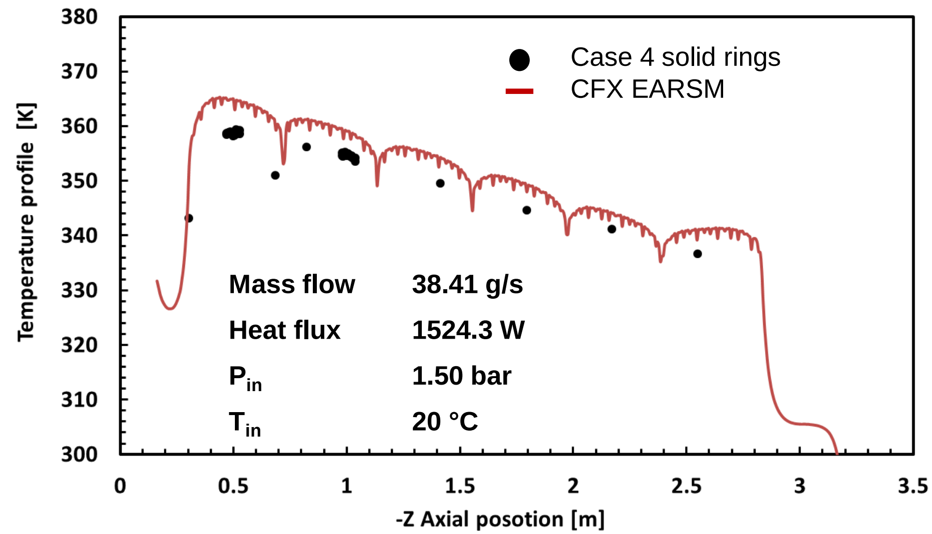






Axial rod surface temperature profile - Other cases -





- Simulations capture the form of the rod temperature distribution quite accurately.
- However, temperature deviations are increasing up to 5° .

Structured grid for perforated rings