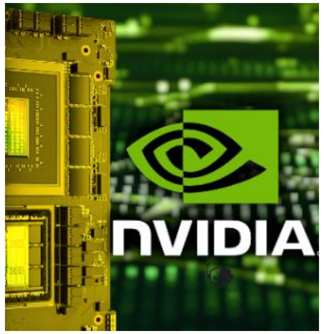
UNIVERSITY OF OXFORD

LES-CHT for Smooth and Micro-structured Walls

L. He
Department of Engineering Science
University of Oxford

‘Machinable Surface’: What Do We Want (& How)?

2017 - *a ‘disruptive’ year.*

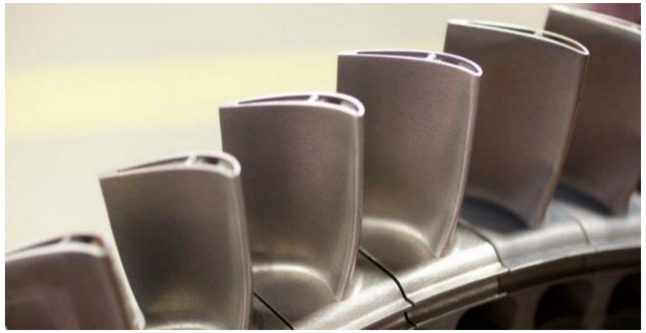


- ***World*** **sees the foundational work on the LLMs** *(thus the current ‘AI Storm’)*
  - *Vaswani et al* (2017) *“**Attention is All You Need**” (~190,000 cites)*➔ ‘Transformer’
  - ***Nvidia*** (market value $3 Trillions, ↑100 times, 2017-*2024)*

- **Additive Manufactured HP Turbine:** *AM made & tested at*

  13,000 rpm; 1523 K

  - *Siemens Press Release: Feb 2017;*
  - *ASME Emerging Tech Award: Dec 2017*



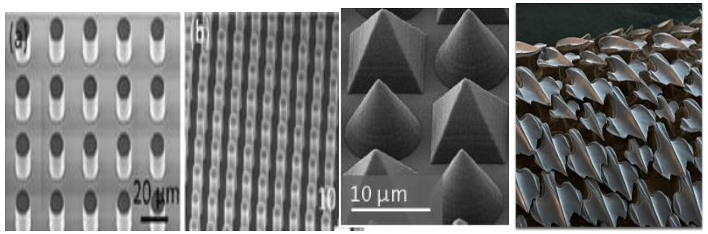
- **‘Role Reversal’: Manufacture Engineer** *vs.* **Aerodynamic Designer:**
  - ***Past*** *(20-30 years ago)*

    Aero-Designer: *‘ here is my design’.*

    Manufacturer: *‘very nice, but we cannot make it’;*
  - ***Present*** *(& Near Future?)*

    AM Manufacturer: *‘what surface finish would you like?’*

    Aero-Designer: *‘ oh…, how can we **design** it in the first place?’*



Chu et al (2012) KIT (2015) Nature (…?!)

➔ ***“Surface Design” (both Shape and Finish) ??***

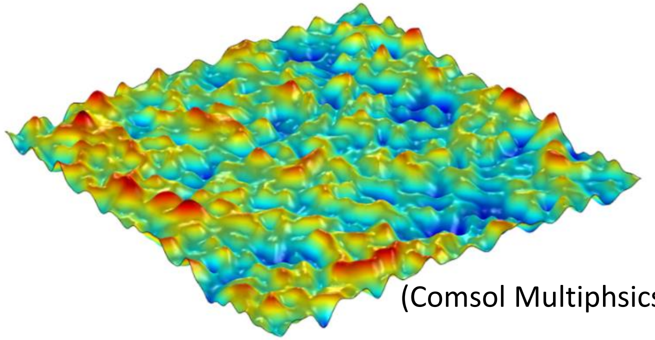
Outline *('Multiscale Solution for Multiscale Problem')*

- **Multi-scale Issues of Interest (Motivations & Challenges):**
  - *Spatial Scale Disparity (Macro vs. Micro): Random/'Regular' Surface Roughness.*
  - *Temporal Scale Disparity (Fluid vs. Solid): Conjugate Heat Transfer.*
- **Two-scale Solution *(in Time)***
  - *Long-scale Slow Transient: 'Dual Time-Marching'*
  - *Short-scale Turbulence: Fluid-Solid 'Temperature Harmonic Transfer Function'*
- **Two-scale Solution *(in Space)***
  - *Applied to Fluid-domain with Micro-structured Wall.*
  - ***Extended to Solid-domain** (**Source-term for Coarse-mesh** (ML or not): **Reynolds Stresses?!**)*
- **Case Examples**
  - *CHT validation (VKI ribbed channel)*
  - *LES for micro-structured wall (Fluid-domain only)*
  - ***Conduction for micro-structured wall (Solid-domain only)***
  - *Coupled CHT for micro-structured wall (Fluid-Solid domain).*

Surface Roughness: Multi-scale Problems *(Adiabatic Flow Domain)*

UNIVERSITY OF OXFORD

Stochastic Roughness



(Comsol Multiphsics)

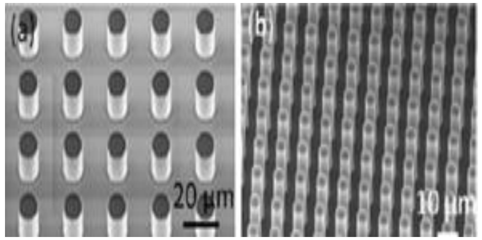
- **Conventional Modelling Path** (Nikuradse, 1933):
  - *same BL structure as smooth with* ***velocity offset*** *by* ***'Roughness Function'*** *(ΔU^+)*

- **Validity in Question** (e.g. for large roughness), ΔU^+ *depending on detailed geometry* (Flack, 2019)

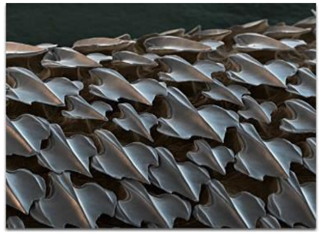
➔ ***Need for Local Resolving Capability***

'Regular Roughness'

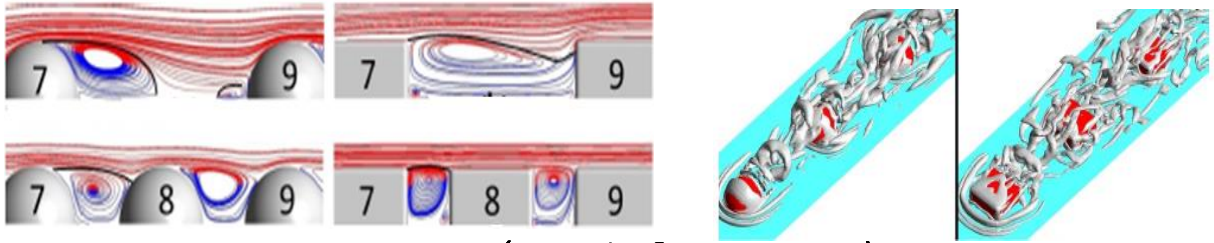
(New Impetus: Additive Manufacture, AM)



Chu et al (2012)



Nature (!)



(Kapsis & He, 2018)

- *Roughness Shapes & Patterns Do Matter.*

➔ ***Need for Local Resolving Capability***

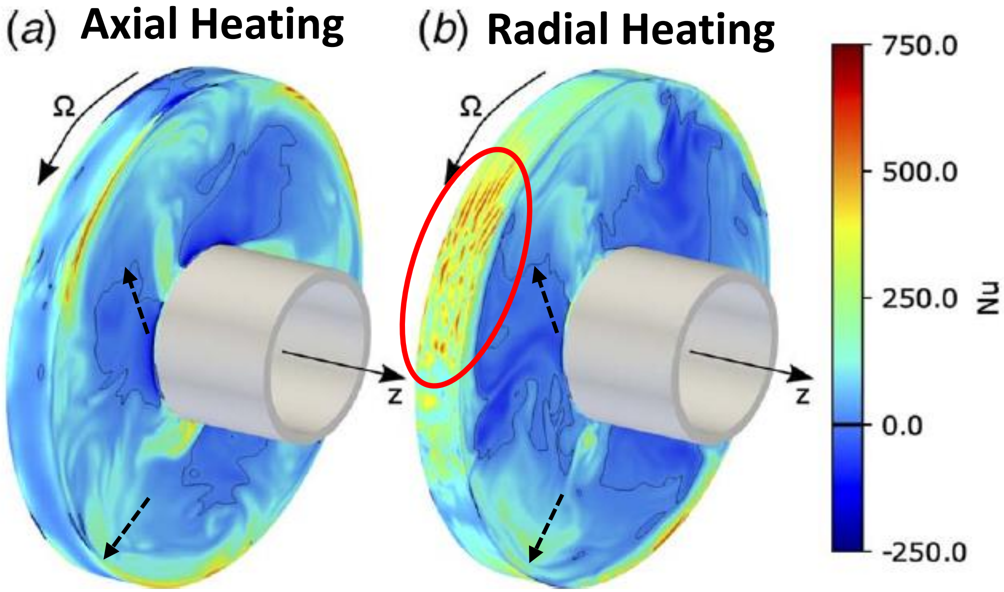
Issues of Interest: Interplay between ***roughness*** ***& bulk flow/surface shape.***
Long-term Prospect: towards ***'Surface Design'*** *(both Shape & Finish)*

Why LES & CHT? – *'Feedback' of Heat Transfer to Turbulence* (***smooth wall***)

Rotating Cavity at Different Thermal BC *(Hickling & He, 2023)*

Heat Transfer

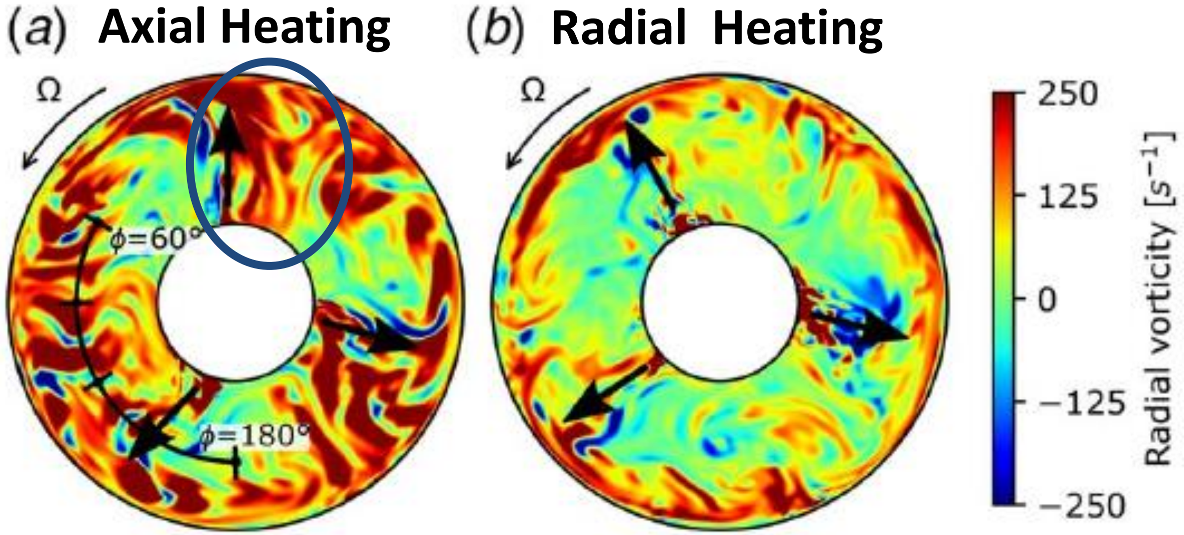
(on shroud and disk surfaces)



Instantaneous Nusselt Number
(normalised heat fluxes)

Flow

(on axial cut-plane at $2\delta_{Ek}$) *Ekman layer thickness*



Radial Vorticity *(arrows: outflow 'radial arms')*

- *Disk heating ➔ Imbalance (ΔP vs. $F_{Coriolis}$)*
  (thus, unstable vortices / large-scale turbulence)

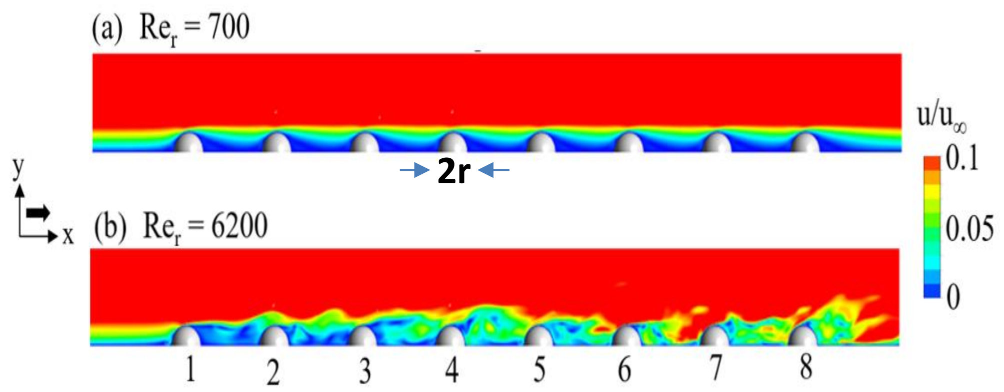
- **Wall Heat Transfer (Temperature T_w) does affect Nearwall Turbulence Generation**

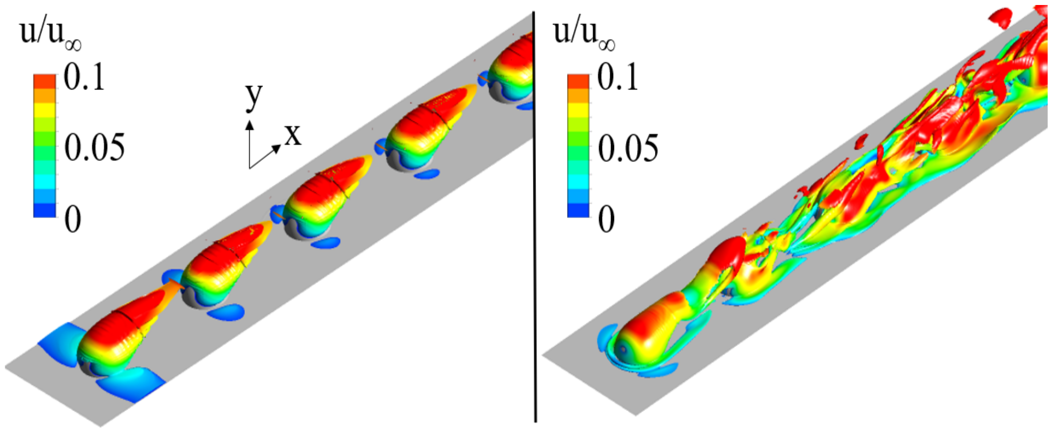
Why LES & CHT?–‘*Feedback*’ *of Heat Transfer to Transition* (***micro-structured wall***)

(Campanaro & He, 2023)

Adiabatic BC at Two Reynolds Numbers

(**$Re_r = \rho_\infty V_\infty r/\mu_\infty$** --- *bulk flow based Re*)

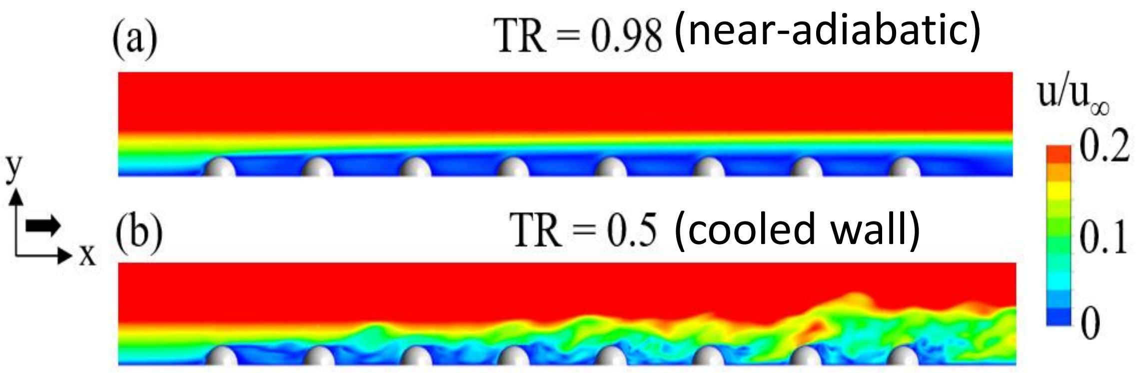




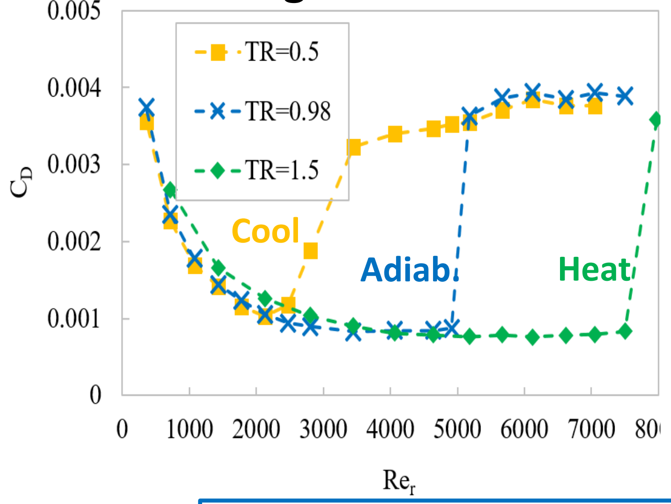
(a) $Re_r = 700$ (a) $Re_r = 6200$

Diabatic at Same Reynolds Number (*$Re_r = 4000$*)

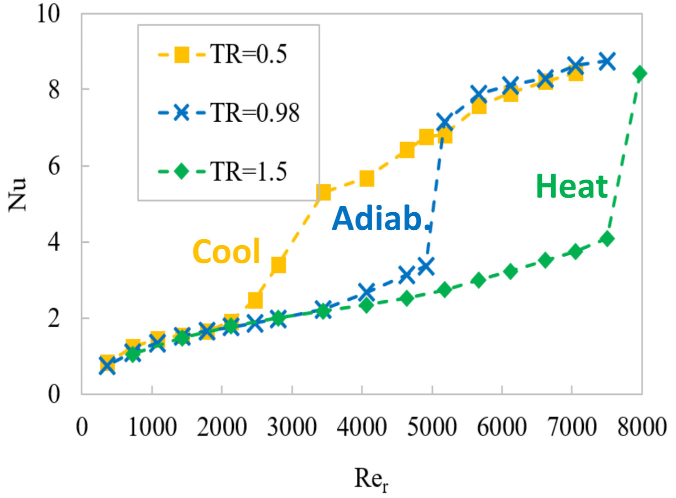
(Temperature Ratio: ***TR = T_w / T_{01}***, *with specified T_w)*



Drag Coefficient



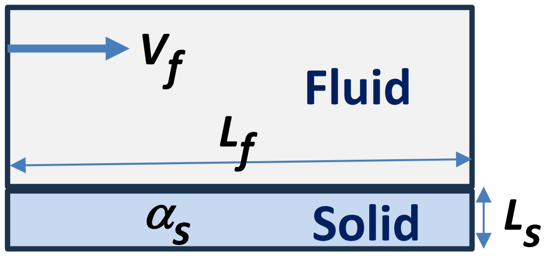
Nusselt Number



- *Wall cooling ➔ increase of **Local** Reynolds number*

Time-Scale Disparity: Fluid vs. Solid

UNIVERSITY OF OXFORD



Fluid Convection: $\tau_f = L_f / V_f$; ***Solid Diffusion*** $\tau_s = L_s^2 / \alpha_s$

$$\Rightarrow \frac{\tau_s}{\tau_f} = \left(\frac{Cp_s}{Cp_f}\right)\left(\frac{\rho_s}{\rho_f}\right)\left(\frac{k_f}{k_s}\right)\left(\frac{L_s}{L_f}\right)^2 (Pr_f)(Re_{L_f})$$ *(He, 2023)*

Take: Stainless steel & Air, $L_s = 0.1\, L_f$ and $Re_{L_f} \sim 10^5$

$$\Rightarrow \frac{\tau_s}{\tau_f} \sim 10^4$$

(cf. $\frac{\Delta t_s}{\Delta t_f} \sim 10^4$ - *numerical stability requirement (He & Oldfield, 2011)*)

Dual Requirement for Unsteady CHT:

Time-accuracy: $\Delta t_{CHT} = \Delta t_f$ ***(much smaller Δt required for LES)***

Time-consistency: $\tau_{CHT} = \tau_S$ ***(otherwise initial transients still remain in domain)***

Time steps for unsteady CHT (N_{CHT}) compared to that for a flow-only solution (N_f):

$N_{CHT} \sim 10^4\, N_f$

- Direct time-accurate and consistent CHT: prohibitive!

- 'Fixes' (different materials/initial conditioning): erroneous.

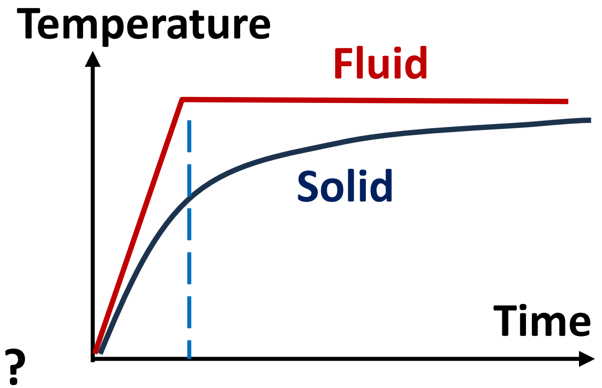
Long Time-scale Transient Process: 'Quasi-Steady' Flow Model?

-Applications: Engine startup/shutdown, Flexible operations

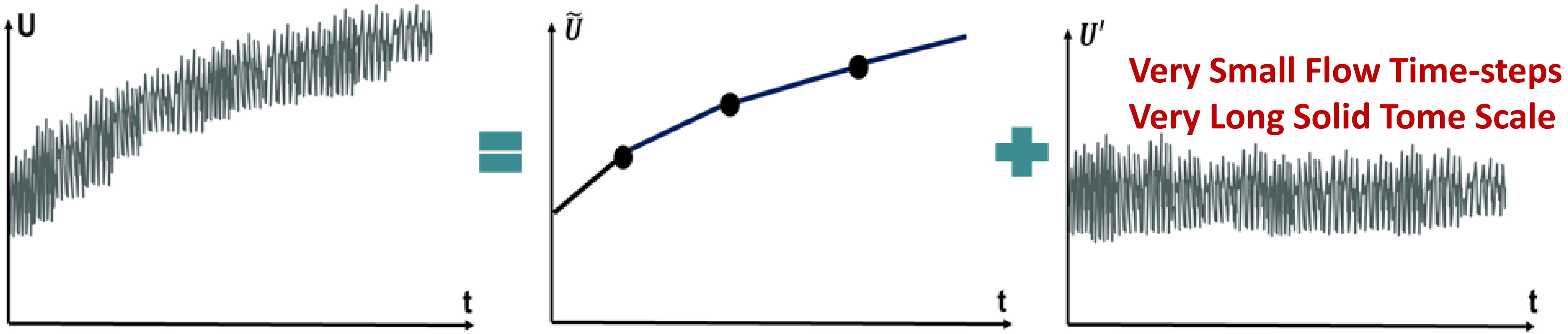
-Common 'Quasi-steady' CHT: Unsteady Solid + 'Steady Flow' Each Solid Step

-Quasi-steady assumption may be challenged in *part of an overall long process*

-Can we do without the quasi-steady assumption for the fluid side (*at what cost*) ?



Conventional Scale-split: $\boldsymbol{U}(x,t) = \widetilde{\boldsymbol{U}}(x,t) + U'(x,t)$

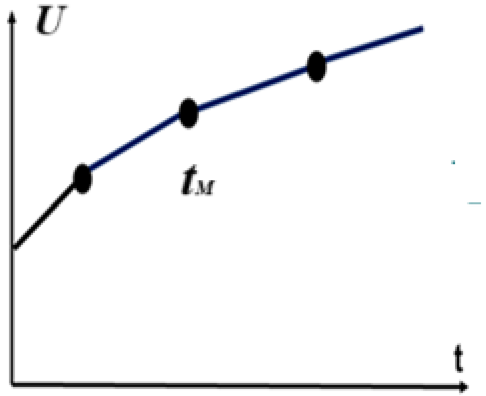


(a) Full Unsteady Variable (b) Filtered Base Part (*Large Step Sampling*) (c) Fluctuation Part (*small step sampling*)

‘Dual Time-Marching’ for Long Transient CHT *(He and Fadl, 2017)*

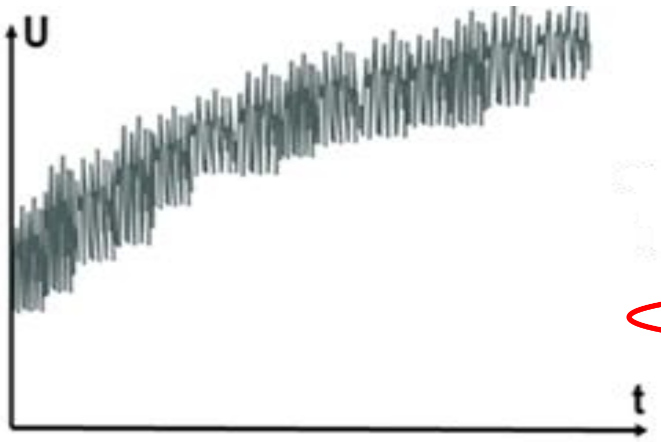
- **Dual Time-stepping for <u>URANS</u>** *(Jameson 1991)*

$$\frac{\partial U}{\partial t} + R(U) = 0 \quad \xrightarrow{\text{Sub } \textit{Iteration} \text{ at } t_M} \quad \left(\frac{\partial U}{\partial \tau}\right)_k + R(U)_k = -\left(\frac{\partial U}{\partial t}\right)_{t_M}$$

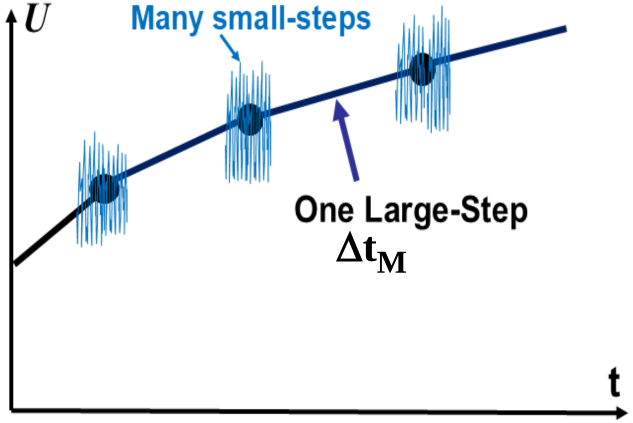


- **Dual Time-marching** $\xrightarrow{\text{‘Sub } \textit{Time-marching}\text{’ at } t_M}$

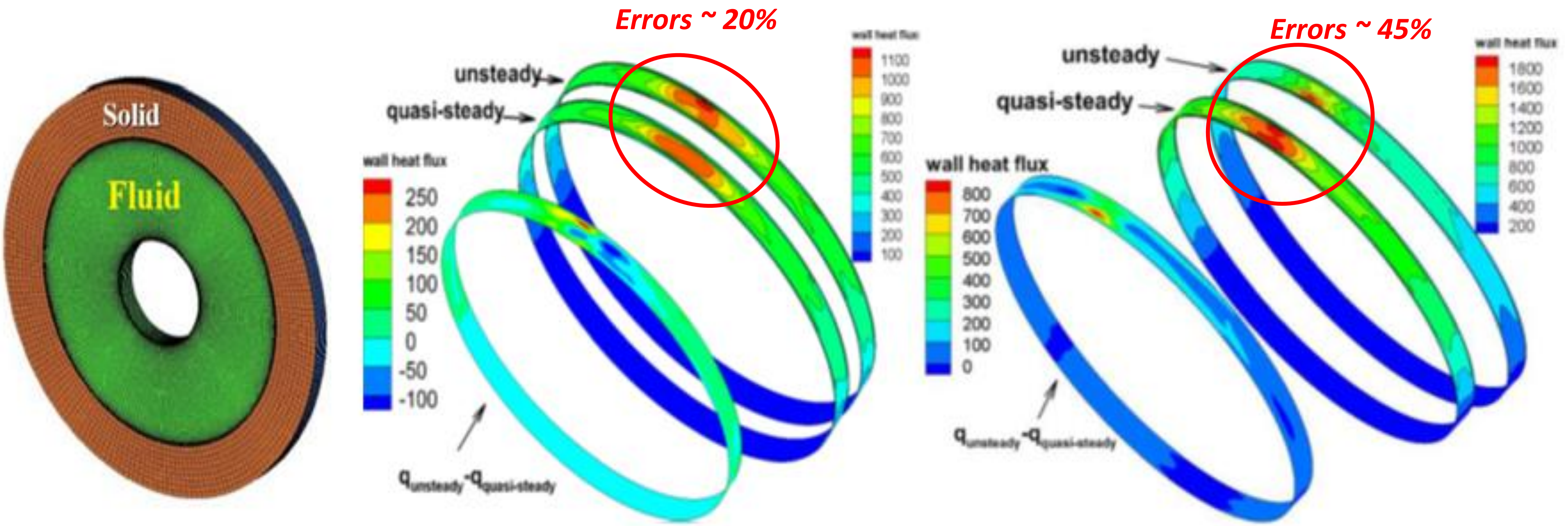
$$\left(\frac{\partial U}{\partial t}\right)_n + R(U)_n = -\left(\frac{\partial \tilde{U}}{\partial t}\right)_{t_M}$$



Local Small-step Time-marching/integration conditioned by Large-step Time Gradient



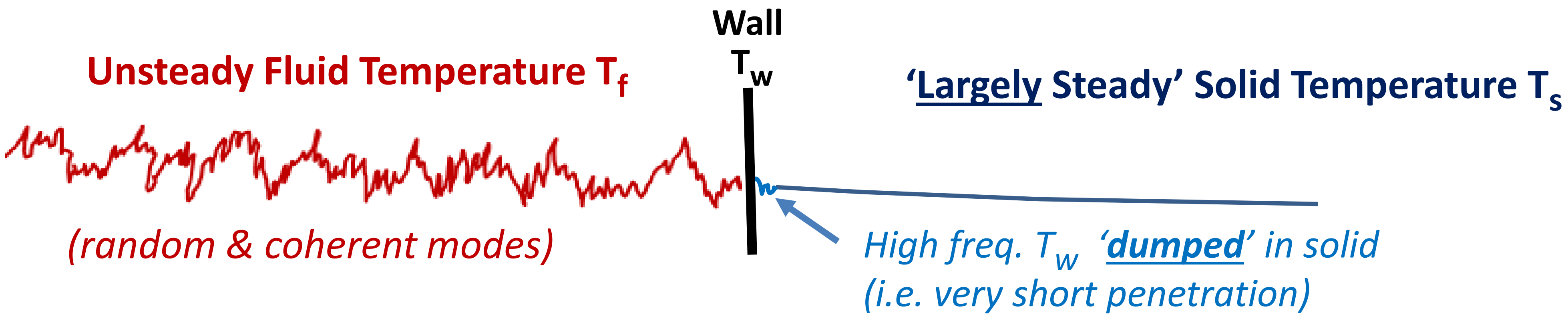
Unsteady vs. Quasi-steady (LES-CHT for Transient Natural Convection, *Fadl & He, 2017*)



(a) Configuration (b) Slow Transient *(100K/30s)* (c) Fast Transient *(100K/1s)*

- **Quasi-steady Model: Unsafe for local high-gradient <u>changing part</u> in an otherwise slow process.**
  (& some history effects on later parts of the process as well)

Short Time-scale Turbulence: *Why & Where Should We Bother?*



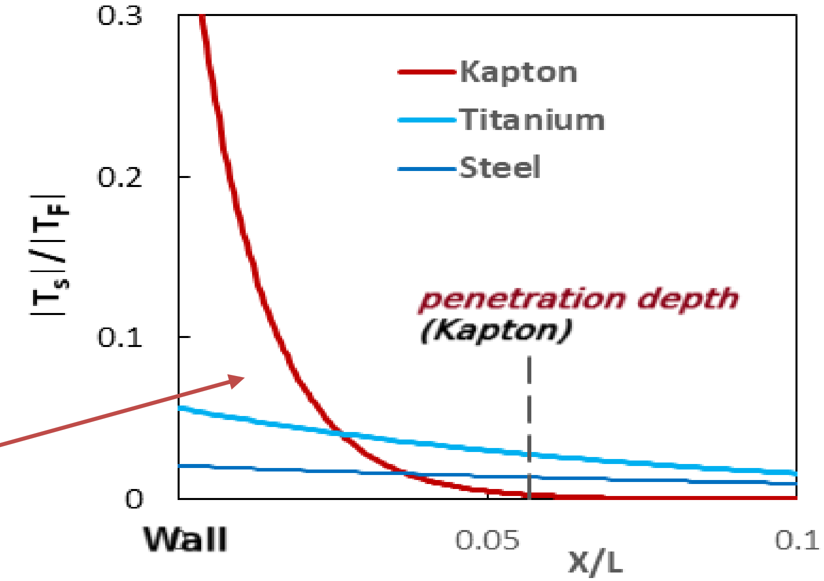
- **The conventional direct time-domain** CHT:
  1) Time-consistency: Number of time-steps has to be up by ~ $O(10^4)$
  2) Truncat. err/strong solid mesh-dependency

Penetration Depth: $\delta_p \sim \sqrt{\alpha_s / f}$ ***(material & frequency-dependent)***

e.g. Low conductivity 'TBC' at high frequency: small penetration depth

i) High Tw fluctuations (physical)

ii) very High mesh-dependency (numerical)



Penetration of Unsteadiness in Solid

(He, CHT chapter 2023)

Target Framework for LES-CHT: Pay When & Where Needed

- **'Deconstruct' One Full Time-domain CHT into Two Parts**

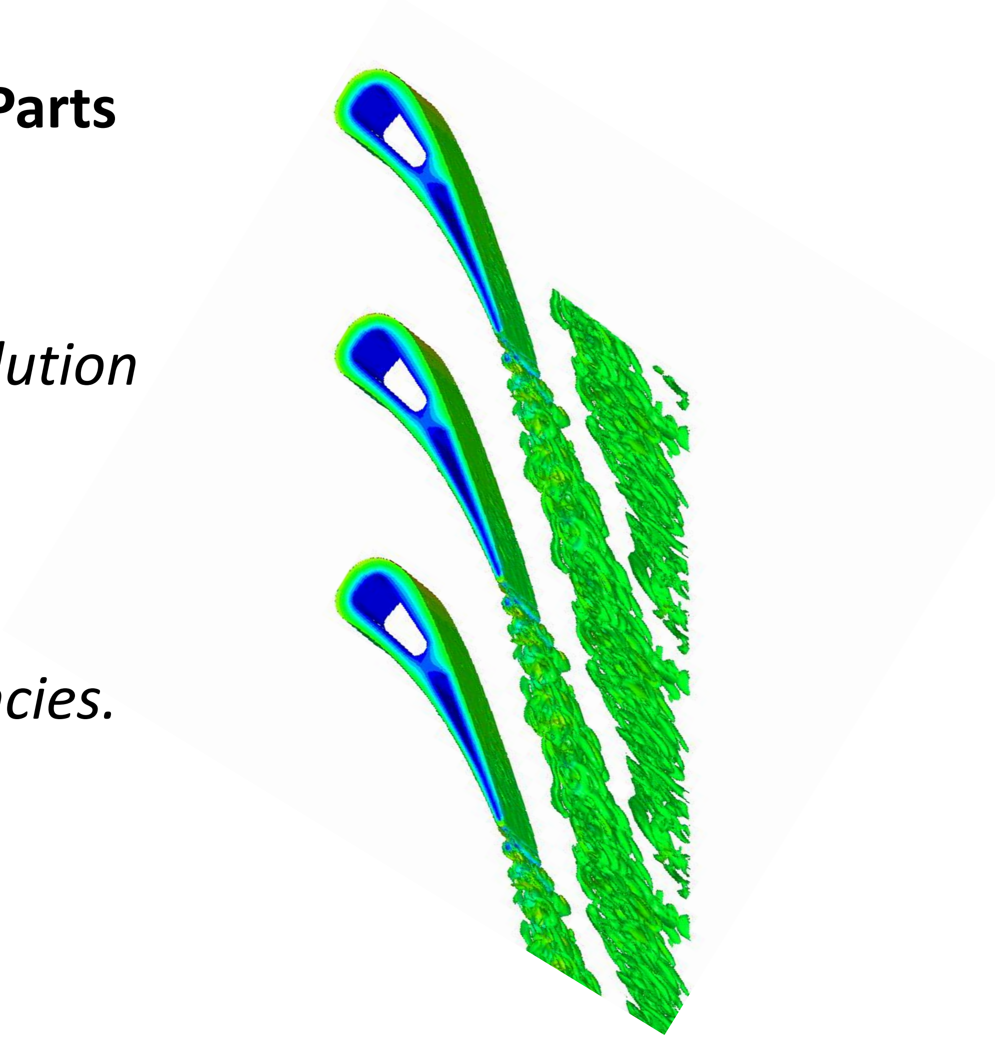
(i) Baseline 'Steady' Part:

-*coupling time-averaged fluid & solid conduction solution (Cost ~ Steady CHT).*

(ii) 'Add-on' Unsteady CHT:

- *capturing Tw unsteadiness over a range of frequencies.*

(Cost $\leq$ Baseline Steady-like CHT)



Primary Intent: *'Time Realignment' at Fluid-Solid Interface*

- **Fourier Spectrum for Temperatures**

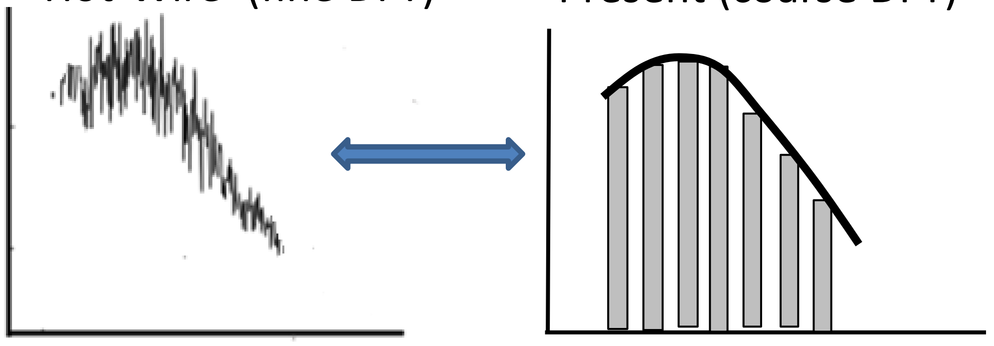
$$\mathrm{T}(x,t) = \overline{T}(x) + T'(x,t)$$

$$T'(x,t) = \sum \hat{T}(x) e^{in\omega t}$$

- ***Unsteady Interface in Time-domain***
  ➔ ***A set of harmonic ('steady') interfaces***

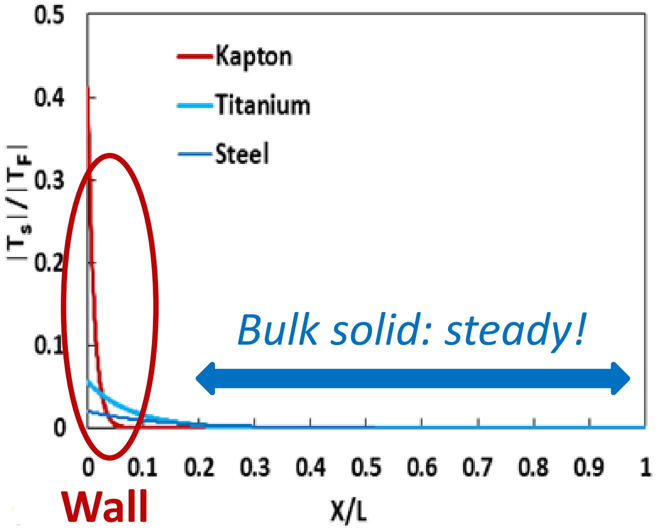
(0th harmonic: Time-average 'Steady' Baseline CHT!)

'Hot-Wire' (fine DFT)　　Present (coarse DFT)



However,

- ***Solving N_F harmonics (for Solid Conduction): Not appealing*** *(if $N_F \sim 10^2$!)*
- ***Unsteady conduction for bulk of solid domain (>penetration depth) is hardly relevant.***



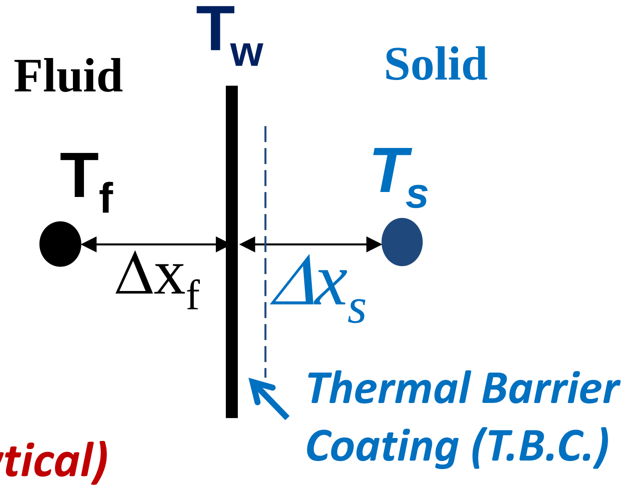
(a) Full Domain View *(Wall at x/L=0)*

➔ **Only small region near/on WALL *(not bulk solid!)* is where we need/want to know!**
Can we get Unsteady T_w without solving Unsteady Conduction in Solid Domain?

- **Analytical harmonic transfer function** *(Unsteady **1-D Conduction for Solid**)*
  heat flux (q_w) vs. wall temperature (T_w), (Schulz & Jones, 1973)

$$\hat{q}_w = TF_{Tq}\,\hat{T}_w$$

(TF_{Tq} – "T_w-q Transfer Function" - Analytical)



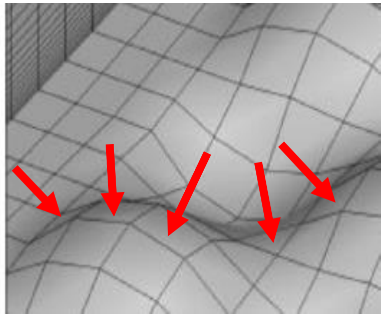
- **Linking to Fluid side** by **Harmonic Balance** (n = 0,1,2, ……, N_F) :

$$(\hat{T}_w)_n = (TF_w)_n \hat{T}_{f\,n}$$

(TF_w –"T_f-T_w Harmonic Transfer Function"- Semi-Analytical)

➔ Very Efficient Framework for Unsteady CHT

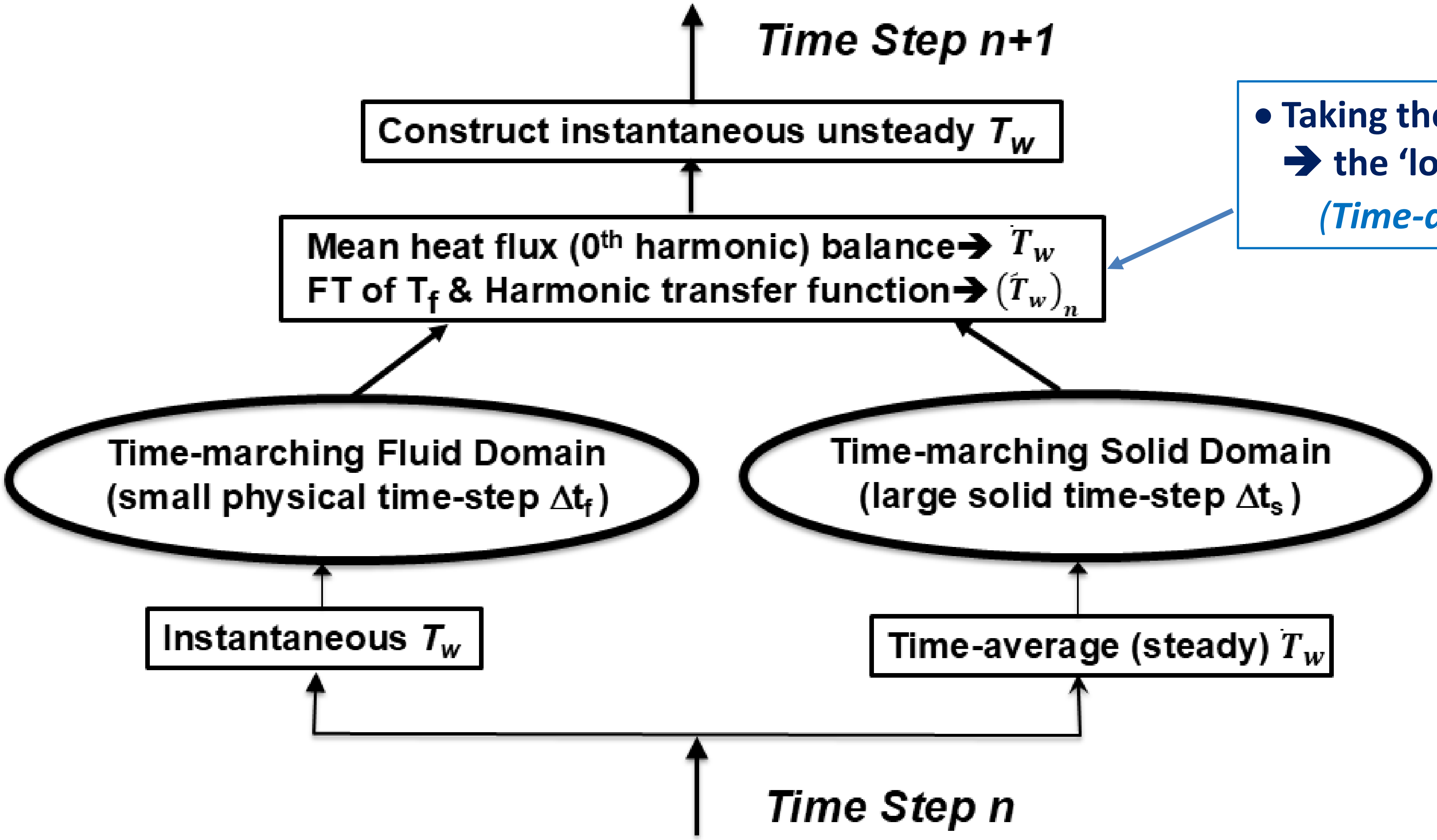
- **Fluid**: Time-domain scale-resolving URANS/LES *(subject to unsteady T_w)*
- **Interface**: Frequency-domain (input FT on-the fly for T_f)
  the baseline 0th harmonic ($\overline{T}_w$): time-mean (steady) CHT
  *other harmonics $(\hat{T}_w)_n$: **updated analytically** by* $(\hat{T}_f)_n$, $(TF_{Tq})_n$
- **Solid**: **Steady Conduction** (thus a much faster solution with **~10^4 larger Δt_s**).



'Local 1-D' (each mesh cell)

- ***Unsteady CHT at largely the cost as Steady CHT*** *(No solid temperature harmonics needed!)*
  -the fluid-side DFT ('moving-average'): only ~20% overhead to Baseline 'Steady' CHT!

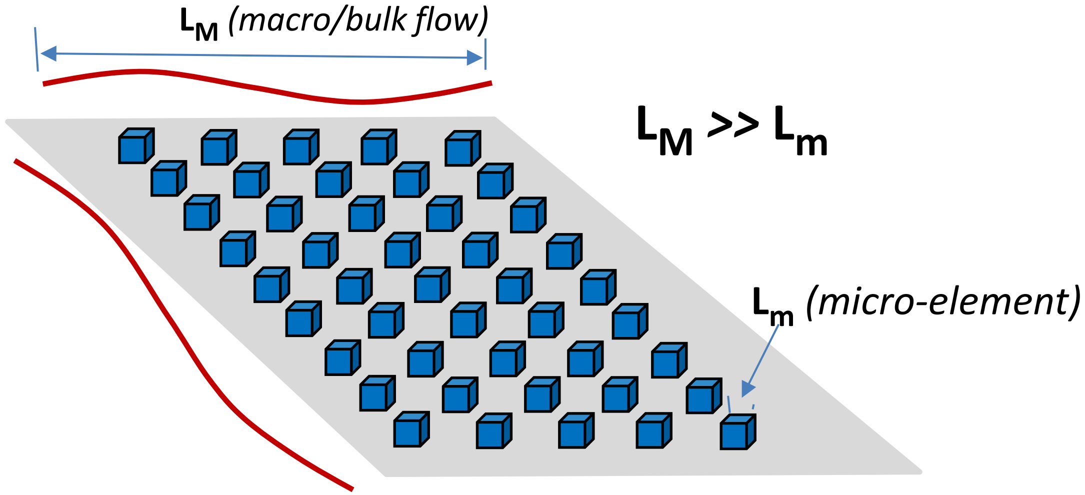
Flow Chart of Time-Frequency Domain Unsteady CHT



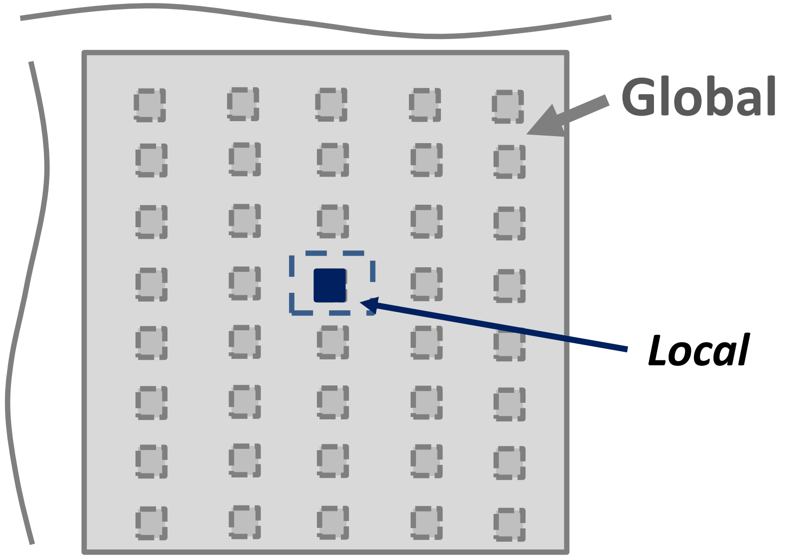
- **Taking the 0^{th} harmonic only (Baseline)**
  ➔ the 'loosely coupled CHT' for LES
  (Time-average Fluid ⇔ Steady Solid)

***MULTI-SCALE IN SPACE*: Micro-structure based Two-scale Method**

Micro-structured Surface
(with slow-varying bulk flow)

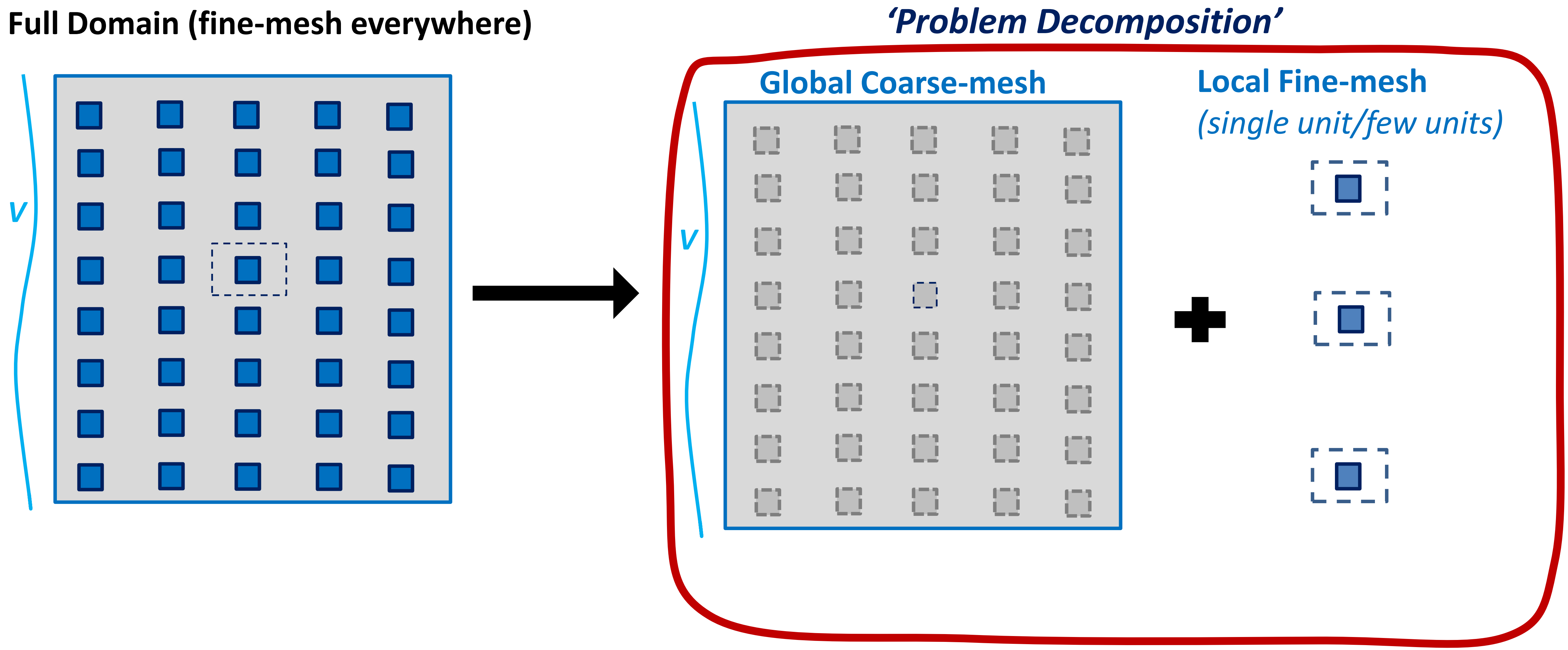


Macro-scale (*Global*) vs. **Micro-scale** *(Local)*



'Scale-dependent Solvability':
- *Local Micro-scale: High gradient within a Unit*
- *Global Macro-scale: Smooth Unit-Unit variation*

Basic Conflict: Local Resolution vs. Global Conditioning



Pathway to Solution: *to couple two sub-systems to correct each other.*

Solving Solid Temperature with a Unified *('Monolithic')* CFD Method

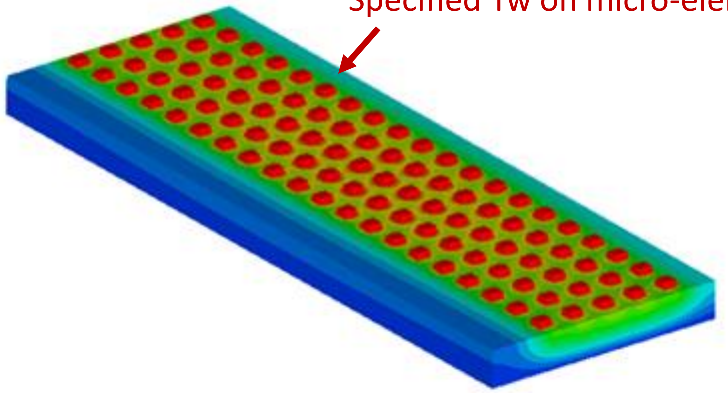
The Same Method for both Fluid & Solid

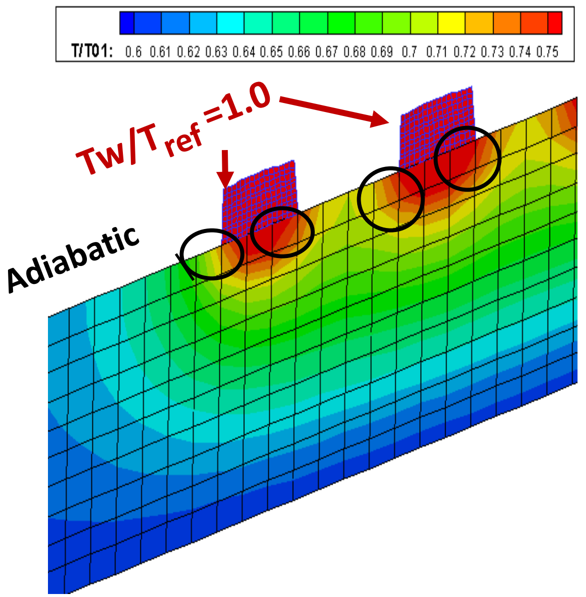
-**Conduction Equation**: *Fluid energy equation with zero velocities and solid properties.*

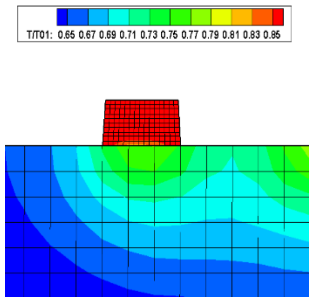
- **Discretization**: *Finite-Volume on multi-block meshes (with local embedding)*

- **Solution:** *Time-marching (Multi-step Runge-Kutta) for a steady temperature field in solid*

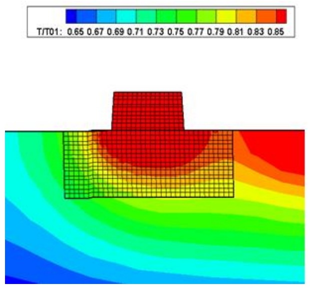
- ***The two-scale method also extended to solid domain for solving the conduction eq.***







Base Coarse-mesh



With Local Refinement

Large errors around corners !

***Space-Averaging* Two-scale *Method for Steady Conduction* in Solid**

- **Dual meshing (the same as flow)**

- **Local spatial-averaging (same as flow domain)** : volumetric average of fine-mesh results as the corresponding **coarse-mesh cell target:**

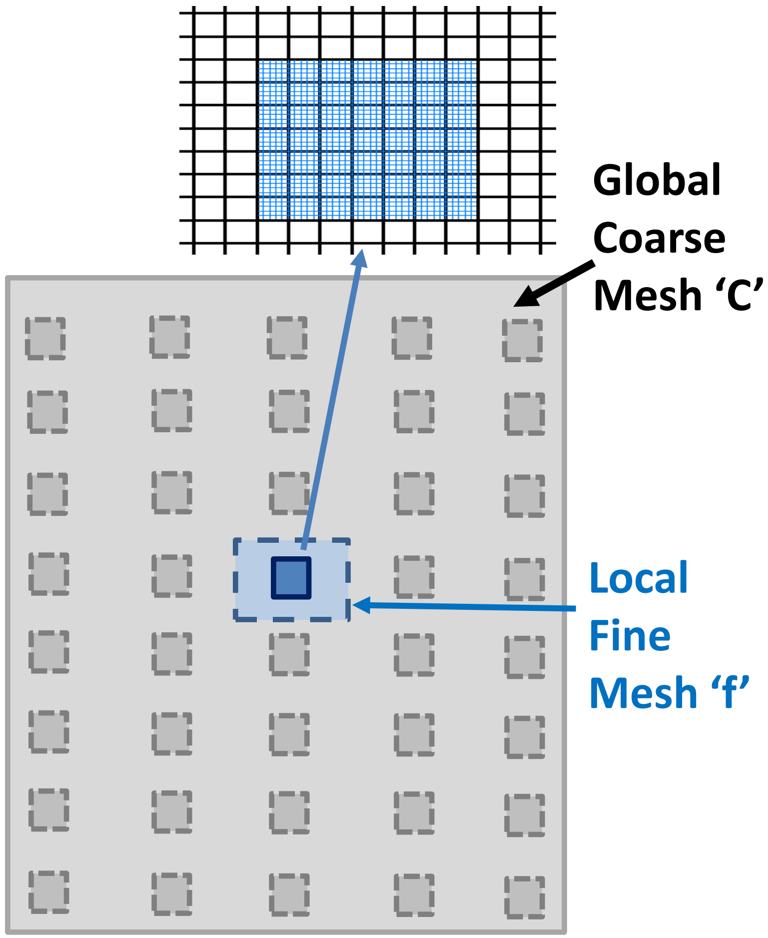
$$\widetilde{U}_f = \frac{1}{V}\sum U_f \Delta v$$

- **No Time-averaging here : we are only after steady temperatures in solid**

- **Coupled System of Two parts/domains (as for flow domain):**
  - **Local fine-mesh 'f' ('Inverse Mode'):** $S_S = R_C(\widetilde{U}_f)$
  - **Global coarse-mesh 'C' ('Direct Mode'):** $\frac{\partial U_C}{\partial \tau} + R_C(U_C) = S_S$

  (Source term S_S drives the coarse-mesh solution to the target: $U_C \Rightarrow \widetilde{U}_f$)

- **Converged Solution (same as flow domain):**
  - **Local fine-mesh:** ***much improved conditioning***
  - **Global coarse-mesh:** ***much improved resolution***



Attention to Source Term for Solid Conduction: Why/How Should It Work ?

UNIVERSITY OF OXFORD

Contrast (in Equations):

- Flow domain:

  Space-Time averaging mimics Reynolds-averaging (source terms originate from ***Nonlinearity*** *of flow equations*).

BUT:

- Solid domain:

  Linear conduction equation (for given material property/conductivity). Where does the source originate ?

Similarity (Balancing the Averaged Equations)

- Flow Domain:

$$\overline{\boldsymbol{R}(\boldsymbol{U})} = 0 \quad \text{but} \quad \boldsymbol{R}(\overline{\boldsymbol{U}}) \neq 0$$

➔ Need lumped ***Reynolds stress terms*** to balance the time-averaged equation, to produce the target $\overline{\boldsymbol{U}}$.

- Solid Conduction:

$$\boldsymbol{R}_f\widetilde{(\boldsymbol{U}_f)} = 0 \quad \text{but} \quad \boldsymbol{R}_C(\widetilde{\boldsymbol{U}_f}) \neq 0$$

Target solution does not hold on coarse-mesh, due to ***'mesh-dependent" discretization errors***.

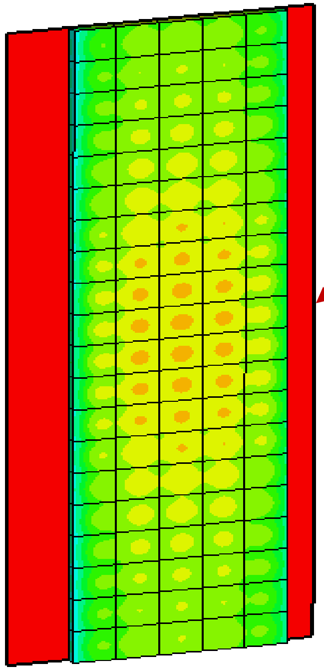
➔ Need ***'mesh-informed' source term*** to balance the coarse-mesh equation, to produce the target $\widetilde{U_f}$.

Global Fine-mesh vs. **Local Embedded Fine-mesh** *(Solid-domain only, He 2023)*

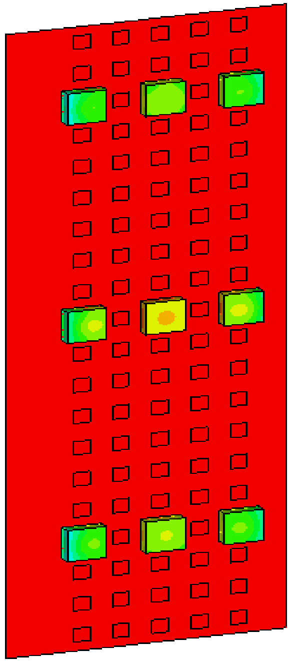
(Coarse–mesh Solution : no Reynolds Stresses to Close!)

UNIVERSITY OF OXFORD

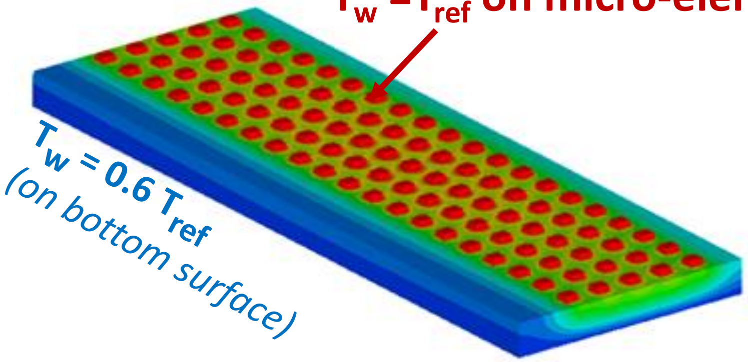
Direct Solution
(100 fine-mesh blocks)

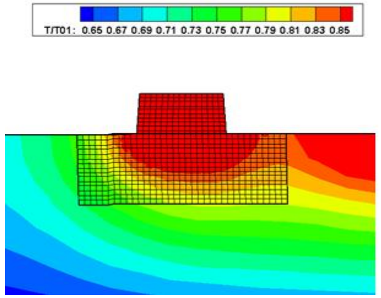


Local Fine-mesh Blocks
(only 9 fine-mesh blocks)

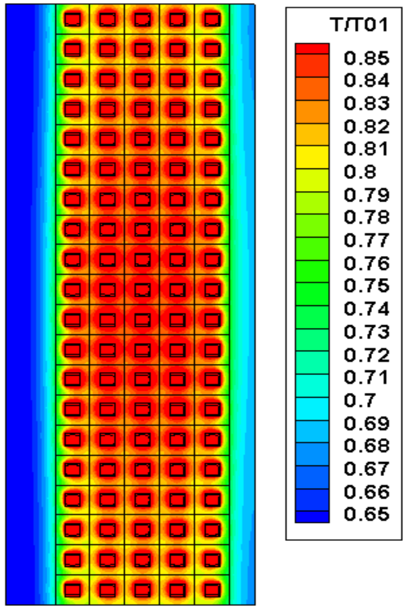


Back View *(only fine-mesh blocks & top surface shown)*

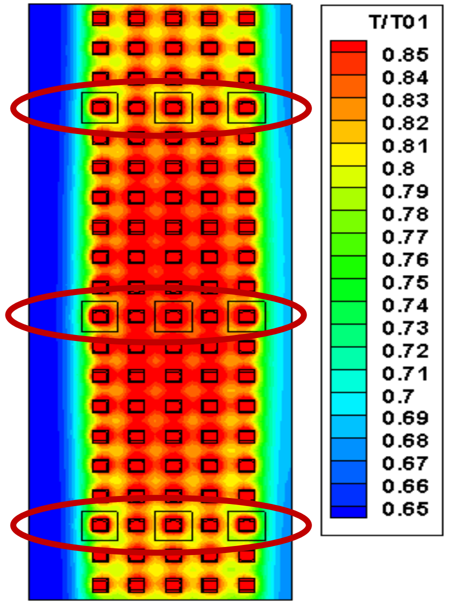




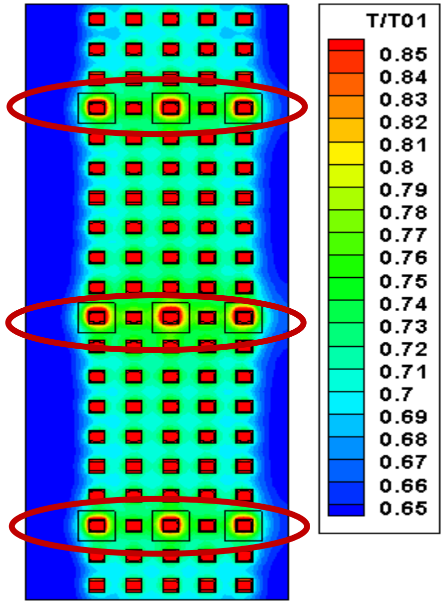
Locally Embedded Fine-mesh (*5x5x5*)



Full Fine-mesh Solution
(100 fine-mesh blocks)



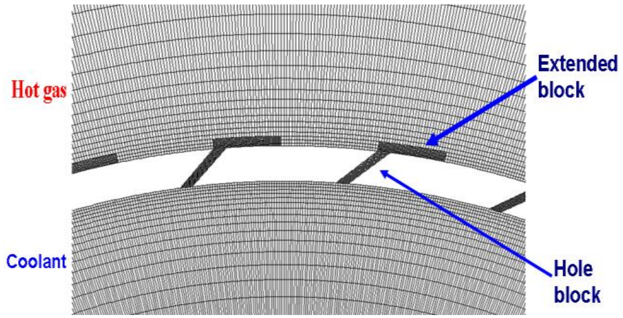
Two-scale Coupling
(9 fine-mesh blocks)

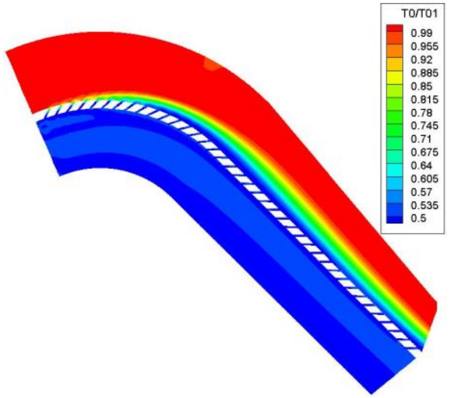


'One-scale' (no coupling)
(9 fine-mesh blocks)

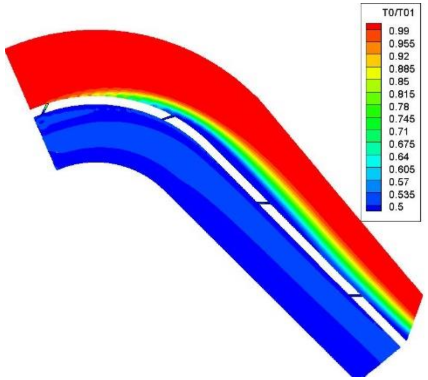
Two-scale Tests on Cooling: Multi-hole Film/Effusion Cooling (RANS/URANS)

RANS *(He, 2012)*



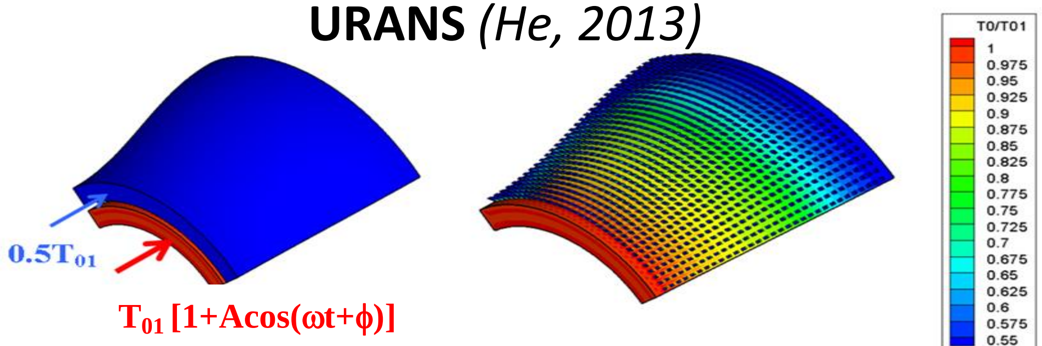


Direct Global Solution
(resolving 39 holes)



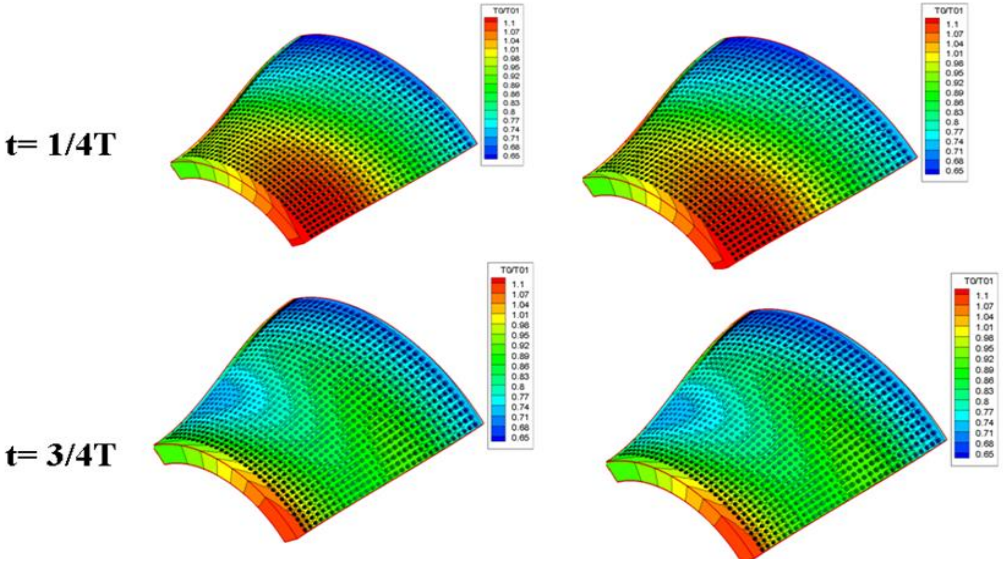
Two-scale solution
(resolving 4 holes)

URANS *(He, 2013)*



(a) Sector Domains and inflow temperatures

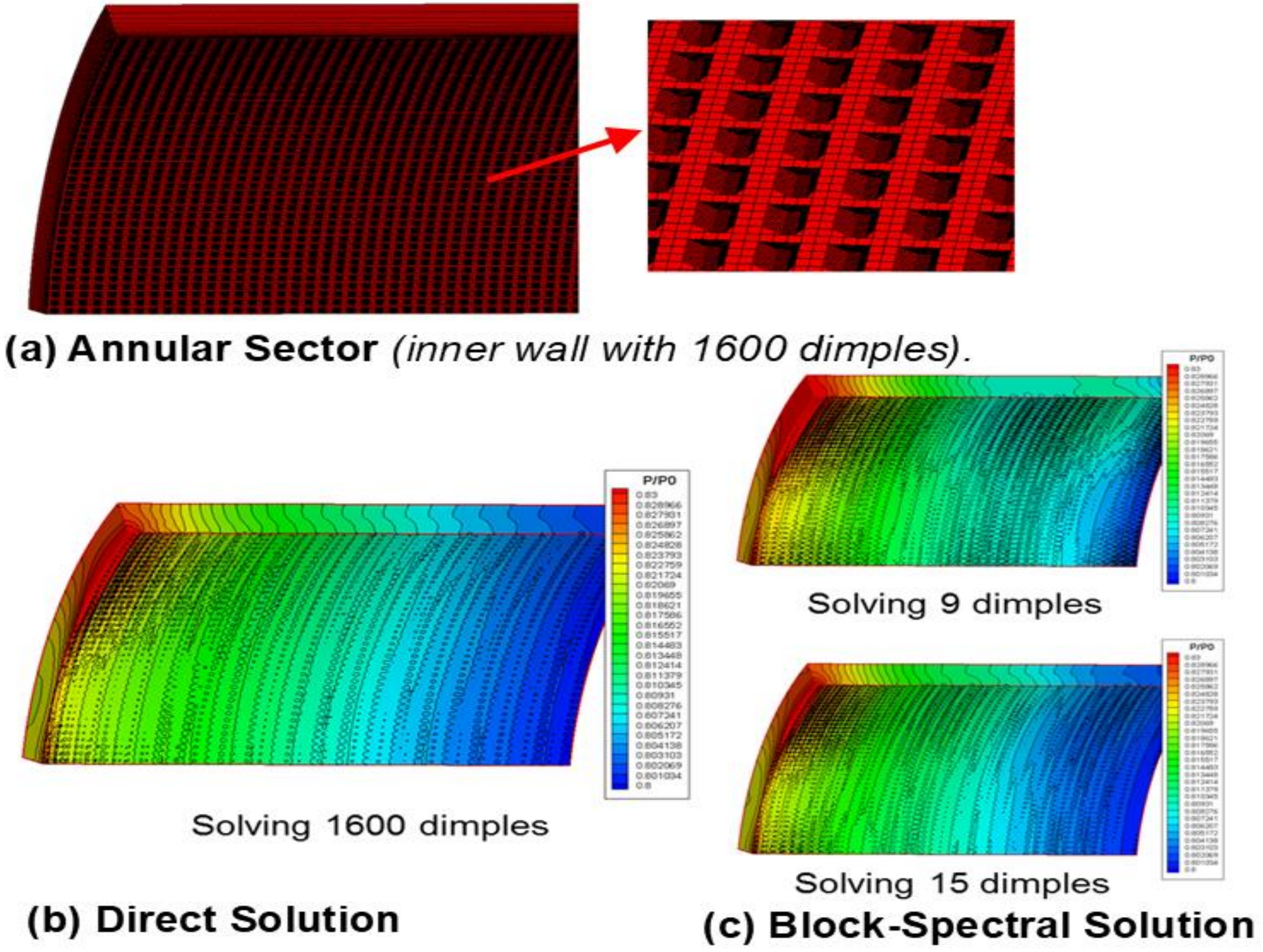
(b) Effusion cooling holes and steady wall temperatures



Direct Global Solution
(Fine-mesh for 992 holes)

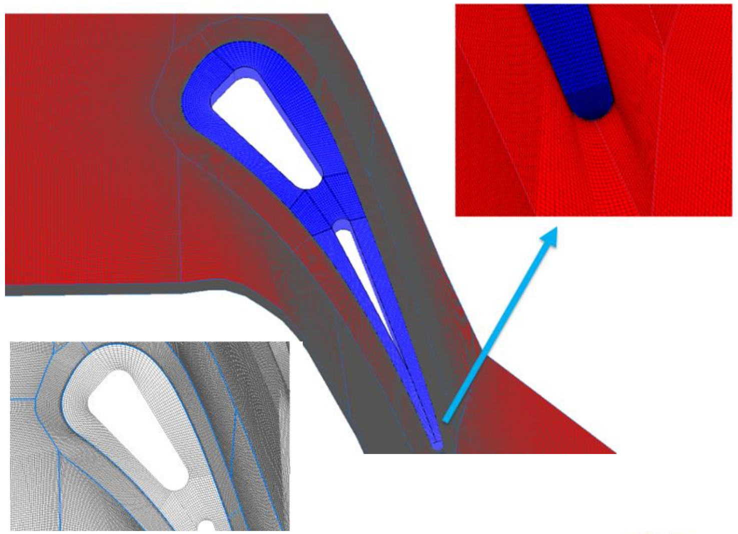
Two-scale Solution
(Fine-mesh for 8 holes)

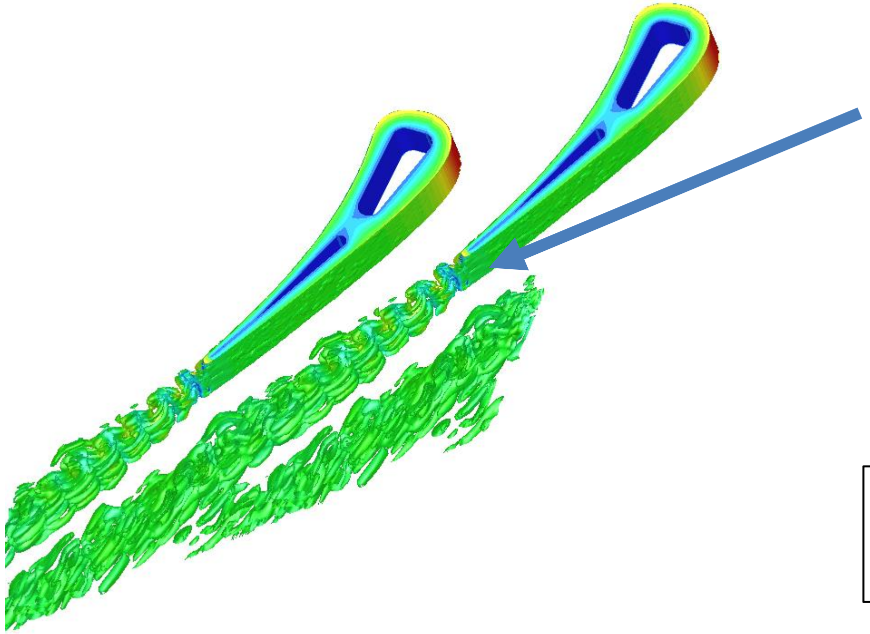
Two-scale Tests for Surface Micro-structures *(RANS, He, 2013)*



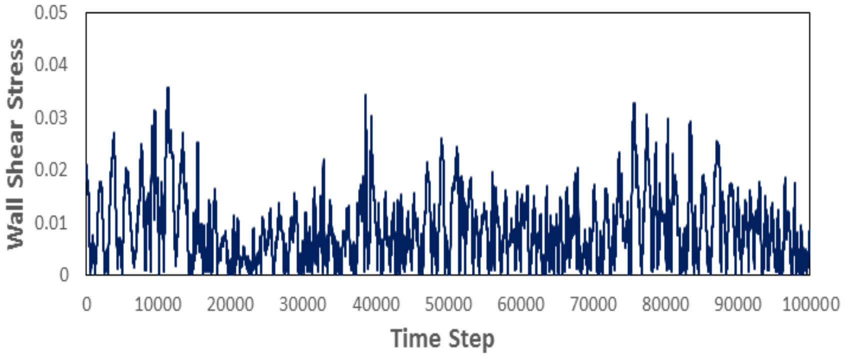
Impact of Heat Transfer on Near-wall Flow (smooth wall)

(LES-CHT for internally cooled blade passage, He 2019)

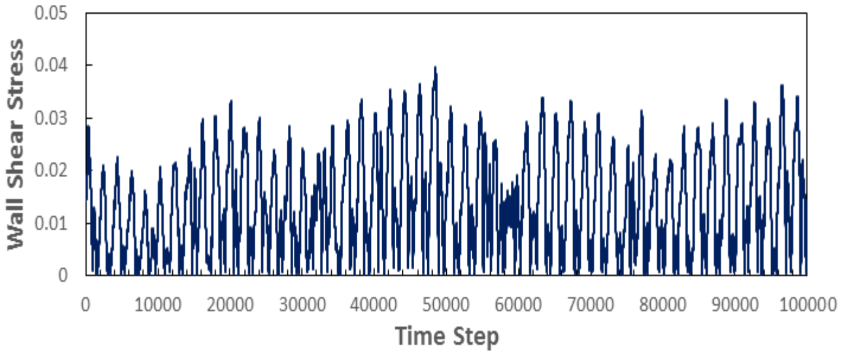




Time traces of Shear Stress at Trailing-Edge



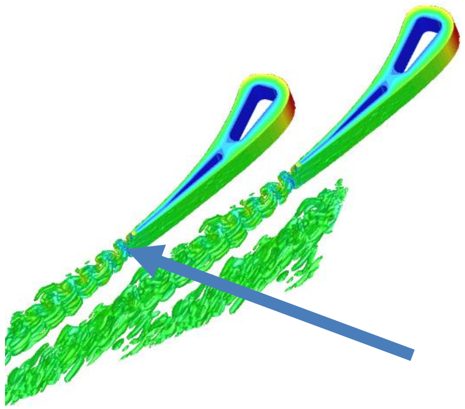
a) Adiabatic Wall Condition

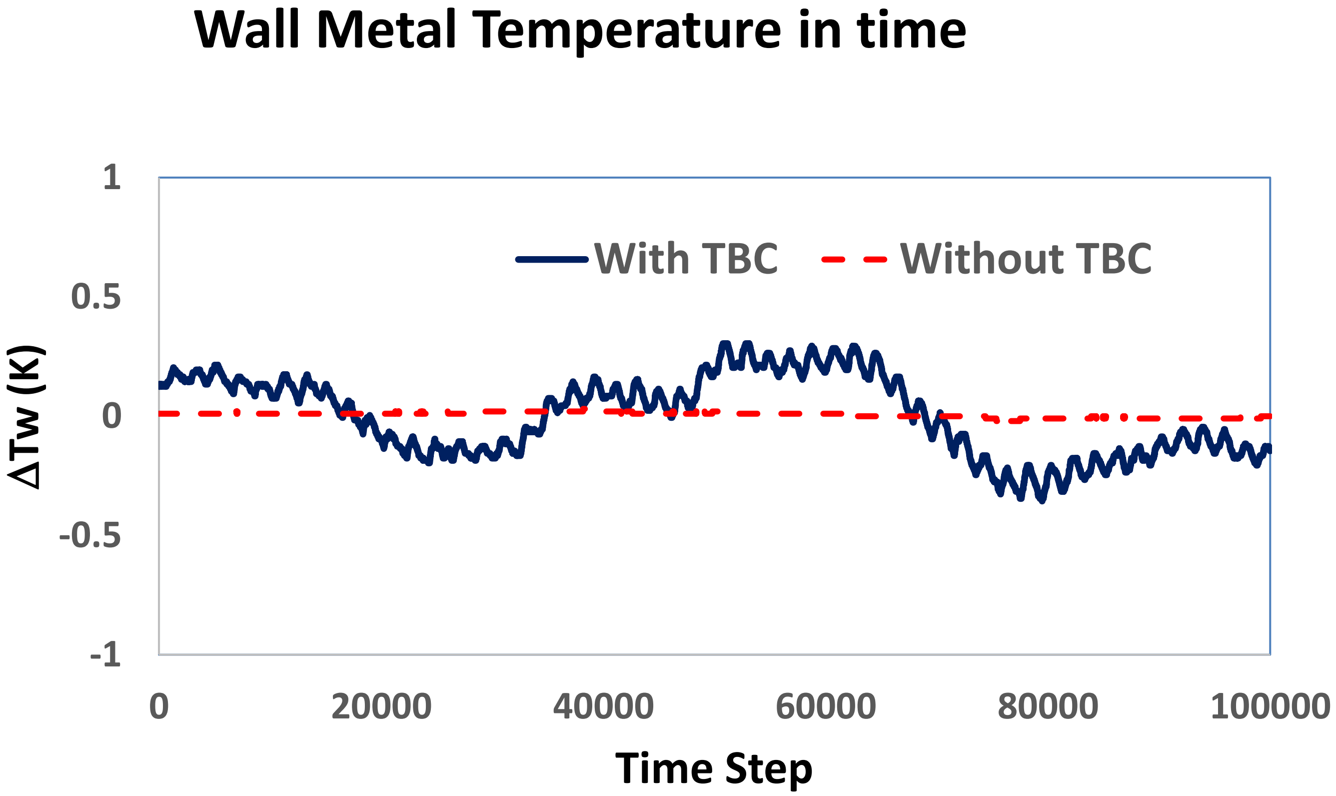


b) Conjugate Heat Transfer

- **Time-mean:** ***changed by more than 50%***
- **Unsteady:** ***markedly different characteristics***

Impact of Solid Material Property
(with a thin TBC layer of 100μm)

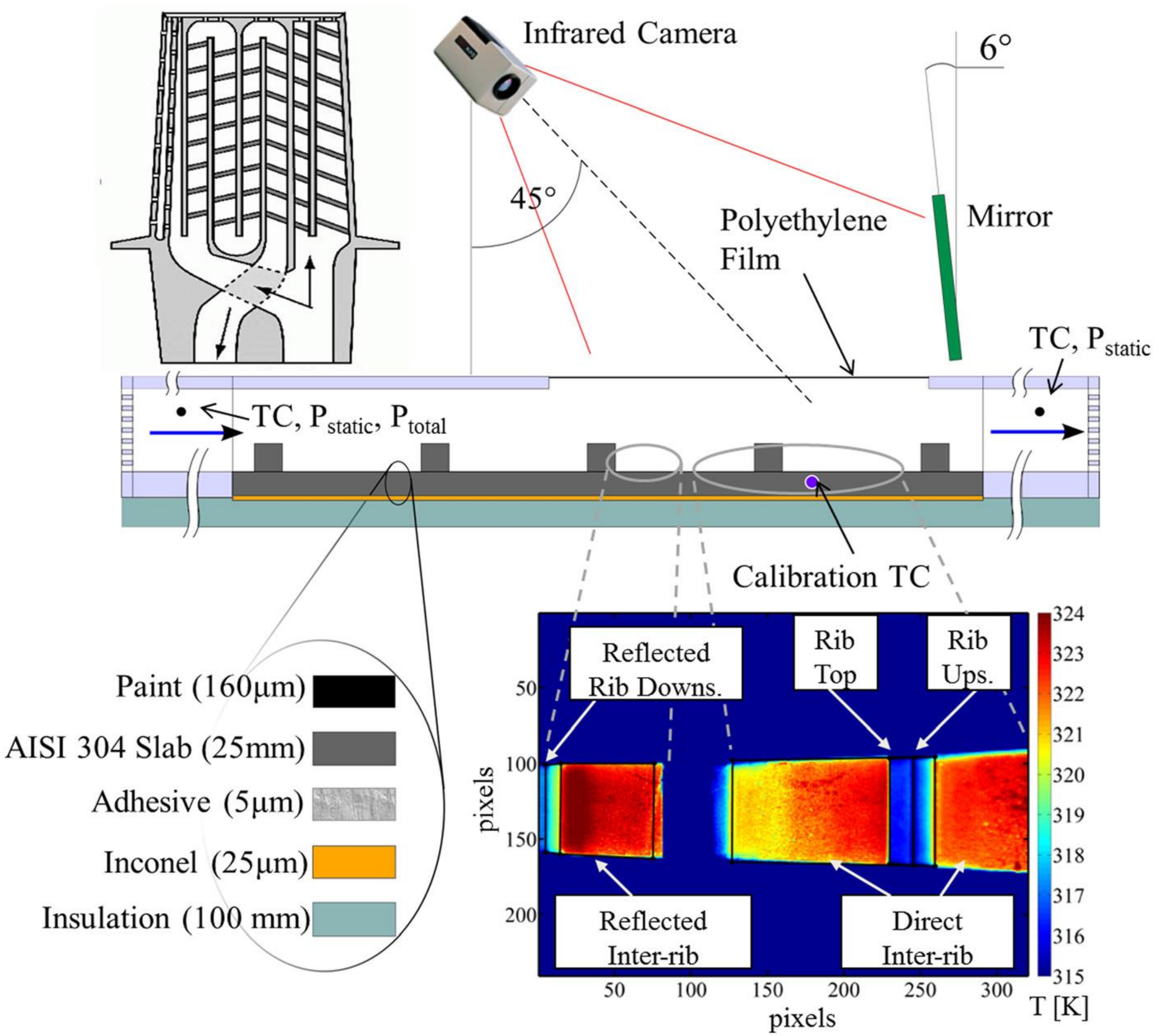




- **High Conductivity Solid:** ***largely constant wall temperature (~isothermal)***
- **Low Conductivity TBC :** ***much higher wall temperature fluctuations.***

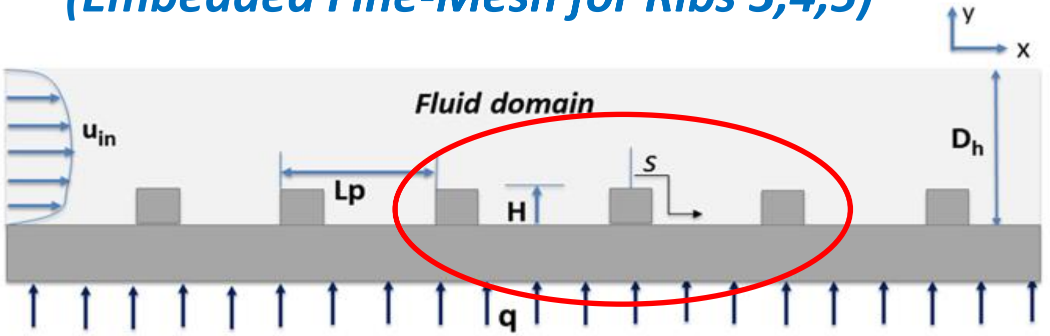
CHT Validation: VKI Ribbed Internal Channel *(Cukurel & Arts, 2013)*

Experimental Setup

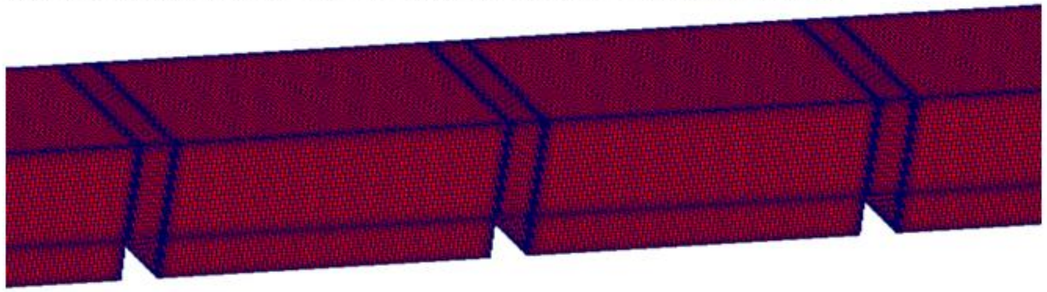


Computational Base Mesh *(He, 2023)*

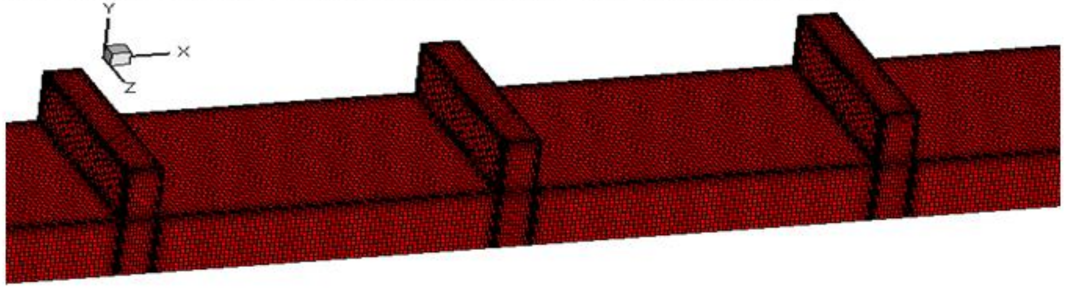
(Embedded Fine-Mesh for Ribs 3,4,5)



(a) Computational domains and boundary conditions



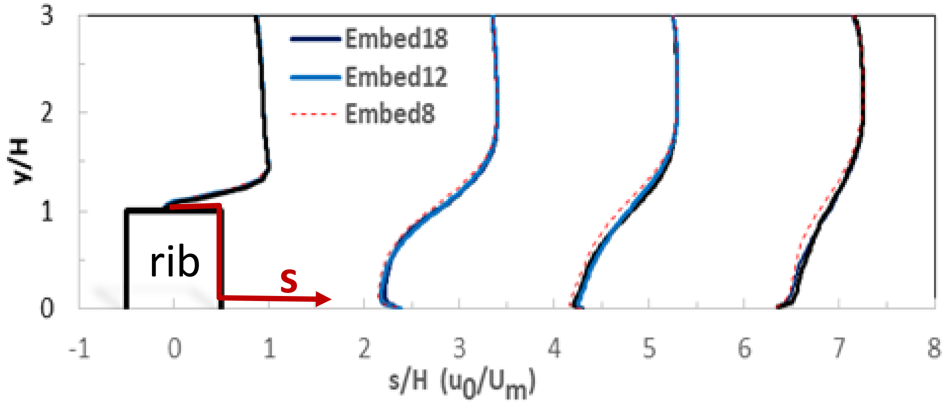
(b) Base coarse-mesh around ribs 3, 4, 5 *(fluid domain)*

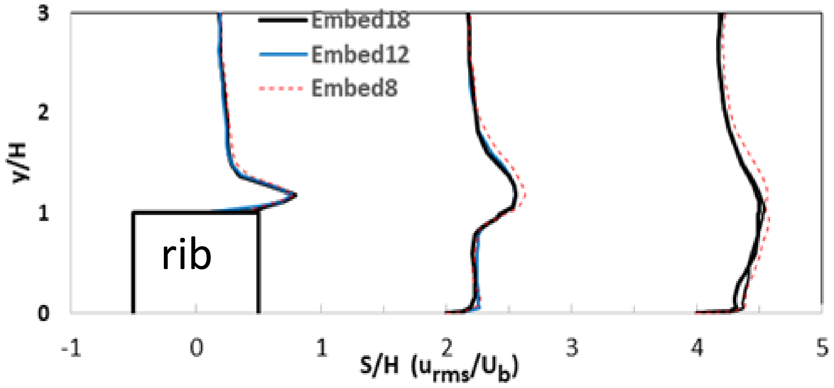


(c) Base coarse-mesh around ribs 3, 4, 5 *(solid domain)*

Mesh Sensitivity (distance: ‘s’ measured along rib surface)

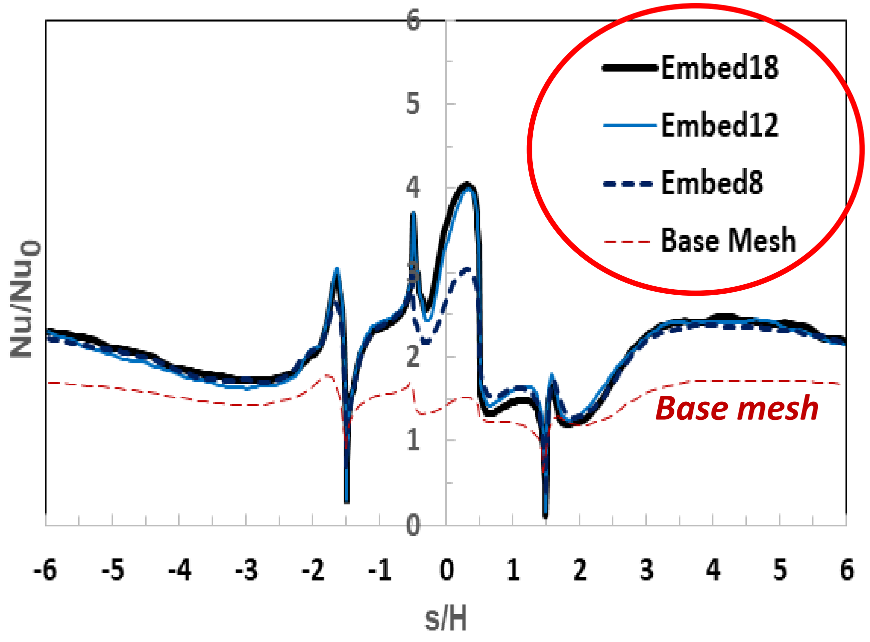
Aerodynamics *(Velocity Traverses)*





Heat Transfer *(Nu/Nu_0)*

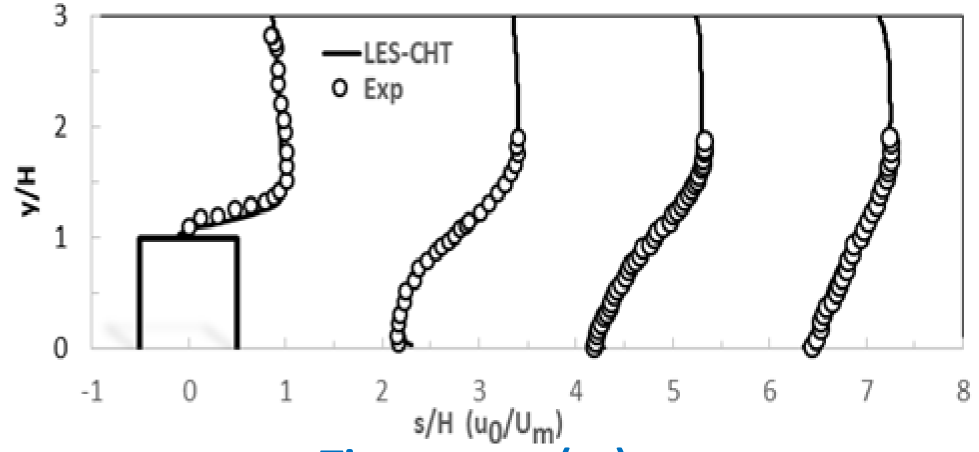
(Nu_0 – smooth (no rib) channel)



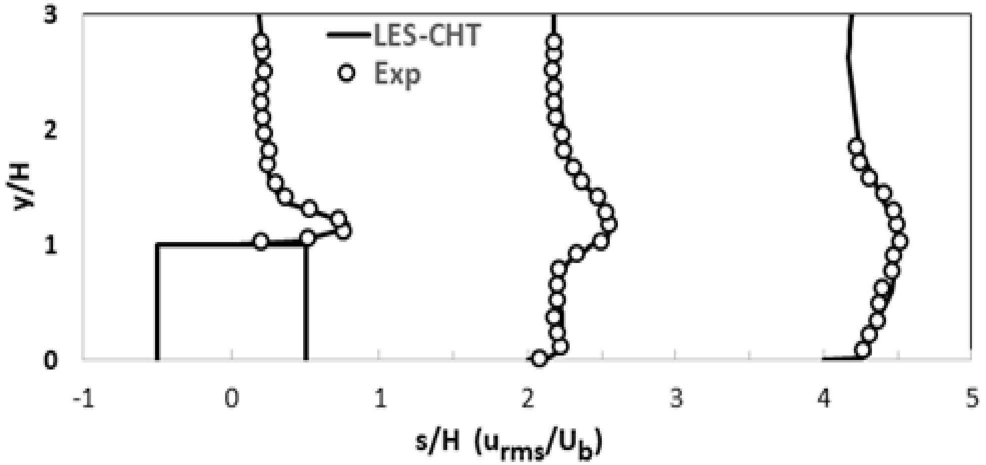
- ***Heat Transfer more sensitive than Flow!***

Comparison between Present LES-CHT and VKI Exp Data

Aerodynamics *(Velocity Traverses)*

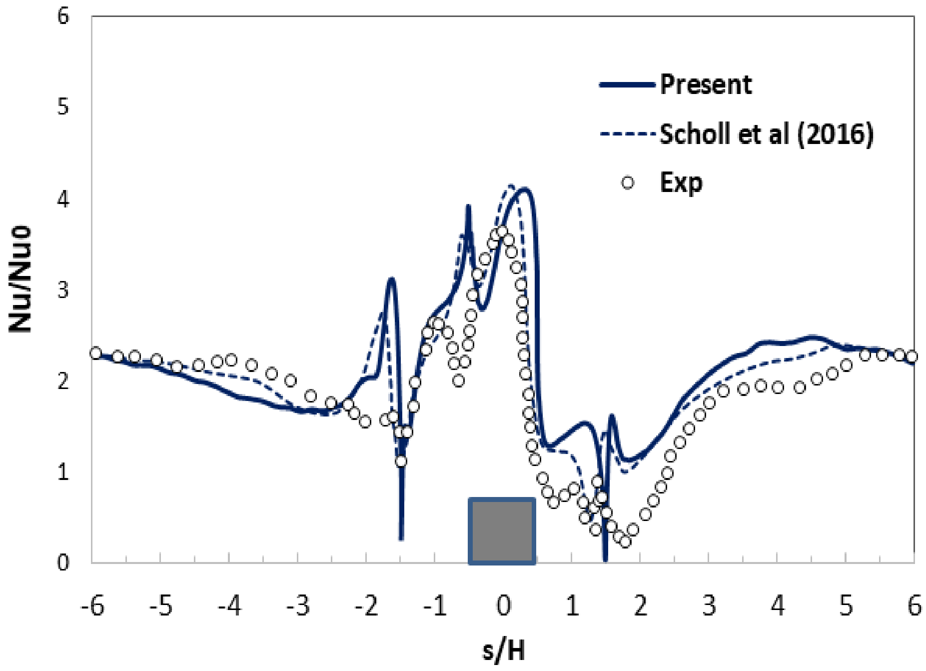


Time-mean (u_0)



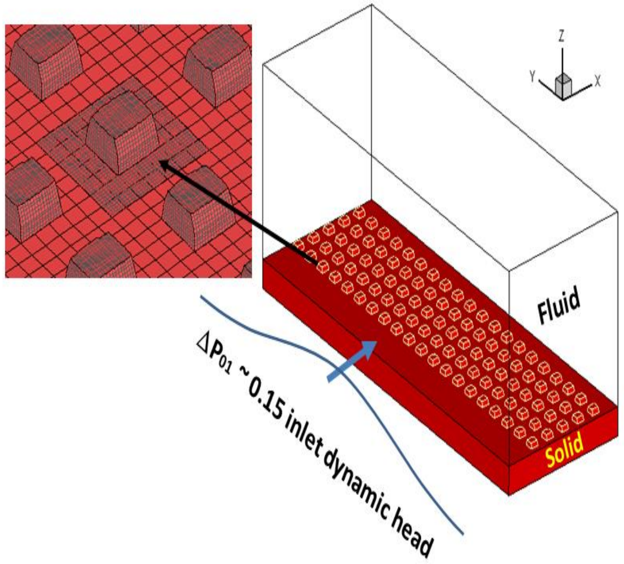
Turbulence Fluctuations (u_{rms})

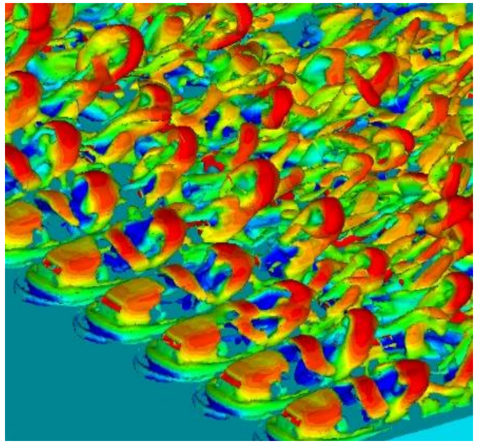
Heat Transfer *(Nu/Nu_0)*

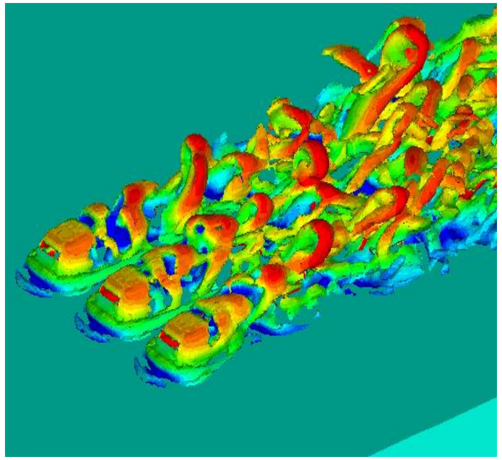


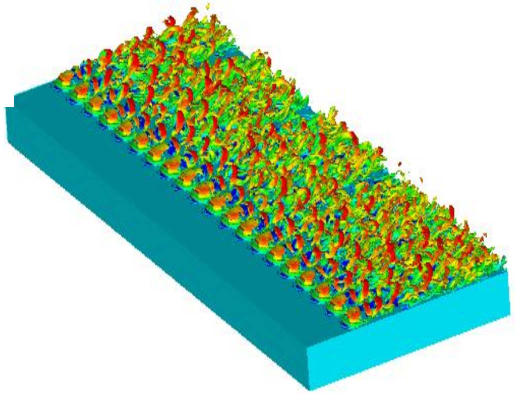
- ***Heat Transfer more sensitive than Flow!***

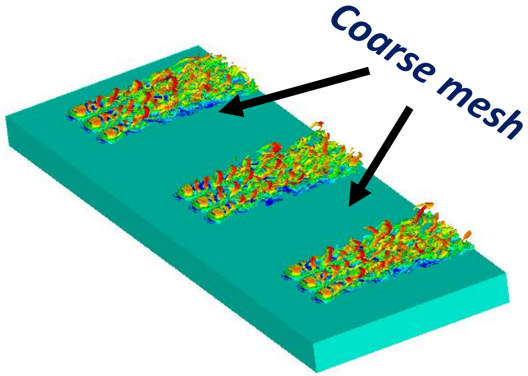
Micro-structured Wall: *100 micro-elements* ***(Fluid-domain with Adiabatic wall)***
(**Direct Full-Domain Solution** *vs.* **Local Embedded Two-scale Solution** *(He, IJNFM 2023)*

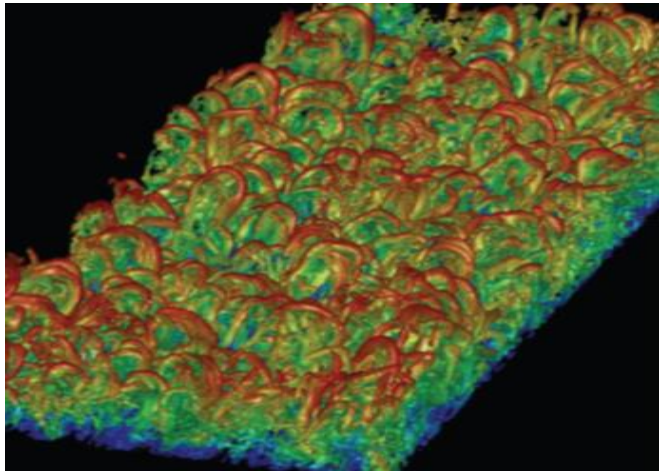












-Base coarse mesh ~0.6 million
-Direct fine-mesh: ~10 million
*(100 micro-elements with local fine-mesh embedding: **5x5x5**)*

- ***Local 3D refinement* by 0(*10*^{2}*)!***

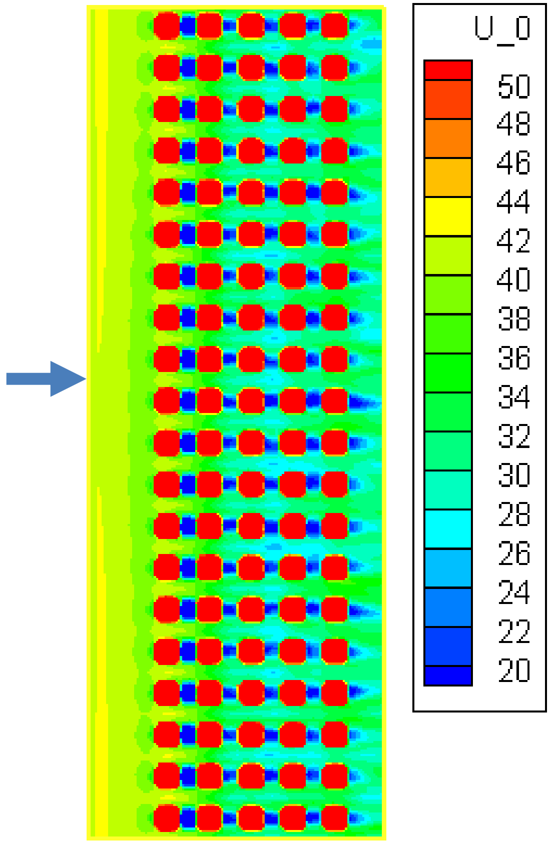
Direct Solution
(20 fine-mesh arrays)

Two-scale Solution
(3 fine-mesh blocks)

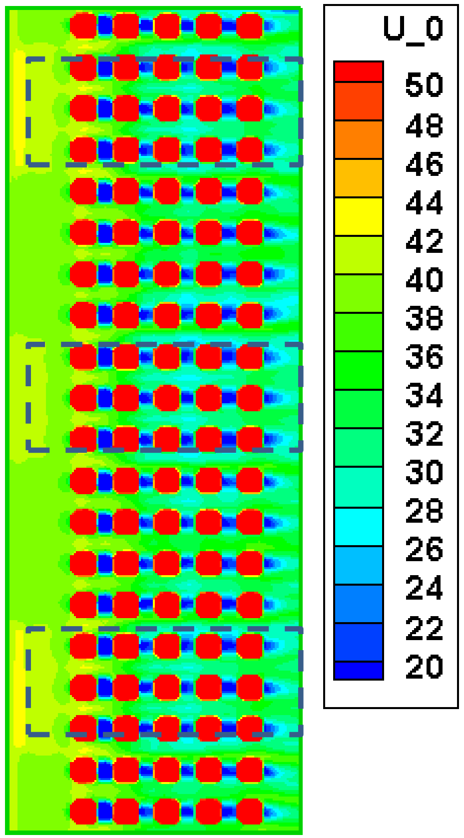
Perspective of Hairpin Vortices (DNS)
(Marusic & Monty, Ann Rev Fluid, 2019)

Direct Solution vs. **Block spectral Solution (Fluid-domain only)**

(V_{X0} Contours on Plane cut at top of micro-elements)

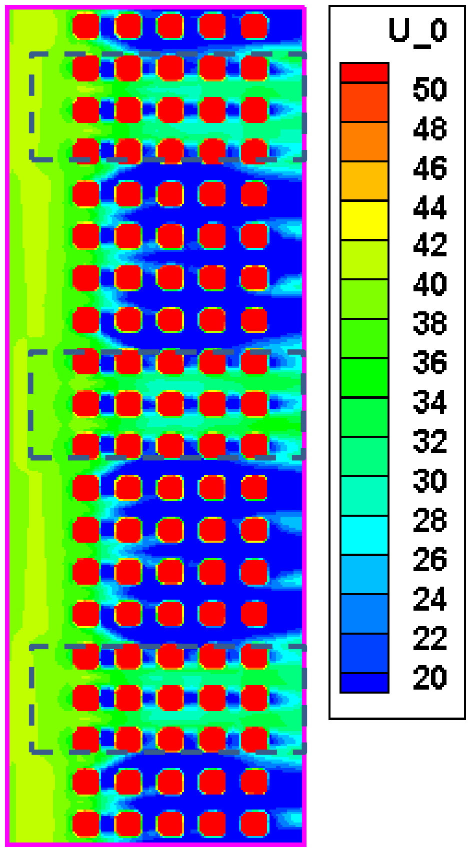


Full fine-mesh Solution



Two-scale

(Local fine-mesh; ***With Coupling****)*

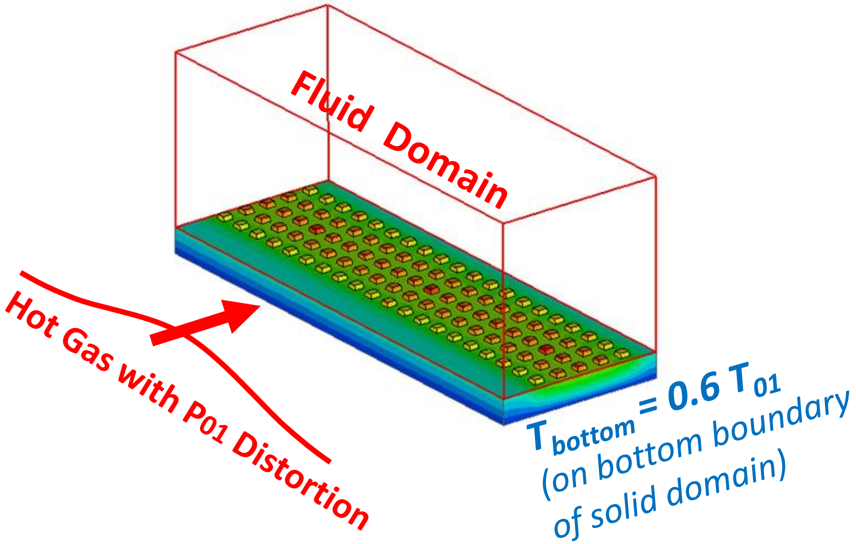


‘One-scale’

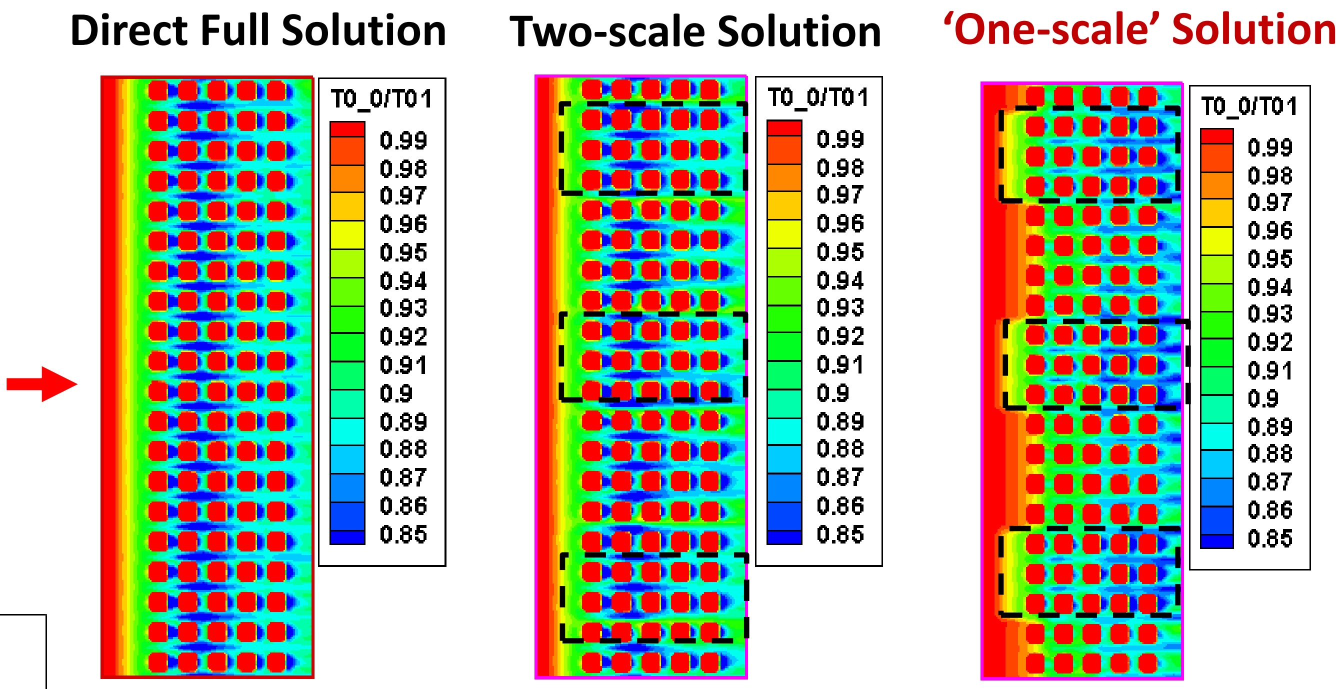
(Local fine-mesh; ***No Coupling****)*

Fluid-Solid coupled Conjugate Heat Transfer (CHT) Solution

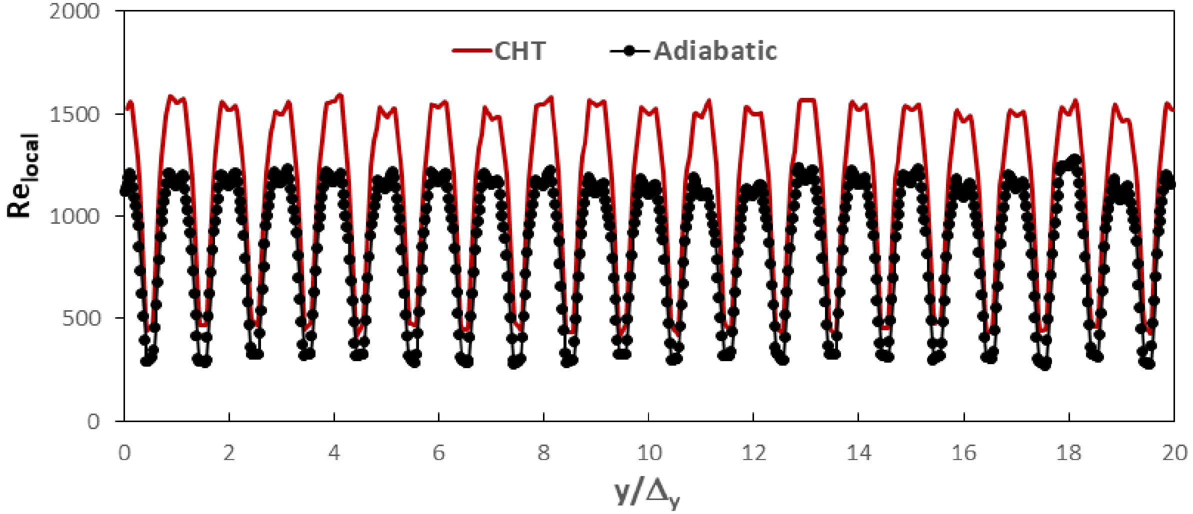
(Time-mean Fluid Temperature T_0)



Fluid Stagnation Temperature on Near-wall Plane



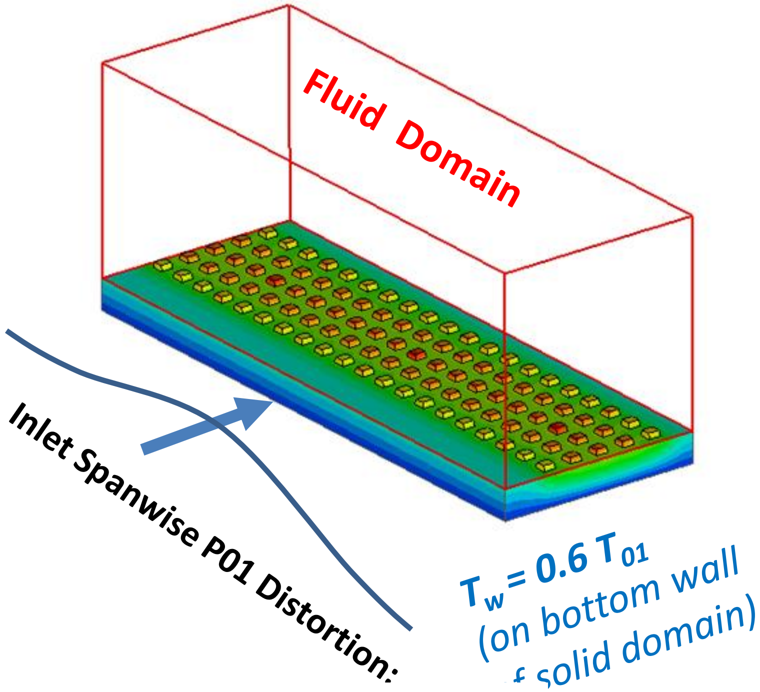
Downstream Traverse of Local Reynolds Number

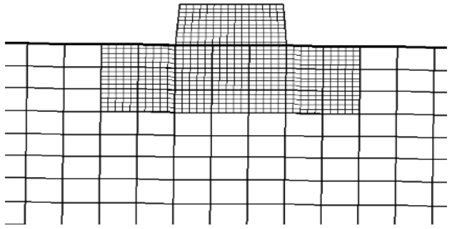


Wall Cooling raises the Local Reynolds number
- more usefully indicative than bulk flow based Re!

Conjugate Heat Transfer (CHT) Solution (Fluid-Solid Coupled Domain)
(Solid Surface Temperatures)

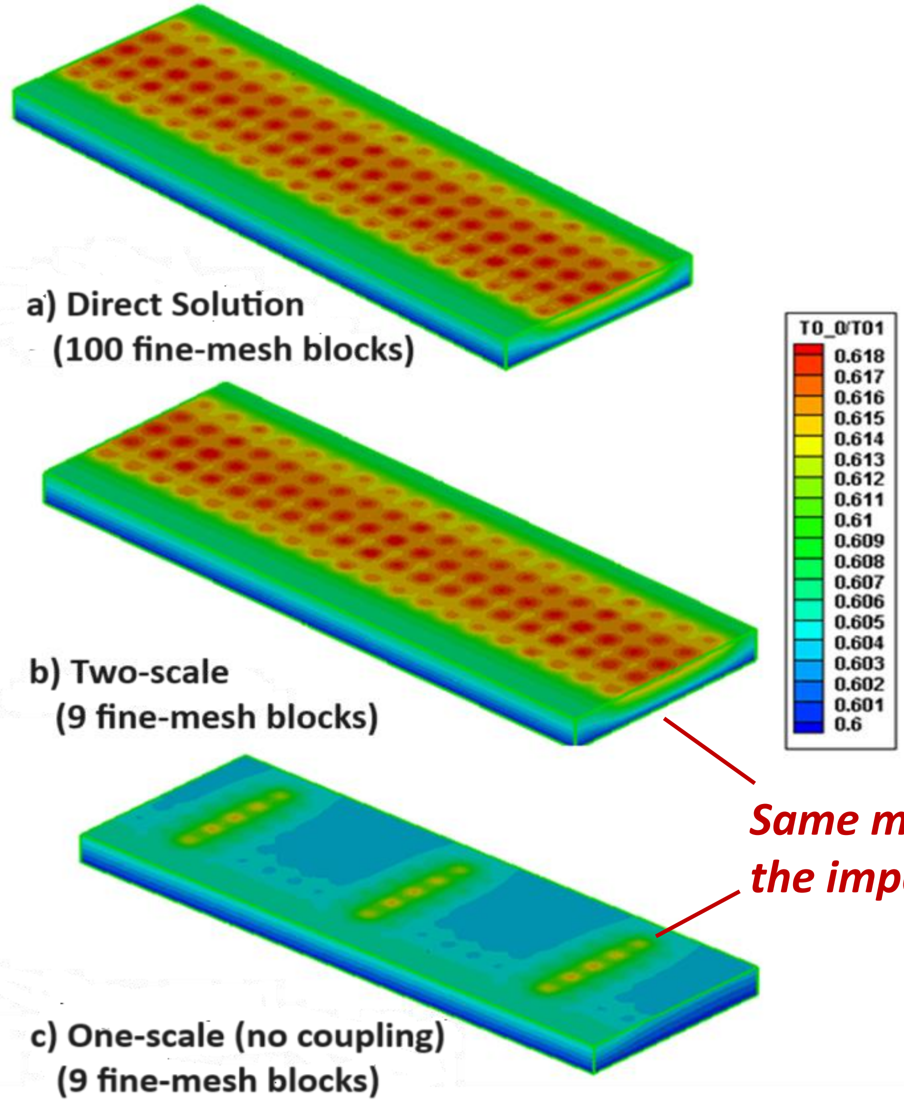
UNIVERSITY OF OXFORD





Local mesh for micro-structure
(10^2 refinement: 5x5x5 fine/coarse)

Solid Temperature on Top Wall

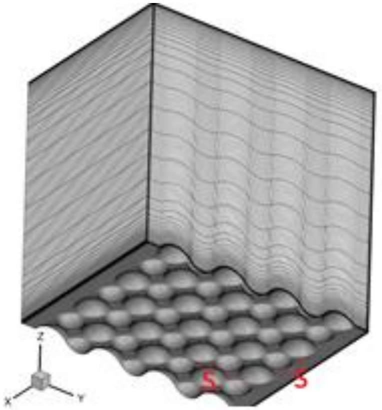


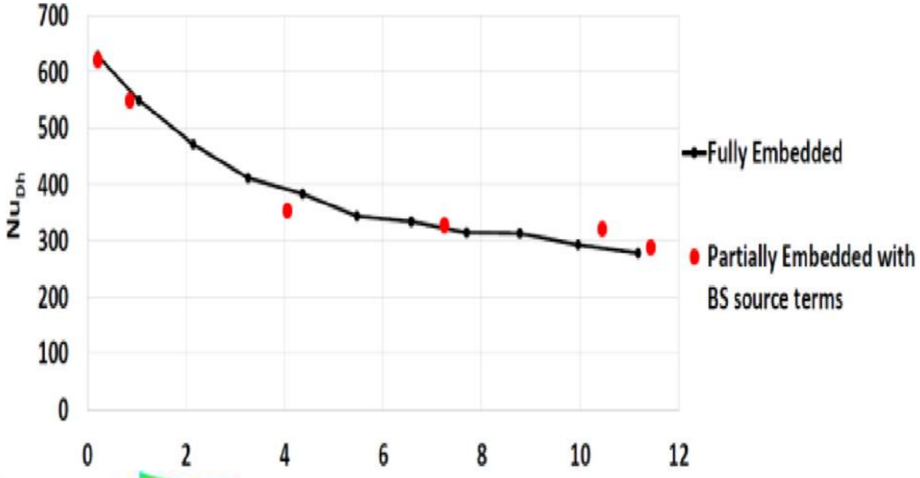
Same mesh for both cases: underlining the impact of Two-scale coupling

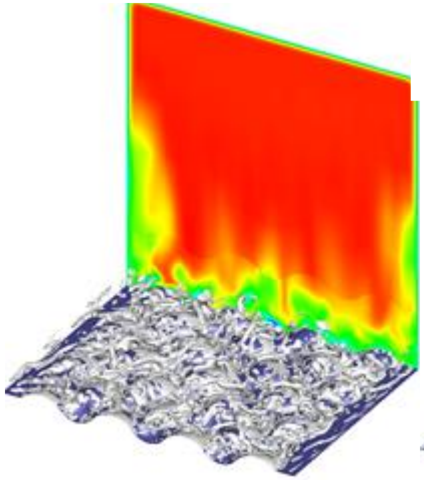
Validation & Demo for Dimpled Surface and Large-scale Problems

(Kapsis et al, 2020)

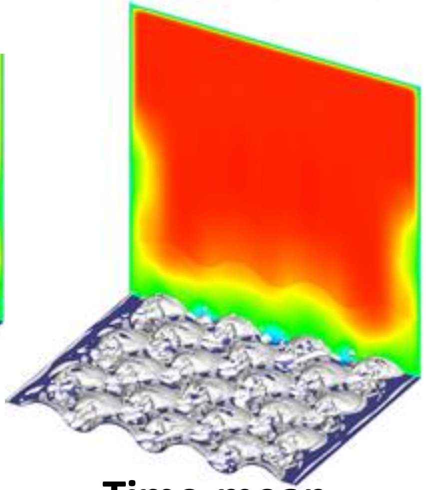
Pimple-Dimple Surface (Two-scale LES)







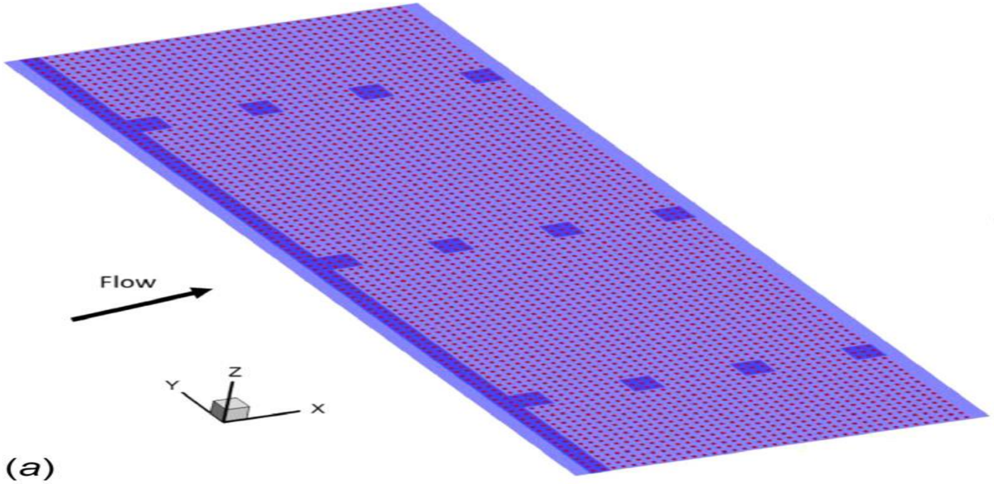
Instantaneous



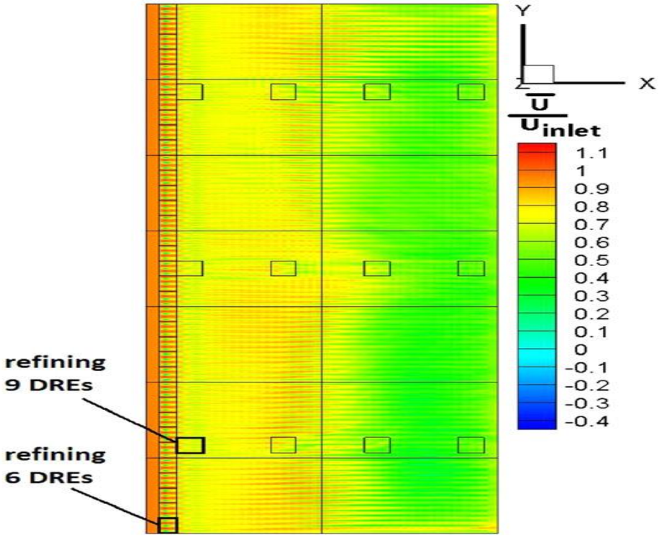
Time-mean

4000 Microstructures on Wall Surface

(5x5x5 embedding)



(a)



(b)

Closing Remarks

- **Wall Microstructure (Random/Regular Roughness, Micro-Cooling):** ***Multi-scale Challenges*****.**

- **Prospect of *'Surface-Design'* (*both SHAPE and FINISH*):** ***Multi-scale Opportunities*****.**

- **Two-scale Approach (*in Space, Time, Fluid, Solid*):** ***Multi-scale Source-term based Method*****.**
  - *Aimed at correcting* ***'Mesh-dependent' discretization errors*** *in coarse-mesh (adopted by choice);*
  - ***'Mesh-informed' source terms*** *generated in situ to drive coarse-mesh solution to the target;*
  - *Inclusive of closing Reynolds-Stresses (part of the problem in Fluid/not a problem at all in Solid!).*

Reynolds Stresses: *Only Part of the Problem for Coarse-mesh WMLES – Attention to Mesh Errors..*