2011 UTSR Workshop
Co-Organized by The Ohio State University and DoE NETL
25-27 October 2011

Verification and Validation Issues in CFD Analysis of Turbine Cooling

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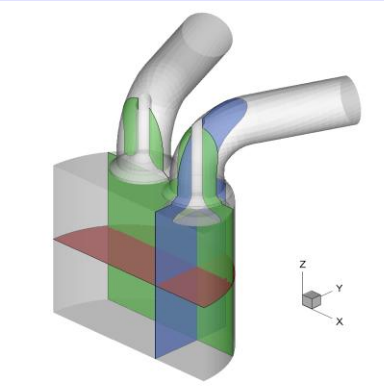
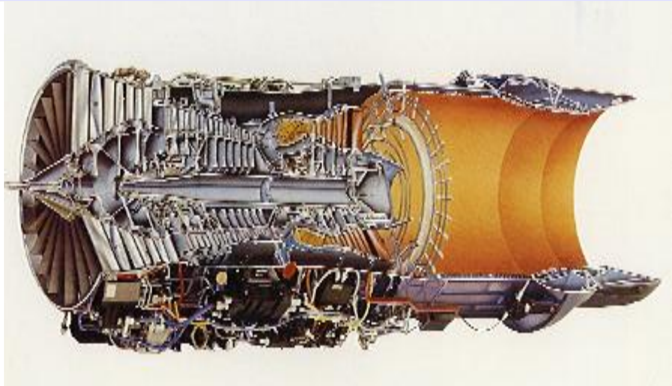
DoE – NETL & Ames Laboratory

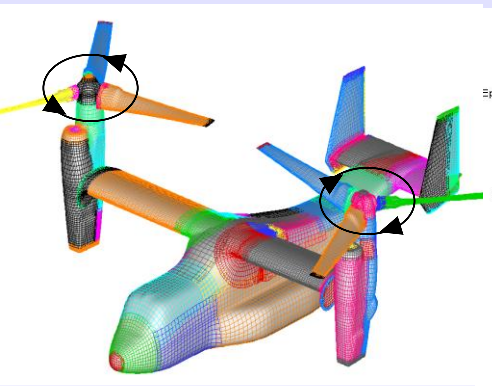
PURDUE UNIVERSITY

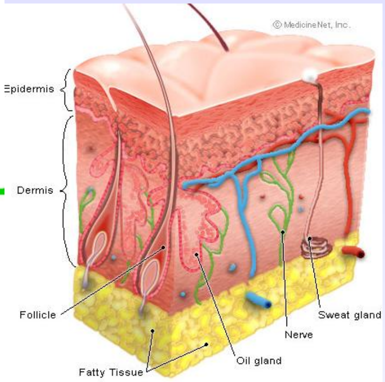
CFD has come a long way!

CFD is now used to study a wide range of problems, including **turbine cooling**.





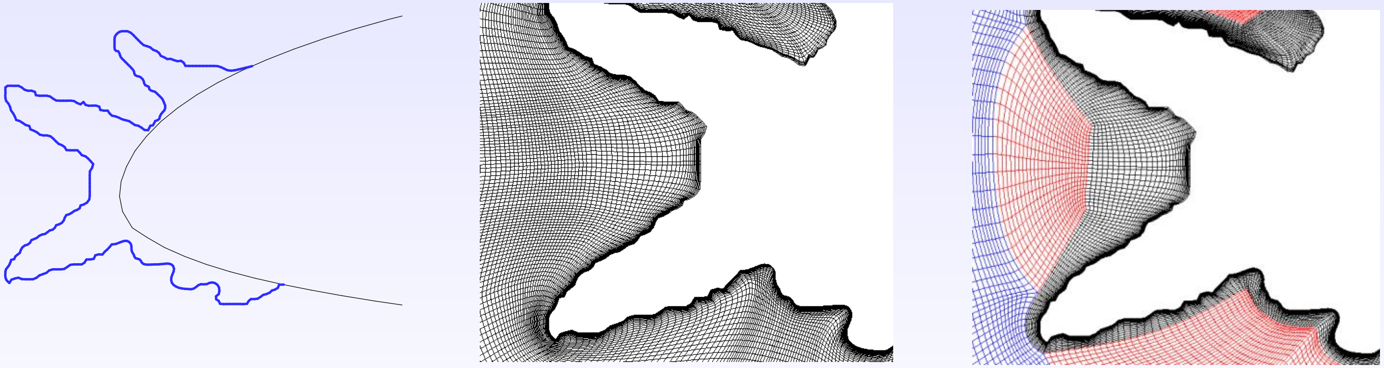




Despite the tremendous progress, there is still **serious concern** on the ability of CFD **to guide decisions**.

Why the uncertainty?

- unknown & variable material properties
- modeling uncertainties (*turbulence, multiphase, chemical kinetics, radiation, …; even atomic simulations have models*)
- unknown/incorrect initial & boundary conditions (inflow/outflow)
- discretization error (*PDE → FD/FV/FE: spurious modes*)



- cannot get converged solution
- **cannot afford to do grid-independent solution**

for realistic problem. Also, one never sees grid sensitivity studies on LES & DNS.

How to assess errors & uncertainty?

Governing PDEs (IC/BCs + models) → Grid + Numerical Methods → Numerical Solution

Verification: solve the PDE “right”

Do a grid sensitivity study!

Validation: solve the “right” PDE

Compare with experimental data!

Uncertainty Quantifications:

Bound uncertainties from all solutions for all parts of the system for RISK analysis and DECISION MAKING.

code V&V versus **solution V&V**

What are the issues of V&V and UQ in turbine cooling?

Verification: solve the PDE "right"

- Requires a grid sensitivity study! NOT PRACTICAL!
- Need **single-grid** or "near" single-grid error estimator!

Validation: solve the "right" PDE

- Compare CFD results with experimental data!
- CFD & EFD must solve the same problem!
- How good are the experiments?
- When to use RANS, unsteady RANS, LES?

Uncertainty Quantifications:

- Assess RISK for DECISION MAKING! … a future talk!

Outline of Talk

Verification: grid sensitivity

- A single-grid / "near" single-grid error estimator

Validation: compare with experiments

- Make it possible for CFD to solve the EFD!
- What is the bulk temperature used to compute h?
- How well is h measured by transient liquid crystal?
- Steady & unsteady RANS vs LES

Summary

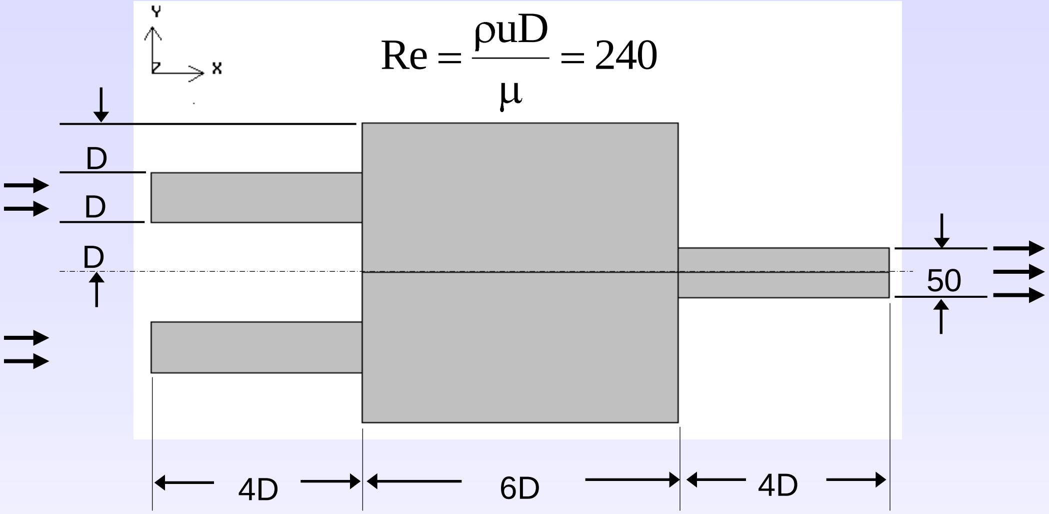
Verification: a single-grid error estimator

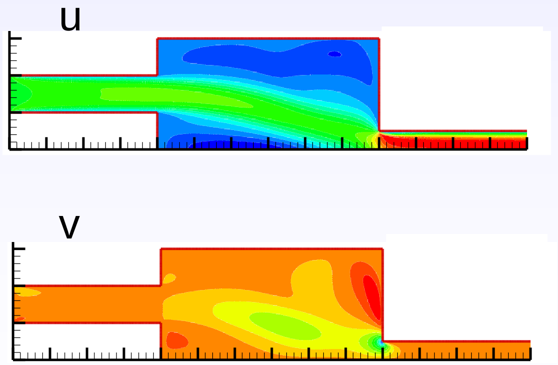
Is error = f(local grid, local solution) ???

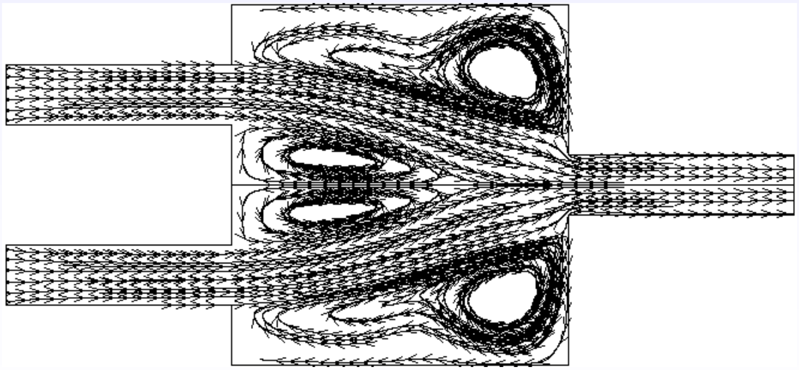
To examine, consider the **grid-independent** solution of

55,296 cells

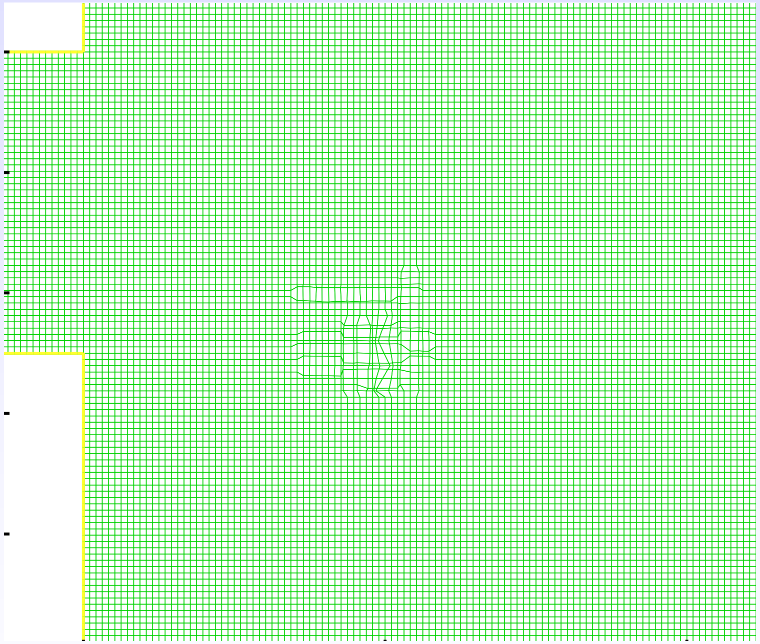
$\Delta x = \Delta y = D/50$

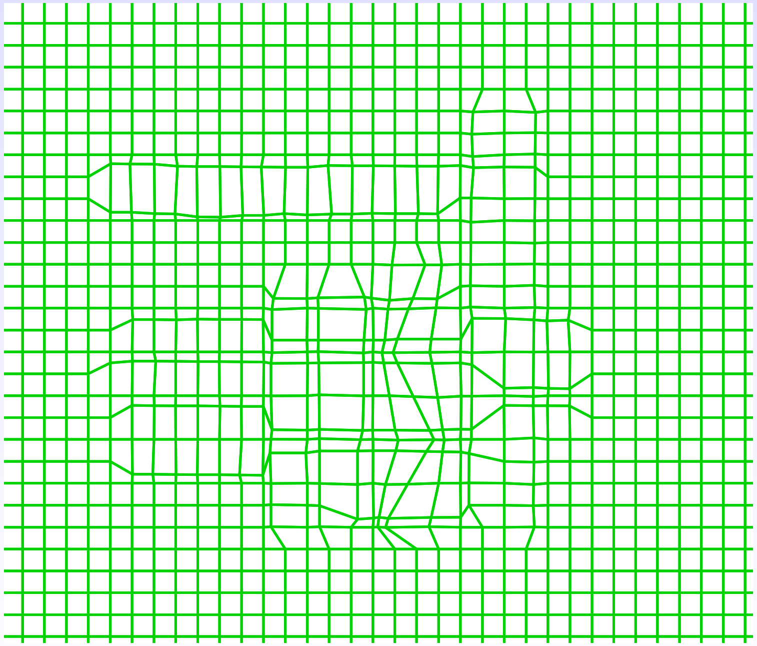




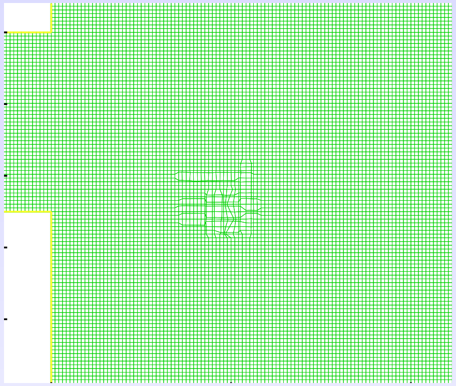


Now, we perturb the GRID, making it coarser & poor quality at one location.

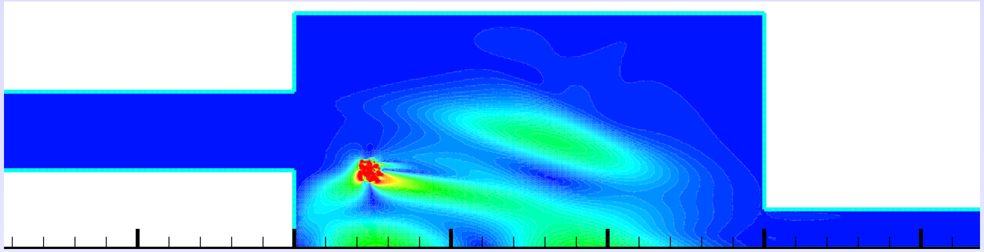


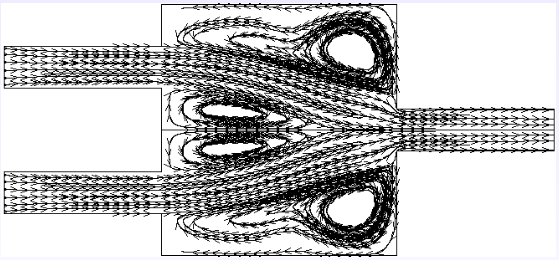


Error in Solution on Perturbed Grid

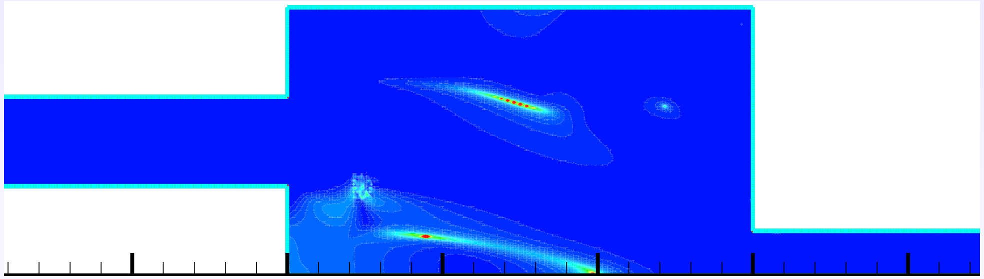


absolute error





relative error



Since the grid is "perfect" except at one location, error is clearly **not a local function** in CFD.

If error $\neq$ f(local grid, local solution)
then a transport equation for error is needed.

In finite-element, this idea has been proposed (Babuska (1978), Sonar (1993), Mackenzie, et al. (1994); see review by Roach in his V&V book).

Application of idea to finite-difference/finite-volume was first proposed by

- Zhang, Trepanier, & Camarero (2000)
- Zhang, Trepanier, Pelletier, & Camarero (2001)

where the residual is the leading term of the modified equation.

Celik (2004) presented a study using this approach with an approximate modified equation.

Zhang, et al. (2000, 2001) followed the finite-element approach in deriving the error-transport equation, which is

$$L(U) = f$$

$$L(U_a) - f = R$$

Linearizing and then subtracting gives

$$L(e) = -R$$

L = differential operator

f = non-homogeneous term

U = exact solution

U_a = approximate solution

R = residual

$e = U - U_a$ = error

ISSUES:

- OK for FE, but not FD/FV! Why?
  - operator changed; operator is discontinuous
- How to model R?

So, what can we do?

FD, FV, FE, spectral methods can all be unified under the method of weighted residuals by appropriate weighting functions.

For FD/FV, an integral form is needed since weighting functions are discontinuous.

Integral: **Giles** (1997, 1998, 1999)
Venditti & Darmofal (2000, 2003)
Parks (2004)
Hicken & Zingg (2011) - unsteady

Used adjoint variable method to optimize grid distribution that improves the prediction of an integral number (drag or lift).

Qin & Shih (2002, 2003, 2004, 2005, 2006) and
Williams & Shih (2009, 2010)

took a different approach that **disregards the original PDE** in deriving a **discrete error transport equation (DETE)**.

So far, have applied it to

- 1-D advection-diffusion equation — AIAA 2002-0906
- 1-D/2-D wave equation — AIAA 2003-0845
- 1-D Burger Equation with weak solutions
- 2-D Euler: flow over wedge
- 2-D N-S: iced airfoil — AIAA 2005-0567
- 2-D N-S: steady laminar flow over airfoil: subsonic & transonic — AIAA 2009-1499
- 2-D N-S: moving vortex, oscillating flow past cylinder — AIAA 2010

Challenge: How to model the residual, R?

Challenge in DETE:
How to model the Residual?

Single-Grid Methods

- Modified Equation:
  - very complicated to derive for Euler & N-S FDE/FVE
  - TE involve high-order terms
  - "**approximate**" **modified equations (AME):**
    (a) neglect terms multiplied by Δt; (b) linearize/decoupled Euler

$$\frac{\partial q_m}{\partial t} + u\frac{\partial q_m}{\partial x} + v\frac{\partial q_m}{\partial y} = S_m \qquad q_1 = \rho, \quad q_2 = u, \quad q_3 = v, \quad q_4 = E + p$$

$$S_1 = -\rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \quad S_2 = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \quad S_3 = -\frac{1}{\rho}\frac{\partial p}{\partial y}, \quad S_4 = -(E + p)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \frac{\partial p}{\partial t}$$

- generate 2 solutions by using a high and a low order method and then subtract: $e_a = U_h - U_{low}$ ⟹ $L(e_a) = -R_a$
- construct a differentiable higher-order solution from a lower-order solution (**PDE**) - *Chris Roy (global spline), Williams & Shih (local)*

"Near" Single-Grid (Multiple-Grid) Methods

“Steady” Test Problems

- **Laminar cylinder**

  L1 - L4 uniformly refined grids

  $M_\infty = 0.3$, $Re_D = 40$, $T_\infty = 300$ K

- **NACA 0012 airfoil**

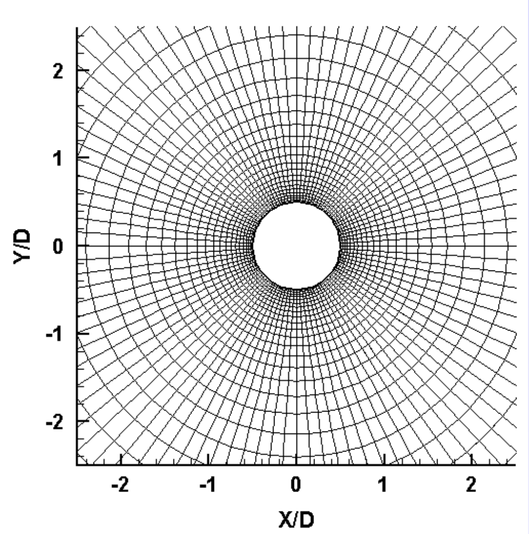
  L1 - L4 uniformly refined grids

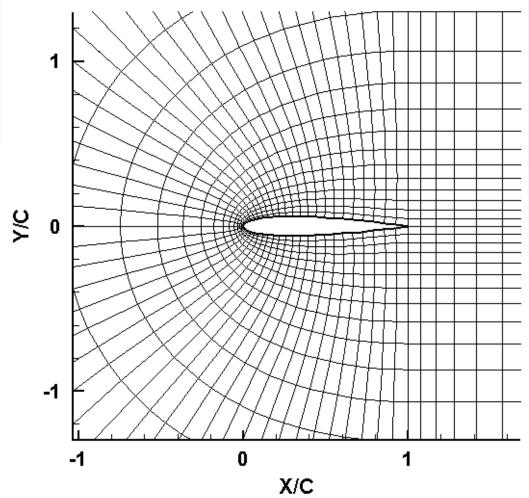
  Case 1: Subsonic

  $M_\infty = 0.5$, $Re = 1000$, $T_\infty = 300$ K, $\alpha = 1^o$

  Case 2: Transonic

  Inviscid, $M_\infty = 0.85$, $\alpha = 0^o$

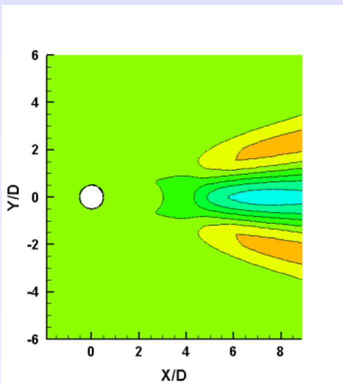




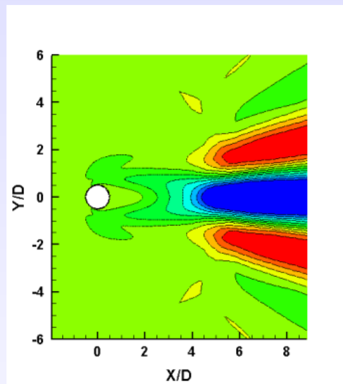
Steady Cylinder Flow: AME, E, & PDE

- **Steady Cylinder Results**

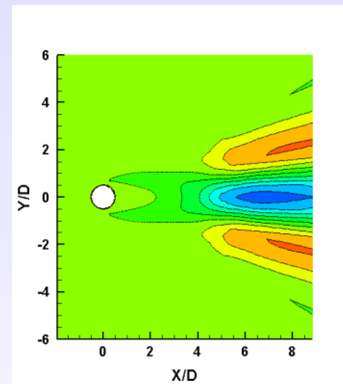
  DETE solutions on Grid 2 vs. actual error of x-momentum (kg/m-s)



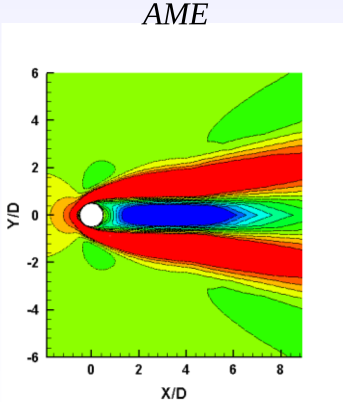
AME



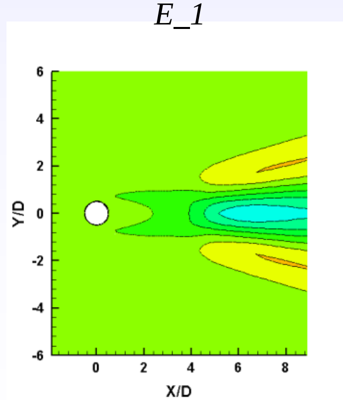
E_1



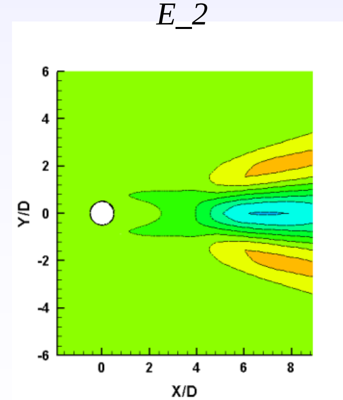
E_2



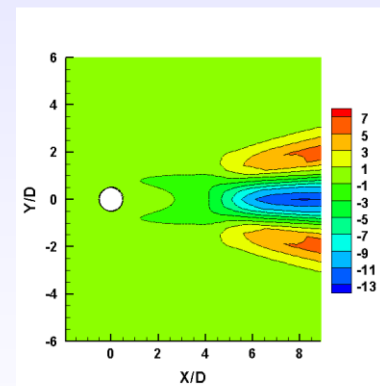
PDE_1



PDE_2



PDE_3

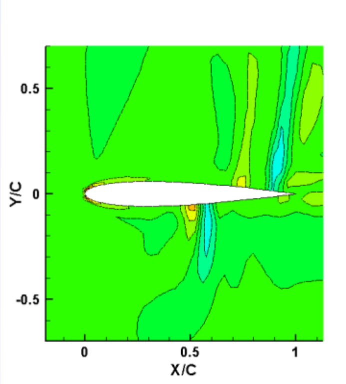


Actual Error
Grid 3 – Grid 2

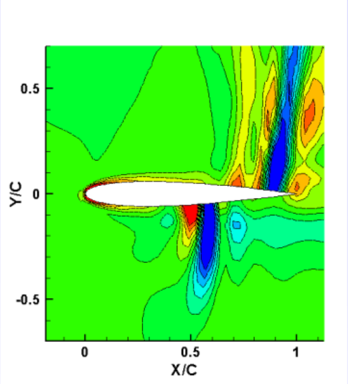
Steady Transonic Airfoil: AME, E, & PDE

- **Transonic Airfoil Results**

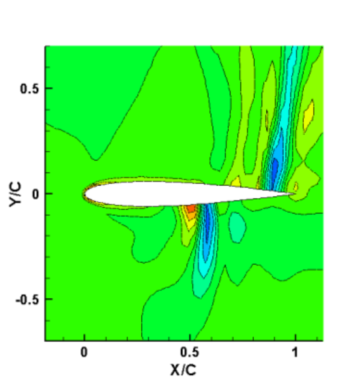
  DETE solutions on Grid 2 vs. actual error of x-momentum (kg/m-s)



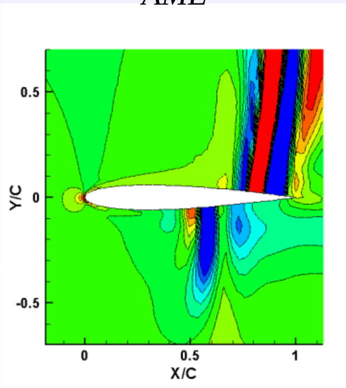
AME



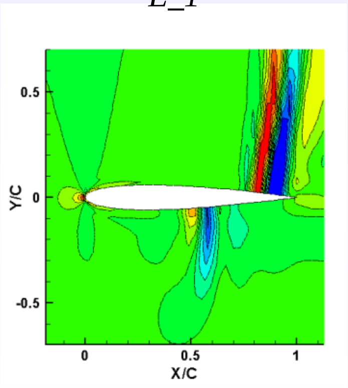
E_1



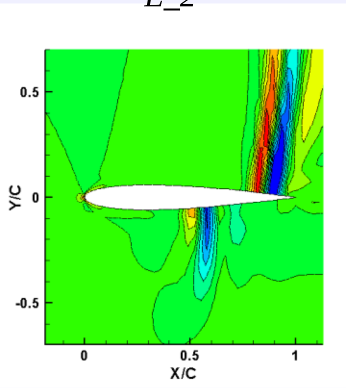
E_2



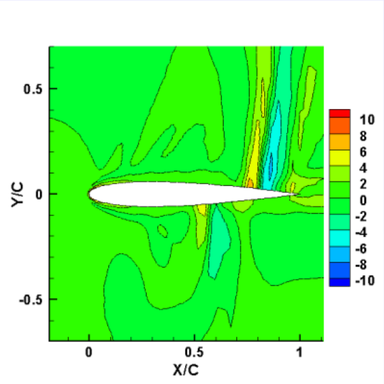
PDE_1



PDE_2



PDE_3



Actual Error
Grid 3 – Grid 2

“Unsteady” Test Problem: Translating Vortex

- **Isentropic Vortex**
  - Unsteady, inviscid flow
  - Mean flow:

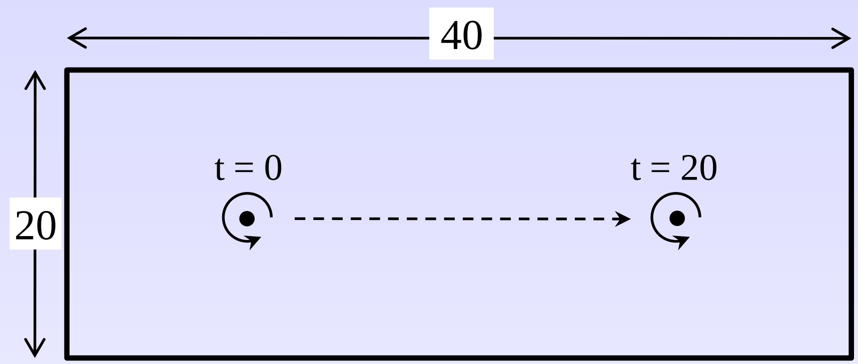
    $(u,v) = (1,0),\ p = \rho = T = 1$
  - Vortex starts at (10,10)
  - Vortex perturbations:

$$(\delta u, \delta v) = \frac{\beta}{2\pi} \exp\left(\frac{1-r^2}{2}\right)(-\eta, \xi)$$

$$\delta T = -\frac{\gamma - 1 \ \ \beta}{8\gamma\pi^2} \exp \ 1 - r^2$$

$$r^2 = \xi^2 + \eta^2$$

$$(\xi, \eta) = (x, y) - (xc, yc)$$



Domain

- Characteristic far field on all sides

Series of 3 grids

- Grid 1: 80 x 40
- Grid 2: 160 x 80
- Grid 3: 320 x 160

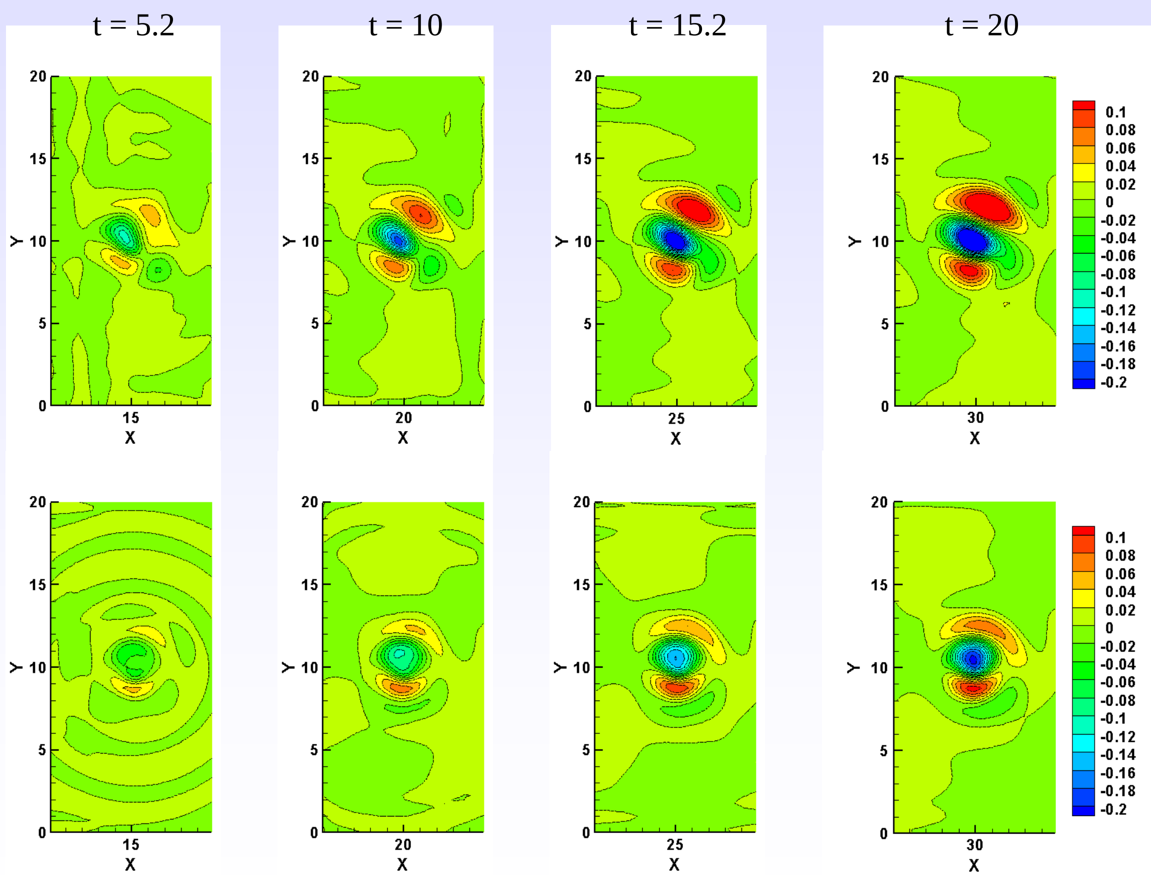
Results for Translating Vortex: AME

- **Isentropic Vortex Results**

  AME solution on Grid 2 vs. actual error of x-momentum (kg/m-s)

AME

Actual Error
Grid 3 – Grid 2



Results for Translating Vortex: PDE

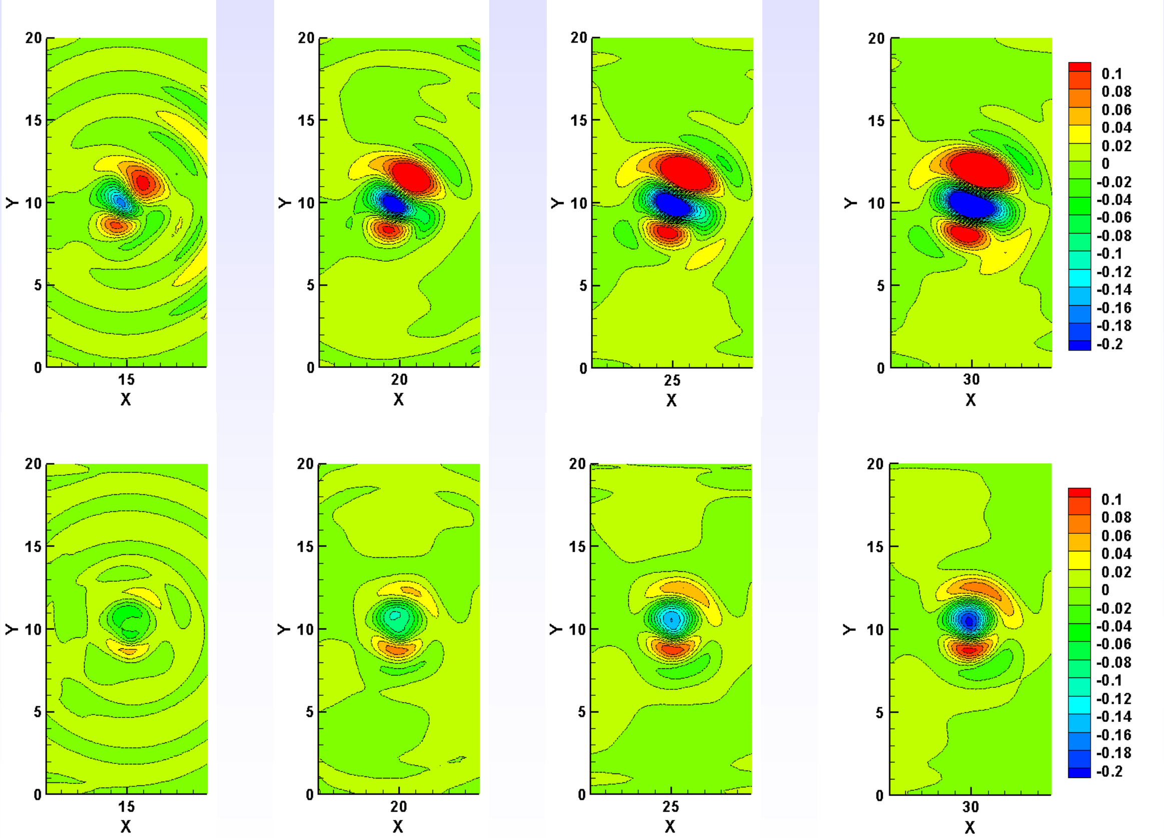
- **Isentropic Vortex Results**

  PDE_1 solution on Grid 2 vs. actual error of x-momentum (kg/m-s)

t = 5.2 | t = 10 | t = 15.2 | t = 20

PDE_1

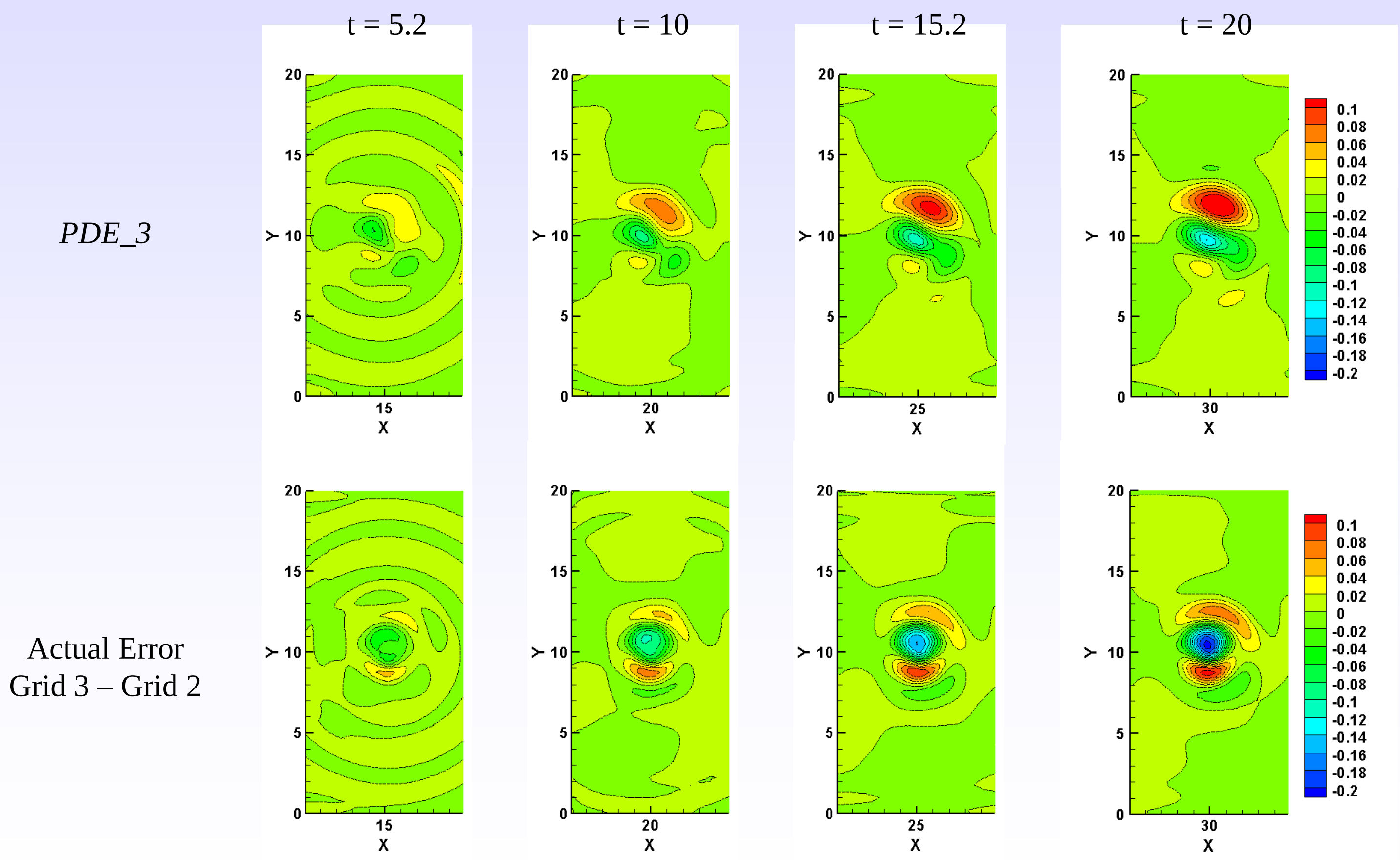
Actual Error
Grid 3 – Grid 2



Results for Translating Vortex: PDE

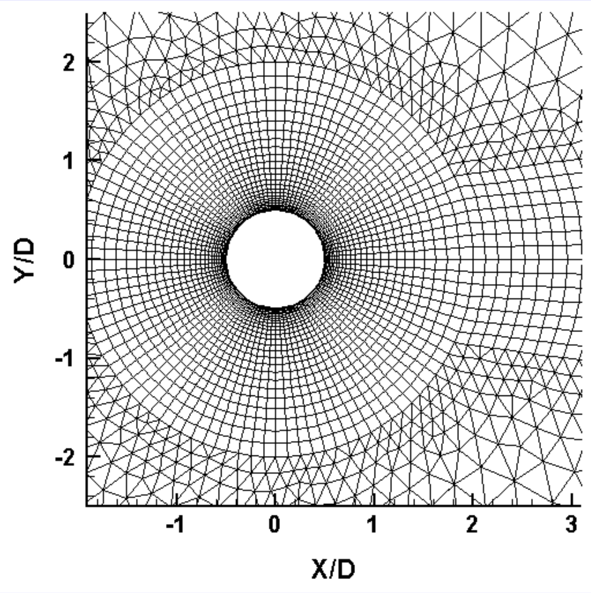
- **Isentropic Vortex Results**

  PDE_3 solution on Grid 2 vs. actual error of x-momentum (kg/m-s)

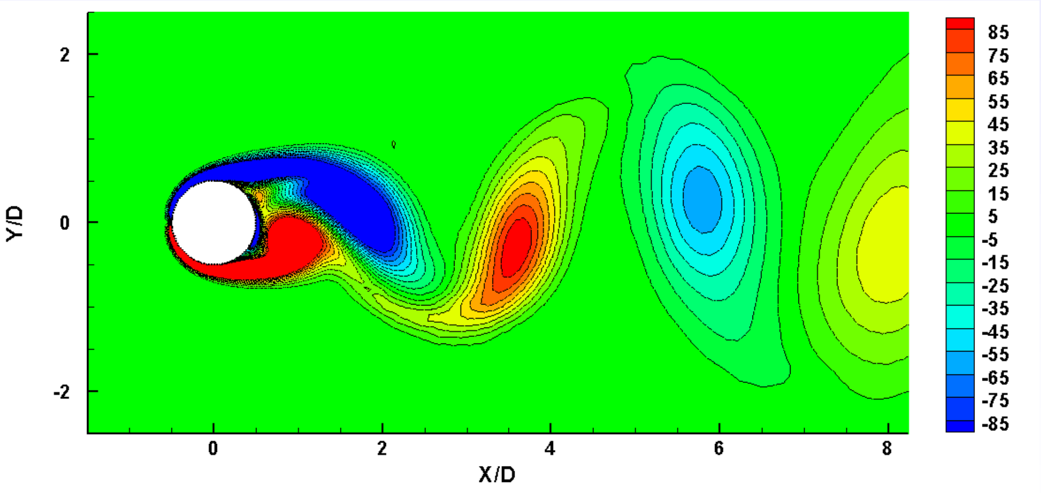


“Unsteady” Test Problem: Cylinder Wake Flow

- **Unsteady Cylinder**
  - Unsteady, laminar flow
  - $Re_D = 300$
  - Periodic vortex shedding (Von Karman vortex street)
  - Adiabatic, no-slip wall
  - Characteristic far field



Grid 1



Contours of vorticity

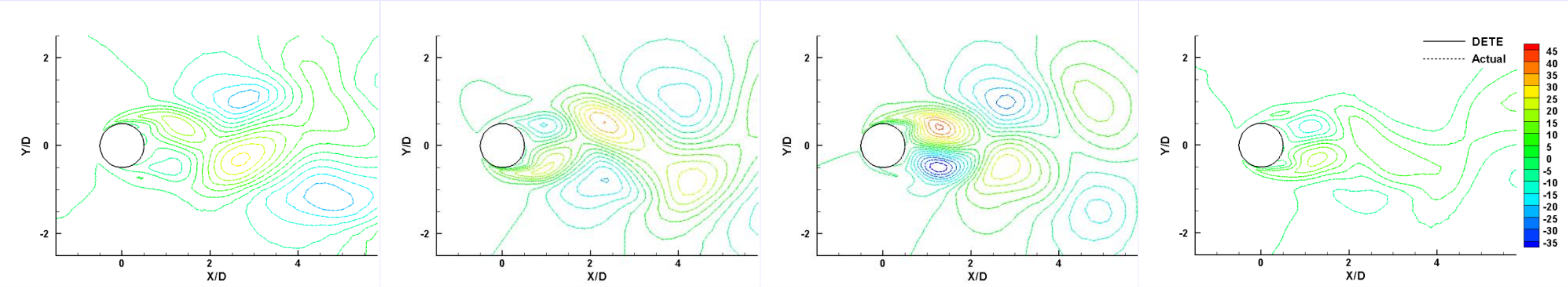
Series of 3 grids

- Grid 1: 5,466 cells
- Grid 2: 21,864 cells
- Grid 3: 87,456 cells

Results for Unsteady Cylinder Wake Flow

- **Unsteady Cylinder Results**

  DETE solution on Grid 1 vs. actual error of x-momentum (kg/m-s) relative to Grid 2

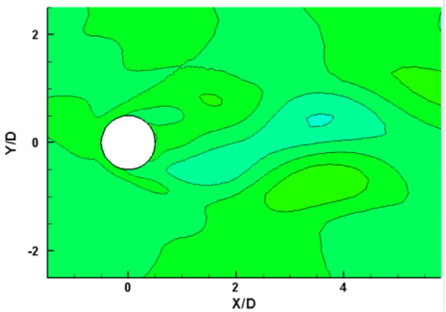


t = 0.5 | t = 1 | t = 1.5 | t = 2

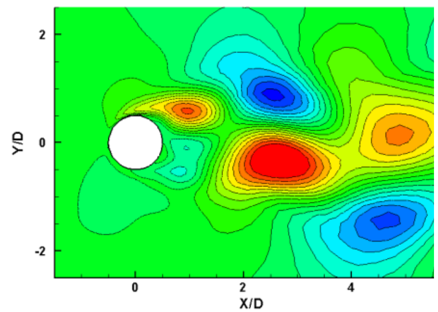
Results for Unsteady Cylinder Wake Flow

- **Unsteady Cylinder Results**

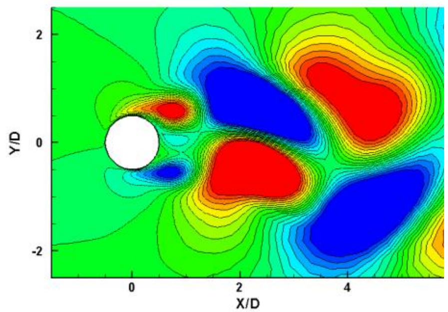
AME solution on Grid 1



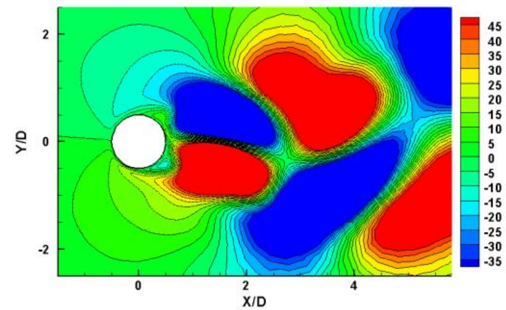
t = 0.5



t = 1

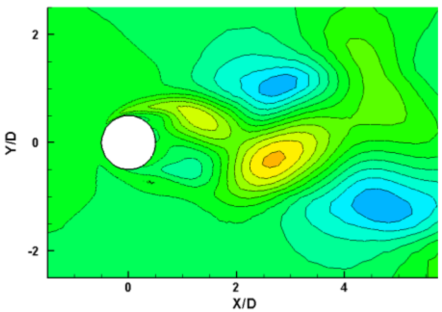


t = 1.5

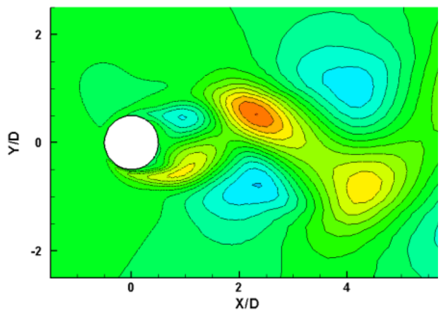


t = 2

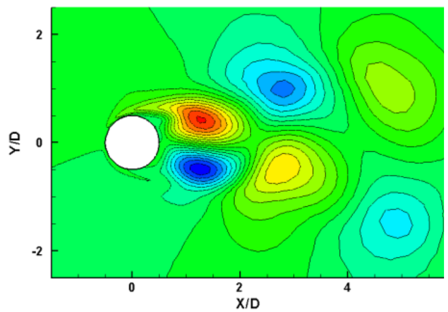
Actual Error Grid 2 - Grid 1



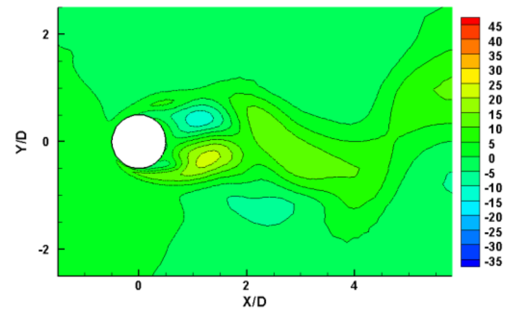
t = 0.5



t = 1



t = 1.5



t = 2

Outline of Talk

Verification: grid sensitivity

- single-grid error estimator

Validation: compare with experiments

- **Make it possible for CFD to solve the EFD!**
- What is the bulk temperature used to compute h?
- How well is h measured by transient liquid crystal?
- Steady & unsteady RANS vs LES

Summary

Make It Possible for CFD to Solve the EFD

There are no such thing as a "fully developed" compressible flow! Thus, need to know the flow conditions and geometry upstream of test section.

Measurements of velocity profiles at inflows and outflows will never be good enough for CFD. CFD profiles go all the way to the wall.

THUS, design experiments with test sections that have simple flows at the inlet and the outlet with no reverse flow so that CFD could reproduce the RIGHT PROFILES and use the right initial and boundary conditions.

Outline of Talk

Verification: grid sensitivity

- single-grid error estimator

Validation: compare with experiments

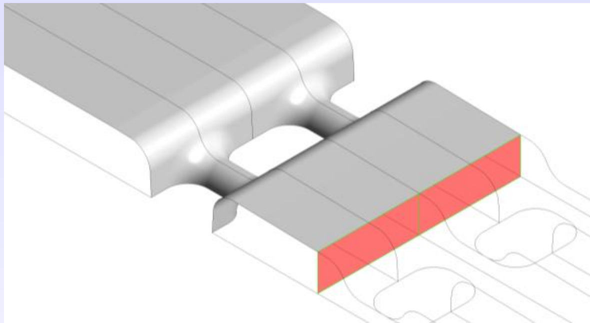
- Make it possible for CFD to solve the EFD!
- **What is the bulk temperature used to compute h?**
- How well is h measured by transient liquid crystal?
- Steady & unsteady RANS vs LES

Summary

HTC and the Bulk Temperature, T_b

To get $h = q''/(T_{wall} - T_b)$, one needs to define T_b.

T_b is easy to define only for ducts without flow separation:



$$T_b = \frac{\int_A \rho u C_p T \, dA}{\int_A \rho u C_p \, dA}$$

For complex configurations, a CV formulation is easier to implement (but only works for steady):

$$T_b(x) = \left(\frac{C_{p,in}}{C_{p,x}}\right) T_{in} + \frac{1}{C_{p,x}\dot{m}} \oiint q'' dA \Big|_{x_{in}}^{x}$$

HTC and the Bulk Temperature, T_b

Bottom line: both equations are rarely used in experimental studies when h is reported because it is hard to measure.

$$T_b = \frac{\int_A \rho u C_p T \, dA}{\int_A \rho u C_p \, dA} \qquad T_b(x) = \left(\frac{C_{p,in}}{C_{p,x}}\right) T_{in} + \frac{1}{C_{p,x}\dot{m}} \oiint q'' dA \Big|_{x_{in}}^{x}$$

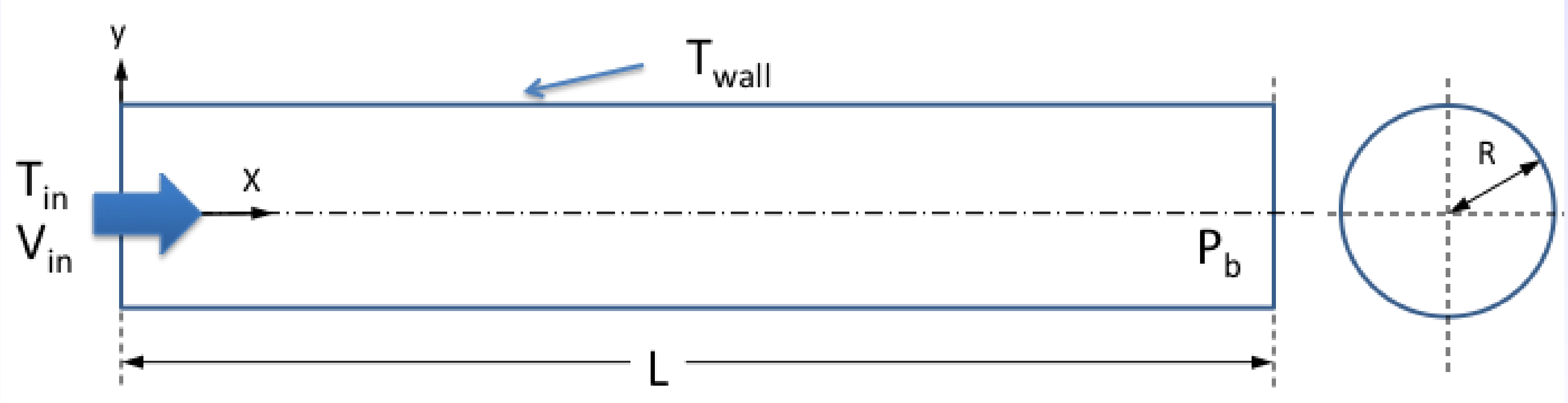
In practice, T_b is often approximated by

$$T_b(x) = T_{b,\, x=0}$$
$$T_b(x) = (T_{b,\, x=0} + T_{b,\, x=L})/2$$
$$T_b(x) = T_{b,\, x=0} + (T_{b,\, x=L} - T_{b,\, x=0})(x/L)$$

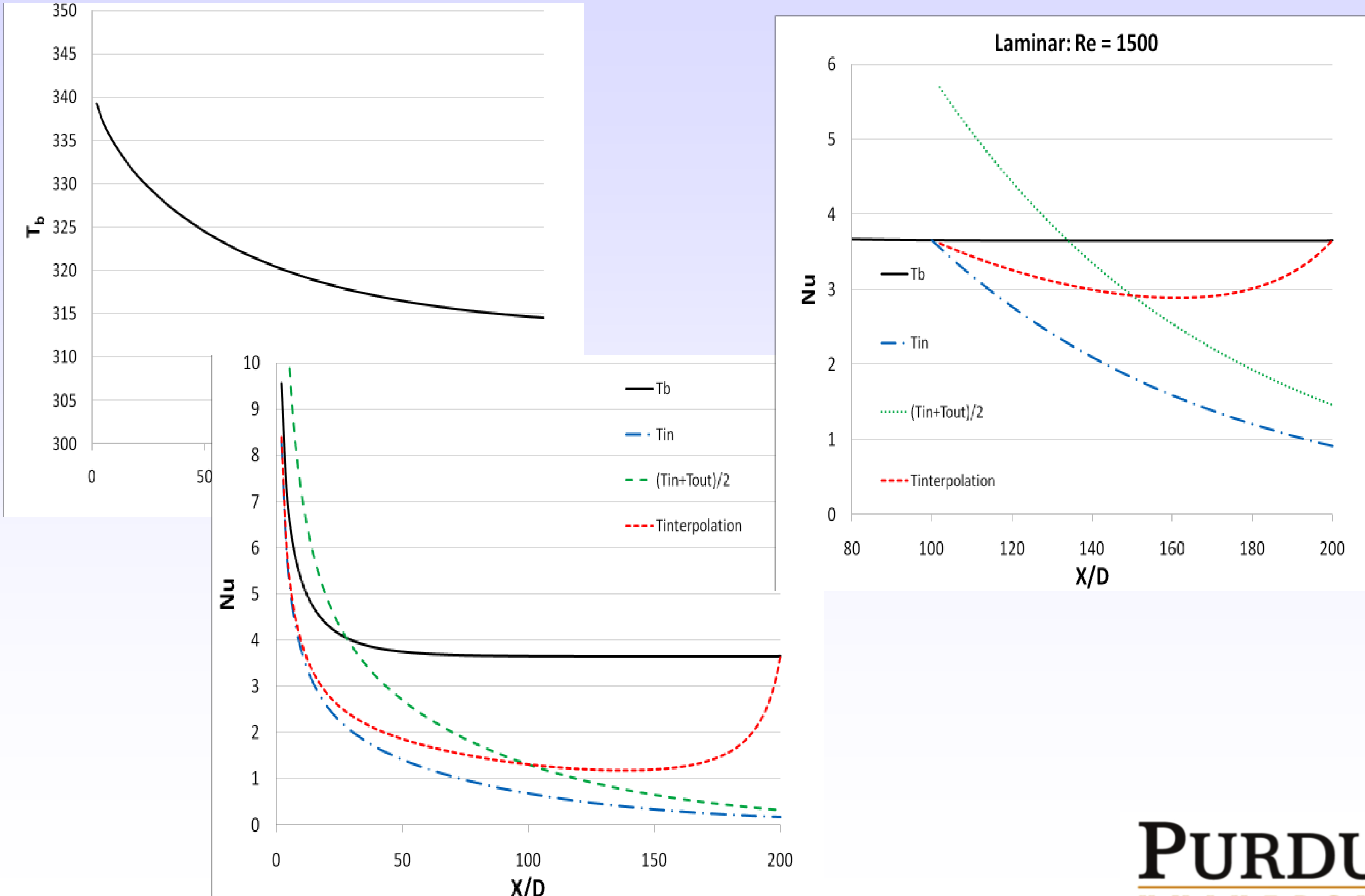
Let's see how good they are.

Test Problem: Incompressible "Fully Developed" Flow & HT in a Straight Pipe

For such flows, we know Nu = constant for laminar (theory)and for turbulent (Dittus-Boelter) flows.



Test Problem: Incompressible "Fully Developed" Flow & HT in a Straight Pipe - LAMINAR



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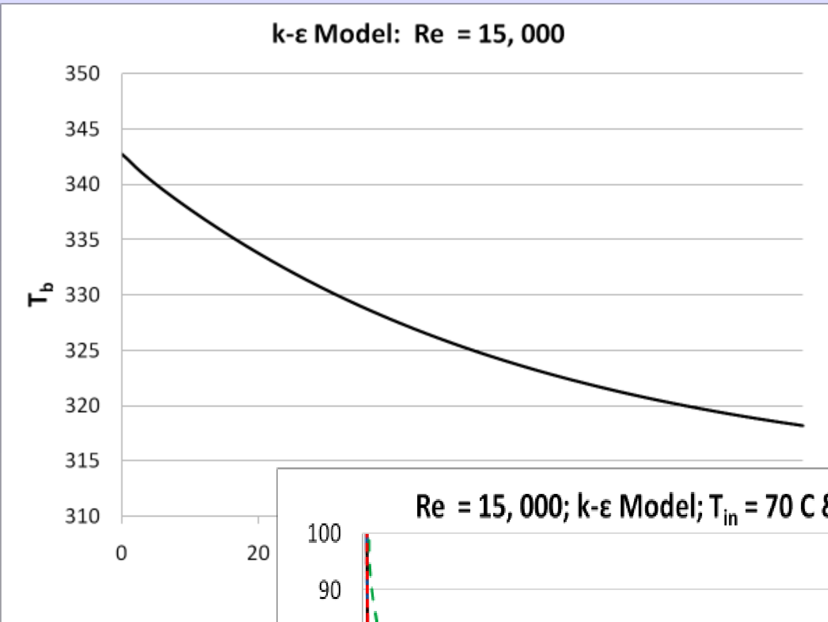
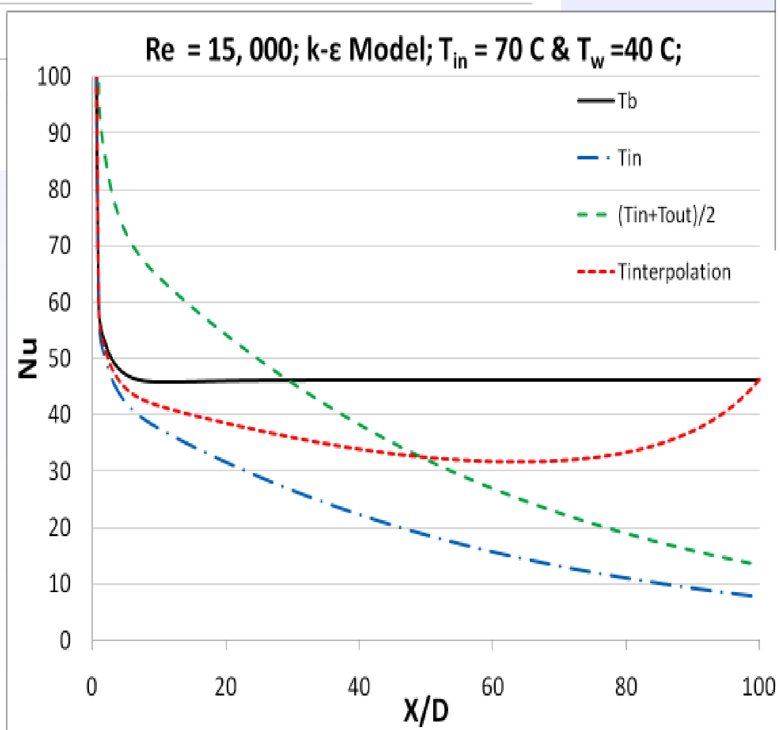
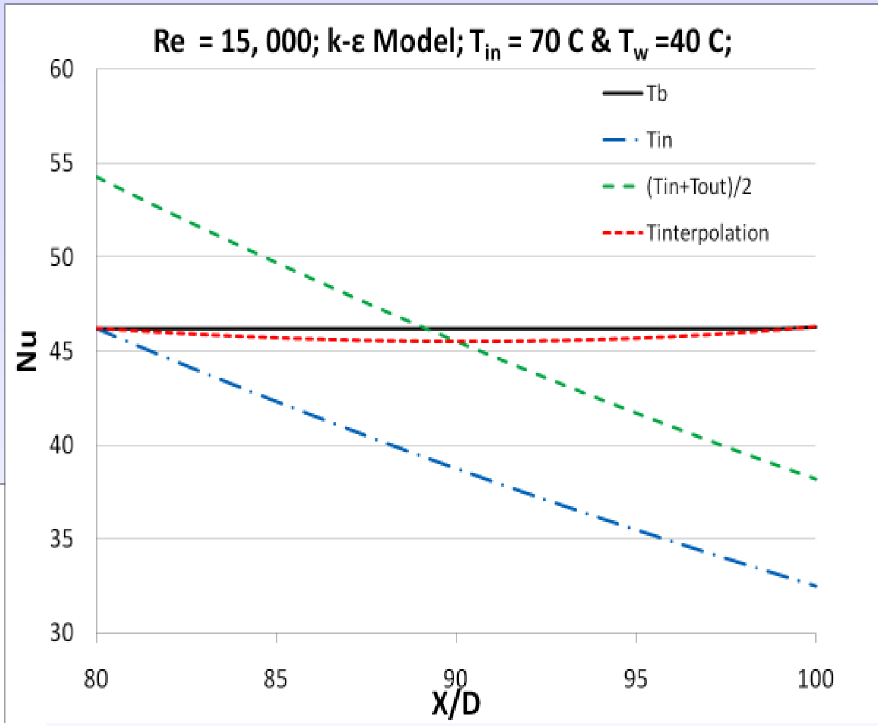
Test Problem: Incompressible "Fully Developed" Flow & HT in a Straight Pipe - TURBULENT







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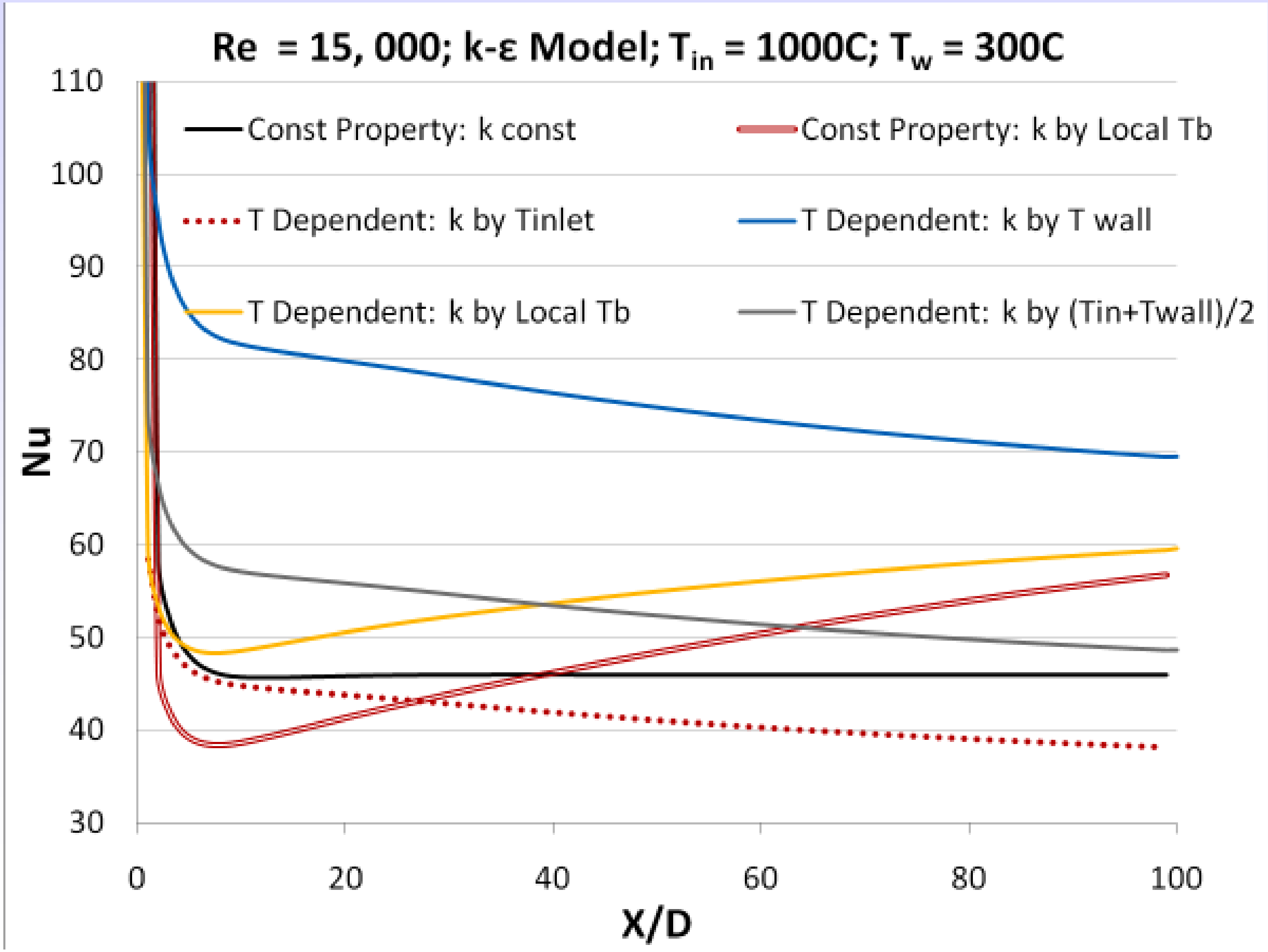
Test Problem: Incompressible "Fully Developed" Flow & HT in a Straight Pipe - TURBULENT



Outline of Talk

Verification: grid sensitivity

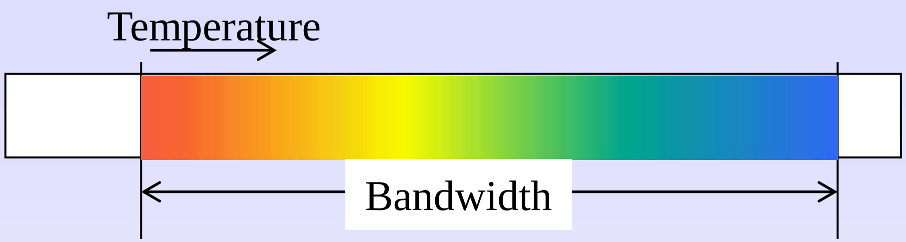
- single-grid error estimator

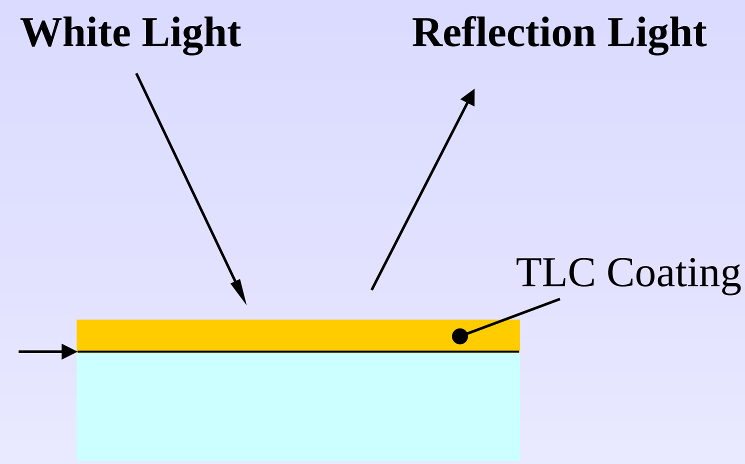
Validation: compare with experiments

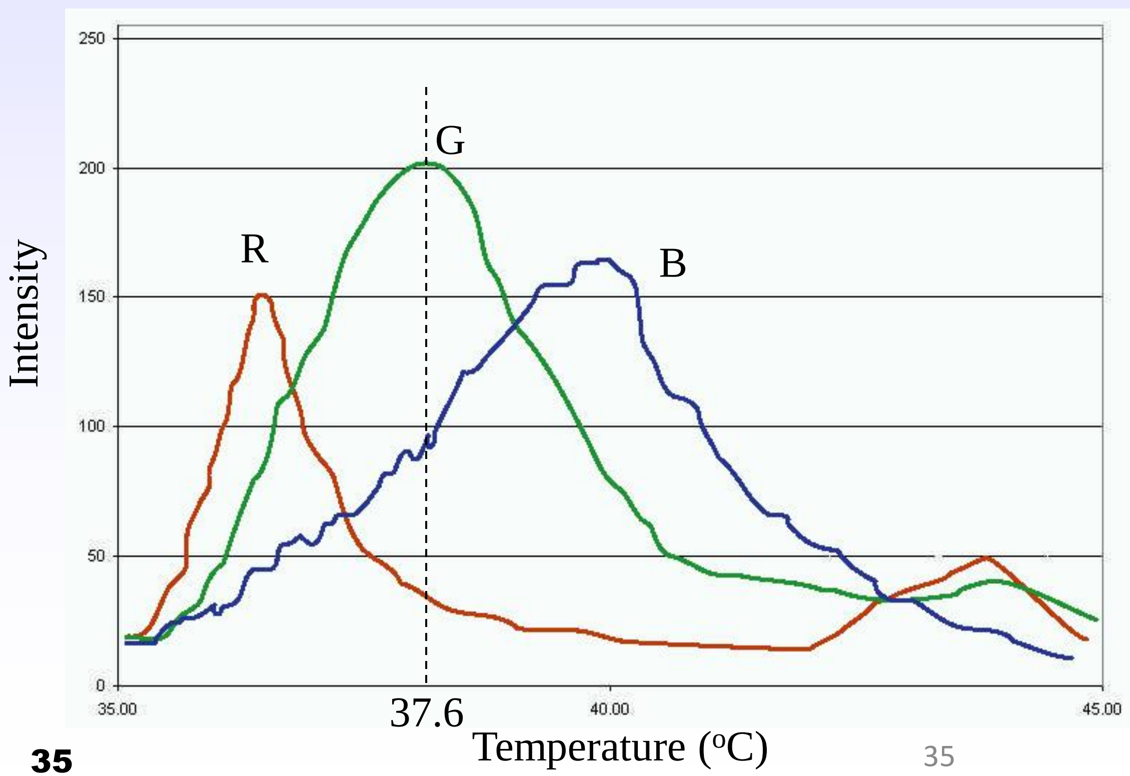
- Make it possible for CFD to solve the EFD!
- What is the bulk temperature used to compute h?
- **How well is h measured by transient liquid crystal?**
- Steady & unsteady RANS vs LES

Summary

Transient Liquid Crystal Technique







Thermochromic Liquid Crystal (TLC)

- Green light reflection gives the best intensity.

Experimental Approach -TLC Technique

One-Dimensional Semi-Infinite Conduction Model

Governing equation

$$k\frac{\partial^2 T}{\partial x^2} = \rho C_p \frac{\partial T}{\partial t}$$

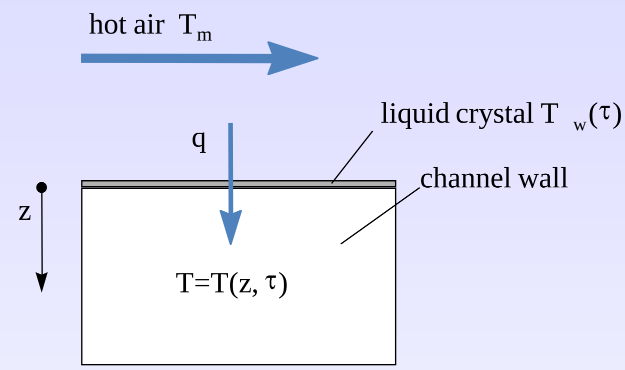
Boundary conditions

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=0} = h(T_w - T_r)$$

$$T|_{x=\infty} = T_i$$

Initial condition

$$T|_{t=0} = T_i$$



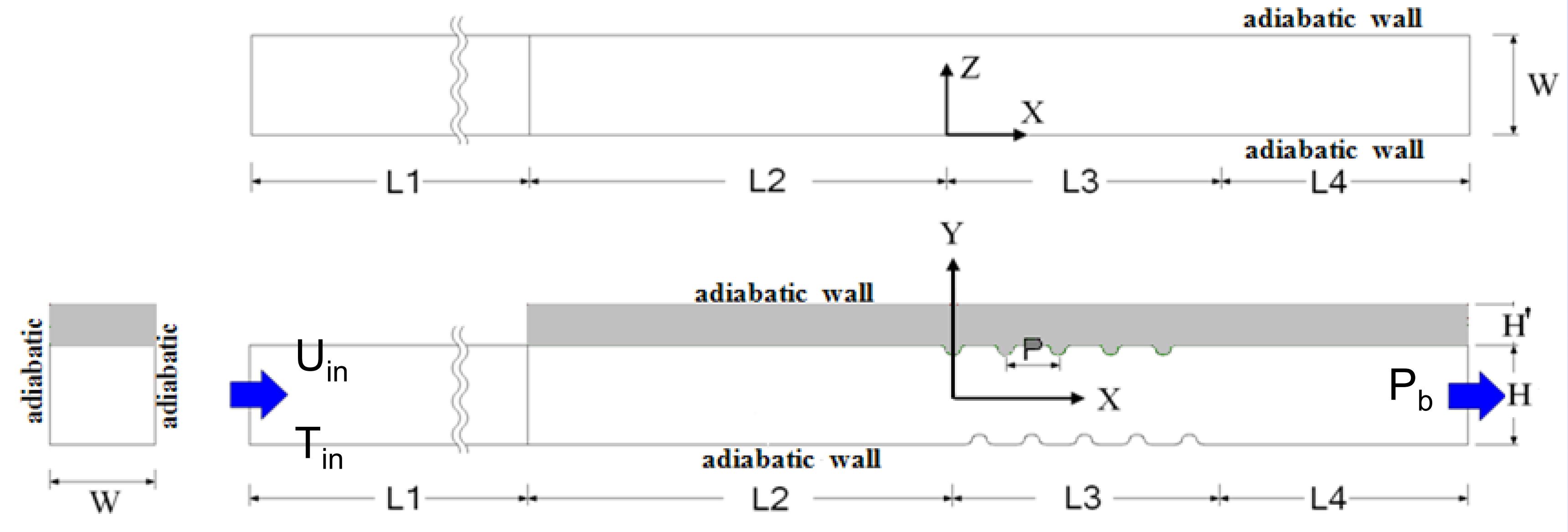
$q=h(T_r-T_w)$, $T_r=T_m$

Analytic solution

$$\frac{T_w - T_i}{T_r - T_i} = 1 - \exp\left[\frac{h^2 \alpha t}{k^2}\right] \mathrm{erfc}\left[\frac{h\sqrt{\alpha t}}{k}\right]$$

where $\alpha = \dfrac{k}{\rho C_p}$

Test Problem 1: inclined ribs



Problem Description:

D = 12.5 mm ; L1 = 200D ; L2 = 20D ; L3 = 25D ; L4 =48D ; H’ = 2.5D ; H= 10D ; W = 10D

Initially, T_{solid} = 300 K and T_{in} = 350 K with flow field at steady state based on T_{in} = 350K, U_{in} = 20 m/s; P_b = 1 atm. At time = 0, conduction to solid starts and T_{in} = 350 K.

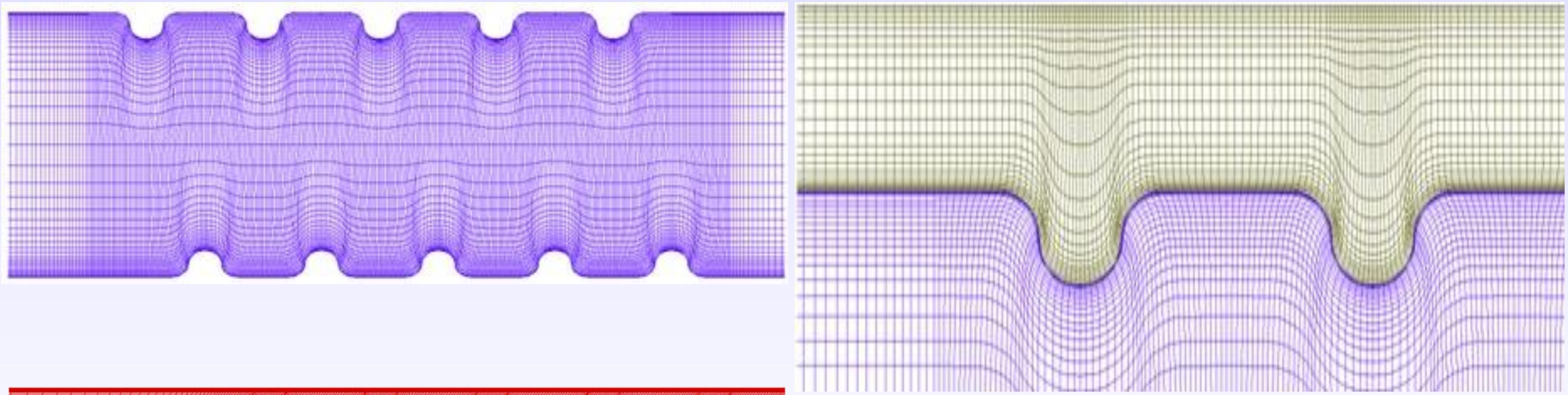
Solid phase:

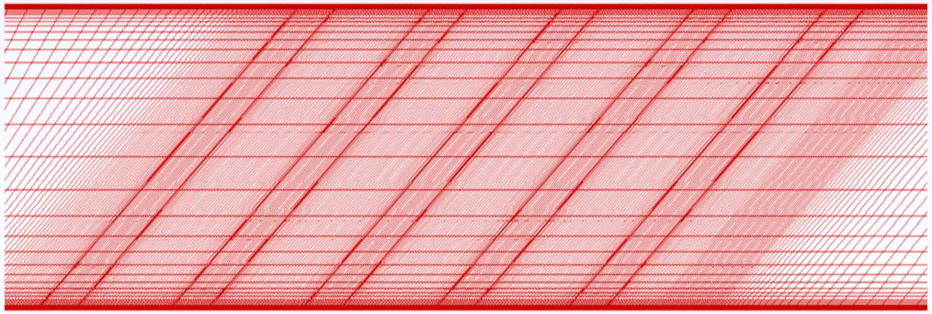
Plexiglass, ρ = 1180 kg/m^3, C_p = 1466 J/kg/K, k = 0.2 W/m-K,
α = 1.1561 x 10^{-7} m^2/s

Gas Phase: Air (assume incompressible with constant properties)

At 350 K: ρ = 1.000 kg/m^3, C_p = 1.009 kJ/kg/K , k = 0.0299 W/m-K , μ = 2.094 x 10^{-5} kg/m-s

Grid





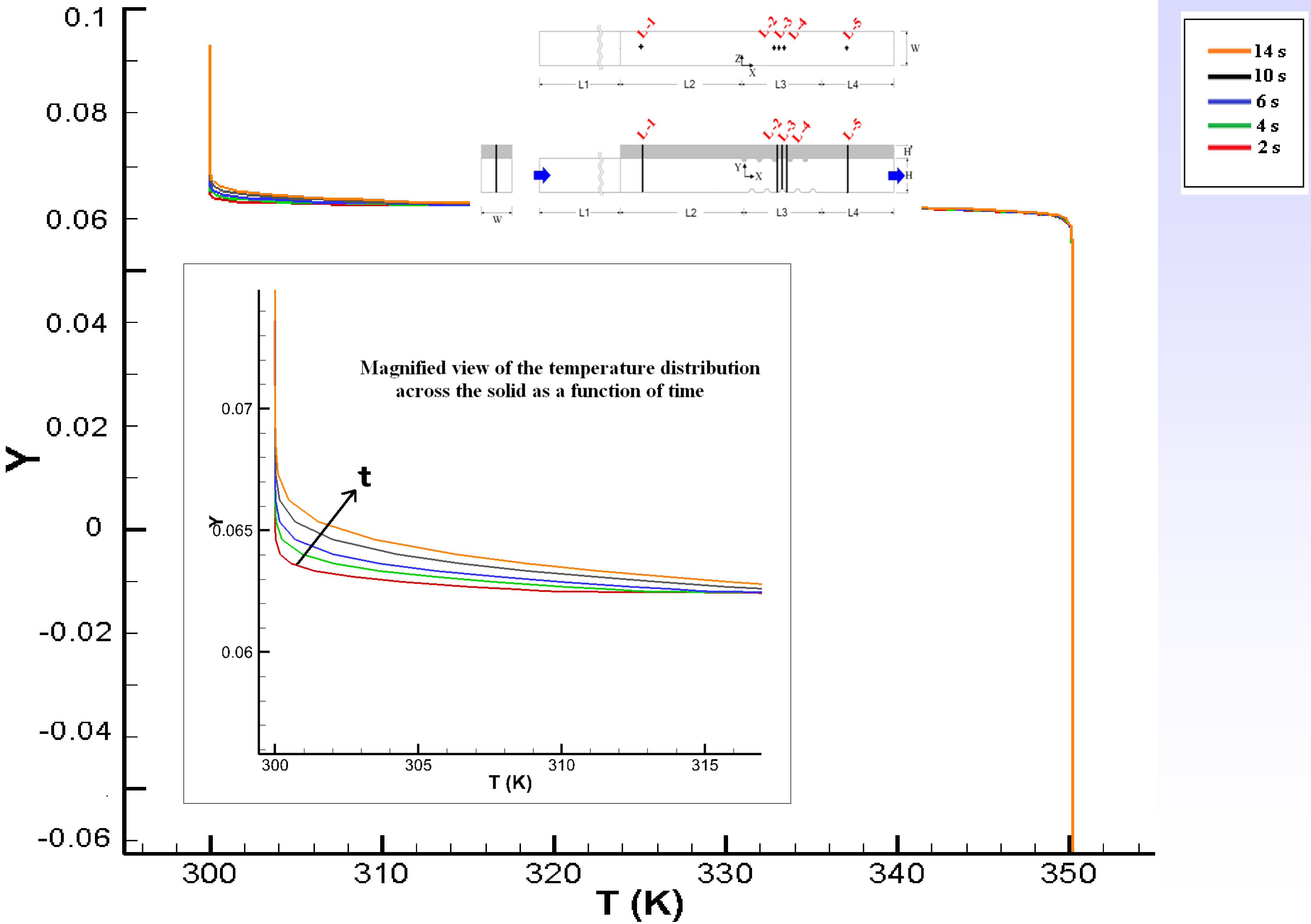
Grid details:

Number of nodes: 2,593,742

Face numbers: 7,585,418

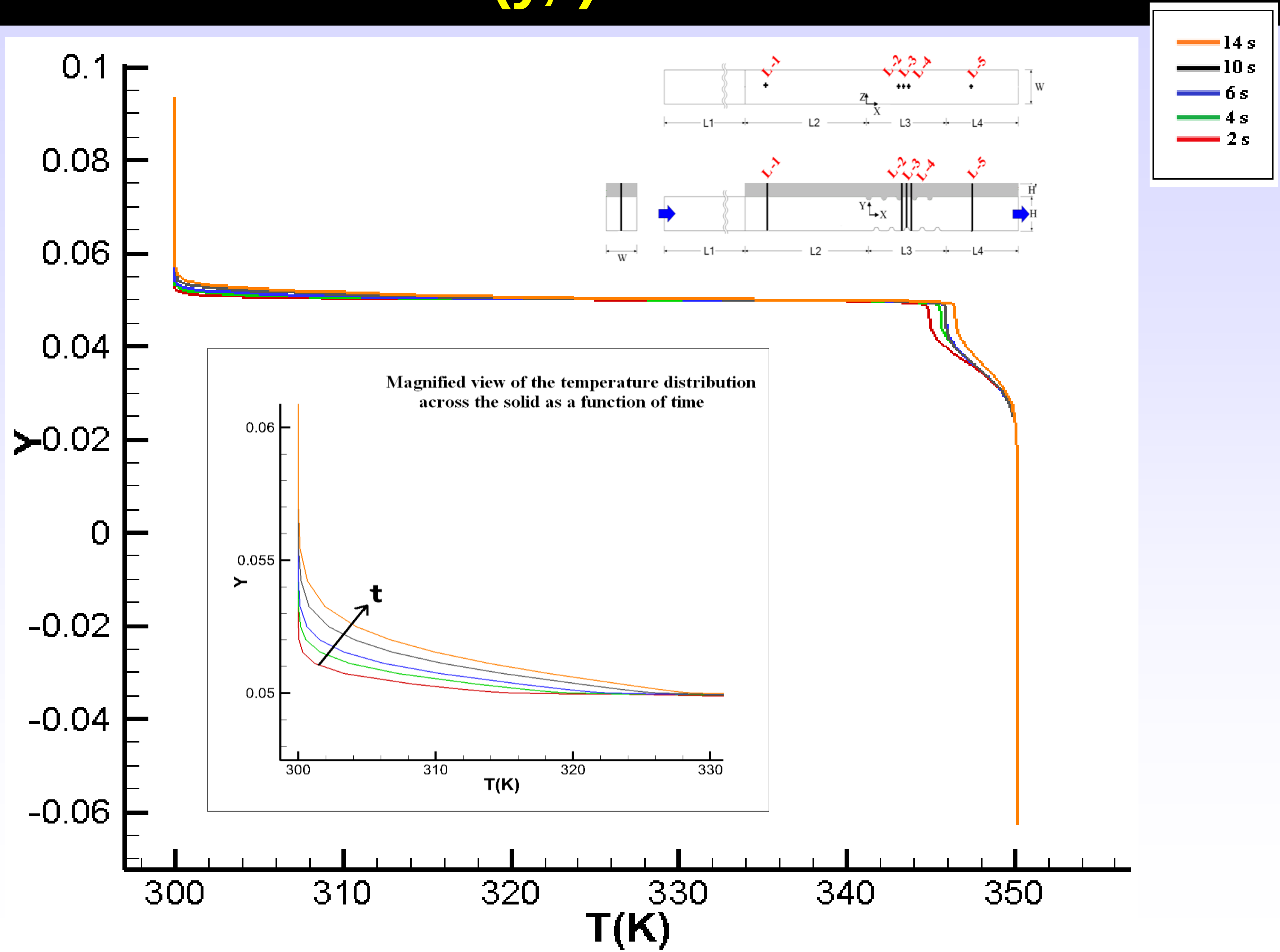
Cells cluster near walls ($y+ < 1$ for 1^{st} layer)

T (y,t) at L-1



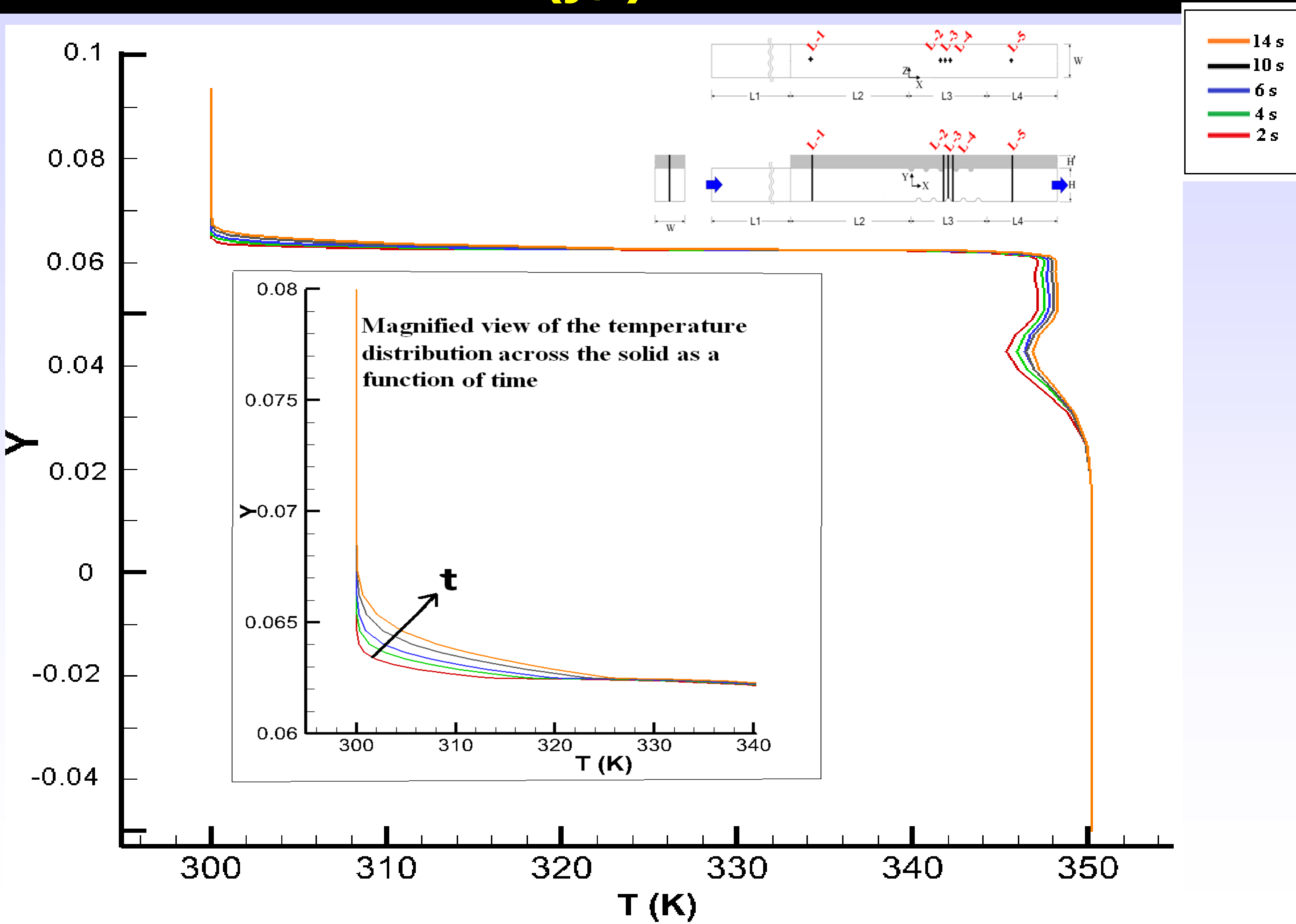
Magnified view of the temperature distribution across the solid as a function of time
t
14 s
10 s
6 s
4 s
2 s
Y
T (K)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
300
310
320
330
340
350
0.07
0.065
0.06
305
315
L-1
L-2
L-3
L-4
L-5
L1
L2
L3
L4
W
H
H'

T (y,t) at L-2



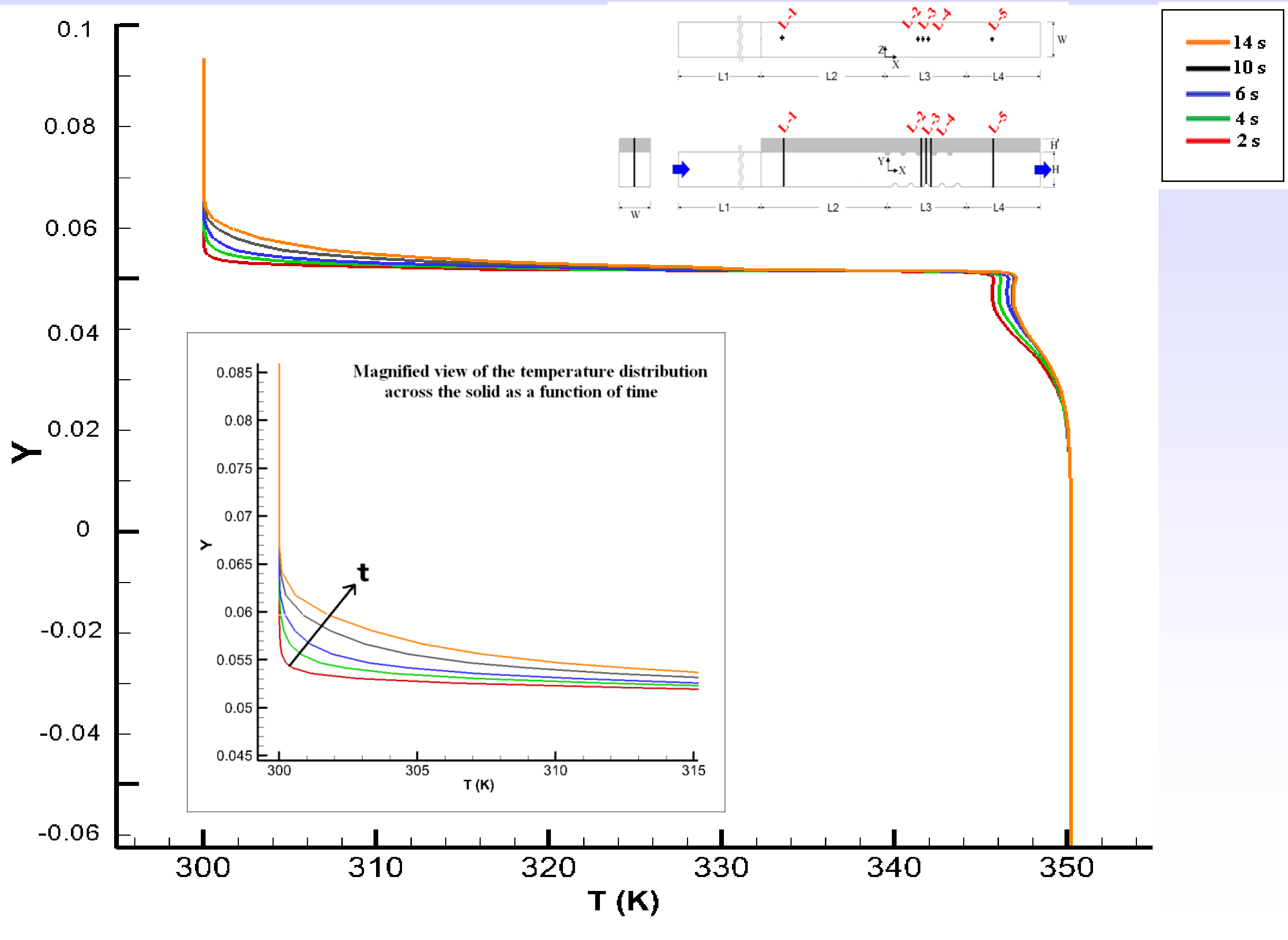
14 s
10 s
6 s
4 s
2 s
Y
T(K)
Magnified view of the temperature distribution across the solid as a function of time
t
L-1
L-2
L-3
L-4
L-5
L1
L2
L3
L4
W
H
H'

T (y,t) at L-3



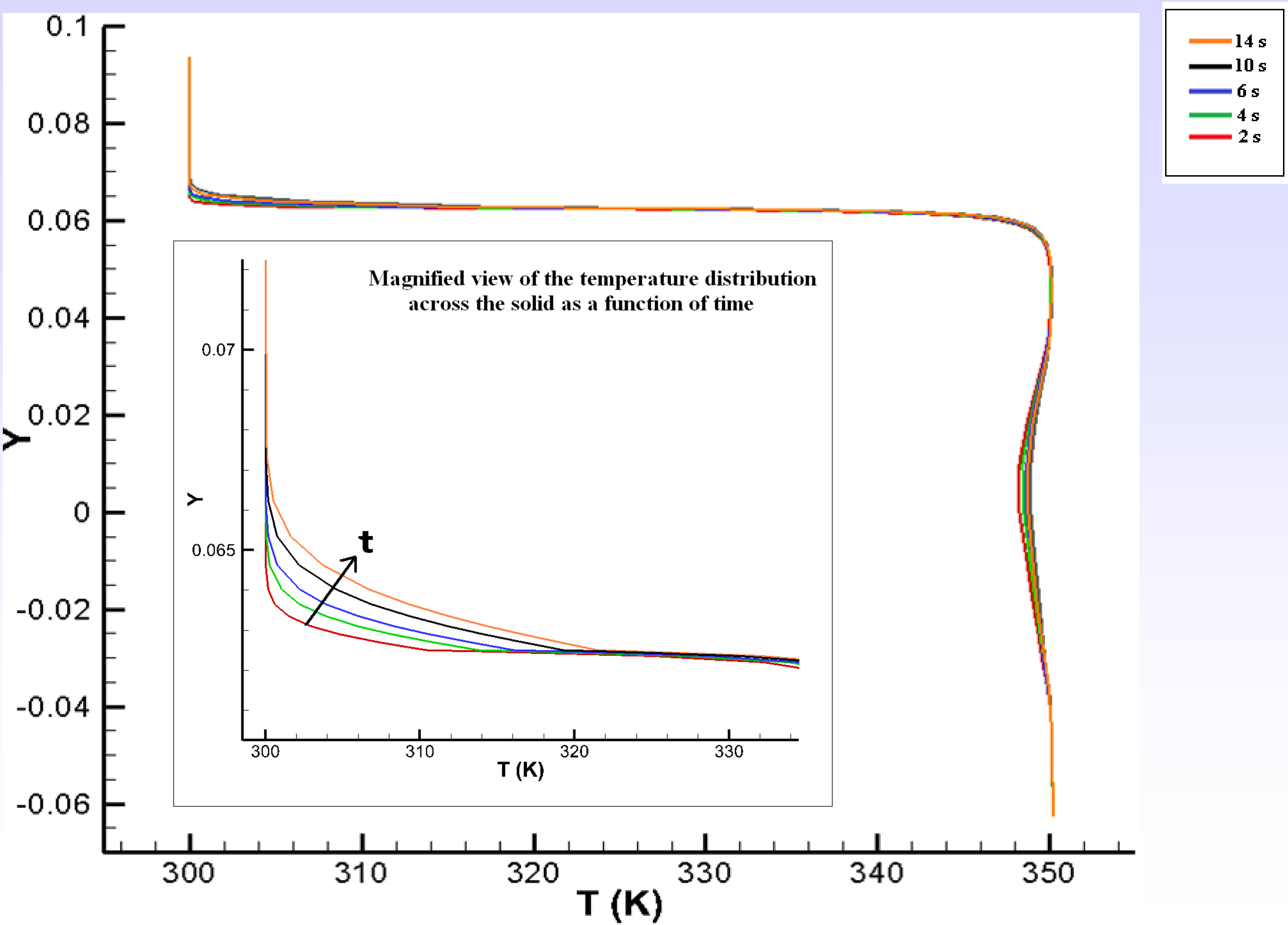
14 s
10 s
6 s
4 s
2 s
L-1
L-2
L-3
L-4
L-5
W
H
H'
L1
L2
L3
L4
Magnified view of the temperature distribution across the solid as a function of time
t
Y
T (K)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
300
310
320
330
340
350
0.075
0.07
0.065
0.06

T (y,t) at L-4



0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
Y
300
310
320
330
340
350
T (K)
14 s
10 s
6 s
4 s
2 s
L-1
L-2
L-3
L-4
L-5
L1
L2
L3
L4
W
H
H'
Magnified view of the temperature distribution across the solid as a function of time
0.085
0.08
0.075
0.07
0.065
0.06
0.055
0.05
0.045
300
305
310
315
T (K)
t

T (y,t) at L-5



14 s
10 s
6 s
4 s
2 s
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
Y
300
310
320
330
340
350
T (K)
Magnified view of the temperature distribution across the solid as a function of time
0.07
0.065
Y
t
300
310
320
330
T (K)

CFD vs 1-D Theory

CFD: $h_{CFD} = q''/(T_{wall,CFD}(\text{time}) - T_{inlet})$ $\quad q'' = -k \frac{\partial T}{\partial y}\Big|_{w,\ CFD}$

1-D Theory

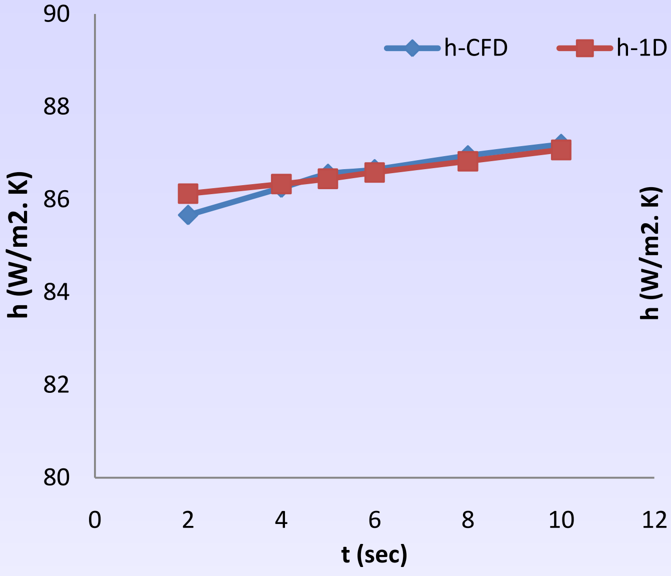
$$\frac{T_w - T_i}{T_r - T_i} = 1 - \exp\left[\frac{h^2 \alpha t}{k^2}\right] \operatorname{erfc}\left[\frac{h\sqrt{\alpha t}}{k}\right]$$

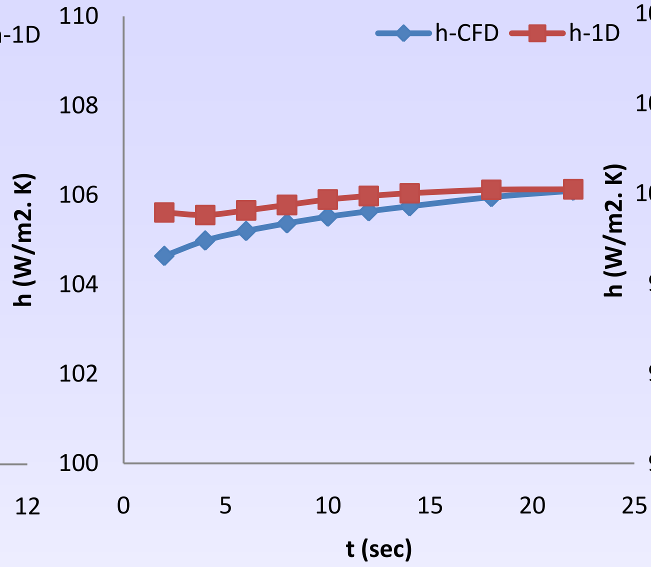
$$T_r = T_{inlet}, \quad T_w = T_{wall,\ CFD}(\text{time})$$

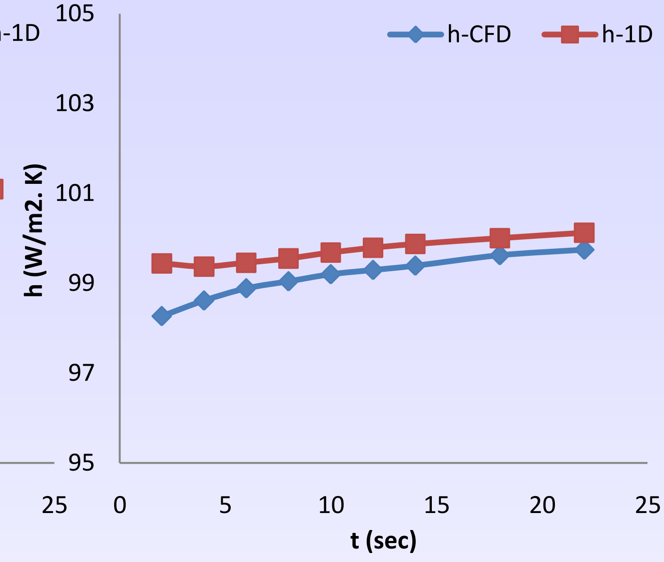
Questions:

1. Does h → constant as time increases?
2. Is that constant the steady state h?
3. Is that h correct?

h_{CFD} vs h_{1D} @ s0, s0_1, s0_2



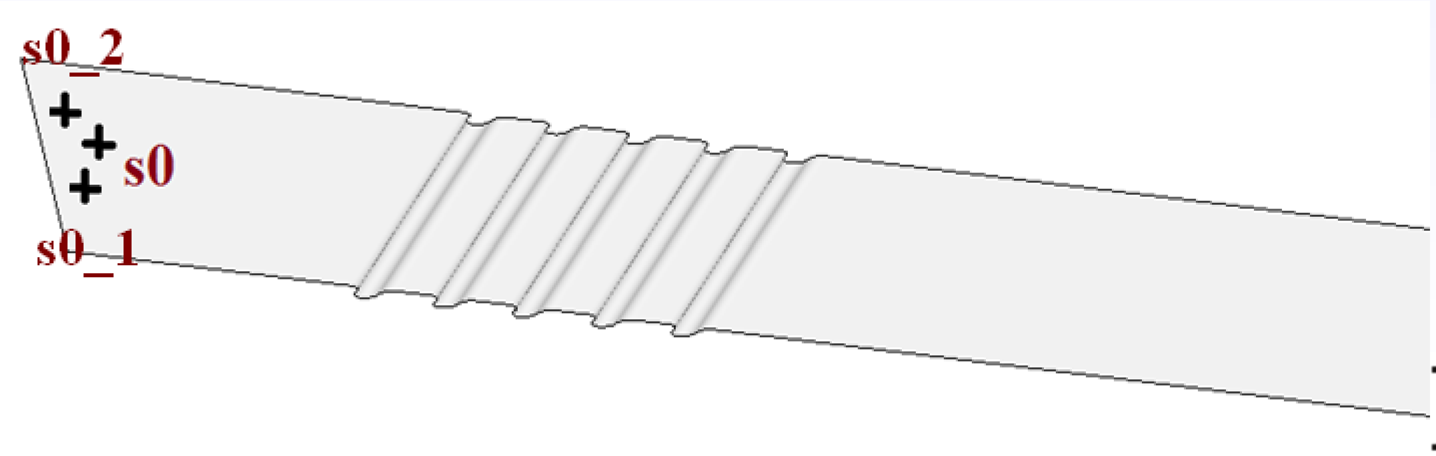




Error : 0.07 – 0.5%

Error : 0.02 – 0.9%

Error : 0.3 – 1.2%



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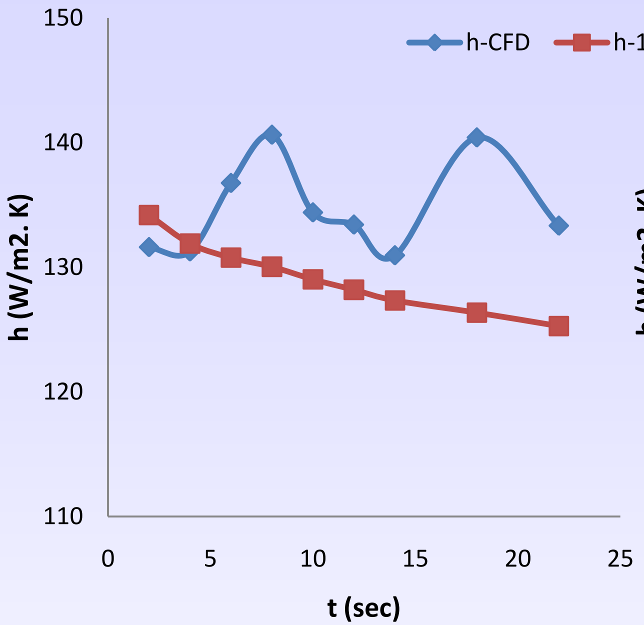
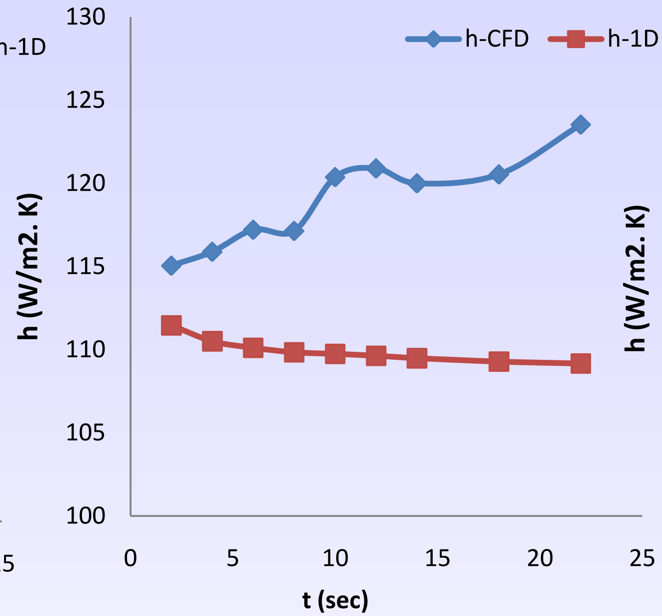
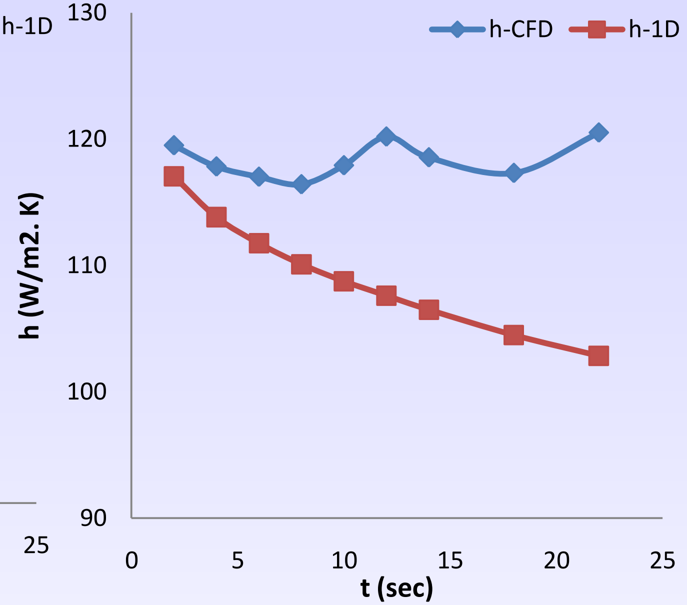
h_{CFD} vs h_{1D} @ a, a1, a2



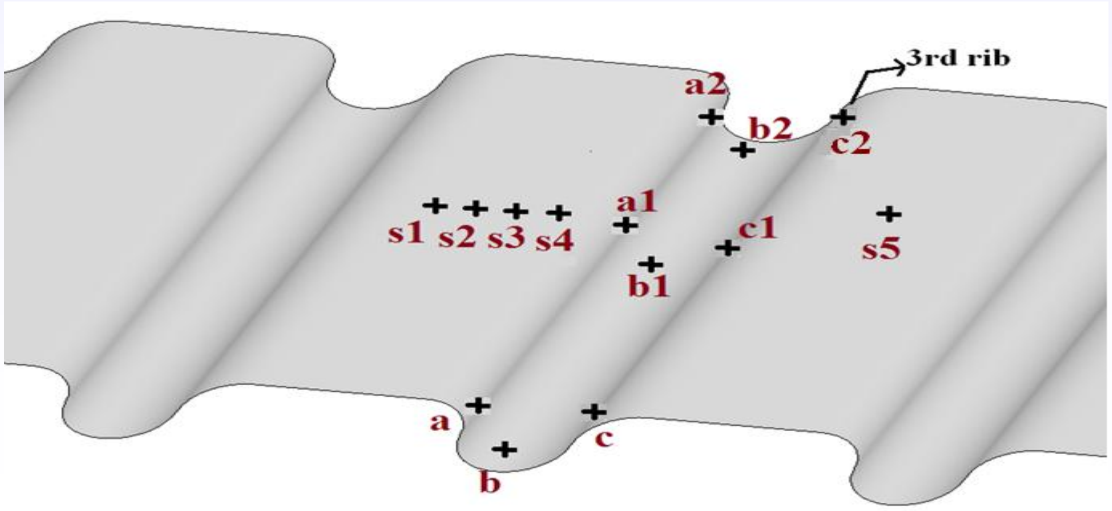
Error : 0.5 -10%



Error : 3 - 12%



Error : 2 - 15%



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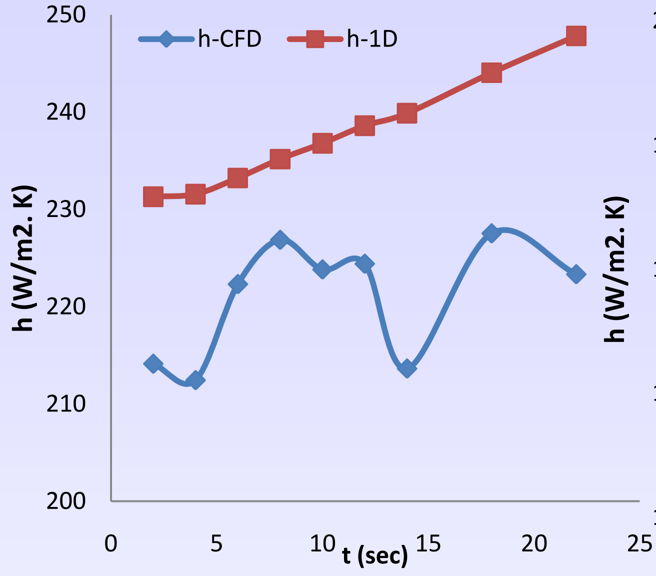
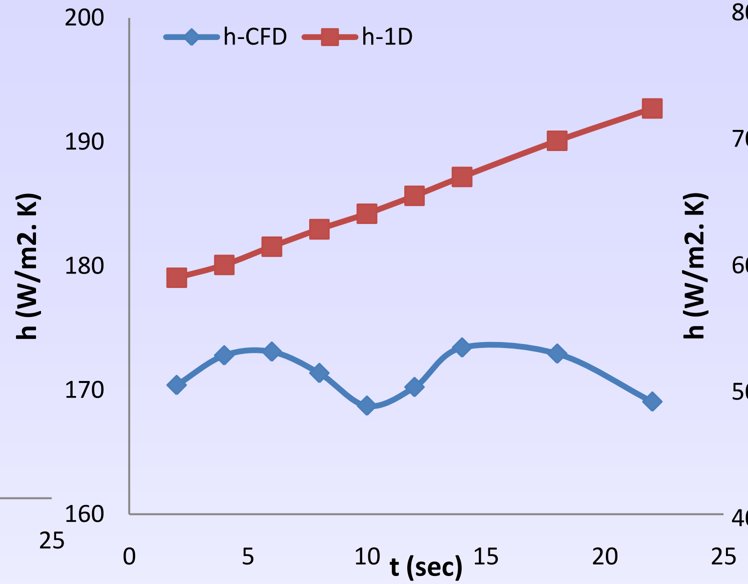
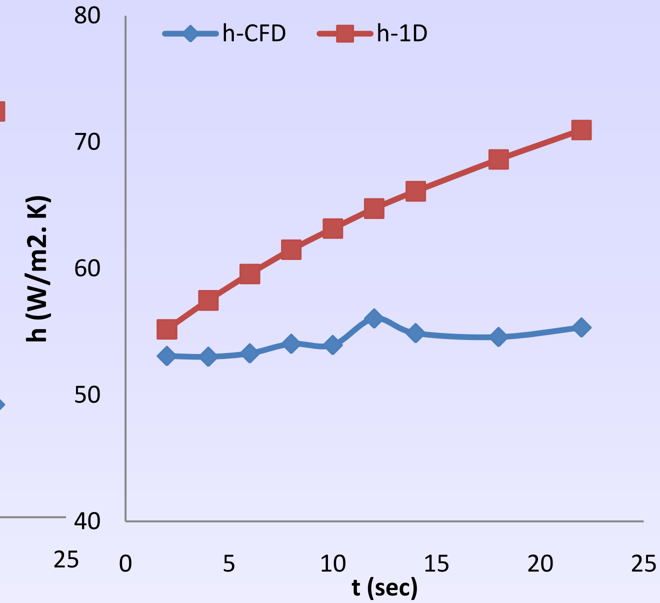
h_{CFD} vs h_{1D} @ b, b1, b2



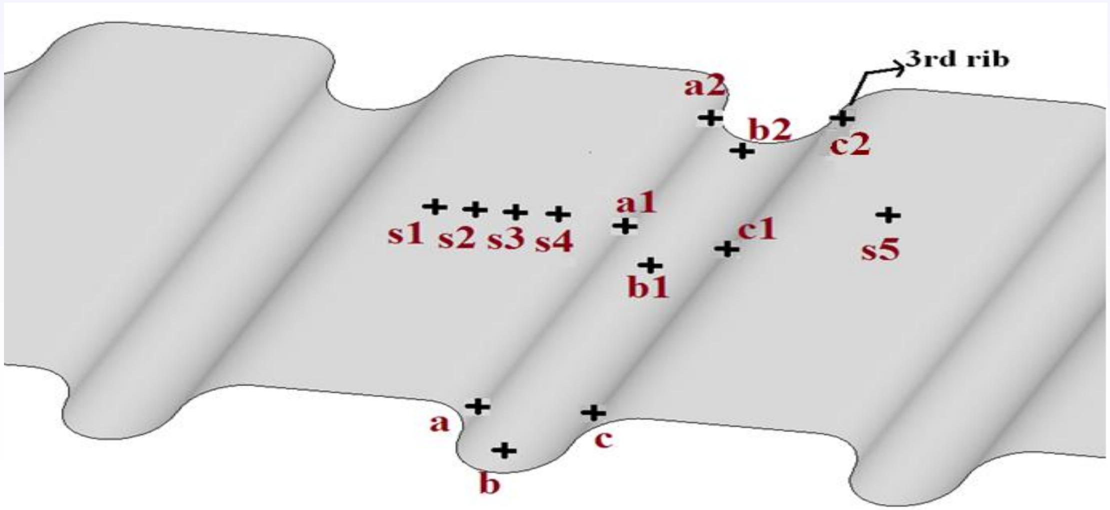




Error : 4 -12%

Error : 4 - 14%

Error : 4 - 28%



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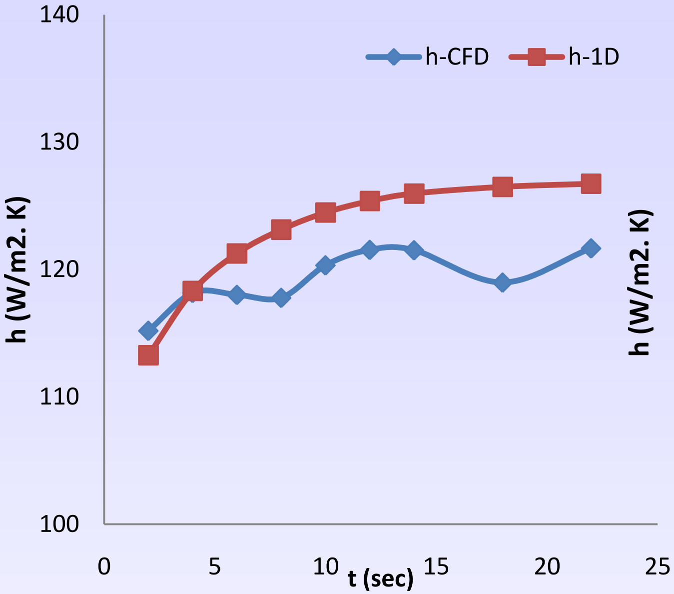
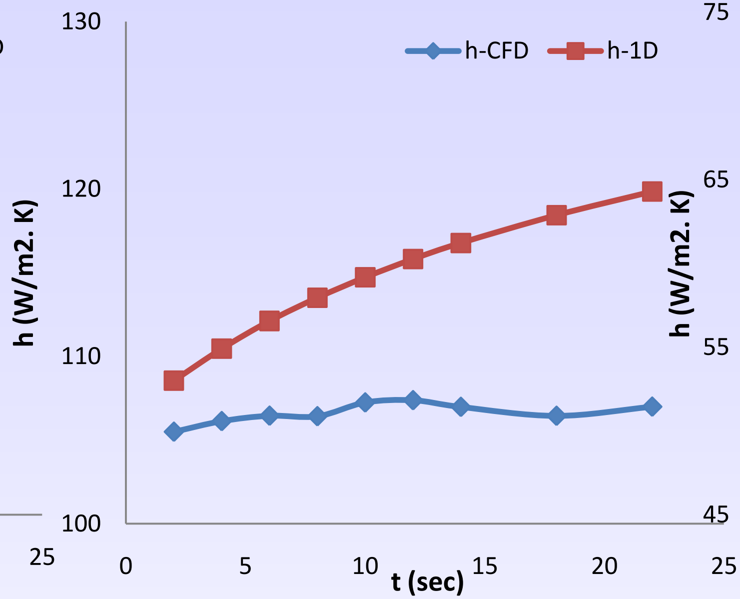
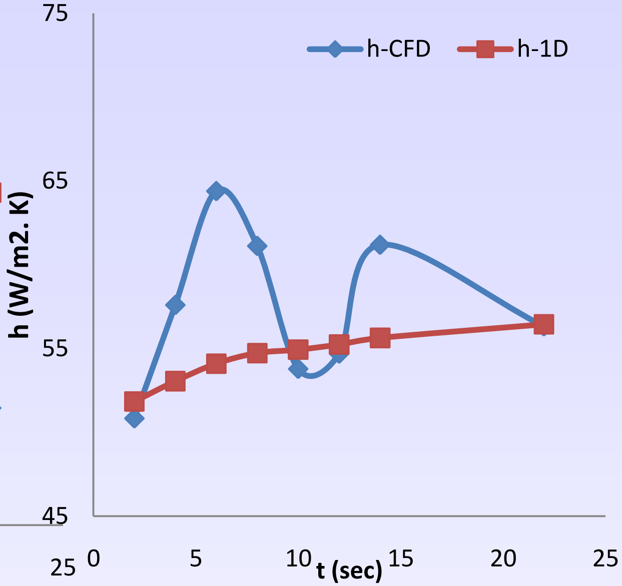
h_{CFD} vs h_{1D} @ c, c1, c2



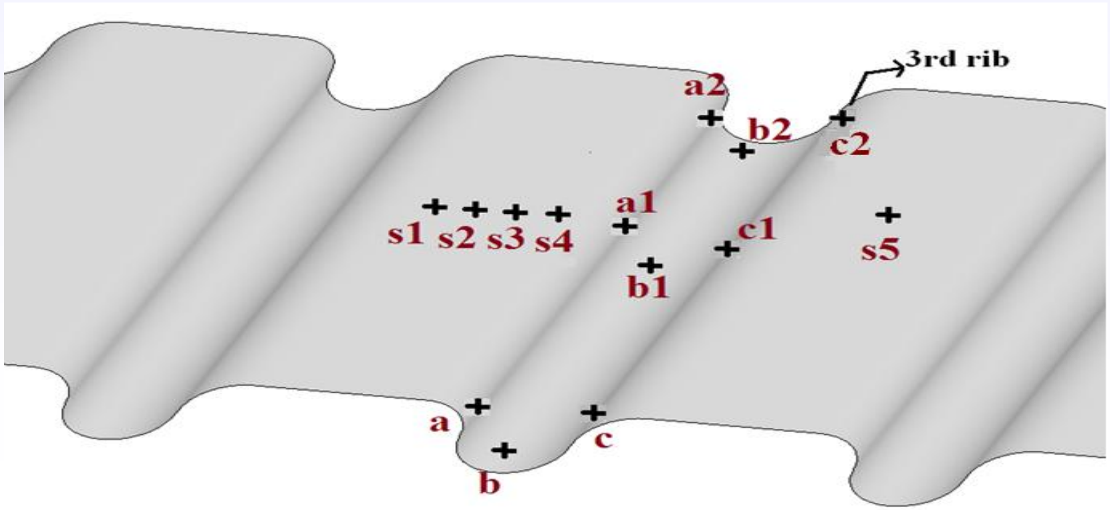




Error : 0.1 - 4%

Error : 3 -12%

Error : 0.2 -16%



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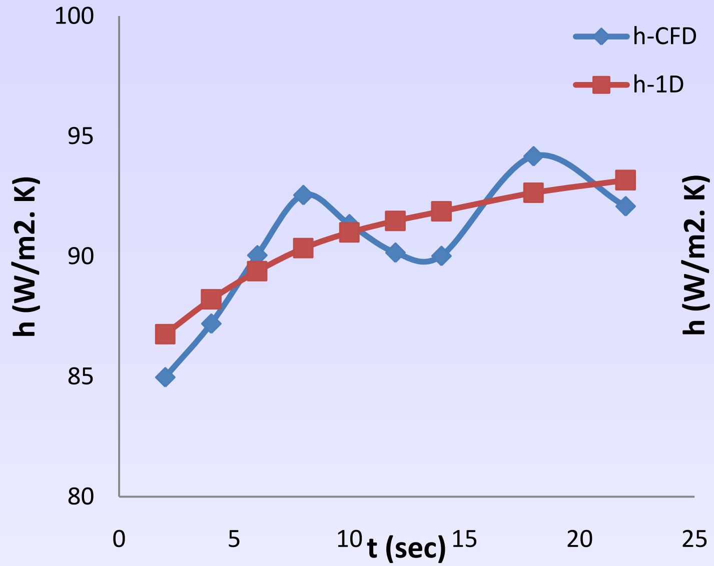
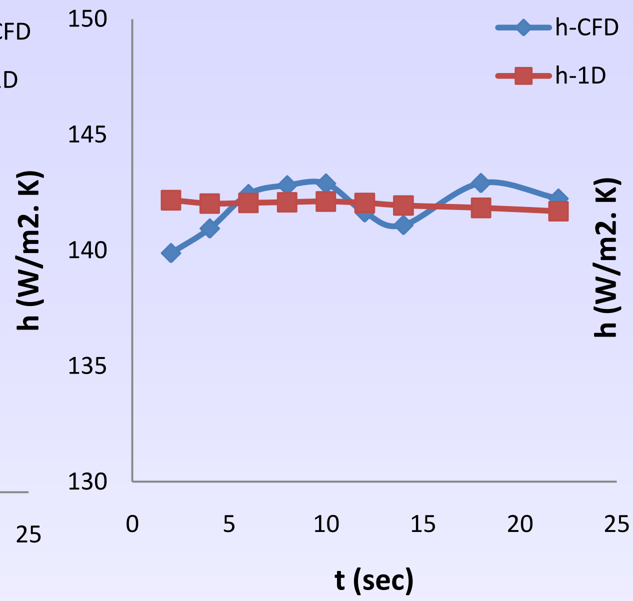
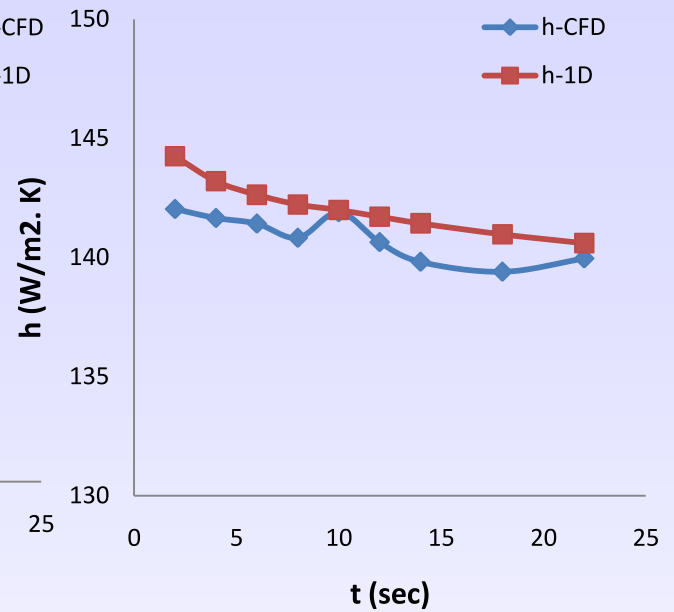
h_{CFD} vs h_{1D} @ s1, s2, s3



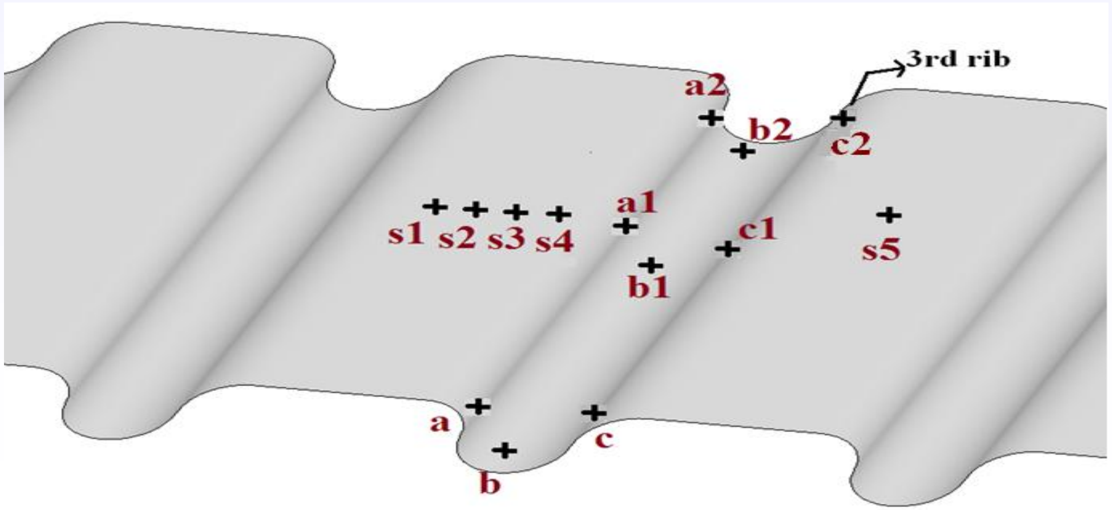
Error : 0.3 – 2.4%



Error : 0.3 – 1.6%



Error : 0.06 – 1.5%



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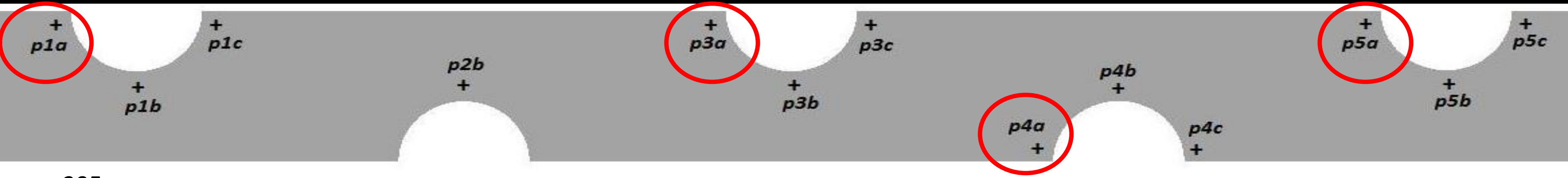
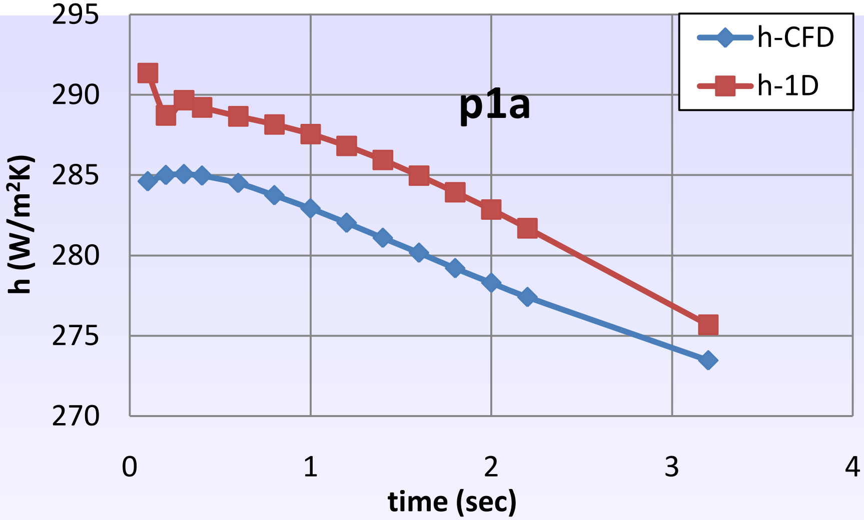
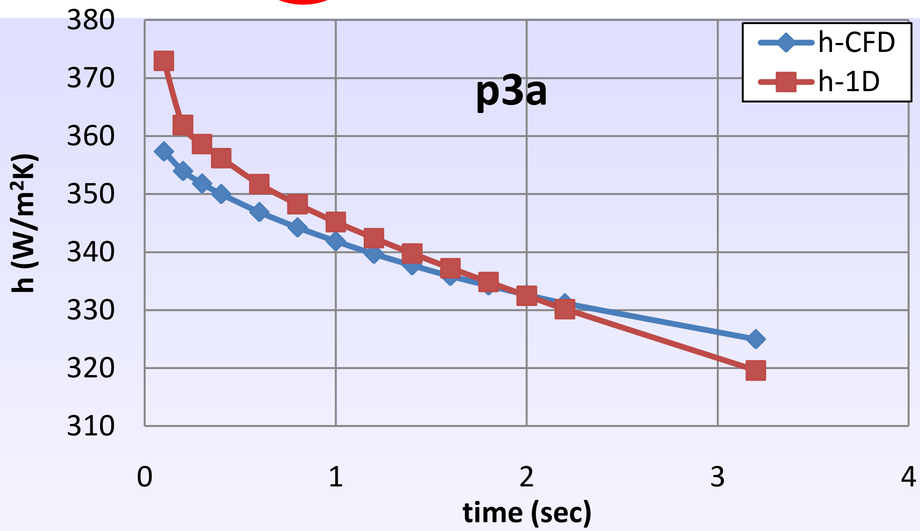
h_{CFD} vs h_{1D}



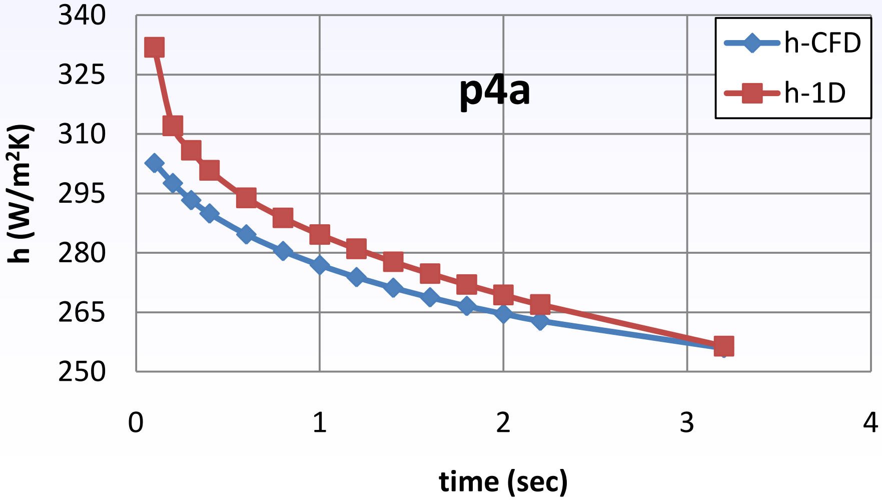
p1a
p1c
p1b
p2b
p3a
p3c
p3b
p4a
p4b
p4c
p5a
p5c
p5b



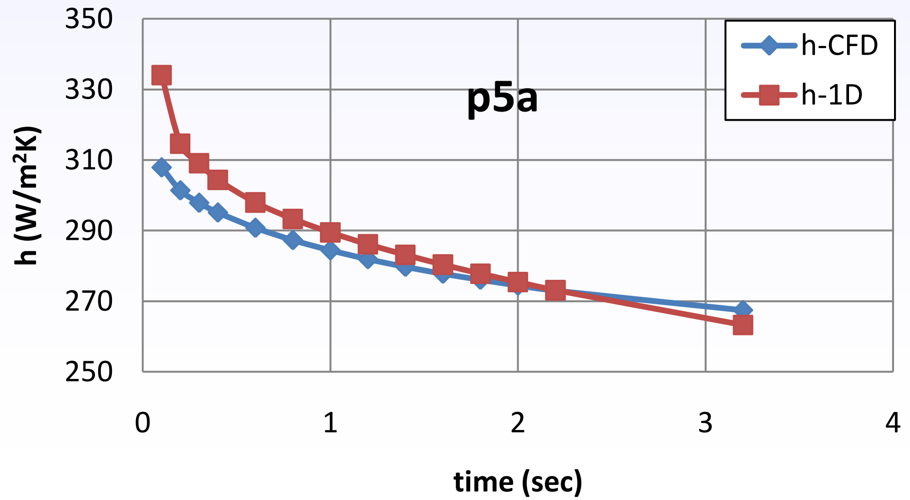
p1a
h-CFD
h-1D
h (W/m²K)
time (sec)



p3a
h-CFD
h-1D
h (W/m²K)
time (sec)

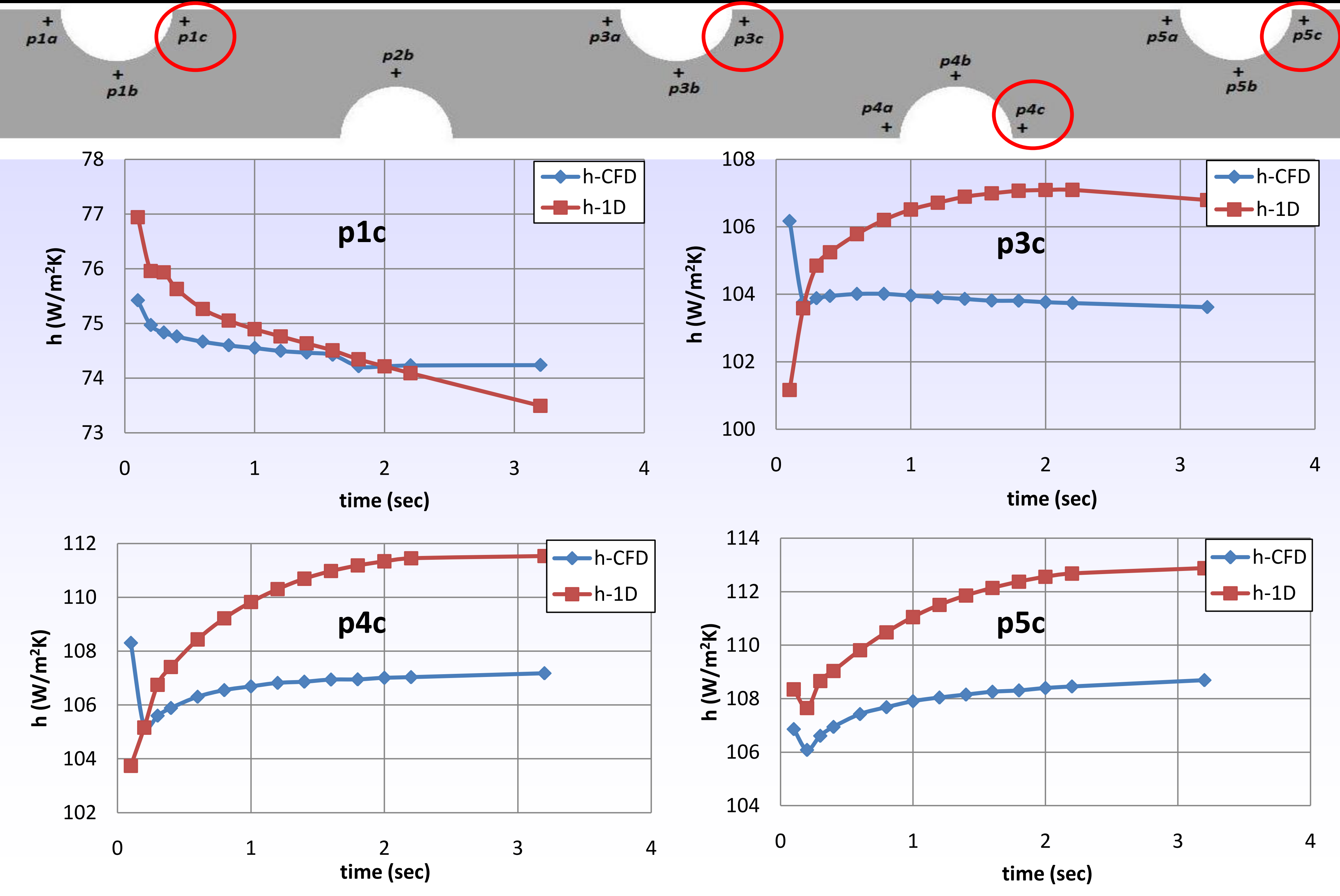


p4a
h-CFD
h-1D
h (W/m²K)
time (sec)



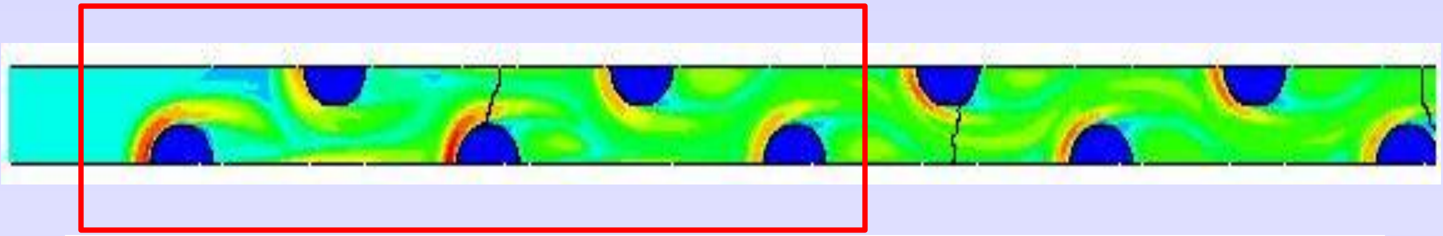
p5a
h-CFD
h-1D
h (W/m²K)
time (sec)

h_{CFD} vs h_{1D}

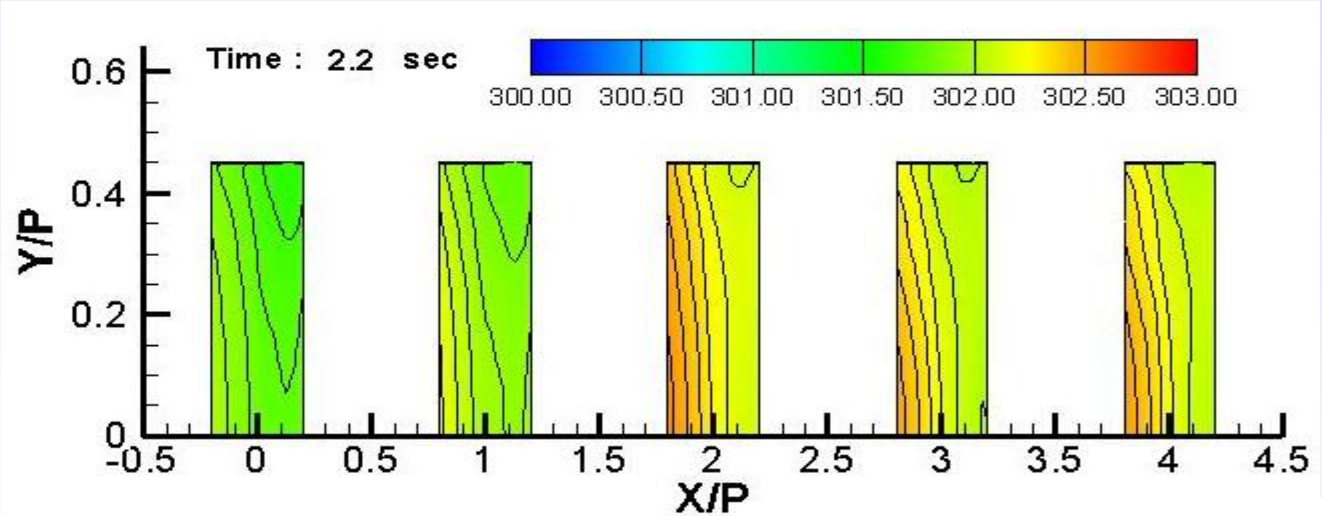


p1a
p1c
p1b
p2b
p3a
p3c
p3b
p4b
p4a
p4c
p5a
p5c
p5b
p1c
h-CFD
h-1D
h (W/m²K)
time (sec)
p3c
h-CFD
h-1D
h (W/m²K)
time (sec)
p4c
h-CFD
h-1D
h (W/m²K)
time (sec)
p5c
h-CFD
h-1D
h (W/m²K)
time (sec)

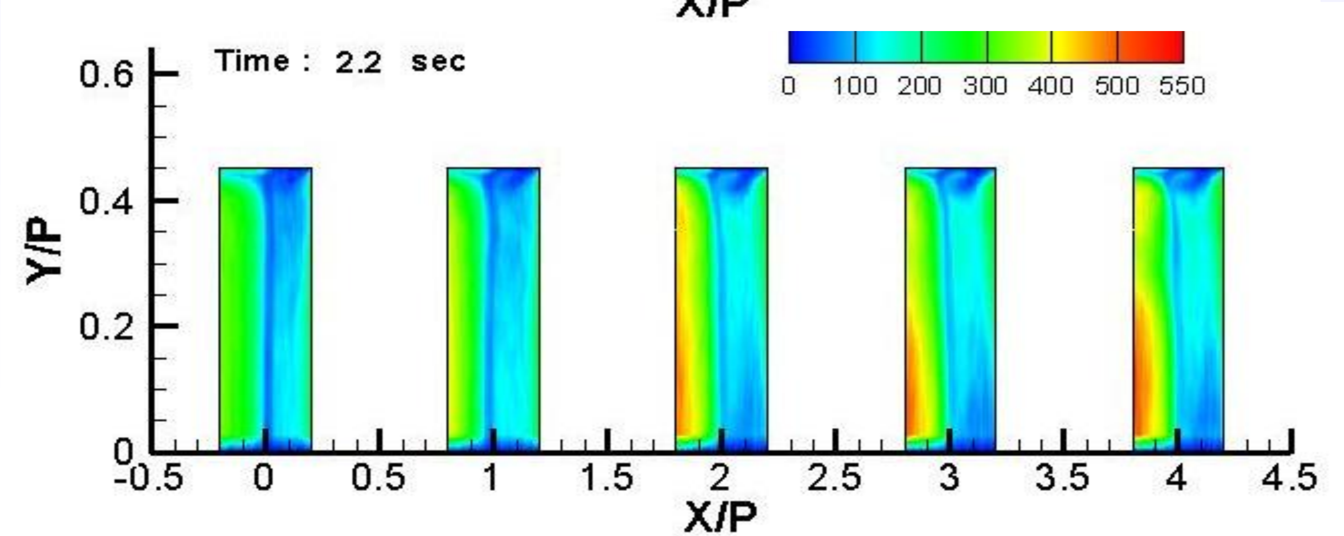
T & h on Pin Fins



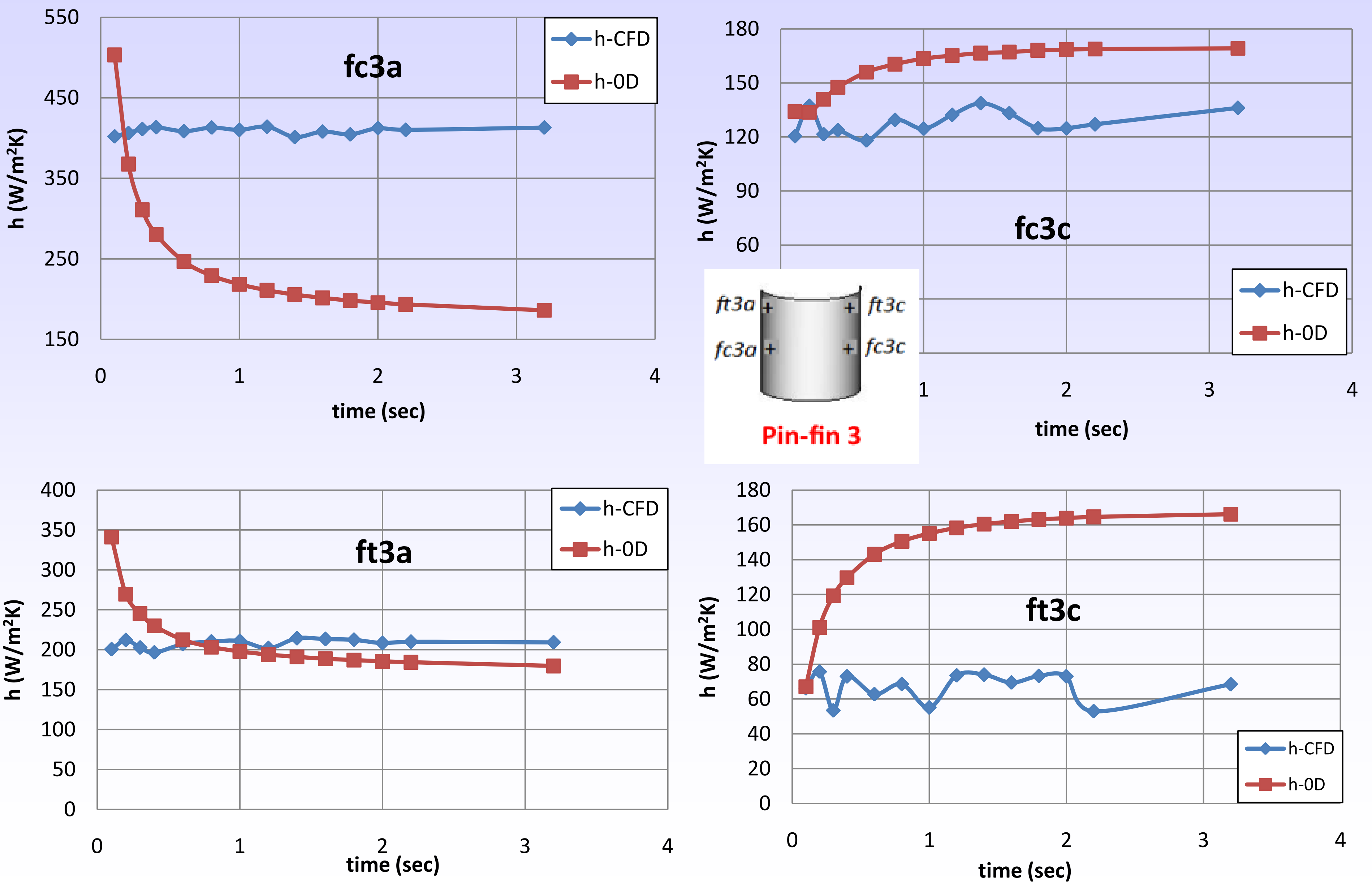
temperature



heat-transfer coefficient



h_{CFD} vs h_{1D}


fc3a
h-CFD
h-0D
h (W/m²K)
time (sec)
550
450
350
250
150
0
1
2
3
4
fc3c
180
150
120
90
60
ft3a
ft3c
fc3a
fc3c
Pin-fin 3
ft3a
400
350
300
250
200
100
50
ft3c
160
140
120
100
80
60
40
20

Outline of Talk

Verification: grid sensitivity

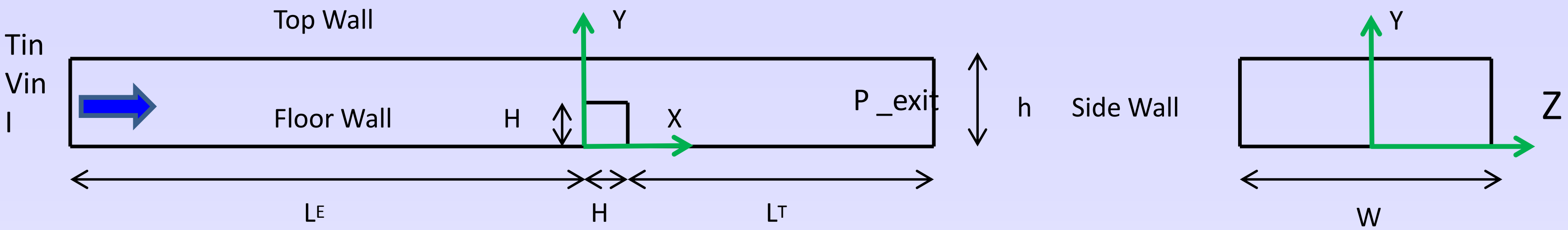
- single-grid error estimator

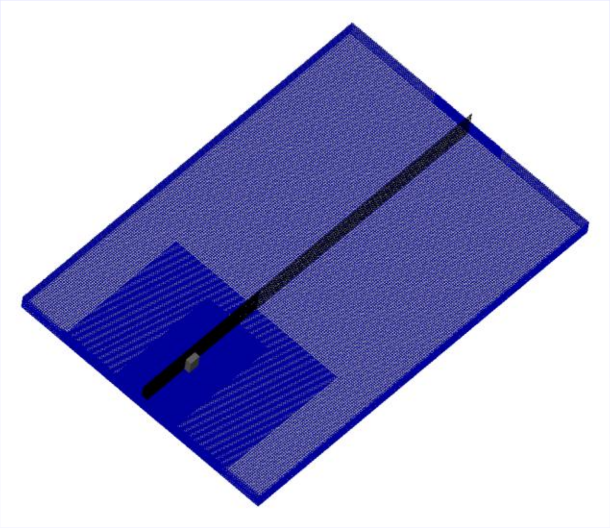
Validation: compare with experiments

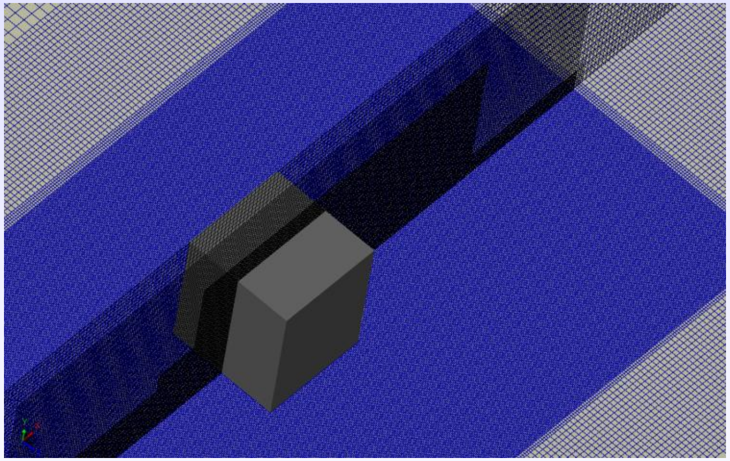
- Make it possible for CFD to solve the EFD!
- What is the bulk temperature used to compute h?
- How well is h measured by transient liquid crystal?
- **Steady & unsteady RANS vs LES**

Summary

Wall-Mounted Cube in a Channel



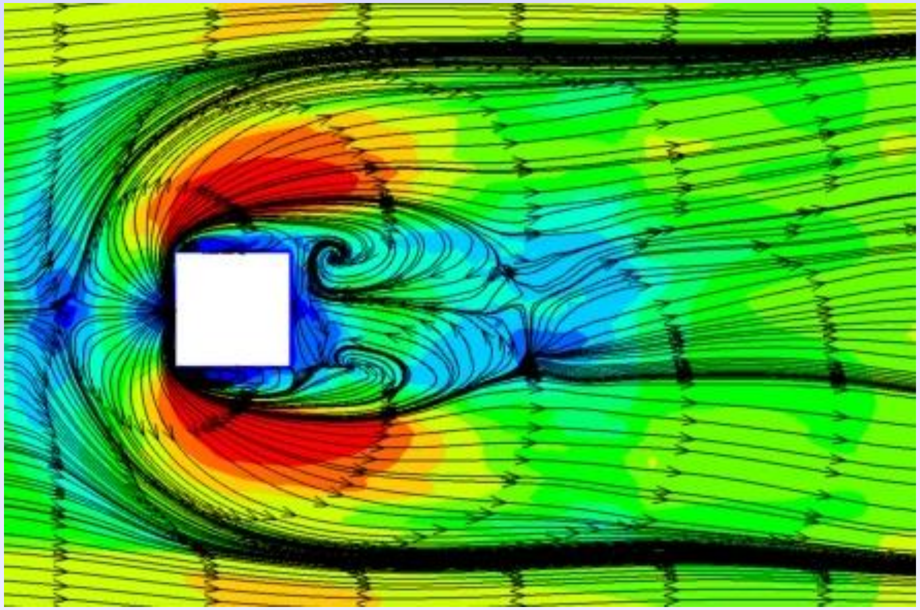




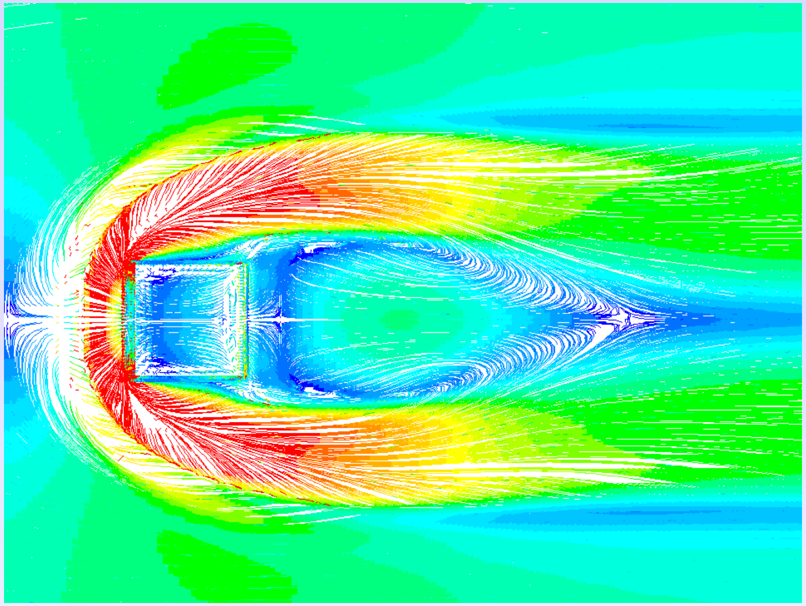
When is LES needed? Accuracy alone is not enough!

What insight will LES generate that RANS will miss?

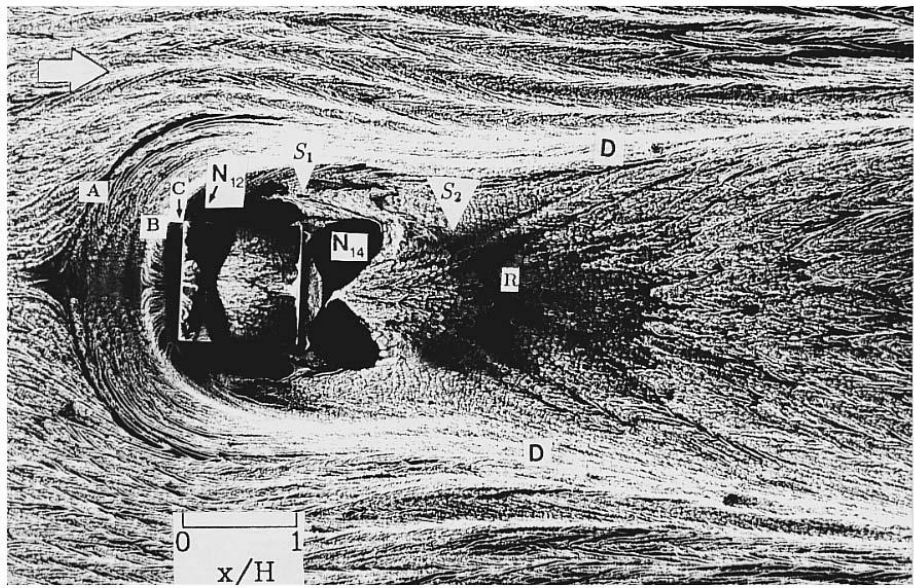
Oil Film Flow on Surface about Cube



CFD VLES: Colored by |V|

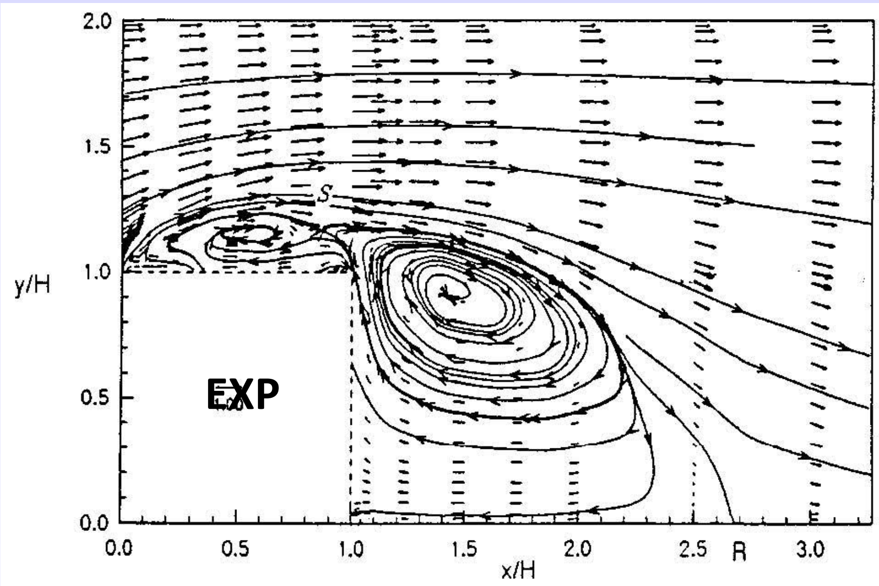


CFD SST Oil Flow; Colored by |V|

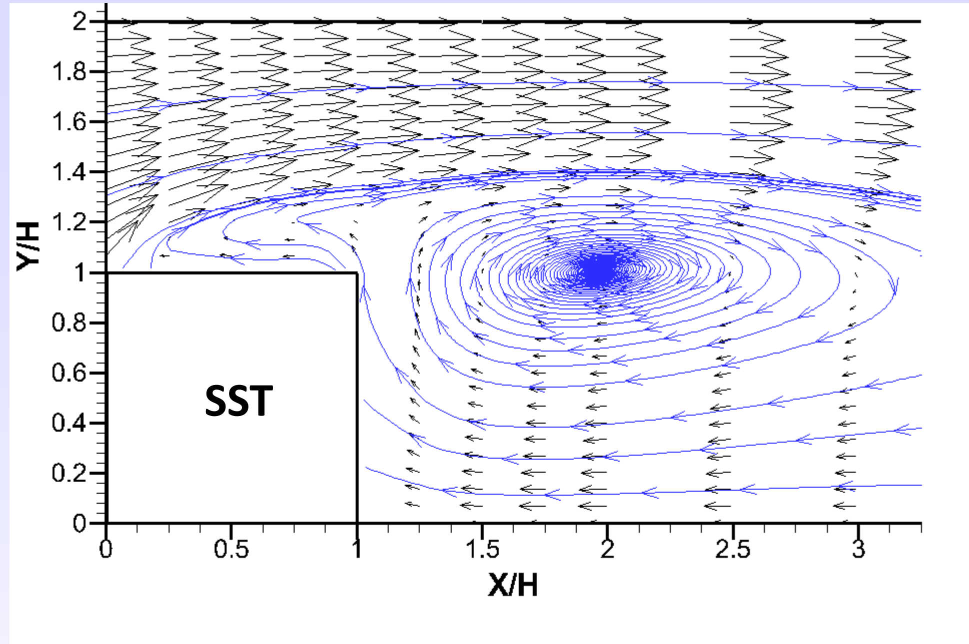


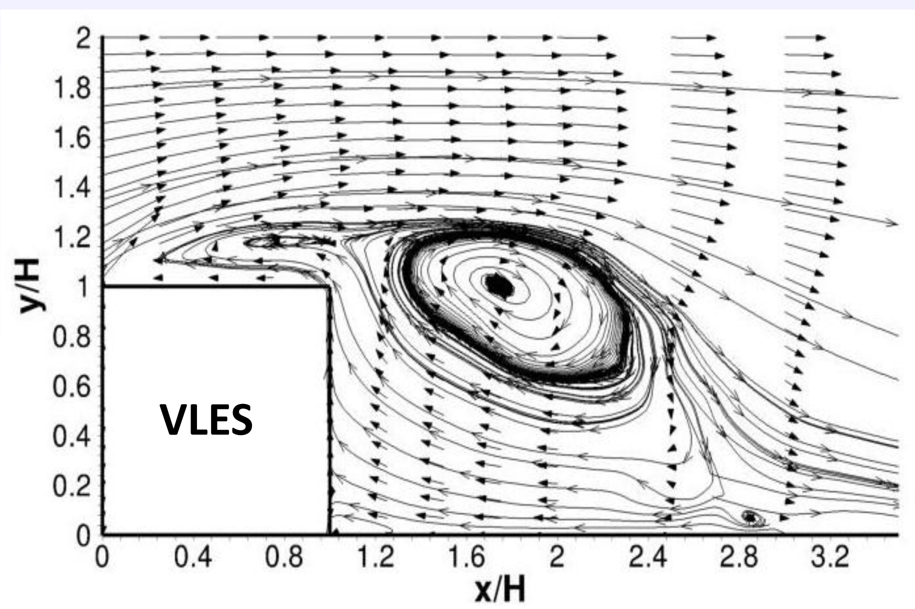
Hussein 1996   Fig 10

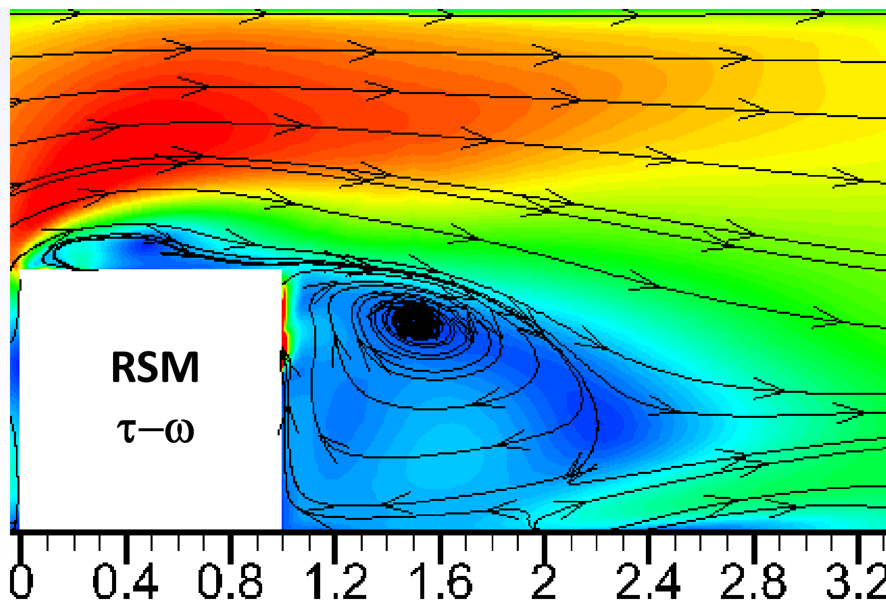
Streamline along Middle Plane



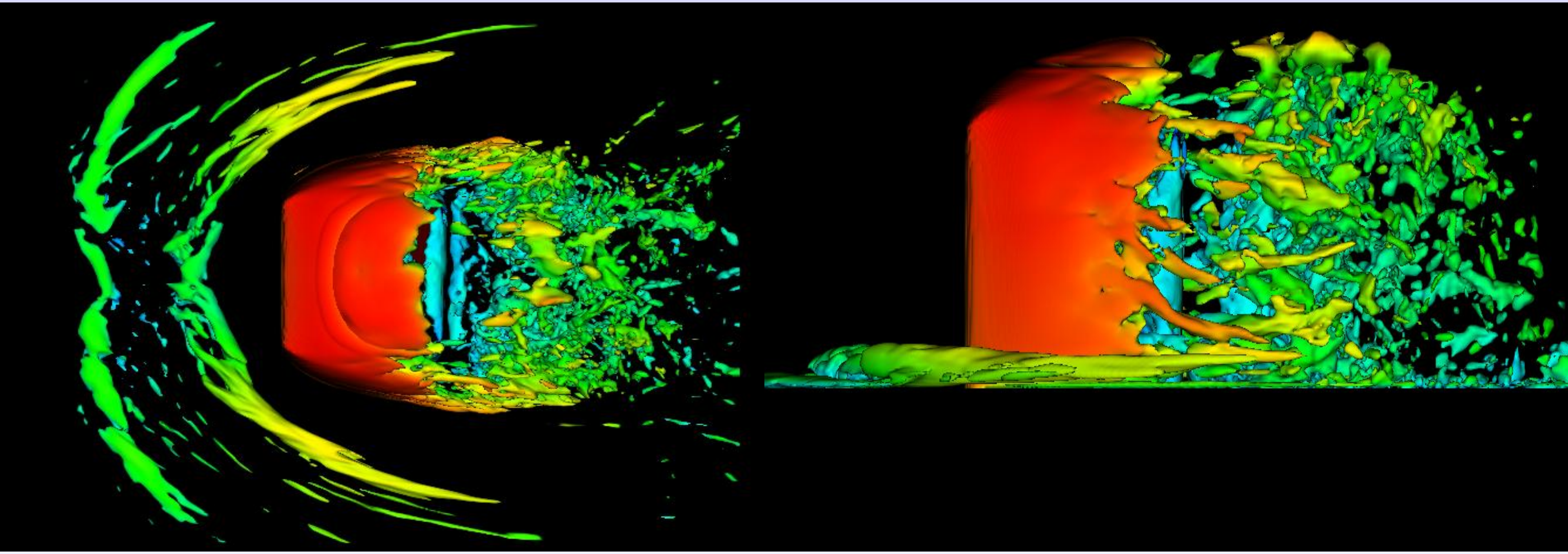
EXP: Hussein 1996 Fig 11

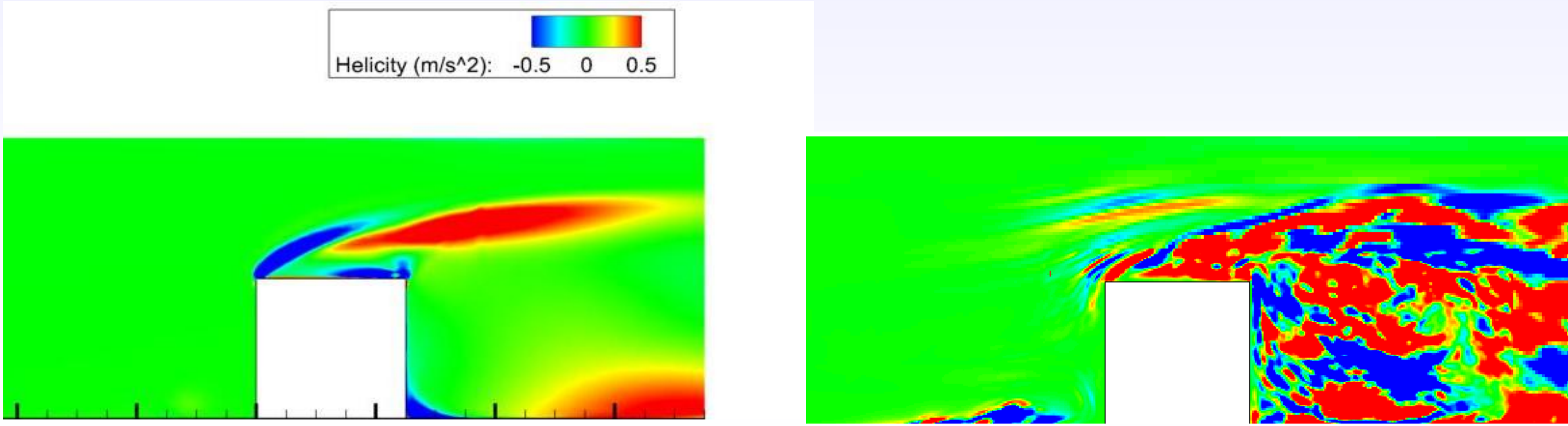




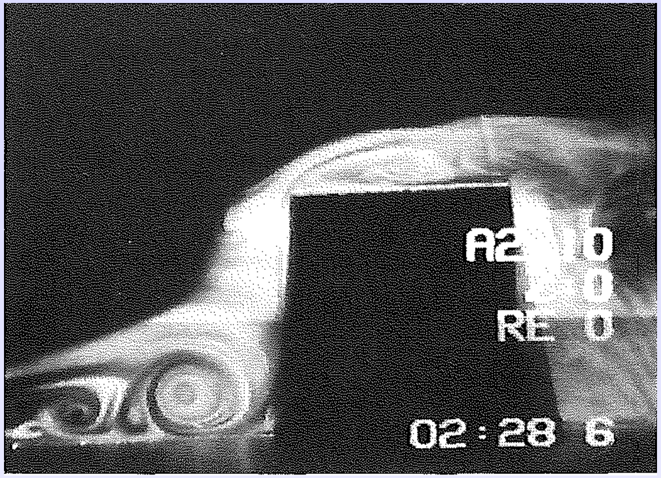


Vortical Structure: λ_2, helicity

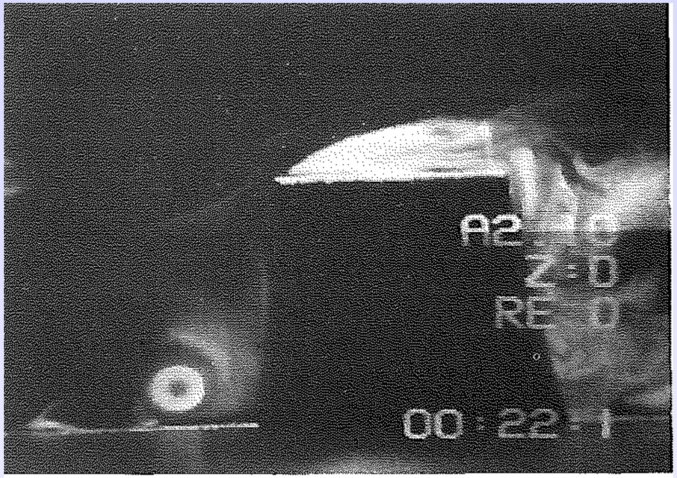




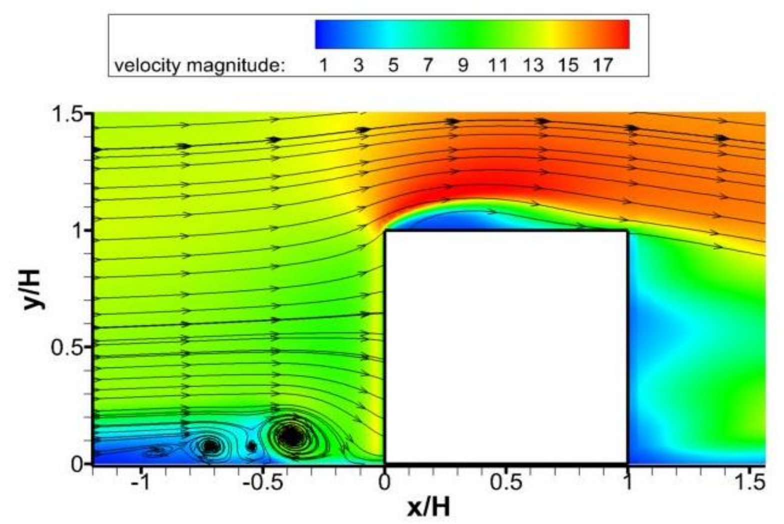
Modes of Non-Equilibrium Flow: VLES

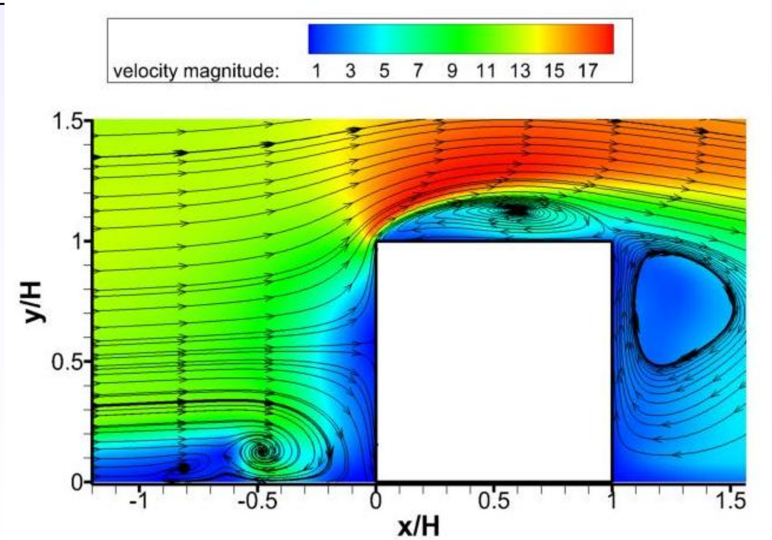


Experiment (Martinuzzi & Tropea, 1993)

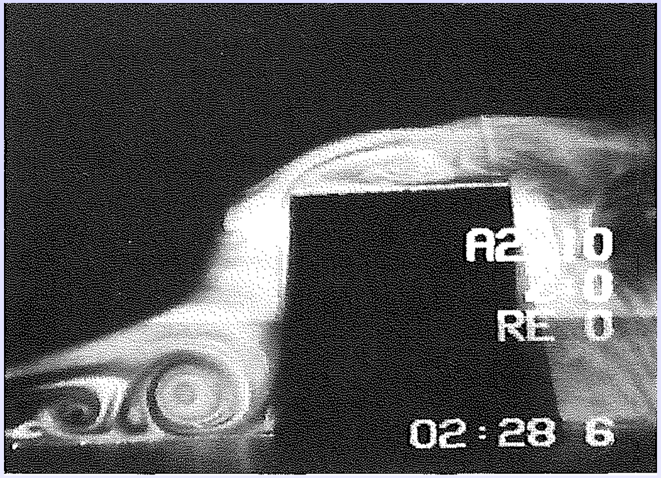


VLES (Present study)

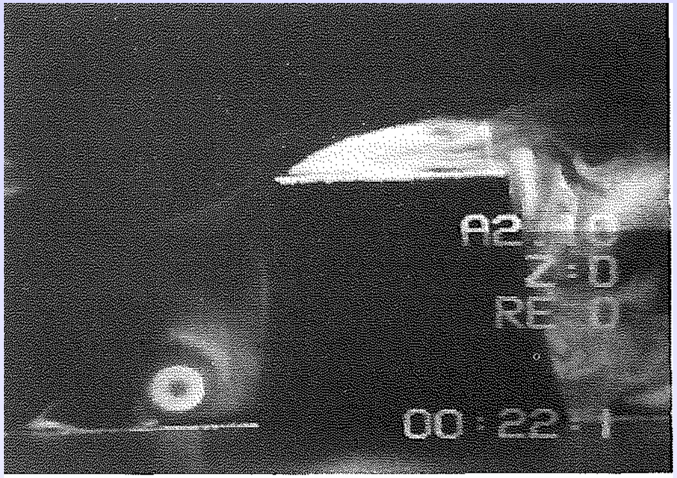


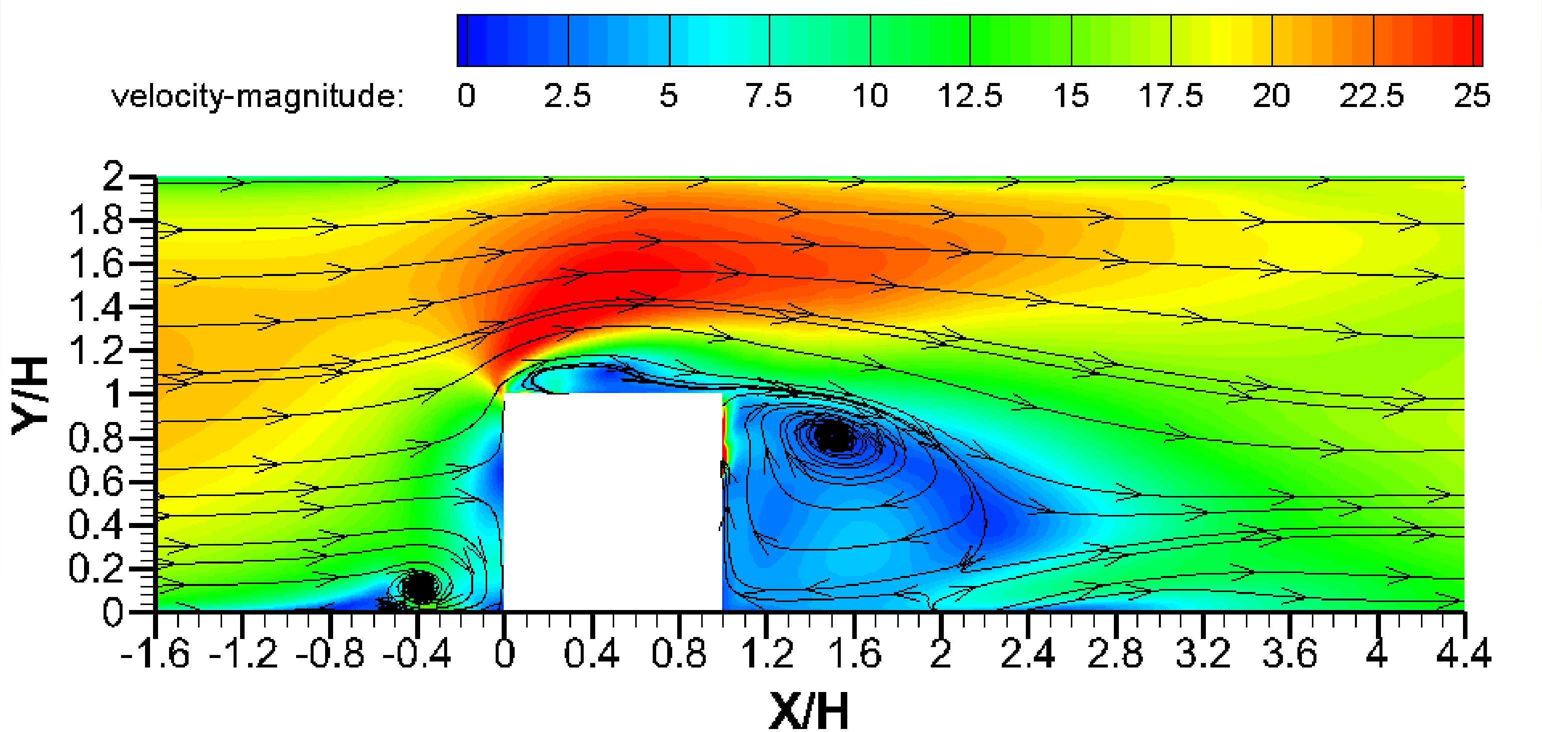


Modes of Non-Equilibrium Flow: unsteady RANS



Experiment (Martinuzzi & Tropea, 1993)





URANS (RSM-τ–ω)

Summary

A single-grid method was developed to estimate grid-induced errors in CFD solutions (verification).

Showed errors induced by approximating T_b in reporting Nu and h in experimental measurements and made recommendations.

Showed errors that can be created by transient liquid crystal measurements if 1-D theory is used.

Though less accurate then LES, steady & unsteady RANS may provide enough insight to guide and develop designs.

Thank You

Impingement Flow and Heat-Transfer of Multiple Confined Turbulent Air Jets

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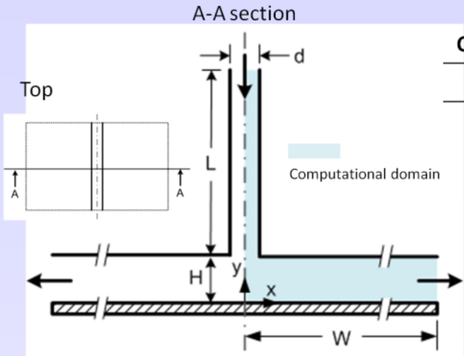
Purdue University

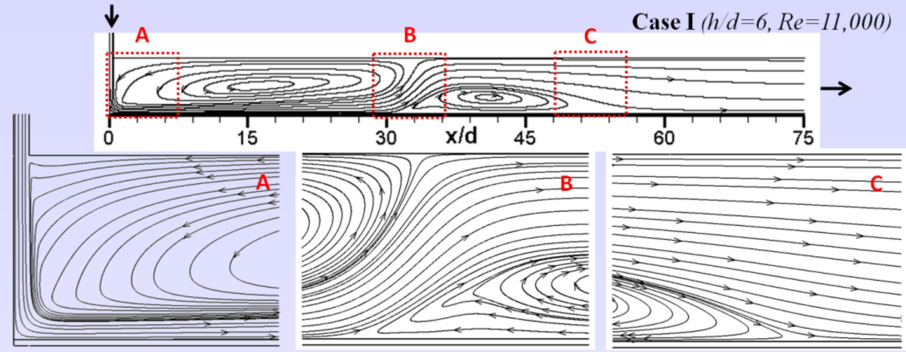
PURDUE
UNIVERSITY

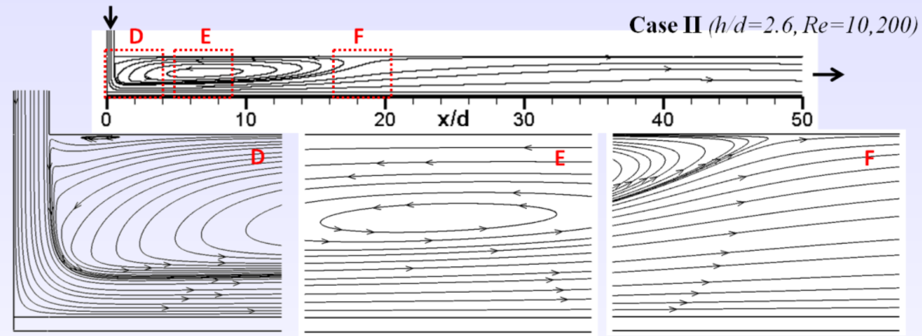
Validation of SST Model on Air Jet Impingement

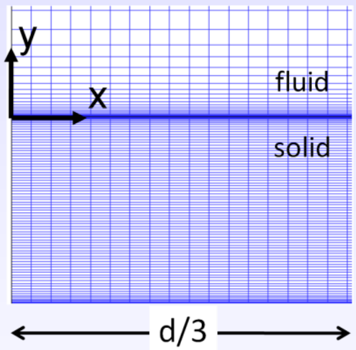


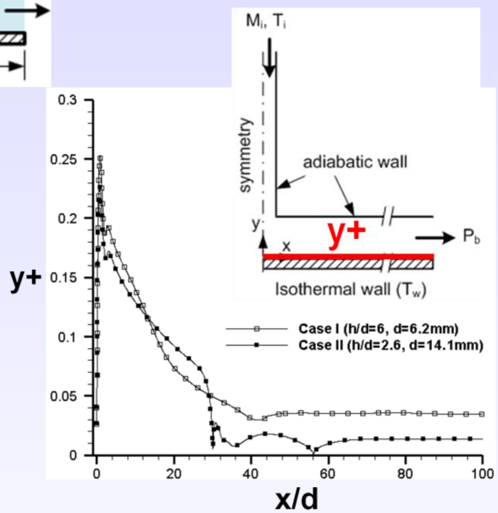
Case#	H/d	Re_d	T_i/T_w (K)
I*	6	11,000	373/338 (heating)
II**	2.6	10,200	310/348 (cooling)

* Gardon, 1966; Cadek, 1968 (d=6.2mm)
** Heiningen, 1982 (d=14.1mm)
\# L=30d, W= 100d, P_b=101,325Pa – same for all cases









Assumptions: steady state, 2-D planar, compressible flow

Formulation for Fluid Phase:

- ensemble averaged continuity, momentum, & energy closed by the SST
- Ideal gas with constant viscosity

Formulation for Solid Phase:

- energy equation (Fourier law with constant k)

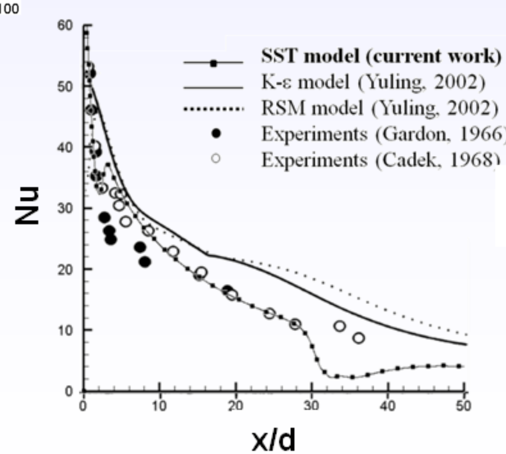
Code: ANSYS Fluent Ver. 12.1 – double precision

Algorithm: conjugate

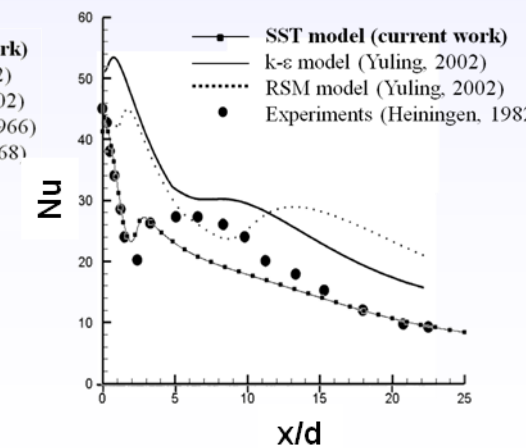
- fluid phase: SIMPLE with 2nd-order upwind for advection terms, pressure eq.
- solid phase: implicit with 2nd-order upwind

Convergence Criteria:

- compute until all residual plateaus
(for continuity < 10^{-7}, momentum < 10^{-6}, energy < 10^{-12}, and k & ω < 10^{-5})

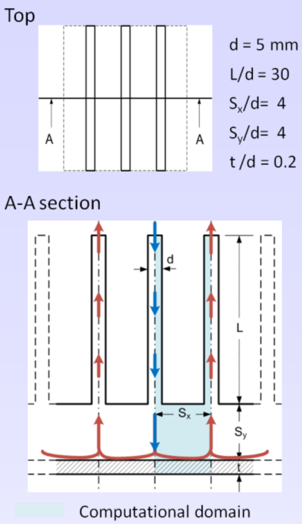


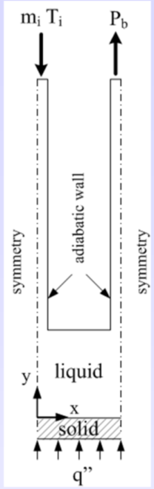
Case I (*h/d=6, d=6.2mm, Red=11,000*)



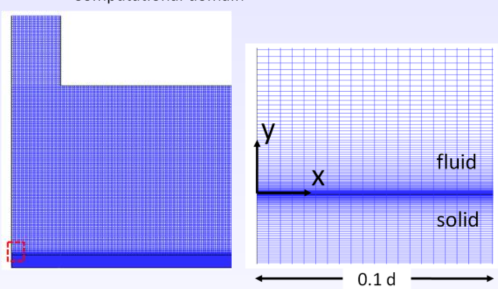
Case II (*h/d=2.6, d=14.1mm, Re_d=10,200*)

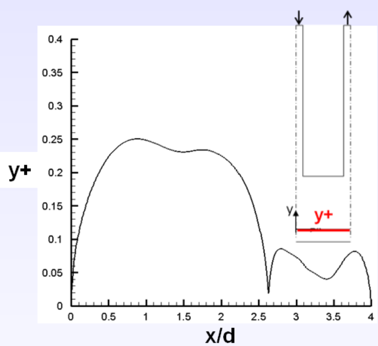
Effects of Sudden Change in Heat Flux for Transient Jet Impingement



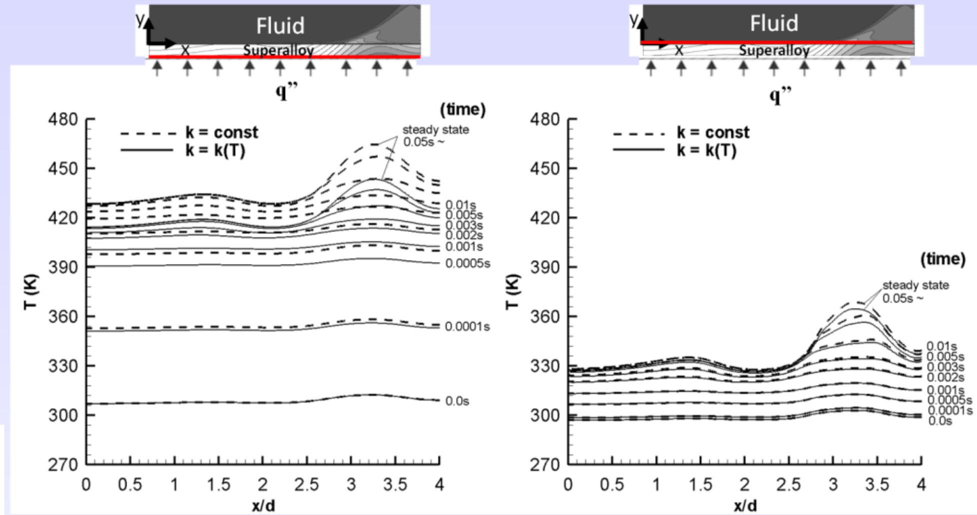


- **Solid:**
  SuperAlloy - k = f(T)
- **Fluid:**
  Water - ρ = 998.2 Kg/m^3
  - μ = f (T)
- **Inlet:**
  - m_i = 11.48 kg/s (Re_d = 23,000)
  - Turb. intensity: TI = 4.58%
  - Turb. length scale : l = 0.00035
  - T_i = 293 K
- **Outlet:**
  - P_b = 101,325 Pa
- **Heat flux:**
  - q'' = 10 -> 100 W/cm^2

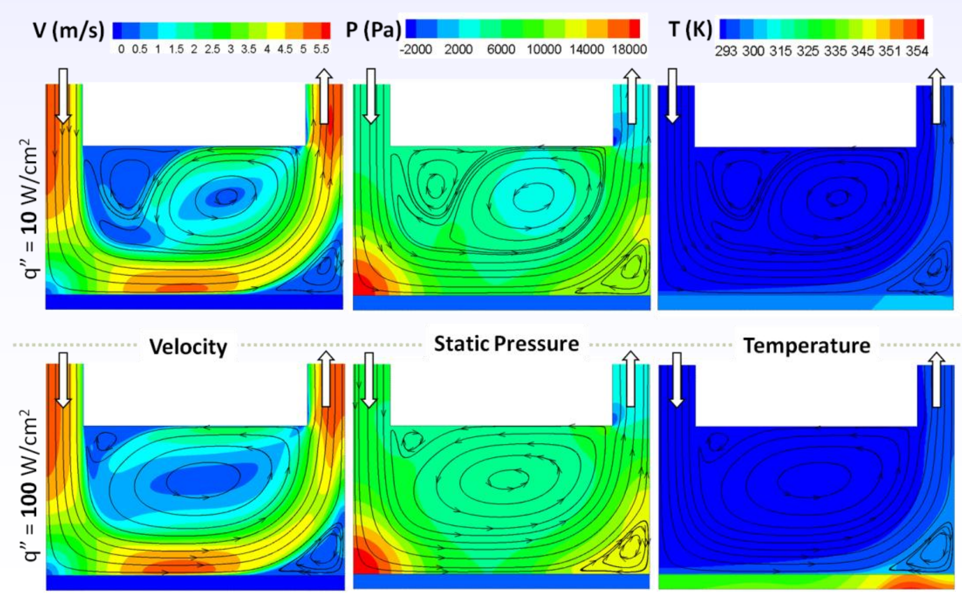




Effect of thermal conductivity: k=k(T)



Velocity Magnitude, Static Pressure, & Temperature



Assumptions: transient, 2-D planar, incompressible flow, constant specific heats

Formulation for Fluid Phase:
- ensemble averaged continuity, momentum, & energy closed by the SST turb. Model
- $\mu = \mu(T)$, k = k(T)

NOTE: for incompressible flow N-S is coupled to energy only through μ!

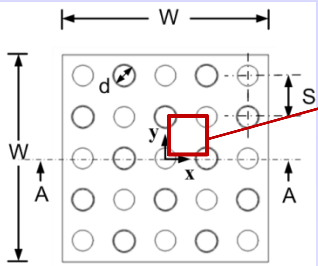
Formulation for Solid Phase:
- energy equation (Fourier law with k = k(T), $C_p = C_p(T)$)

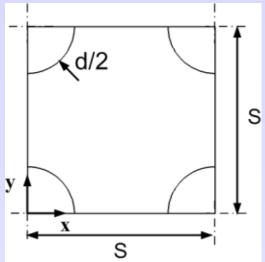
Code: ANSYS Fluent Ver. 12.1 – double precision

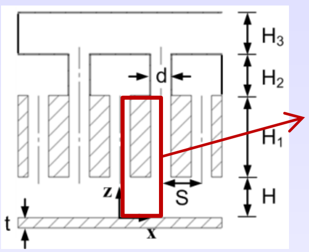
Algorithm: 2nd-order accurate in time for unsteady simulations
- fluid phase: SIMPLE with 2nd-order upwind for advection terms, pressure eq.
- solid phase: implicit with 2nd-order central

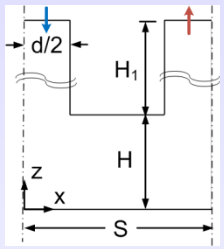
Convergence Criteria for Unsteady Solutions:
- Transient: iterate until converged at each time step –
  normalized residual at the end of each time step
  for continuity < 10^{-5}, momentum < 10^{-6}, energy < 10^{-10}, and k & ω < 10^{-5}

Effects of Jet Placements
(Distance from Jet Opening to Wall – H/d ; Spacing between Jets – S/d)





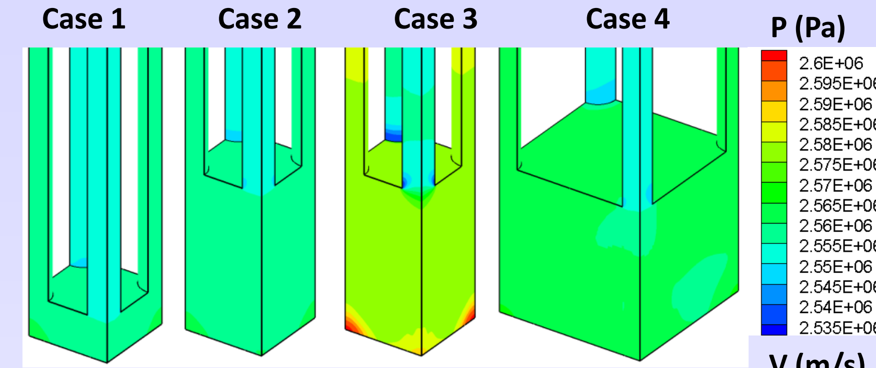


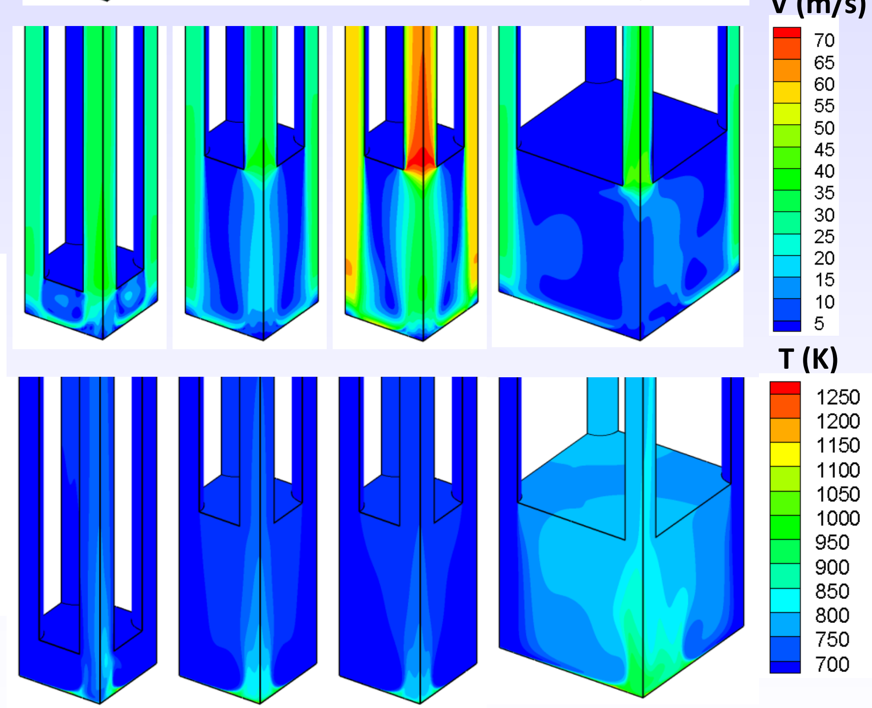


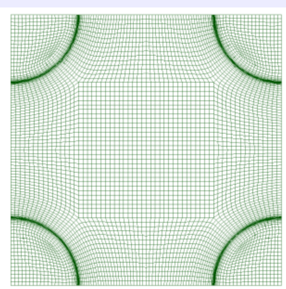
Case	H/d	S/d	Re_d
1	1	2	10,000
2	4	2	10,000
3	4	2	20,000
4	4	4	10,000

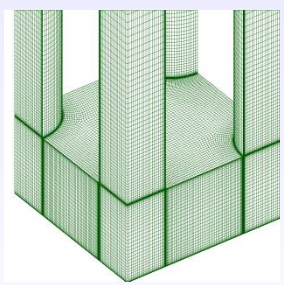
d = 1 mm, H_1/d = 10

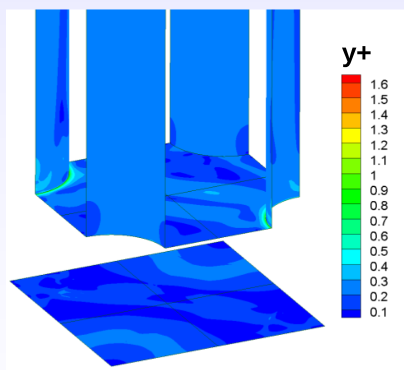
- Fluid:
  Air - $\rho = \rho\,(P, T)$, $\mu = \mu\,(T)$,
  $k = k(T)$, $C_p = C_p(T)$
- Inlet:
  Re_d = 10,000, **20,000**, 30,000
  at **T_i = 673 K (400 C)**
  m_i = 1.3076 x 10^{-4} kg/m^3
  V_i = 50.44 m/s
  TI = 5 %
- Outlet: **P_b = 370 psi (2551060 Pa)**
- Wall: **T_w = 1273 K (1000 C)**











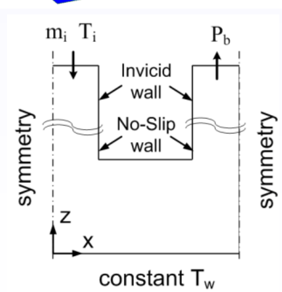
Assumptions: steady, 3-D, compressible flow

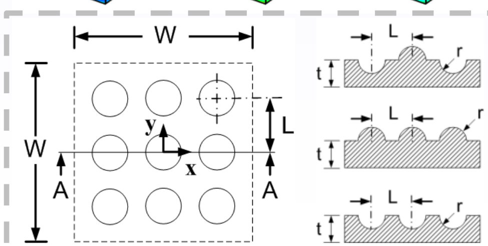
Formulation for Fluid Phase: perfect gas law
- ensemble averaged continuity, momentum, & energy
- SST and stress-omega full Reynolds stress model
- temperature dependent properties: $\mu = \mu(T)$, $k = k(T)$

Code: ANSYS Fluent Ver. 13.0 – double precision

Algorithm:
- SIMPLE with 3rd-order upwind for advection terms, 2nd-order for pressure eq.

Convergence Criteria:
- compute until all residual plateaus (for continuity < 10^{-5}, momentum < 10^{-5}, energy < 10^{-7}, and k & ω < 10^{-5})





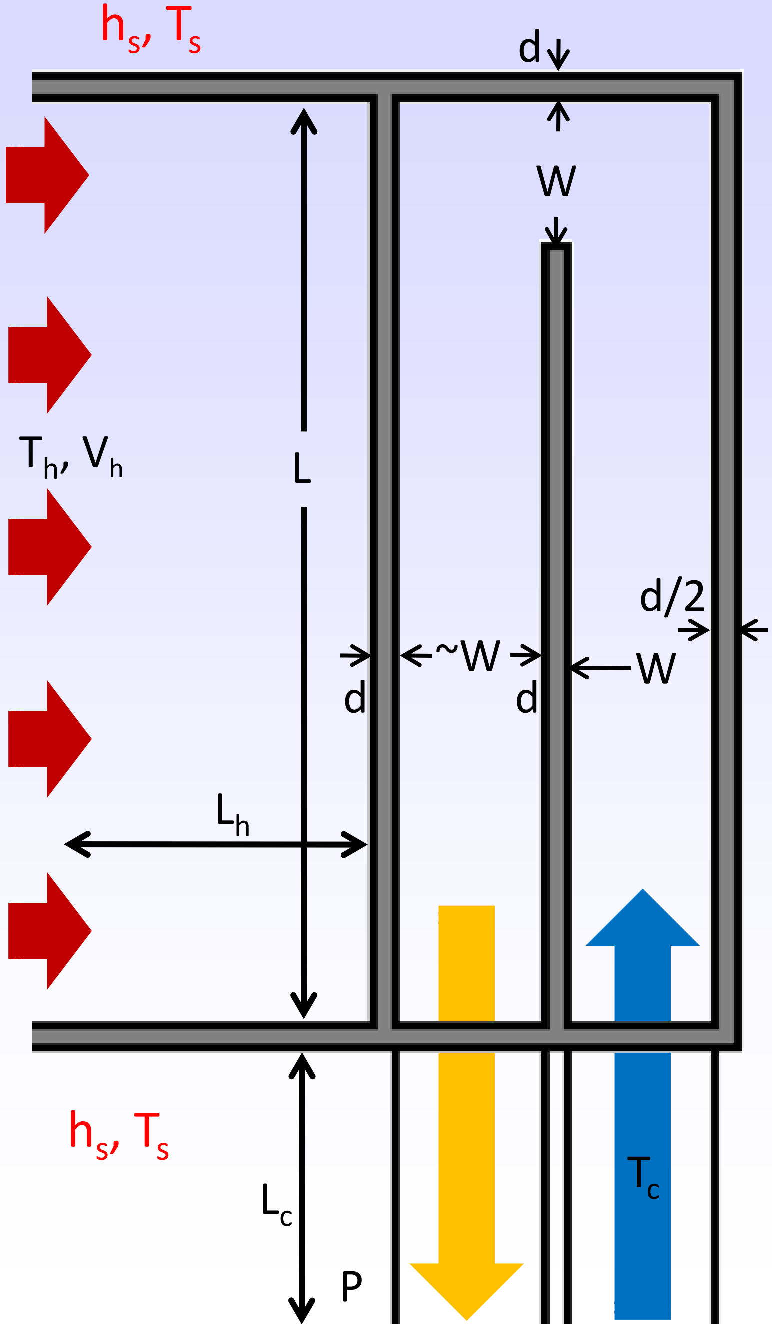
surface roughness to be studied…

Flow & Heat Transfer about Leading Edge and Endwall

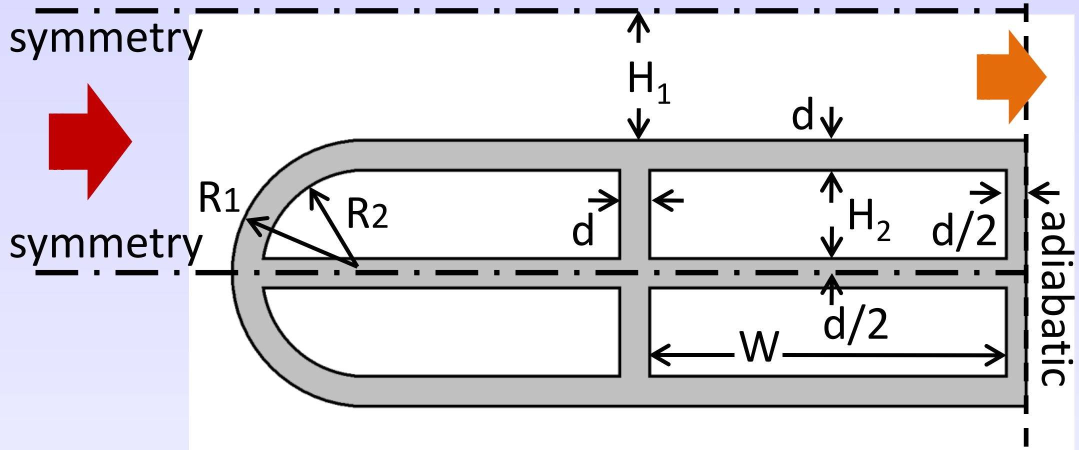
Kenny Hu and T. I-P. Shih
School of Aeronautics and Astronautics
Purdue University

PURDUE
UNIVERSITY

Problem Description



(Unit: mm)



Only half of the domain is simulated.

$d = 5$	$R_1 = 22.5$	$L = 380$
$H_1 = 22.5$	$R_2 = 17.5$	$L_h = 280$
$H_2 = 15$	$W = 60$	$L_c = 480$

Hot Gas at inflow boundary:

- T_h = 1,773 K, V_h = 10 m/s

Coolant at inflow boundary:

- T_c = 623 K, V_c = 13.87 m/s

Seal:

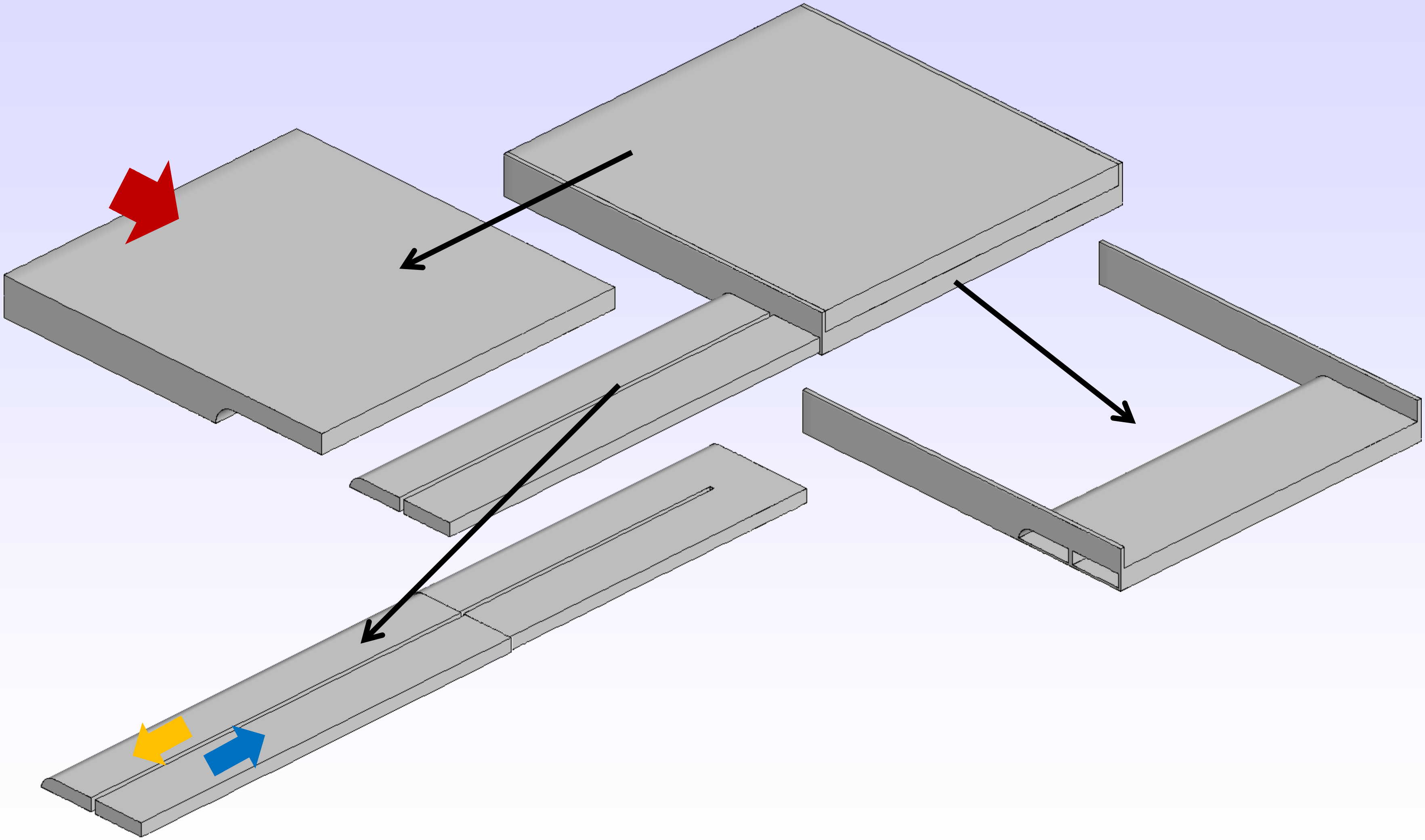
- T_s = 623 K, h_s = 1,000 W/m^2-K

$D_h = 24$, $Re_{D_h} = \cong 150{,}000$

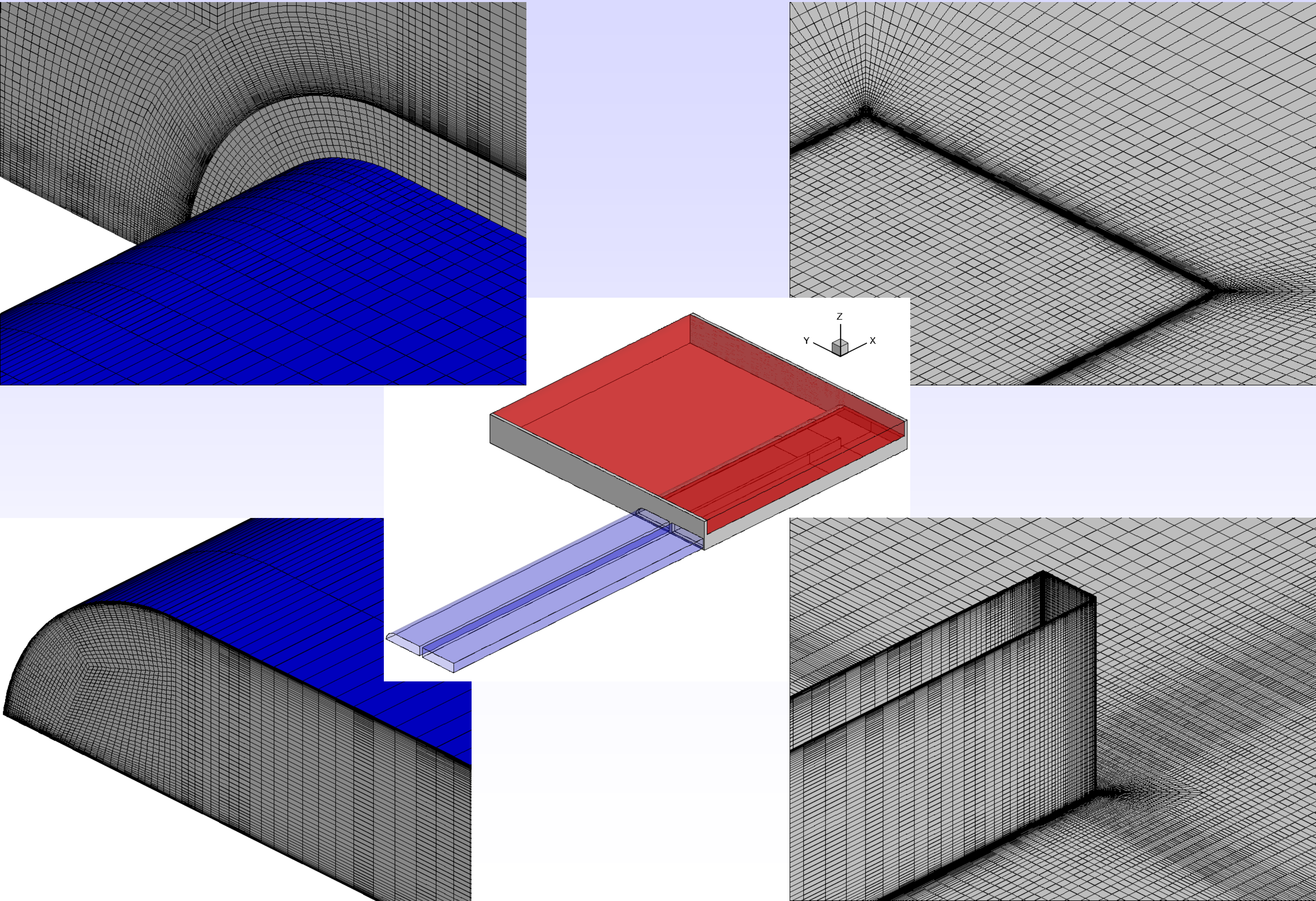
Super alloy (Ti):

- ρ = 4,850 kg/m^3
- C_p = 544.25 J/kg-K
- k = 7.44 W/m-K

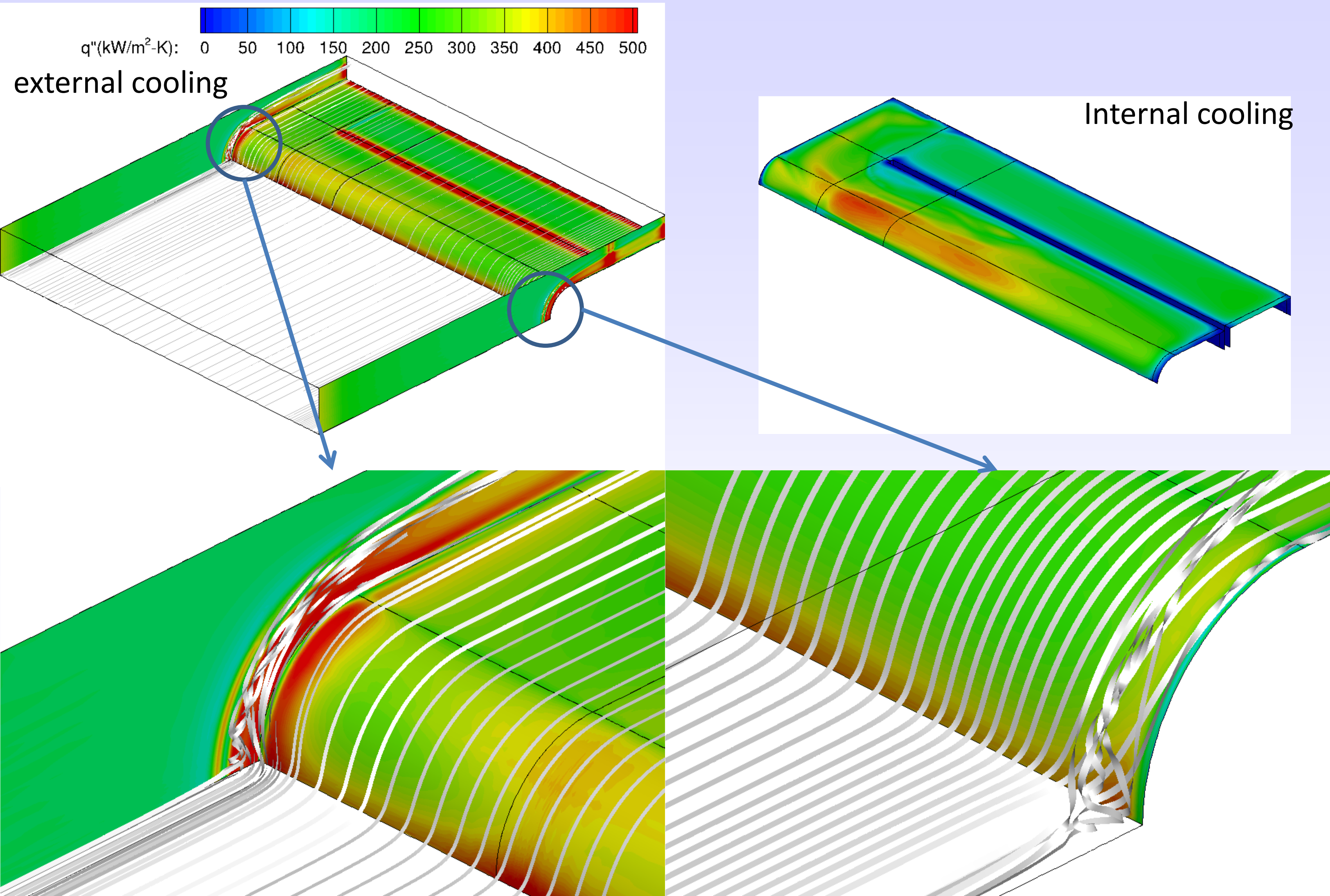
Problem Description



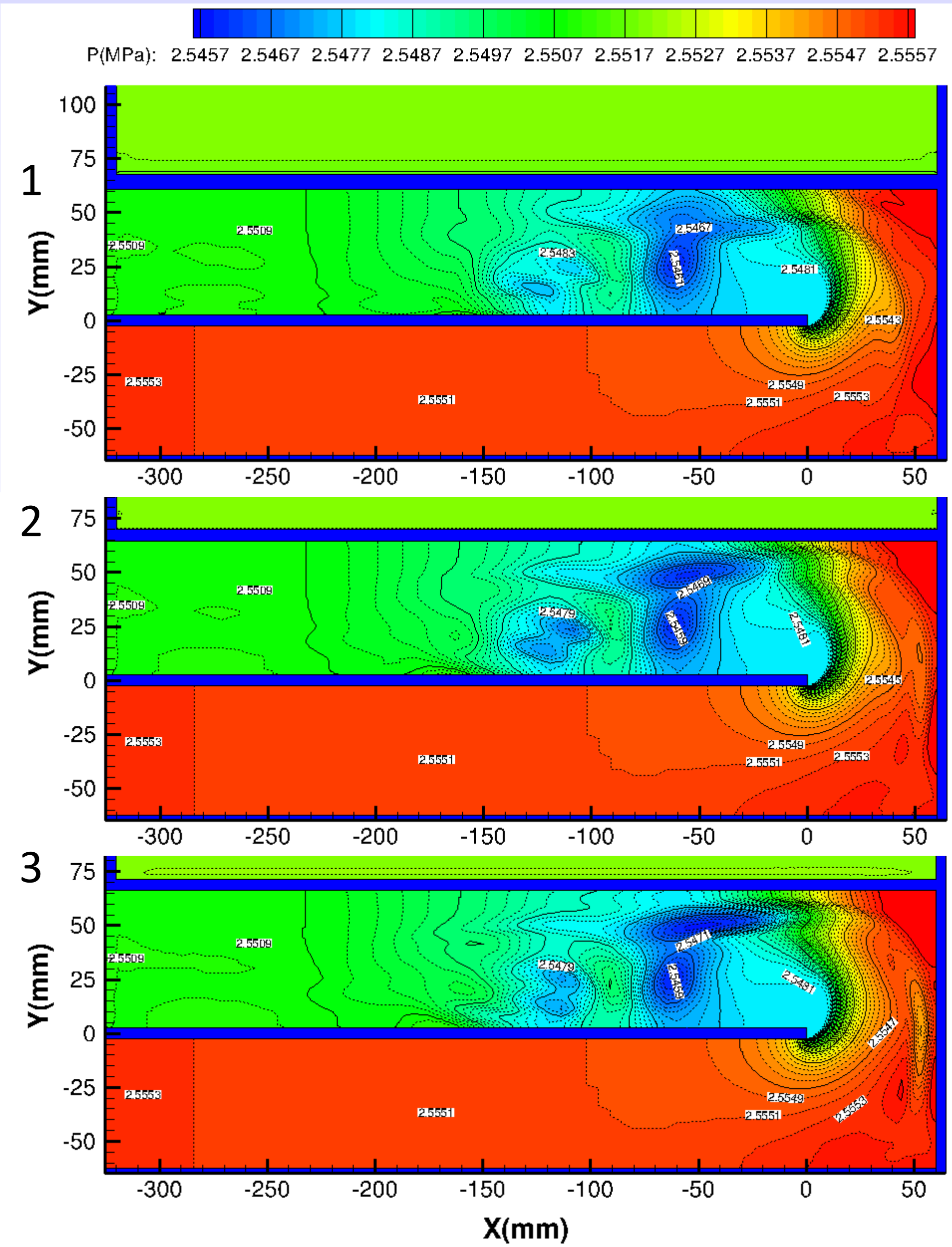
Grid System

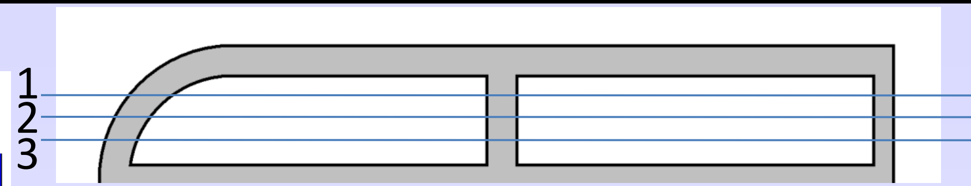


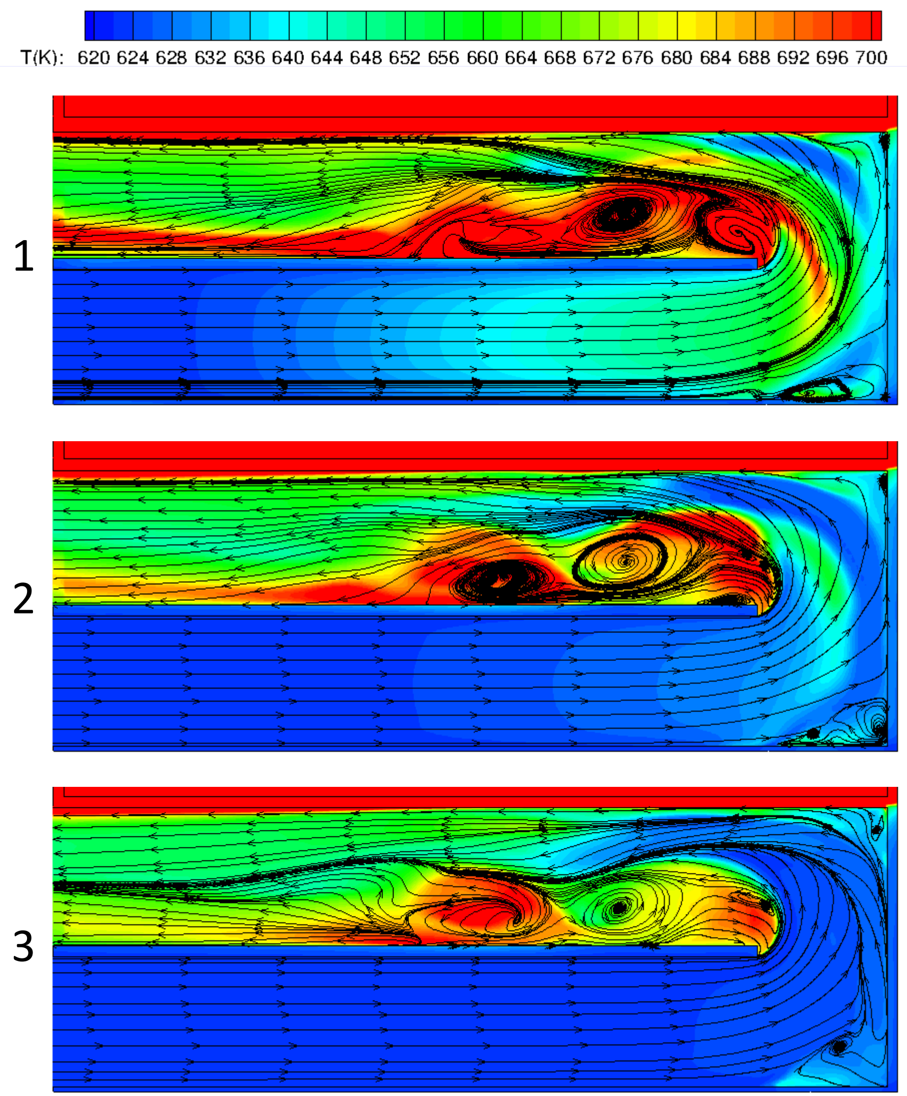
Results: q” & horseshoe vortex



Results: Pressure & Temperature







Triple Impingement Flow and Heat Transfer

: 2011--

School of Aeronautics and Astronautics

Purdue University

Students: Adam Weaver, Jason Liu, and Selcuk Sindir

Faculty: Tom Shih

Mikro Systems, Inc.

Jill Klinger, Mike Price, Ben Heneveld

Siemens

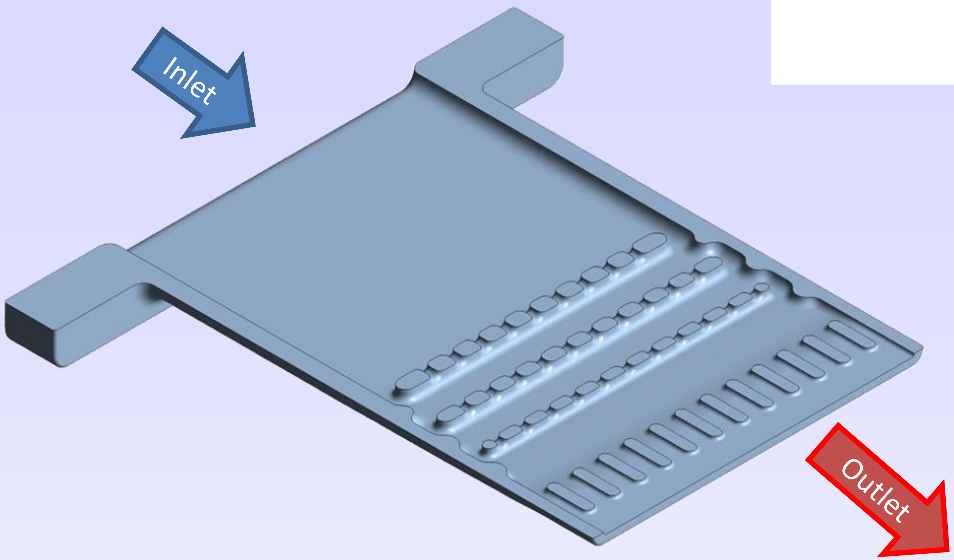
John Marra, Ching-Pang Lee, Mike Crawford

DoE National Energy Technology Laboratory

Rich Dennis, Robin Ames

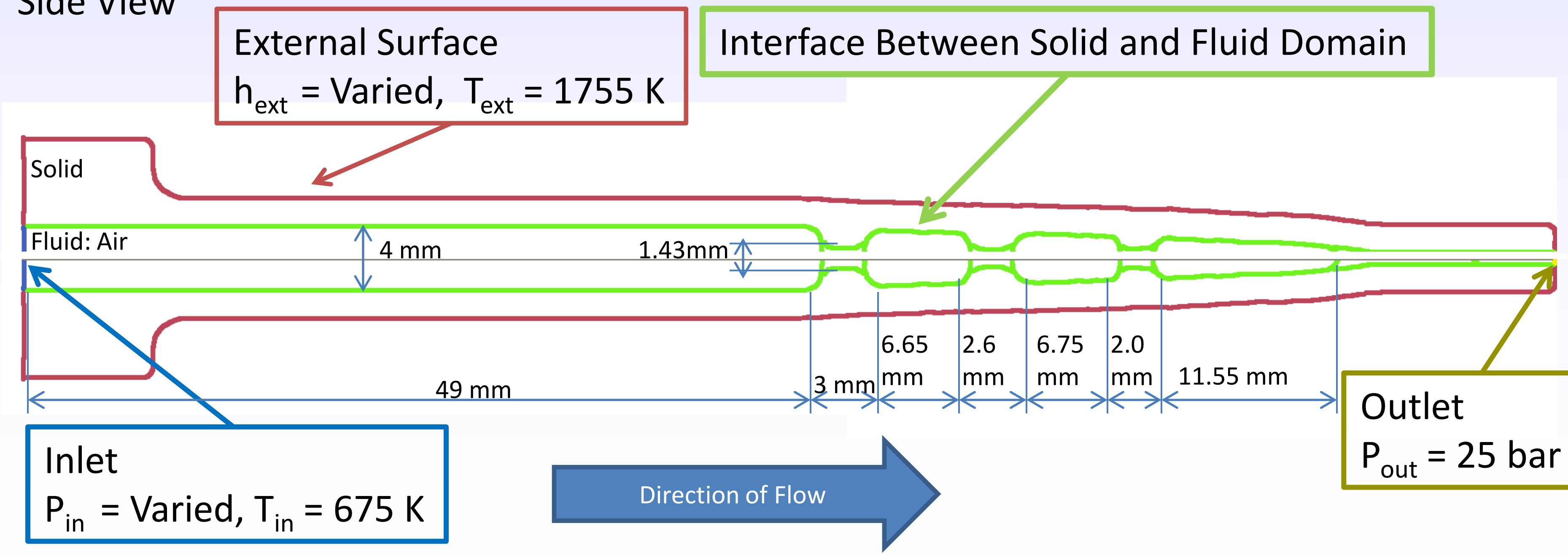
MIKRO BREAKTHROUGH TECHNOLOGIES SIEMENS U.S. DEPARTMENT OF ENERGY PURDUE UNIVERSITY

Problem Description

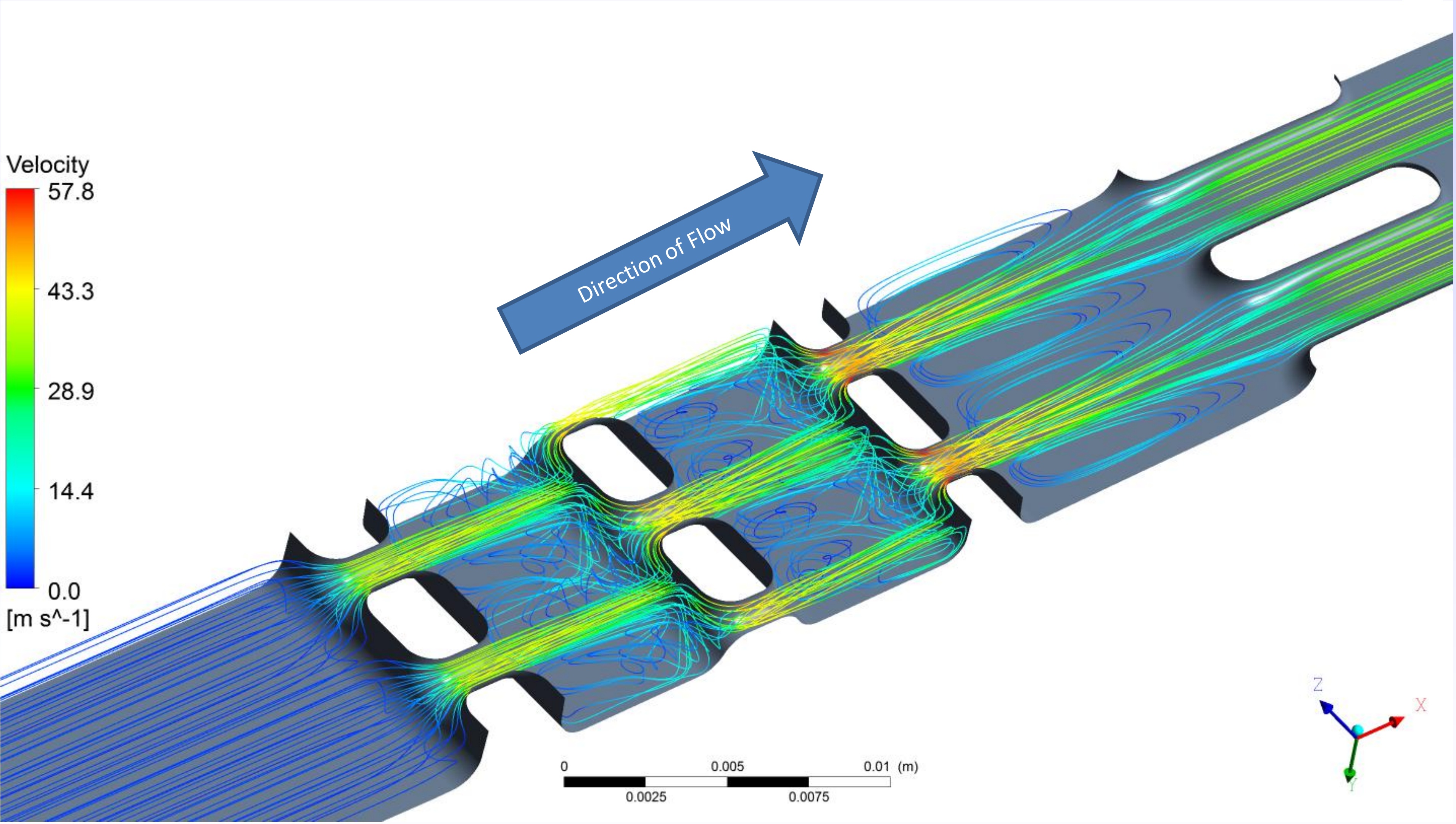


Isometric View of halved test section
Grey: Solid Domain (Nickel Alloy)

Side View

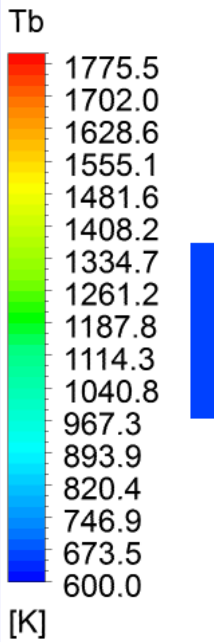


Velocity Streamlines: ΔP = .25 bar, h_{ext} = 2500 W/m^2 K



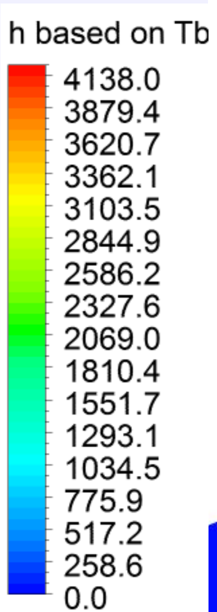
High velocity jets are created within the hourglass regions between solid posts. These jets impinge on the following row of posts, leading to high heat transfer.

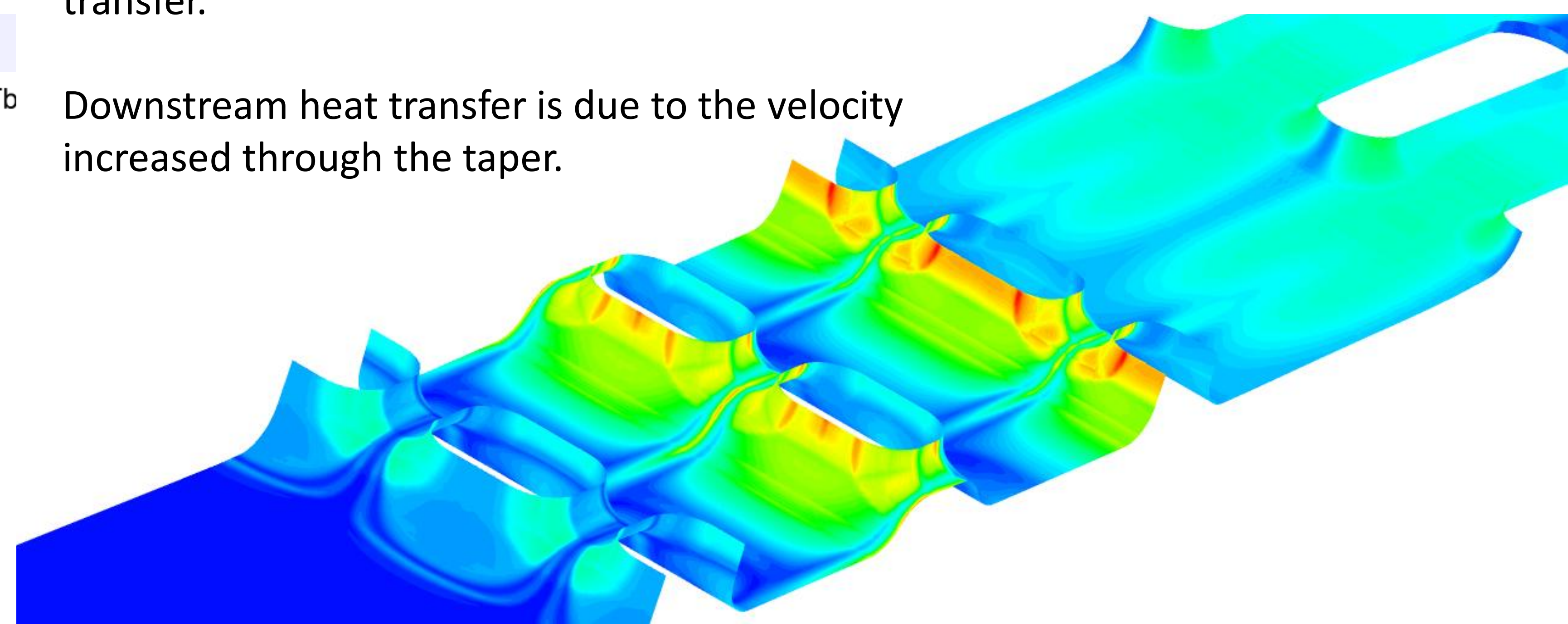
h on interface



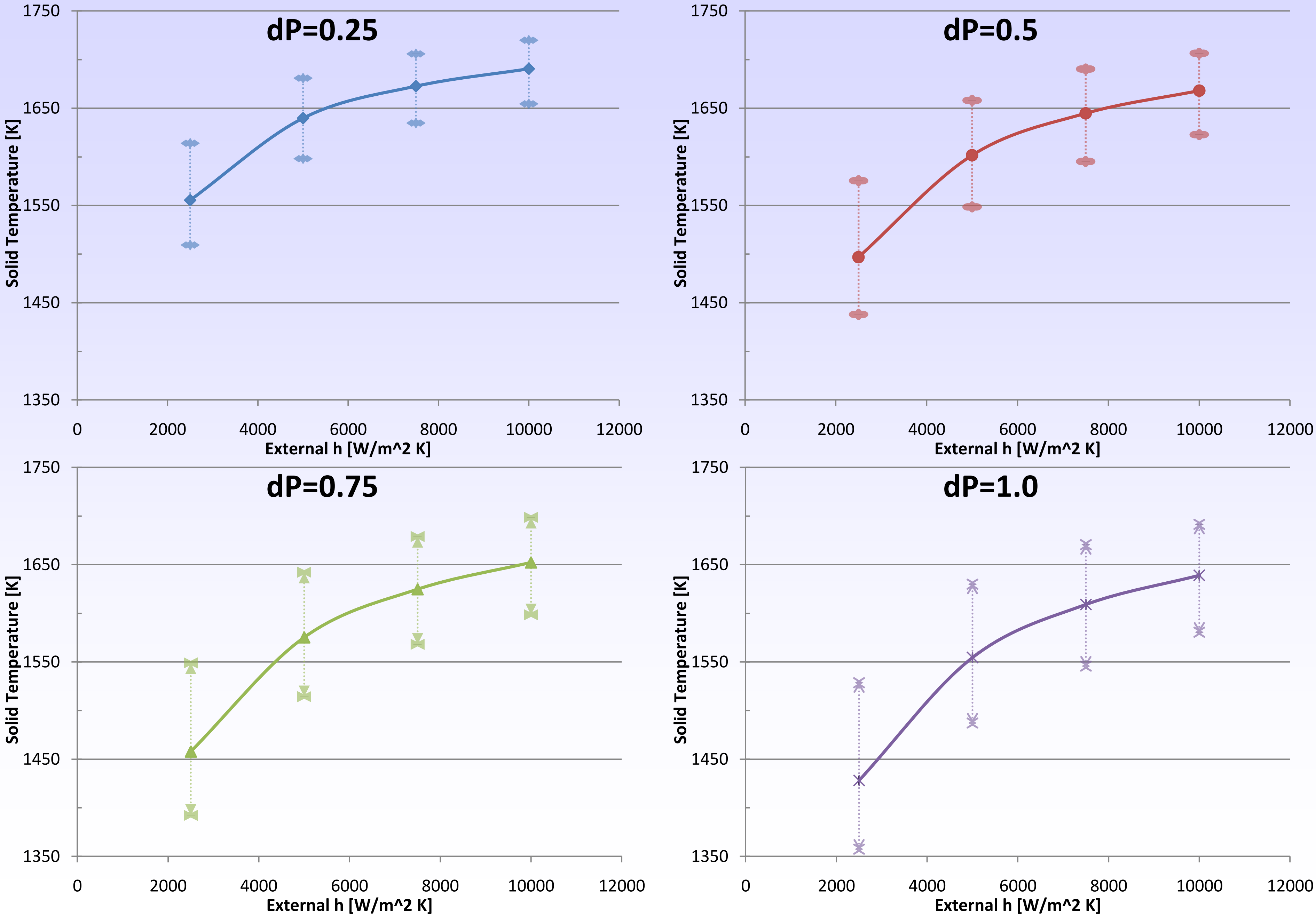
Impingement regions greatly increase heat transfer.

Downstream heat transfer is due to the velocity increased through the taper.





Comparison: Solid Domain Temperatures



Effects of Turbulence Modeling in Predicting Flow and Heat transfer in a Channel with Pin Fins

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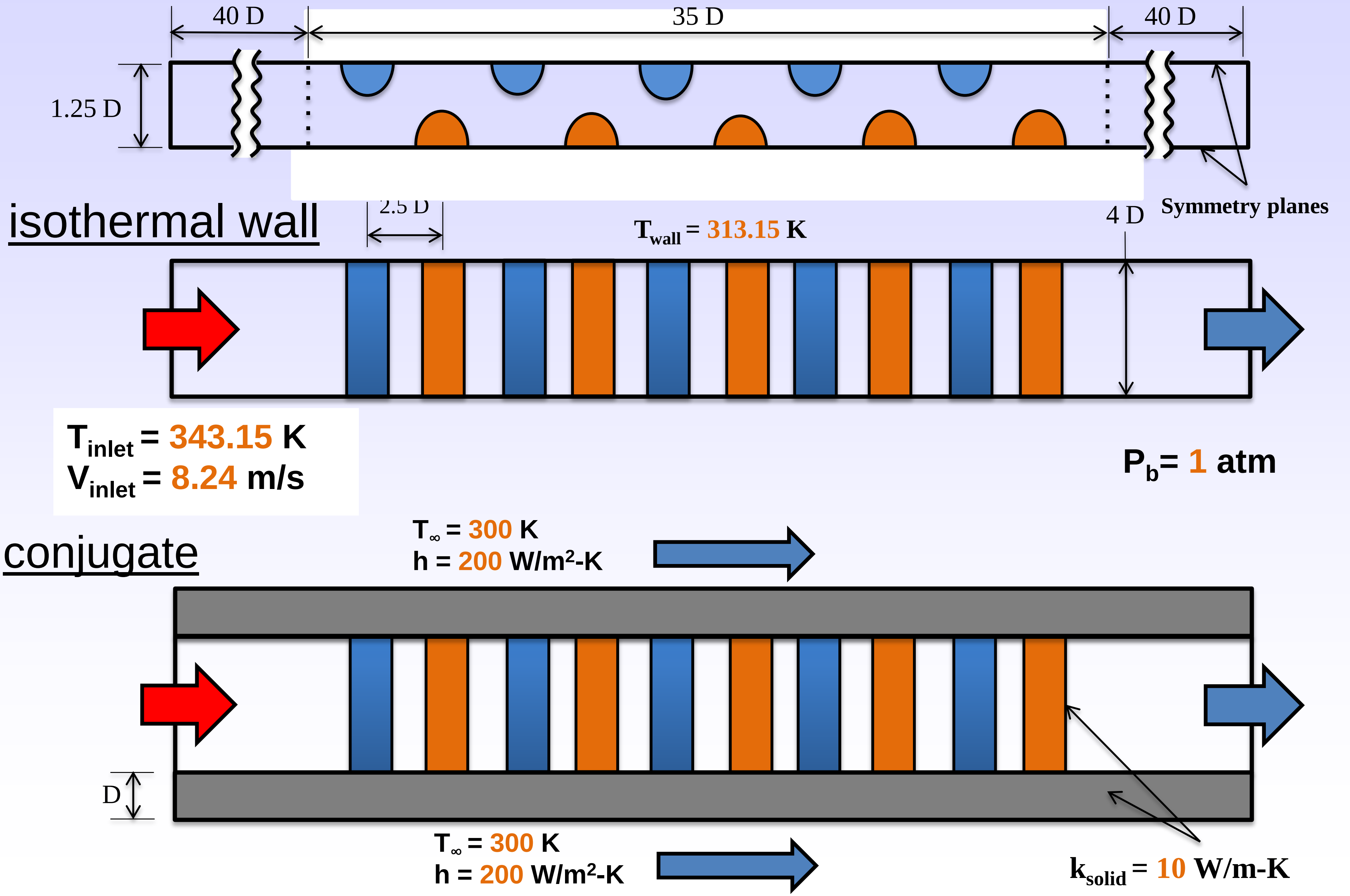
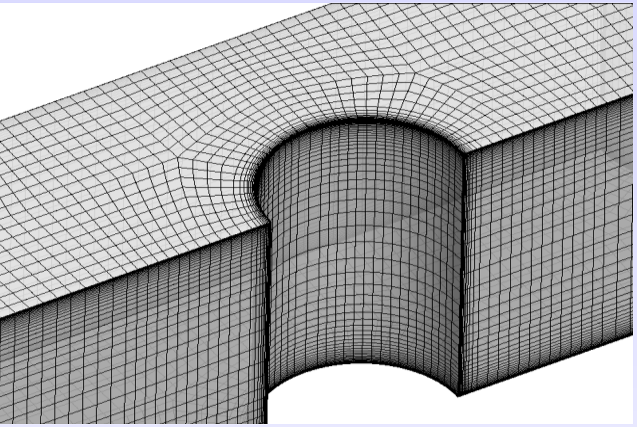
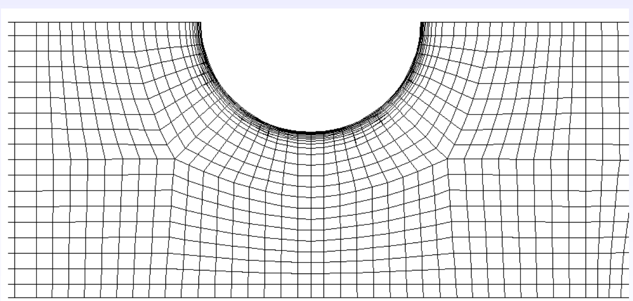
UNIVERSITY

Description of the problem

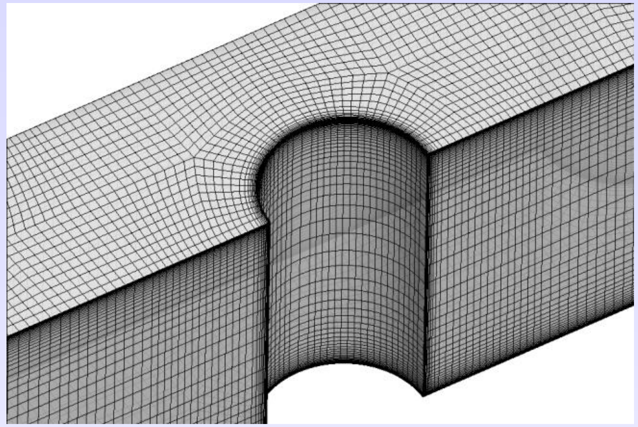


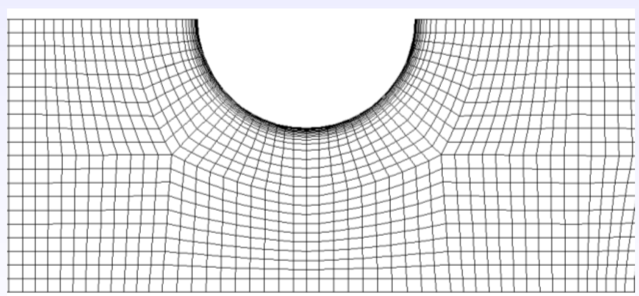
Grid Sensitivity



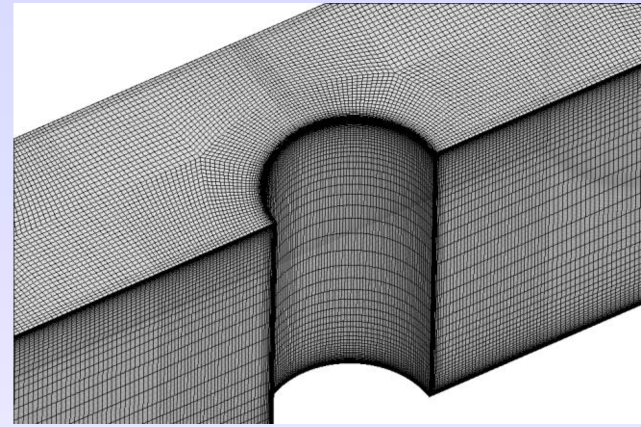


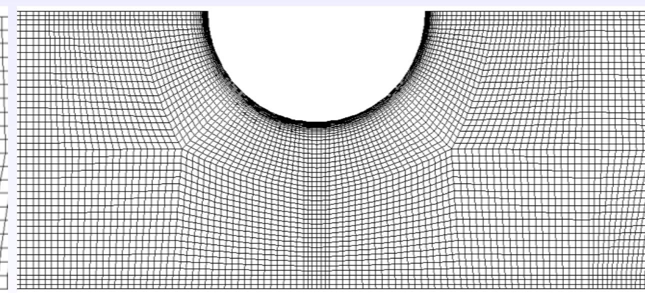
coarser
867,321 cells





baseline
1,050,400 cells



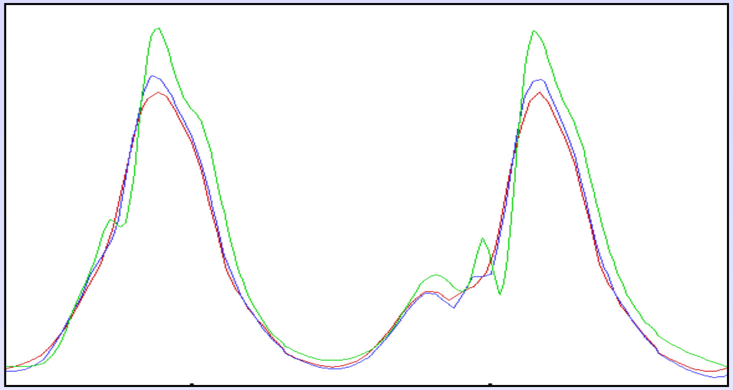


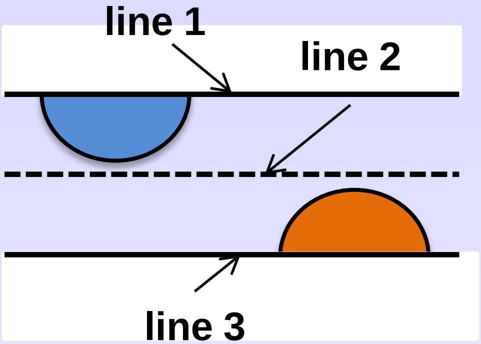
refined
5,045,400 cells

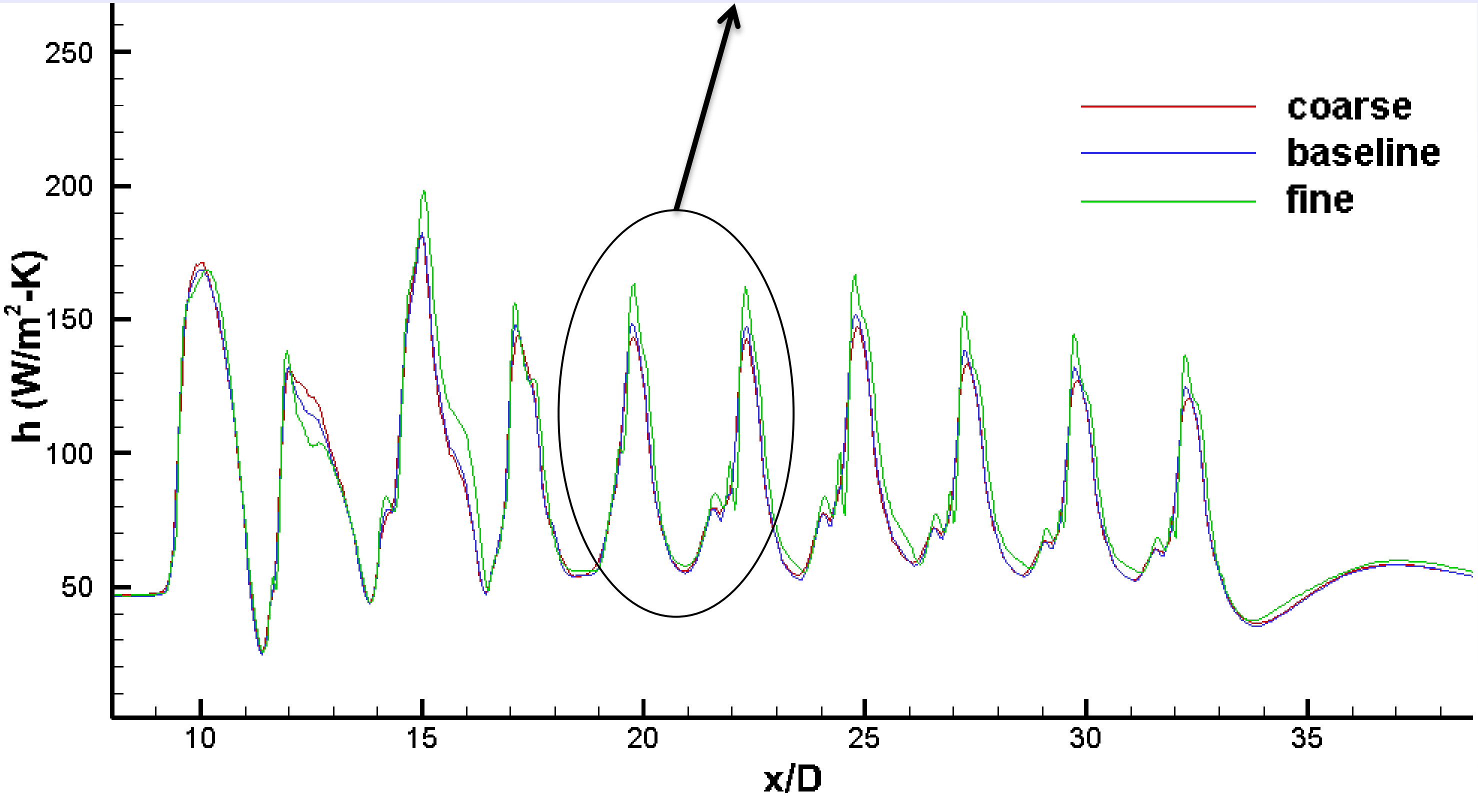
Grid sensitivity

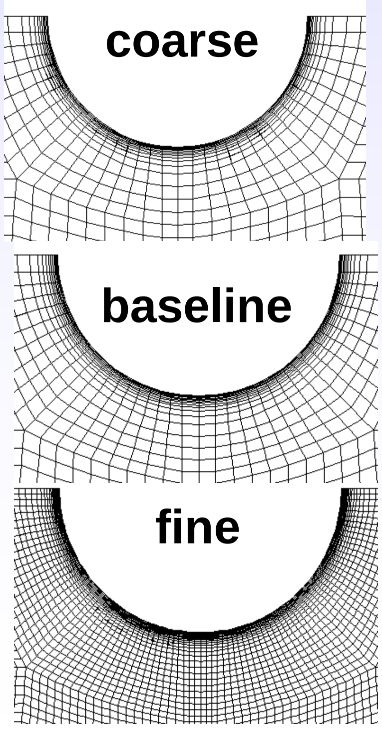
SST model

Top line 2

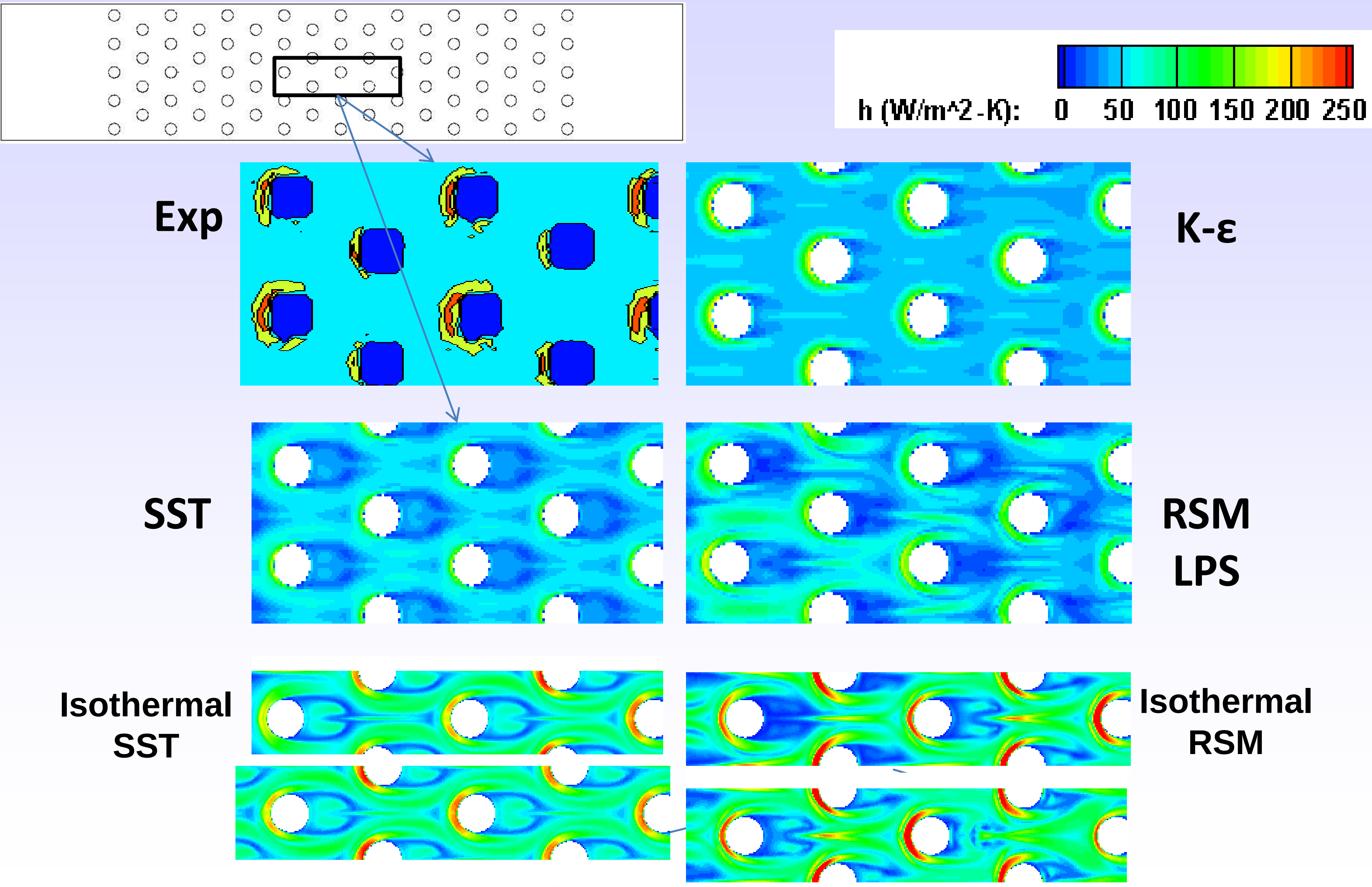




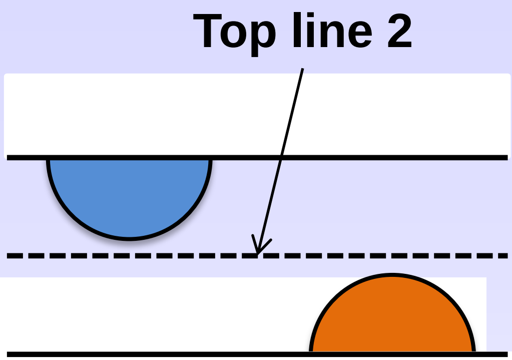


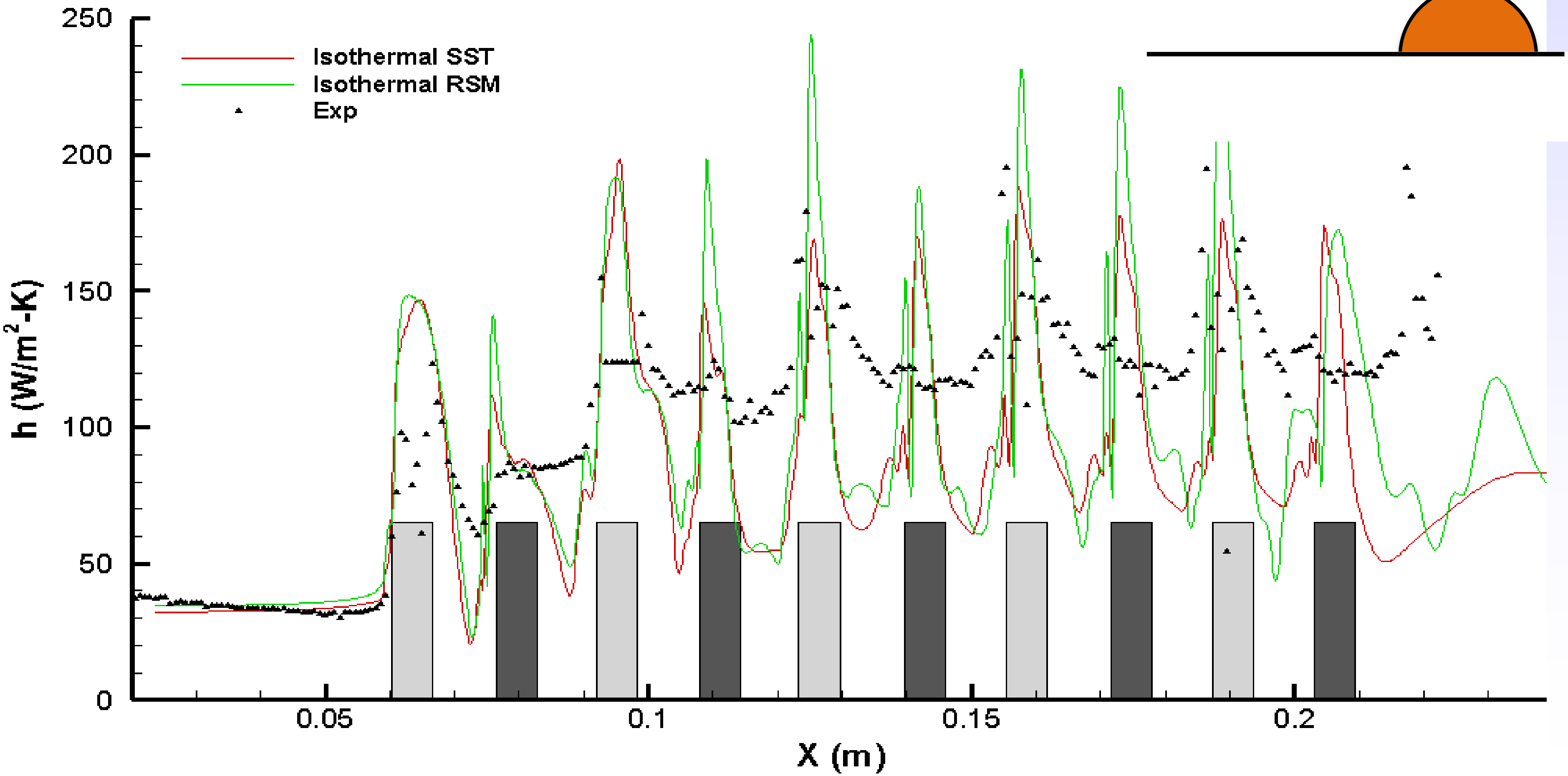


h in Top plane
Experimental vs. computational



h plot at Top line 2





q" in Top plane & Flow structures

SST model