Direct numerical simulation of a hypersonic boundary layer with porous wall injection

Ralf Deiterding, Adriano Cerminara,

Neil Sandham

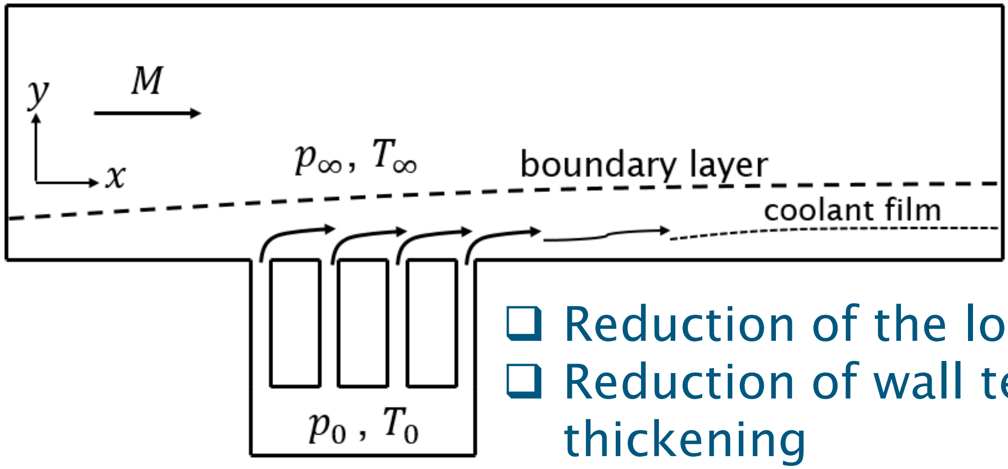
Department of Aerospace Engineering,
University of Southampton

17/11/2020

Contents

Part of EPSRC Programme Grant *Transpiration Cooling Systems for Jet Engine Turbines and Hypersonic Flight*
http://transpirationcooling.eng.ox.ac.uk

Film cooling



- ❑ Formation of a **thin film** of **cold** fluid **adjacent** to the wall
- ❑ Wall heat flux reduction achieved by a dual effect:
  - ❑ Reduction of the local fluid temperature near the wall
  - ❑ Reduction of wall temperature gradient due to BL thickening

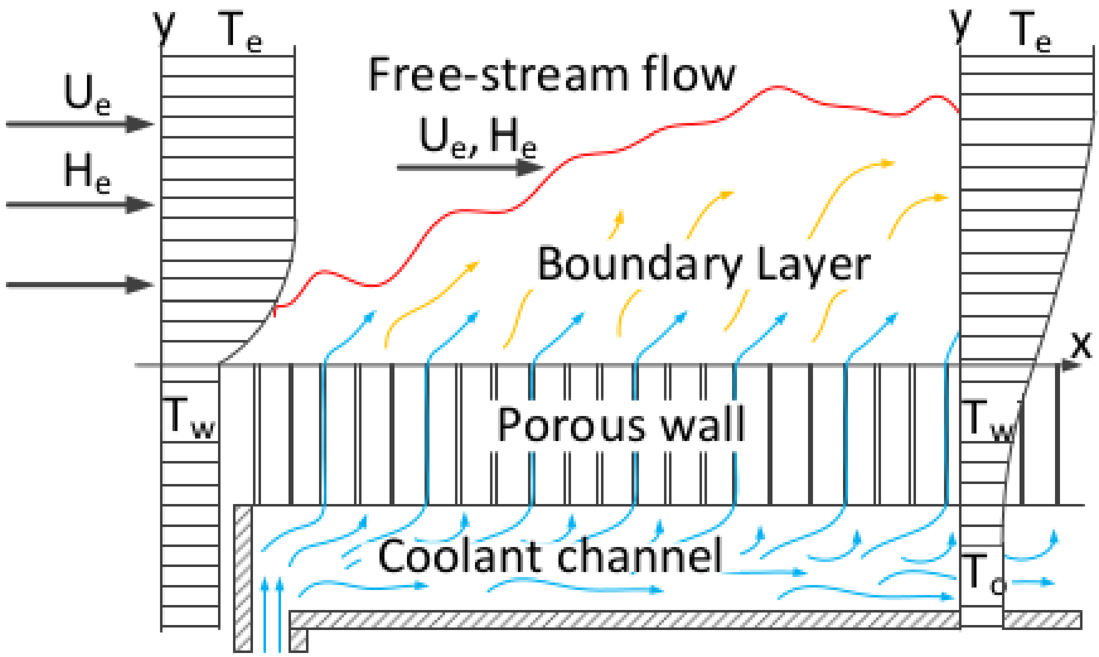
Film cooling (Fitt et al., 1985, 1994): effusion cooling vs transpiration cooling

- ❑ **Effusion cooling** (Wittig et al. 1996, Baldauf et al. 2001): coolant injected by localized holes
  - ➢ 3D effects induced in the BL, which promote transition
  - ➢ Typically used on gas-turbine blades (turbulent BL)

- ❑ **Transpiration cooling** (Meinert et al. 2001, Langener et al. 2011): fluid injected through a porous material
  - ➢ More homogeneous injection
  - ➢ Higher effectiveness

Purpose of direct numerical simulation

- Understand the physics of blowing in hypersonic flow through porous surfaces
- Predict cooling performance – heat transfer rates
- Estimate the effects on BL stability and transition
- Validate results with experiments



Numerical method for full Navier-Stokes equations

- **Finite volume** approach in a Cartesian reference system with embedded boundaries
- Structured-adaptive-mesh-refinement (**SAMR**) algorithm (AMROC - Deiterding, 2005 & 2011): the Cartesian grid is **locally refined** by adding consecutive finer grid levels during the iteration cycles (patch-wise refinement strategy)
- **Hybrid WENO-CD** method up to **6th -order** accurate for both inviscid and viscous fluxes (Cerminara, Deiterding, Sandham, 2018)
- Central Differencing (CD) scheme used in the smooth regions:

  E.g. for 6th -order, the numerical flux at the interfaces is evaluated as

$$\hat{f}_{i+\frac{1}{2}} = \alpha(f_{i+3} + f_{i-2}) + \beta(f_{i+2} + f_{i-1}) + \gamma(f_i + f_{i+1})$$

$$\alpha = 1/60 \quad \beta = -2/15 \quad \gamma = 37/60$$

- 3rd –order Runge-Kutta for time integration
- **Characteristic-based switch** to a high-resolution WENO scheme to handle discontinuities in a computationally efficient way (Hill and Pullin, 2004)

Shock-capturing scheme

- Weighted-essentialy-non-oscillatory - symmetric - order-optimized (**WENO-SYMOO**) scheme (Martin et al. 2006)
- **Reduced dissipation** (compared to 5th-order WENO-JS, Jiang and Shu 1996), and **6th** maximum formal **order** of accuracy, reached through:
  1. Symmetrization: a **fourth** candidate **stencil** is **added** to the initial (r=3)-points upwinded-biased candidate stencils of the WENO-JS
  2. Optimal weights C_k to guarantee 6th-order accuracy

$$\hat{f}^{+}_{i+\frac{1}{2}} = \sum_{k=0}^{r} \omega_k q_k^r \qquad q_k^r = \sum_{l=0}^{r-1} d_{k,l}^r f(u_{i-r+k+l+1})$$

r-th-order polynomial interpolation on the k-th stencil

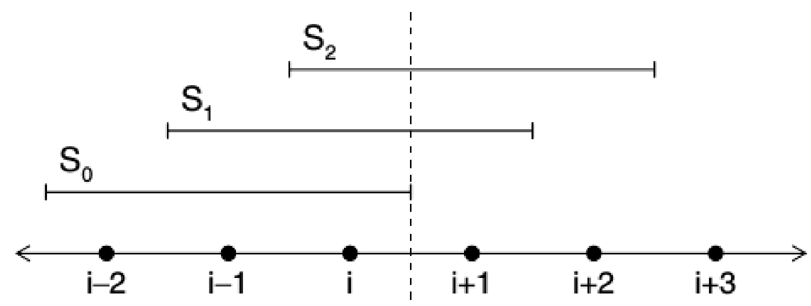
$$\omega_k = \frac{\alpha_k}{\sum_{k=0}^{r-1} \alpha_k}$$

weight of the k-th interp.

$$\alpha_k = \frac{C_k}{(\epsilon + IS_k)^p}$$

$$IS_k = \sum_{m=1}^{r-1} \left(\sum_{l=0}^{r-1} b_{k,m,l}^r f(u_{i-r+k+l+1}) \right)^2$$

smoothness indicator



from Martin et al. 2006

Scheme switch

- Riemann problem is solved at each cell interface through Roe's averaged state
- Lax condition is applied to detect shock/rarefaction waves

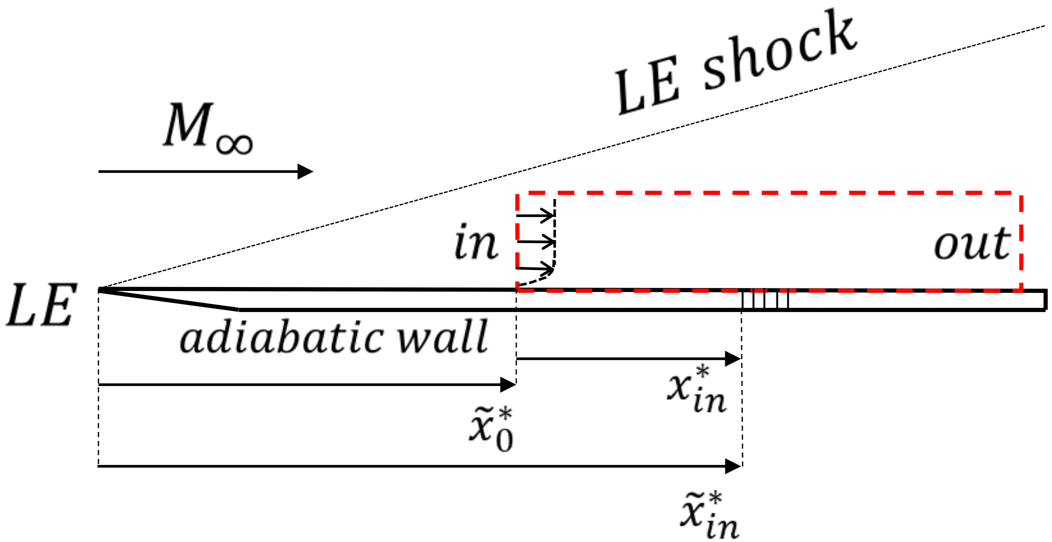
$$|u_R \pm a_R| < |u^* \pm a^*| < |u_L \pm a_L|$$

- A threshold is applied to the residuals between the left/right state and the intermediate state to select the strong waves and neglect the weak ones (Ziegler et al., 2011)
- Another threshold is applied to the function $\phi(\theta_i)$ to allow WENO only in the high pressure-gradient regions (Ziegler et al., 2011):

$$\phi(\theta_i) = \frac{2\theta_i}{(1+\theta_i)^2} \qquad \theta_i = \frac{|p_{i+1} - p_i|}{|p_{i+1} + p_i|}$$

Flat plate studies:
Flow conditions and domain set-up

- $M_\infty = 5$
- $Re_m = 12.6 \times 10^6 \ 1/m$
- $T^*_\infty = 81.7 \ K$
- $T^*_{0\infty} = 490.2 \ K$
- $U^*_\infty = 906 \ m/s$
- $\rho^*_\infty = 0.078 \ Kg/m^3$
- $p^*_\infty = 1.832 \times 10^3 Pa$
- $\rho^*_\infty U^{*2}_\infty = 6.4 \times 10^4 \ Pa$
- $\mu^*_\infty = 5.6 \times 10^{-6} \ Kg/(m \cdot s)$
- $T^*_w = T^*_{ad} = 5.24 \, T^*_\infty$
- $\tilde{x}^*_0 = 127 \ mm$
- $\tilde{x}^*_{in} = 182 \ mm$
- $x^*_{in} = 55 \ mm$



$\tilde{x}^* = distance \ from \ LE$

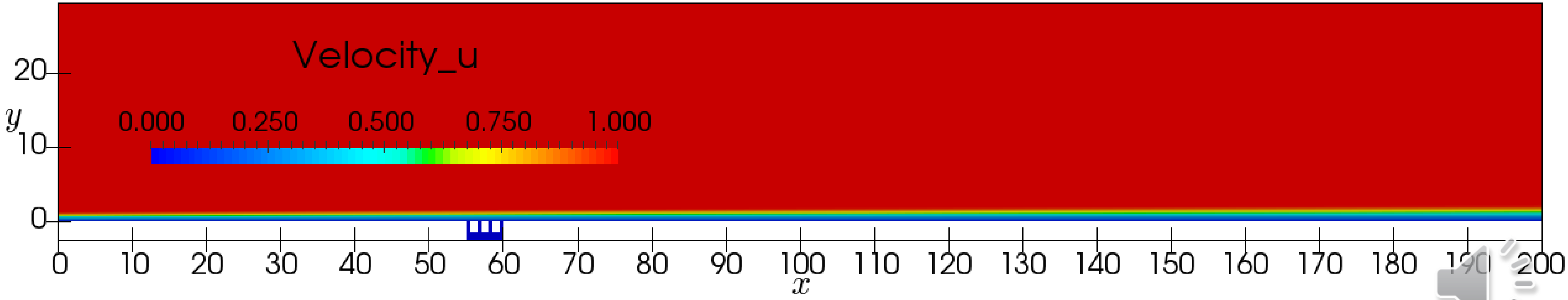
$x^* = distance \ from \ inflow \ in \ the \ domain \ coordinate \ system$

Initialization

From the inflow profile, the displacement thickness of the laminar BL in the initial solution grows in the streamwise direction, following the relation:

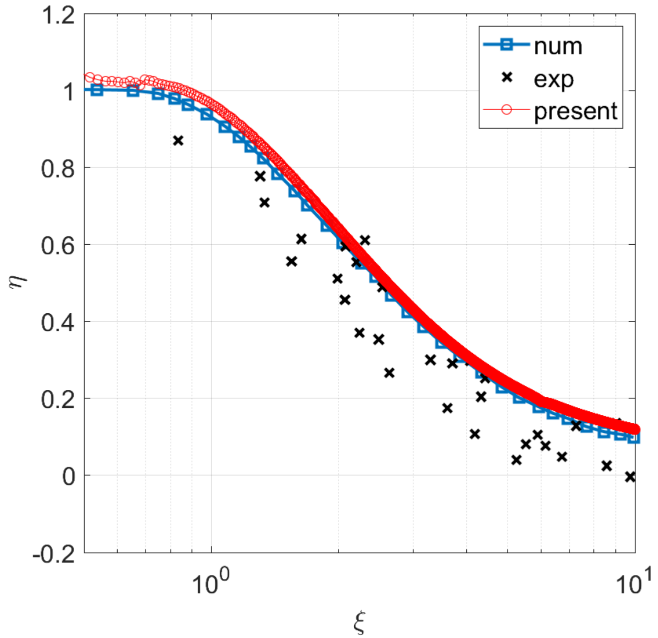
$$\frac{\delta^*(\tilde{x}^*)}{\delta_0^*} = \Delta \frac{\sqrt{2Re_{\tilde{x}^*}}}{Re_{\delta_0^*}} \quad ,$$

where $\Delta = 8.18$ (for the present case) is a scaling factor from the similarity solution.
The result for the initial state at all the x positions is:

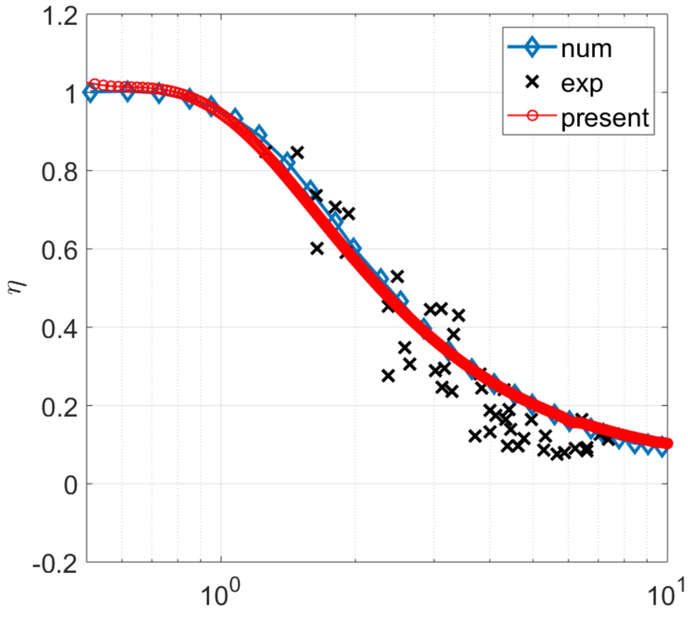


Validation case: slot injection with multi-component gas effects

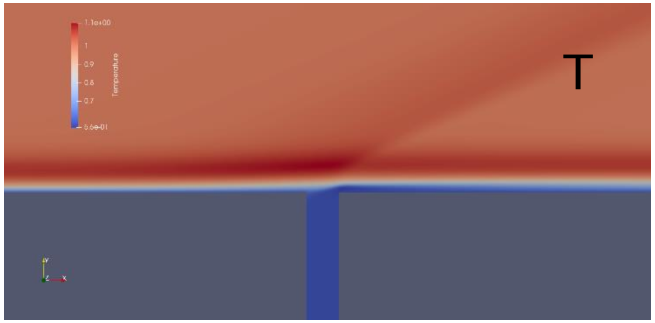
Air injection



CO_2 injection



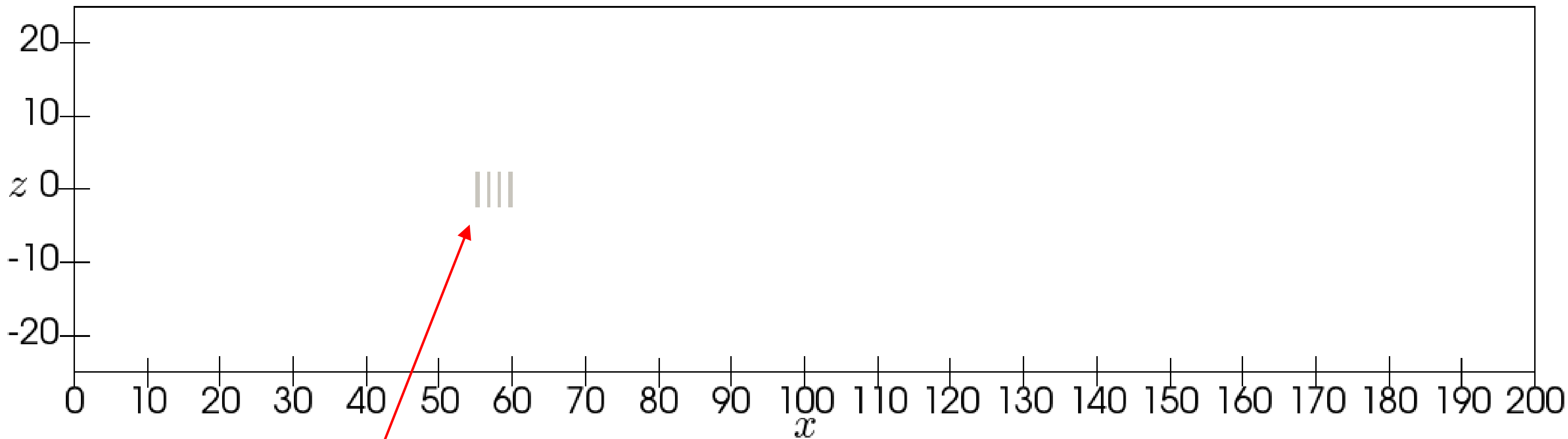
$$\eta = 1 - \frac{q_{w,c}}{q_{w,nc}}$$

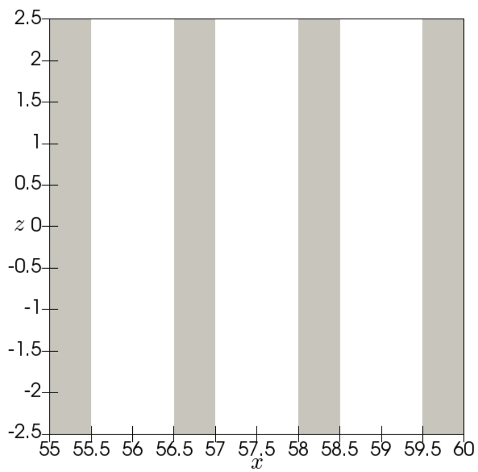


Very good agreement with Keller et al. (2015) results of cooling effectiveness in a Mach 2.6 case

3D flat plate with blowing through finite slots

Grid size (base level) $N_x \times N_y \times N_z = 800 \times 384 \times 100$





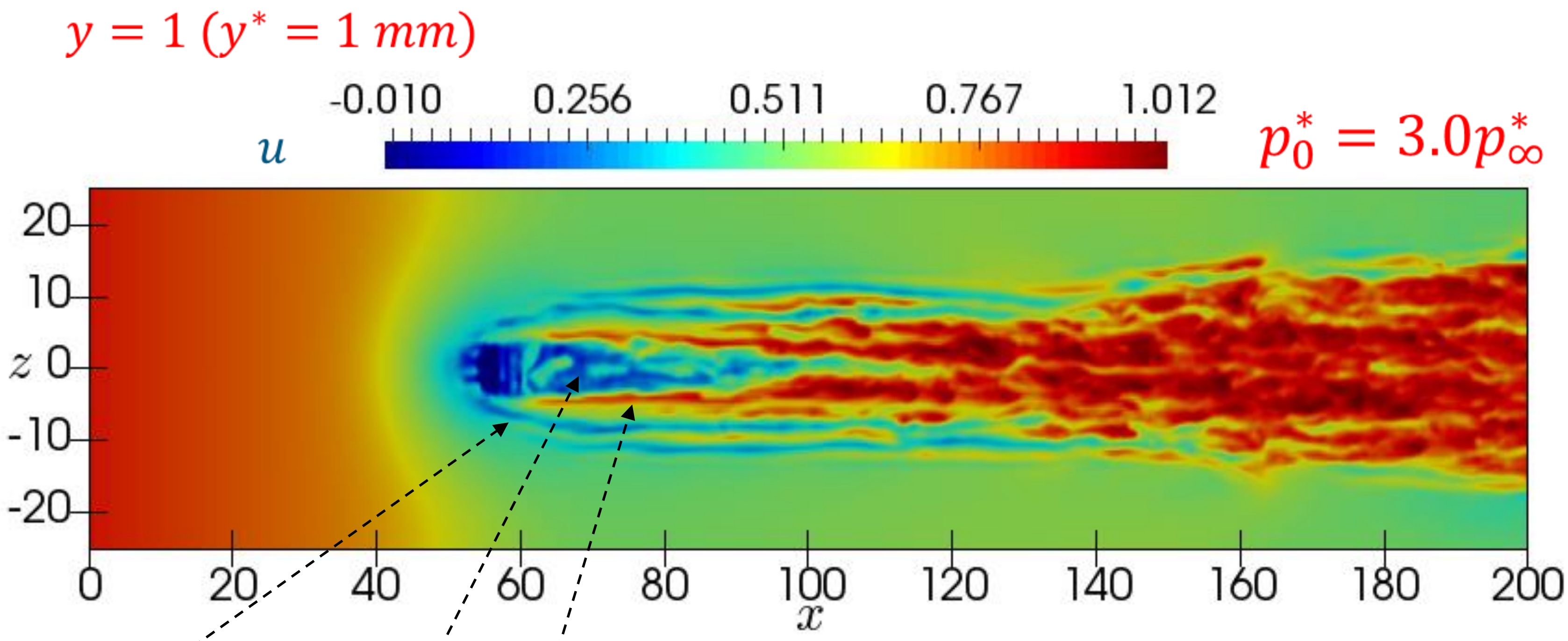
Domain size $L_x \times L_y \times L_z = 200 \times 32 \times 50$

Width of the slot region $= 5\ mm$

Minimum cell sizes $\Delta x = 0.125\ mm, \Delta y = 0.0415\ mm,\ \Delta z = 0.25\ mm$ (with 2 grid levels)

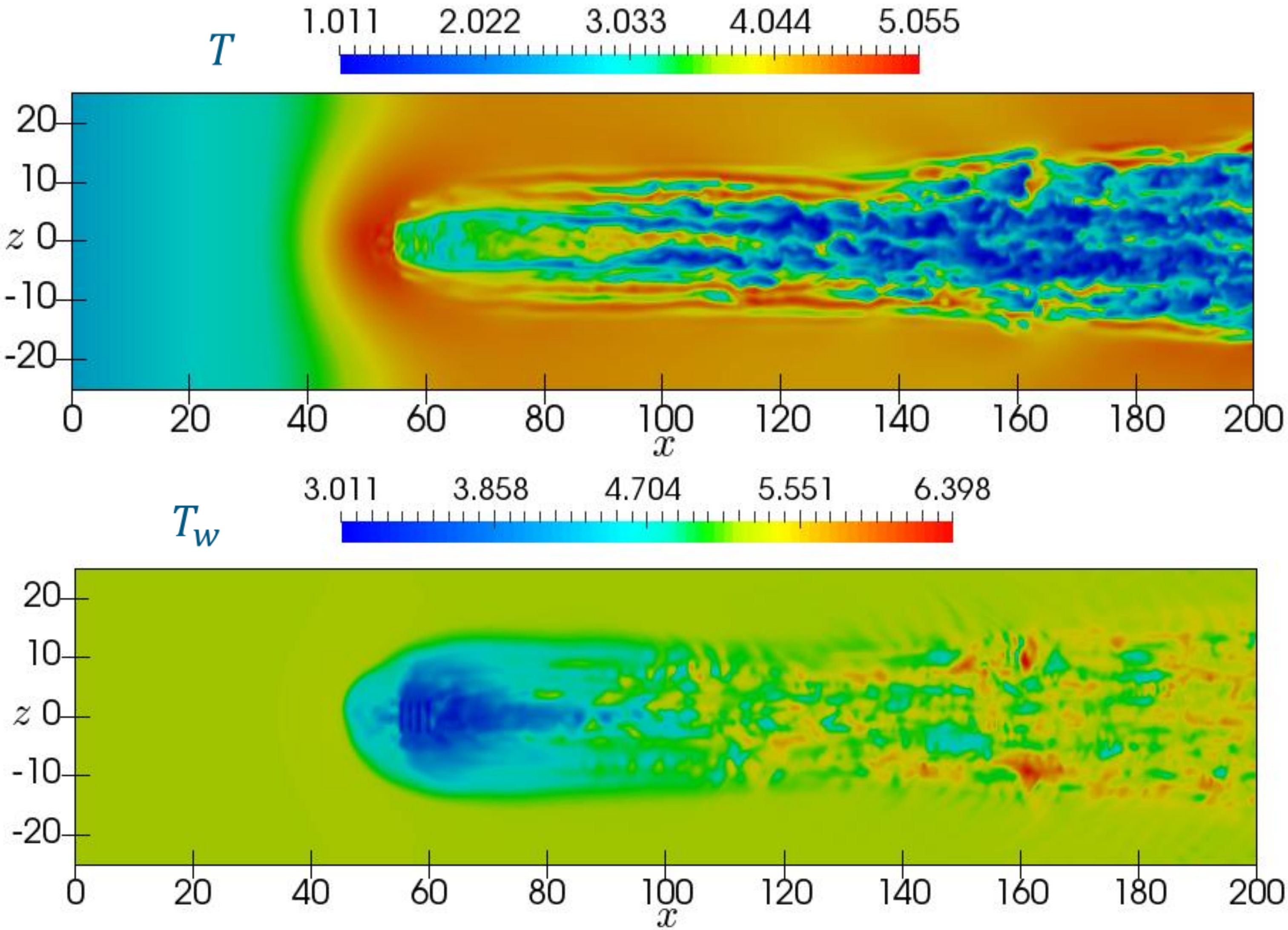
Simulation run with 480 cores on Iridis 4 cluster (Soton HPC facility)

3D flat plate with blowing through slots



- Transition induced by breakdown of the main edge vortices downstream of $x = 90$ ($x^* = 90\ mm$, $\tilde{x}^* = 217\ mm$)
- Wedge-shaped transition front spreading downstream

3D flat plate with blowing through slots

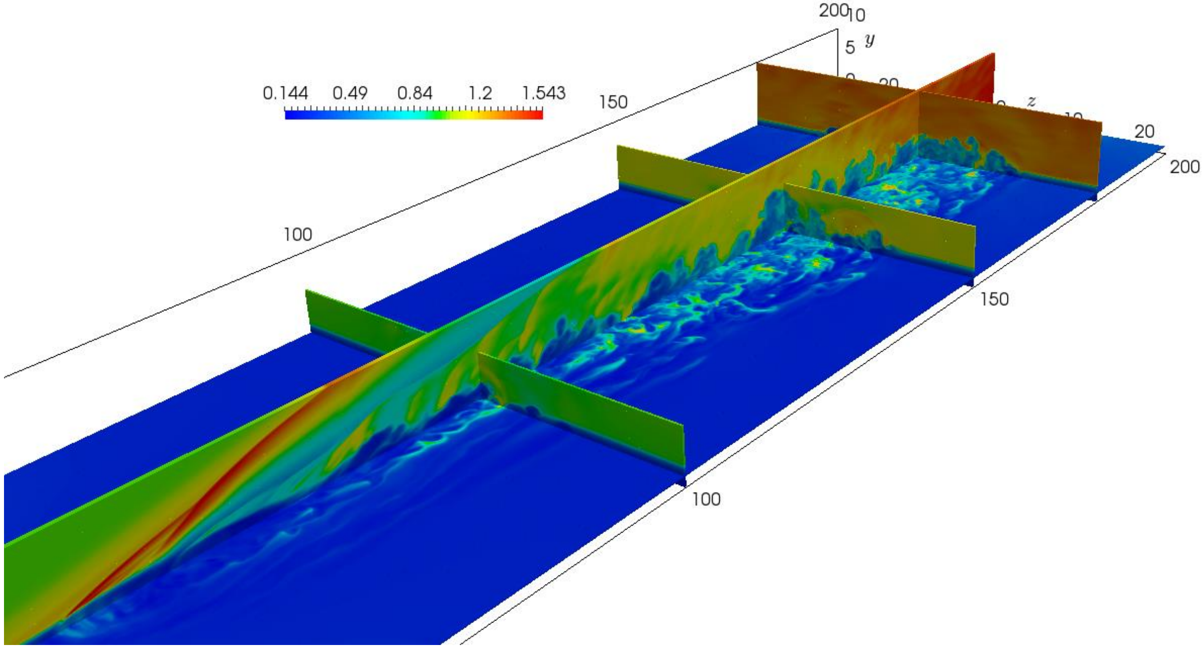


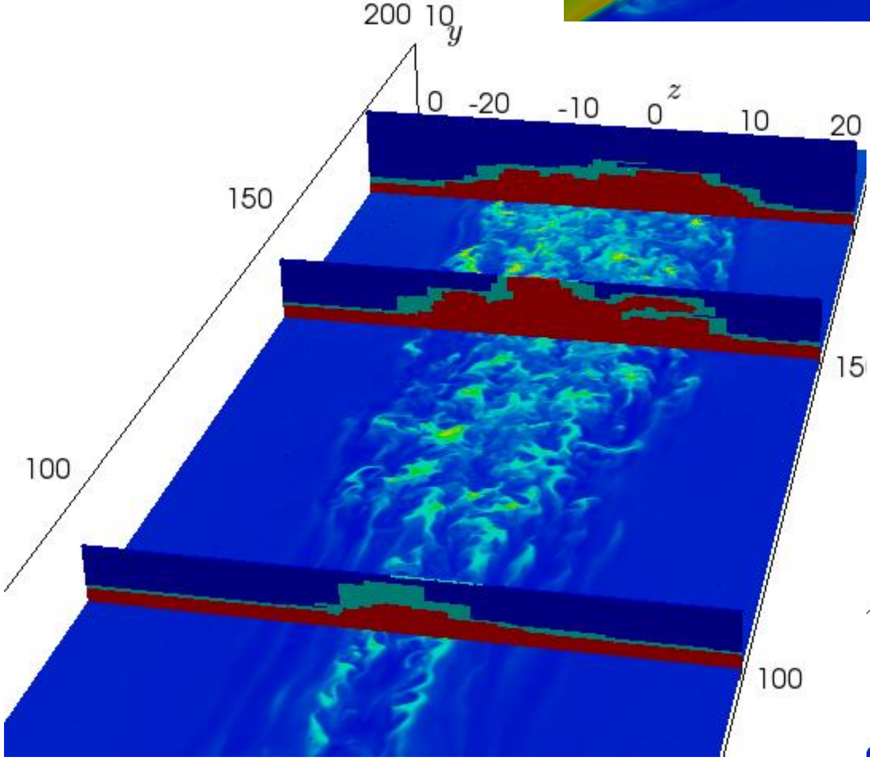
- Cooling performed mainly at the slot sides and along the wake
- Limited streamwise extent of the cooled region due to transition to turbulence

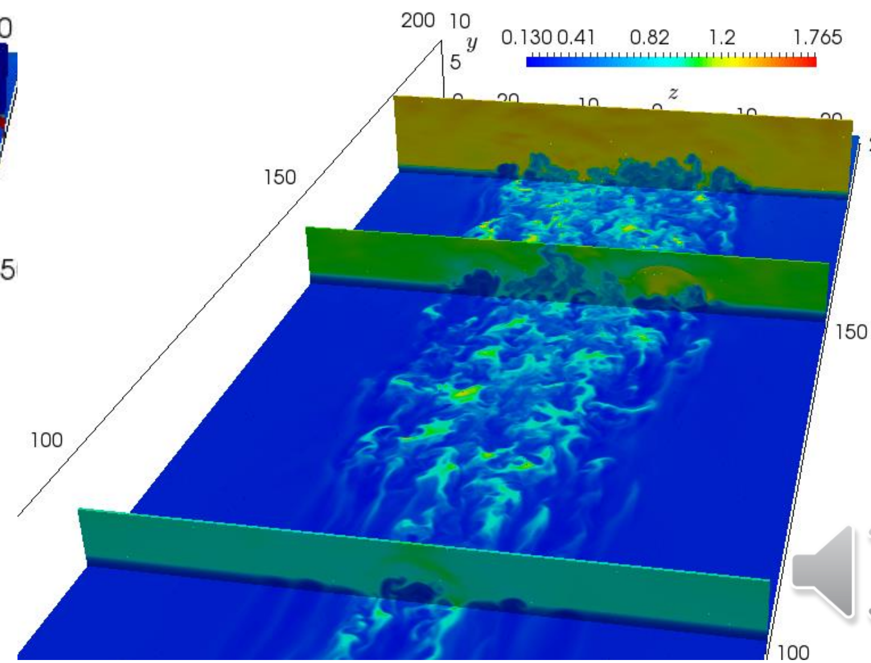
3D results

Right, bottom right: density field

Left, bottom: AMR levels



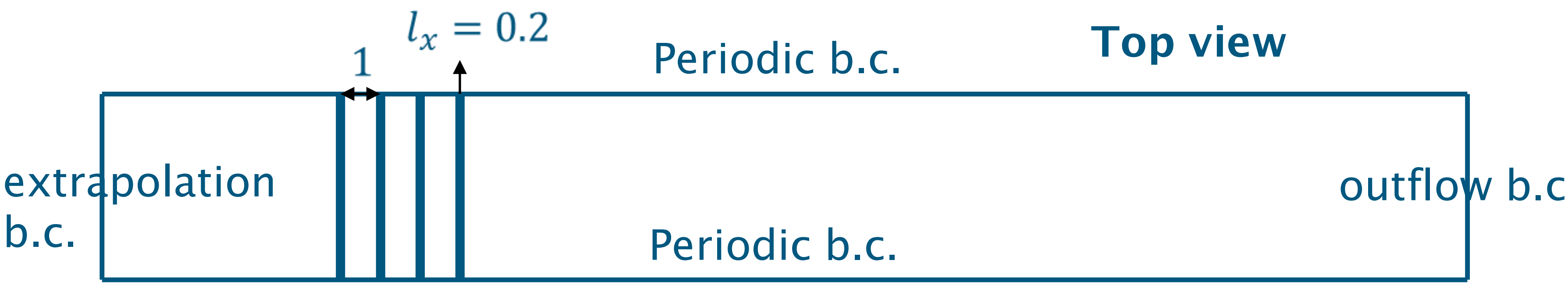


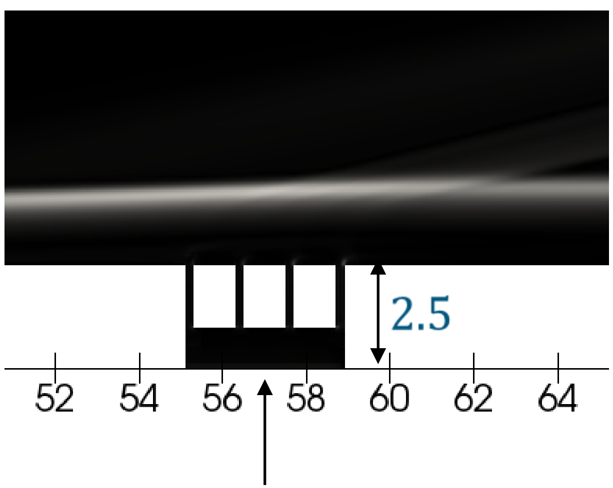


Oxford slot experiments

Characteristic length = 1 mm (BL displacement thickness at inflow)

$L_x = 160, L_y = 32, L_z = 4$ $\quad$ $N_x \times N_y \times N_z = 3200 \times 384 \times 40$



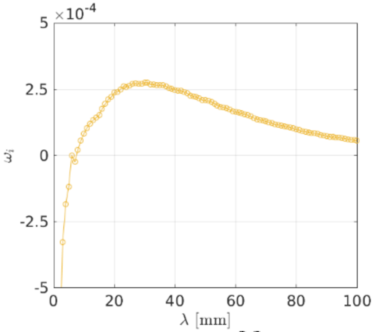


Plenum b.c. : $p_0, T_0 = 290\ K$

Injection conditions:

1. *no injection*
2. $\frac{p_0}{p_\infty} = 1.6$
3. $\frac{p_0}{p_\infty} = 1.8$
4. $\frac{p_0}{p_\infty} = 2.7$
5. $\frac{p_0}{p_\infty} = 4.8$

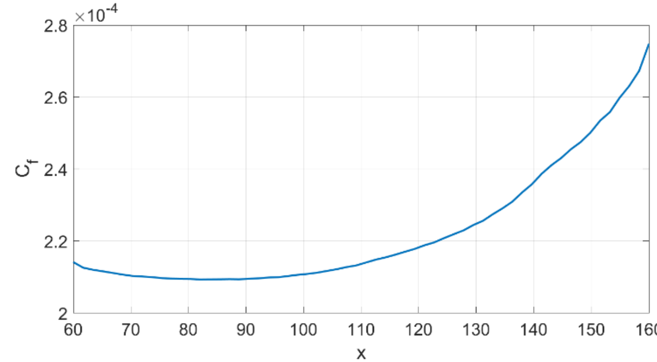
Transitional flow state



LST to identify the most unstable frequencies and wavenumbers

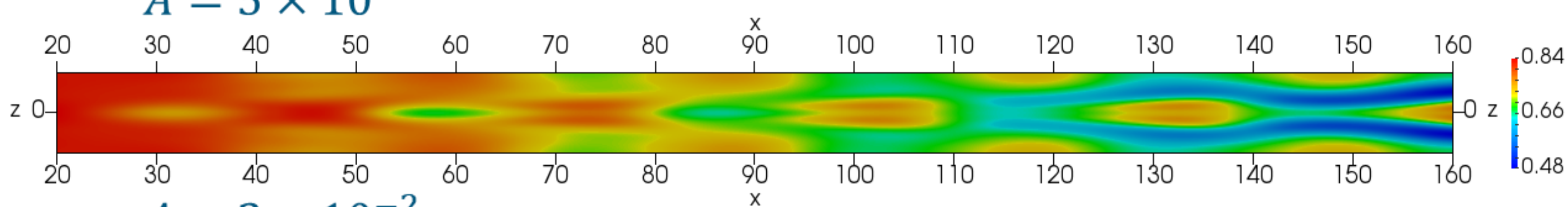
Model to reproduce instability modes

$$v'(x,z,t) = \sum_{m=1}^{M} A\cos\left(\beta_m z + \phi_m\right)\cos\left[\alpha(x - x_0) - \omega t + \psi\right]$$



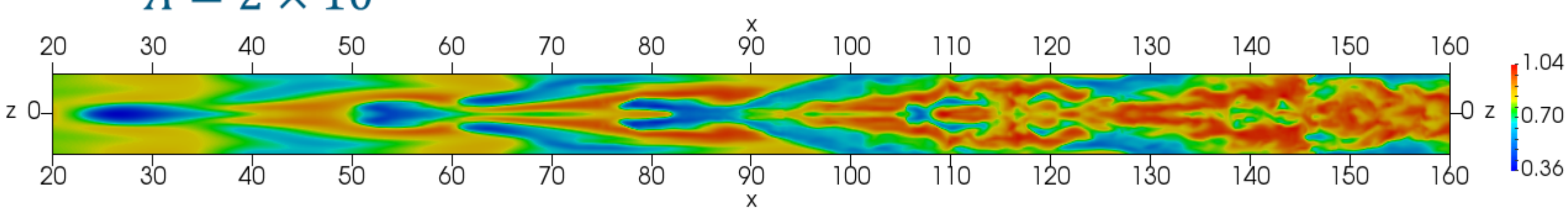
Most unstable mode: α=0.2, β=0.78

$A = 5 \times 10^{-3}$



Low A – imprint of growing instability

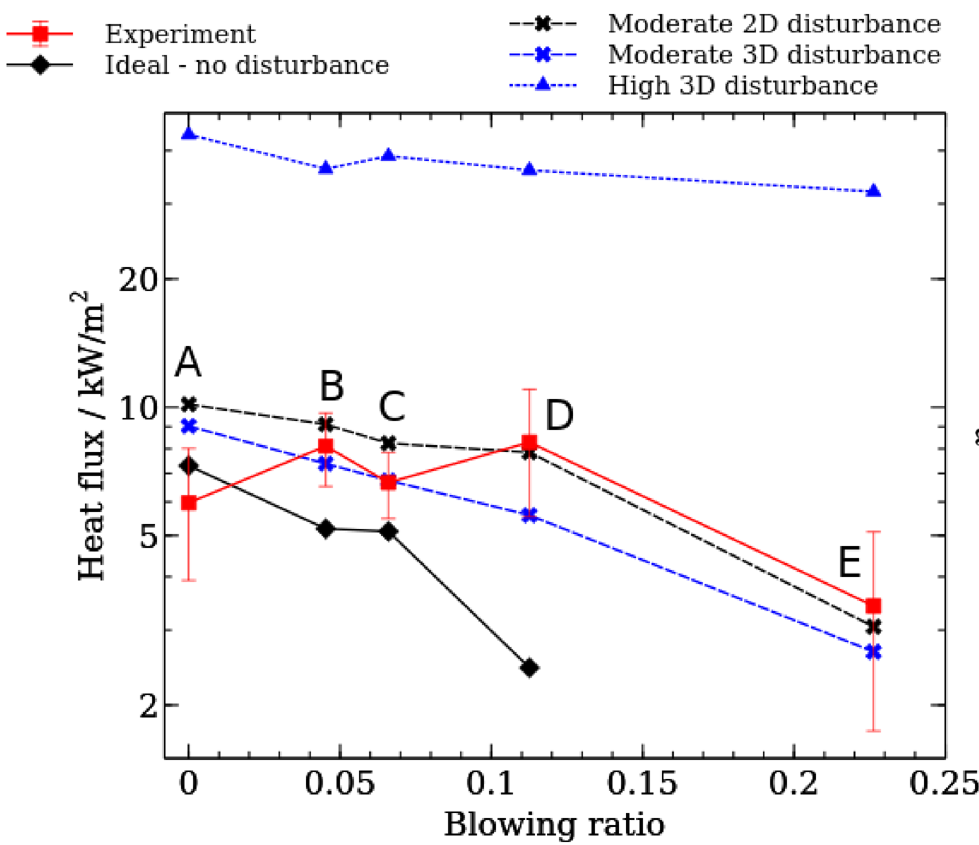
$A = 2 \times 10^{-2}$



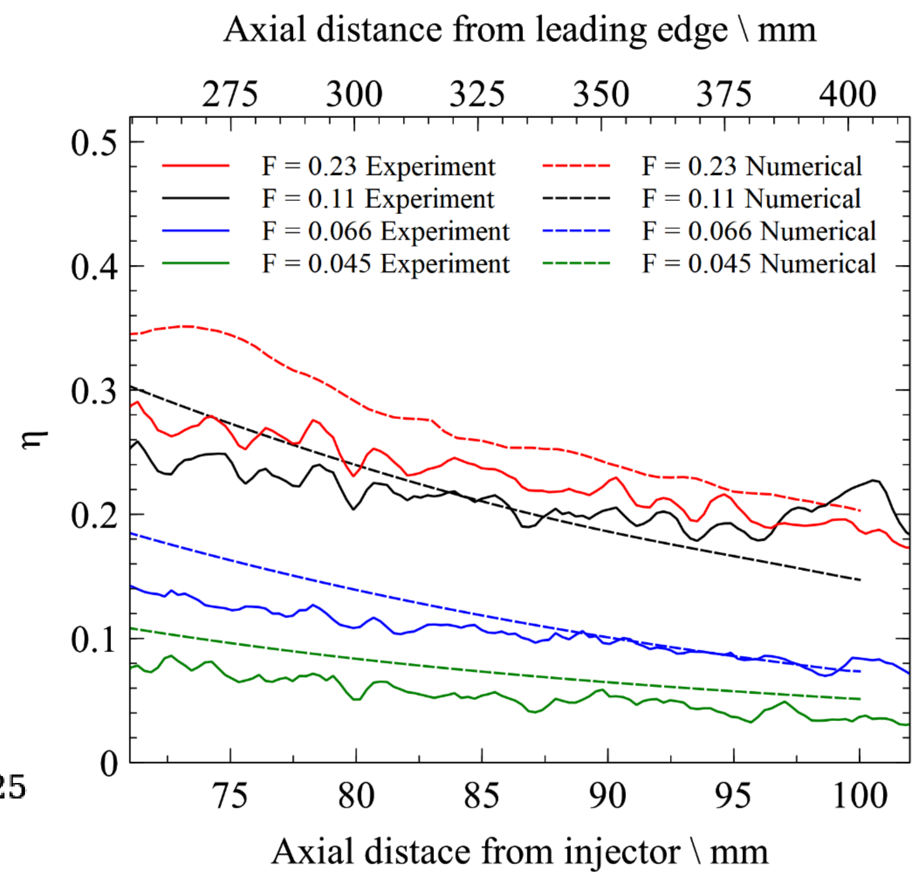
High A

Heat flux and effectiveness predictions

Heat flux



Effectiveness measure based on concentration

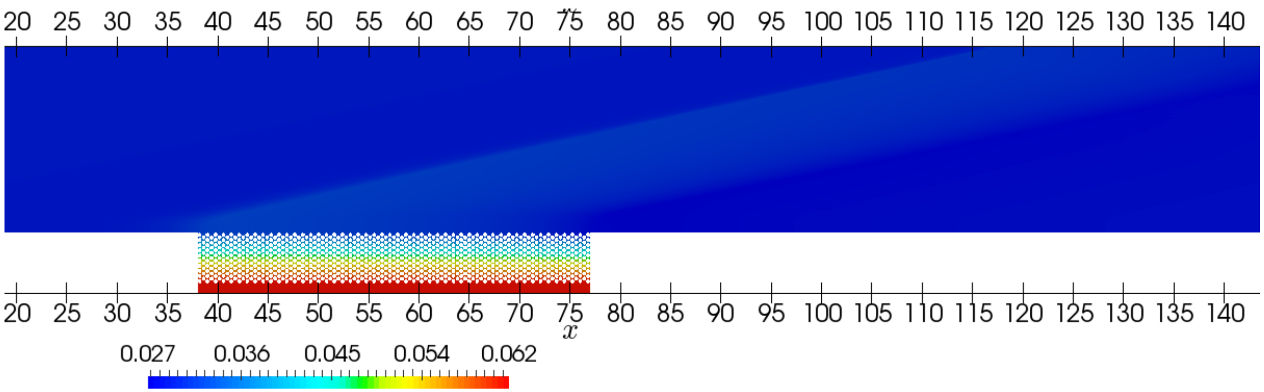


(Cerminara et al., Aerospace Science Technology, 2020)

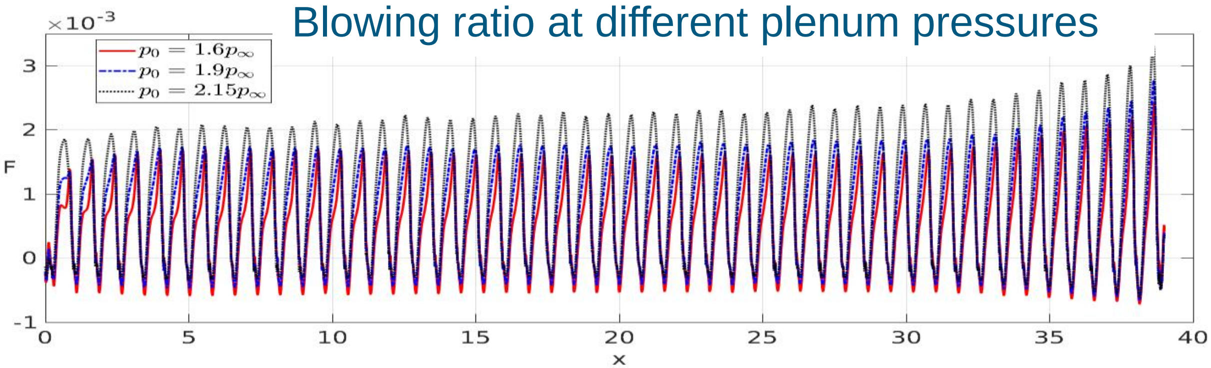
Modelling of porous material

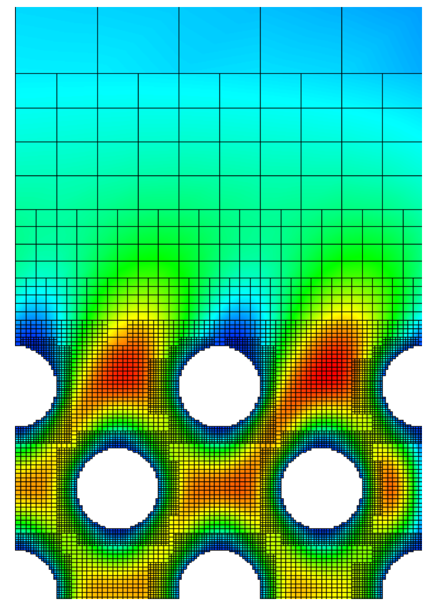
- Original project proposal assumed grain structures of >50μm
- Used material has grains <2μm (cost of DNS in porous material increases by factor approx. 25^4=390625)
- Our approach: model the porous media flow using regular sphere/cylinder arrays of resolvable mesoscopic size

Cylinders with radius of 200μm, pressure contours



Blowing ratio at different plenum pressures



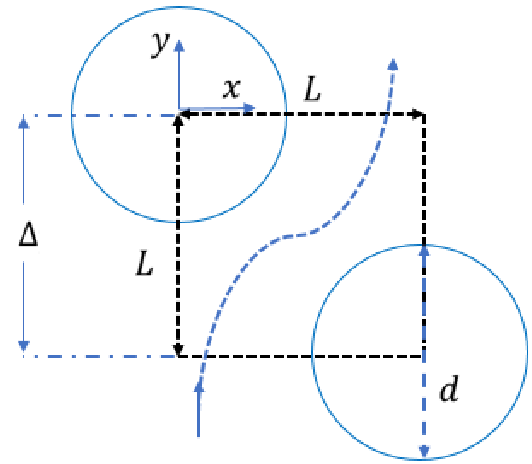


Automatic adaptive mesh (vertical velocity)

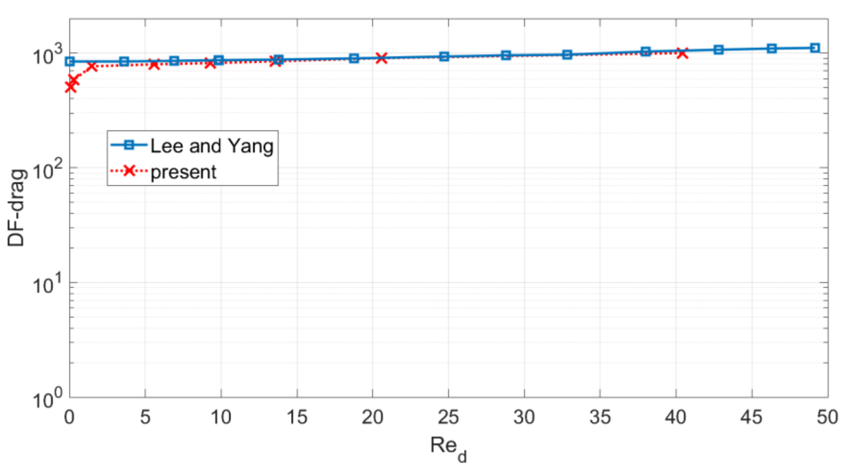
Mesoscopic Darcy-Forchheimer model

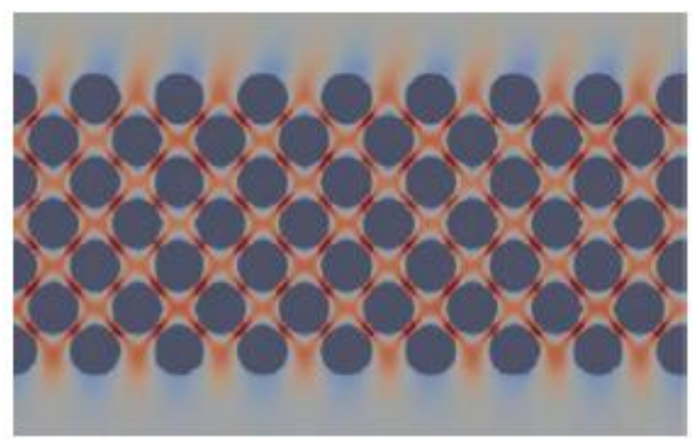
$$\left(\frac{d^2}{K} + FRe_d\right) = \frac{\Delta p}{L}\frac{d^2}{\mu U} = \text{D} - \text{F drag} \qquad Re_c = \frac{\rho U_C L}{\mu} \qquad U_c = \sqrt{\frac{\Delta p}{\rho}} \qquad Re_d = \frac{qd}{\mu} = Re_c\left(\frac{d}{L}\right)q$$

$$q = \frac{1}{\rho U_C}\frac{1}{L}\int_0^L \rho u dx \qquad \frac{d}{L} = \text{f}(\varepsilon) \qquad \Delta p = \rho\left(\frac{Re_C \mu}{\rho L}\right)^2$$



- Objective: represent the pressure drop of micro-structured material with larger cylinders
- Idea is to vary *d* but maintain *q*
- Preliminary study follows approach of Lee and Yang (1997)





Zoom in: y-momentum in porous layer for *d*=12µm

Matching with experiment in terms of blowing ratio, and rescaling to higher pore sizes

Quantifying integrated blowing ratio solution (q) for the different pore/particle sizes:

$$Re_C = 1.67$$

$$d = 12\,\mu m \rightarrow q = 3.8 \times 10^{-3}$$

$$d = 24\,\mu m \rightarrow q = 3.7 \times 10^{-3}$$

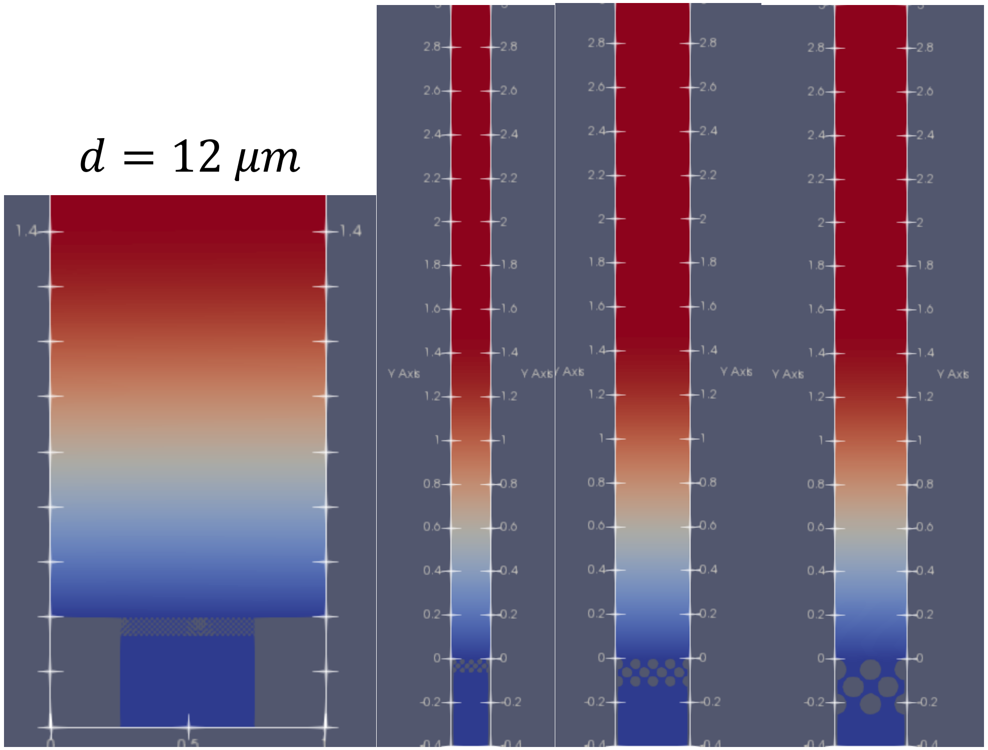
$$d = 48\,\mu m \rightarrow q = 3.6 \times 10^{-3}$$

$$d = 96\,\mu m \rightarrow q = 3.8 \times 10^{-3}$$

Simulation results show rescaling capability from very small pore sizes to higher scales in terms of the D-F behaviour

$d = 24\,\mu m$ $d = 48\,\mu m$ $d = 96\,\mu m$

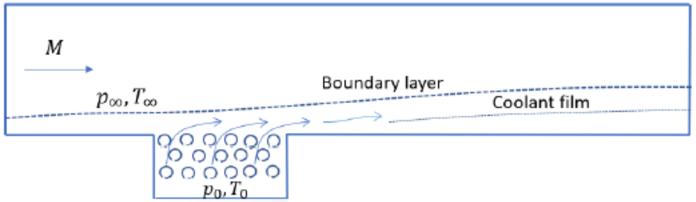
$d = 12\,\mu m$

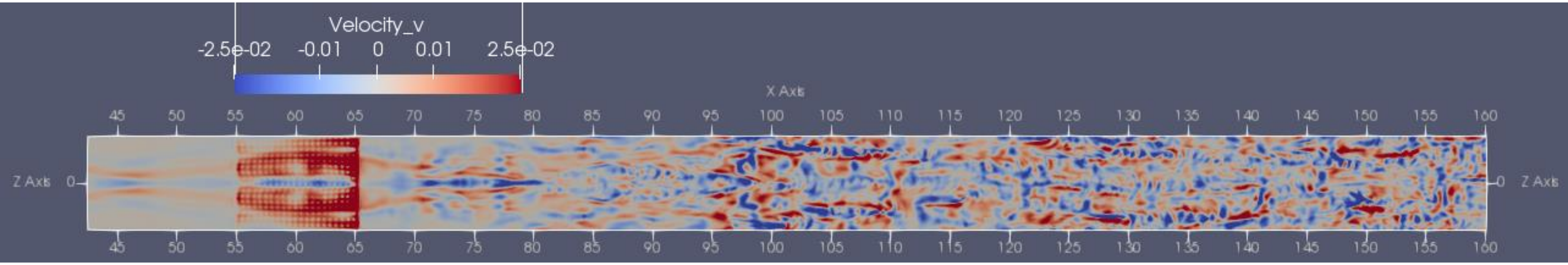


Streamwise velocity

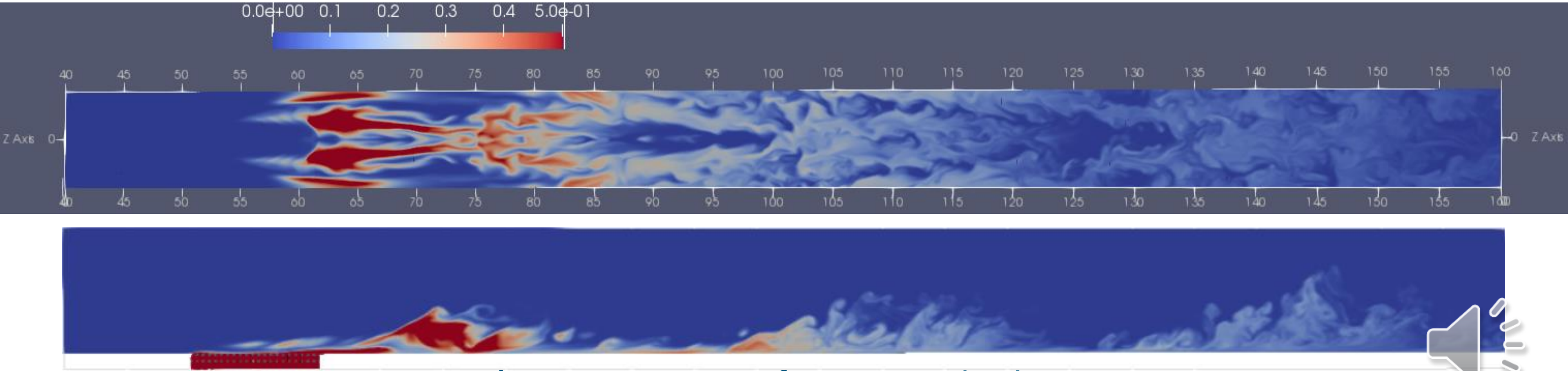
Oxford ultra-high temperature ceramics experiment

- M=5, Re=12.6E6 1/m from Herman et al. HiSST (2018)
- F_{porous}=0.002, porosity 42% modelled with spheres of diameter d=340μm
- p_0=1.3 p_{inf}, to match blowing ratio
- 2000 x 300 x 100 mesh plus 2 levels refined factor 2





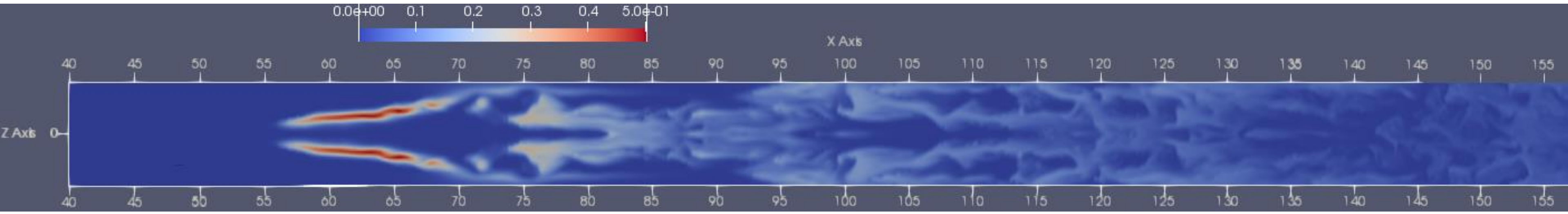
v-velocity: note specimen on left and transition to turbulence towards the right



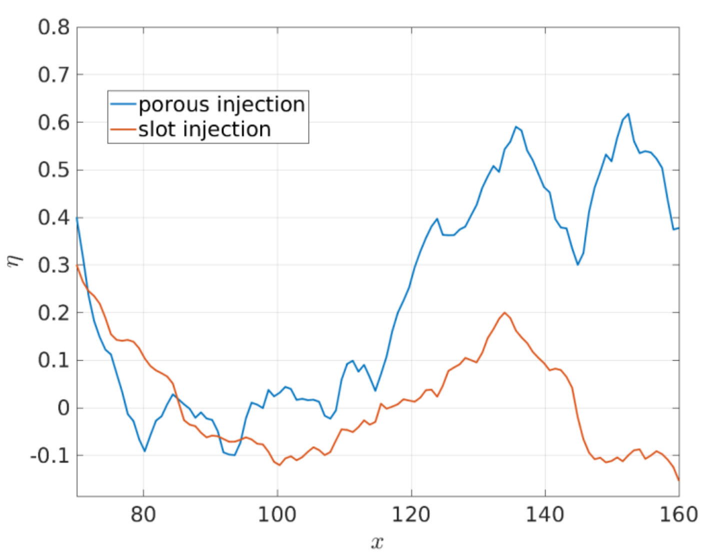
Coolant concentration from top and side view

Comparison with suitable slot case

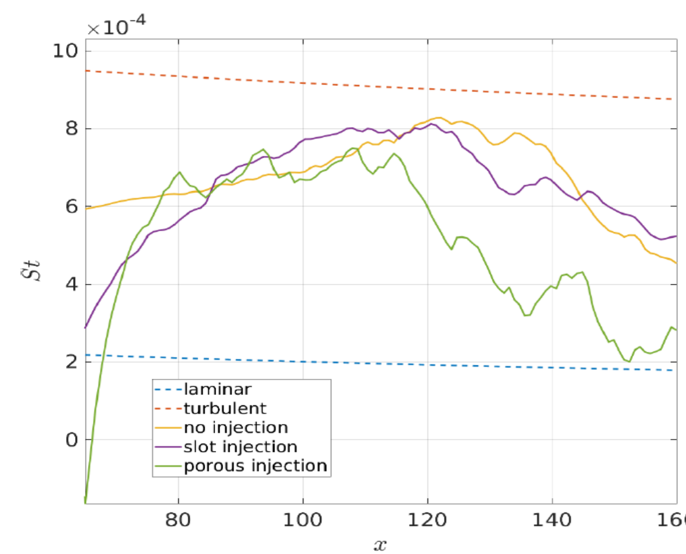
- Chose a slot case with comparable non-dimensional mass flow of injected coolant $d=\rho UA_{inj}$
- F_{porous}=0.002, F_{slots} =0.045,
- d_{slots} = 0.173, d_{porous} = 0.144



Cooling effectiveness (averaged spanwise and in time)



Stanton number (averaged spanwise and in time)



(Cerminara, Deiterding, Sandham. Int. J. Heat Fluid Flow, 2020)

Conclusions

- A hybrid 6th order multi-species WENO/CD method in the AMROC framework for DNS of hypersonic boundary layers with wall injection has been implemented
    - Method is efficient, robust and runs well on large parallel systems
- Have developed a novel mesoscopic model for flow through porous structures that can be used with accurate hypersonic boundary layer DNS, thereby avoiding resolving the O(1-2μm) structures of the manufactured material
- Validation cases for both slot injection and porous injection have demonstrated a good agreement with available experimental results
- Level of realism in order to model realistic flight conditions will be increased further by supplementing the implementation with
    - Transient surface heat conduction modelling
    - Thermochemical and vibrational nonequilibrium models