Wall Tangential Zero Mass Flow Jets for Friction Drag Reduction

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Funded by EU H2020 DRAGY Project and University of Sheffield

Workshop on Turbulent Skin Friction Drag Reduction, December 4-5, 2017, Imperial College London

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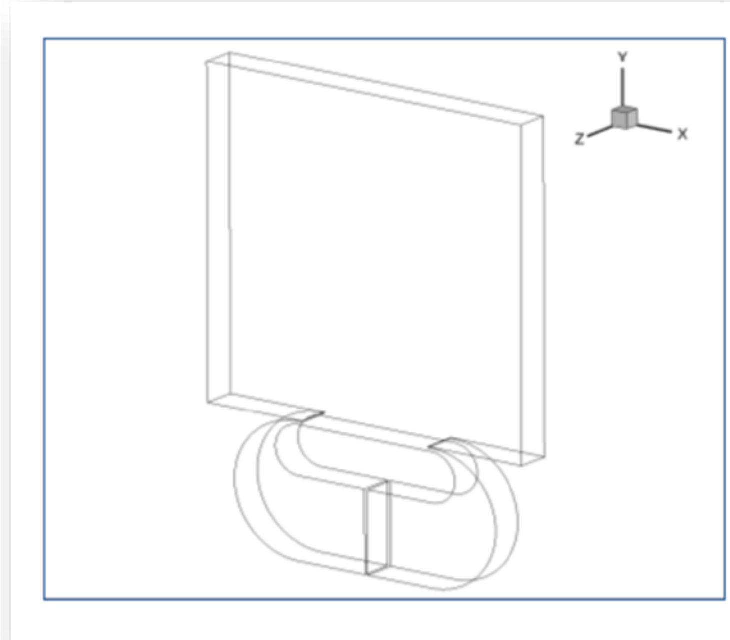
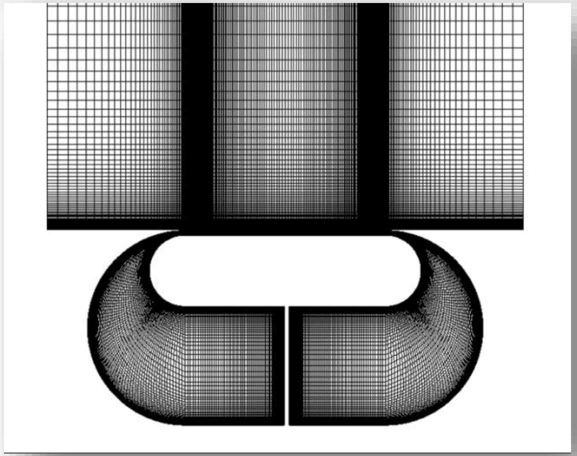
Methodology

- In-house code
  - SHEFFlow (for DNS)
- Unstructured solver with dynamic meshing
  - Simulation with moving surface, e.g. synthetic jets
- Extended to high order for structured mesh
  - 5th order by MUSCL scheme

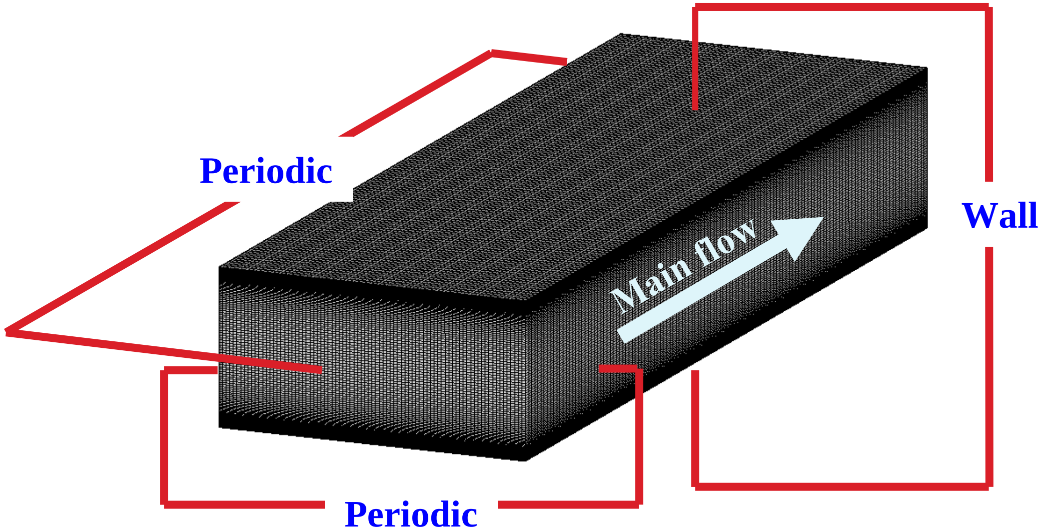


- Simulation of synthetic jets generation process
  - Jet exit velocity, slot height/spacing/number
- Analysis of energy efficiency of synthetic jet generation
  - Chamber shaping
- Validation of DNS for channel flow
  - Mesh sensitivity
  - parallel efficiency



Validation

The fully developed turbulent channel flow (constant flow rate)



Schematic of the channel flow and the boundary conditions

Flow condition:

$Re_{bulk} = 2800 \Rightarrow Re_{\tau} = 180$;
$U_{bulk} = 42$ m/s $\Rightarrow U_{\tau} = 2.7$ m/s

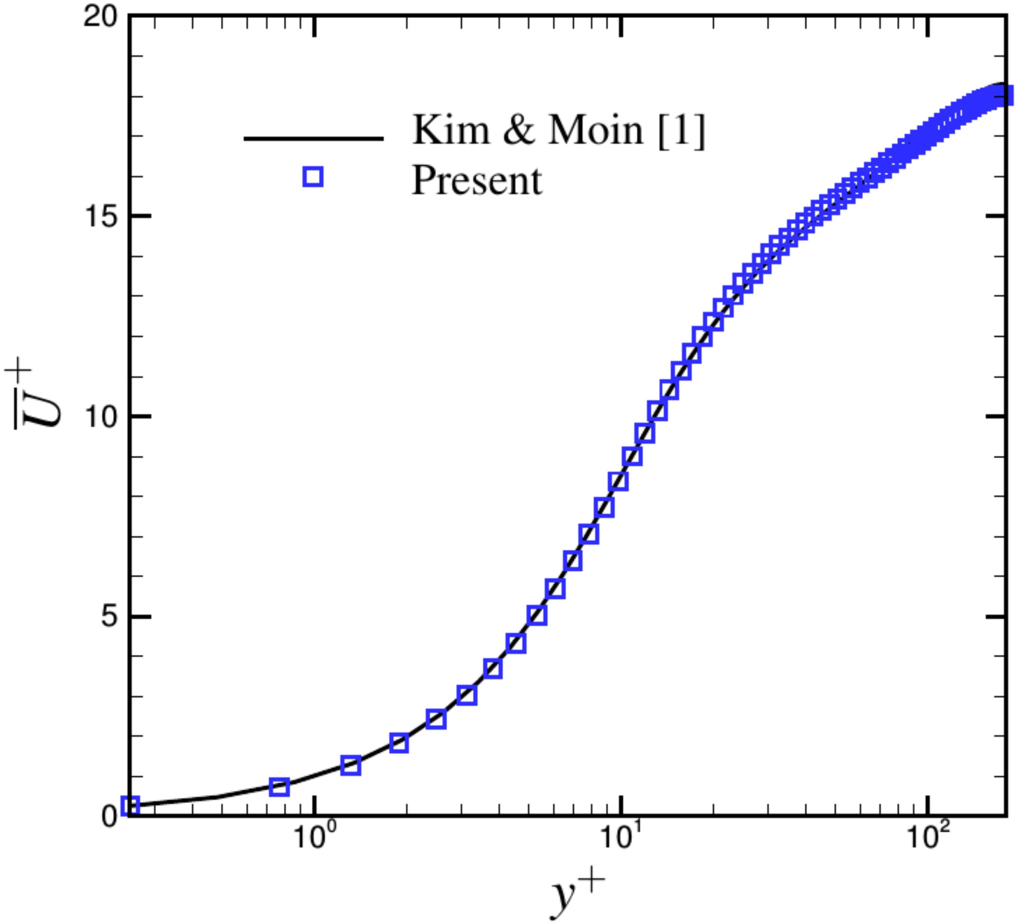
Mesh size : $128 \times 128 \times 84$
$\Delta x^{+} = 17.67$
$\Delta y^{+} = 0.2 \sim 7.098$
$\Delta z^{+} = 8.976$
$\Delta t^{+} = 0.486$
$L_x^{+} = 2262, L_y^{+} = 360, L_z^{+} = 754$

Result:

Data source	C_f
SHEFFlow	8.16×10^{-3}
Kim & Moin[1]	8.18×10^{-3}

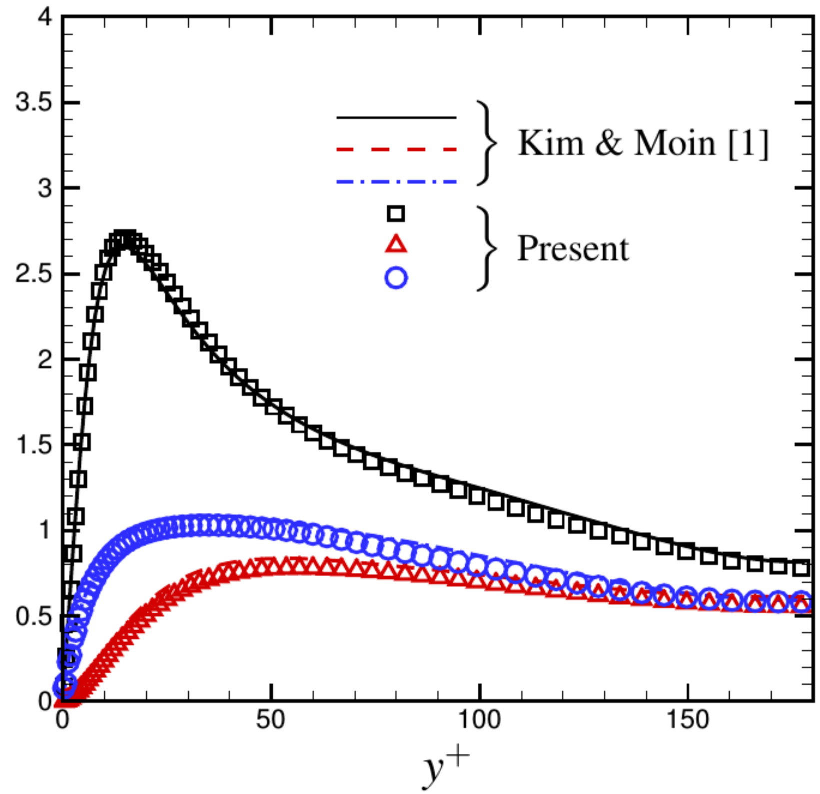
[1] Kim John, Parviz Moin, and Robert Moser. "Turbulence statistics in fully developed channel flow at low Reynolds number." Journal of fluid mechanics 177 (1987): 133-166.

Validation - I



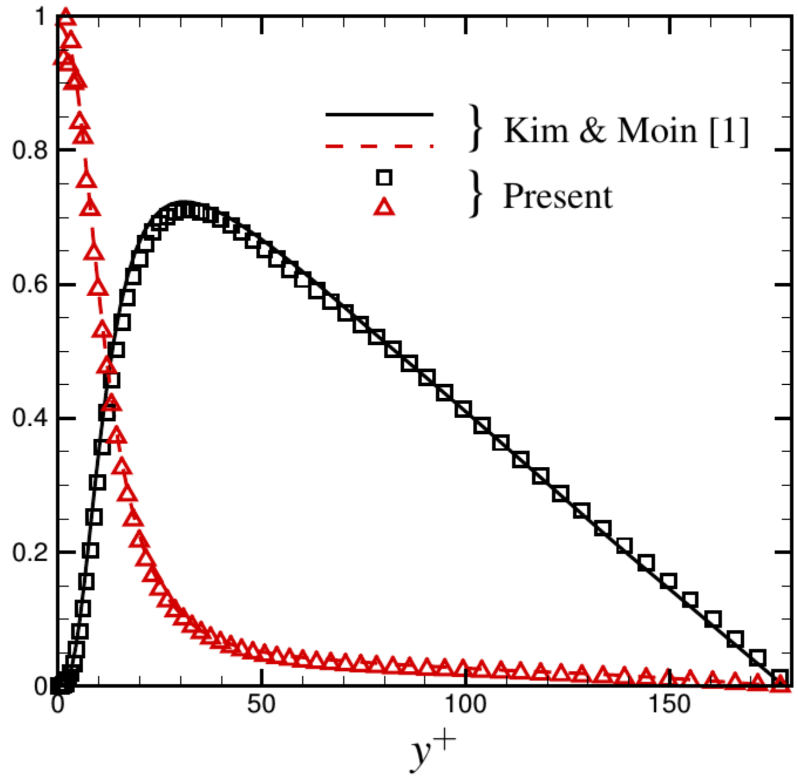
(a) The mean velocity profile.

Validation - II



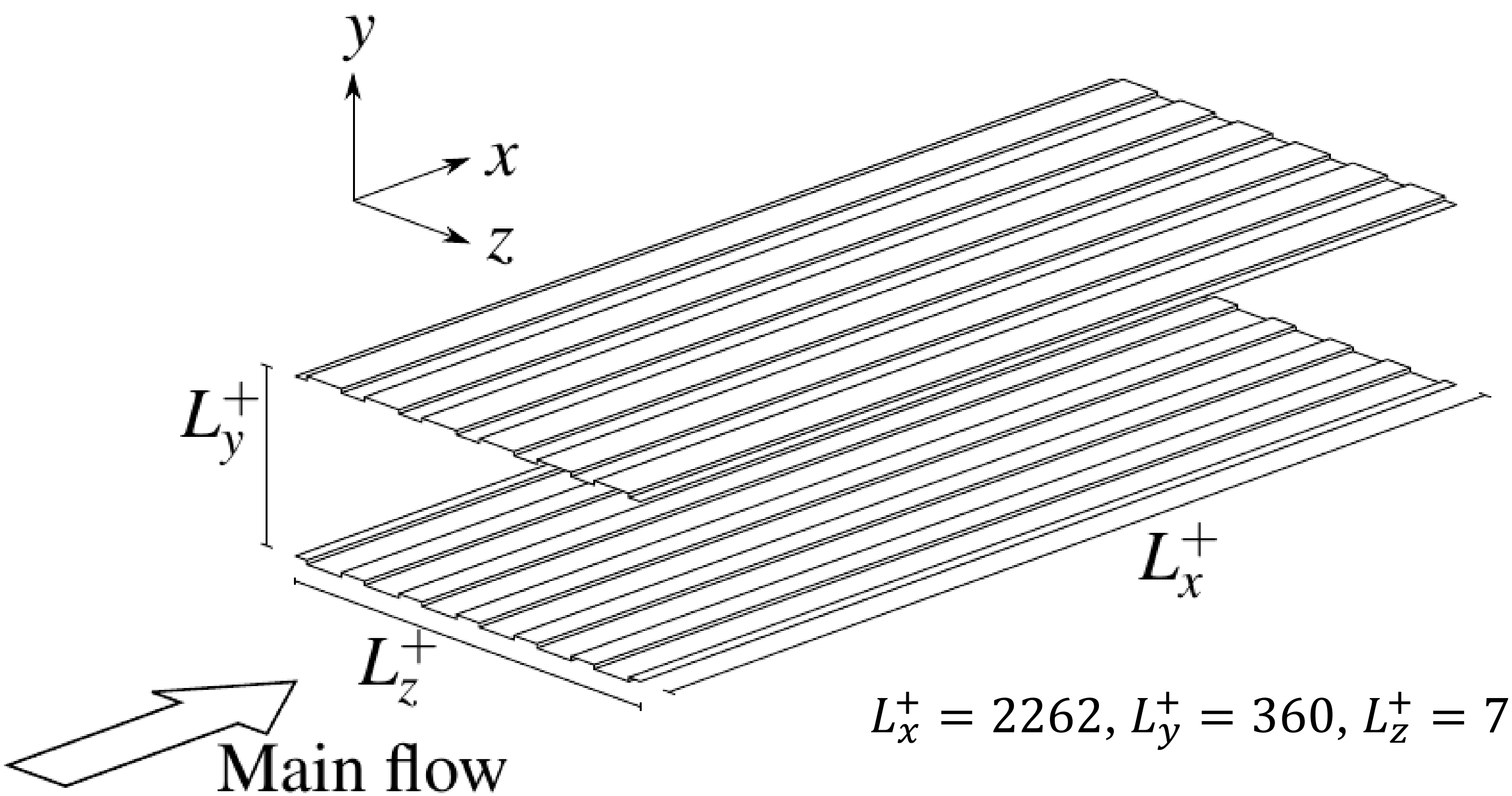
(b) Root-mean-square velocity fluctuations normalized by the friction velocity: u'_{rms}/u_τ, ———, □; v'_{rms}/u_τ, - - - -, △; w'_{rms}/u_τ, -·-·-, ○.

Validation - III



(c) Comparisons of the normalised viscous shear stress $\mu \frac{\partial u}{\partial y} / \tau_w$, - - - -, △; and Reynolds shear stress $-u'v'/\tau_w$, ——, □.

Setup of the ZMFJ control model



$L_x^+ = 2262,\ L_y^+ = 360,\ L_z^+ = 754$

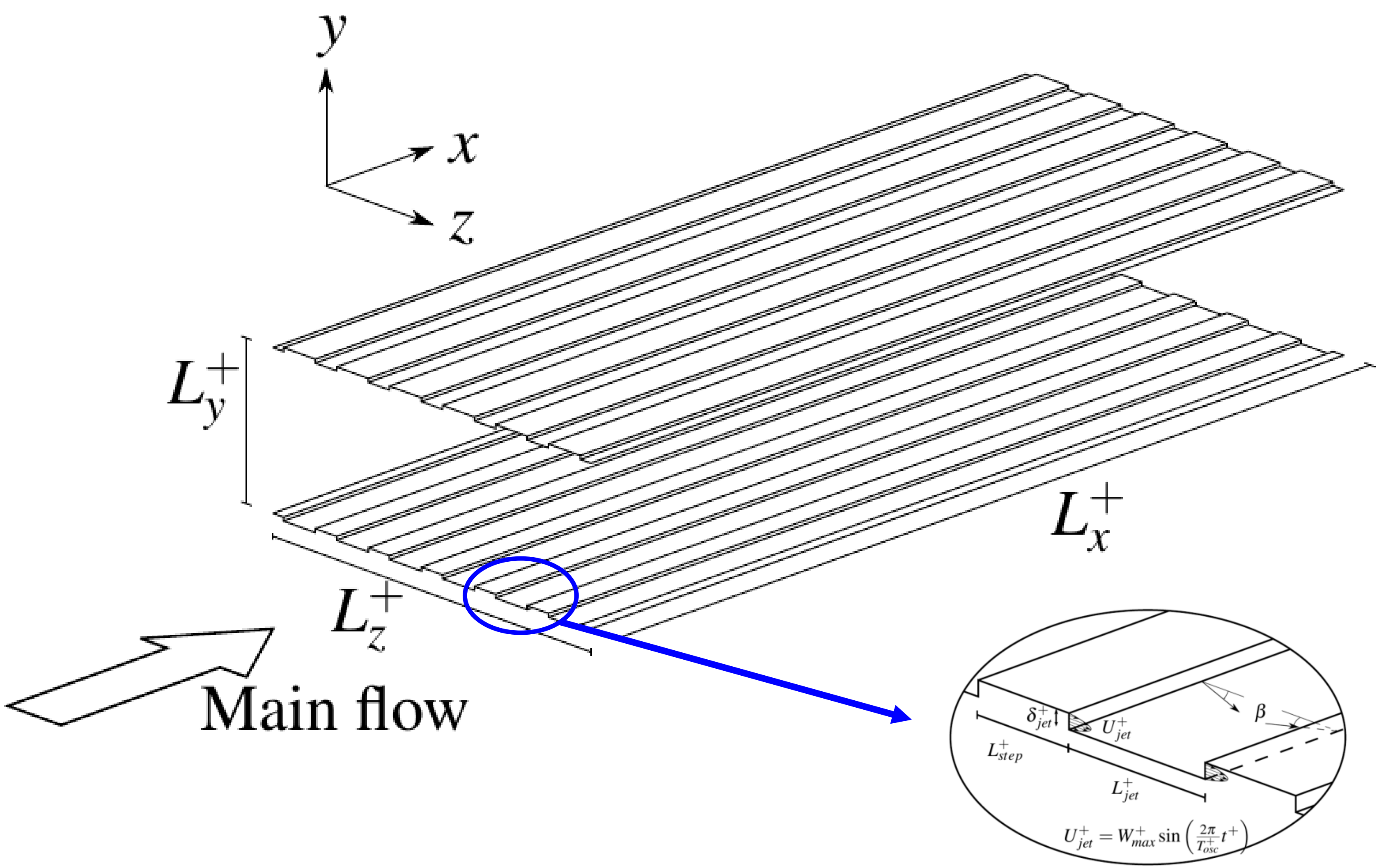
The definition of wall-units, where u_τ is defined by the baseline channel flow:

V^+ velocity V in wall unit, $V^+ = V/u_\tau$,

L^+ length L in wall unit, $L^+ = \rho u_\tau L/\mu$,

T^+ time T in wall unit, and $T^+ = \rho u_\tau^2 T/\mu$.

Setup of the ZMFJ control model



Setup of the ZMFJ control model

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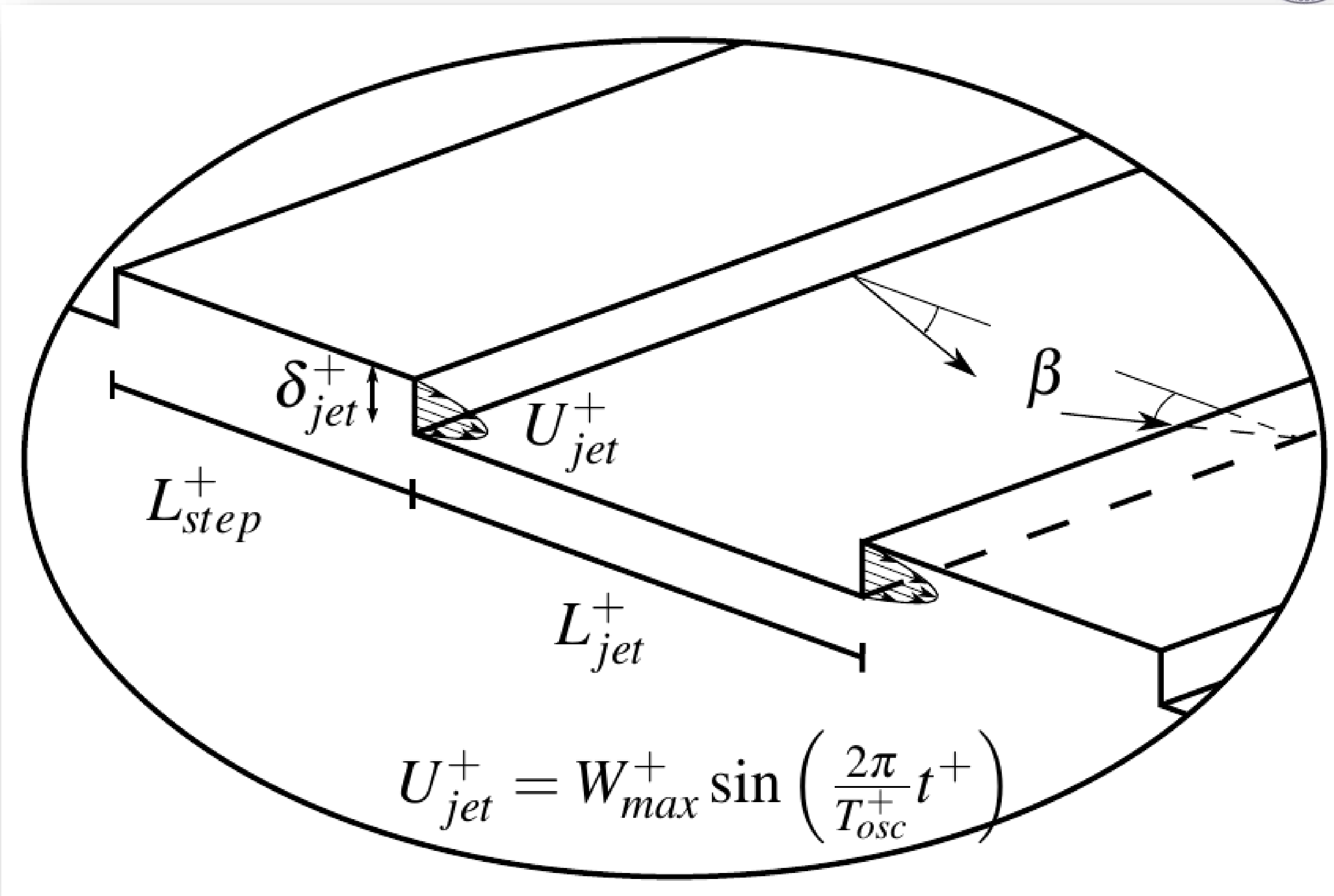


$\delta^+_{jet} = 2$, $W^+_{max} = 18$, $T^+_{osc} = 125$, $L^+_{step} = 36$, $L^+_{jet} = 90$,

$\Delta x^+ = 8.84$, $\Delta y^+ = 0.2 \sim 4.09$, $\Delta z^+ = 4.49$

Velocity decomposition

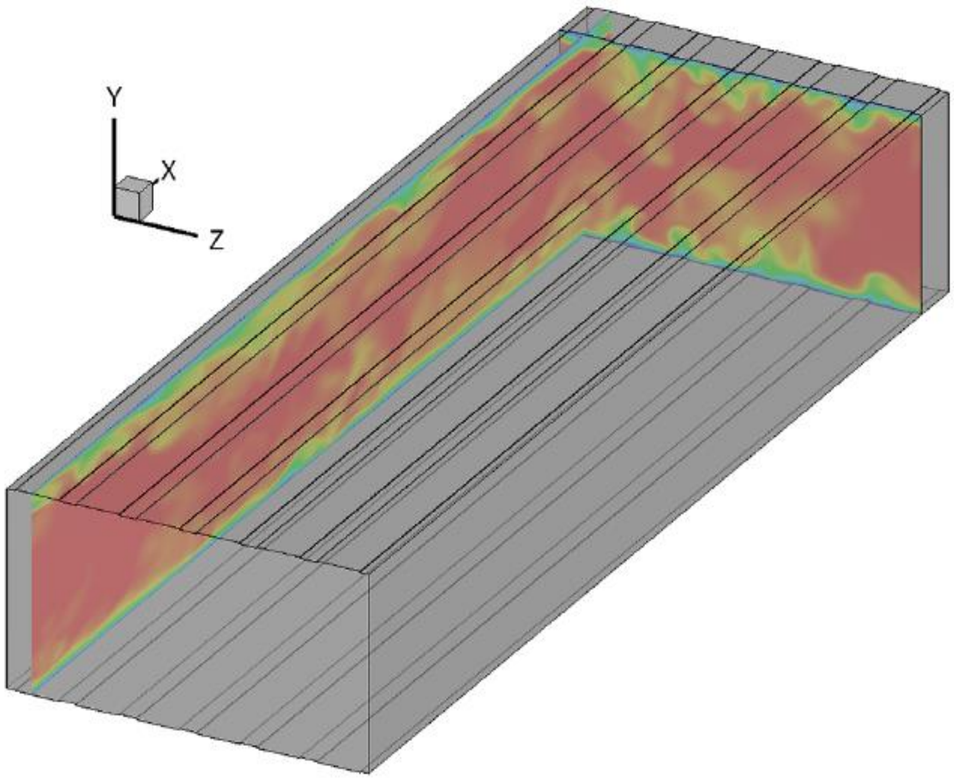
Triple decomposition of velocity:

The oscillating jets impose periodic velocity fluctuations in the flow, in addition to the pure turbulent fluctuations. Thus, the velocities (u, v, w) can be decomposed into three components

$$u = \bar{u} + \tilde{u} + u'', \; u' = \tilde{u} + u'', \; \langle u \rangle = \bar{u} + \tilde{u}$$

$\bar{u}$ time-averaged value, $\tilde{u}$ periodic velocity, u'' turbulent fluctuation of u, u' total fluctuation, $\langle u \rangle$ phase averaged value.

Post-processing of flowfield data



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Spatial averaging of flowfield data

Post-processing of flowfield data

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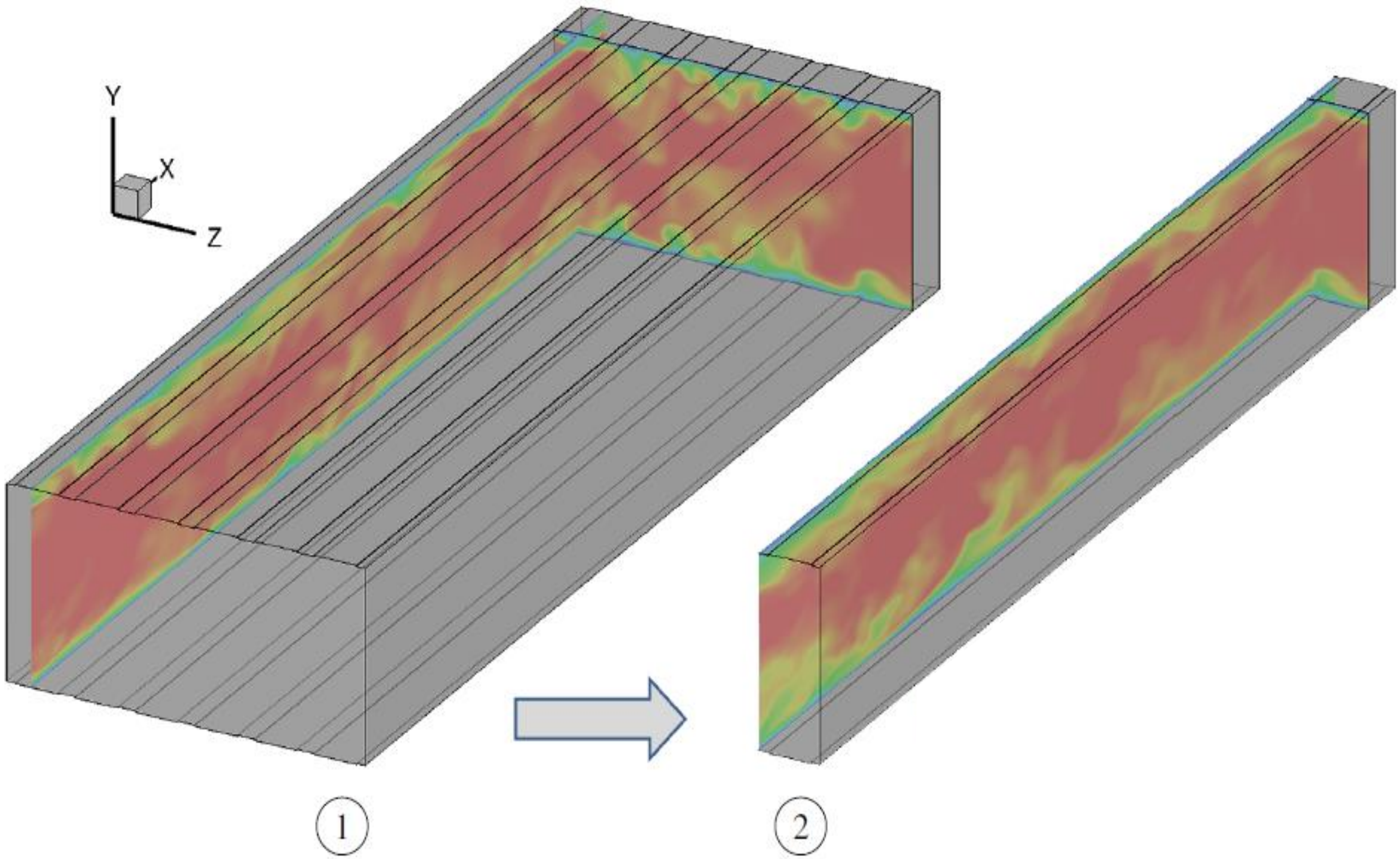

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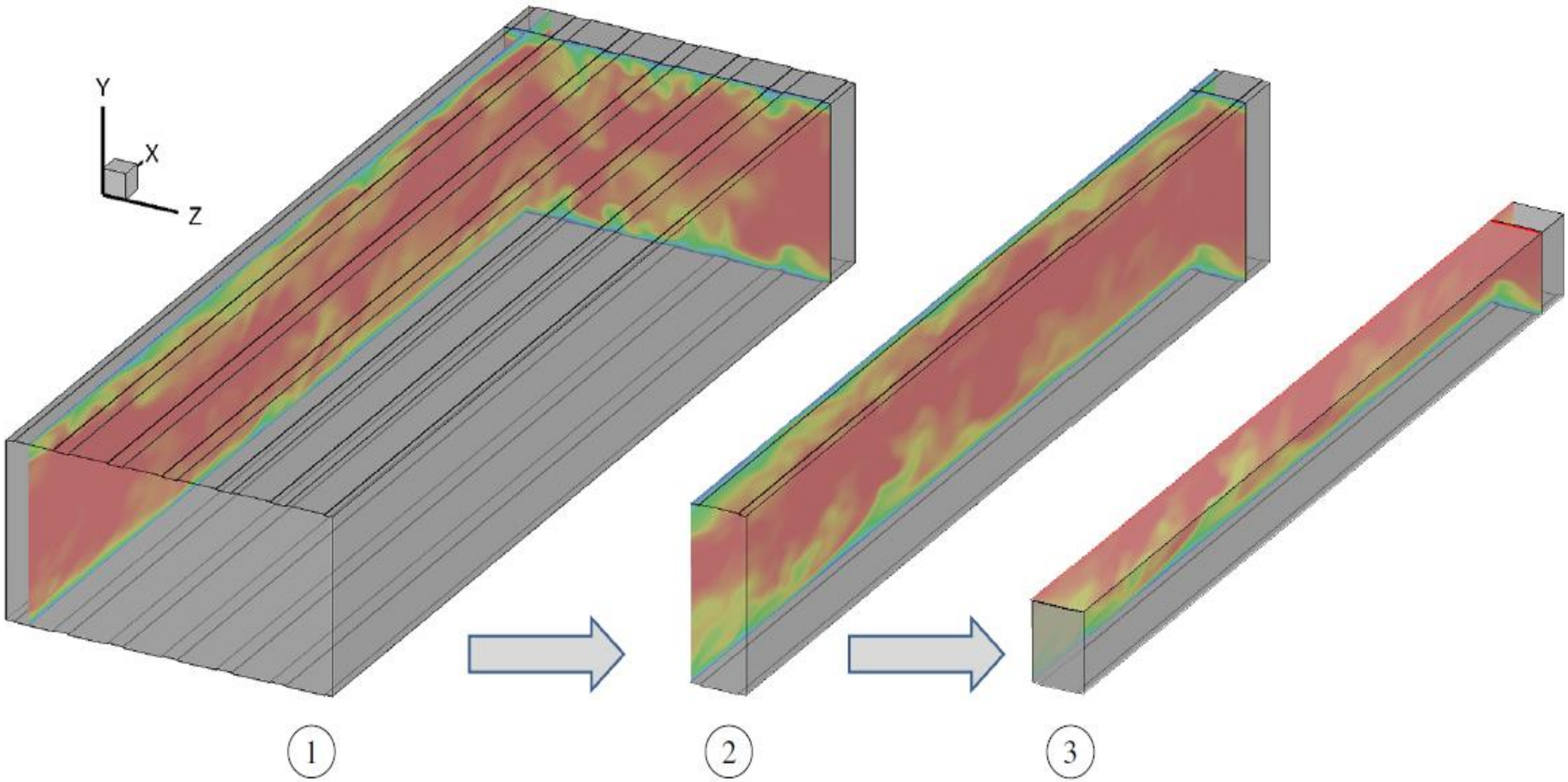

Spatial averaging of flowfield data

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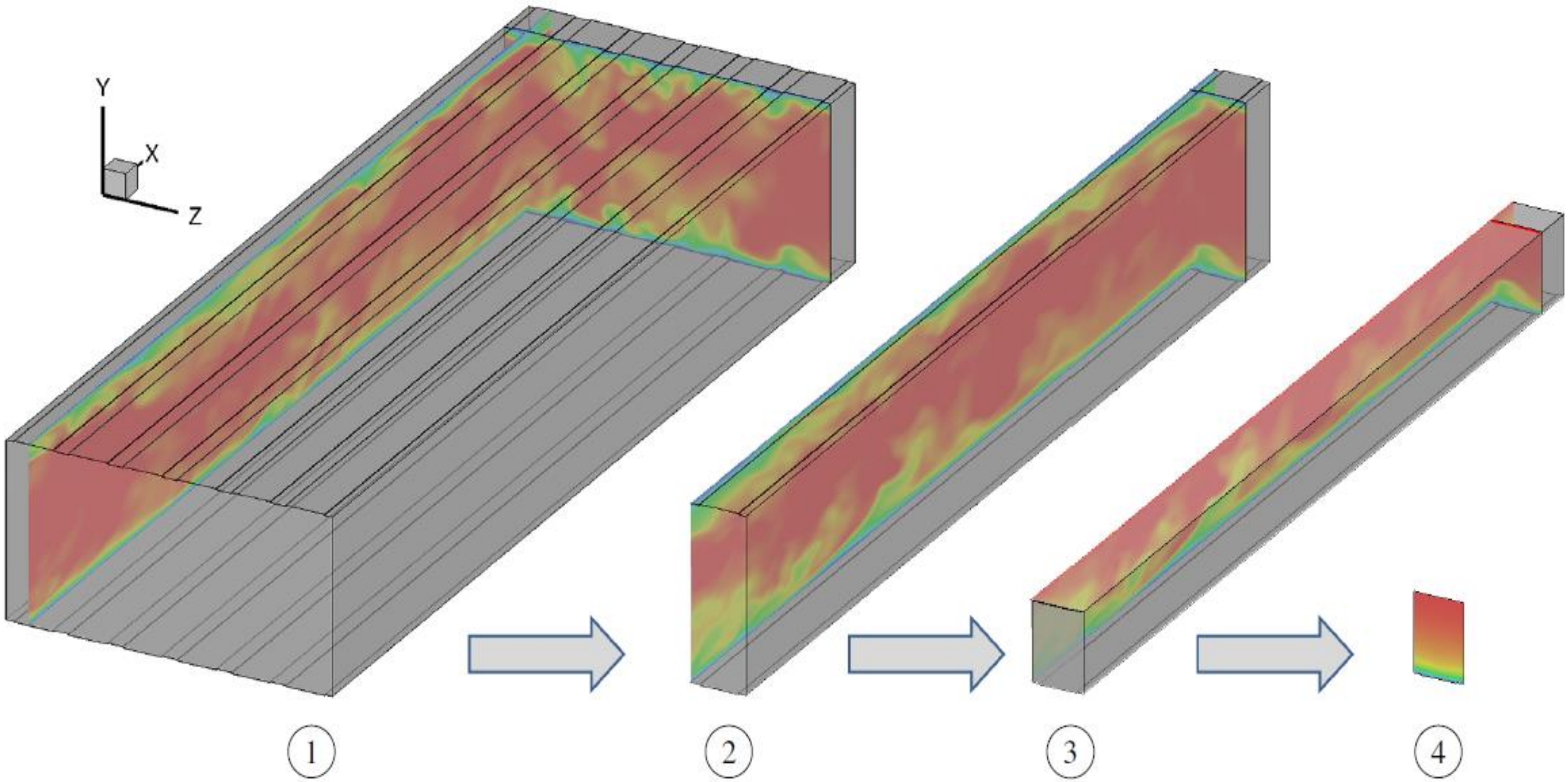
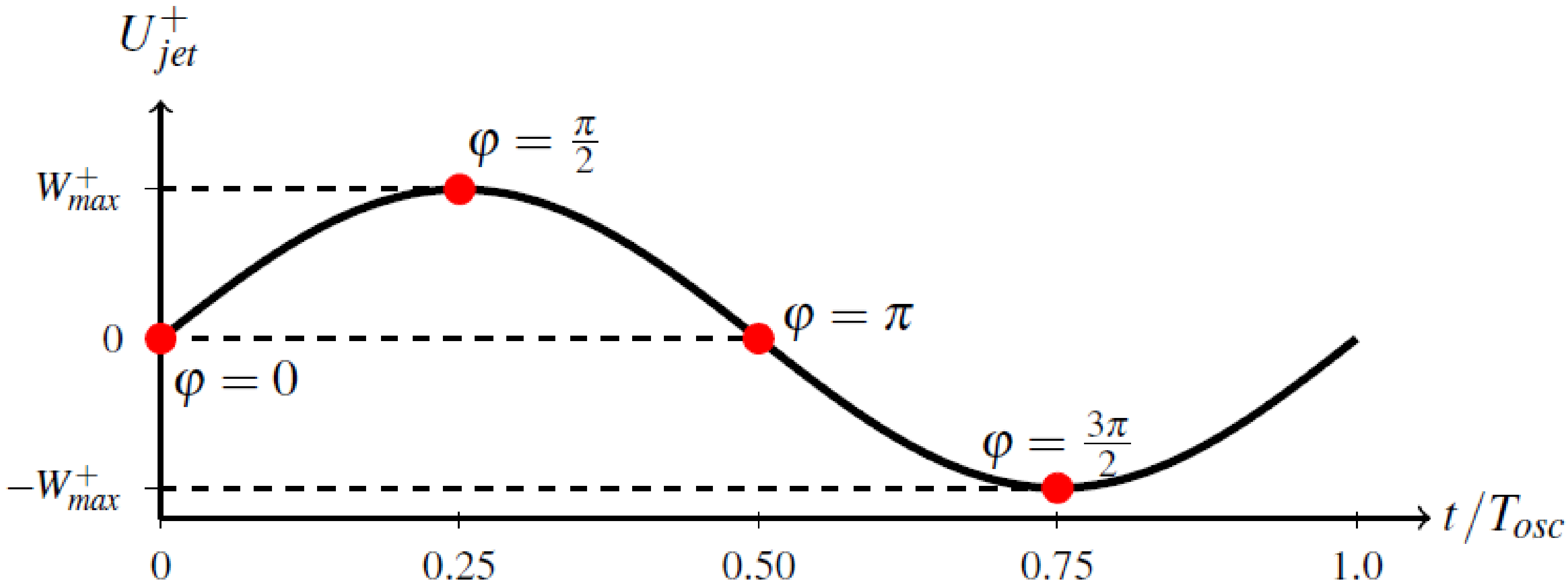


Spatial averaging of flowfield data

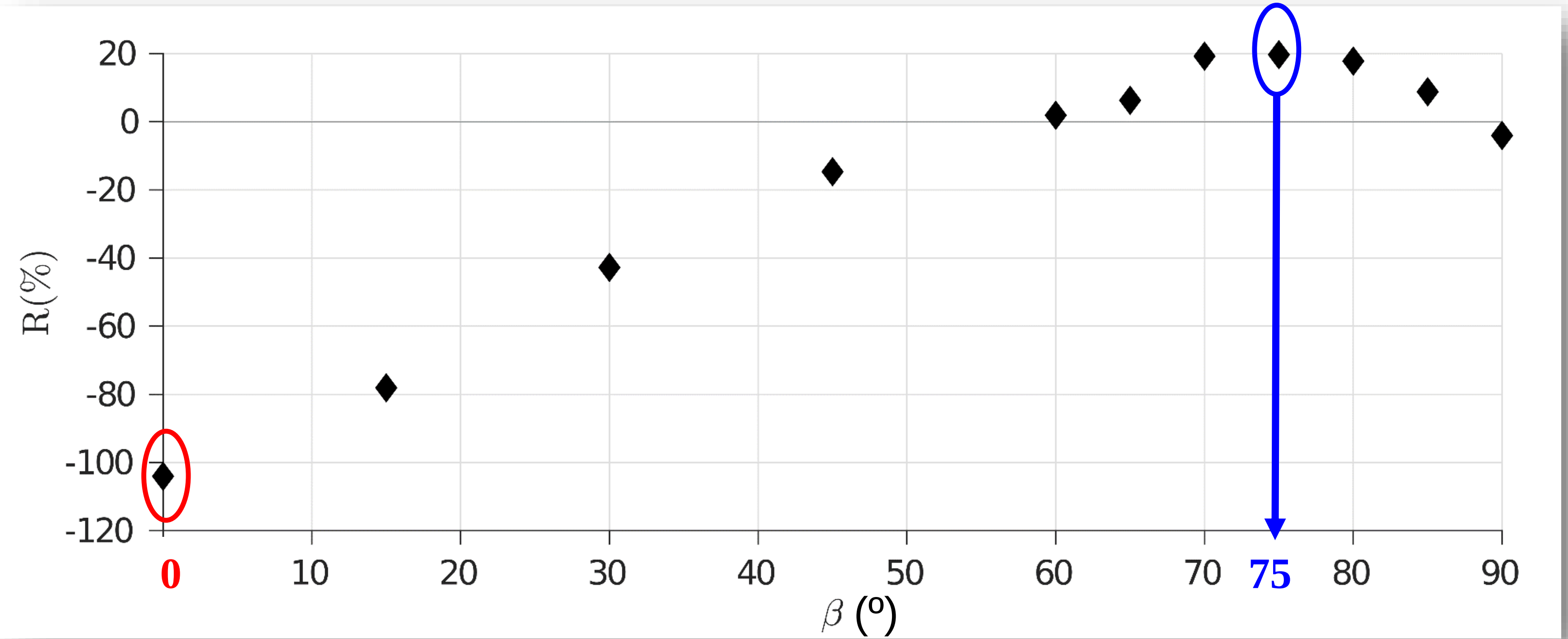
Periodic ZMJ



Periodic jet velocity distribution

- ❑ **Jets from the two opposing slots are exactly anti-phase**
- ❑ **Time mean mass flow for each slot is zero**
- ❑ **Mass flow to flow field is also zero instantaneously**

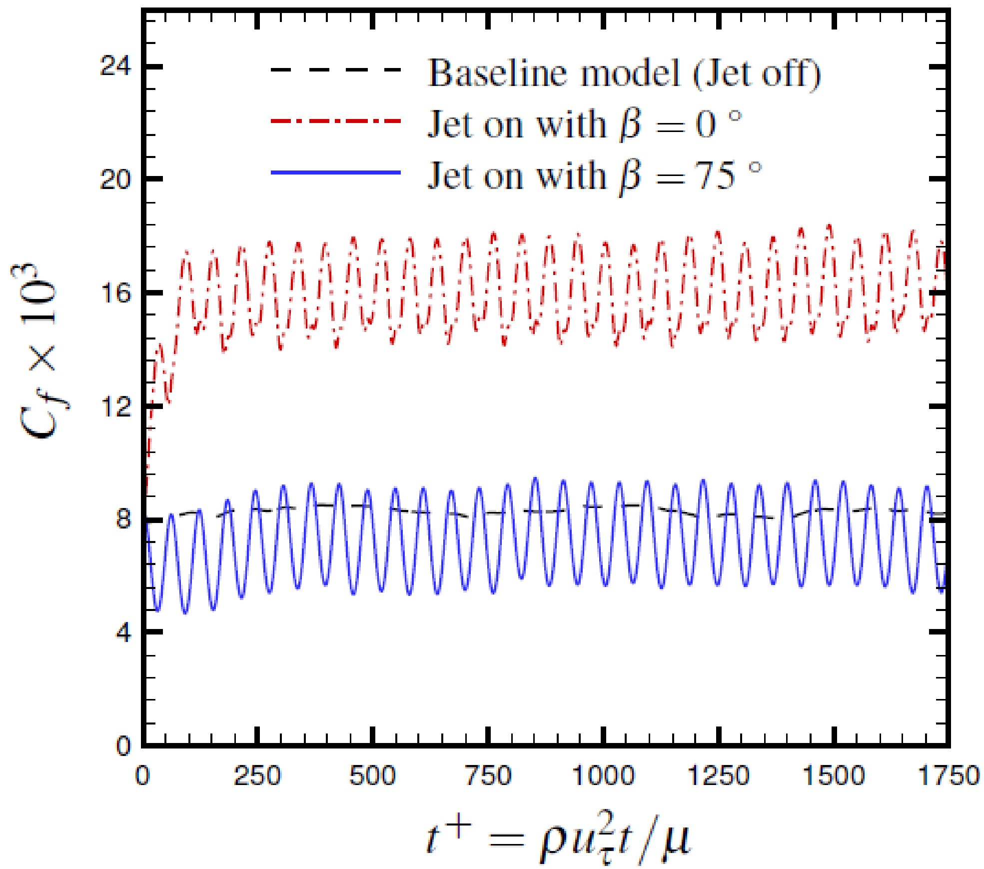
Effect of jet inclination angle on skin friction



Sensitivity of reduction of c_f to changes in β for $T^+_{osc} = 125$.

- Optimal angle was found at about 75 º between 70º and 80º
- Pure spanwise jets do not work

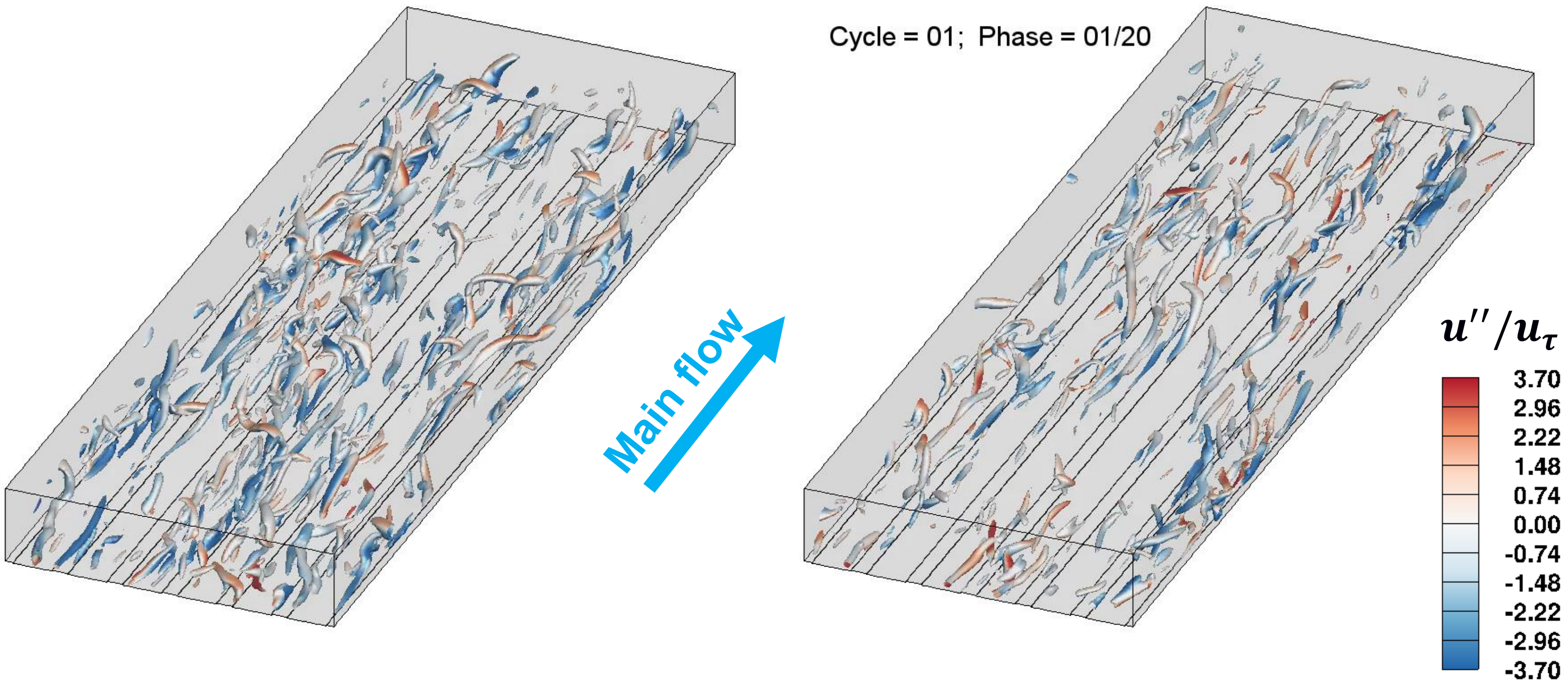
Comparison of skin friction



Case	Averaged C_f
Baseline model (jet off)	8.19×10^{-3}
Jet on with $\beta = 0^0$	16.08×10^{-3}
Jet on with $\beta = 75^0$	7.32×10^{-3}

- ✓ Pure spanwise jets have significant increase of averaged c_f
- ✓ Skin friction drag reduction with ZMFJ.

ZMJ on flow structures



Baseline model | **Jets on with $\beta = 75°$**

Iso-surface of λ_2 coloured by $\frac{u''}{u_\tau}$

Finer turbulent structures observed

ZMFJ on turbulent fluctuation

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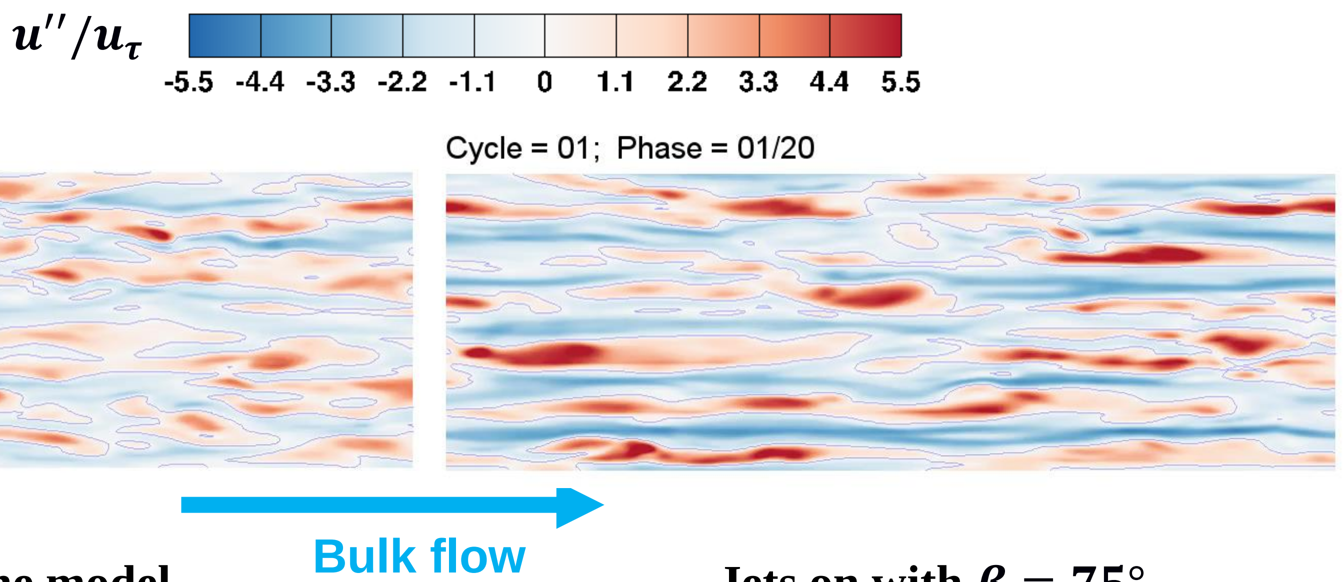


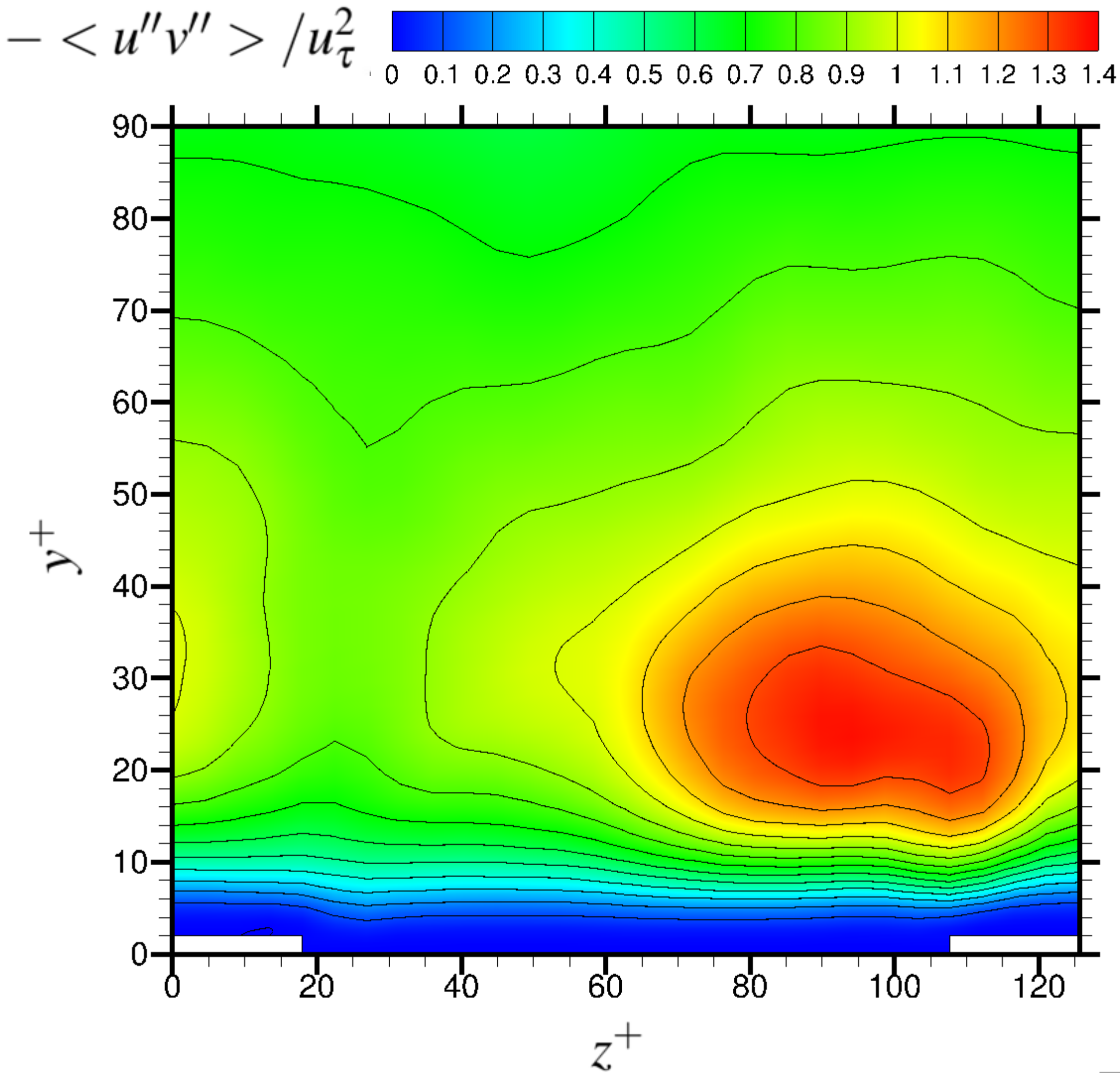
Baseline model

Jets on with $\boldsymbol{\beta = 75°}$

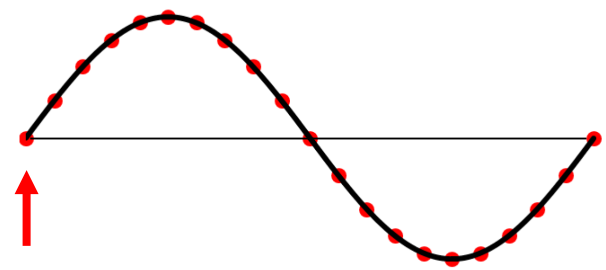
The contours of instantaneous $\boldsymbol{u''/u_\tau}$ at $y^+ = 5$.

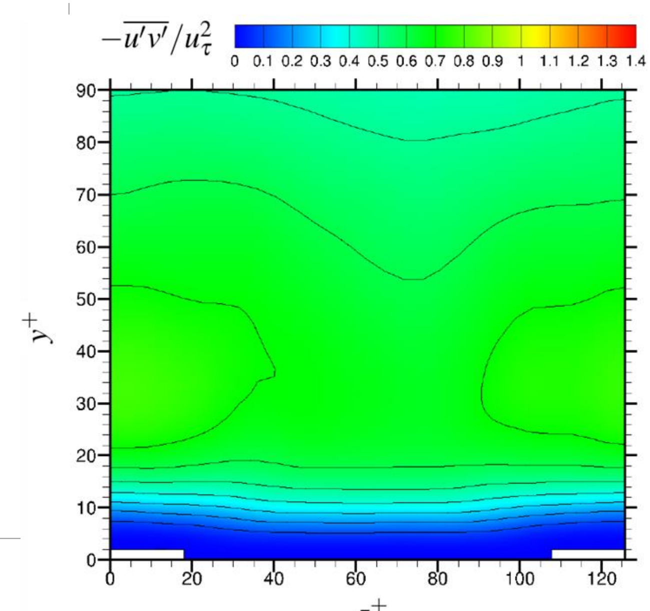
- Increased fluctuation can be clearly observed with control.

Reynolds shear stress in the inner layer



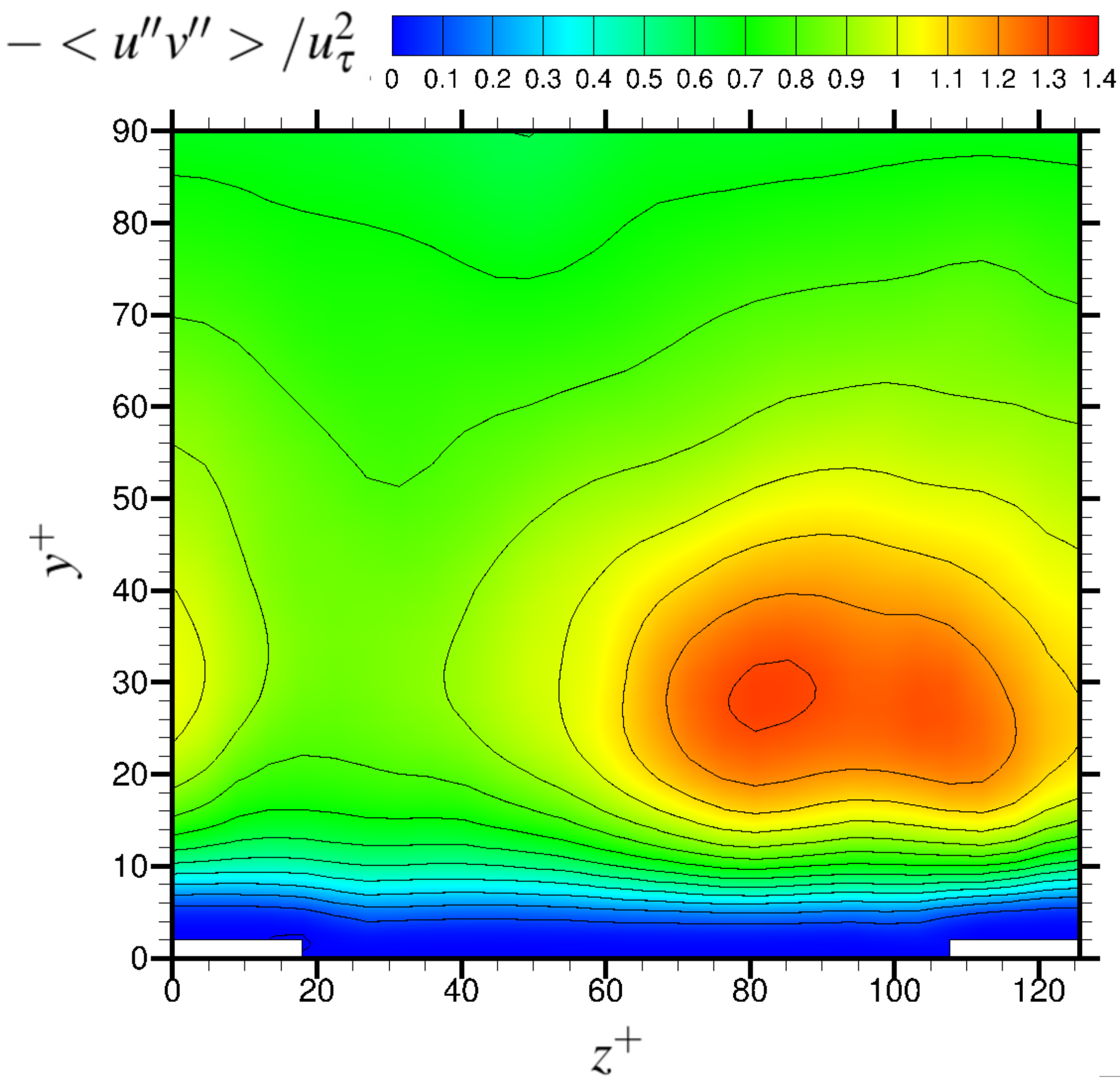
Jet on with $\beta = 75^0$

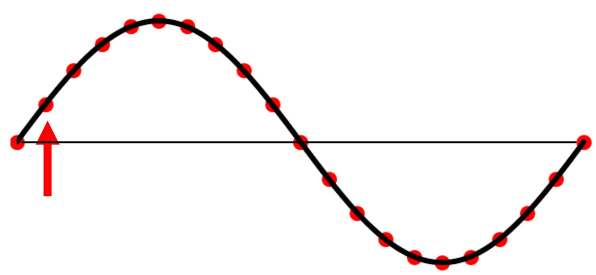




Baseline model (no jets)

Reynolds shear stress





Jet on with $\beta = 75^0$

Reynolds shear stress

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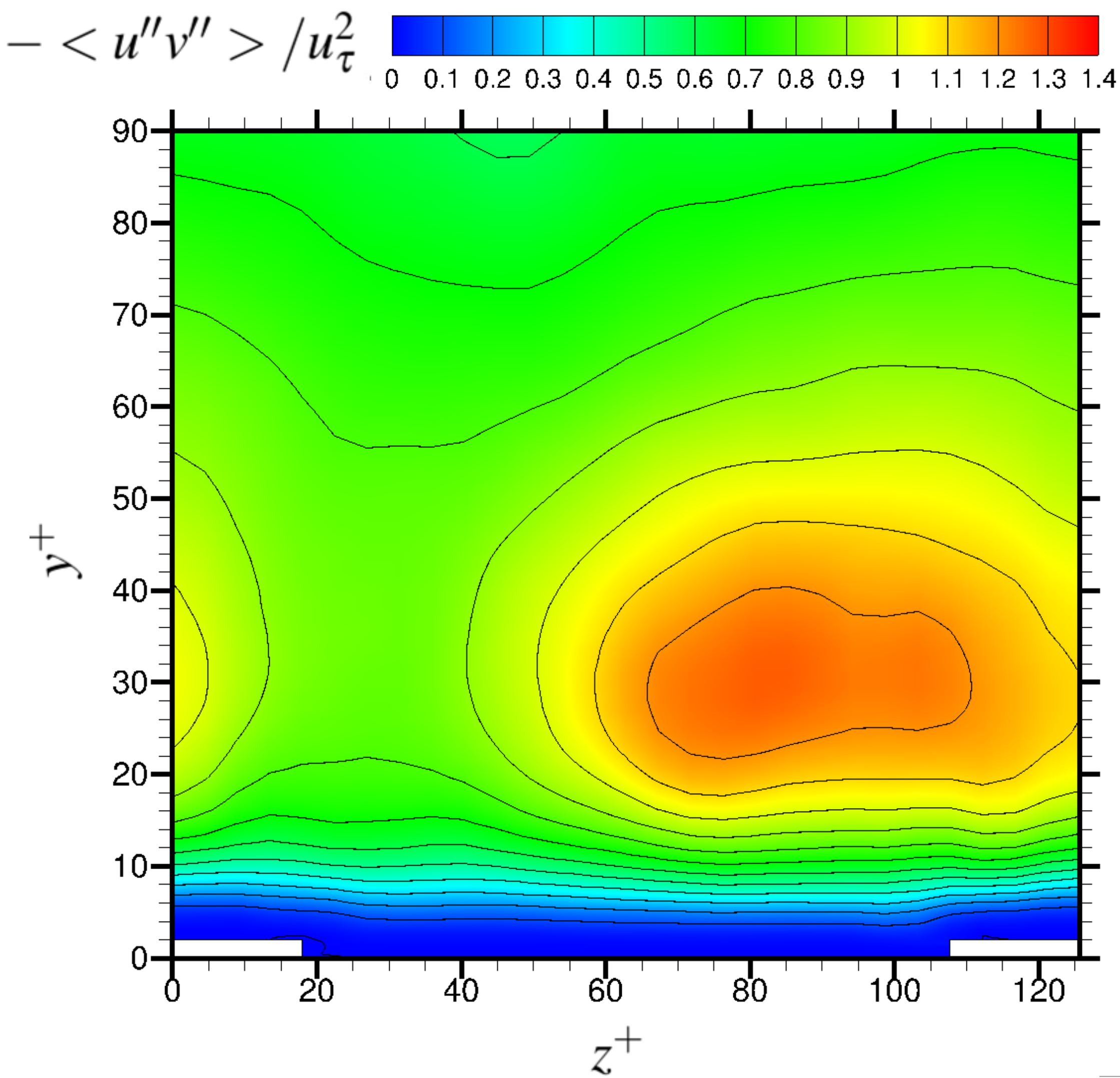

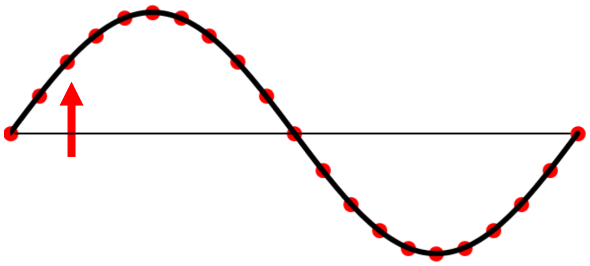

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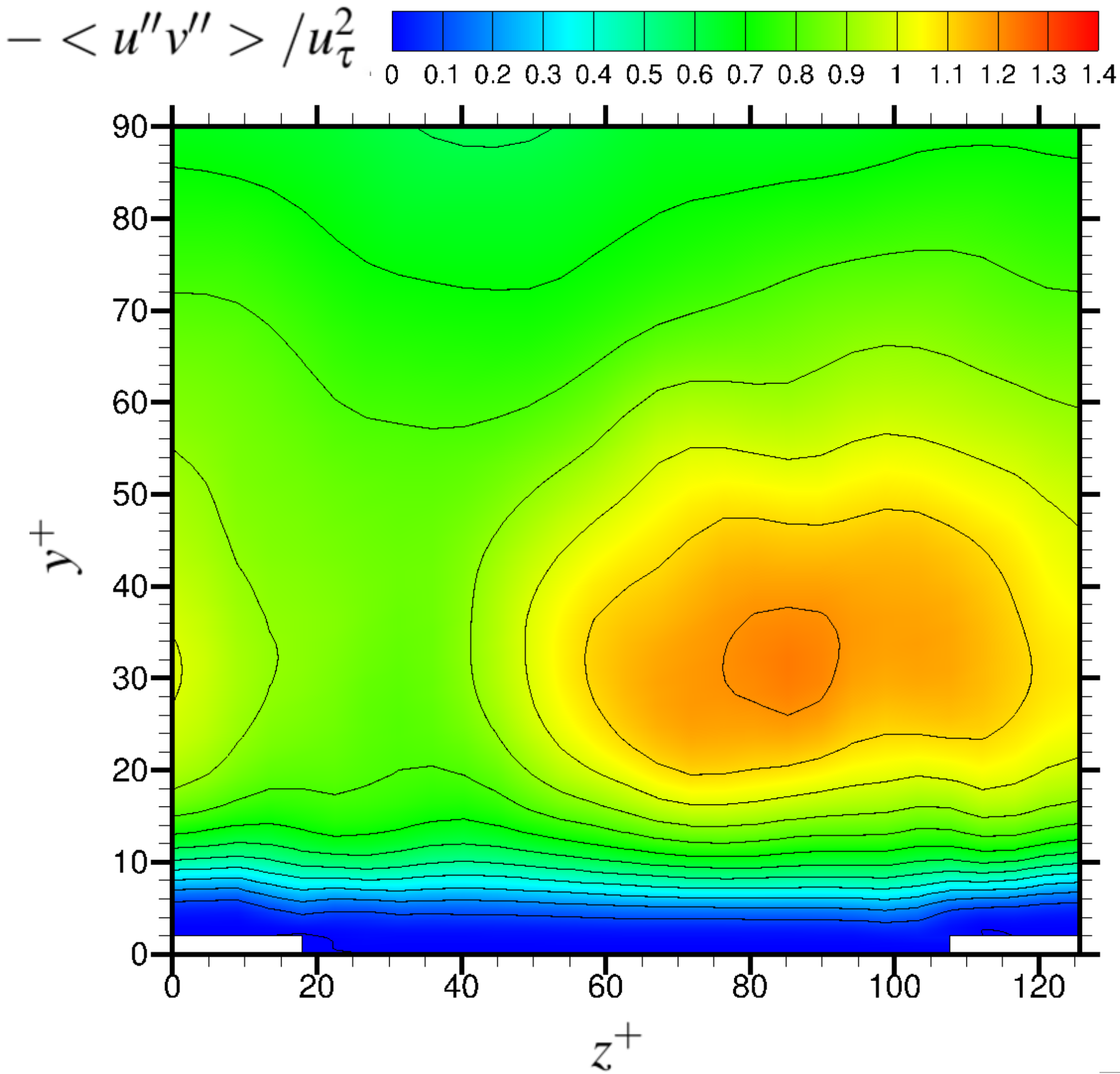
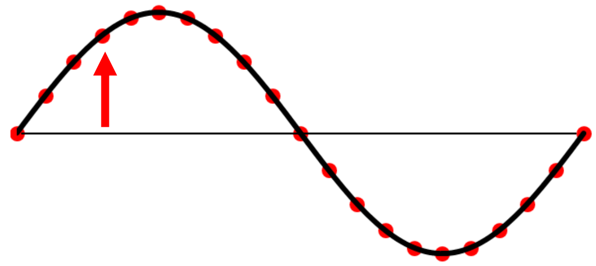
Reynolds shear stress





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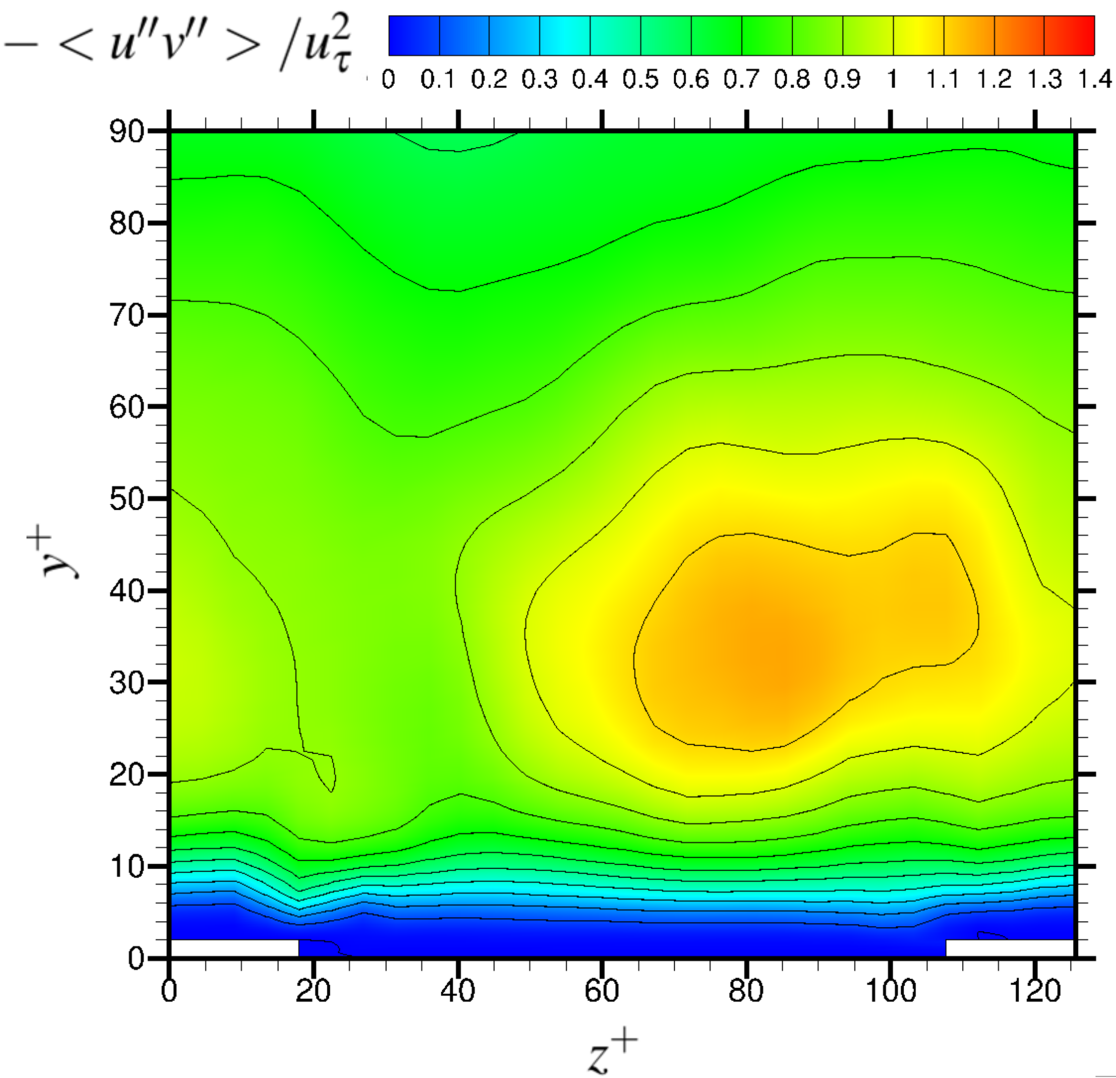

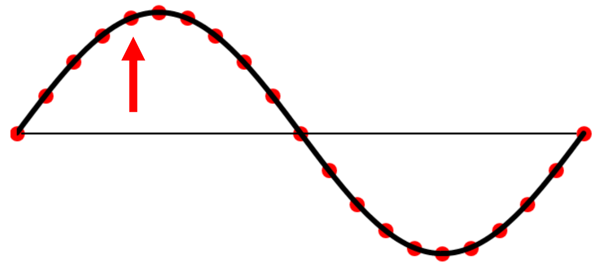

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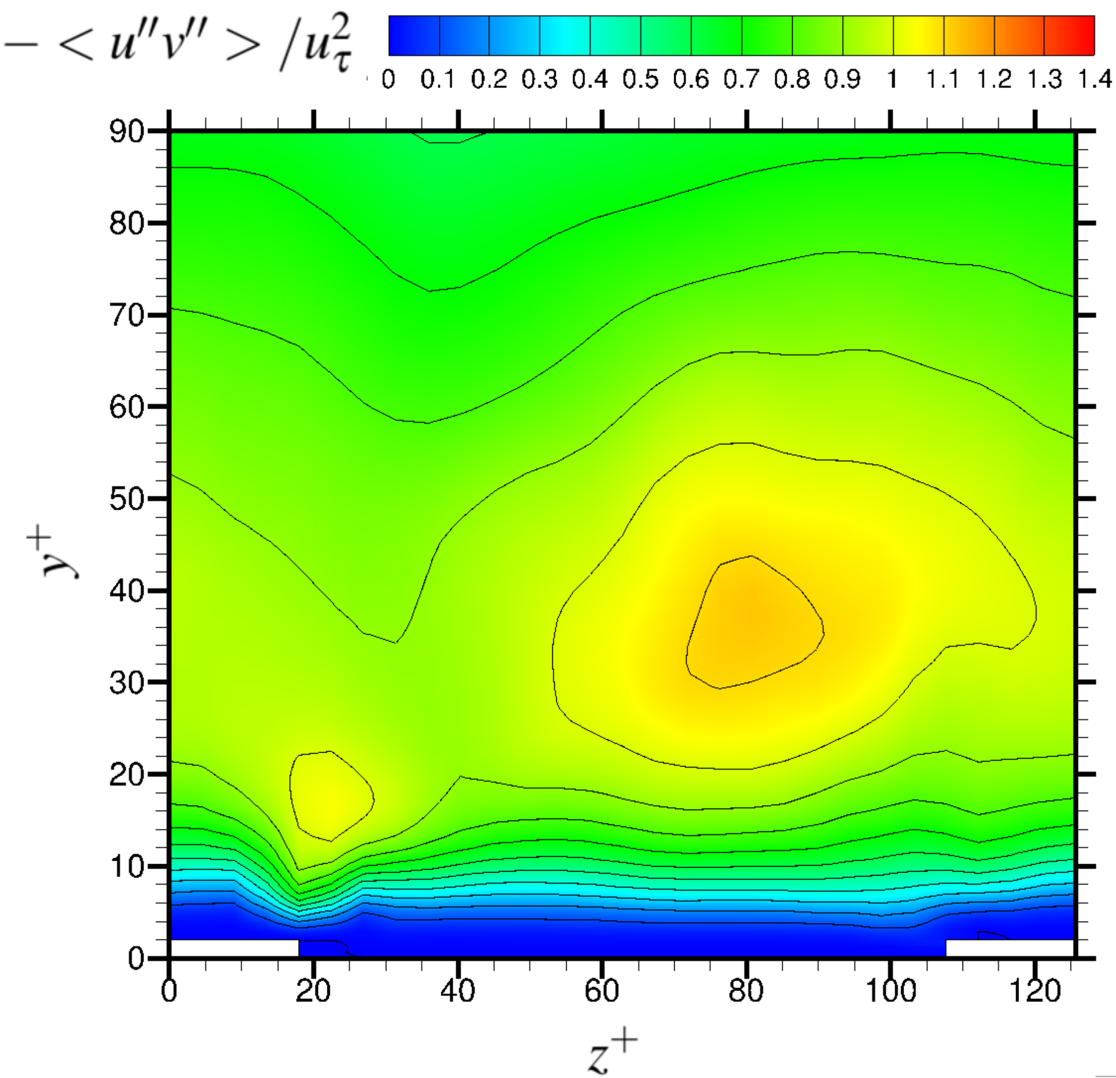

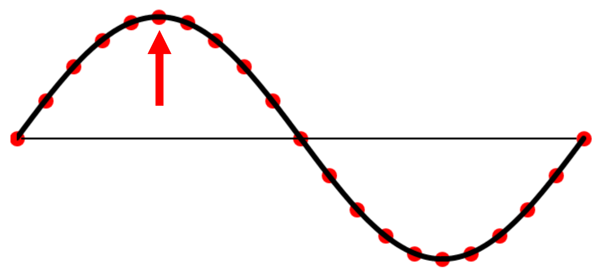

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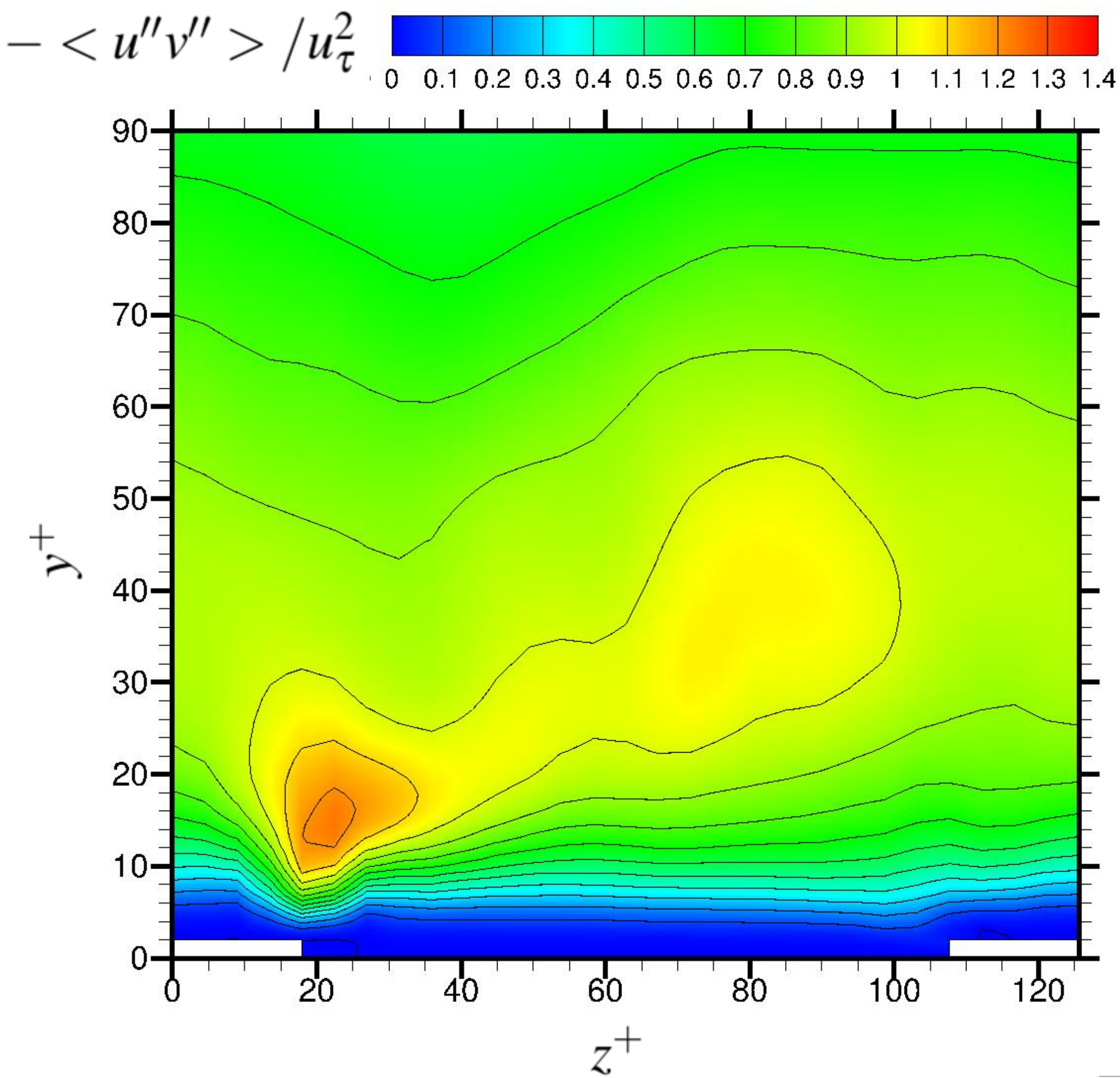
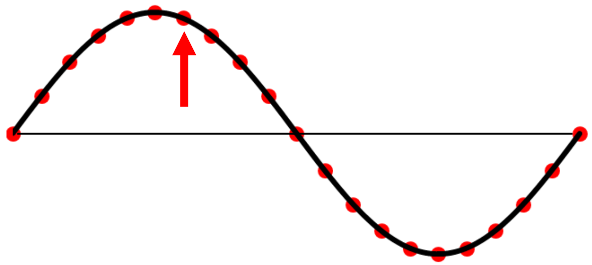
Reynolds shear stress





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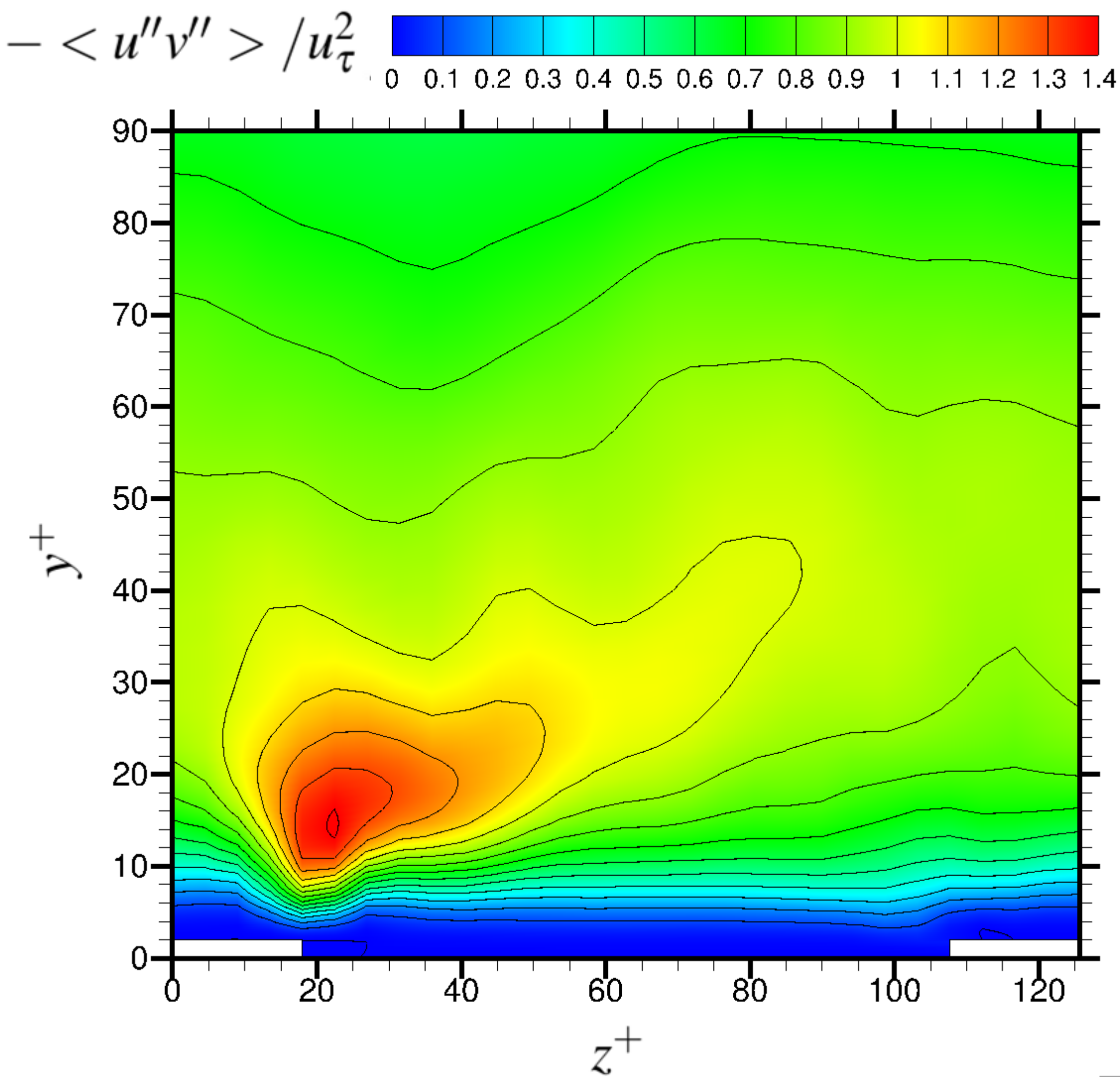
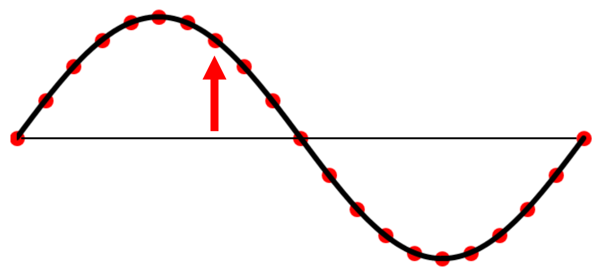
Reynolds shear stress





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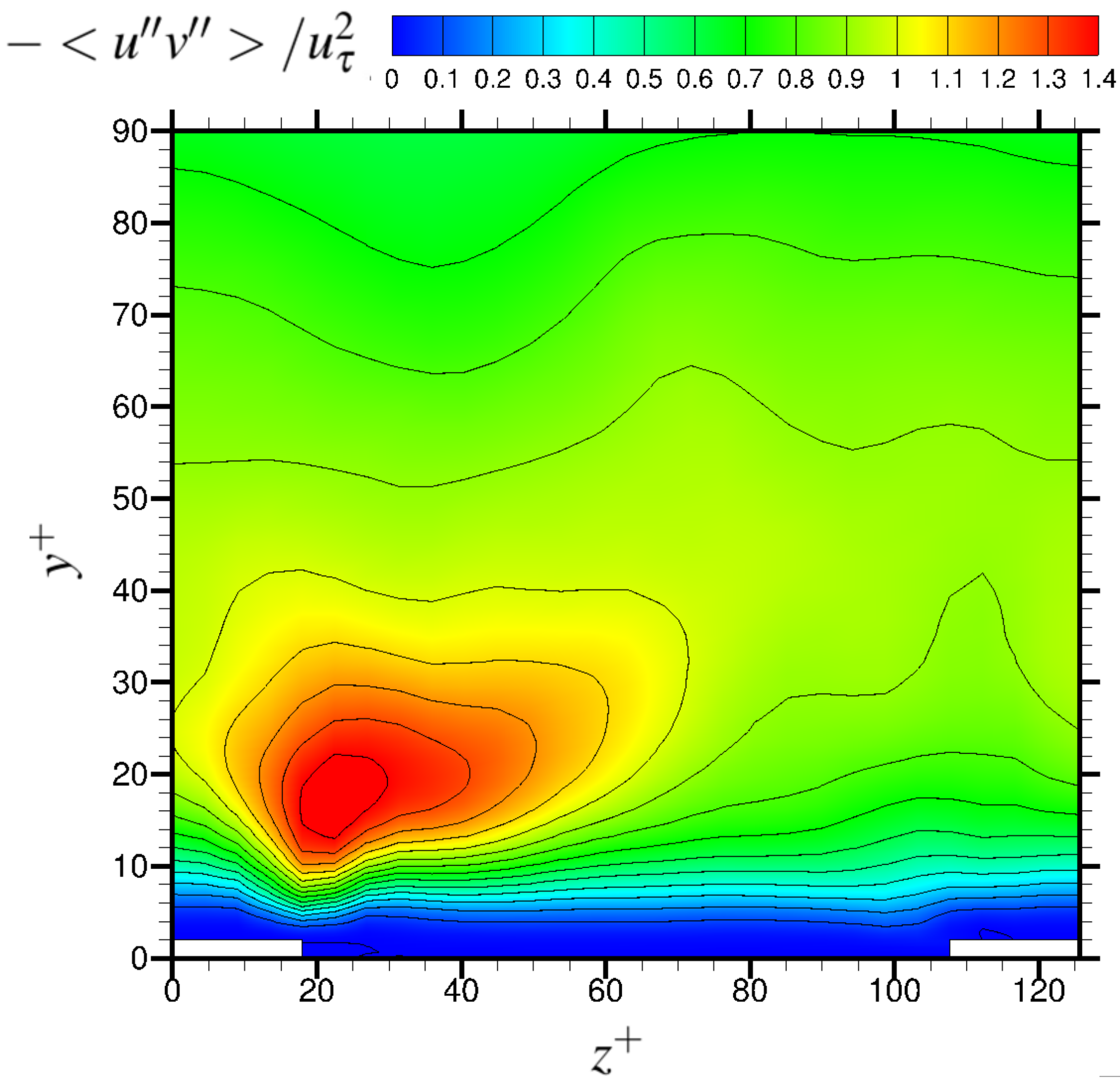

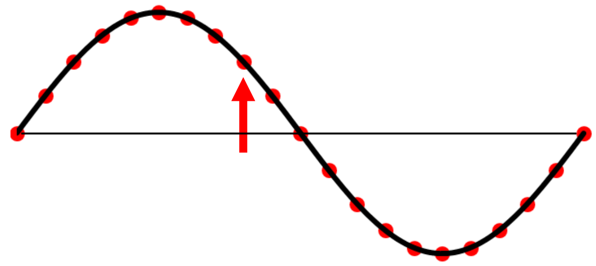

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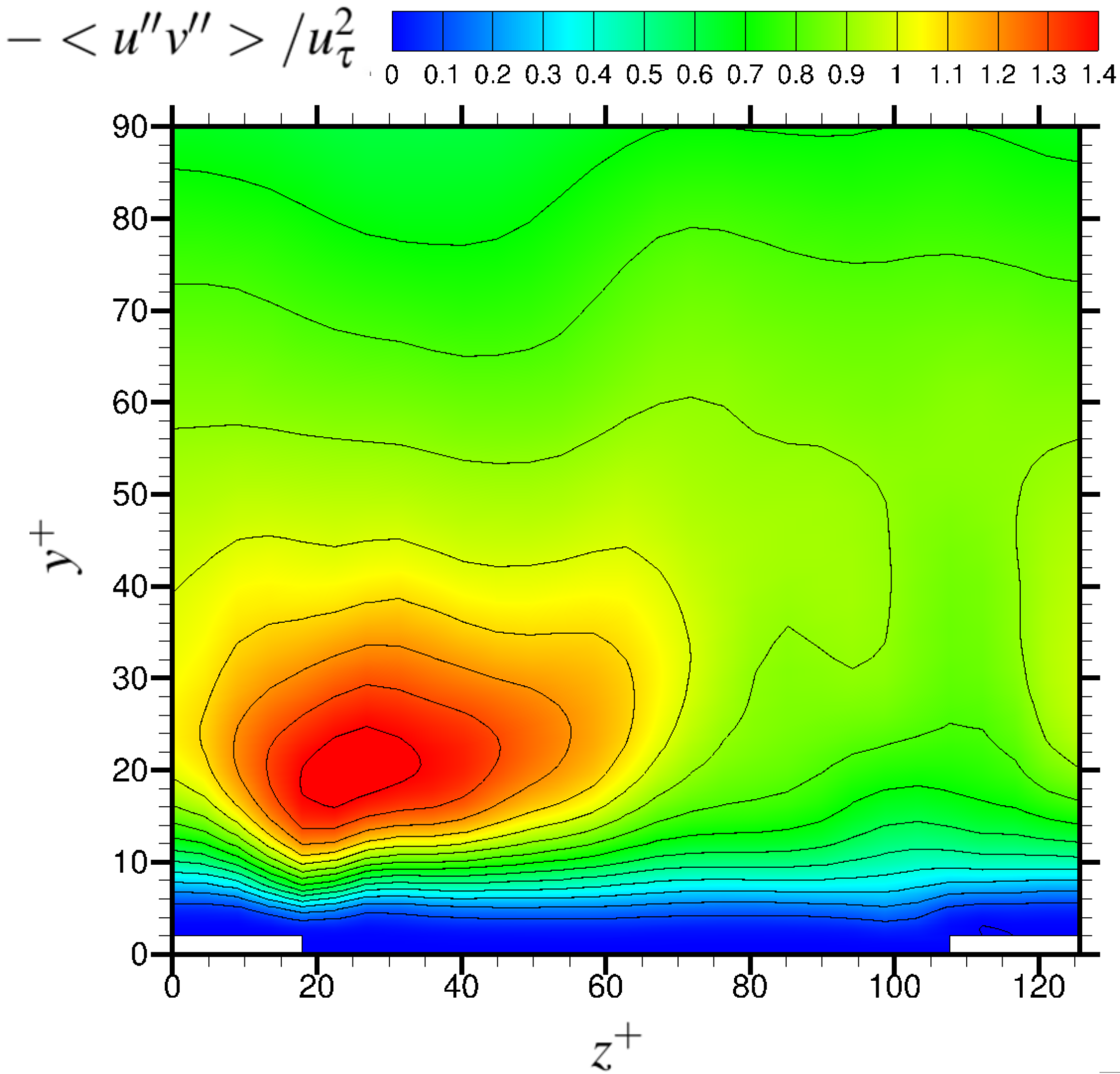

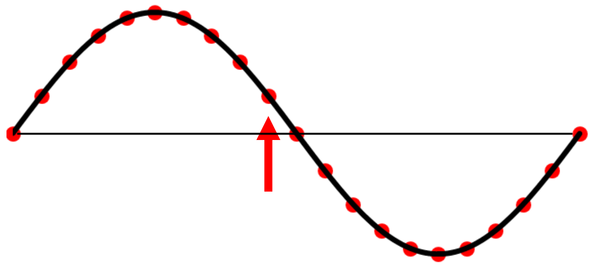

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Reynolds shear stress

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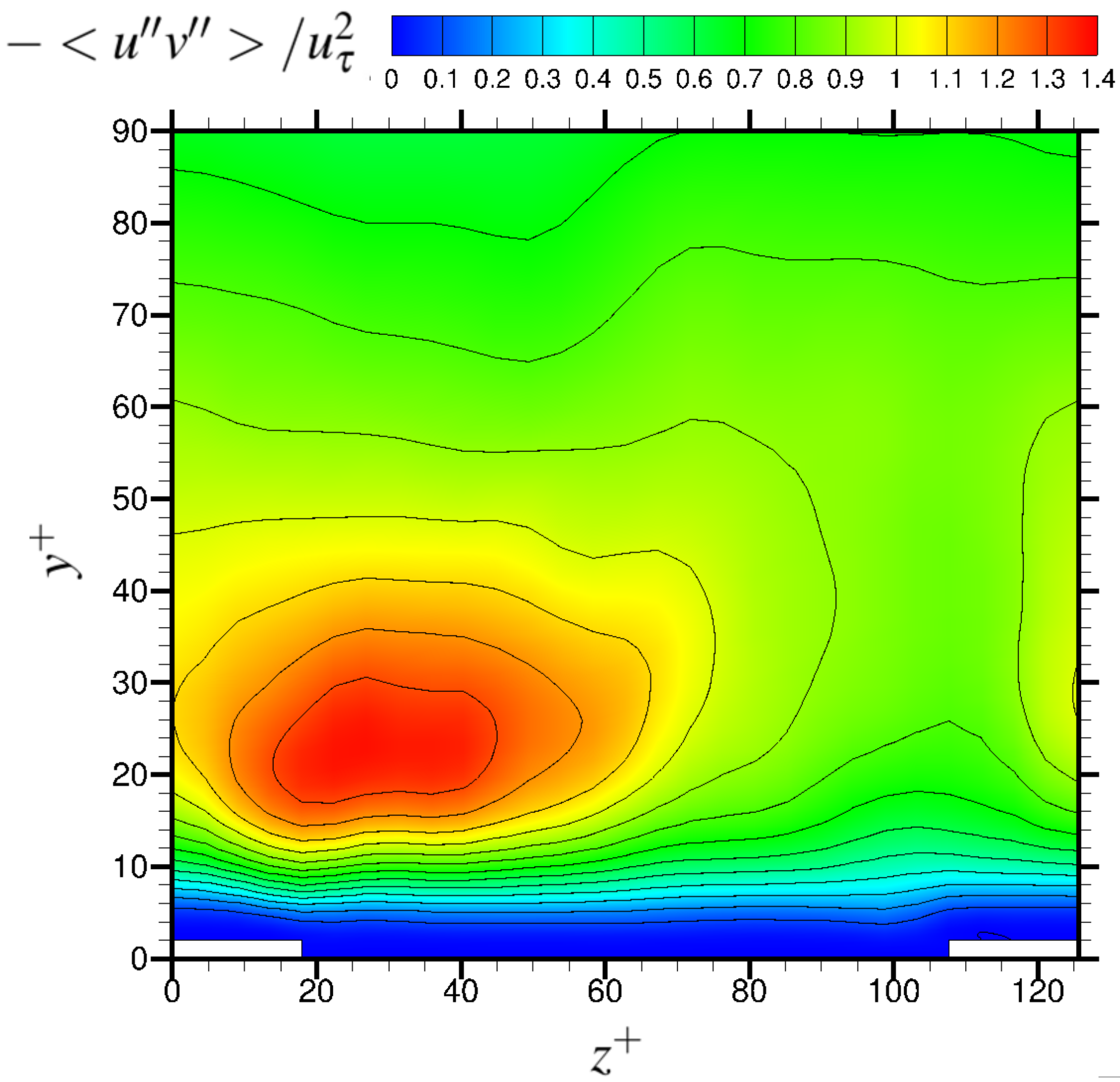

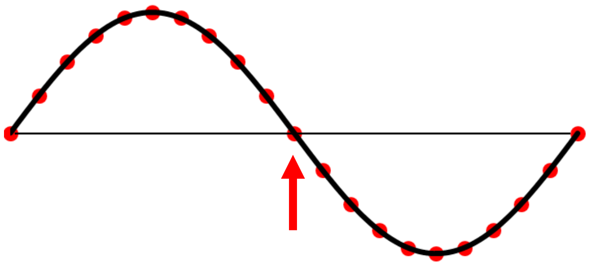

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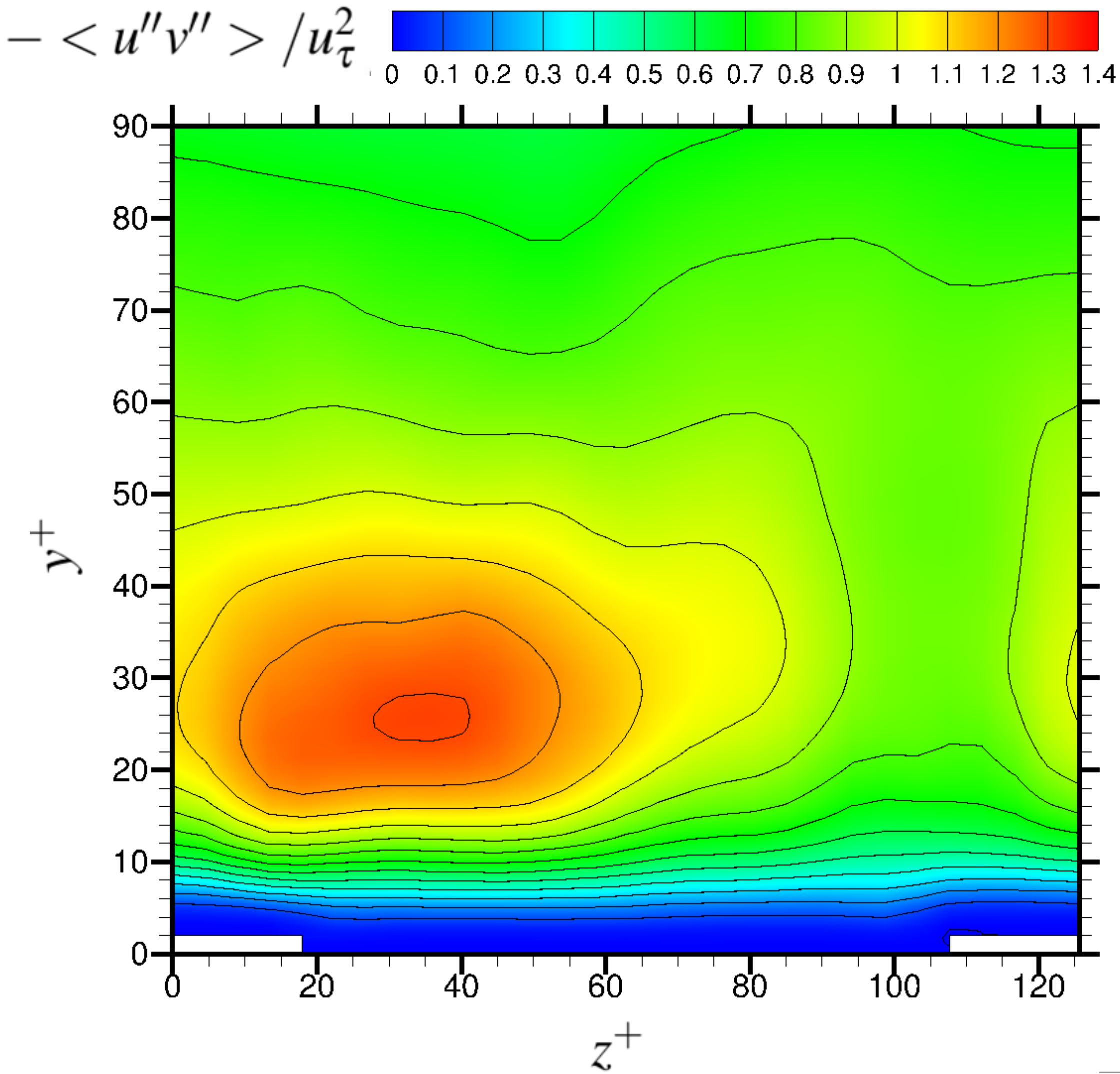

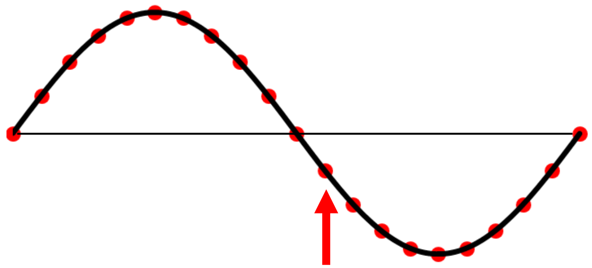

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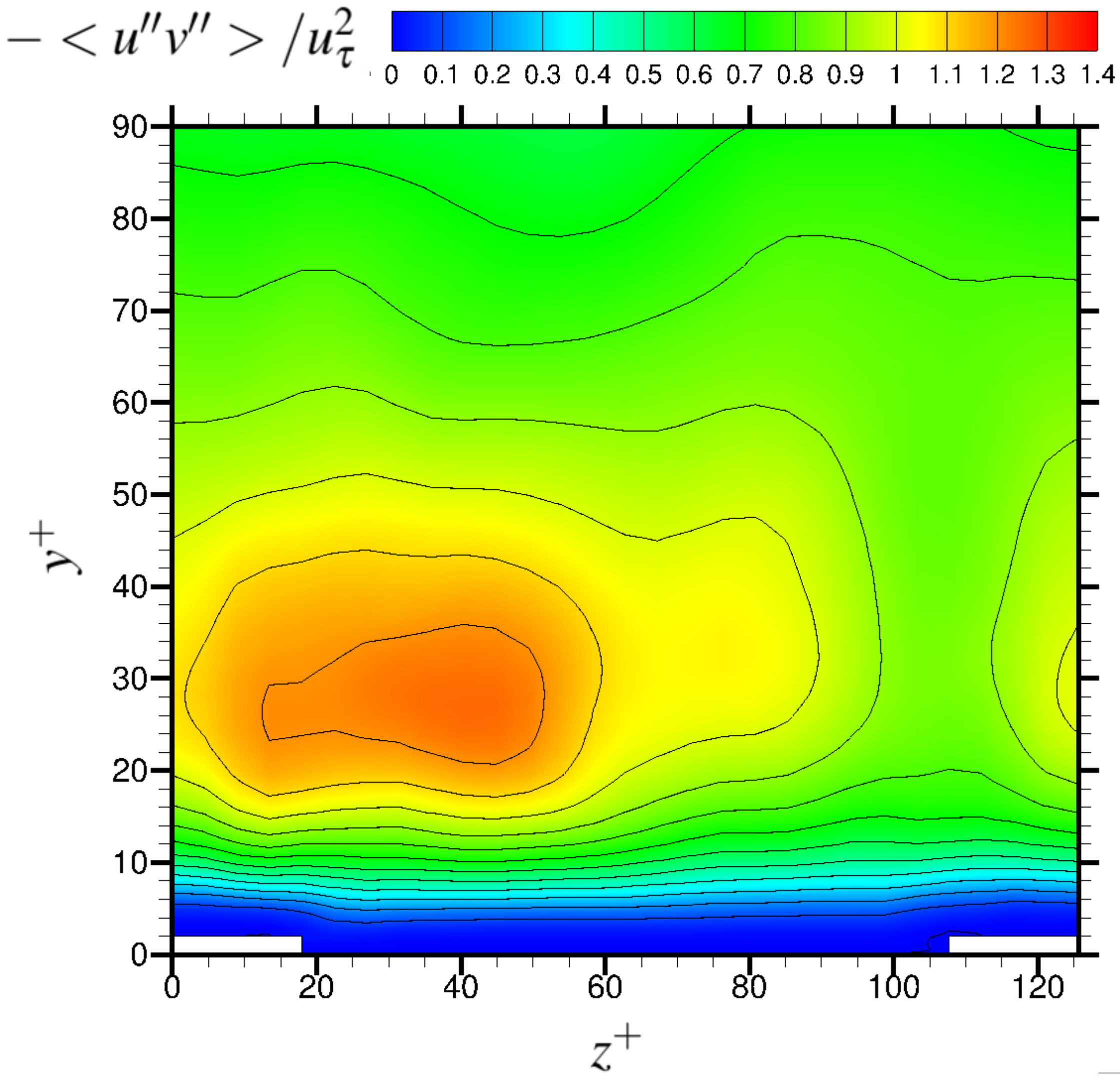

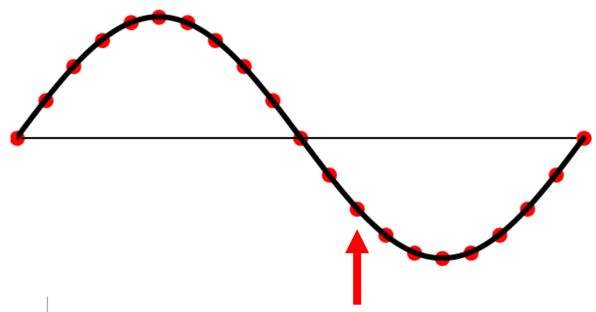

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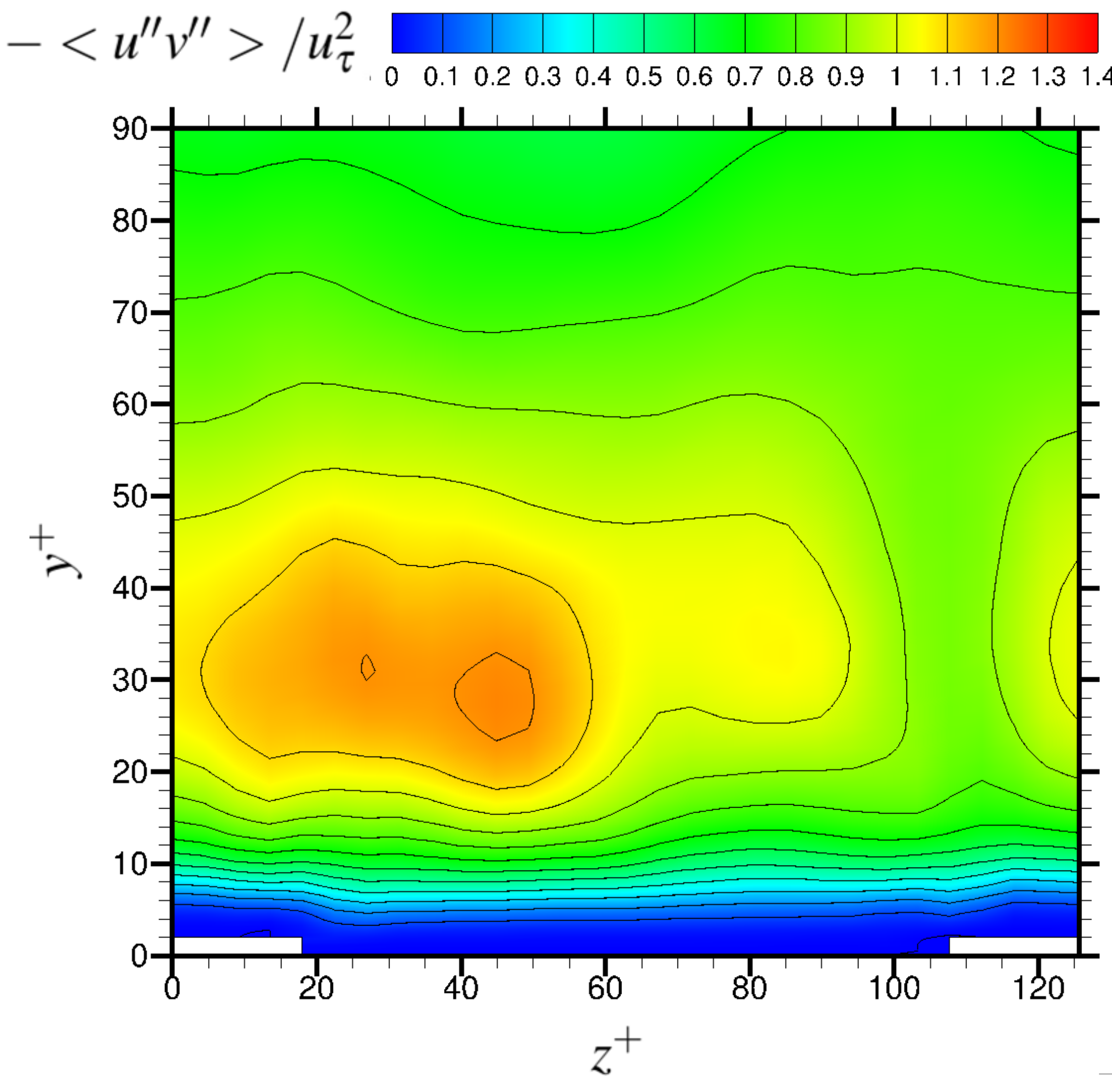

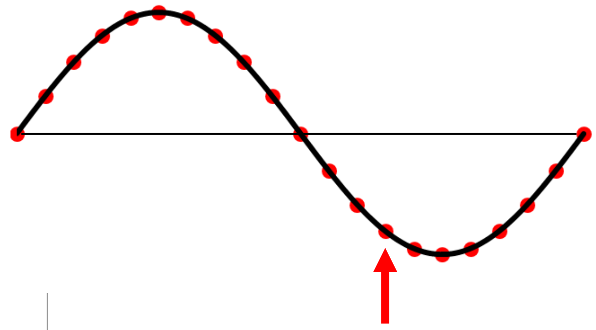

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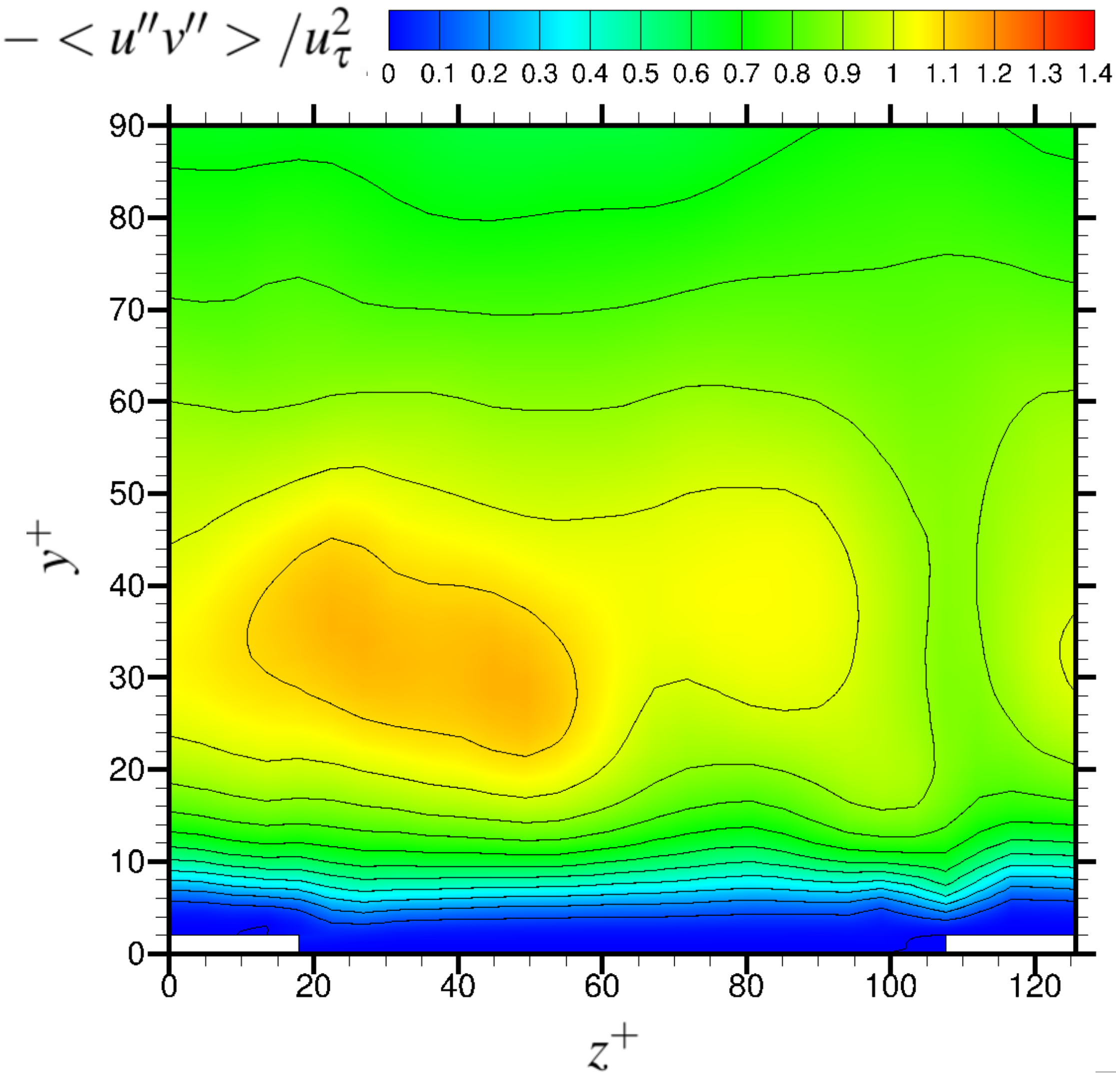

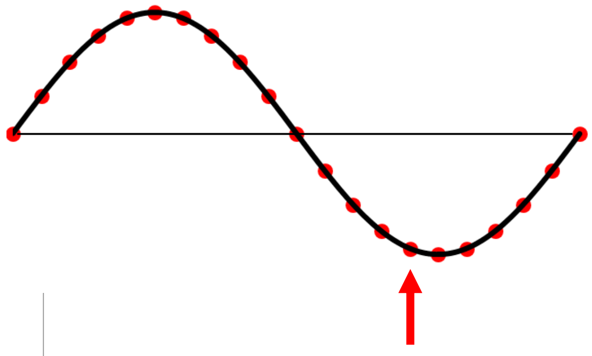

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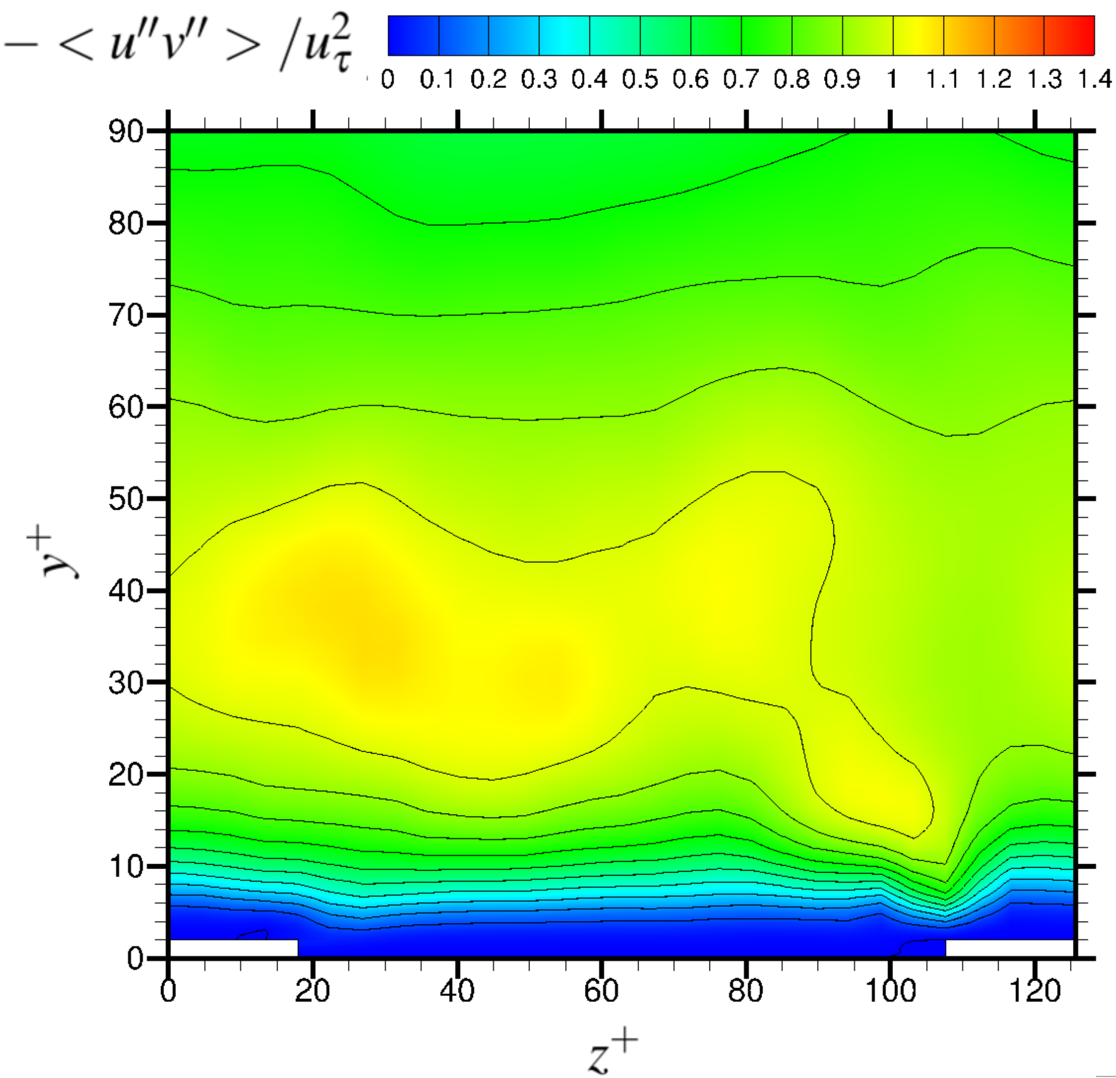

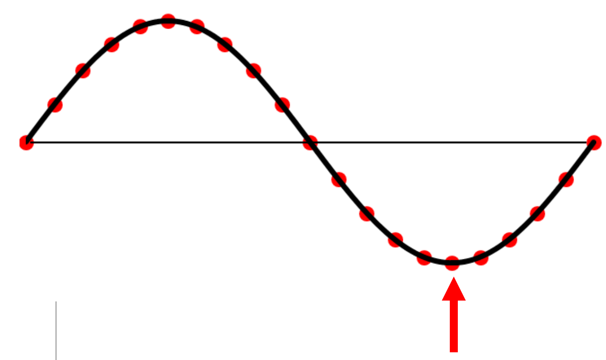

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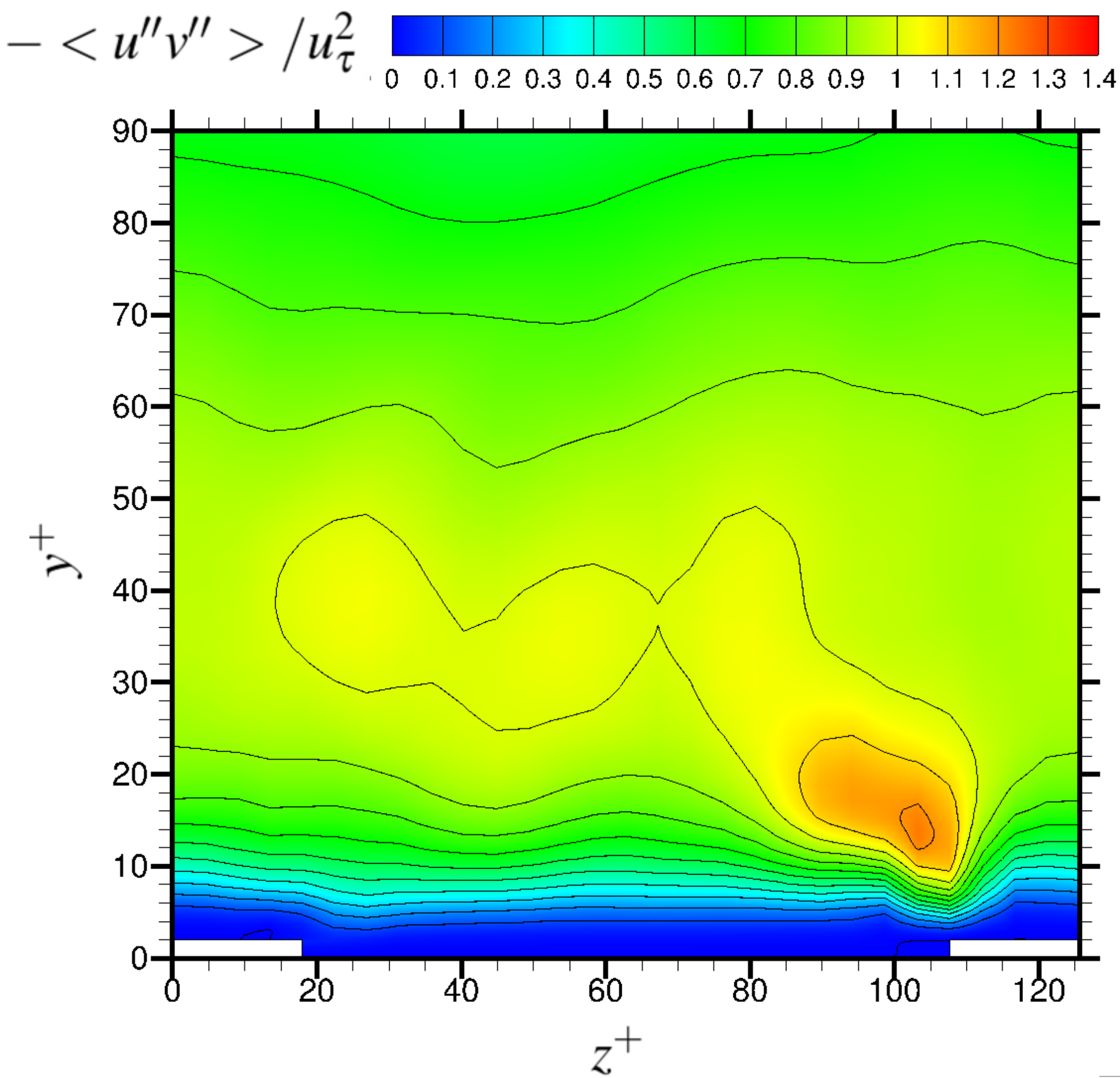

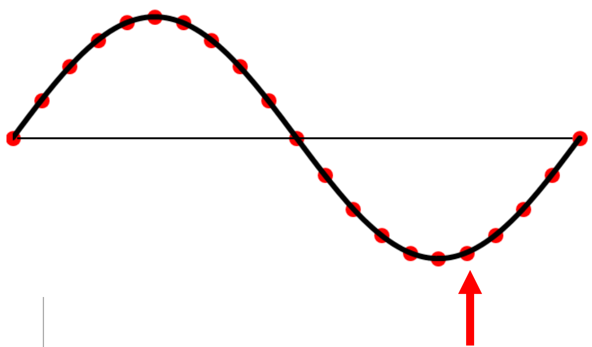

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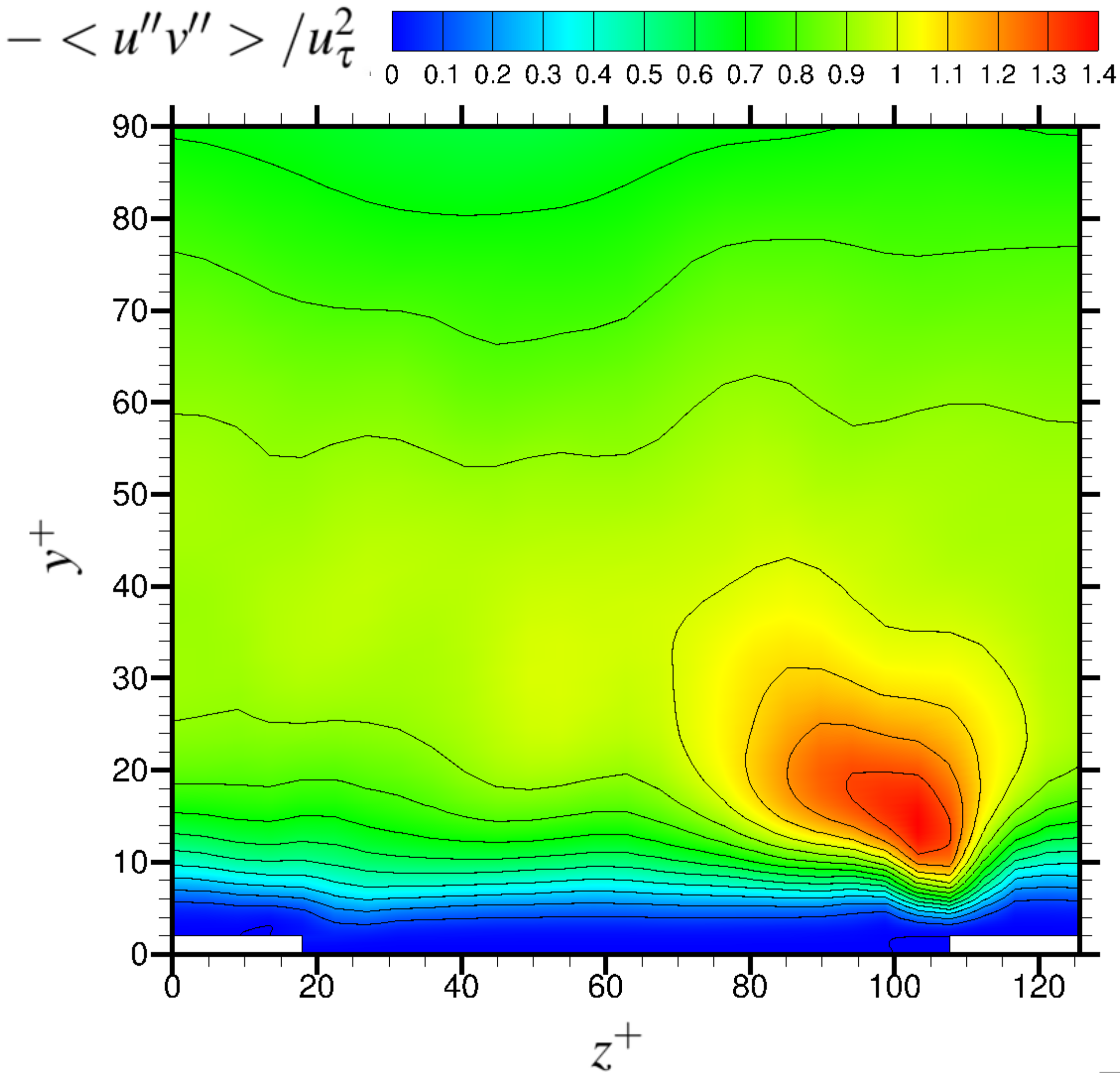

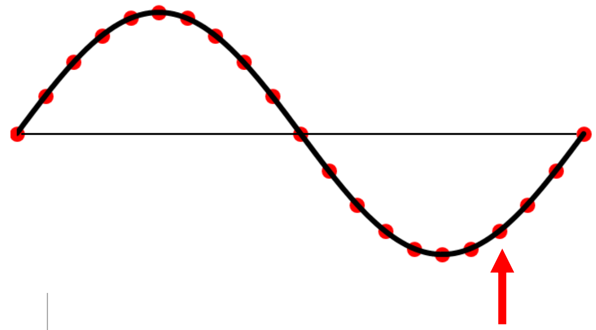

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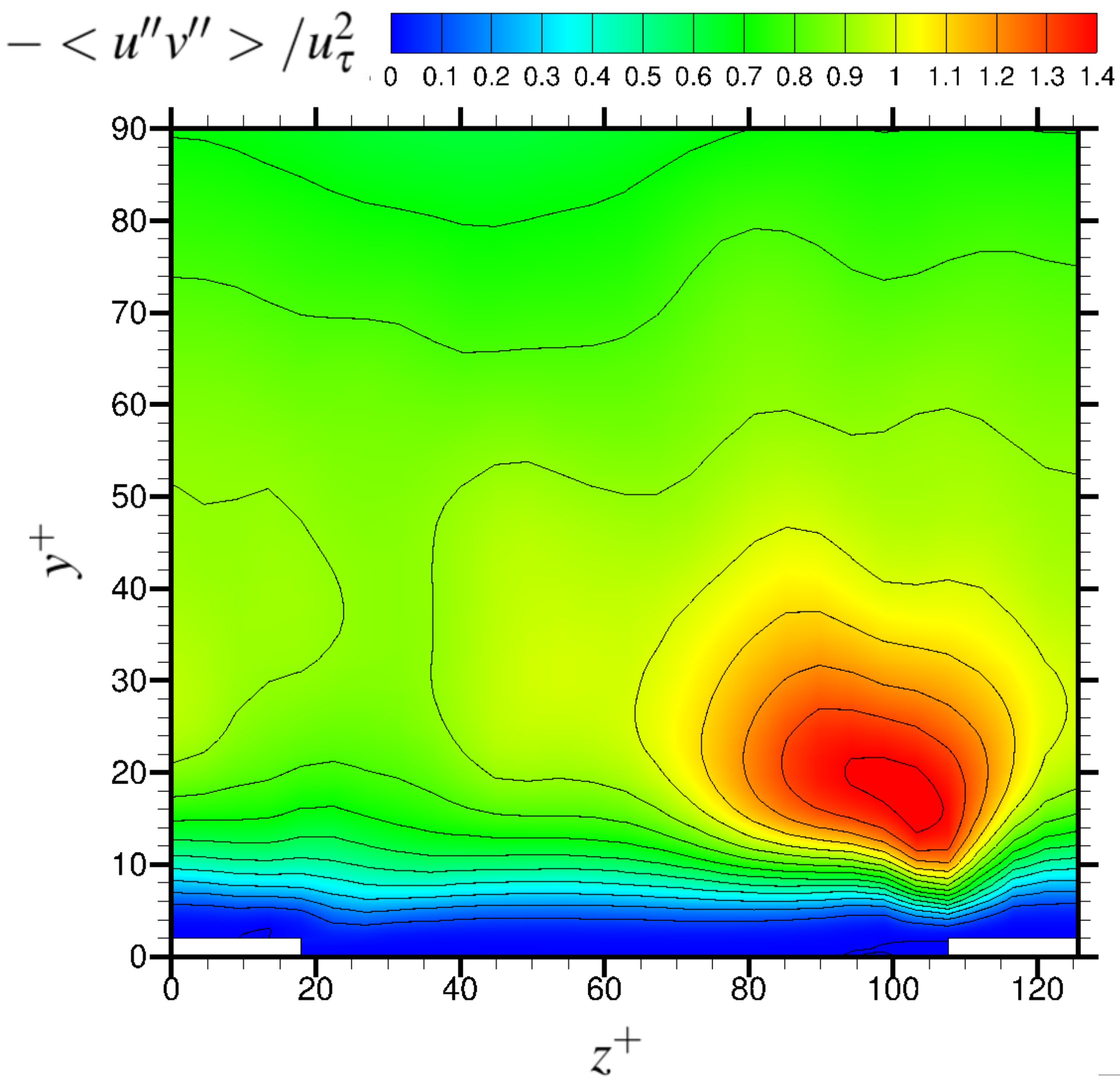

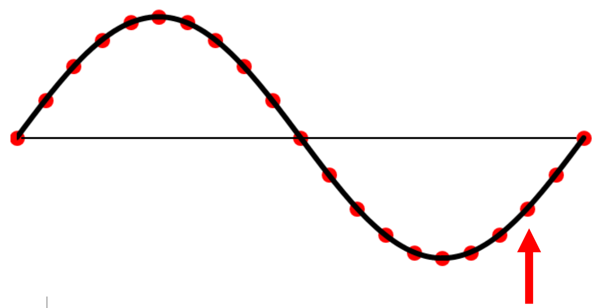

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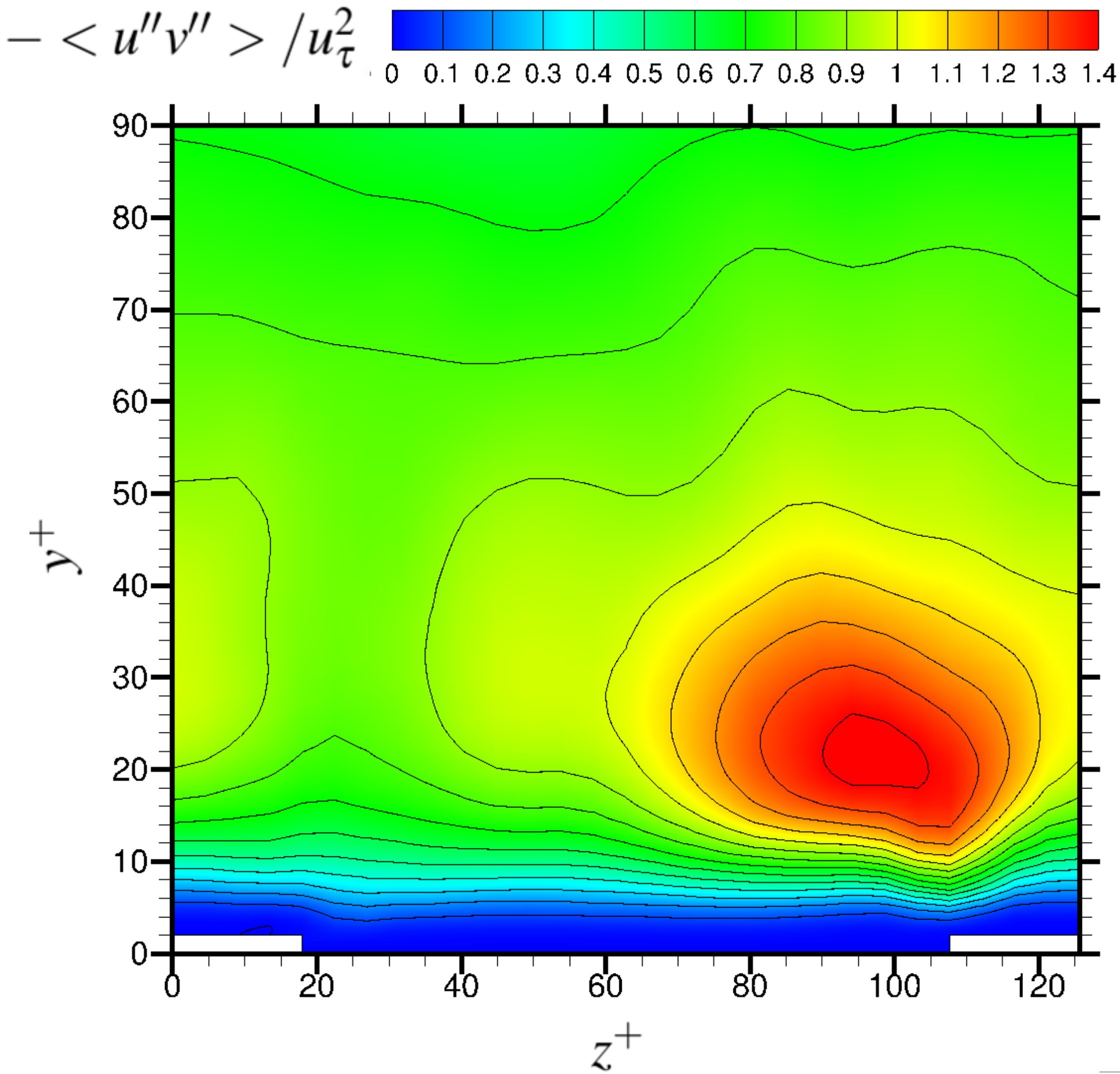
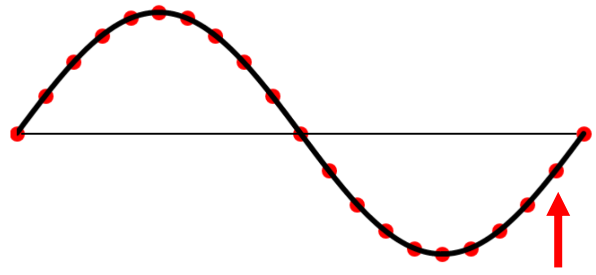
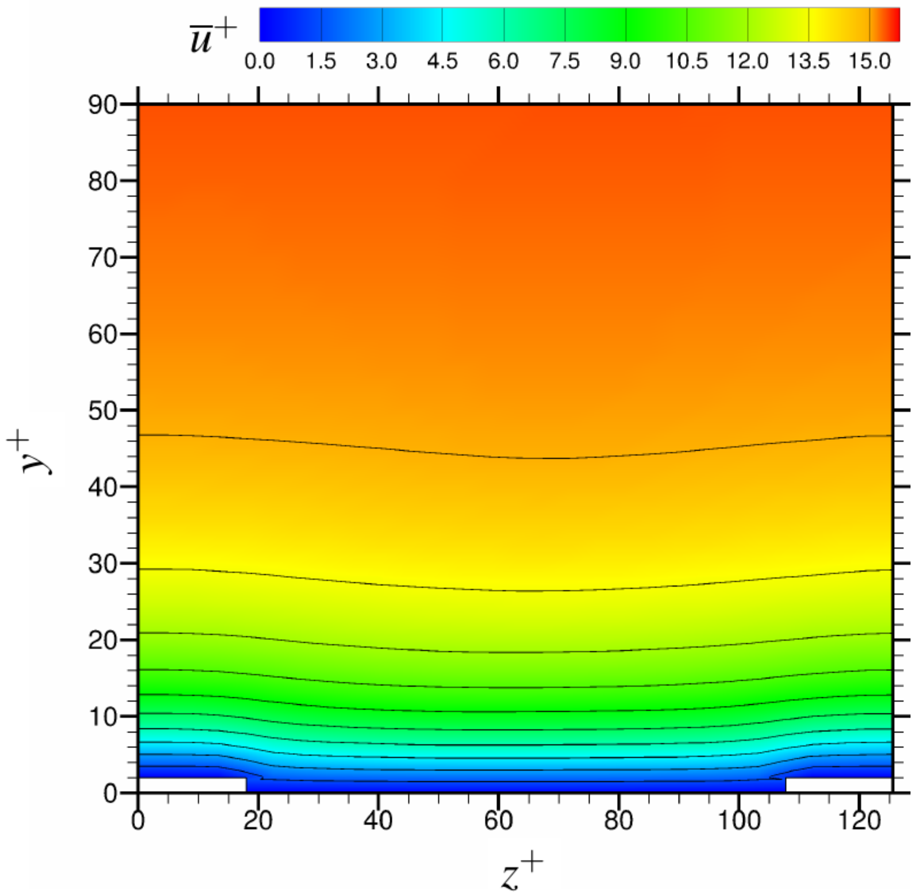




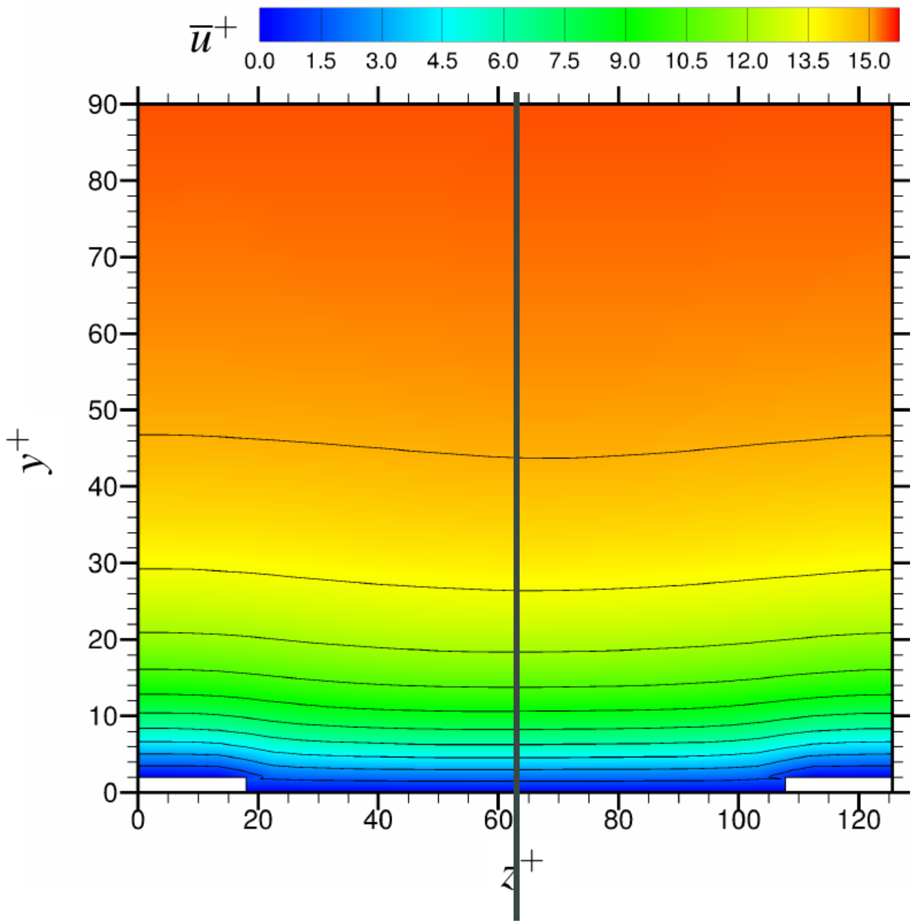
Jet on with $\beta = 75^0$

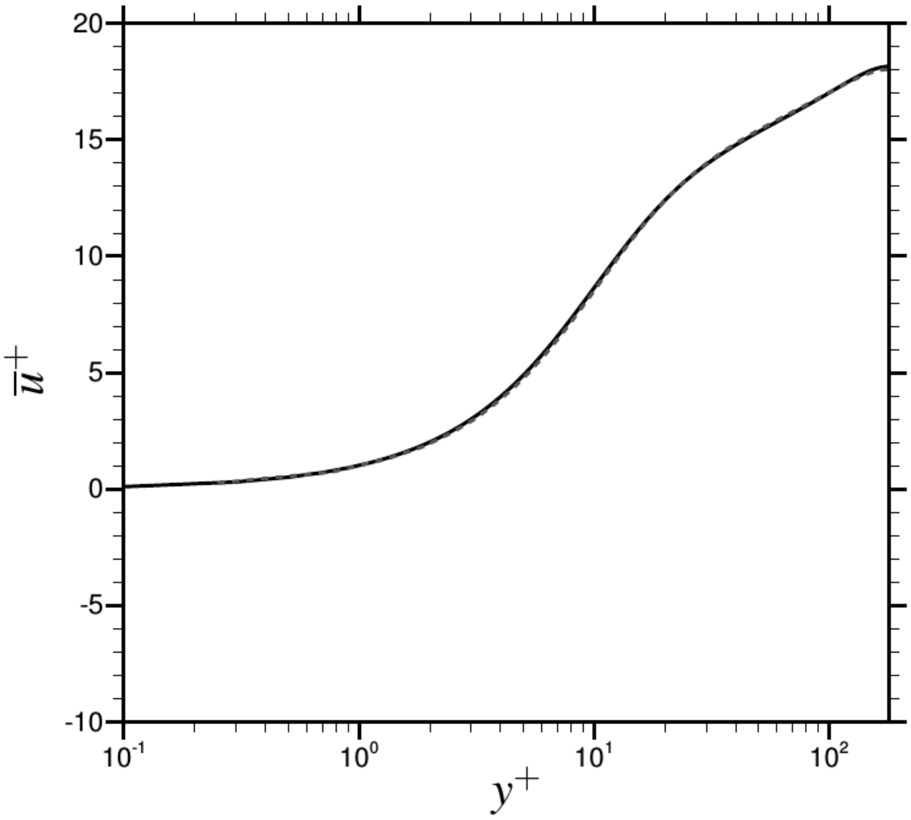
Streamwise mean velocity profiles



Baseline model (no jets)

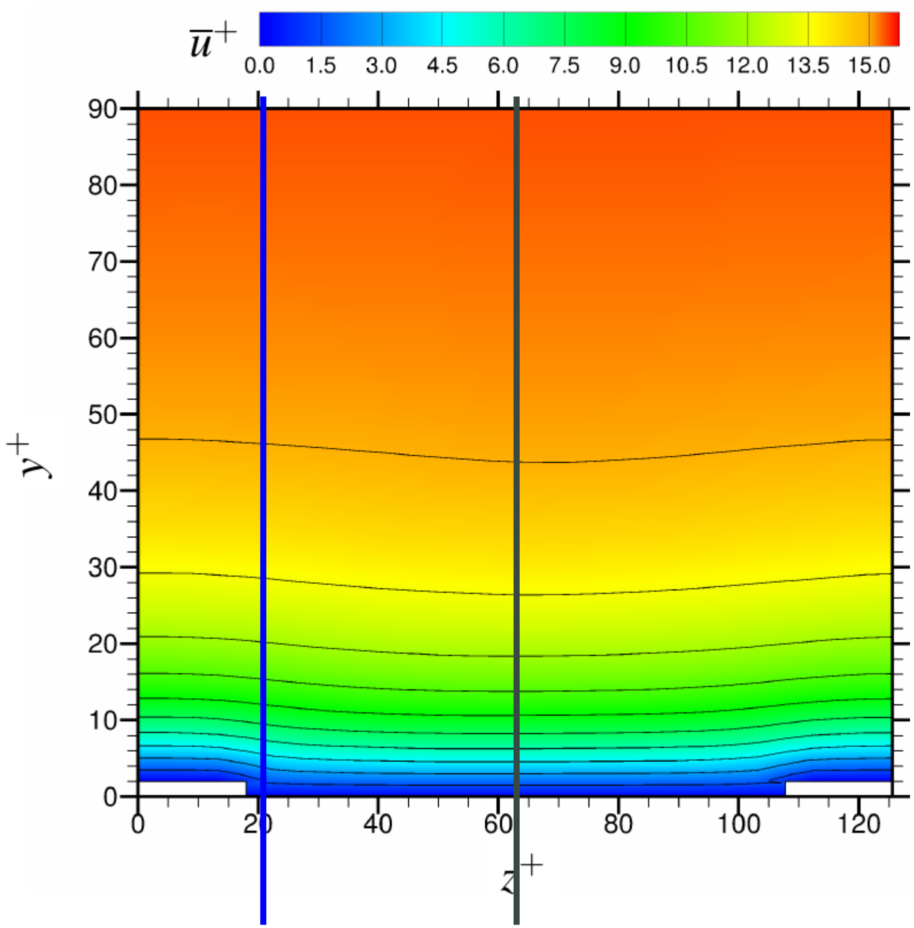
Streamwise mean velocity profiles

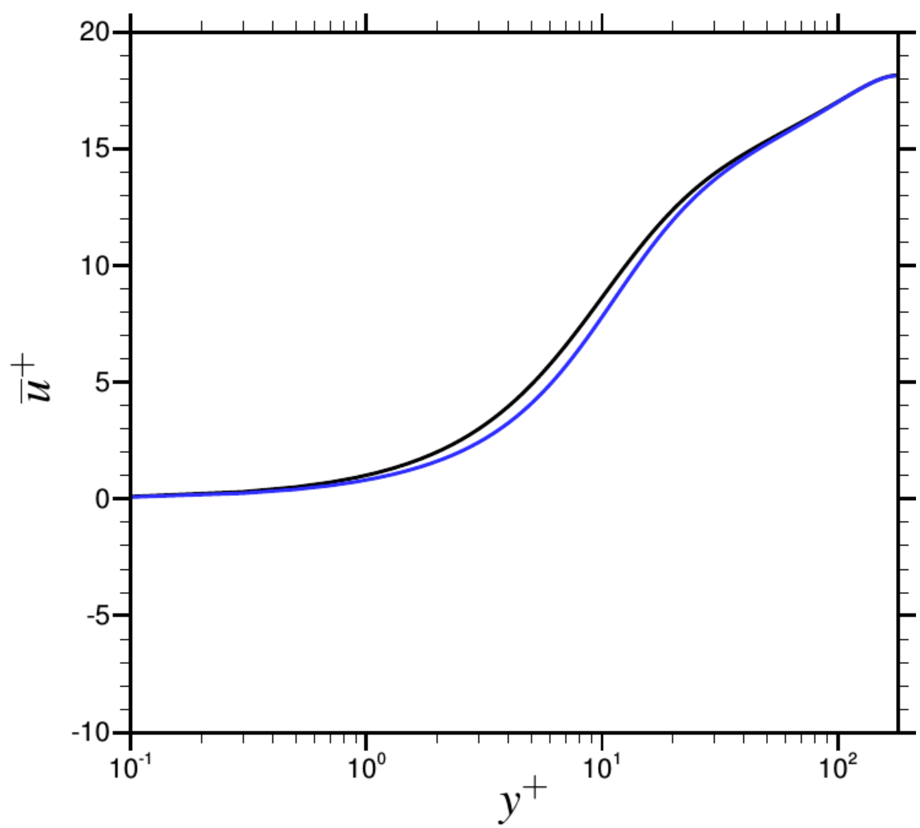




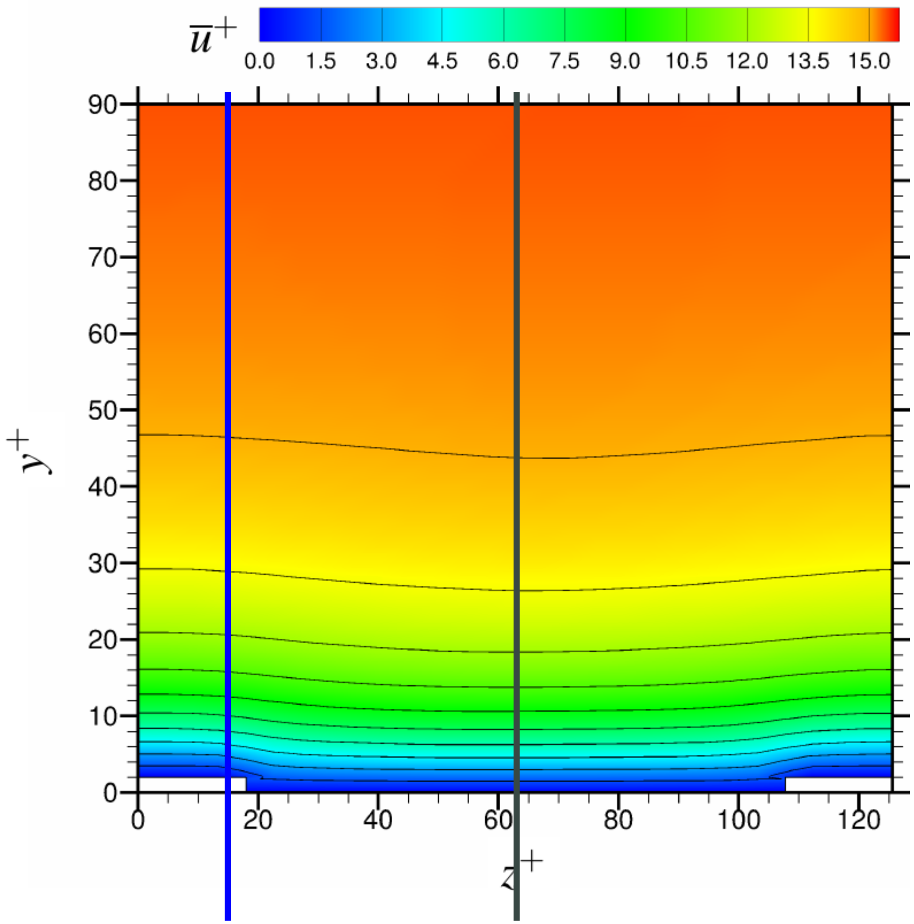
The dash line is the case of baseline channel.

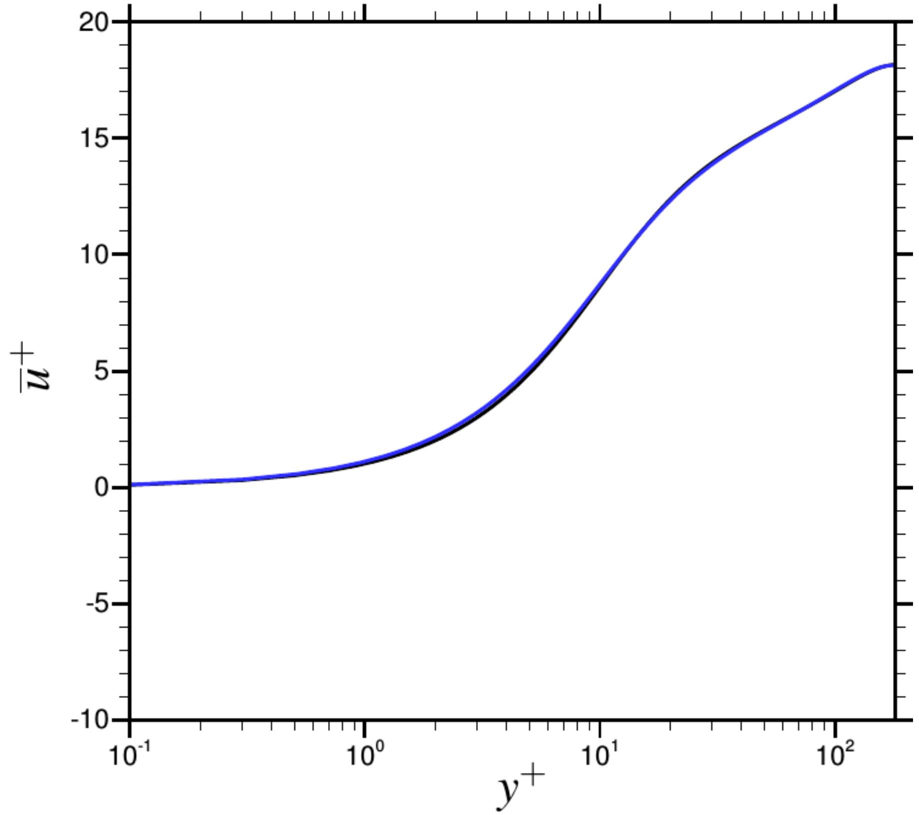
Streamwise mean velocity profiles





Streamwise mean velocity profiles





Streamwise mean velocity profiles with jets

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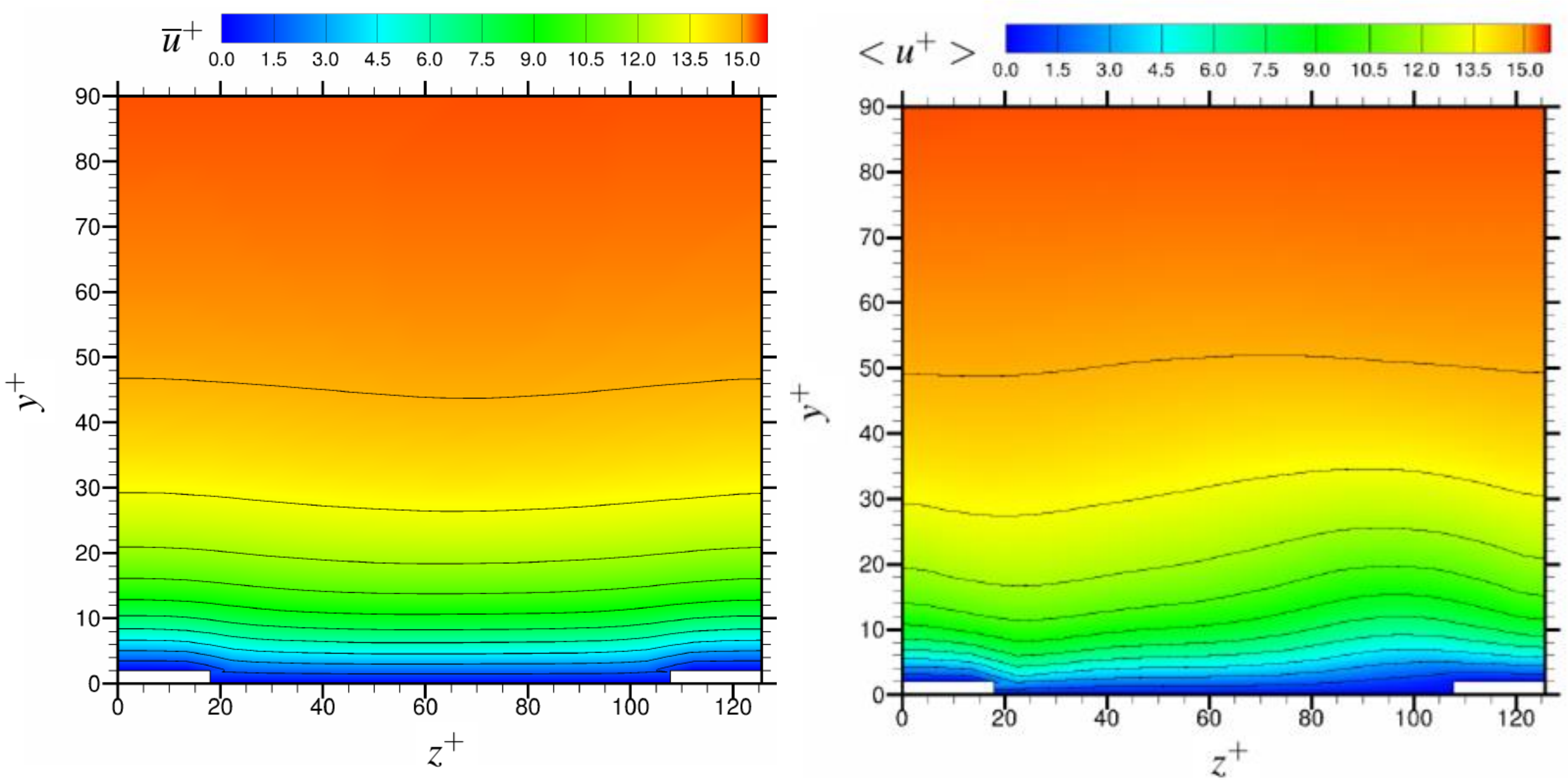
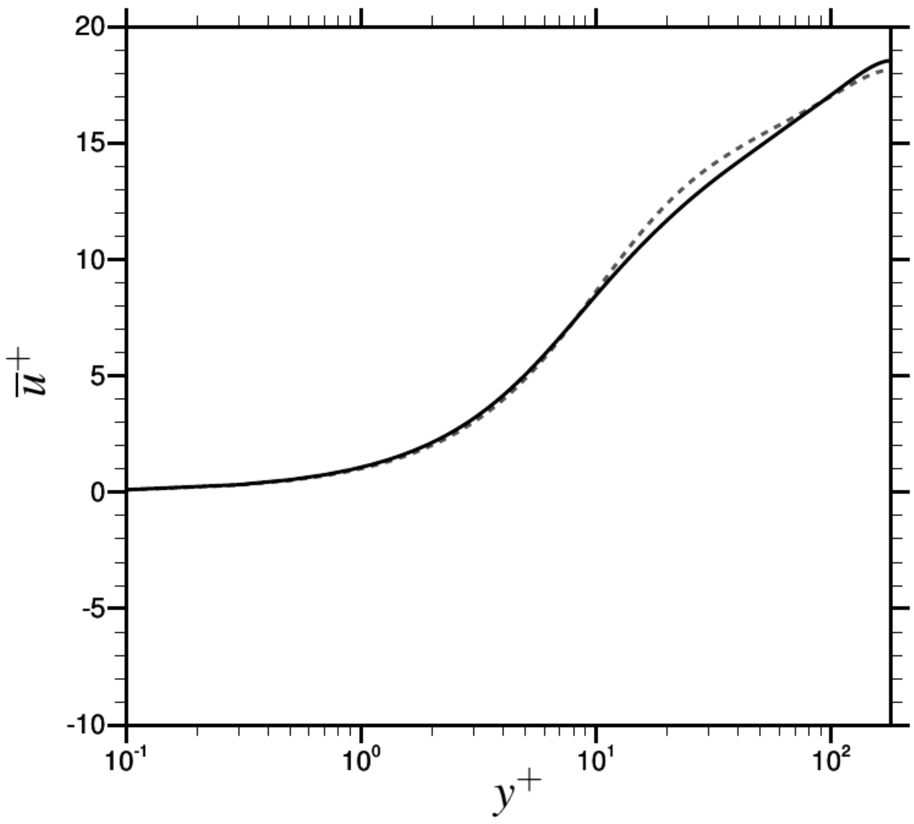


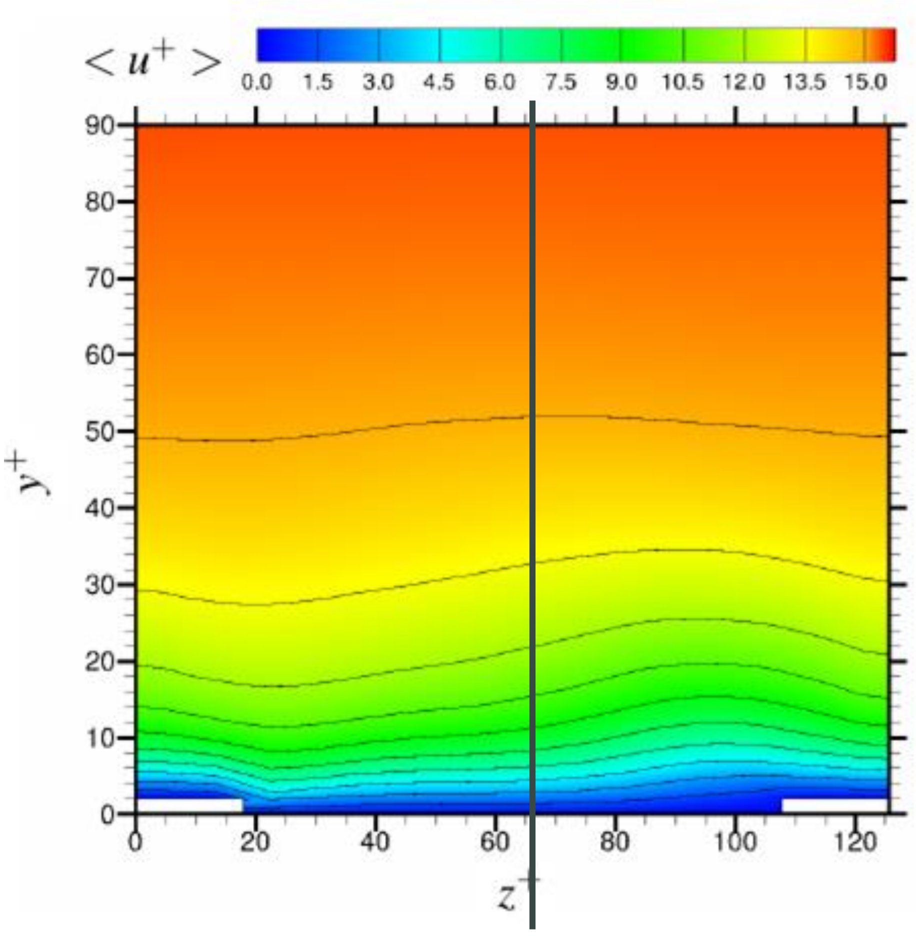
(a) $\varphi = 0$

Streamwise mean velocity profiles with jets

The University Of Sheffield.



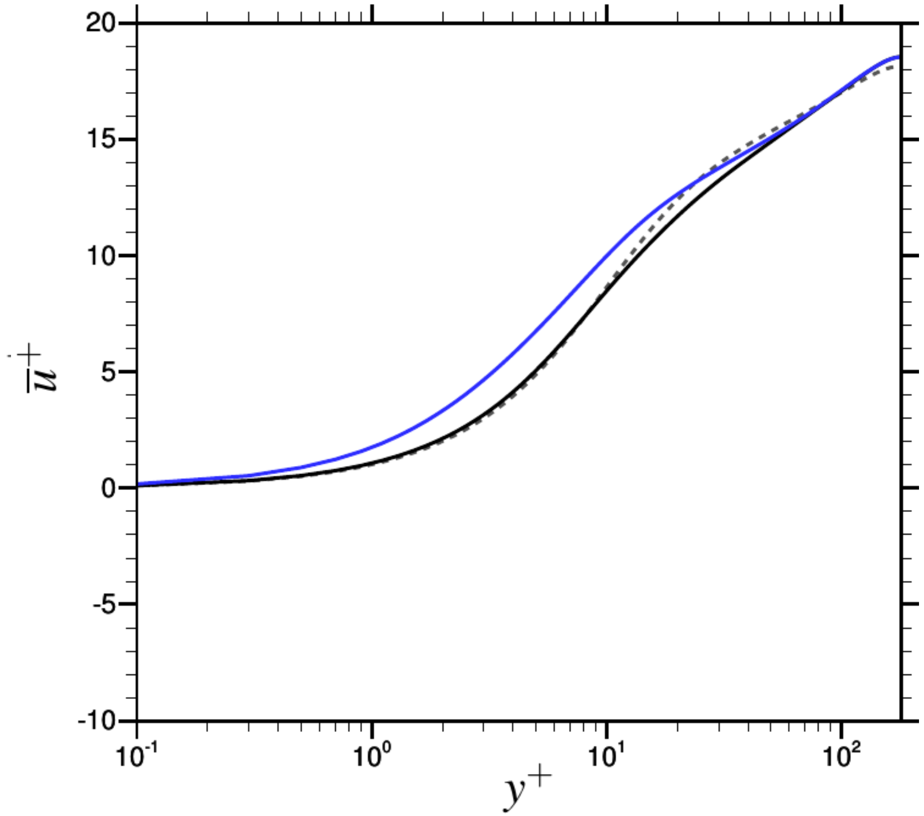
The dash line is baseline model.



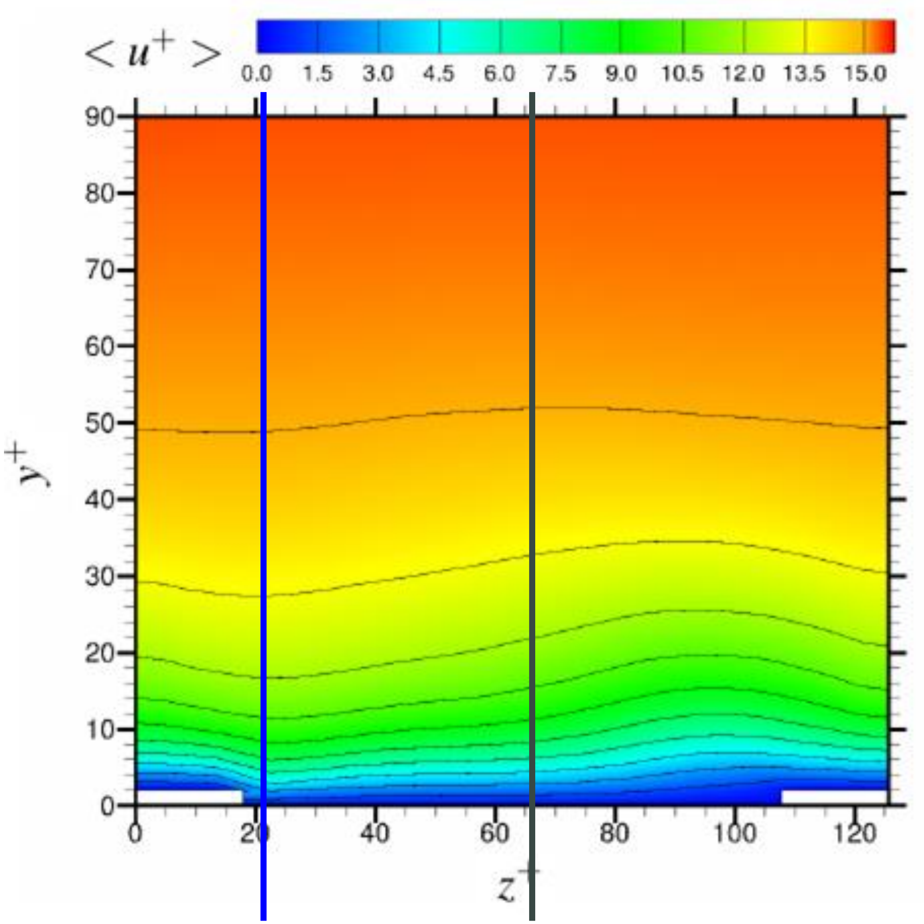
$\varphi = 0$

Streamwise mean velocity profiles with jets

The University Of Sheffield.

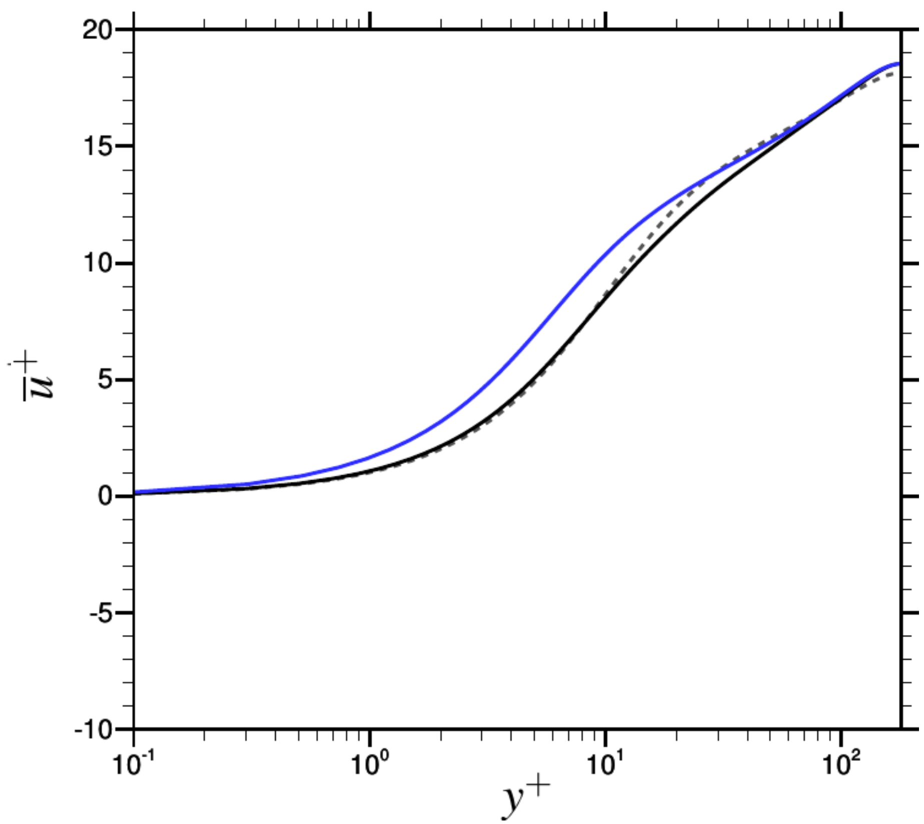


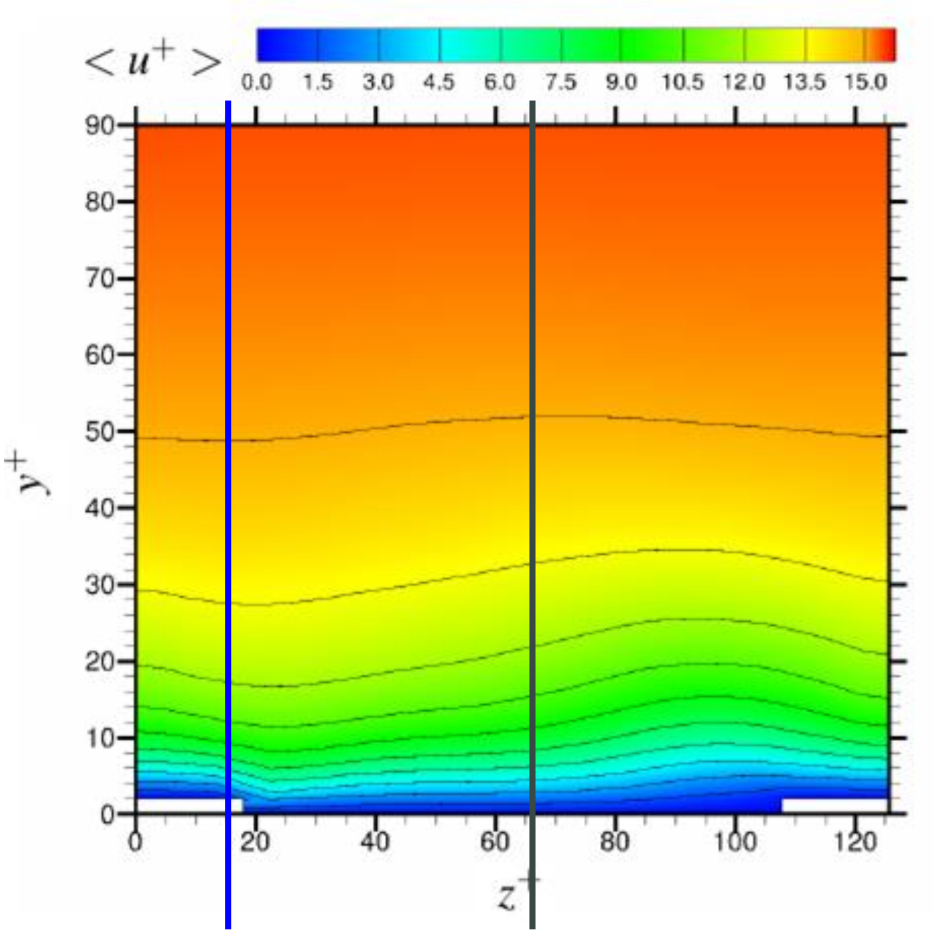
The dash line is baseline model.



$\varphi = 0$

Streamwise mean velocity profiles with jets



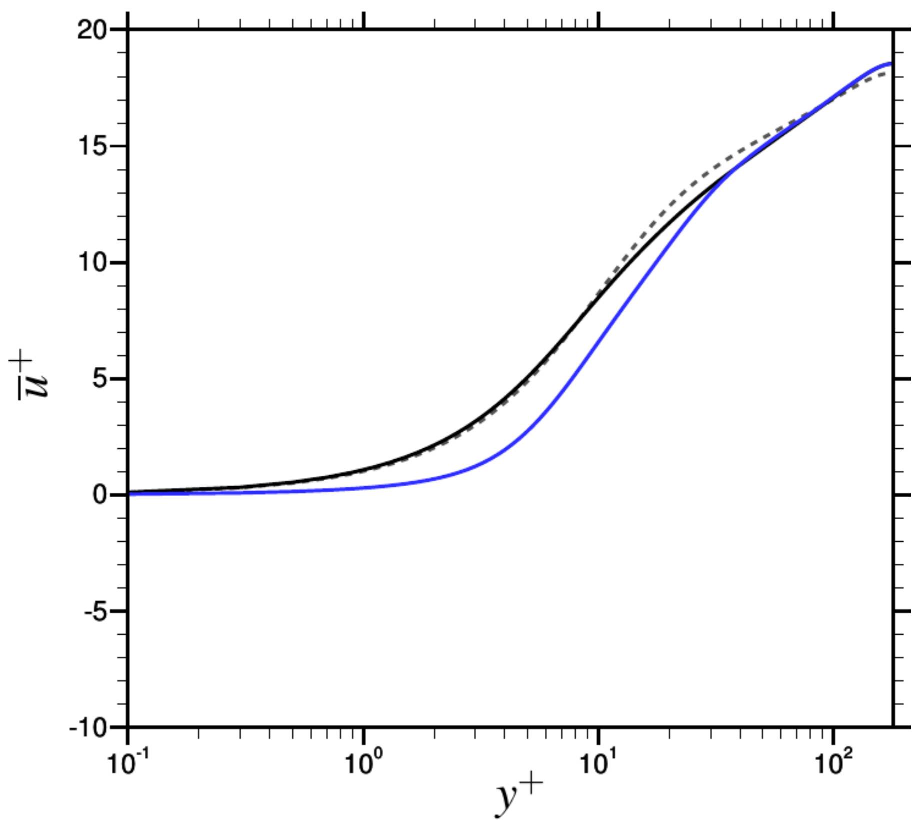


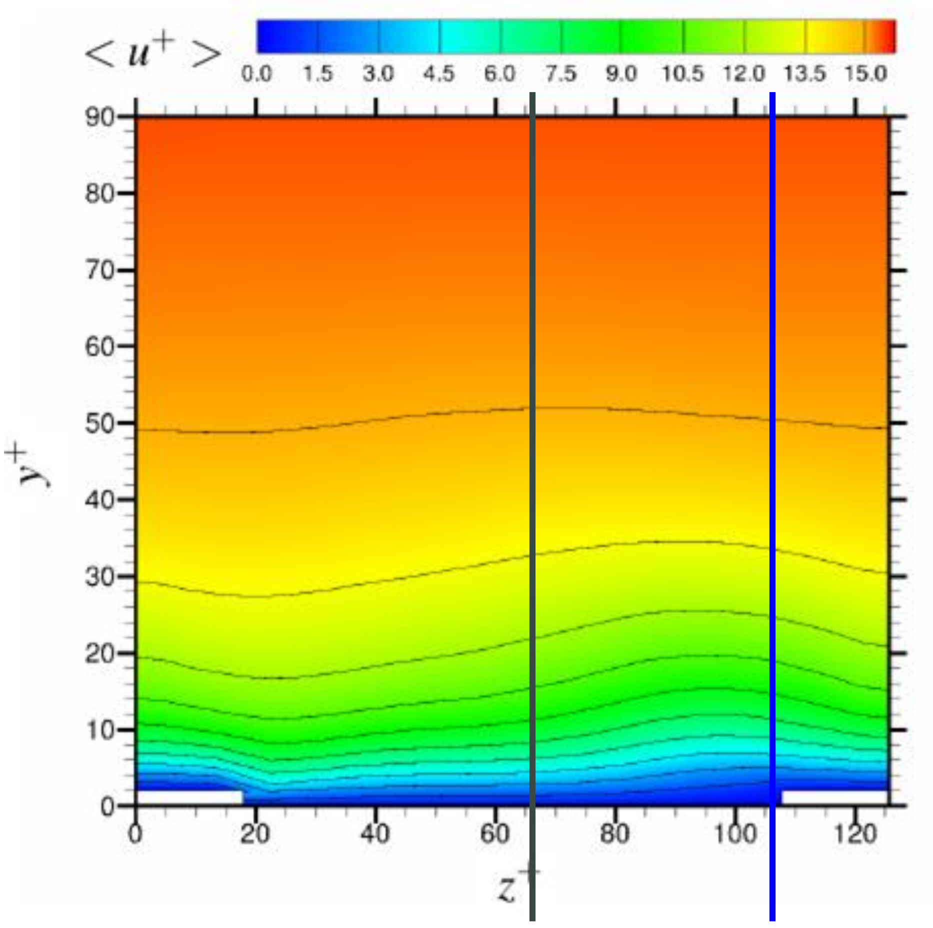
The dash line is baseline model.

$\varphi = 0$

Streamwise mean velocity profiles with jets

The University Of Sheffield.



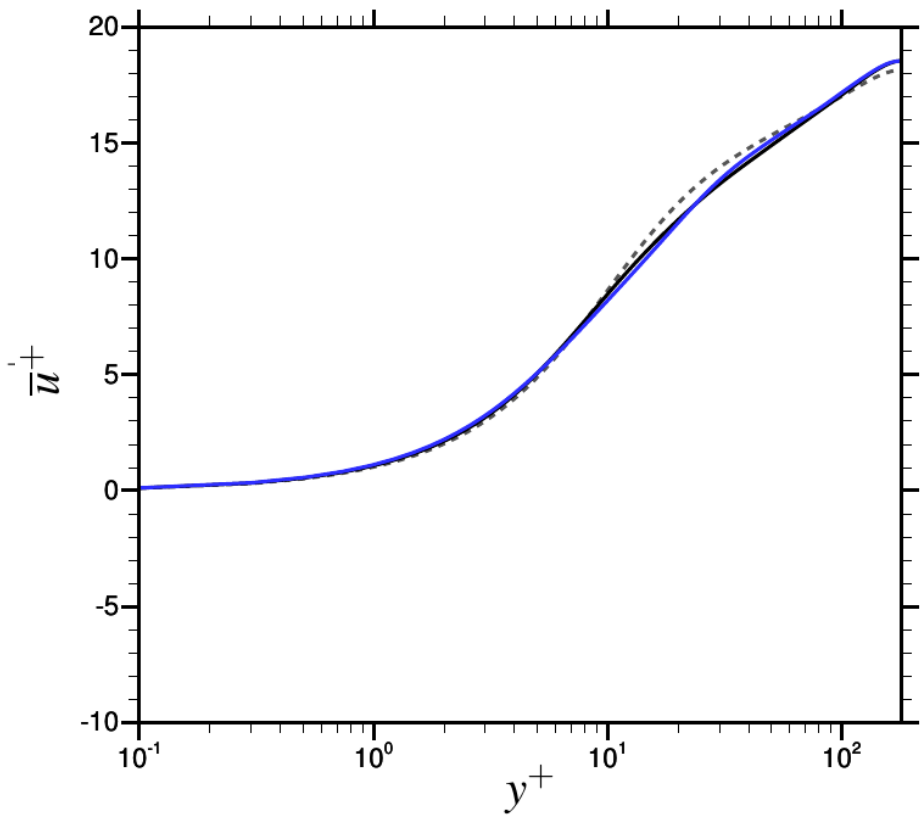


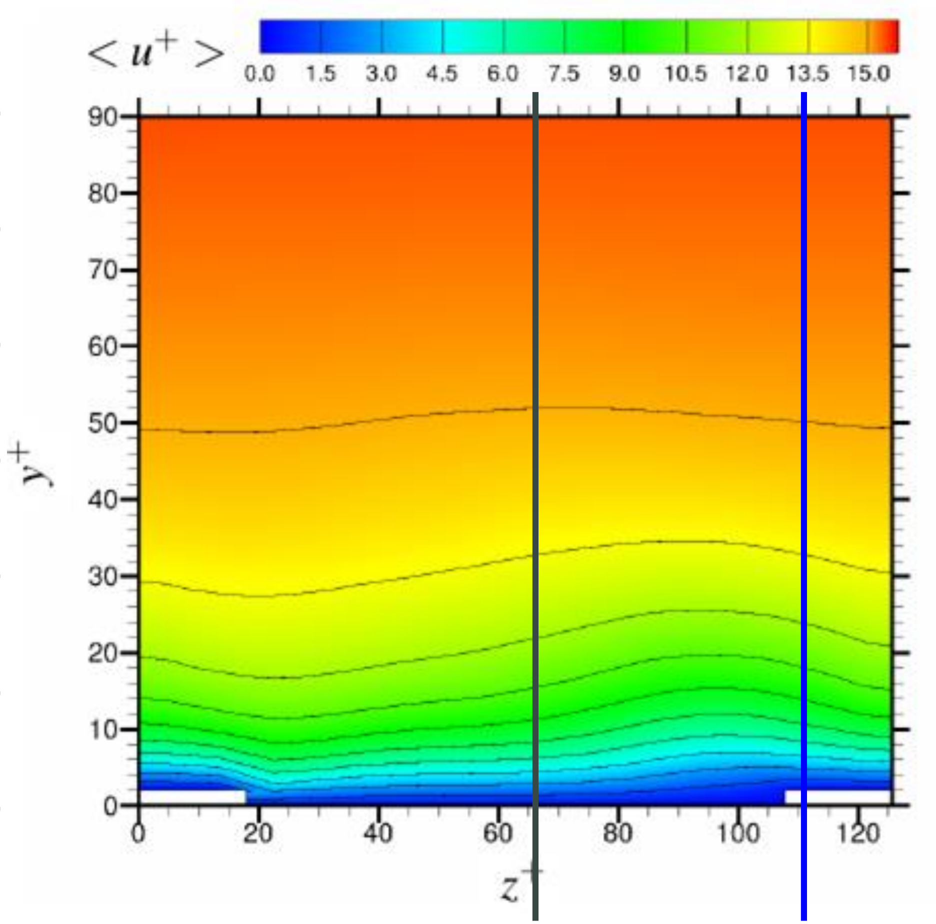
The dash line is baseline model.

$\varphi = 0$

Streamwise mean velocity profiles with jets

The University Of Sheffield.

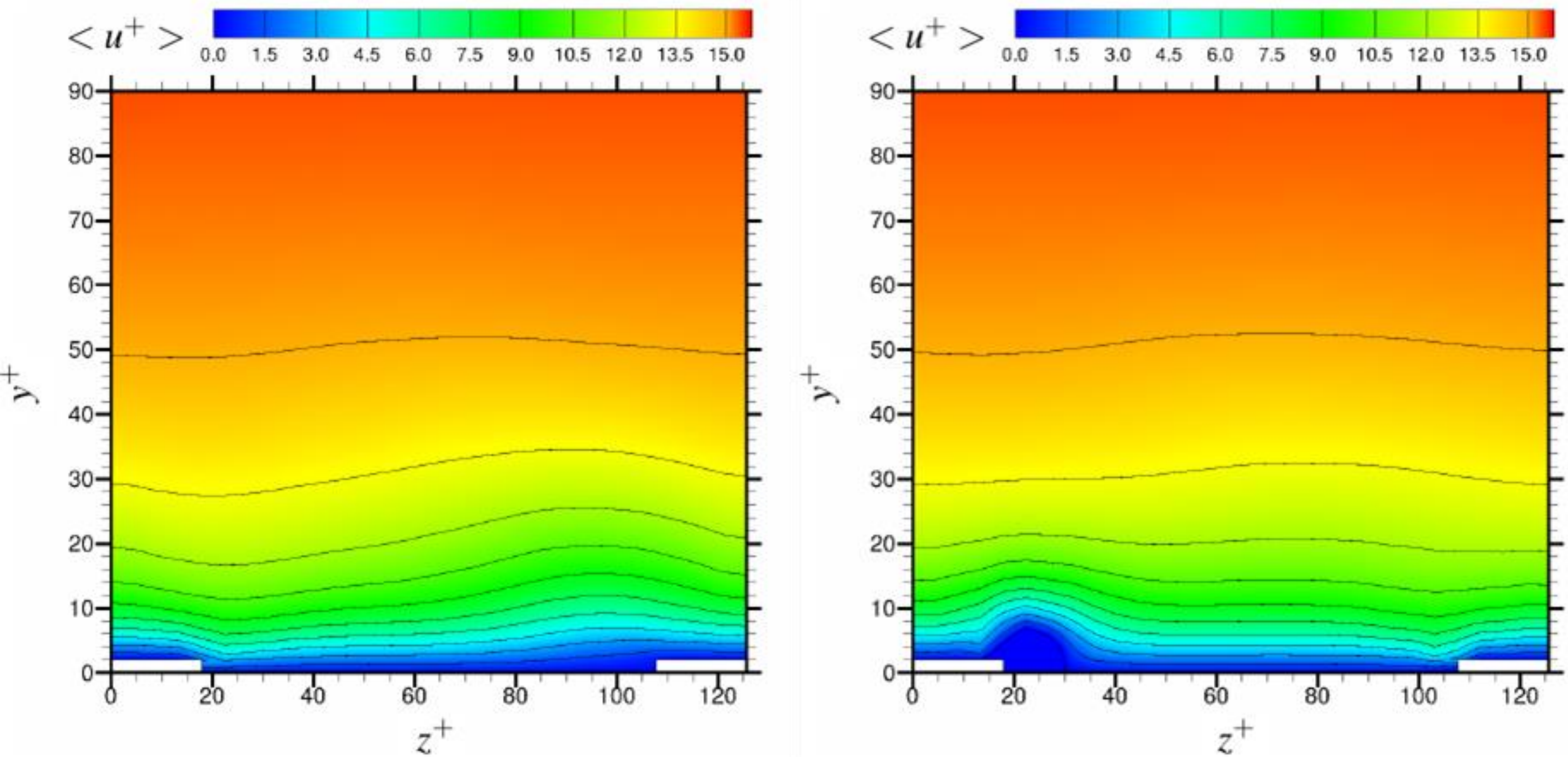




The dash line is baseline model.

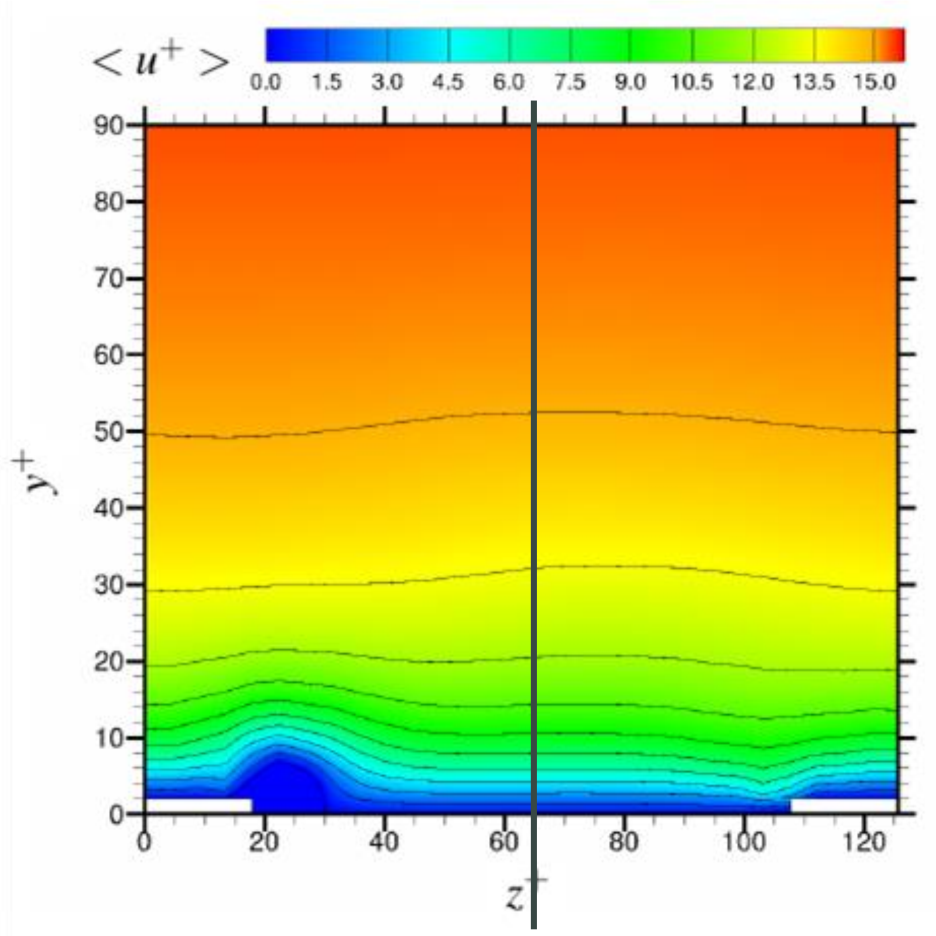
$\varphi = 0$

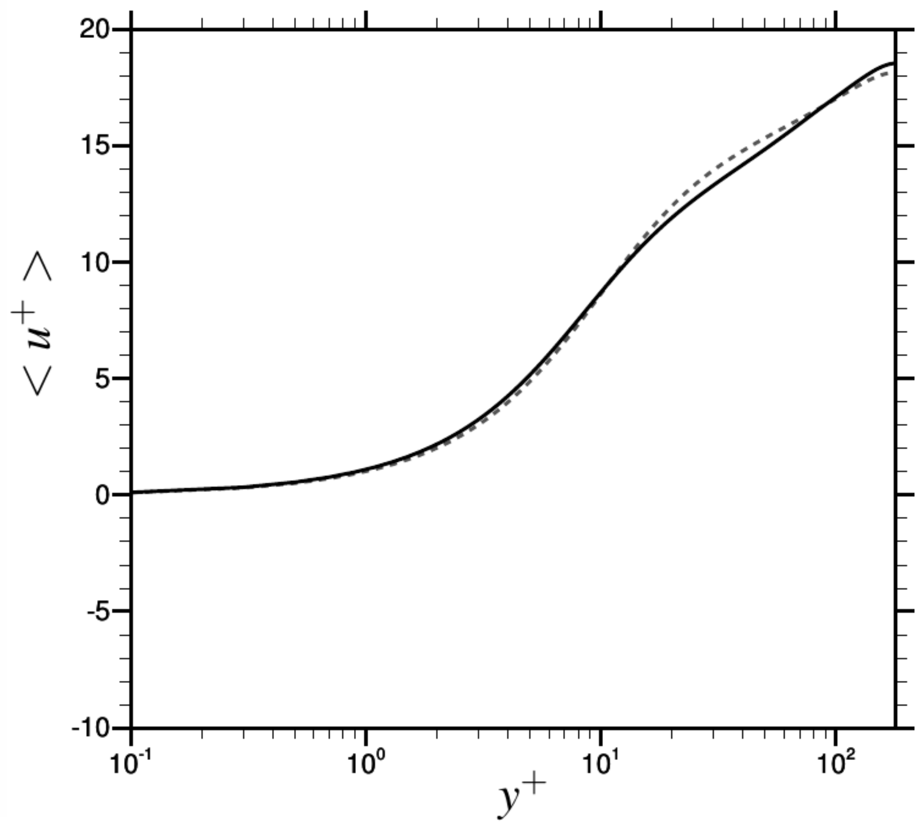
Streamwise mean velocity profiles with jets



(a) $\varphi = 0$ (b) $\varphi = \frac{\pi}{2}$

Streamwise mean velocity profiles with jets

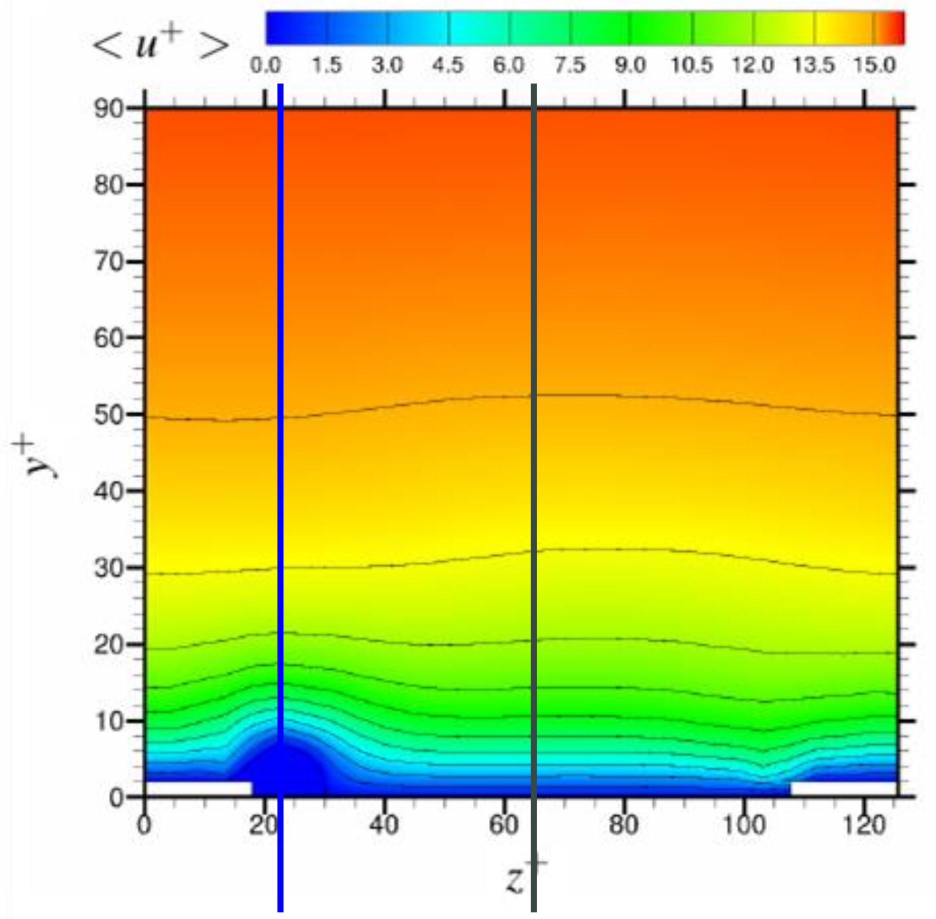


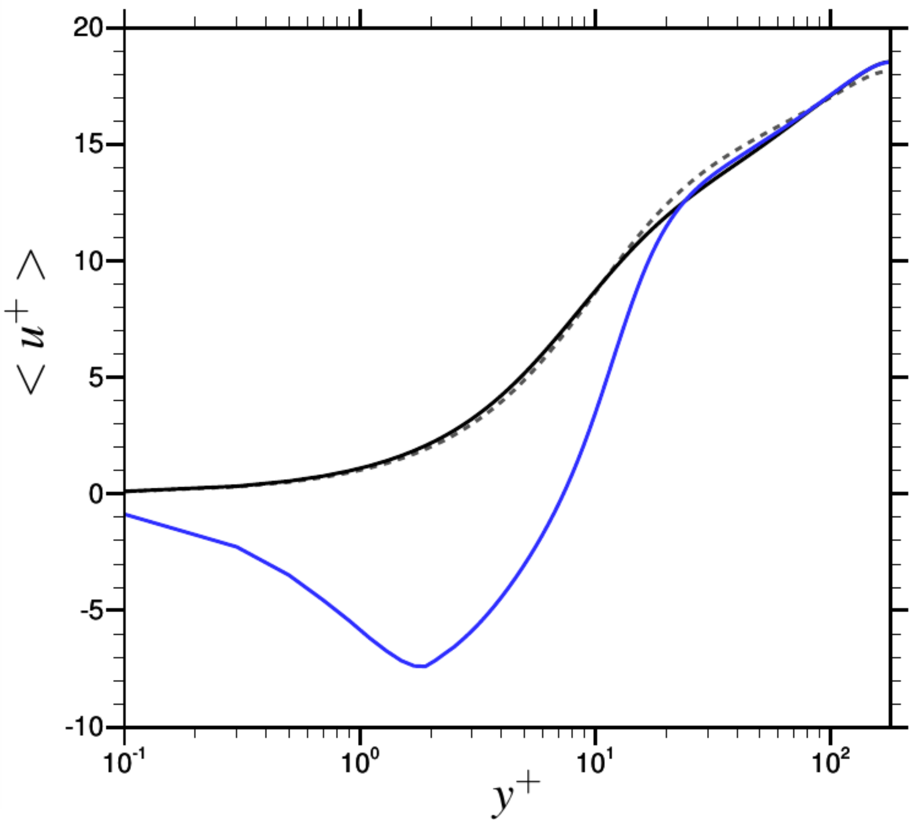


The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Streamwise mean velocity profiles with jets

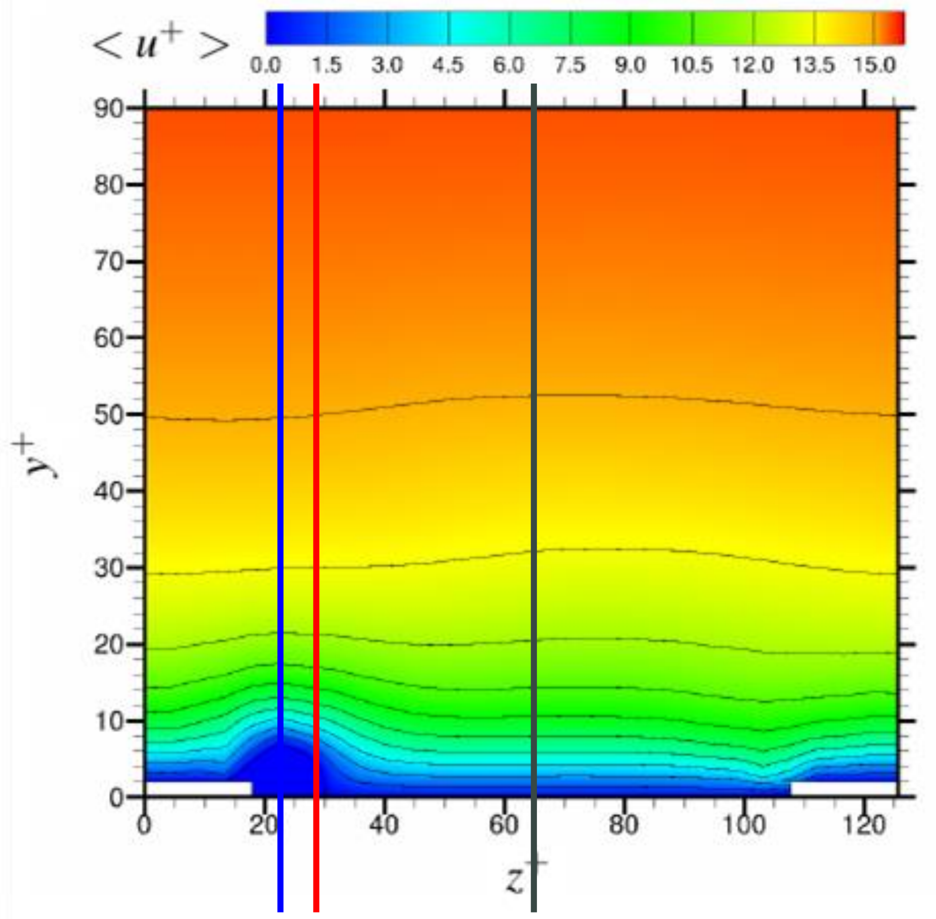


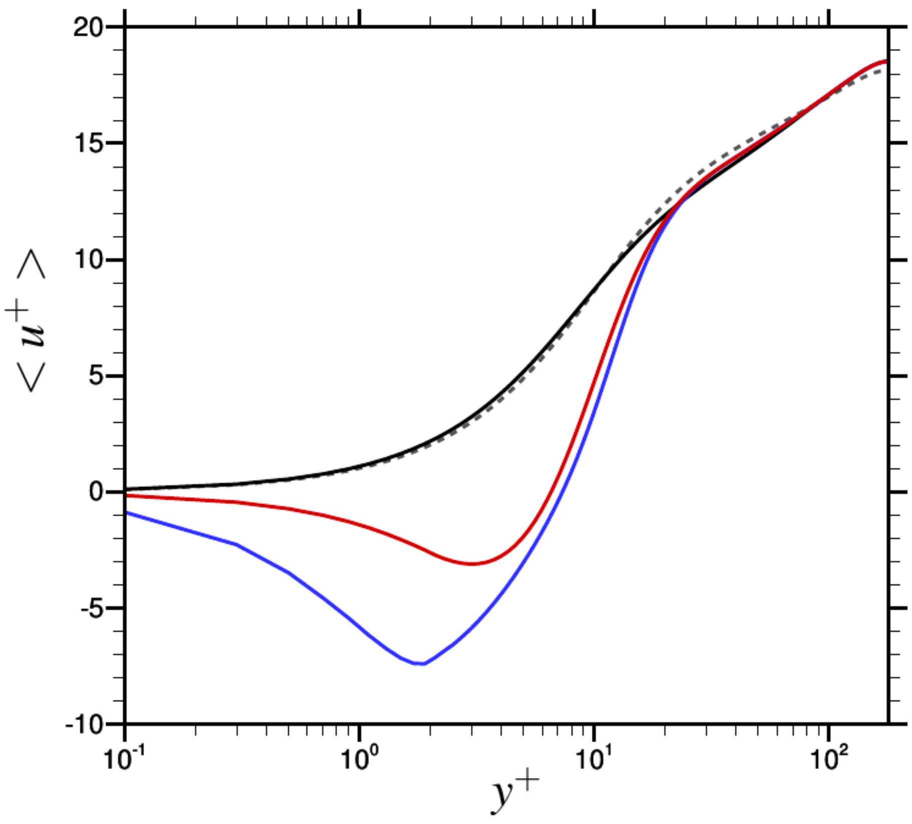


The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Streamwise mean velocity profiles with jets

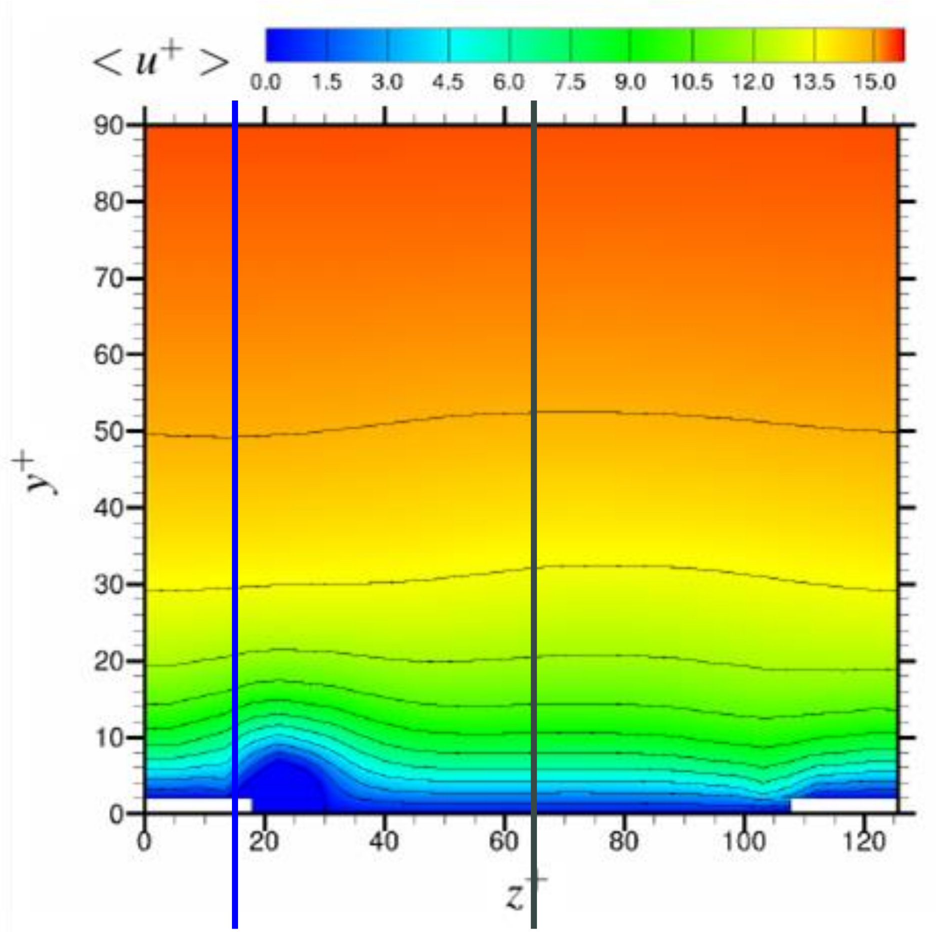


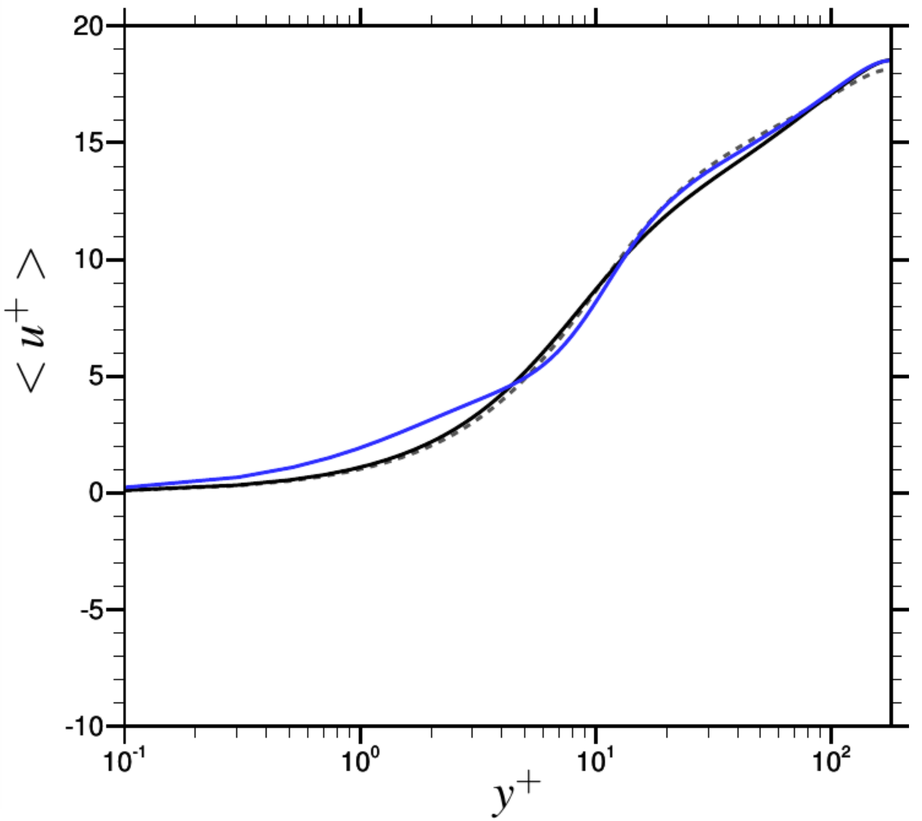


The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Streamwise mean velocity profiles with jets

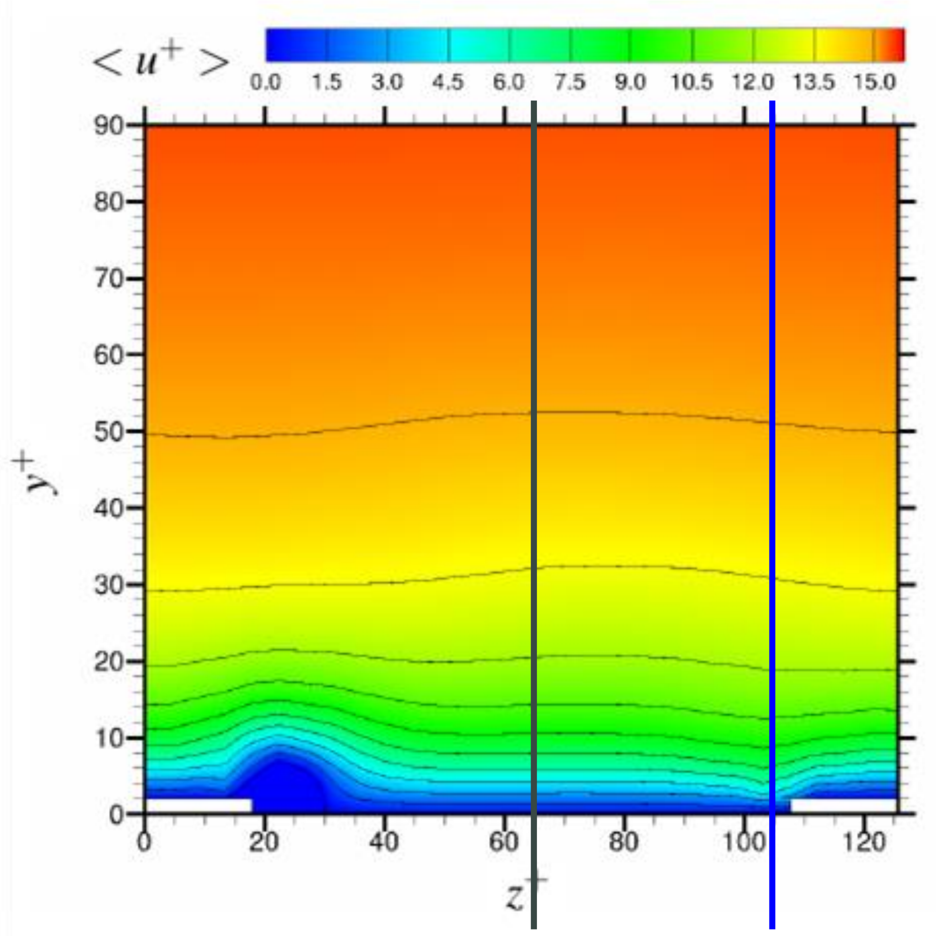


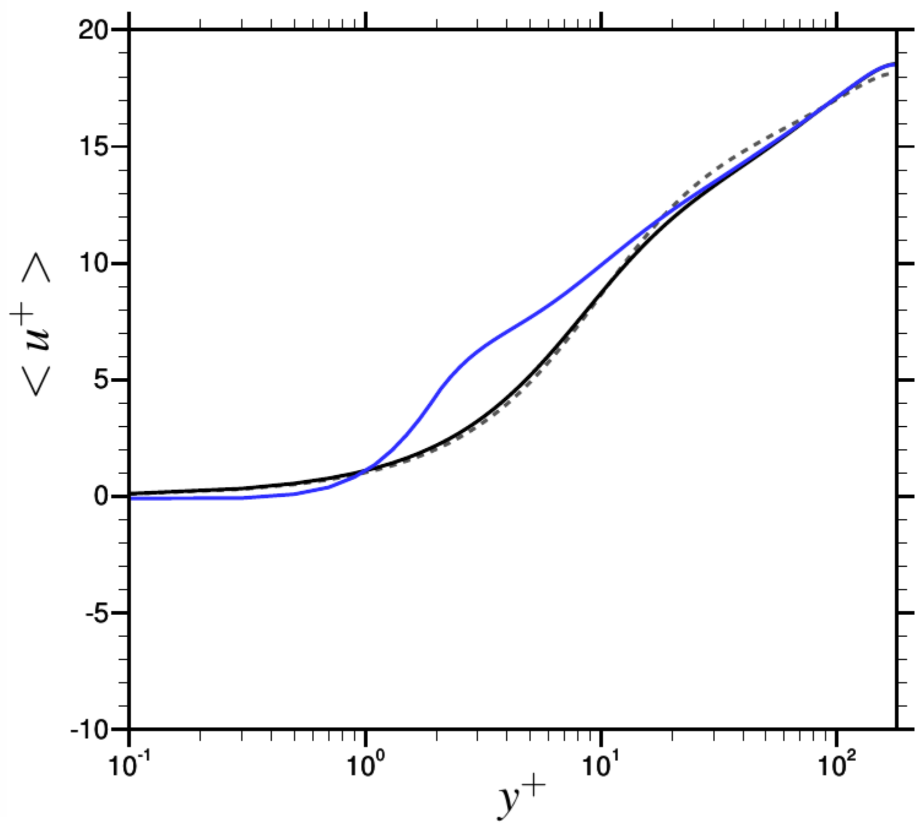


The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Streamwise mean velocity profiles with jets

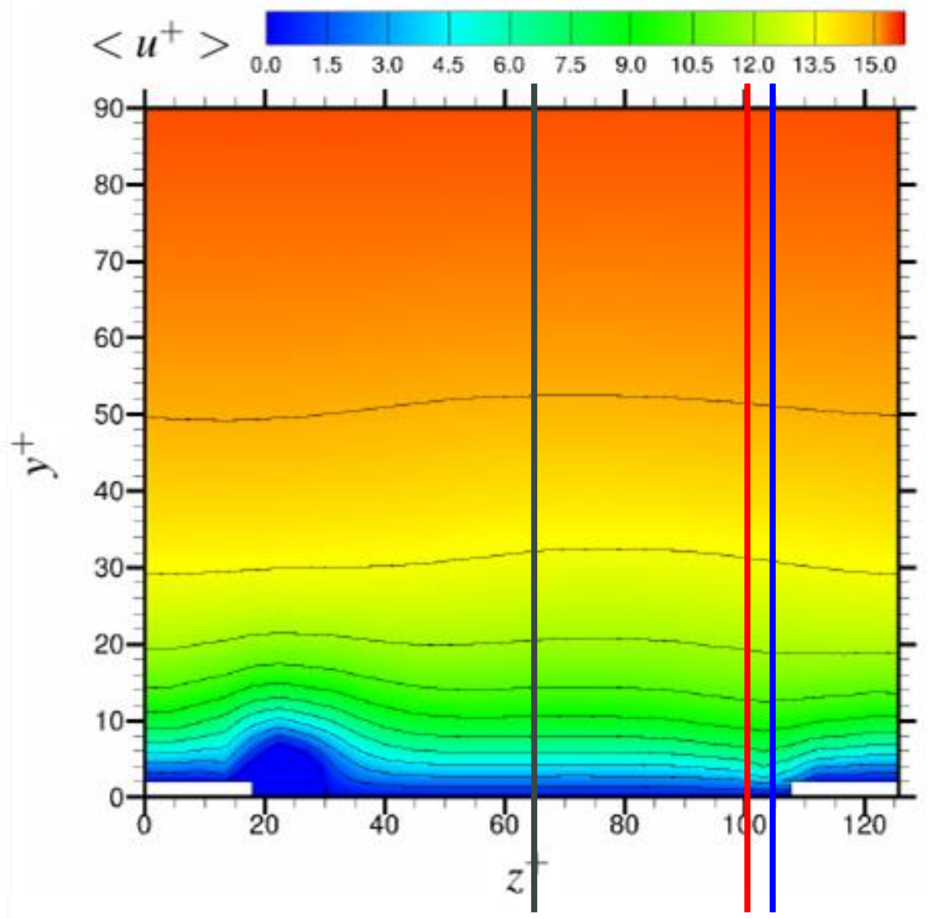


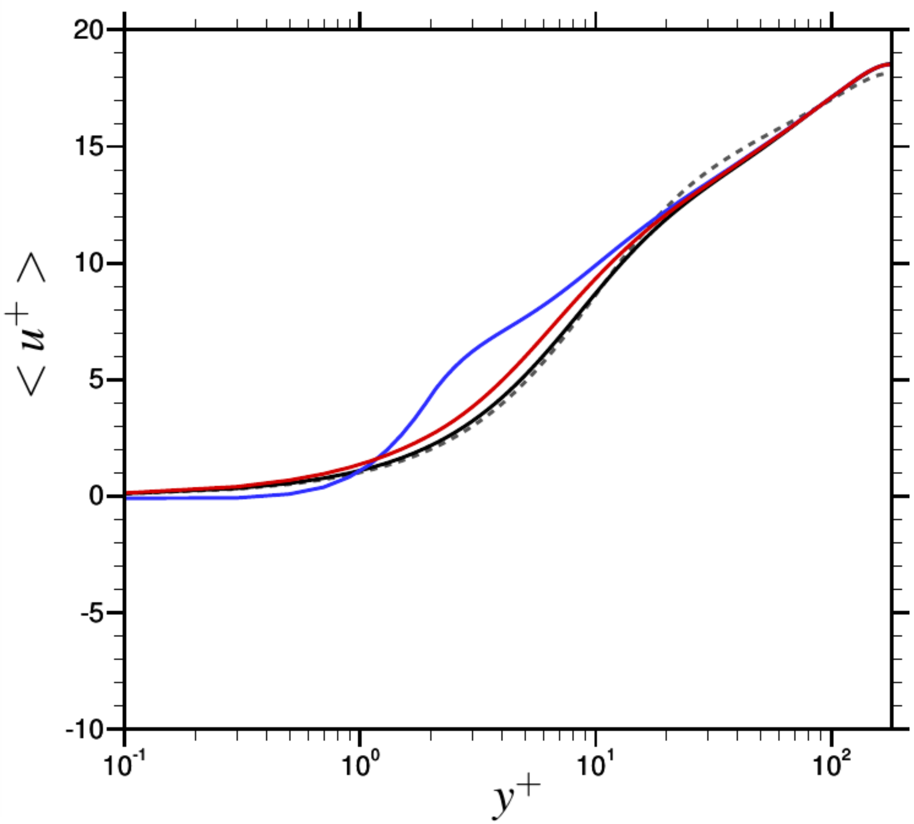


The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Streamwise mean velocity profiles with jets

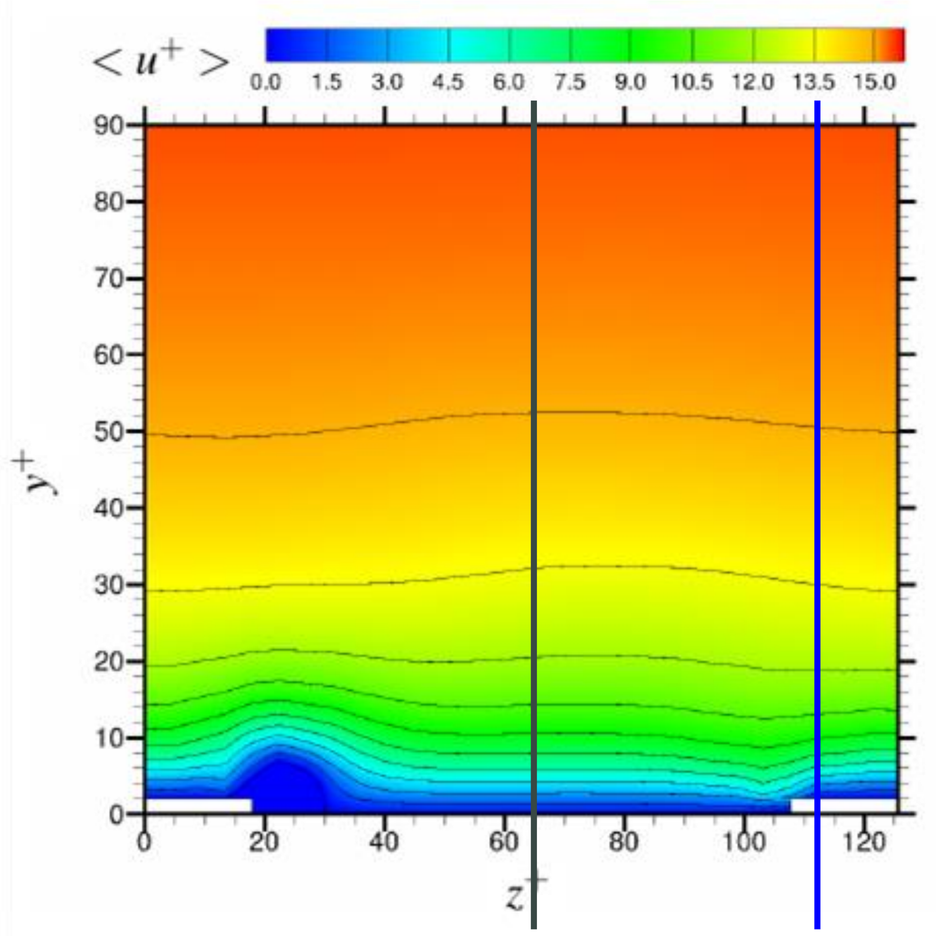


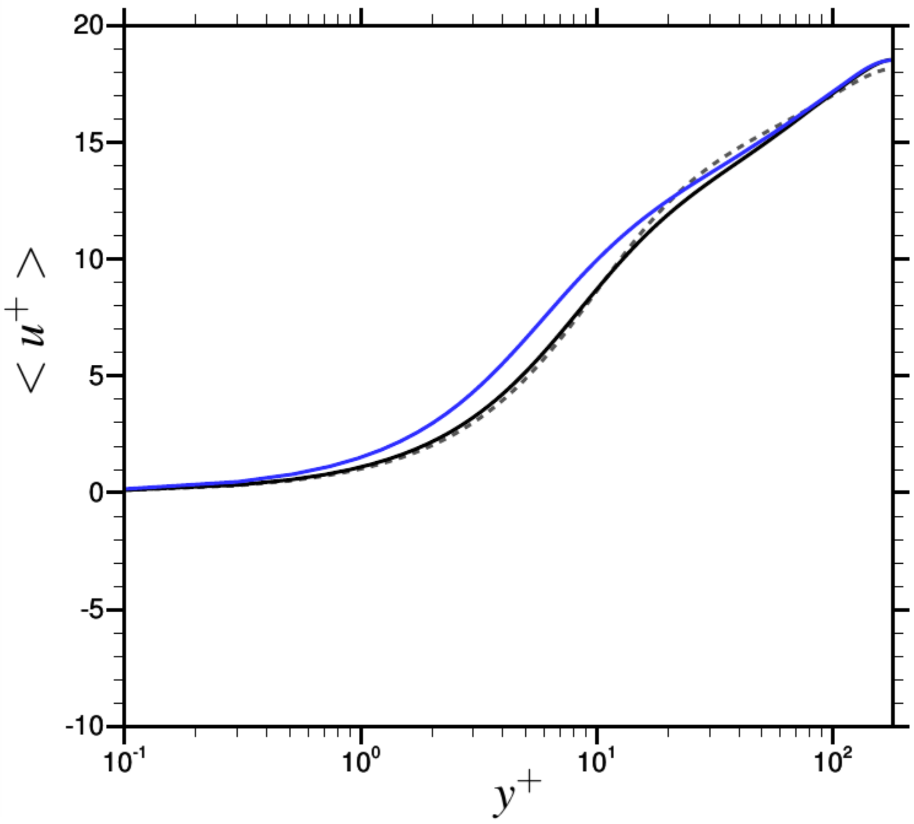


The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Streamwise mean velocity profiles with jets





The dash line is baseline model.

$$\varphi = \frac{\pi}{2}$$

Effect of ZMFJ on mean velocity profile

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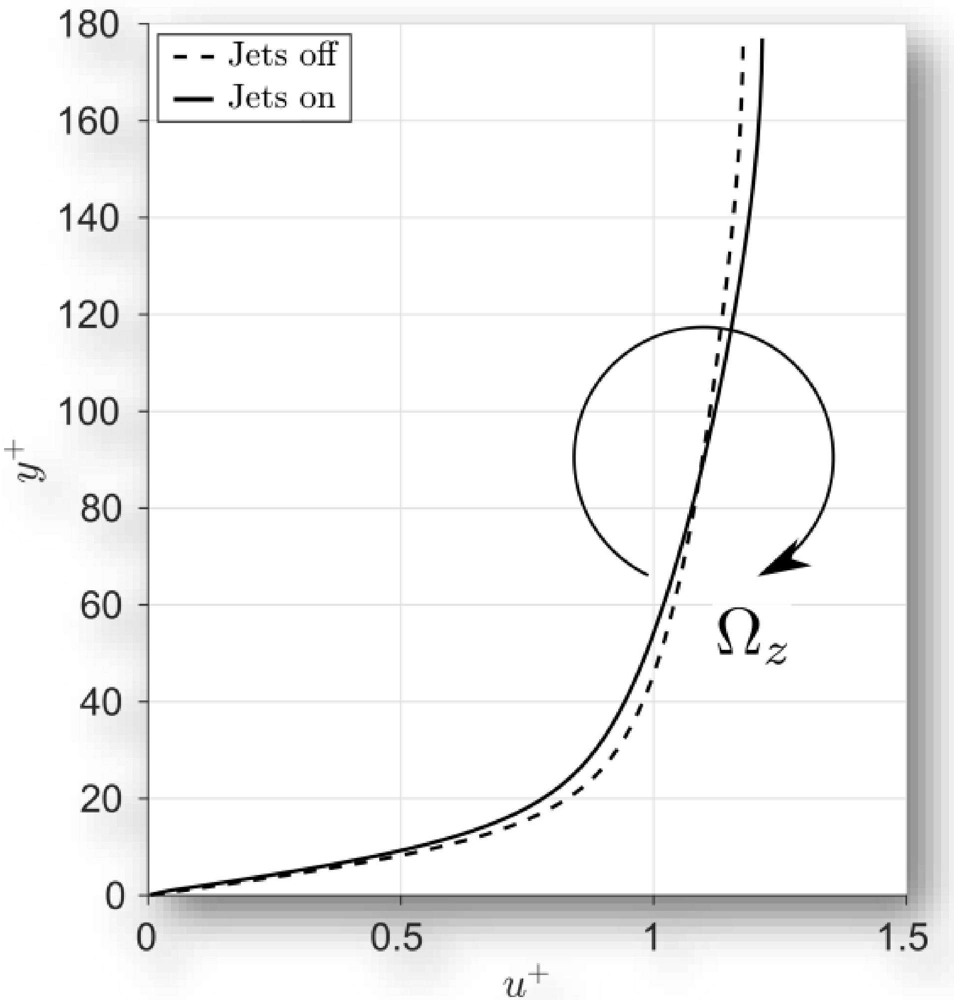

Stream-wise mean velocity profile is twisted by the spanwise vorticity.

Conclusions

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- ✓ Wall tangential zero mass jets can have a significant effect on skin friction drag, depending on the inclination angle against the main flow
- ✓ For pure spanwise (0^0) ZMFJ, a large increase in skin friction is observed for the given conditions. However, if the jets are at a range between $70^0$and 80^0, substantial reduction of friction can be achieved.
- ✓ The physical mechanism for drag reduction is different from spanwise oscillating walls. There is an increase of pure turbulent shear stresses ($u''v''$) using triple decomposition, which leads us to speculate that the reduction comes from $\tilde{u}$ and $\tilde{v}$ in ($u'v'$), to be verified by generalized FIK analysis
- ✓ The drag reduction comes primarily from the blowing phase

- ✓ A lot of further work need to be done for understanding!