Turbulent drag reduction using spanwise forcing in compressible regime

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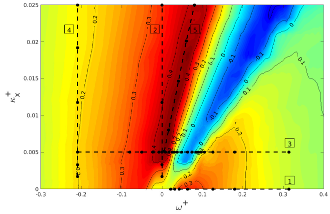
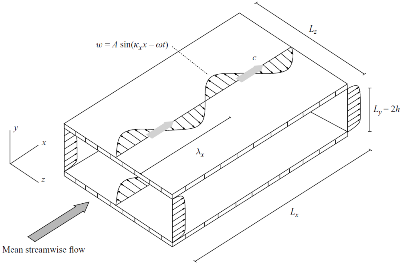


Skin friction drag reduction by spanwise forcing

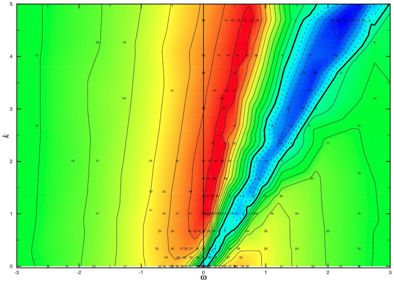
Travelling waves of spanwise oscillation

(Quadrio et al., JFM 2009)

$$W(x,t) = A \sin(\kappa_x x - \omega t)$$

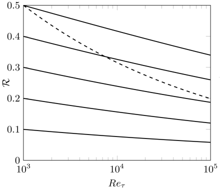


- At $Re_\tau = 200$ and $A^+ = 12$ Drag reduction up to $\approx 48\%$
- Steady waves and oscillating wall are obtained for $\omega = 0$ and $\kappa_x = 0$



Towards real-world applications

- Reynolds number dependence



Gatti & Quadrio, JFM 2016

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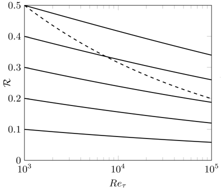
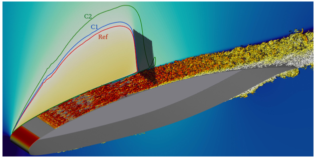


Gatti & Quadrio, JFM 2016

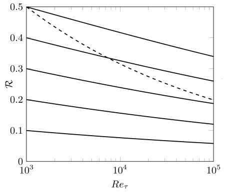
- Effect on the other drag sources in complex bodies



Quadrio et al., JFM 2022

Towards real-world applications

- Reynolds number dependence



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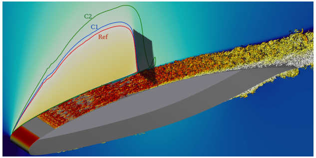


Quadrio et al., JFM 2022

- Effect of the Mach number

≈ Yao & Hussain, JFM 2019

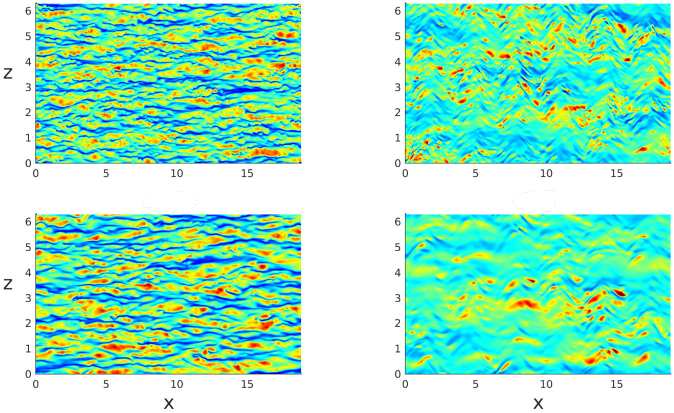
In this work

We extend the work by Yao & Hussain (JFM, 2019) and study streamwise travelling waves for drag reduction in the compressible regime at different Mach numbers

Uncontrolled | Controlled

$M_b = 0.8$

$M_b = 1.5$



Simulation details

- Direct Numerical Simulations of a perfect heat-conducting gas
- STREAmS solver (Bernardini et al, CPC 2021)
- $M_b = U_b/c_w = 0.3, 0.8$ and 1.5
- Constant flow rate (CFR)
- For the uncontrolled case: $Re_\tau = 400$
- For each M_b: 1 uncontrolled and 42 controlled simulations
- $A^+ = 12$ for the controlled simulations
- $(L_x, L_y, L_z) = (6\pi h, 2h, 2\pi h)$ with L_x that is adjusted depending on λ_x
- $(N_x, N_y, N_z) = (1024, 258, 512)$

The bulk temperature T_b

Two possibilities for the time evolution of

$$\boxed{T_b = \frac{1}{2h\rho_b U_b} \int_{-h}^{h} \langle \rho u T \rangle \mathrm{d}y}$$

- T_b freely evolves in time
- T_b/T_w is kept constant

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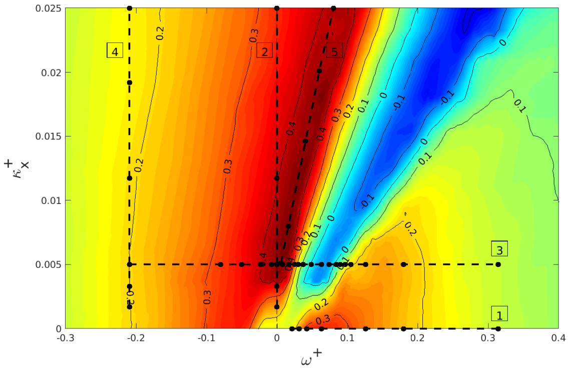
- T_b/T_w is kept constant
  - $\frac{T_b}{T_w} = \frac{1}{1+s\frac{\gamma-1}{2}rM_b^2}$ to set the ratio of bulk flow kinetic energy converted into wall heat flux s
  - $s = 0.75$, meaning that 75% of the kinetic energy is transformed into thermal energy

Simulations



- Line 1: Oscillating wall
- Line 2: Steady wave
- Line 3: Travelling wave with $\kappa_x^+ = 0.005$
- Line 4: Travelling wave with $\omega^+ = -0.21$
- Line 5: Optimum ridge for drag reduction

Performance indicator

- Drag reduction rate DR

$$DR = \frac{P_0 - P}{P_0}$$

where

$$P = \frac{U_b}{T_{ave} L_x L_z} \int_{t_i}^{t_f} \int_0^{L_x} \int_0^{L_z} \tau_x \mathrm{dzdxdt}$$

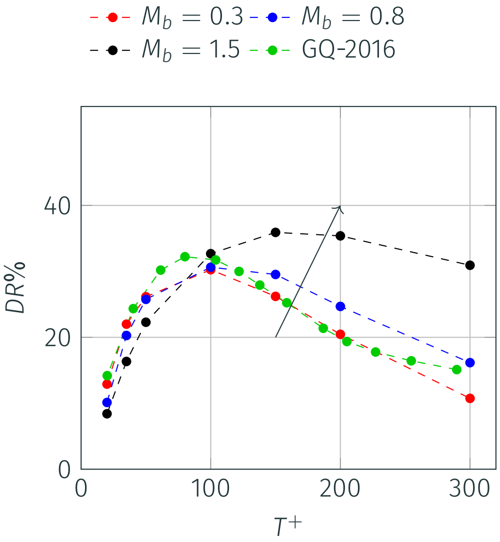
- Power required to create the wall forcing P_{in}

$$P_{in} = \frac{1}{T_{ave} L_x L_z} \int_{t_i}^{t_f} \int_0^{L_x} \int_0^{L_z} W \tau_z \mathrm{dzdzdt}$$

- Net energy saving rate P_{net}

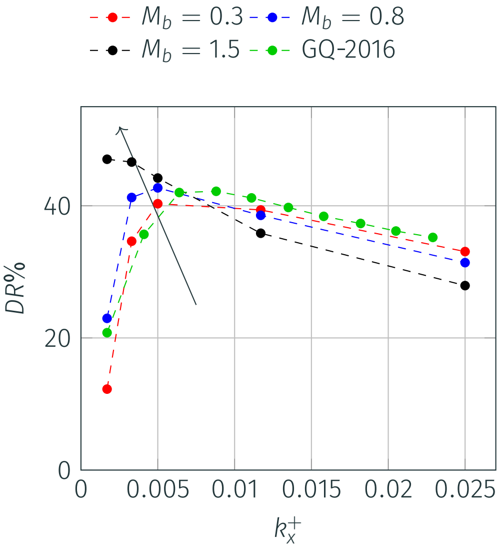
$$P_{net} = DR - \frac{P_{in}}{P_0}$$

Line 1: Oscillating wall



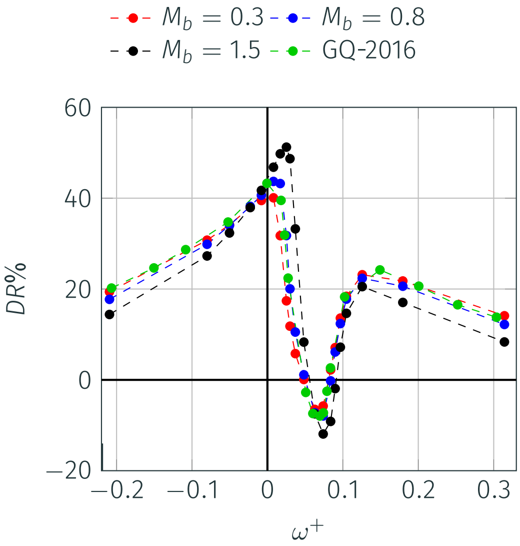
- For $M_b = 0.3$: $T^+_{\text{max}} \approx 100$, like in the incompressible regime
- When $M_b \uparrow$, the $DR - T$ trend qualitatively does not change
- When $M_b \uparrow$
  - $DR \downarrow$ for small T
  - $DR \uparrow$ for large T

Line 2: steady wave



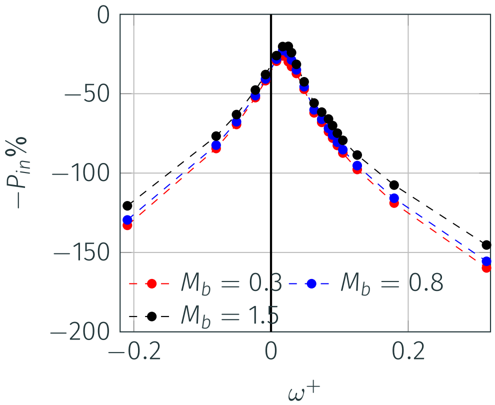
- For $M_b = 0.3$: $\kappa^+_{x,\mathbf{max}} \approx 0.005$, like in the incompressible regime
- When $M_b \uparrow$
  - $DR \uparrow$ for small κ_x
  - $DR \downarrow$ for large κ_x

Line 3: Travelling waves with $\kappa_x^+ = 0.005$



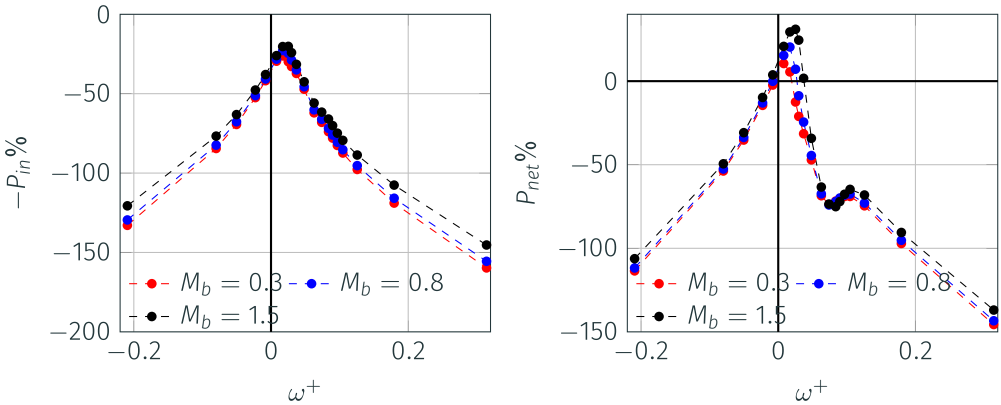
- For $M_b = 0.3$: results agree with the incompressible regime
- When $M_b \uparrow$:
  - $DR \downarrow$ for $\omega^+ < 0$ and $\omega^+ > 0.06$
  - $DR \uparrow$ for $0 < \omega^+ < 0.06$
- When $M_b \uparrow$
  - the global DR peak moves towards larger ω
  - the second local DR peak moves towards smaller ω
- When $M_b \uparrow$ the DI region shrinks

Power budgets: Line 3



- $|P_{in}|\% \downarrow$ when $M_b \downarrow$

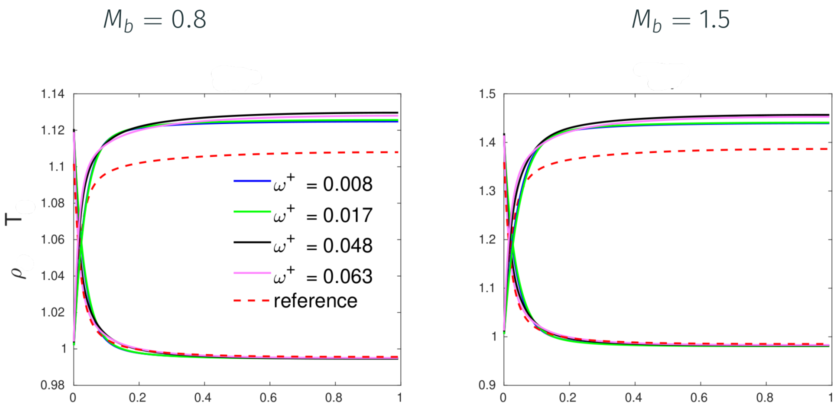
Power budgets: Line 3



- $|P_{in}|\% \downarrow$ when $M_b \downarrow$

- $P_{net}\% \uparrow$ when $M_b \uparrow$.
- $P_{net} = 10\%, 20\%$ and 30% for $M_b = 0.3, 0.8$ and 1.5.

The bulk temperature T_b: Line 3 ($\kappa_x^+ = 0.005$)



- $T_b \uparrow$ when $M_b \uparrow$
- $T_b \uparrow$ when the control is active and $\Delta T_b = T_b - T_{b,0} \uparrow$ with M_b

Is the increase of ΔT_b the dominant effect?

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Two possibilities for the time evolution of

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- T_b/T_w is kept constant

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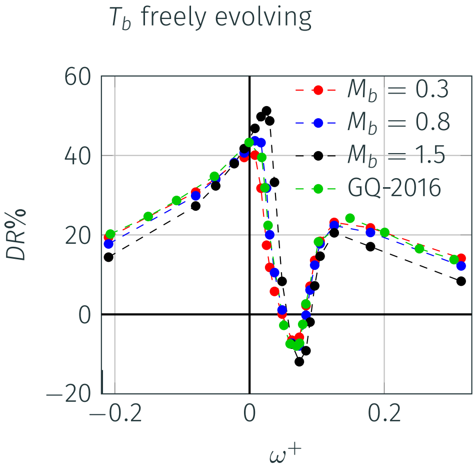
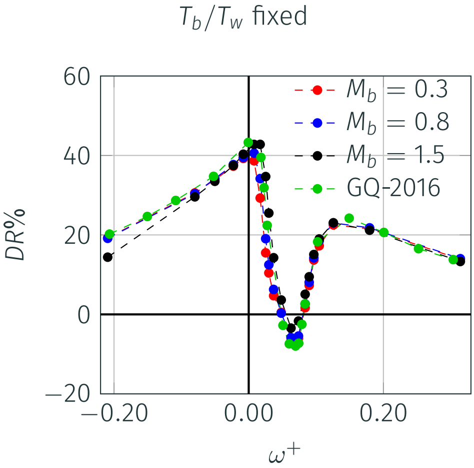
$$T_b = \frac{1}{2h\rho_b U_b} \int_{-h}^{h} \langle \rho u T \rangle \mathrm{d}y$$

- T_b freely evolves in time

- T_b/T_w is kept constant
- $\boxed{\frac{T_b}{T_w} = \frac{1}{1 + s\frac{\gamma-1}{2} r M_b^2}}$ to set the ratio of bulk flow kinetic energy converted into wall heat flux s
- 75% of the kinetic energy is transformed into thermal energy ($s = 0.75$)
- Same T_b/T_w for the reference and controlled cases

Line 3 ($\kappa_x^+ = 0.005$): Effect of T_b





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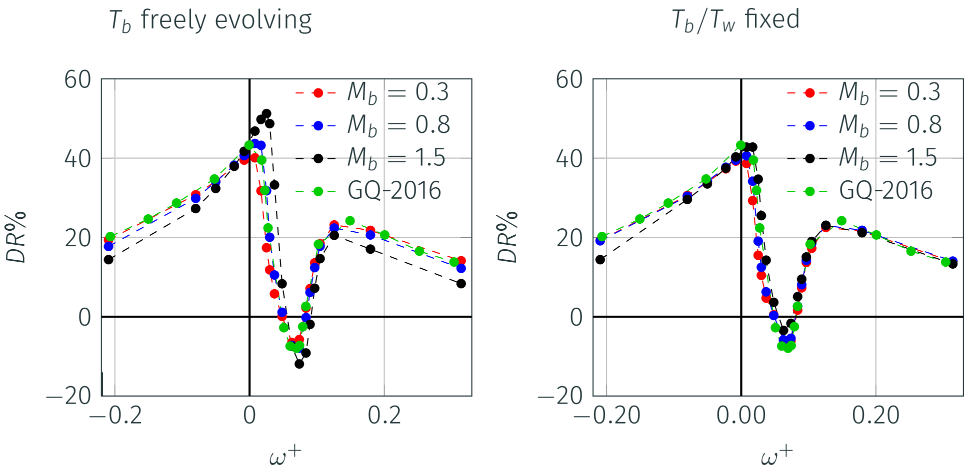


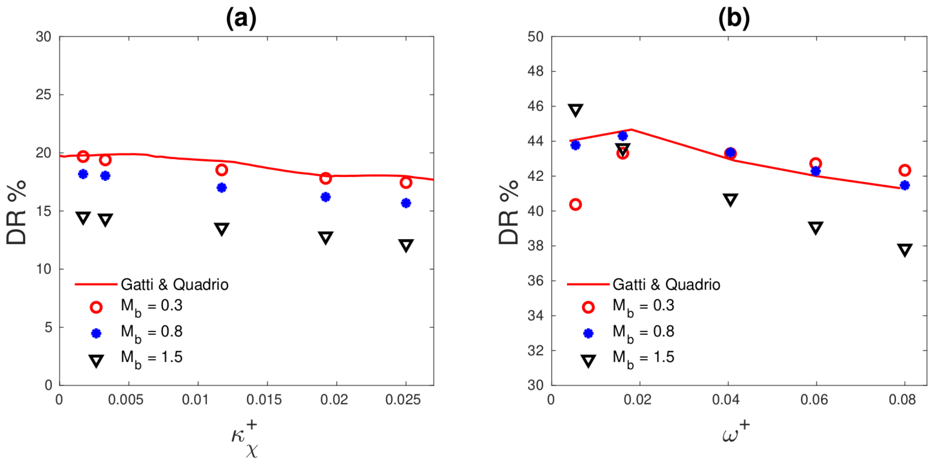
- When T_b/T_w is fixed the DR curves almost collapse

Conclusions

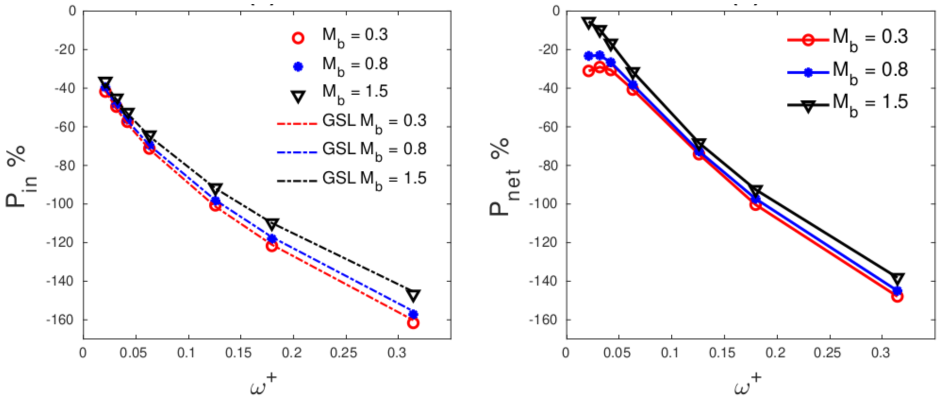
- Influence of the compressibility on the performance of spanwise forcing
- $M_b = 0.3, 0.8$ and 1.5 at $Re_\tau = 400$
- The effect of the control depends on how T_b is set
- If T_b is left free to evolve the maximum DR increases by 27%, when the Mach number increases from $M_b = 0.3$ to $M_b = 1.5$
- If T_b/T_w is kept constant the DR curves almost collapse

Thanks for your attention!

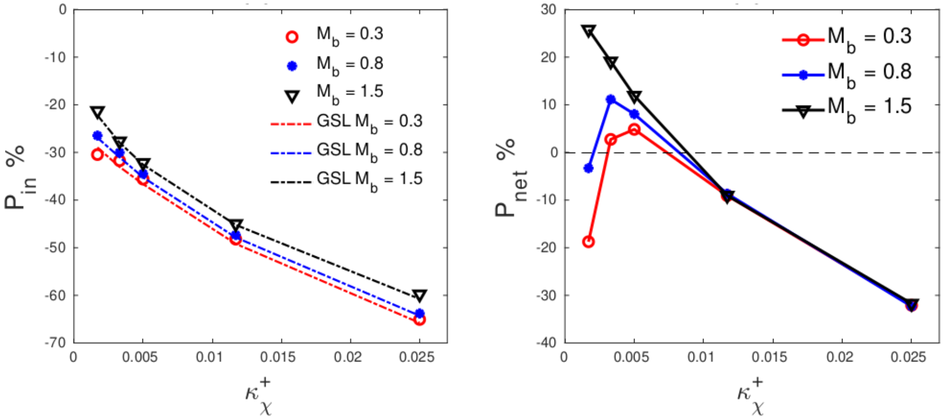
DR for lines 4 and 5



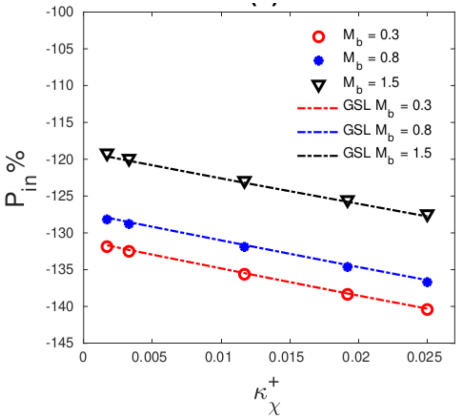
P_{in} and P_{net} for line 1

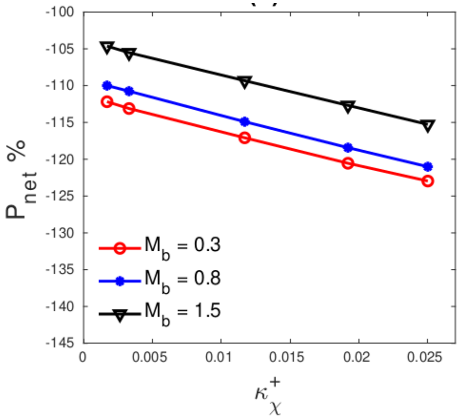


P_{in} and P_{net} for line 2

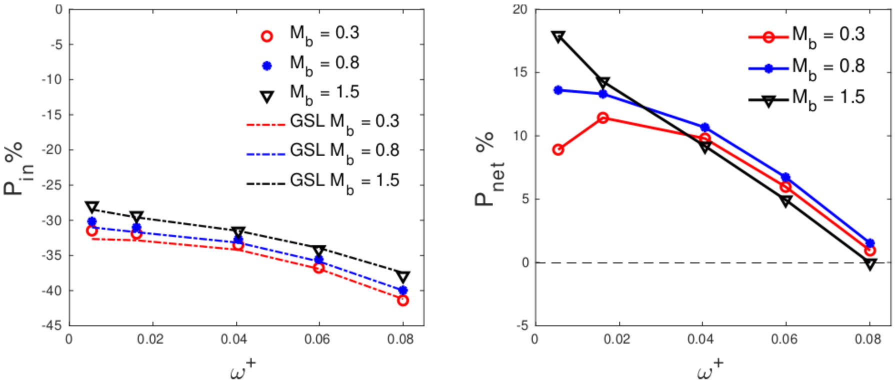


P_{in} and P_{net} for line 4





P_{in} and P_{net} for line 5



Governing Equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} + f\delta_{i1} \tag{2}$$

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho (e + p/\rho) u_j}{\partial x_j} = \frac{\partial \sigma_{ij} u_i - \partial q_j}{\partial x_j} + f u_1 + \Phi \tag{3}$$

where: $e = c_v T + u_i u_i/2$, $\sigma_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right)$

q_j is the heat flux vector, modelled as $q_j = -k \frac{\partial T}{\partial x_j}$, and $k = c_p \mu / Pr$ where $Pr = 0.72$.

Φ is a uniformly distributed cooling term (heat sink) to control the value of T_b and to absorb, when needed, the heat produced by viscous dissipation. It is zero when T_b is left freely to evolve in time. When T_b/T_w is constant Φ is evaluated at each time step.