Data-driven correlations for thermohydraulic roughness properties

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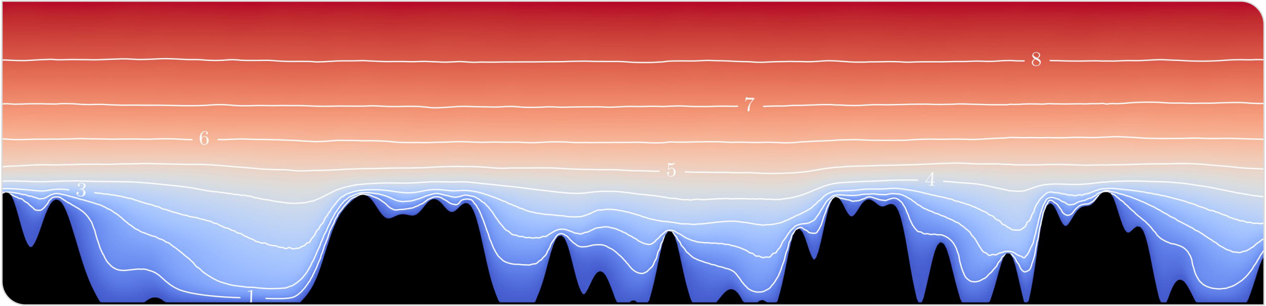
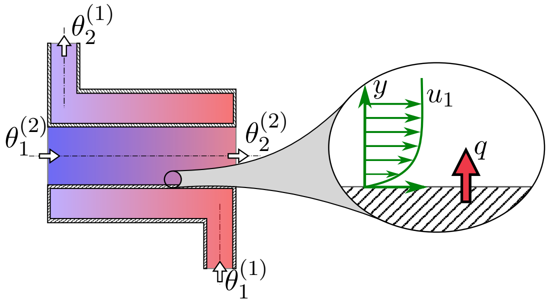


Reynolds Analogy: Velocity and Heat

Example: Heat Exchanger



Reynolds analogy

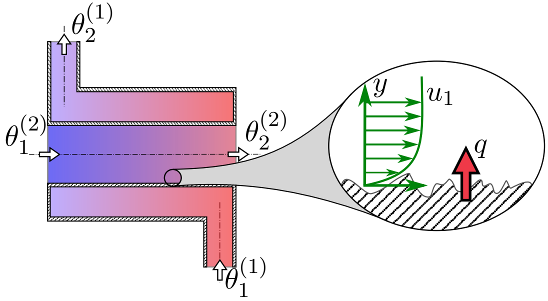
- Heat and momentum transfer are proportional
- Reynolds analogy factor:

$$RA = \frac{2St}{C_f} = \frac{2Nu}{C_f \, Re \, Pr} \tag{1}$$

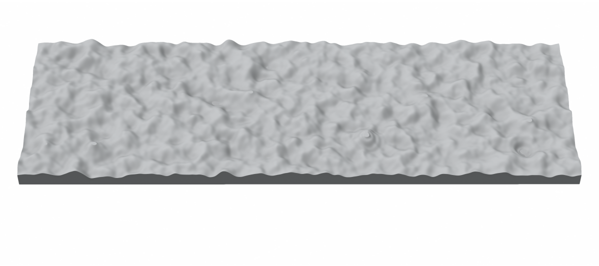
- Classical application: smooth surfaces

Reynolds Analogy: Velocity and Heat

Example: Heat Exchanger

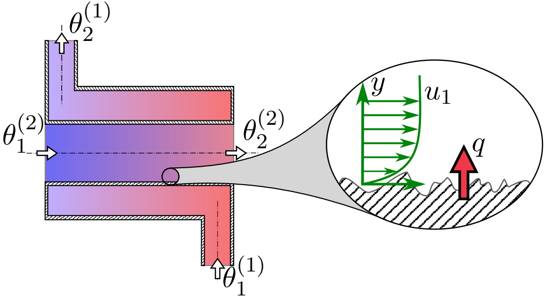


Rough surface

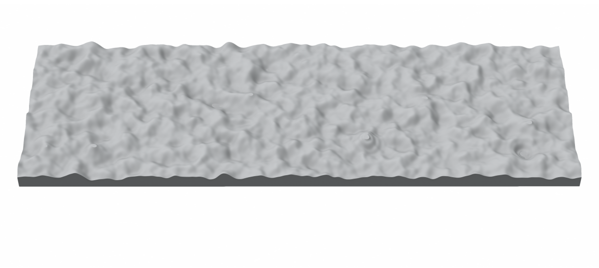


Reynolds Analogy: Velocity and Heat

Example: Heat Exchanger



Rough surface



Question

- ➙ How does the presence of rough surfaces influence velocity and temperature distribution?
- ➙ Is everything from the rough surface important?

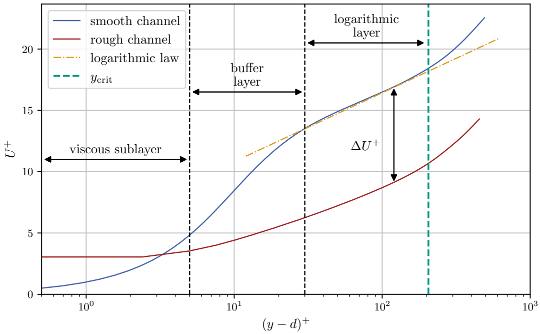
Roughness Influence on Channel Flow I

Velocity Augmentation:

- Roughness function (Hama, 1954; Clauser, 1954)

$$\Delta U^+ = U_\mathrm{S}^+ - U_\mathrm{R}^+$$
$$= \frac{1}{\kappa} \ln\left(k_\mathrm{s}^+\right) + A - B(k_\mathrm{s}^+)$$

- $B(\infty) = 8.5$ in fully rough regime $\rightarrow$ only k_s necessary for ΔU^+



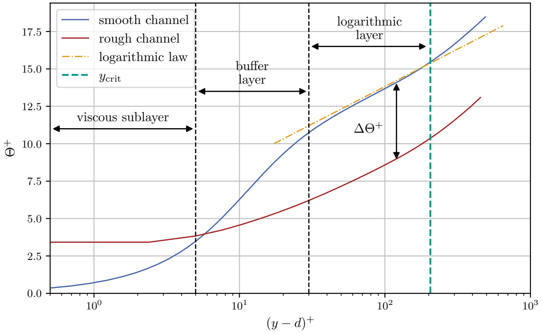
Roughness Influence on Channel Flow II

Temperature Augmentation:

- Equations following Dipprey and Sabersky (1963), Brutsaert (1975) and Yaglom (1979)

$$\begin{aligned}\Delta\Theta^+ &= \Theta_\mathrm{S}^+ - \Theta_\mathrm{R}^+ \\ &= \frac{1}{\kappa_\theta}\ln\left(k_\mathrm{s}^+\right) + A_\theta(Pr) - g(k_\mathrm{s}^+, Pr) \\ &= \frac{1}{\kappa_\theta}\ln\left(y_\mathrm{I}^+\right) + A_\theta(Pr) - \Theta_\mathrm{I}^+(k_\mathrm{s}^+, Pr)\end{aligned}$$

- Empirical and phenomenological relations

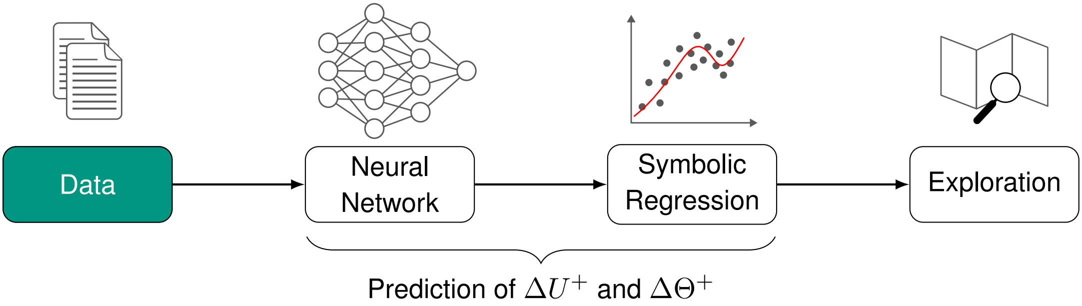


Important

- → Breakdown of Reynolds analogy for flow with rough surfaces (e.g. Hantsis and Piomelli (2024))
- → Predict ΔU^+ and $\Delta\Theta^+$ without detailed simulation

Approach

Procedure:

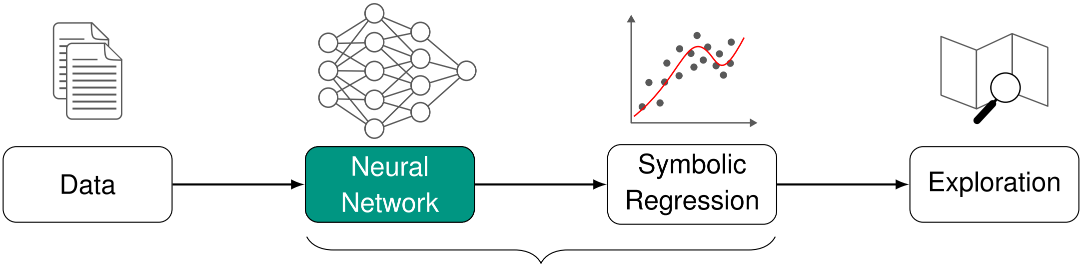


Data:

- 4200 rough surfaces and 93 high-fidelity simulations ($Re_\tau \approx 800$, $Pr = 0.71$) (Yang et al., 2023)
- External data set for additional testing

Approach

Procedure:



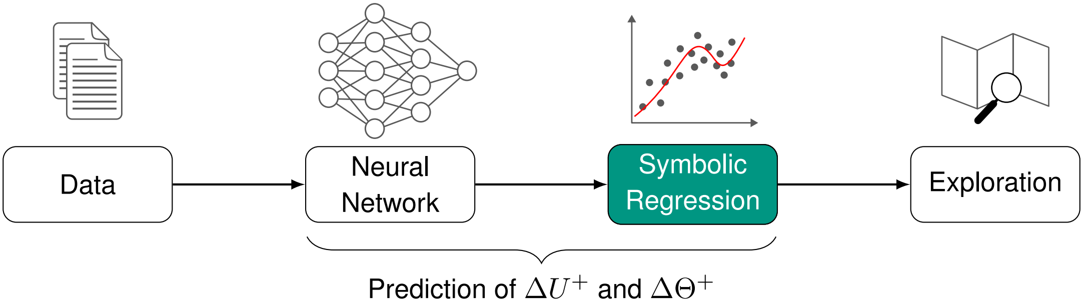
Prediction of ΔU^+ and $\Delta\Theta^+$

Neural Network:

- Data-driven function approximation given powerful statistical measures

Approach

Procedure:

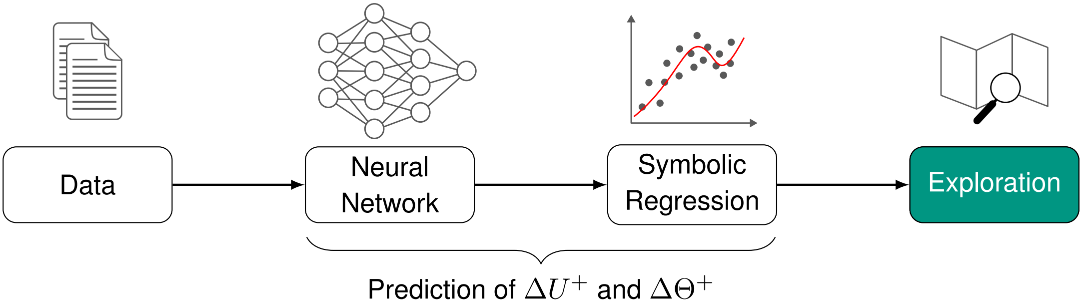


Symbolic Regression:

- Convert hidden function in human-understandable symbolic expression

Approach

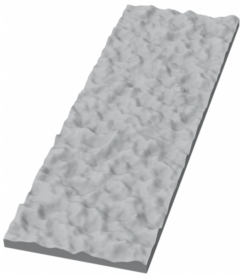
Procedure:



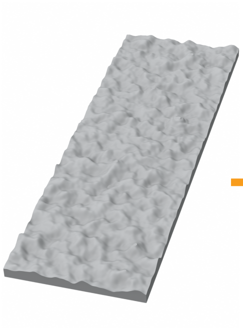
Exploration:

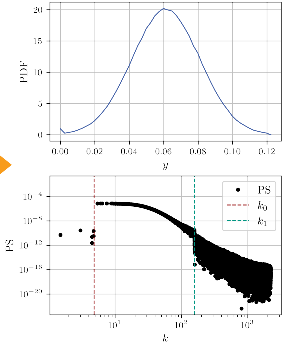
- Use predictive tools on rough surfaces

Neural Network Prediction

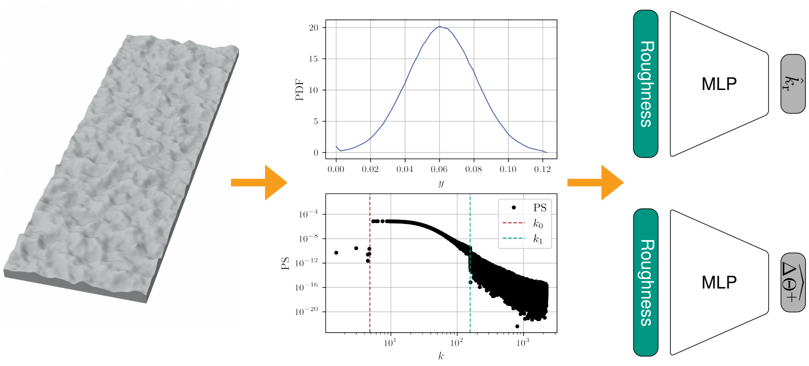


Neural Network Prediction

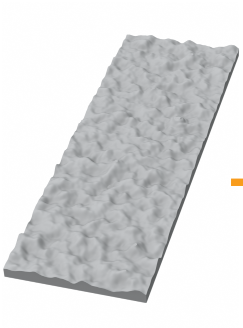


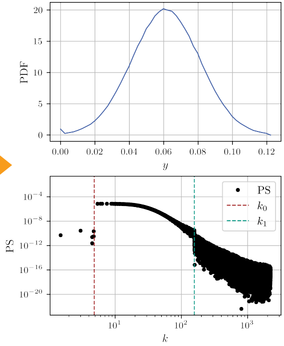


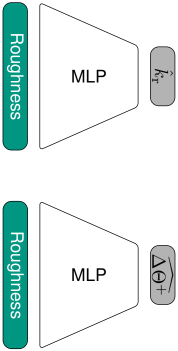
Neural Network Prediction

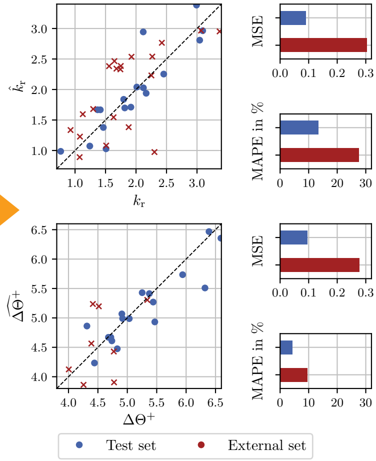


Neural Network Prediction







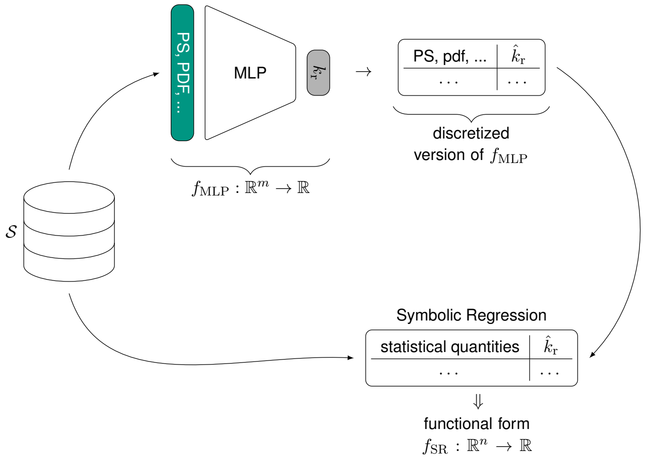


Symbolic Regression

Goal

→ Translate network to correlation using simple statistical properties

- Statistical parameters vs. power spectrum & probability density function
- Genetic Programming
- `Python` library `PySR` (Cranmer, 2023)



Results

Correlation	R^2	Result
$k_\mathrm{r} = \frac{k_\mathrm{s}}{k_{99}} = ES_x \left(-ES_x + Sk + 2.21 \right) + 0.819$	0.931	exceed references

Results

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$k_r = \frac{k_s}{k_{99}} = ES_x(-ES_x + Sk + 2.21) + 0.819$	0.931	exceed references

Measure of Height

- k_{99} is 99% confidence interval of p.d.f
- Related to height

Measure of Slope

$$ES_x = \frac{1}{A}\int_A \left|\frac{\partial h}{\partial x}\right| \mathrm{d}A$$

- Related to frontal solidity

Measure of Shape

$$Sk = \frac{1}{A}\int_A \frac{h^3}{k_{rms}} \mathrm{d}A$$

- Asymmetry in height

→ Selected statistical parameters align with conclusion by Flack and Chung (2022) and other correlations (Chung et al., 2021)

Results

Correlation	R^2	Result
$k_\mathrm{r} = \frac{k_\mathrm{s}}{k_{99}} = ES_x\,(-ES_x + Sk + 2.21) + 0.819$	0.931	exceed references
$\Delta\Theta^+ = 6.02\left(k_\mathrm{s}\left(-0.18\,Sk + \frac{k_\mathrm{z}}{k_\mathrm{rms}}\right)\right)^{0.138}$	0.827	less powerful

➙ Limited reference data

➙ Missing Pr-dependency ($\Delta\Theta^+ = f(Pr)$)

Explore Symbolic Expression

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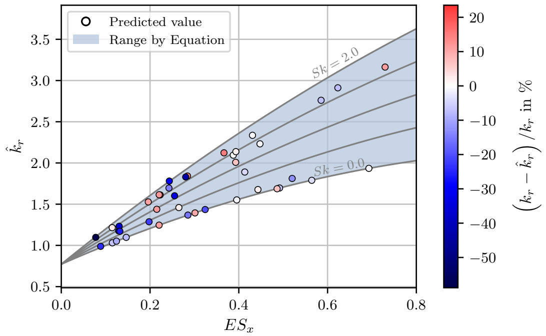
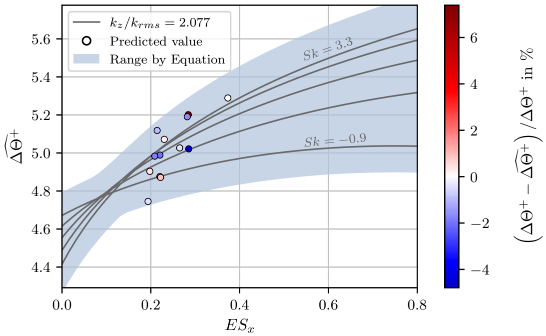
Velocity Augmentation



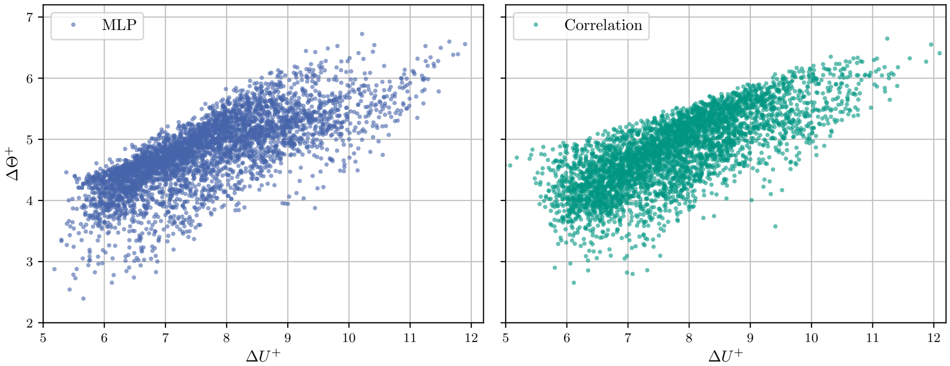
Temperature Augmentation



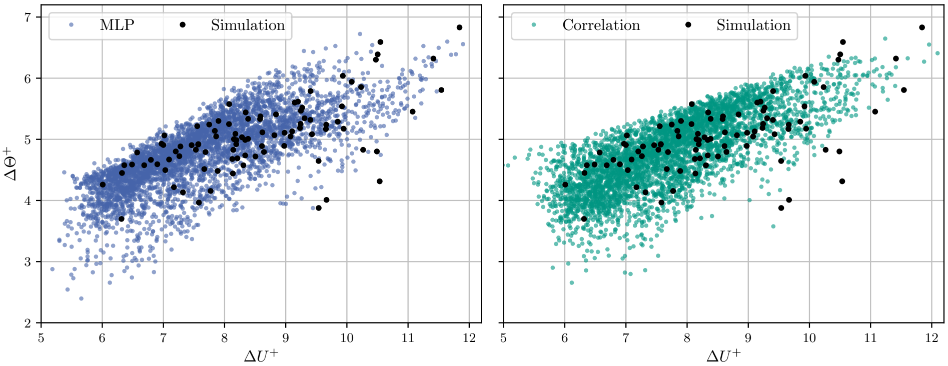
Observation

→ Velocity correlation follows known behaviors (Kuwata et al., 2023); temperature is limited

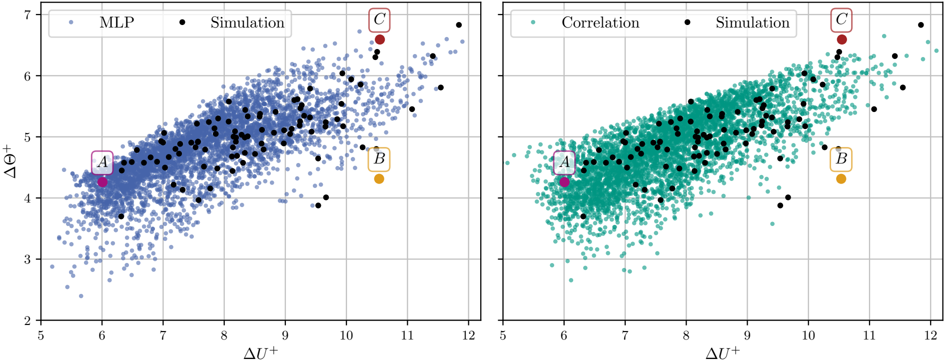
Explore Predictive Tools

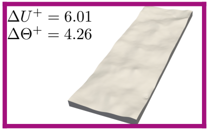


Explore Predictive Tools

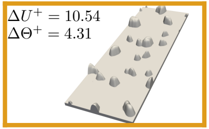


Explore Predictive Tools

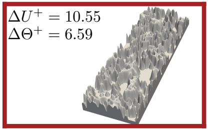




A



B

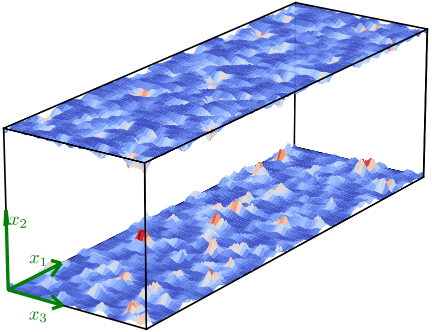


C

Summary

Summary

- ➛ Different features of rough surface are important for ΔU^+ and $\Delta\Theta^+$
- ✔ Prediction without detailed simulation
- ✔ Correlation aligns with literature and simulations
- ✘ Limitation in generalization for $\Delta\Theta^+$



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