Simulation and Analysis of Heat-Transfer Effects in Dense-Gas Turbulent Cylinder Flows

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Motivation

- sCO_2 power cycles are more compact and efficient than traditional cycles, but many cycle components are yet to be optimized
- External flows, such as flow over compressor and turbine blades, affect heat transfer and thus cycle efficiency and performance
- **Goal: investigate heat transfer effects in large-eddy simulations of canonical ideal and dense gas cylinder flows that can be extended to blade configurations**

Equations of State

- Peng-Robinson (PR) EOS[1]:

$$p_r = \frac{T_r}{v^* - b^*} - \frac{a^* \alpha(T_r)}{v^{*2} + 2v^* b^* - b^{*2}}$$

$$p_r = \frac{p}{p_c} \quad T_r = \frac{T}{T_c} \quad v^* = \frac{p_c}{RT_c} v$$

- Perfect gas (PG) EOS:

$$p_r v^* = T_r$$

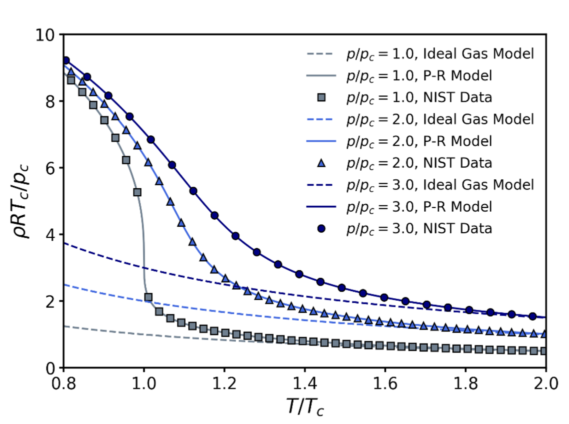

Fig. 1. Comparison of nondimensionalized density for PR model, PG model, and empirical data from NIST.

Simulation setup

Setup

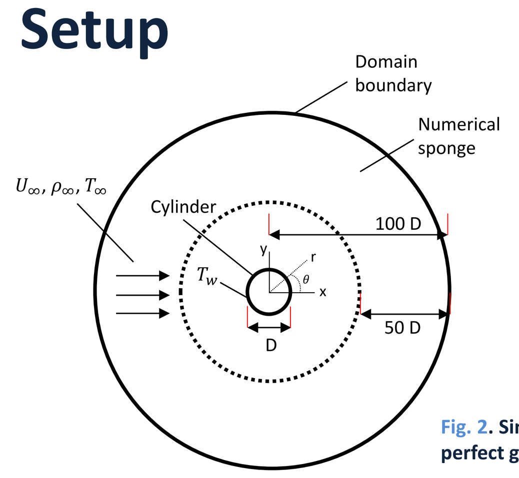

Fig. 2. Simulation configuration for dense and perfect gas cylinder cases.

	$T_{w,r}$	$T_{\infty,r}$	Re_∞	M_∞	ρ_w/ρ_∞	Mesh
PR	0.95	1.15	3900	0.2	1.57	384 x 256 x 128
PG	0.95	1.50	3900	0.2	1.57	384 x 320 x 128

Tab. 1. Simulation parameters for dense and perfect gas cylinder cases. The mesh resolution represents the number of grid points in the radial, azimuthal, and spanwise directions.

Solver

- In-house high-performance code, *PadeLibs*[2]
- Uses 6^{th}-order compact finite-difference schemes
- Highly parallelizable and scalable up to 24576 GPUs on *Summit*[3]
- No solution filtering or artificial dissipation for stabilization

Analysis

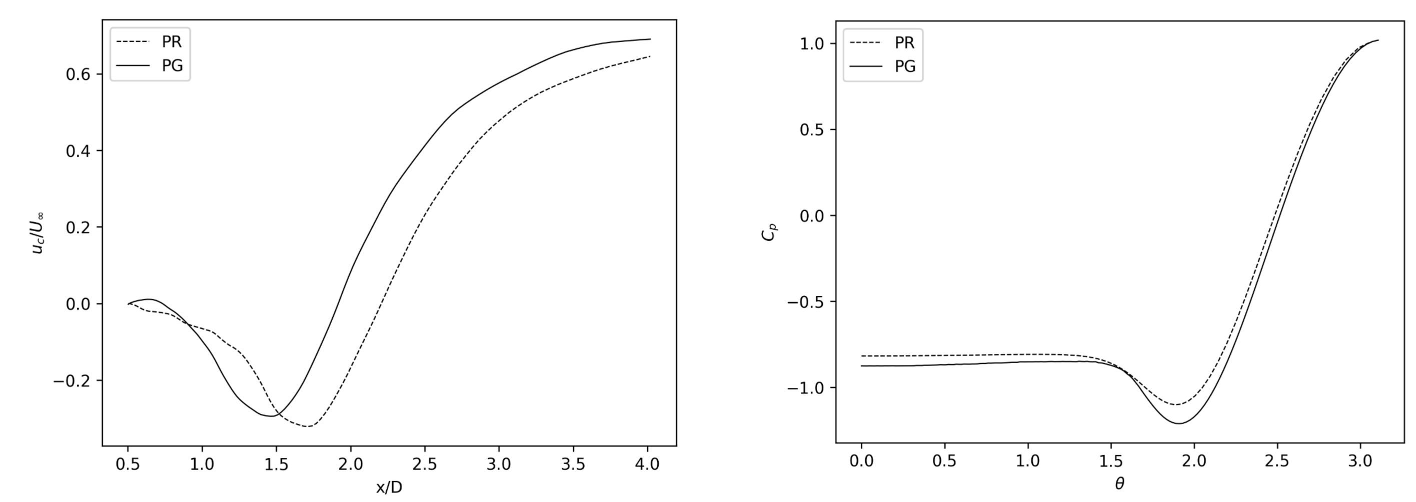

Fig. 3. Centerline velocity and pressure coefficient for dense (dashed line) and perfect gas (solid line) cylinder cases.

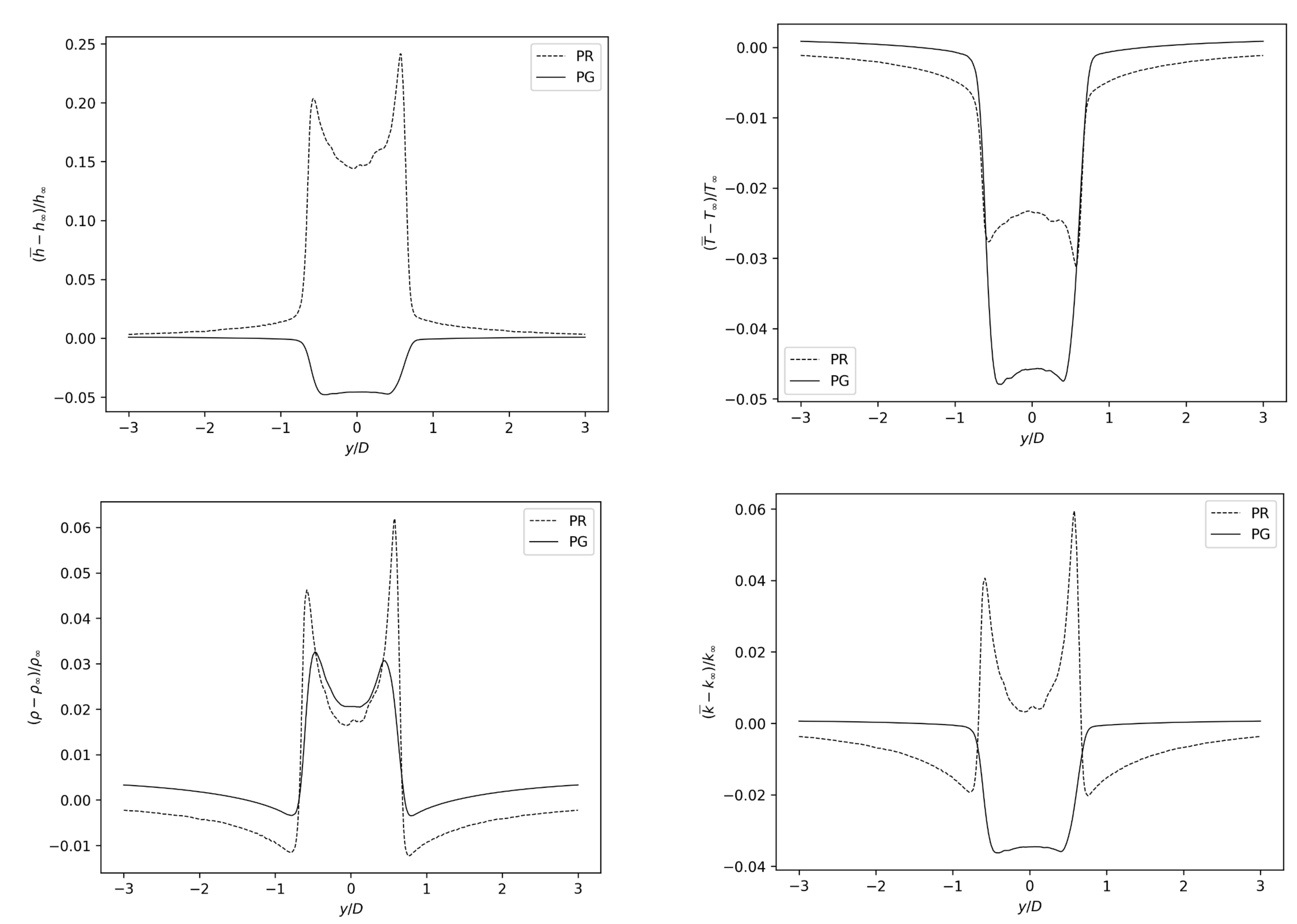

Fig. 4. Enthalpy (top left), temperature (top right), density (bottom left), and thermal conductivity (bottom right) defect profiles in the y-direction taken at a wake location of x/D = 1.54.

Conclusions

- Trough of **centerline velocity shifted farther from cylinder** and **trough of pressure coefficient more diffuse** for dense gas case
- Density, enthalpy, and thermal conductivity profiles exhibit **greater wake deficit** for dense gas
- Instantaneous density wake contours suggest **greater fluctuations for dense gas** and slightly more diffuse wake
- Trends consistent with **greater viscosity magnitude and nonlinearity** in EOS for dense gas case

Visualizations

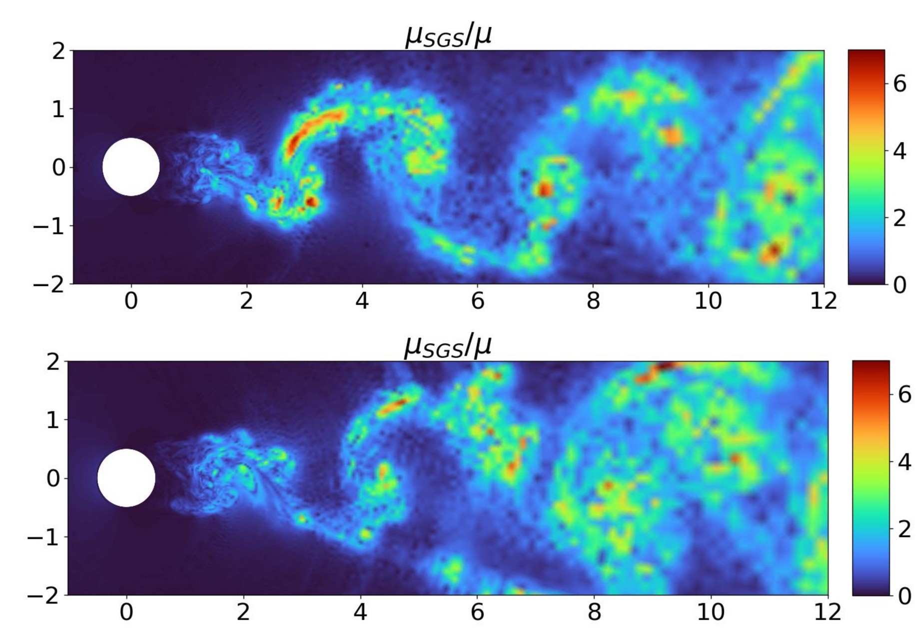

Fig. 4. Contours of the ratio of SGS viscosity to total viscosity in the wake of the perfect gas (top) and dense gas (bottom) cylinder cases. The magnitude of the ratio justifies the quality of the LES as it is near zero in the wall region and order one in the wake region.

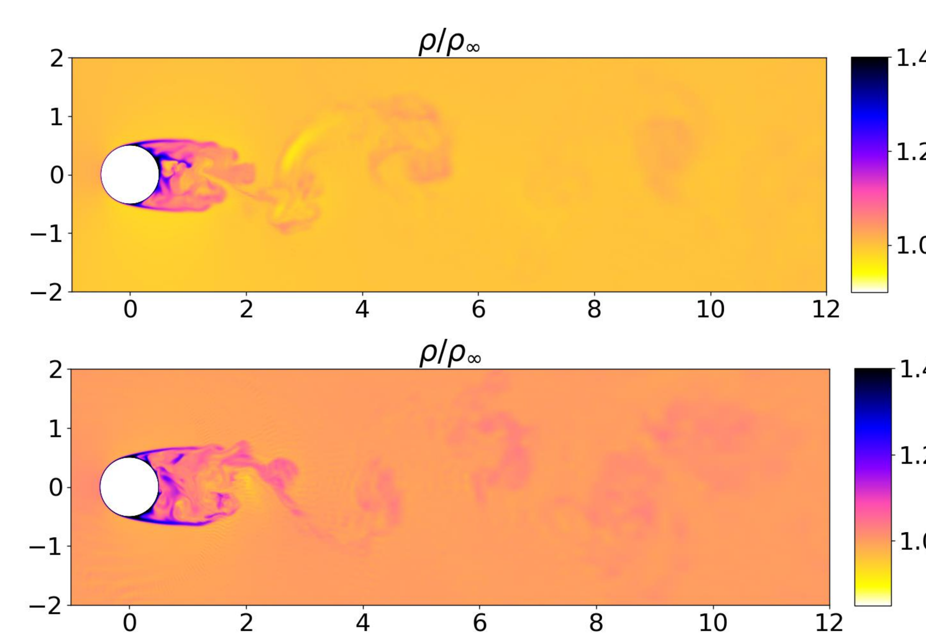

Fig. 5. Contours of density in the wake normalized by freestream density for perfect gas case (top) and dense gas case (bottom). The wake appears slightly more diffuse for the dense gas case and with greater density fluctuations compared to the perfect gas case.

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References

1. Peng & Robinson, 1976, *Industrial & Engineering Chemistry Fundamentals*, Vol. 15, 59–64.
2. Song et al., 2023, *AIAA Aviation Forum*, AIAA 2023-3690.
3. Song et al., 2022, *Journal of Computational Physics*, Vol. 468, p.111443.