Heat Transfer to sCO_2 in a Staggered Cylindrical Pin Fin array

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Abstract

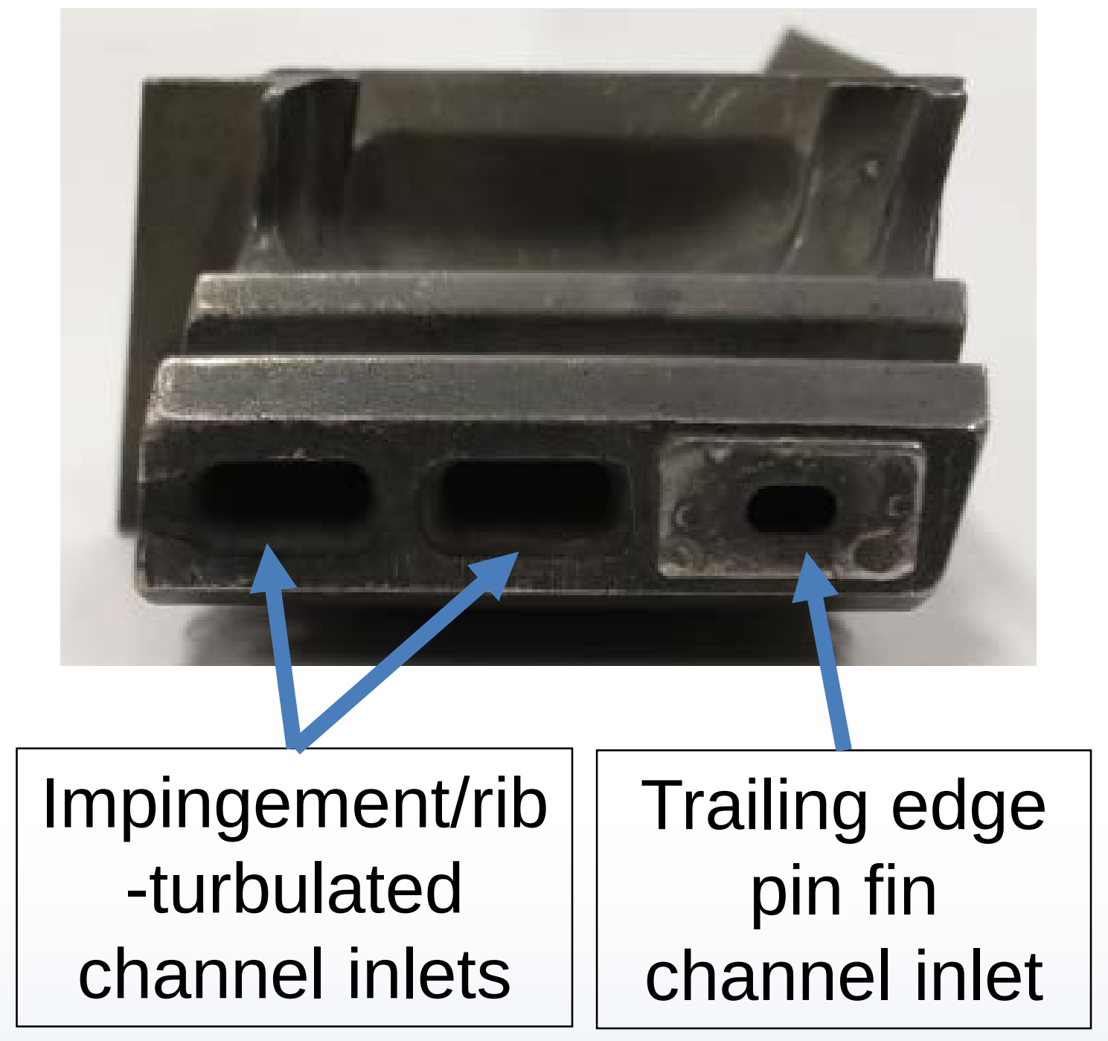
Numerical simulations are conducted to determine the applicability of benchmarking simulations in air for sCO_2 heat transfer in a pin-fin channel. The goal of this work is a comparison, in a simple pin-fin geometry, of the heat transfer behavior in steady Reynolds-Averaged Navier-Stokes (RANS) solutions: one using air at an operating pressure of 1 atmosphere, with results validated against experiment, and the second, a set of solutions using sCO2 at conditions expected inside turbine blades in a direct-fire Brayton cycle. The ability of existing correlations to predict heat transfer is investigated under these conditions, with the long-term goal of assessing their suitability to sCO2 turbines in a direct-fired cycle.

Background

- Experimental, numerical work primarily performed on simple geometries
  - Vertical circular tubes
  - Horizontal circular tubes
- Direct-fire oxy-combustion cycles present TIT -> 1200° C
- Active turbine blade cooling likely necessary
  - Cylindrical pin fin geometry explored
  - Staggered array, x/D = y/D = 3, h/D =2

- Known: Heat transfer non-dimensional parameters scale well with geometry in air
  - sCO_2 scaling behavior unknown

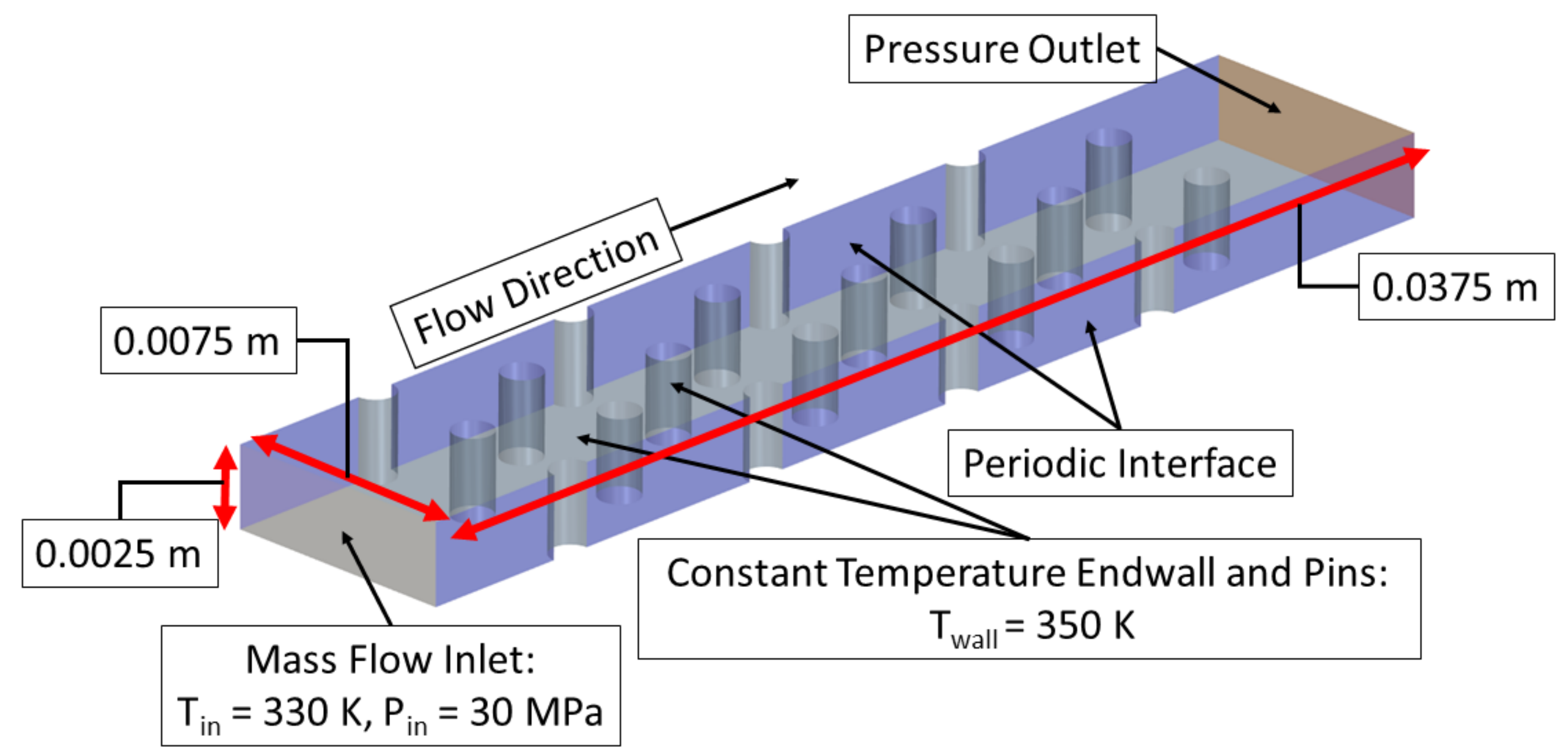
CFM56 turbine blade chord: ~32 mm



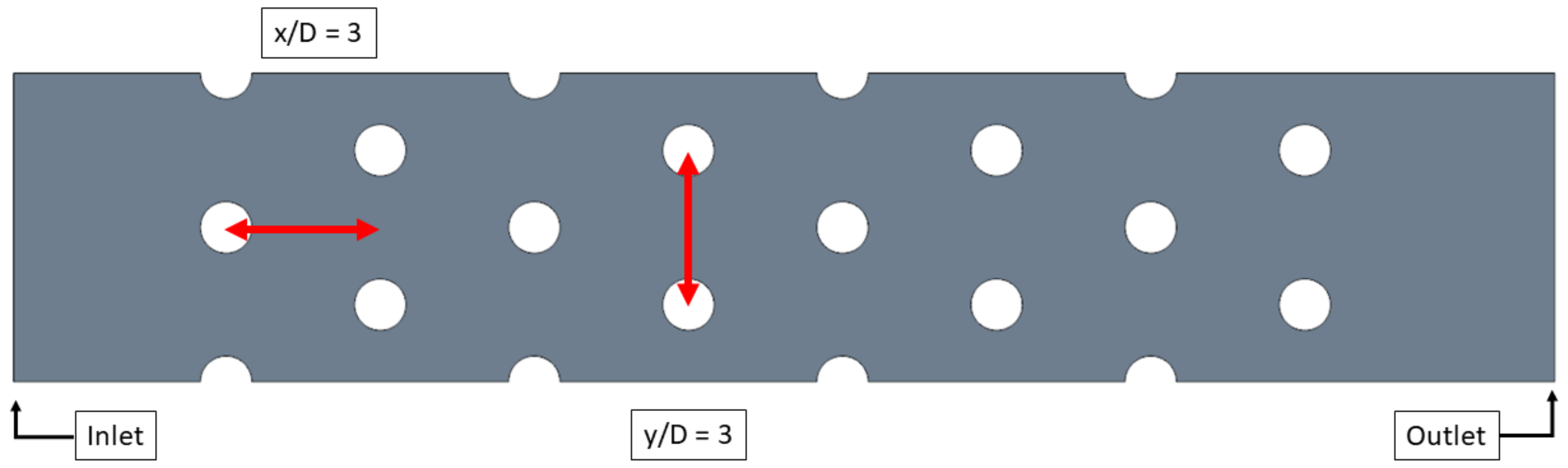
Pin fin channel: $\frac{D_h}{c} = 0.1$

Use ratio for sCO_2 blade, chord: 51 mm

Methodology



Computational domain (Pai, 2019)



Array planform

- Cooling channel inlet temperature assumes:
  - Compressor inlet temperature: 300 K
  - Compressor inlet pressure: 10 MPa, $\pi_c = 3$
  - Isentropic compression
- Endwall and pins temperature assumes:
  - Turbine inlet temperature: 1200 K
  - 1-D Conduction model
  - 0.5 mm thick Inconel blade wall

Data Reduction

Non-dimensionalization

$$Re_D = \frac{\rho_{inlet} u_{inlet} D_{pin}}{\mu_{inlet}}$$

$$f = \frac{2\Delta P}{\rho_{bulk} u_{bulk}^2} \frac{D_h}{L}$$

$$Nu_{sCO_2} = \frac{hD_{pin}}{k_{bulk}}$$

h: surface average of bottom endwall and pins

Correlations

$$Nu_D = 0.079 {Re_D}^{0.717}$$

Metzger (1982)

$$Nu_D = 1.12 \left(\frac{D}{D'}\right)^{0.153} {Re_{D'}}^{0.685}$$

Van Fossen (1982)

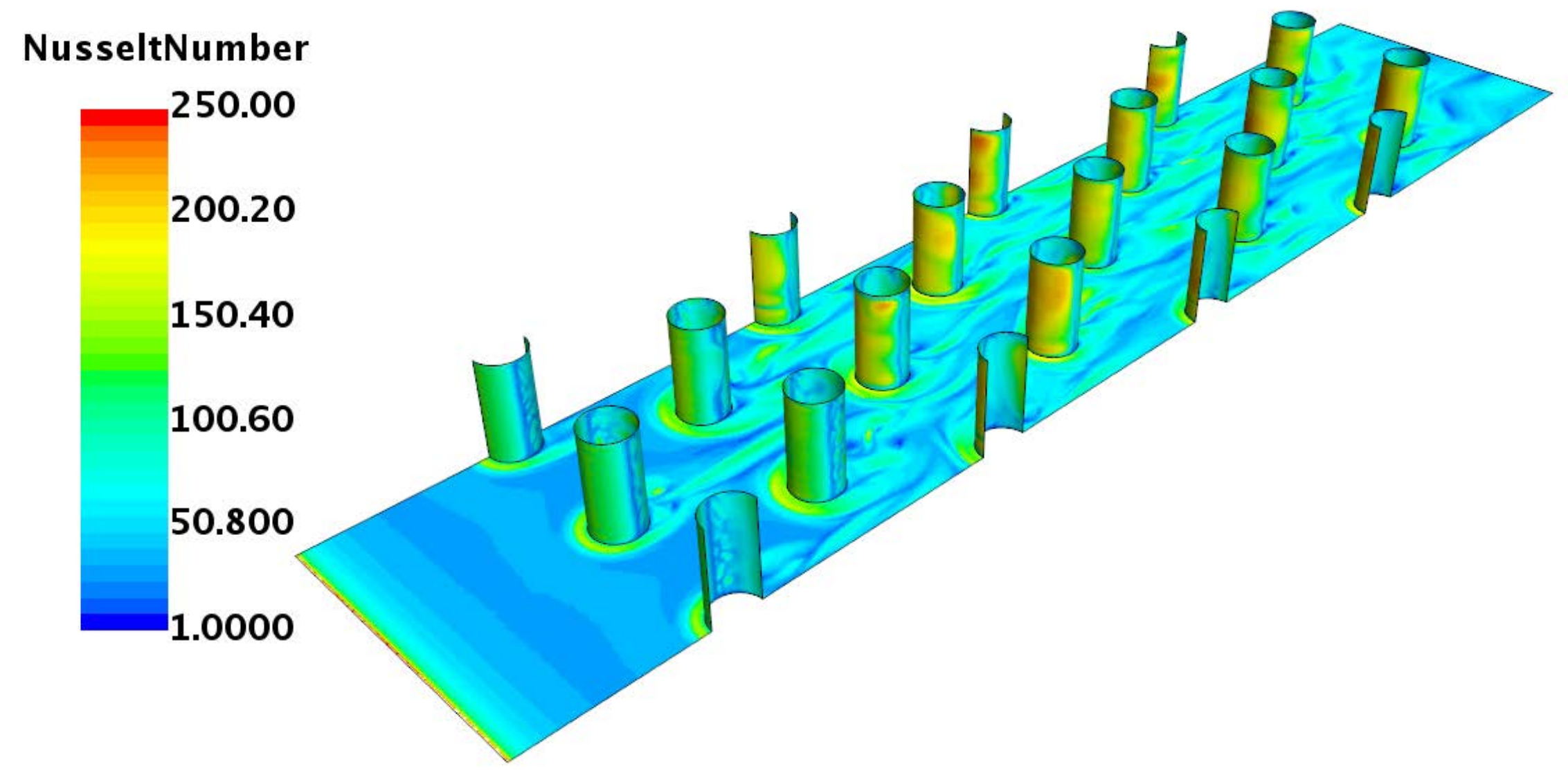
$$Nu_{D_h} = 0.419 \left(\frac{H_{pin}}{D_h}\right)^{-0.3} \left(\frac{S_L}{D_h}\right)^{0.077} \left(\frac{S_T}{D_h}\right)^{0.2} {Re_{D_h}}^{0.45} Pr_{bulk}^{\frac{1}{3}}$$

Short (2002)

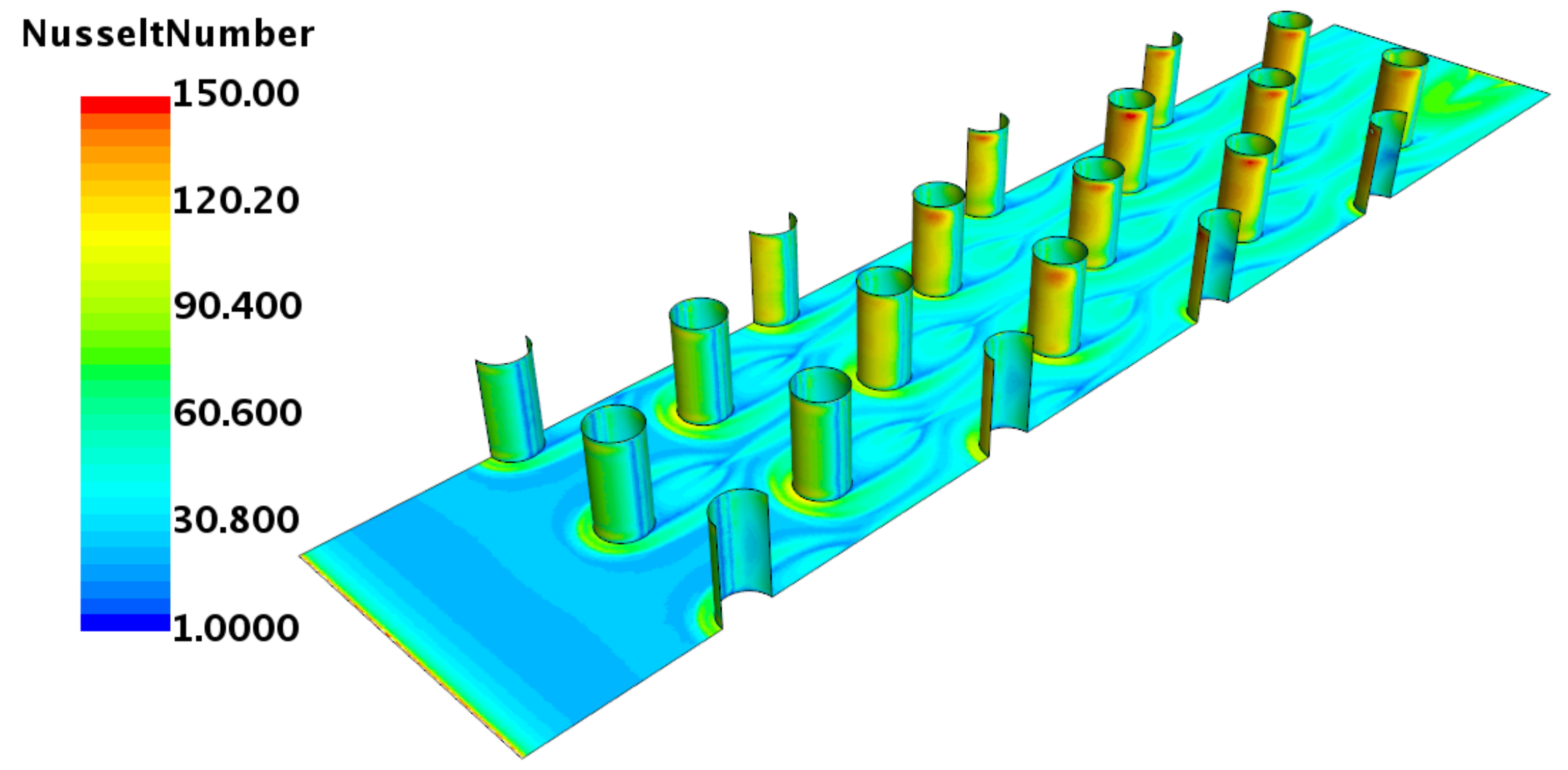
Results

Case	Fluid	D_h [m]	Mass Flux [kg/m²s]	$Re_{D_{pin}}/Re_{D_h}$	Cells
1	Air	0.06 (Validated)	19.01	15k / 61k	11M
5	Air	0.005	228.06	15k / 61k	11M
7	sCO_2	0.005	546.67	8.6k / 34k	15M
8	sCO_2	0.005	1066.67	17k / 67k	15M
9	sCO_2	0.005	2133.33	34k / 135k	15M
10	sCO_2	0.005	5333.33	84k / 336k	15M

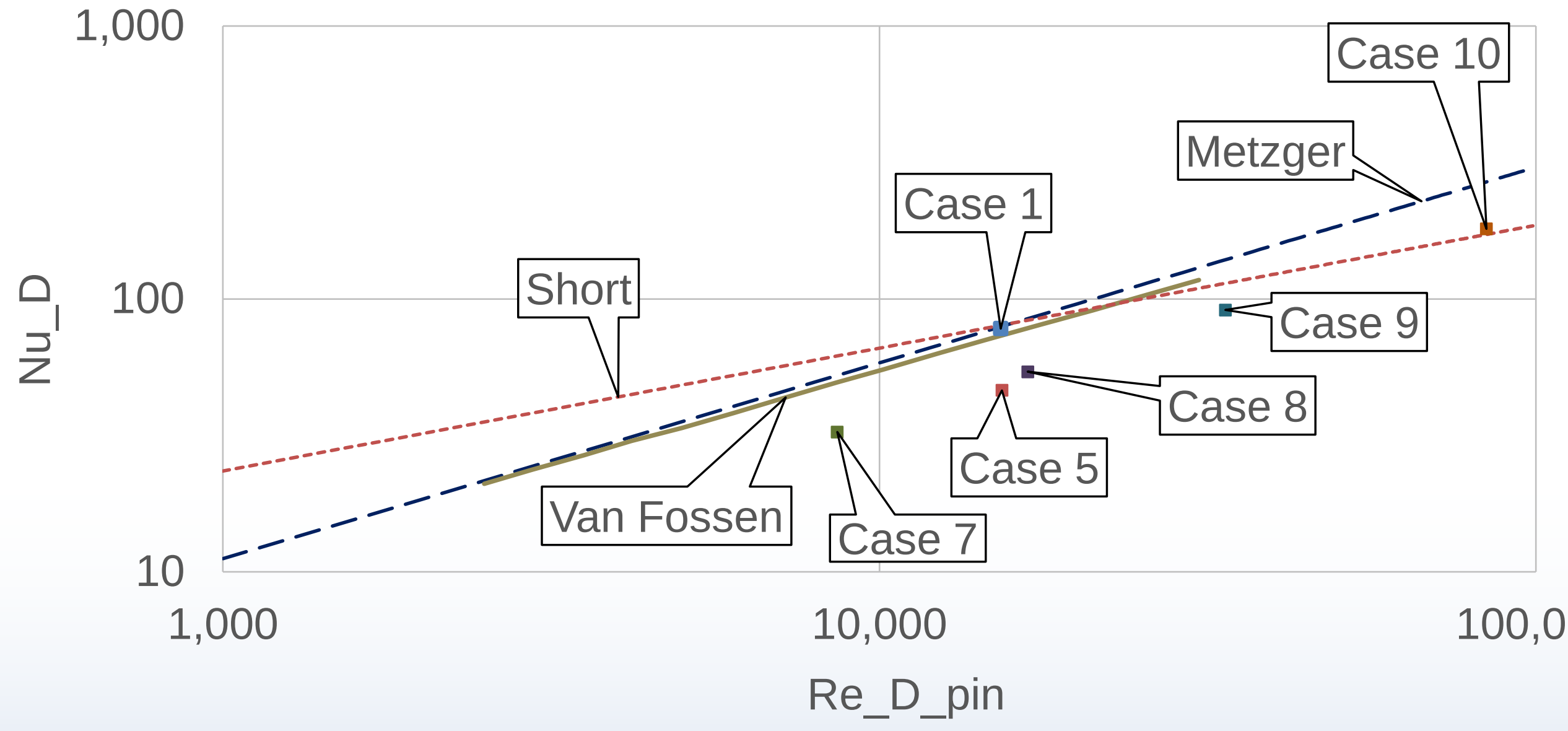
Test Matrix: mesh/solver independence performed in air



Nusselt number contour, Air, Re_D = 15,000



Nusselt number contour, sCO_2, Re_D = 17,000



Endwall and pin surface average Nusselt number results

References:
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Short, B. et al., “Performance of pin fin cast aluminum coldwalls, part2: Colburn j-factor correlations,” Journal of Thermophysics and Heat Transfer, Vol. 16, 2002, pp. 397-403..
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Van Fossen, G., “Heat-transfer coefficients for staggered arrays of short pin fins,” ASME Journal of Engineering for Power, Vol. 104, 1982, pp. 268-274.

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