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sCO_2 pin-fin channel flow heat transfer simulation using benchmark in air

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ABSTRACT

A numerical simulation campaign is 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 unsteady Reynolds-Averaged Navier-Stokes (uRANS) solutions: one using air at an operating pressure of 1 atmosphere, with results validated against experiment, and the second, a set of solutions using sCO_2 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 sCO_2 turbines in a direct-fired cycle. Real fluid behavior of the sCO_2 is captured by implementing a user-defined equation of state (EoS) and tabular fluid data. This data is extracted from the National Institute of Standards and Technology (NIST) code REFPROP and input to the CFD code in temperature and pressure lookup tables. Results from this CFD campaign will inform experimental work in this working group with a future sCO_2 heat transfer apparatus at the Gas Turbine Laboratory (GTL).

INTRODUCTION

There has been much experimental and numerical research in heat transfer to sCO_2 in natural, forced, and mixed convection. The vast majority of this work has been in simple flow geometries: horizontal and vertical circular pipes. There is a gap in the literature in applied heat transfer geometries, specifically those likely to be found in the internal cooling passages of turbine blades. With the increasing turbine inlet temperatures specific to direct-fired sCO_2 Brayton cycles, such work is needed, and research is predicted to accelerate in this area.

Supercritical carbon dioxide has been proposed as a working fluid in a number of advanced thermodynamic cycles for power generation (Yoonhan, 2015). Indirectly heated cycles have been proposed, with sources including geo-thermal, solar-thermal, nuclear and coal. It is well-known that these cycle thermal efficiencies approach the Carnot efficiency with increasing TIT (Çengel, 2011). Recently, sCO2 cycles involving oxy-combustion inside the carbon dioxide medium have been proposed. These cycles feature TIT approaching 1200° C and thermal efficiency approaching 65%. A distribution comparing the performance of several proposed cycles is presented in Figure 1.

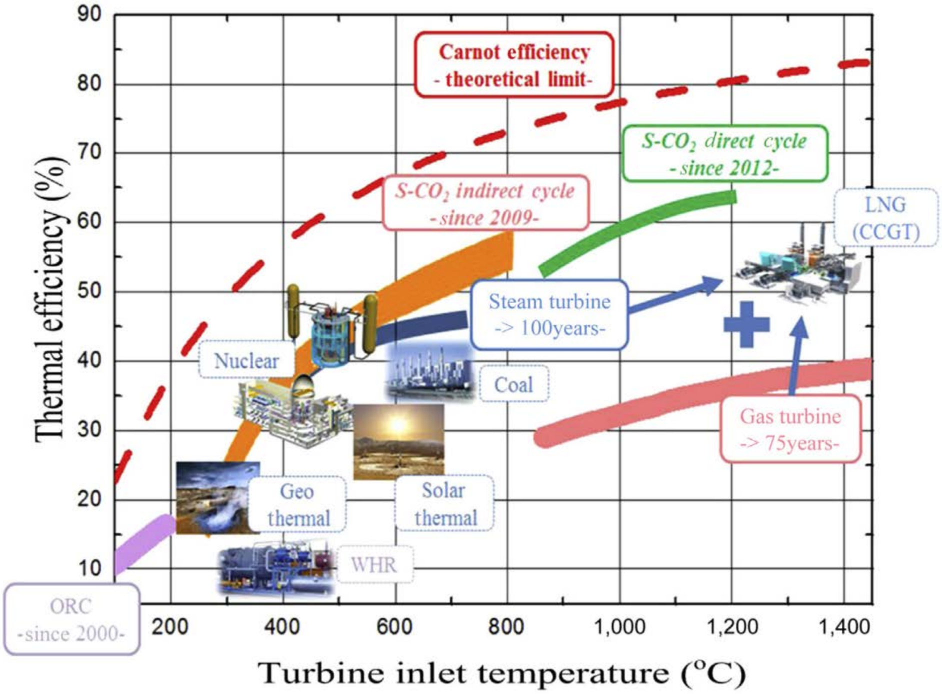

Figure 1 Efficiency vs. TIT: Assorted sCO$_2$ Power Cycles (Yoonhan, 2015)

Due to increased TIT in the direct-fired sCO2 Brayton cycle, more heat needs to be recuperated after expansion to increase thermal efficiency (Yoonhan, 2015). Effective, low cost heat exchangers are essential, often in a recompression/recuperator layout, to the development of these cycles. There is also a significant need for turbine blade cooling, as TIT approaches 1200 K (Brun, 2014).

It is desired to simulate internal blade cooling using bleed sCO$_2$ from the compressor outlet. To this end, computational work that has been validated by experiment in air at laboratory conditions is used as a benchmark for current work. A classical staggered cylindrical pin fin array is used, and the computational domain is seen in Figure 2.

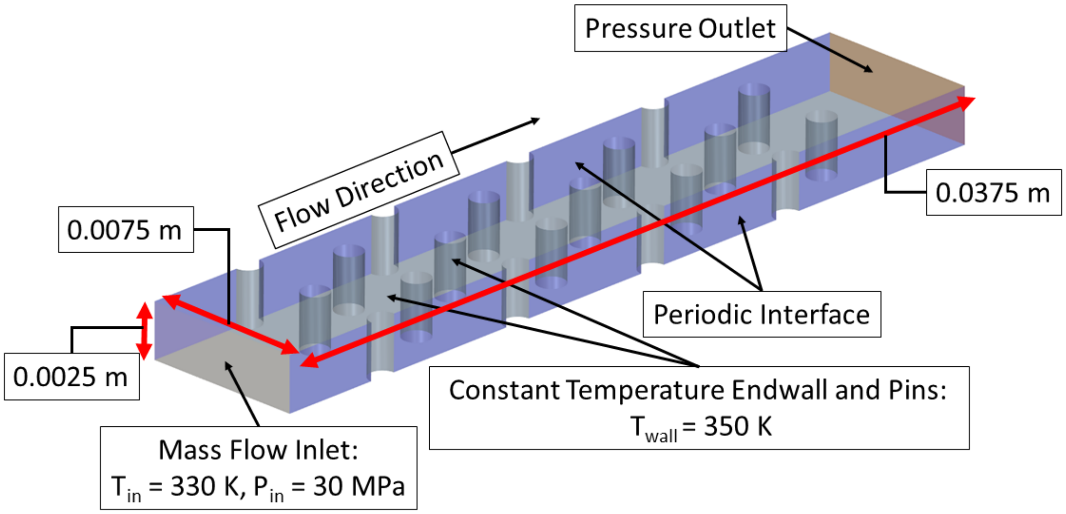

Figure 2 Computational Domain (Pai, 2019)

The cooling channel inlet temperature assumes compressor inlet temperature of 300 K, and an isentropic compressor with inlet pressure 10 MPa and pressure ratio 3. The endwall and pin temperature assumes TIT of 1200 K, and uses a 1-D conduction model through a 0.5 mm thick Inconel turbine blade wall.

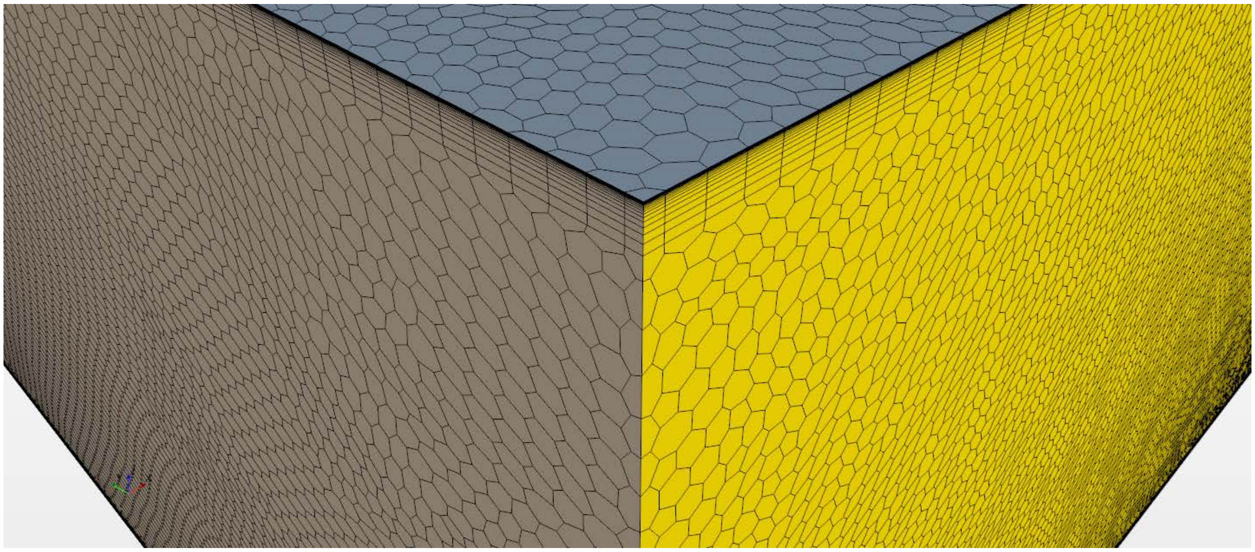

Figure 3 Computational Mesh: Polyhedral Cells with Rectangular Prism Boundary Layers

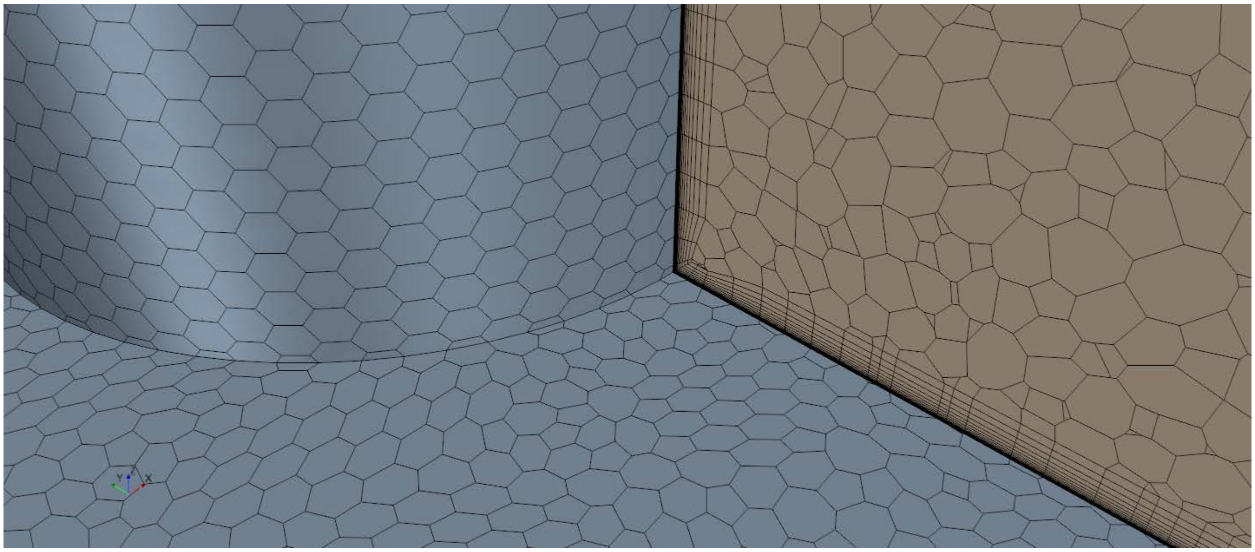

Figure 4 Prism Layers on Endwall and Pin Surface

RESULTS AND DISCUSSION

Thermodynamic and transport properties of carbon dioxide were extracted from REFPROP, a software package released by NIST, using an open-source MATLAB script and compiled into .csv files. These files contain pressure-temperature tabulated fluid properties and partial derivatives and were imported into each STAR-CCM+ simulation file. The code linearly interpolates these tables at each iteration, assigning a realistic fluid property for each thermodynamic state. Properties were sampled from the library from 300 K to 400 K and from 20 MPa to 60 MPa, at 1000 temperature points and 1000 pressure points. Speed of sound, specific heats, enthalpy, thermal conductivity, dynamic viscosity, density and entropy were included in the model. The 3-dimensional computational domain has a mass flow inlet and pressure outlet, along with periodic side boundary conditions. No-slip, constant temperature walls were selected for the bottom endwall and pin surfaces, and the top wall is adiabatic. The test matrix is shown in Table 1. Test cases with air as the working fluid are run at an operating pressure of 1 atmosphere (~0.1 MPa) and cases with sCO_2 are run at 30 MPa, representing bleed CO_2 at compressor outlet conditions. Mesh independence solver type (pressure vs. density-based) agnosticism was established in cases 1-6. Turbulence closure was achieved with k-ω SST using default model coefficients.

Table 1 Test Matrix, Current Work

Case	**Fluid**	**D_h [m]**	**Solver Type**	**Mass Flux [kg/m^{2}s]**	**Cells**
1	Air	0.06 (validated case)	Pressure-based	19.01	11M
2	Air	0.06	Pressure-based	19.01	19M
3	Air	0.06	Density-based	19.01	11M
4	Air	0.06	Density-based	19.01	19M
5	Air	0.005	Density-based	228.06	11M
6	Air	0.005	Density-based	228.06	19M
7	sCO_2	0.005	Density-based	546.67	15M
8	sCO_2	0.005	Density-based	1066.67	15M
9	sCO_2	0.005	Density-based	2133.33	15M
10	sCO_2	0.005	Density-based	5333.33	15M

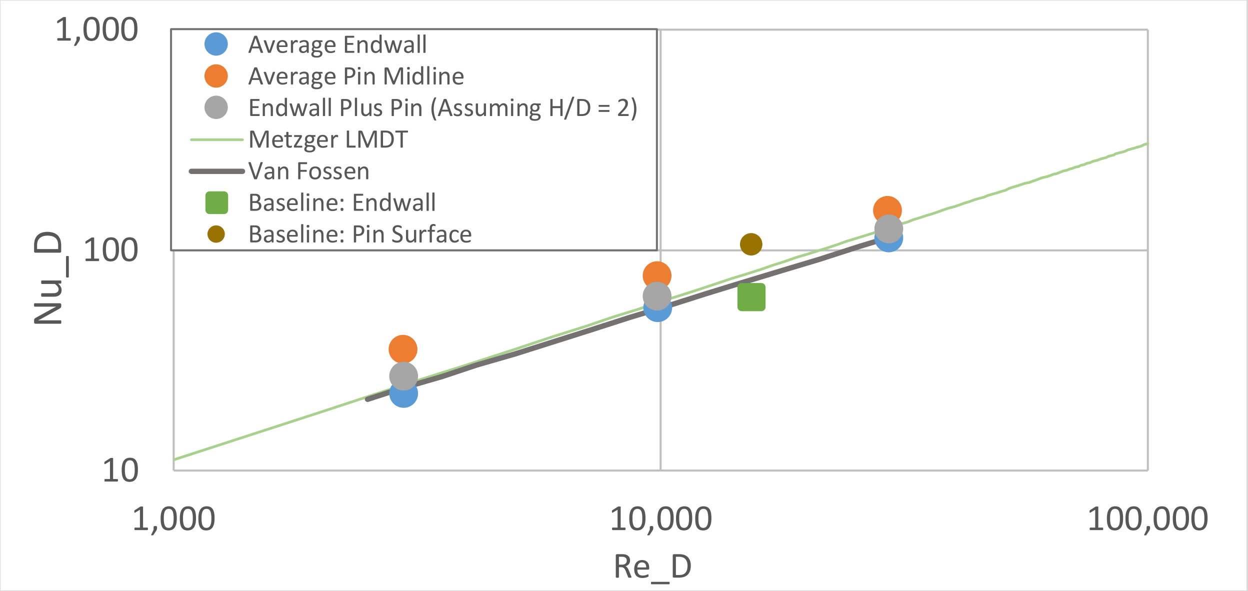

Figure 5 Typical Experimental Values: Pin Fin Arrays in Air (Ames, 2007)

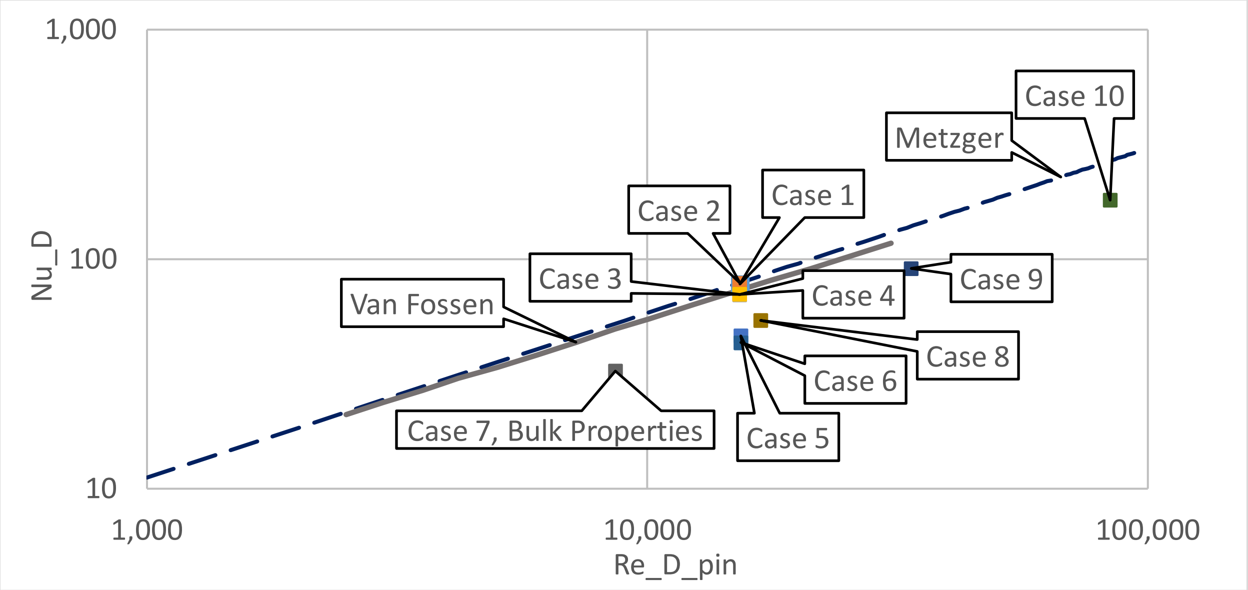

Figure 6 Nusselt Number Results, Re_{pin}, Current Work

Results from air and sCO_2 cases are compared against Nusselt number correlations developed for staggered pin fin arrays in air, as shown in Figure 6. Reynolds number is taken with respect to pin diameter for these correlations:

Metzger:

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

Van Fossen:

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

Where D’ is a hydraulic diameter defined by:

$$D' = 4\frac{V}{S}$$

Where V is the fluid volume and S is the wetted surface area.

Figure 5 compares results against Nusselt correlations developed more recently in the literature, which account for changes in bulk properties, often encountered in supercritical fluid flows. Reynolds numbers are taken with respect to channel hydraulic diameter.

(Short et al., 2002):

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

Where S_L is the pin pitch in the streamwise direction and S_T is pin pitch in the transverse direction. This correlation was developed for macro pin fin arrays.

(Rasouli et al., 2018):

$$Nu_{A_{min}} = 0.039\left(\frac{S_T - D_h}{D_h}\right)^{-0.19} Re_{A_{min}}{}^{0.837} Pr_{bulk}^{0.557}$$

Where the subscript A_{min} refers to the minimum cross-sectional area in the apparatus, where flow is blocked by pins. It should be noted that the geometry of current work lies outside the range of $\frac{S_T}{D_h}$ values to which the authors of this correlation have vetted it, and a minimum value of 0.7 is used for the term $\frac{S_T - D_h}{D_h}$.

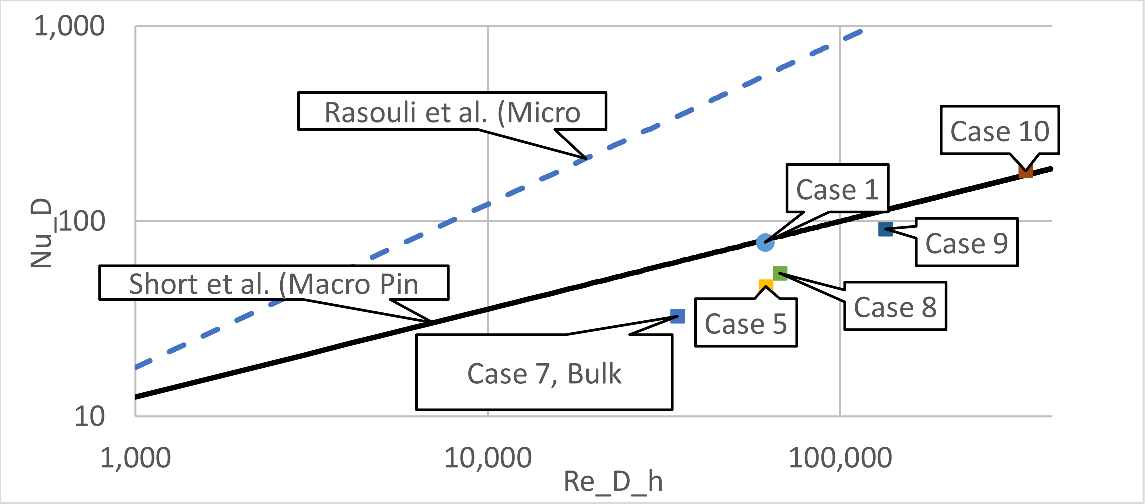

Figure 7 Nusselt Number Results, Re_{Dh}

The above results indicate the commercial code may be underpredicting Nusselt number for sCO_2 flows in the small geometry representative of turbine internal cooling channels. As the purpose of this work is to identify the applicability of previous work done by this laboratory in air at lab conditions, no changes were made to the numerical method apart from the use of real fluid data and an increased mesh density in the boundary layer. It is suggested this behavior is due to both the exclusion of buoyancy effects from the solution, which has been well noted in the literature to have a significant impact on heat transfer rates in sCO_2 (Jiang, 2018), and the performance of the RANS turbulence model, which relies on the Boussinesq assumption, itself relying on fluid property homogeneity.

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