Numerical Investigation of Potential Erosion Mechanisms in Turbulent Flow of sCO2 Pipe Bends

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International Symposium-sCO2 Power Cycles

Talk Organization

- Background and Motivation
- Objectives and Problem Statement
- Computational Approach and Validation Studies
- Simulations and Results
- Summary and Outlook

Background and Motivation

1. Supercritical CO2 for power generation in thermal solar, fossil, and nuclear power plants
   - Ideal fluid for closed-loop cycles as it is non-toxic, non-flammable and cheaper
   - High pressure operation (200-350 bar) means low specific volume, compact designs
   - High temperatures (500-750 C) may require analysis of erosion resistance
2. Erosion Mechanisms
   - Particulate erosion (mechanical abrasion) in nozzles and turbines
   - Erosion in heat exchangers at high temperatures

Background and Motivation

1. Particulate Erosion
   - Mechanical abrasion in nozzles and turbines due to particulates[1]

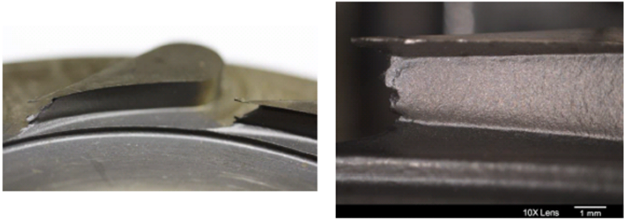


Figure: Erosion of sharp corners.

2. Erosion *due to flow shear* in heat exchanger pipes at high temperatures.

[1] **Fleming and Kruizenga, Sandia Report SAND2014-15546.**

Background and Motivation

Hypotheses:

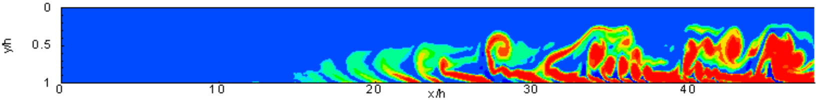
- Large fluctuations in local temperature and pressure due to turbulence, secondary flow patterns, and property variations may cause substantial shear stresses on the pipe walls.
- Surface or geometric irregularities in pipe fixtures (bends, junctions etc.) may impact wall shear stresses and cause erosion.

Example

- Erosive burning in solid propellant rocket motors[2]
- Erosion of endothelial walls in arteries.

[2] **Apte and Yang**, **JFM 2003**.

Erosive Burning in Solid Propellant Rocket Motors[3]



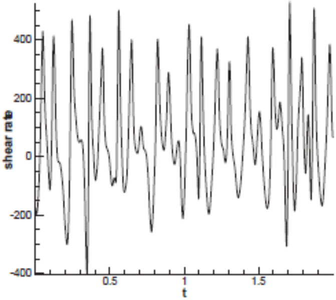


Figure: Instantaneous vorticity contours and shear rate history.

[3] **Apte and Yang, JFM 2003.**

Objectives

- Using predictive numerical simulations, investigate potential erosive mechanism in heat exchanger pipes carrying sCO2 with minimal impurities.
- Investigate effects of heat transfer and temperature dependent property variations on the pipe shear stresses and their eventual impact on erosion.

Problem Statement

Investigate, using predictive large-eddy simulations (LES), turbulent shear force distribution in a 90° bend with and without heat transfer with conditions similar to sCO2 heat exchangers.

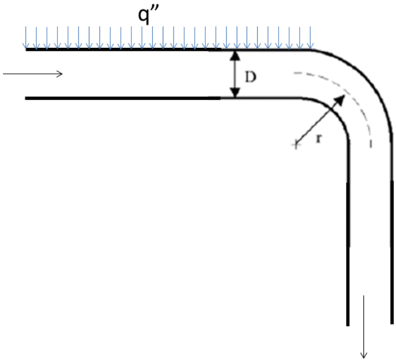


Figure: Flow configuration.

Flow parameters of importance

- Pipe Reynolds number $Re_D = DU/\nu = 5000$, 27000, 100000
- Pipe Dean's number $De = (D/2r)^{1/2} Re_D$ = 2886, 15589, 57720.
- Bend curvature $r/D = 1, 3$
- Thermally developing pipe flow with heat influx (or outflux)

Mathematical Formulation

- Large Eddy Simulation (LES) on arbitrary shaped, unstructured grids for large Reynolds number turbulent flows.
- Variable density, zero Mach number formulation with variable properties.

$$\frac{\partial \overline{\rho_g}}{\partial t} + \frac{\partial \overline{\rho_g} \tilde{u}_j}{\partial x_j} = 0 \qquad (1)$$

$$\frac{\partial \overline{\rho_g} \tilde{u}_i}{\partial t} + \frac{\partial \overline{\rho_g} \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\overline{\mu}\tilde{S}_{ij}\right) - \frac{\partial q^r_{ij}}{\partial x_j} \qquad (2)$$

$$\frac{\partial \overline{\rho_g} \tilde{h}}{\partial t} + \frac{\partial \overline{\rho_g} \tilde{h} \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\overline{\rho_g}\tilde{\alpha}_h \frac{\partial \tilde{h}}{\partial x_j}\right) - \frac{\partial q^r_{hj}}{\partial x_j} \qquad (3)$$

Mathematical Formulation

Subgrid scale (or unresolved scale) terms are modeled using dynamic Smagorinsky model[4], with model constants obtained directly from the solver (NO tuning parameters)

$$q^r_{ij} = \overline{\rho}(\tilde{u}_i\tilde{u}_j - \widetilde{u_i u_j}) = 2\mu_t\tilde{S}_{ij} - \frac{1}{3}\overline{\rho}q^2\delta_{ij}; \quad \mu_t = C_\mu\overline{\rho}\overline{\Delta}^2\sqrt{\widetilde{S_{ij}}\widetilde{S_{ij}}}. \quad (4)$$

$$q^r_{hj} = \overline{\rho}(\tilde{h}\tilde{u}_j - \widetilde{hu_j}) = \overline{\rho}\alpha_t\frac{\partial\tilde{h}}{\partial x_j}; \quad \overline{\rho}\alpha_t = C_\alpha\overline{\rho}\overline{\Delta}^2\sqrt{\widetilde{S_{ij}}\widetilde{S_{ij}}}, \quad (5)$$

[4] **Germano 1991.**

Flow Solver Features

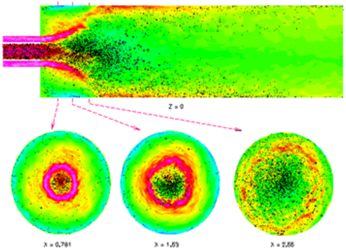
- Unstructured grids with arbitrary elements capable of simulating turbulent flow through complex geometries
- Solves variable density, zero Mach number flow equations
- Finite Volume, collocated grid based algorithm based on the non-dissipative, energy-conserving concepts[5]
- Dynamic subgrid scale modeling
- MPI-Fortran 90 based parallel solver, scalable to 1000s of processors
- Lagrangian particle tracking for particulate flow simulations[6]
- Solver has been validated for turbulent flows in channels, swirling flows in co-axial combustors, as well as flows through complex gas-turbine combustion chambers (Pratt and Whitney)[7]

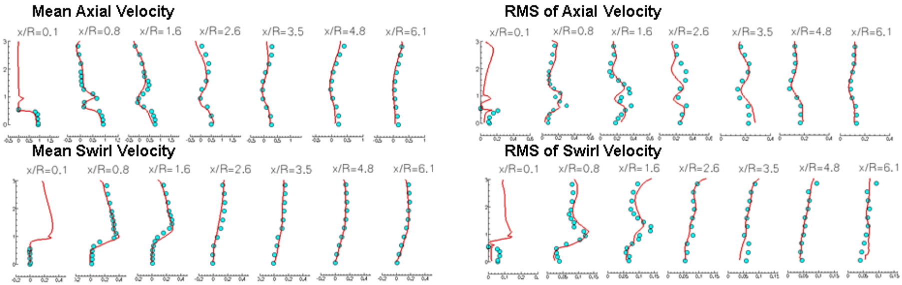
[5] **Mahesh et al.**, **ASME J. App. Mech. 2006**.
[6] **Apte et al.**, **IJMF**, **2003**.
[7] **Moin and Apte**, **AIAA J. 2006**.

Validation Studies

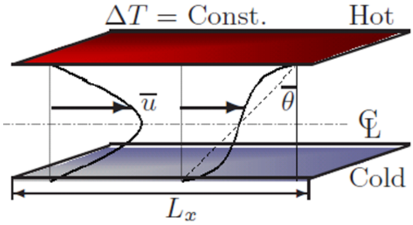
Sommerfeld Coaxial Combustor Experiment

- 1.6 million total hexahedral cells
- 1.1 million particles (glass beads)
- Run on 96 processors
- Re = 26200
- 100 CPU-hrs for 1 flow through time on

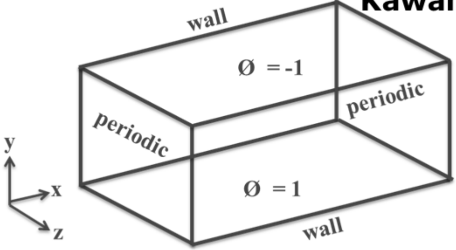




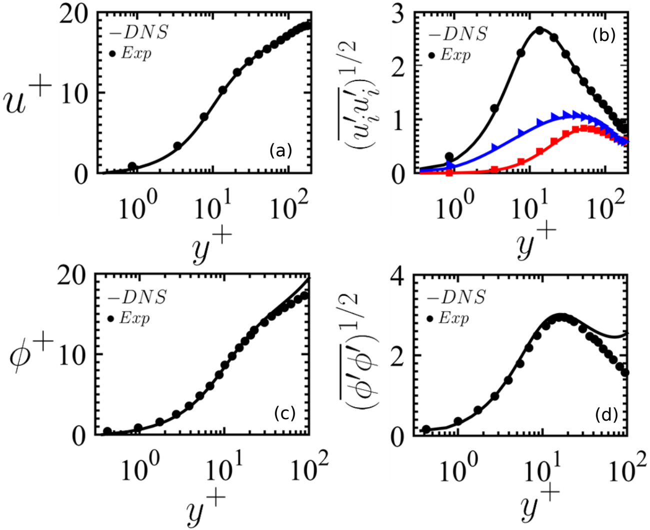
Turbulent Channel with Heat Transfer



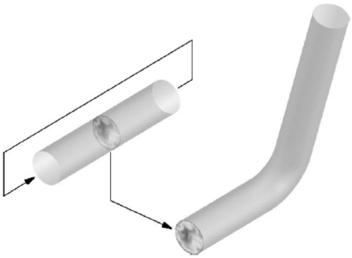
- Re_τ = 180, Pr = 1
- Periodic x and z-dir.
- **no-slip isothermal wall BC in y-dir.**
- Validate Kawamura (1998)

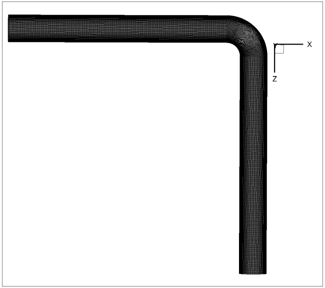


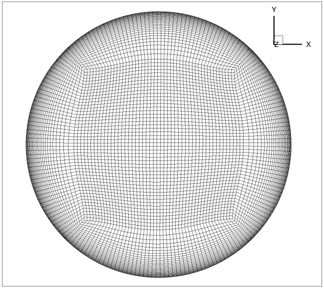
Turbulent Channel with Heat Transfer



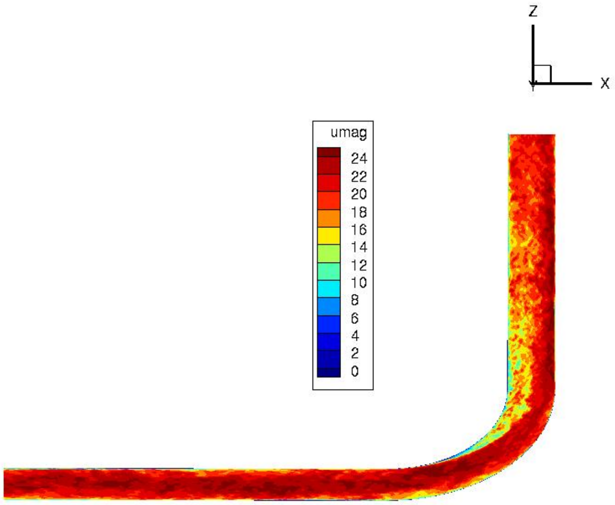
Cold Flow Through Pipe Bend



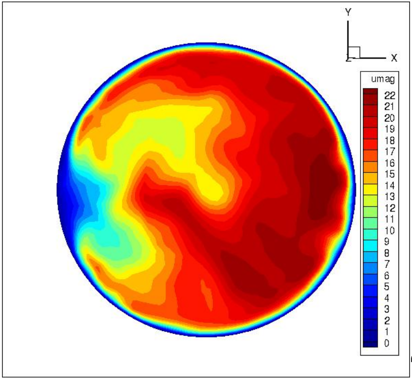




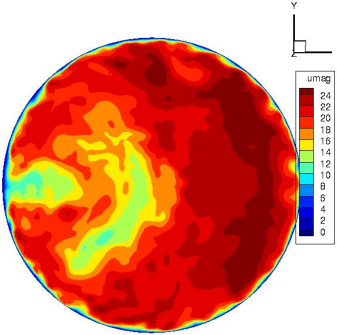
Velocity Magnitude: $Re = 27000$, $R/D = 3$



Velocity Magnitude, 1D after the bend

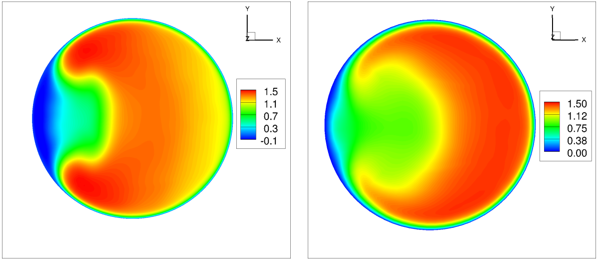


Re = 5000

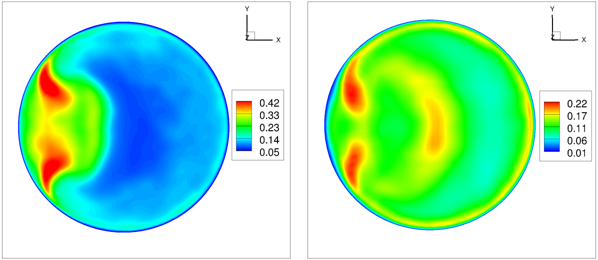


Re =27000

Mean and RMS Flow, $Re = 5000$ at $Z/D = 1$

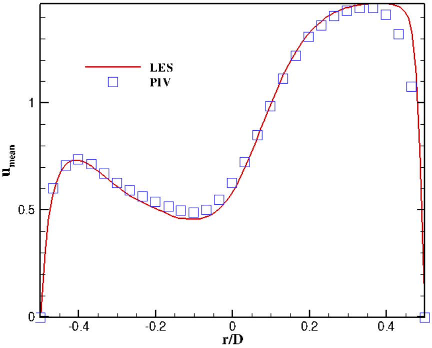


(d) $R/D = 1$ (e) $R/D = 3$

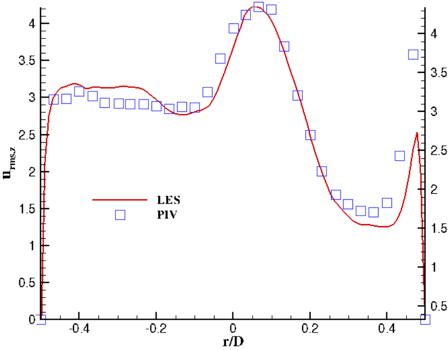


Validation, Re=5000, $R/D = 1$

PIV Data of Brucker, 1998 from Rutten et al. 2005, PoF.

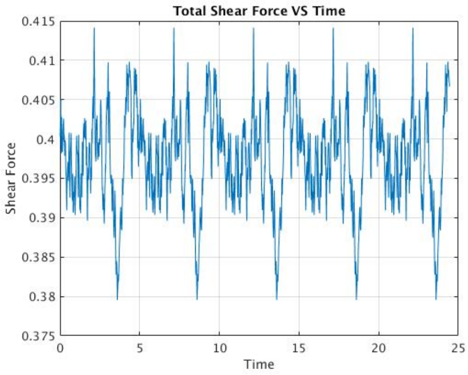


Mean Velocity

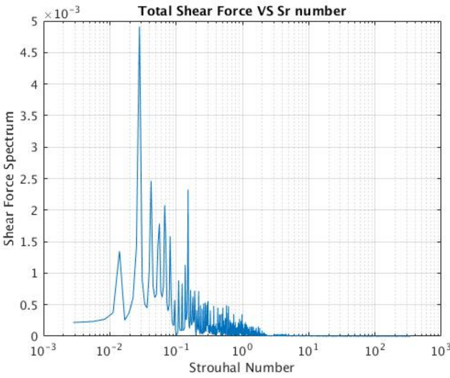


RMS Velocity

Total Shear Force on Bend (Re = 5000, $R/D = 3$)

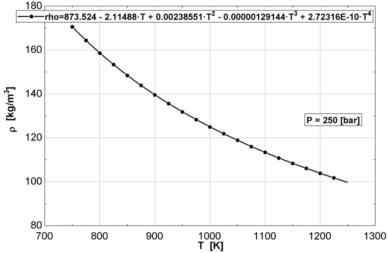


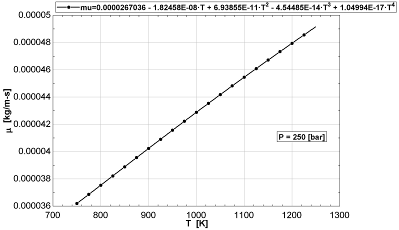
Temporal Signal

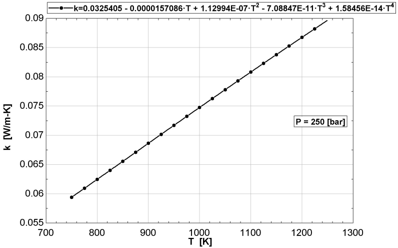


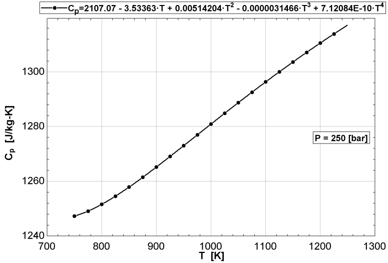
Spectrum

Simulations with Heat Transfer









Summary and Outlook

1. Initiated predictive large eddy simulations on erosion in pipe bends due to flow shear carrying sCO2
2. Validated the flow solver, capable of handling unstructured grids, for turbulent flow with and without heat transfer in pipes/channels
3. Conducted LES in 90° pipe bends at $Re = 5000, 27000$ and $R/D = 1, 3$.
4. Variations in shear forces on the bend walls resulted in a broad band spectrum with peaks corresponding to oscillations in the stagnation point after the bend.
5. Future work will focus on turbulent flow through the bend with heat transfer and sCO2 property variations.

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