CFD Evaluation of Shroud Gap Performance Effects on a Supercritical CO2 Radial Inflow Turbine

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SCO2 Turbine Performance

- SCO2 has high density and low viscosity compared to air at typical turbine inlet conditions
  - ➢ Compact machines with high power density
  - ➢ Can be problematic leakage losses can have significant impacts on machine performance such as rotor stator tip / shroud gaps.
- Smaller shroud clearances reduce cross blade leakage and increase efficiency
  - ➢ If to small?
    - ▪ differential thermal growth
    - ▪ rotodynamic instabilities
    - ▪ poor manufacturing tolerances

    → **Collision Damage!**
- Appropriate blade tip or shroud gaps in turbomachinery
  - ➢ **Balance between machine performance and reliability!**

Peregrine 1MW SCO2 Turbopump

PTT 1MW Turbopump Specifications

General

N	118000 rpm
W	12.125 lbm/s (5.5kg/s)
p_3	6280 psi (43.3 MPa)
T_3	190.7 °F (361 K)
$PR_{1\text{-}3}$	5.5
p_4	6135 psi (42.3 MPa)
T_4	1381.2 °F (1022.7 K)

Turbine

Z_{stator}	8
Z_{rotor}	17
P	454 hp (338.5 kW)
η_{tt}	90.40%
$PR_{4\text{-}5}$	1.4
D	1.6 in (40.6 mm)

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Turbine Initial Design

- Initial aerodynamic design of HP turbine was performed using AxSTREAM® 1D mean line analysis
  - ➢ total – total isentropic efficiency 90.4%
  - ➢ 0.005in (0.127mm) uniform shroud gap
- Reliability oriented features:
  - ➢ Thick trailing edges of turbine blades and nozzle vanes
  - ➢ Previous work [1] showed erosion and corrosion issues on SCO2 turbines
- Test turbine manufactured with 0.025in (0.635mm) shroud gap
  - ➢ Machine robustness for initial testing
  - ➢ Efficiency losses not viable for final design
- Final design required further analysis beyond a 1D solution

SCO2 Radial Inflow Turbine Loss Correlations

- Experimental data / empirical correlations for shroud gap losses
  - SCO2 Radial inflow turbines
    - Not yet available
  - Non SCO2 radial inflow turbines
    - Futral and Holeski [3] 1970 is widely applied across numerous published radial inflow turbine designs, analyses, and experiments
      - ✓ Conclusions:
        - radial shroud gap is dominant in efficiency loss and mass flow rate increase
        - axial tip clearance is a second order effect
      - ✓ Has been utilized in SCO2 design work [4], [5]
      - ✓ ***Has yet to be applied to an experiment or computational models exploring a range of shroud gaps or mass flow changes***

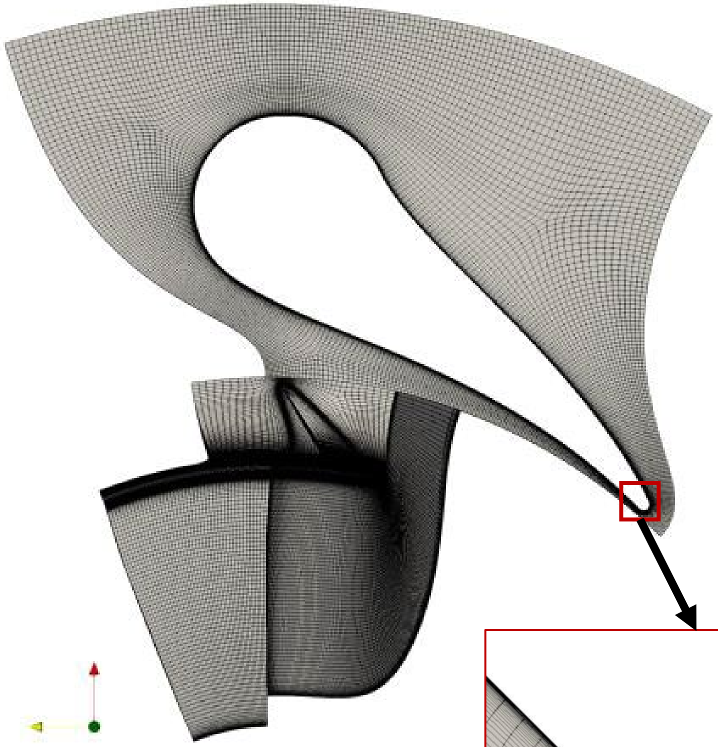
Futral and Holeski → SCO2 Turbine?

- Utilize conclusions and data presented by Futral and Holeski [3] to build simple empirical model
    - Total efficiency loss
    - Mass flow rate change
    - Function of:
        - Blade tip clearance
        - Inlet blade height
        - Outlet blade height
- Construct CFD models across a range of shroud gaps
    - Compare results to empirical model

Computational Models

- Eleven CFD models
  - Shroud gaps between 0in (no gap ideal case) to 0.025in (0.635mm)
  - Workbench R19.2 environment using ANSYS Turbogrid and CFX
  - Turbine nozzle and blade geometry were obtained via AxSTREAM® output
  - Steady state (SS)
  - Reynolds Averaged Naiver Stokes (RANS)
  - k-ω-SST turbulence model
  - Second order discretization schemes
  - Multiple frame of reference (MFR) mixing plane model
  - Real gas CO2 model was applied to all model via ANSYS .rgp files/tables generated from NIST REFPROP [8].

Computational Domain and Mesh

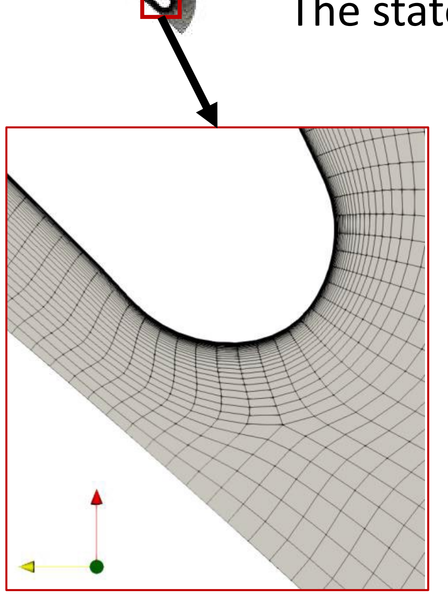


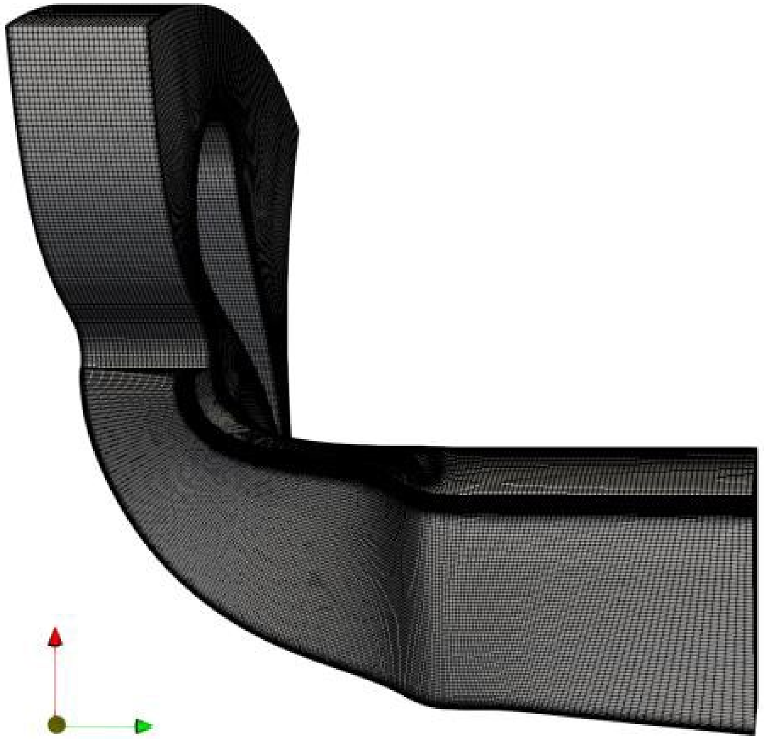
ANSYS Turbogrid Mesh

45° periodic stator
21.176° periodic rotor

Cell counts for the rotating domain ranged between 1,710,300 and 4,030,100

The stator mesh cell count: 860,750

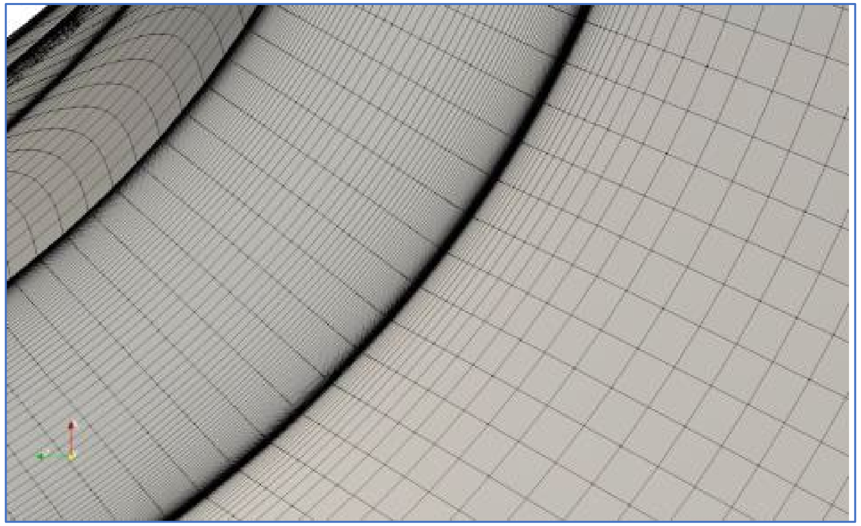




- All wall inflation layers except for the shroud gap were meshed based on a y+ = 1 with a Re = 1e6
- maximum inflation rate 1.5.
- first cell heights in the range of 1e-6 in.

Computational Domain and Mesh

- Uniform shroud gap for each model was generated using the shroud tip gap function in ANSYS blade modeler
- subsequently meshed in the corresponding feature in Turbogrid
- Number of elements across the gap varied between 50 and 100
- The number of constant thickness elements across the gap was varied between 25 and 50 to achieve maximum expansion rates of ≈ 1.2.



Boundary Conditions

- Inflow and outflow conditions obtained from AxSTREAM® 1D results
- Identical for all models
  - Consistent with parameters and results presented by Futral and Holeski [3]
- Inlet
  - P_{t4} = 6135 psi (42.3 MPa)
  - T_{t4} = 1382.1 °F (1022.7 K)
- Outlet
  - P_{s5} = 4322 psi (29.8 MPa)
- Rotor Speed
  - 118,350 rpm angular velocity imposed on the rotating domain
  - Shroud wall in rotating domain was counter rotated to appropriately simulate the shearing between the blade tips and shroud wall
- MFR mixing plane interface applied between the rotating and static domain [6]

Futral and Holeski Empirical Model

1% increase in axial clearance as a percentage of inlet blade height ($\varepsilon x\%b4.1$)

- 0.15% decrease in total efficiency
- 0.1% increase in mass flow rate

1% increase in radial clearance as a percentage of outlet blade height ($\varepsilon r\%b4.3$)

- 1.6% decrease in total efficiency
- 0.3% increase in mass flow rate.

$$\varepsilon\%b = \frac{\varepsilon}{b}$$

$$\Delta\eta_{tt} = \left(\frac{-0.0015\varepsilon_x}{b_{4.1}} - \frac{0.016\varepsilon_r}{b_{4.3}}\right) = -\varepsilon_i\left(\frac{0.0015}{b_{4.1}} + \frac{0.016}{b_{4.3}}\right) \quad when\ \ \varepsilon_i = \varepsilon_r = \varepsilon_x$$

$$\Delta W = \left(\frac{-0.001\varepsilon_x}{b_{4.1}} + \frac{0.003\varepsilon_r}{b_{4.3}}\right) = \varepsilon_i\left(\frac{-0.001}{b_{4.1}} + \frac{0.003}{b_{4.3}}\right) \quad when\ \ \varepsilon_i = \varepsilon_r = \varepsilon_x$$

$\varepsilon = shroud\ clearance$ $\quad station\ 4.1 = turbine\ blade\ inlet$

$b = blade\ height$ $\quad station\ 4.3 = turbine\ blade\ outlet$

$r\ and\ x\ indicate\ radial\ and\ axial\ locations$

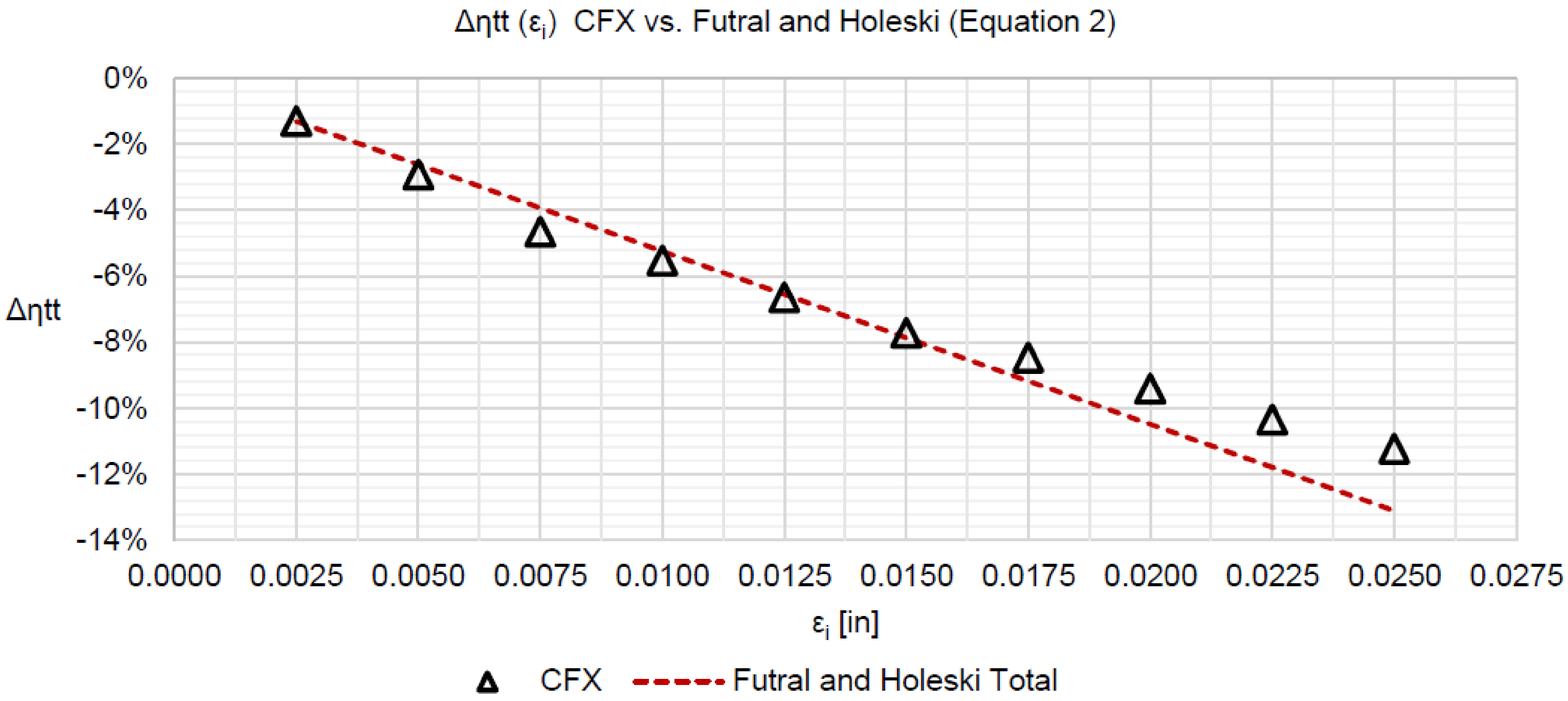
Equations are valid for an axial clearance range of 1%-7% and a radial clearance range of only 1%-3% because the efficiency decrement beyond 3% reduces to less than 1.6% per 1% of blade height.

Results and Discussion

- PTT turbopump HPT blade height dimensions
  - Inlet Passage Height ($b_{4.1}$) = 0.20 in (5.08 mm)
  - Outlet Passage Height ($b_{4.3}$) = 0.35 in (8.89 mm)
- CFX CFD model highlights
  - Ideal case (no shroud gap)
    - η_{tt} = 91.6%
    - W = 12.22 lbm/s (5.54 kg/s)
  - 0.005 in shroud gap case
    - η_{tt} = 88.7% (1.7% less than predicted by AxSTREAM®)
- Results of empirical model vs CFD results plotted

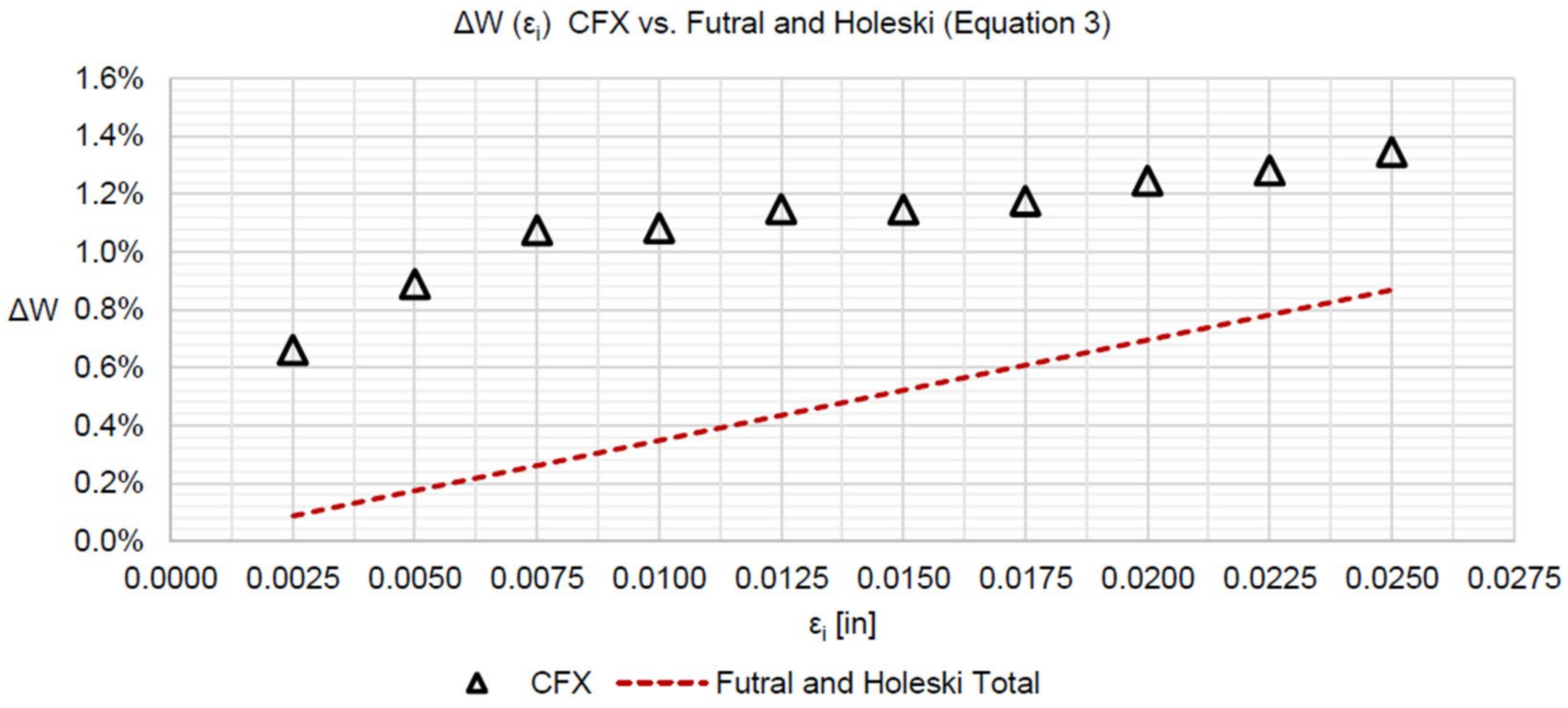
Results and Discussion

Efficiency Decrease



Results and Discussion

Mass Flow Rate Increase



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