Project3

May 3, 2024

[1]:
```
%%capture
%pip install numpy pyfluids scipy matplotlib tqdm pandas seaborn

import numpy as np

from pyfluids import Fluid, FluidsList, Input
from pyfluids.enums import Phases

from scipy.optimize import minimize_scalar, shgo, dual_annealing,␣
↪differential_evolution

import matplotlib.pyplot as plt
from mpl_toolkits.axes_grid1 import make_axes_locatable

import multiprocessing
from tqdm import tqdm
import pandas as pd
```

[2]:
```
import warnings
warnings.simplefilter('error')
```

[3]:
```
GRAVITY = 9.81
```

0.1 Constants

[4]:
```
dioxide_temp = 20
dioxide_temp
```

[4]: 20

[5]:
```
dioxide_pressure = 6e6
dioxide_pressure
```

[5]: 6000000.0

[6]:
```
well_dists = np.array([70, 112])
well_dists
```

[6]: array([70, 112])

[7]:
```
sequestration_rate = 3.24 # kg / s
sequestration_rate
```

[7]: 3.24

[8]:
```
well_depth = 3.2e3 # m
```

[9]:
```
cold_well_temp = 15 # C
```

[10]:
```
tube_diam = 2.375 * 0.0254
tube_thickness = 0.154 * 0.0254

casing_diam = 5.563 * 0.0254
casing_thickness = 0.258 * 0.0254

soil_effective_thickness = 2

tube_radii = [tube_diam / 2 - tube_thickness, tube_diam / 2, casing_diam / 2 -
 ↪casing_thickness, casing_diam / 2, casing_diam / 2 +
 ↪soil_effective_thickness]

conservative_roughness = 0.229e-3 / (2 * tube_radii[0])

carbon_steel_conductivity = 45 # W/mK
copper_conductivity = 401 # W/mK
concrete_conductivity = 2.25 # W/mK
soil_conductivity = 1 # W/mK

down_tube_conductivities = [copper_conductivity, concrete_conductivity,
 ↪carbon_steel_conductivity, soil_conductivity]
up_tube_conductivities = [carbon_steel_conductivity, concrete_conductivity,
 ↪carbon_steel_conductivity, soil_conductivity]
```

1 Stuff To Check

- Make condenser outlet match the CO_2 Supply

1.1 Vertical Pipe Slices

[11]:
```
def radial_thermal_conduction(inner_radius, outer_radius, length, conductivity):
    return np.log(outer_radius / inner_radius) / (2 * np.pi * conductivity *
 ↪length)

radial_thermal_conduction(0.1, 0.2, 1, 0.1)
```

[11]: 1.103178000763258

[12]:
```python
def thermal_convection(mass_flow, fluid: Fluid, radius, length,␣
↪heat_into_fluid):
    volumetric_flow = mass_flow / fluid.density
    velocity = volumetric_flow / (np.pi * radius ** 2)

    reynolds = 2 * radius * velocity / fluid.kinematic_viscosity

    if reynolds < 2300:
        nusselt = 3.66
    else:
        prandtl_exponent = 0.4 if heat_into_fluid else 0.3
        nusselt = 0.023 * reynolds ** 0.8 * fluid.prandtl ** prandtl_exponent

    h = nusselt * fluid.conductivity / (2 * radius)

    return 1 / (2 * np.pi * radius * length * h)



thermal_convection(1, Fluid(FluidsList.CarbonDioxide).with_state(
    Input.pressure(100e3), Input.temperature(-20)
), 0.1, 1, True)
```

[12]: 0.03185715590417421

[13]:
```python
def friction_head_loss(mass_flow, fluid: Fluid, radius, length,␣
↪relative_roughness=conservative_roughness):
    volumetric_flow = mass_flow / fluid.density
    velocity = volumetric_flow / (np.pi * radius ** 2)

    reynolds = 2 * radius * velocity / fluid.kinematic_viscosity

    if reynolds < 2300:
        friction_factor = 64 / reynolds
    else:
        # From https://github.com/MarkusPic/moody_chart/blob/master/moody_chart/
↪moody_chart.py
        def _func(lambda_):
            return abs(1 / np.sqrt(lambda_) + 2 * np.log10(2.51 / (reynolds *␣
↪np.sqrt(lambda_)) + 1 / 3.71 * relative_roughness))

        lambda_bounds = (0.01, 0.1)
        sol = minimize_scalar(_func, method='bounded', bounds=lambda_bounds)

        assert sol.success, f"Failed to find friction factor: {sol.message}"
```

```
        friction_factor = sol.x

        assert friction_factor < lambda_bounds[1] and friction_factor >␣
↪lambda_bounds[0]



    return friction_factor * length / (radius * 2) * velocity ** 2 / 2 / GRAVITY

friction_head_loss(1, Fluid(FluidsList.CarbonDioxide).with_state(
    Input.pressure(100e3), Input.temperature(-20)
), 0.1, 1)
```

[13]: 1.7032344682373965

[14]:
```
def soil_temp(depth):
    return 20 + 62.5 / 1e3 * depth

soil_temp(3.2e3)
```

[14]: 220.0

1.2 Flow Through Formation

1.2.1 Heat Transfer

[15]:
```
A = 2
r = A ** 0.5 / np.pi
P = r * 2 * np.pi

def in_formation_heat_transfer(mass_flow, fluid: Fluid, well_to_well):
    well_temp = 220

    nusselt = 450

    h = nusselt * soil_conductivity / (2 * r)

    outlet_to_inlet_ratio = np.exp(-P * well_to_well * h / (mass_flow * fluid.
↪specific_heat))

    return well_temp - (well_temp - fluid.temperature) * outlet_to_inlet_ratio

in_formation_heat_transfer(1, Fluid(FluidsList.CarbonDioxide).with_state(
    Input.pressure(100e3), Input.temperature(100)
), 140)
```

[15]: 220.0

1.2.2 Pressure Drop

[16]:
```
def in_formation_pressure_drop(mass_flow, fluid: Fluid, well_to_well):
    volumetric_flow = mass_flow / fluid.density

    perm = 1e-12

    return volumetric_flow * fluid.dynamic_viscosity * well_to_well / A / perm

in_formation_pressure_drop(1, Fluid(FluidsList.CarbonDioxide).with_state(
    Input.pressure(100e3), Input.temperature(200)
), 140)
```

[16]: 1425710213.3965037

1.3 Condensor

[17]:
```
def UA_from_cond_ops(inlet_fluid: Fluid, outlet_fluid: Fluid, cold_well_temp,␣
 ↪mass_flow_rate):
    if inlet_fluid.temperature < outlet_fluid.temperature:
        return 0

    heat_transfer = mass_flow_rate * (inlet_fluid.enthalpy - outlet_fluid.
 ↪enthalpy)

    log_mean_temp = inlet_fluid.temperature  - outlet_fluid.temperature
    log_mean_temp /= np.log((inlet_fluid.temperature - cold_well_temp) /␣
 ↪(outlet_fluid.temperature - cold_well_temp))

    return heat_transfer / log_mean_temp

UA_from_cond_ops(Fluid(FluidsList.CarbonDioxide).with_state(
    Input.pressure(100e3), Input.temperature(200)
), Fluid(FluidsList.CarbonDioxide).with_state(
    Input.pressure(100e3), Input.temperature(20)
), 2, 1)
```

[17]: 2219.6061458550016

1.4 System Solving

1.5 Overall State Variables when Optimizing

- Mass flow rate (possible two up values)
- Turbine Outlet Pressure

- Compressor Outlet Pressure
- Turbine & Compressor Efficiency

Fluid State Vector into each slice

constant mass flow rate down

- Enthalpy
  - Changes by Heat Transfer
    - Constant Soil Temp given the linear
    - slice of 2m of soil
    - cond through 3 pipe layer stackup
    - convective analysis with const Ts
  - Increases by frictional losses
- Pressure
  - Increase by rho g delta Z
  - Decrease by frictional losses

[18]:
```python
def SolveSlice(mass_flow, start_depth, end_depth, inlet_fluid: Fluid):
    thermal_network = []

    delta_h = -(end_depth - start_depth)
    length = abs(delta_h)

    avg_depth = (start_depth + end_depth) / 2

    inside_BC = inlet_fluid.temperature
    outside_BC = soil_temp(avg_depth)

    thermal_network.append(
      thermal_convection(mass_flow, inlet_fluid, tube_radii[0], length,␣
 ↪inside_BC < outside_BC)
    )

    for ind, cond in enumerate(down_tube_conductivities if delta_h < 0 else␣
 ↪up_tube_conductivities):
      inner = tube_radii[ind]
      outer = tube_radii[ind + 1]

      thermal_network.append(
        radial_thermal_conduction(inner, outer, length, cond)
      )


    overall_resistance = sum(thermal_network)

    heat_transfer_in = (outside_BC - inside_BC) / overall_resistance
```

```
    frictional_head_loss = friction_head_loss(mass_flow, inlet_fluid,␣
↪tube_radii[0], length)

    outlet_fluid = Fluid(FluidsList.CarbonDioxide).with_state(
      Input.enthalpy(inlet_fluid.enthalpy + heat_transfer_in / mass_flow),
      # Input.internal_energy(inlet_fluid.internal_energy + heat_transfer_in /␣
↪mass_flow + frictional_head_loss * GRAVITY),
      Input.pressure(inlet_fluid.pressure + inlet_fluid.density * GRAVITY *␣
↪(-delta_h - frictional_head_loss))
    )

    # assert outlet_fluid.phase == Phases.Liquid

    return outlet_fluid
```

[19]:
```
class SystemSolution:
  def __init__(self, flow_rates, turbine_outlet_pressure,␣
↪compressor_outlet_pressure, turbine_efficiency, compressor_efficiency,␣
↪supply_fluid: Fluid, VERTICAL_SLICES = 2000):
    self.flow_rates = flow_rates
    self.downward_flow_rate = sum(flow_rates) + sequestration_rate

    self.post_comp_isen =  Fluid(FluidsList.CarbonDioxide).with_state(Input.
↪pressure(compressor_outlet_pressure),
                                                     Input.entropy(supply_fluid.
↪entropy))
    # assert self.post_comp_isen.phase == Phases.Liquid, f"CO2 is now {self.
↪post_comp_isen.phase} after the compressor"


    self.post_compressor =  Fluid(FluidsList.CarbonDioxide).with_state(Input.
↪pressure(compressor_outlet_pressure),
                                                     Input.enthalpy(supply_fluid.
↪enthalpy + (self.post_comp_isen.enthalpy - supply_fluid.enthalpy) /␣
↪compressor_efficiency))
    # assert self.post_compressor.phase == Phases.Liquid

    # self.slice_log = []

    input = self.post_compressor
    for slice in range(VERTICAL_SLICES):
      output = SolveSlice(self.downward_flow_rate,
                          slice / VERTICAL_SLICES * well_depth,
                          (slice + 1) / VERTICAL_SLICES * well_depth,
                          input)
```

```
      # self.slice_log.append(output)
      input = output

    self.pre_formation = output

    self.up_states = [Fluid(FluidsList.CarbonDioxide).with_state(Input.
↪pressure(self.pre_formation.pressure - in_formation_pressure_drop(flow_rate,␣
↪self.pre_formation, well_dist)),
                                                        Input.
↪temperature(in_formation_heat_transfer(flow_rate, self.pre_formation,␣
↪well_dist))) for flow_rate, well_dist in zip(flow_rates, well_dists)]
    # for up_state in self.up_states:
    #   assert up_state.phase == Phases.Liquid

    # upward_logs = [[], []]

    self.pre_turbines = []

    for usi, up_state in enumerate(self.up_states):
      input = up_state
      for slice in range(VERTICAL_SLICES):
        output = SolveSlice(flow_rates[usi],
                              well_depth - slice / VERTICAL_SLICES * well_depth,
                              well_depth - (slice + 1) / VERTICAL_SLICES *␣
↪well_depth,
                              input)

        # upward_logs[usi].append(output)
        input = output

      self.pre_turbines.append(output)

    self.post_turb_isens = [ Fluid(FluidsList.CarbonDioxide).with_state(Input.
↪pressure(turbine_outlet_pressure),
                                                            Input.entropy(pre_turbine.
↪entropy)) for pre_turbine in self.pre_turbines]

    # for post_turb_isen in self.post_turb_isens:
    #   assert post_turb_isen.phase == Phases.Liquid

    self.post_turbines = [ Fluid(FluidsList.CarbonDioxide).with_state(Input.
↪pressure(turbine_outlet_pressure),
                                                          Input.enthalpy(pre_turbine.enthalpy␣
↪- turbine_efficiency * (pre_turbine.enthalpy - post_turb_isen.enthalpy)))␣
↪for pre_turbine, post_turb_isen in zip(self.pre_turbines, self.
↪post_turb_isens)]
```

```
    # for post_turbine in self.post_turbines:
    #   assert post_turbine.phase == Phases.Liquid

    self.post_tee =  Fluid(FluidsList.CarbonDioxide).with_state(Input.pressure(turbine_outlet_pressure), Input.enthalpy(sum([post_turbine.enthalpy * flow_rate for post_turbine, flow_rate in zip(self.post_turbines, flow_rates)]) / sum(flow_rates)))
    # assert self.post_tee.phase == Phases.Liquid

    self.condenserUA = UA_from_cond_ops(self.post_tee, supply_fluid, cold_well_temp, sum(flow_rates))

    self.turbine_production = sum([(pre_turbine.enthalpy - post_turbine.enthalpy) * flow_rate for pre_turbine, post_turbine, flow_rate in zip(self.pre_turbines, self.post_turbines, flow_rates)])
    self.compressor_consumption = (self.post_comp_isen.enthalpy - supply_fluid.enthalpy) * self.downward_flow_rate

  def summary(self):
    sol_table = pd.DataFrame({
      "Downward Flow Rate (kg / s)": [self.downward_flow_rate],
      "Left Upward Flow Rate (kg / s)": self.flow_rates[0:1],
      "Right Upward Flow Rate (kg / s)": self.flow_rates[1:2],
      "Post Pump Pressure (Pa)": [self.post_compressor.pressure],
      "Turbine Production (W)": [self.turbine_production],
      "Pump Consumption (W)": [self.compressor_consumption],
      "Net Power (W)": [self.turbine_production - self.compressor_consumption],
      "Condenser UA (W / K)": [self.condenserUA],
    })

    return sol_table.T

  def __repr__(self):
    return f"Condenser UA:           {self.condenserUA:.5g} W/K\nTurbine Production:     {self.turbine_production:.5g} W\nCompressor Consumption: {self.compressor_consumption:.5g} W\nNet Power:              {self.turbine_production - self.compressor_consumption:.5g} W"

sol = SystemSolution( flow_rates=[2.852, 1.852],
                      turbine_outlet_pressure=dioxide_pressure,
                      compressor_outlet_pressure=100.000e+06,
                      turbine_efficiency=0.85,
                      compressor_efficiency=0.85,
                      supply_fluid=Fluid(FluidsList.CarbonDioxide).with_state(
                                          Input.pressure(dioxide_pressure),
                                          Input.temperature(dioxide_temp)
```

```
                                            ))
sol
```

[19]:
```
Condenser UA:            59727 W/K
Turbine Production:      3.9428e+05 W
Compressor Consumption: 8.1002e+05 W
Net Power:               -4.1574e+05 W
```

[20]:
```
def slice_print(sol):
    presses = [s.pressure for s in sol.slice_log]
    denses = [s.density for s in sol.slice_log]
    temps = [s.temperature for s in sol.slice_log]
    enthalps = [s.enthalpy for s in sol.slice_log]
    internal_energies = [s.internal_energy for s in sol.slice_log]
    entropies = [s.entropy for s in sol.slice_log]

    depths = [ind / len(sol.slice_log) * well_depth for ind, _ in enumerate(sol.
 ↪slice_log)]

    # Create a figure with two subplots
    fig, axes = plt.subplots(6, figsize=(8, 12))

    axes[0].plot(depths, presses)
    axes[0].set_title('Pressures')
    axes[0].set_xlabel('Depth')
    axes[0].set_ylabel('Pressure Pa')

    axes[1].plot(depths, denses)
    axes[1].set_title('Density')
    axes[1].set_xlabel('Depth')
    axes[1].set_ylabel('Density Kg/m^3')

    axes[2].plot(depths, temps)
    axes[2].set_title('Temperature')
    axes[2].set_xlabel('Depth')
    axes[2].set_ylabel('Temps C')

    axes[3].plot(depths, enthalps)
    axes[3].set_title('Enthalpy')
    axes[3].set_xlabel('Depth')
    axes[3].set_ylabel('Enthalpy KJ/Kg')

    axes[4].plot(depths, internal_energies)
    axes[4].set_title('Internal Energy')
    axes[4].set_xlabel('Depth')
    axes[4].set_ylabel('Internal Energy KJ/Kg')
```

```
    axes[5].plot(depths, entropies)
    axes[5].set_title('Entropy')
    axes[5].set_xlabel('Depth')
    axes[5].set_ylabel('Entropy KJ/KgK')

    # Adjust the layout of the subplots
    plt.tight_layout()

    # Show the plot
    plt.show()
```

[21]:
```
# Define the objective function
def objective_function(args, VERTICAL_SLICES = 2000):
  lfr, rfr, compressor_outlet_pressure = args
  try:
    sol = SystemSolution(flow_rates=[lfr, rfr],
              turbine_outlet_pressure=dioxide_pressure,
              compressor_outlet_pressure=compressor_outlet_pressure,
              turbine_efficiency=0.85,
              compressor_efficiency=0.85,
              supply_fluid=Fluid(FluidsList.CarbonDioxide).with_state(Input.
 ↪pressure(dioxide_pressure),
                                                                  Input.
 ↪temperature(dioxide_temp)),
              VERTICAL_SLICES=VERTICAL_SLICES)
    return sol.turbine_production - sol.compressor_consumption
  except Exception as e:
    return 0

objective_function((1.5, 1.5, 7.000e+08))
```

[21]: -2418820.9870144073

[22]:
```
def topo_map(left_flows, right_flows, presses, drop_zeros=False,␣
 ↪drop_negatives=False):
    # Create` a list of parameter combinations
    param_combinations = [(lfr, rfr, compressor_outlet_pressure)
                for lfr in left_flows
                for rfr in right_flows
                for compressor_outlet_pressure in presses]

    # Define the number of processes to use
    num_processes = multiprocessing.cpu_count() # * 3//4

    print(f"Using {num_processes} processes")

    # objective_function(param_combinations[len(param_combinations) // 2])
```

```python
    # Create a multiprocessing pool
    pool = multiprocessing.Pool(processes=num_processes)

    # Apply the objective function to each parameter combination using␣
↪multiprocessing
    results = []
    with tqdm(total=len(param_combinations)) as pbar:
      for result in pool.imap_unordered(objective_function, param_combinations):
        results.append(result)
        pbar.update(1)

    # Close the multiprocessing pool
    pool.close()

    # Create a DataFrame from the results and param_combinations
    first_column = [params[0] for params in param_combinations]
    second_column = [params[1] for params in param_combinations]
    third_column = [params[2] for params in param_combinations]

    df = pd.DataFrame({'Left Flow Rate': first_column, 'Right Flow Rate':␣
↪second_column, 'Compressor Outlet Pressure': third_column, 'Net Power':␣
↪results})
    df

    if drop_zeros and drop_negatives:
      df = df[df['Net Power'] > 0]
    elif drop_negatives:
      df = df[df['Net Power'] >= 0]
    elif drop_zeros:
      df = df[df['Net Power'] != 0]


    # Create the figure and subplots
    fig, axes = plt.subplots(1, 3, figsize=(15, 5))

    # Adjust the spacing between subplots
    plt.subplots_adjust(wspace=0.4)
    plt.title("Net Power vs Optimized Parameters")

    ind = 0
    for a in df.columns[:-1]:
      for b in df.columns[:-1]:
        if a != b and a < b:
          ax = axes[ind]
```

```
        # Plot the data in each subplot
        # Group the data by left and right flow rates and find the maximum␣
↪net power
        max_net_power = df.groupby([a, b])['Net Power'].max()

        # Convert the grouped data into a DataFrame
        max_net_power_df = max_net_power.reset_index()
        im = ax.scatter(max_net_power_df[a], max_net_power_df[b],␣
↪c=max_net_power_df['Net Power'], cmap='viridis')

        ax.set_xlabel(a)
        ax.set_ylabel(b)

        # divider = make_axes_locatable(axes[ind])
        # cax = divider.append_axes('right', size='5%', pad=0.0)
        fig.colorbar(im, ax=ax, orientation='vertical')

        ind += 1

    plt.show()
```

[26]:
```
bounds = [(1.5, 2.25), (1.0, 1.75), (10e6, 50e6)]
count = 0
def nobjective_function(args):
  global count
  print(count, end='\r')
  count += 1
  return -objective_function(args, VERTICAL_SLICES=2000)

shgo_sol = shgo(nobjective_function, bounds) # , n=10, iters=10) # ,␣
↪sampling_method='sobol')

if not shgo_sol.success:
    print(shgo_sol)
    raise Exception("Optimization Failed")

print(f"Left Flow Rate:  {shgo_sol.x[0]:.5g} (kg/s)\nRight Flow Rate: {shgo_sol.
↪x[1]:.5g} (kg/s)\nCompressor Outlet Pressure: {shgo_sol.x[2]:.5g} Pa\nNet␣
↪Power Production: {objective_function(shgo_sol.x):.5g} W")
```

```
Left Flow Rate:  1.6871 (kg/s)
Right Flow Rate: 1.3403 (kg/s)
Compressor Outlet Pressure: 1e+07 Pa
Net Power Production: 35457 W
```

[27]:
```
optimal = SystemSolution(flow_rates=[shgo_sol.x[0], shgo_sol.x[1]],
                          turbine_outlet_pressure=dioxide_pressure,
```

```
                          compressor_outlet_pressure=shgo_sol.x[2],
                          turbine_efficiency=0.85,
                          compressor_efficiency=0.85,
                          supply_fluid=Fluid(FluidsList.CarbonDioxide).
 ↪with_state(Input.pressure(dioxide_pressure),
                                                                  Input.
 ↪temperature(dioxide_temp)))
optimal.summary()
```

[27]:

	0
Downward Flow Rate (kg / s)	6.267426e+00
Left Upward Flow Rate (kg / s)	1.687089e+00
Right Upward Flow Rate (kg / s)	1.340338e+00
Post Pump Pressure (Pa)	1.000000e+07
Turbine Production (W)	6.692939e+04
Pump Consumption (W)	3.147269e+04
Net Power (W)	3.545669e+04
Condenser UA (W / K)	5.103347e+04

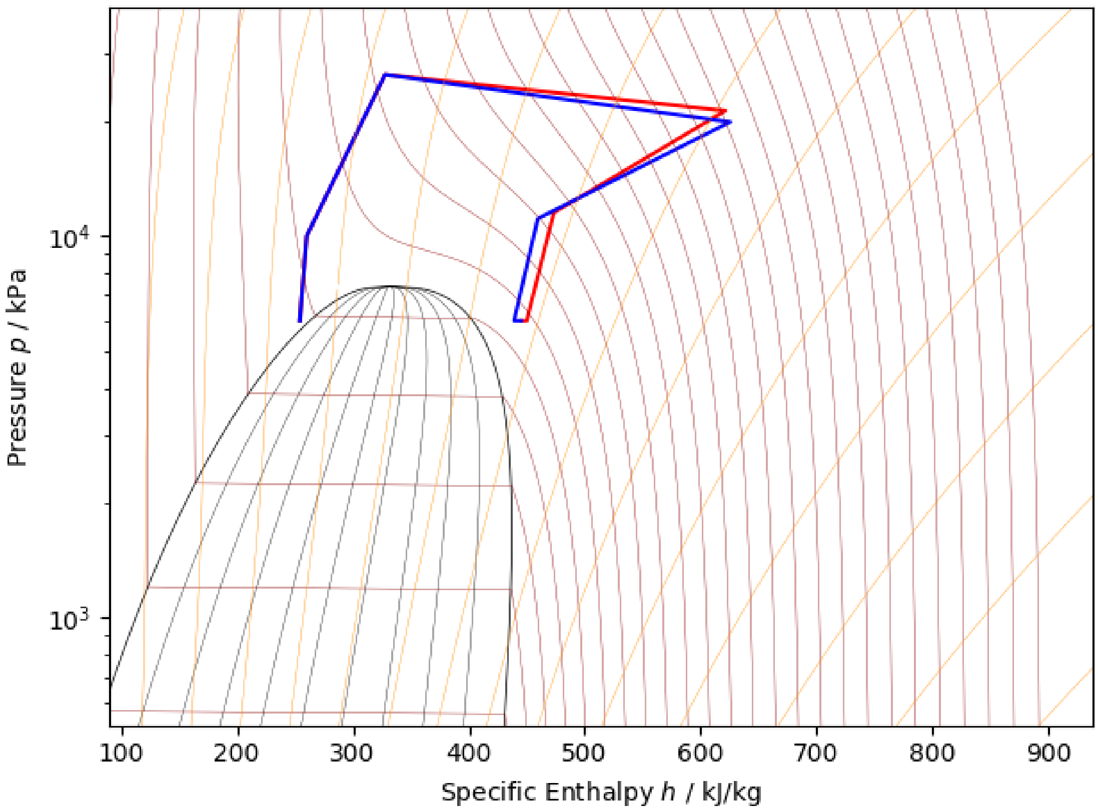
[29]:
```
for p, m_dot in zip(optimal.pre_turbines, shgo_sol.x[0:2]):
  press, dense, temp = p.pressure, p.density, p.temperature
  print(f"Vol Flow: {m_dot / dense:.5g} m^3/s, Pressure: {press:.5g} Pa,␣
 ↪Density: {dense:.5g} kg/m^3, Temperature: {temp:.5g} C")
```

```
Vol Flow: 0.0067552 m^3/s, Pressure: 1.1519e+07 Pa, Density: 249.75 kg/m^3,
Temperature: 89.769 C
Vol Flow: 0.0051609 m^3/s, Pressure: 1.1113e+07 Pa, Density: 259.71 kg/m^3,
Temperature: 80.647 C
```

[30]:
```
def cycle_ph(state_list_a, state_list_b):
    import CoolProp
    from CoolProp.Plots import PropertyPlot
    from CoolProp.Plots.SimpleCycles import StateContainer
    from CoolProp.Plots.Common import BasePlot

    pp = PropertyPlot('CO2', 'PH')

    cycle_states_a = StateContainer()
    for ind, state in enumerate(state_list_a):
        cycle_states_a[ind,'H'] = state.enthalpy
        cycle_states_a[ind,'S'] = state.entropy
        cycle_states_a[ind,'D'] = state.density
        cycle_states_a[ind,CoolProp.iP] = state.pressure
        cycle_states_a[ind,CoolProp.iT] = state.temperature

    cycle_states_b = StateContainer()
    for ind, state in enumerate(state_list_b):
```

```
        cycle_states_b[ind,'H'] = state.enthalpy
        cycle_states_b[ind,'S'] = state.entropy
        cycle_states_b[ind,'D'] = state.density
        cycle_states_b[ind,CoolProp.iP] = state.pressure
        cycle_states_b[ind,CoolProp.iT] = state.temperature

    state_list = state_list_a + state_list_b


    old_limits = pp.get_axis_limits()
    pp.set_axis_limits([
        old_limits[0],
        1.5 * max([state.enthalpy for state in state_list]) / 1e3,
        old_limits[2],
        max(old_limits[3], 1.5 * max([state.pressure for state in state_list]) /
 ↪ 1e3),
    ])

    pp.draw_process(cycle_states_a)
    pp.draw_process(cycle_states_b, line_opts={'color':'blue', 'lw':1.5})


    pp.calc_isolines(CoolProp.iQ, num=11)
    pp.calc_isolines(CoolProp.iT, num=25)
    pp.calc_isolines(CoolProp.iSmass, num=15)

    pp.show()

import warnings
warnings.filterwarnings("ignore")
cycle_ph(
        (
          Fluid(FluidsList.CarbonDioxide).with_state(Input.
 ↪pressure(dioxide_pressure), Input.temperature(dioxide_temp)),
          optimal.post_compressor,
          optimal.pre_formation,
          optimal.up_states[0],
          optimal.pre_turbines[0],
          optimal.post_turbines[0],
          optimal.post_tee),
(
          Fluid(FluidsList.CarbonDioxide).with_state(Input.
 ↪pressure(dioxide_pressure), Input.temperature(dioxide_temp)),
          optimal.post_compressor,
          optimal.pre_formation,
          optimal.up_states[1],
          optimal.pre_turbines[1],
```

```
            optimal.post_turbines[1],
            optimal.post_tee)
)
```



1.6 NS-DS Chart Values

[31]:
```
# Pump Sizing
pump_vol_flow = optimal.downward_flow_rate / Fluid(FluidsList.CarbonDioxide).
  ↪with_state(Input.pressure(dioxide_pressure), Input.
  ↪temperature(dioxide_temp)).density

enthalpy_delta = optimal.post_compressor.enthalpy - Fluid(FluidsList.
  ↪CarbonDioxide).with_state(Input.pressure(dioxide_pressure), Input.
  ↪temperature(dioxide_temp)).enthalpy

# pump_eta = 0.85

pump_eta =  dioxide_pressure / optimal.post_compressor.pressure

print(f"Pump Volumetric Flow Rate {pump_vol_flow:.5g}")
```

```
print(f"Pump Enthalpy Delta {enthalpy_delta:.5g}")
print(f"Pump Eta {pump_eta:.5g}")
```

```
Pump Volumetric Flow Rate 0.008008
Pump Enthalpy Delta 5907.8
Pump Eta 0.6
```

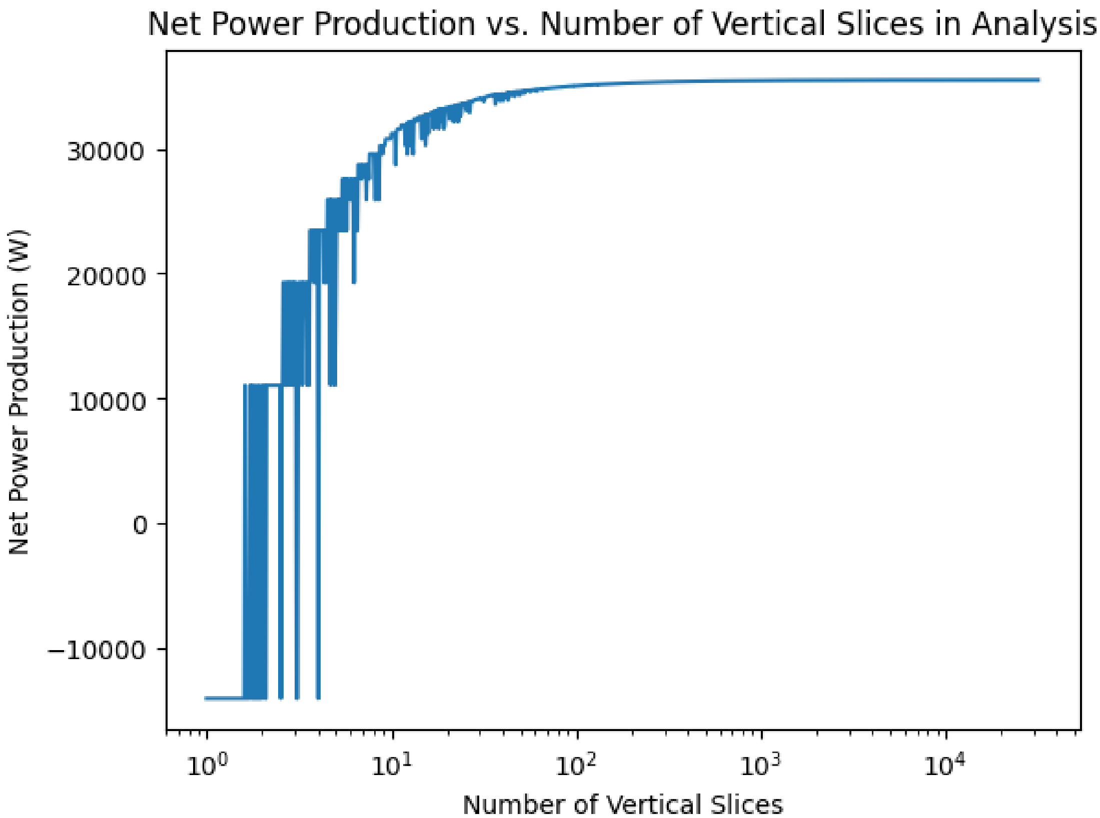
[32]:
```
# Turbine(s) Sizing

turbine_vol_flows = [m_dot / pre_turbine.density for m_dot, pre_turbine in␣
 ↪zip(shgo_sol.x[0:2], optimal.pre_turbines)]

enthalpy_deltas = [post.enthalpy - pre.enthalpy for post, pre in zip(optimal.
 ↪post_turbines, optimal.pre_turbines)]

turbine_etas = [post.pressure / pre.pressure for post, pre in zip(optimal.
 ↪post_turbines, optimal.pre_turbines)]

for v, h, e in zip(turbine_vol_flows, enthalpy_deltas, turbine_etas):
  print(f"Vol Flow: {v:.5g} m^3/s, Enthalpy Delta: {h:.5g} J/kg")
  print(f"Turbine Eta {e:.5g}")
```

```
Vol Flow: 0.0067552 m^3/s, Enthalpy Delta: -23357 J/kg
Turbine Eta 0.52088
Vol Flow: 0.0051609 m^3/s, Enthalpy Delta: -20535 J/kg
Turbine Eta 0.53991
```

[33]:
```
slices = np.logspace(0, 4.5, 1000)

def slice_check(slice_count):
  left_flow, right_flow, compressor_outlet_pressure = shgo_sol.x

  try:
    sol = SystemSolution(flow_rates=[left_flow, right_flow],
              turbine_outlet_pressure=dioxide_pressure,
              compressor_outlet_pressure=compressor_outlet_pressure,
              turbine_efficiency=0.85,
              compressor_efficiency=0.85,
              supply_fluid=Fluid(FluidsList.CarbonDioxide).with_state(Input.
 ↪pressure(dioxide_pressure),
                                                    Input.
 ↪temperature(dioxide_temp)),
              VERTICAL_SLICES=int(slice_count))
    return sol.turbine_production - sol.compressor_consumption
  except Exception as e:
    return 0
```

```python
# Define the number of processes to use
num_processes = multiprocessing.cpu_count()
print(f"Using {num_processes} processes")

# Create a multiprocessing pool
pool = multiprocessing.Pool(processes=num_processes)

# Apply the objective function to each parameter combination using␣
↪multiprocessing
results = []
with tqdm(total=len(slices)) as pbar:
  for result in pool.imap_unordered(slice_check, slices):
    results.append(result)
    pbar.update(1)

# Close the multiprocessing pool
pool.close()

clean_slices = []
clean_results = []

for s, r in zip(slices, results):
  if r != 0:
    clean_slices.append(s)
    clean_results.append(r)


plt.plot(clean_slices, clean_results)
plt.title("Net Power Production vs. Number of Vertical Slices in Analysis")
plt.xlabel("Number of Vertical Slices")
plt.ylabel("Net Power Production (W)")
plt.xscale('log')
plt.show()
```

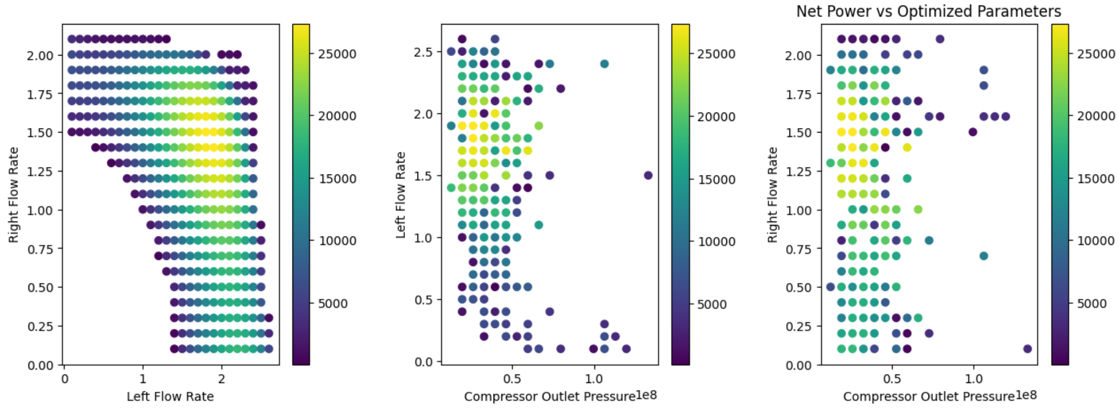
```
Using 80 processes

100%|      | 1000/1000 [02:38<00:00,  6.31it/s]
```



[25]:
```
left_range = np.linspace(0.1, 3.0, 30)
right_range = np.linspace(0.1, 3.0, 30)
press_range = np.linspace(dioxide_pressure, 200e6, 30)

topo_map(left_range, right_range, press_range, drop_zeros=True,
  drop_negatives=True)
```

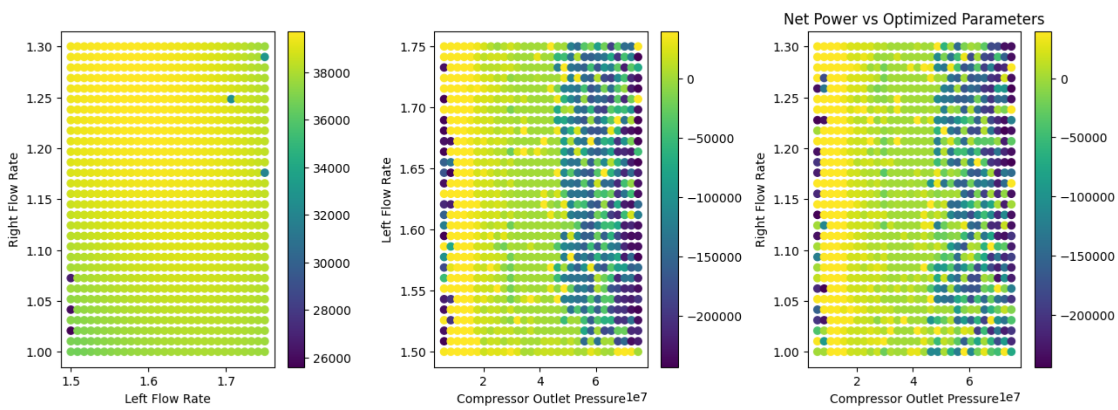
```
Using 80 processes
```

```
100%|      | 27000/27000 [30:24<00:00, 14.80it/s]
```




```
[24]: left_range = np.linspace(1.5, 1.75, 30)
right_range = np.linspace(1.0, 1.3, 30)
press_range = np.linspace(dioxide_pressure, 75e6, 30)

topo_map(left_range, right_range, press_range, drop_zeros=False,␣
    ↪drop_negatives=False)
```

```
Using 80 processes

100%|          | 27000/27000 [30:32<00:00, 14.74it/s]
```



1.7 Values of selected cycle for report tables

```
[36]: sequestration_power = sequestration_rate / optimal.downward_flow_rate * optimal.
    ↪compressor_consumption
sequestration_power
```

```
[36]: 16270.079985056678
```

[37]:
```python
pf = optimal.pre_formation
pf.pressure, pf.temperature, pf.specific_heat
```

[37]: (26484950.892727025, 66.82201607073517, 2148.186285585556)

[38]:
```python
for o in optimal.up_states:
  print(f"Pressure: {o.pressure:.5g}, Temperature: {o.temperature:.5g}")
```

```
Pressure: 2.13e+07, Temperature: 220
Pressure: 1.9894e+07, Temperature: 220
```

[ ]:
```python

```