Short Report on Thermodynamic Analysis of Packed Bed Thermal Energy Storage System

A Project Report Submitted
in Partial Fulfilment of the Requirements
for the course ME-686A completion

By

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Abstract

A packed-bed thermal energy storage (PBTES) device, which is simultaneously restricted by thermal storage capacity and outlet temperatures of both cold and hot heat transfer fluids, is characterized by an unstable operation condition, and its calculation is complicated. To solve this problem, a steady thermodynamics model of PBTES with fixed temperatures on both ends was built. By using this model, the exergy destruction, thermocline thickness, thermal storage capacity, thermal storage time, and other key parameters can be calculated in a simple way. In addition, the model explained the internal reason for the change of thermocline thickness during thermal storage and release processes. Furthermore, the stable operation of the PBTES device was analysed, and it was found that higher inlet temperature of hot air, and lower temperature difference between cold and hot air can produce less exergy destruction and achieve a larger cycle number of stable operation. The work can be employed as the basis of the design and engineering application of PBTES.

1. Introduction

A thermal energy storage (TES) device, which combines thermal storage and heat transfer, aims to overcome the contradiction between heat generation and usage as well as to solve the problem of using intermittent heat sources. For example, in a solar thermal power generation system, the discontinuous and unstable solar thermal energy is stored in TES when sunlight is sufficient. Then, the stored thermal energy is released continuously and stably if needed. In this way, the solar energy can be used efficiently. The heat is stored in thermal storage materials, such as molten salt, microcapsules of phase-change material, pebble, carbon steel, ceramics, aluminium, and stainless steel

In this study, according to the corresponding characteristics of thermal charging and discharging processes, a steady heat transfer model for the PBTES was built, which is suitable for calculating PBTES when it works unsteadily with fixed outlet temperatures of both cold and hot fluids. It also provides a theoretical support for analysis on the PBTES with fixed outlet temperatures of cold and hot fluids. Then the reason of the variation of the thermocline thickness can be obtained. On this basis, a stable operating PBTES model was proposed to reduce large fluctuation of outlet temperatures of cold and hot fluids and keep constant large thermal storage density. The operating condition was analysed and the results can provide a theoretical basis for the design and operation of the proposed PBTES system.

2. Working Principle and Classification of PBTES

A conventional PBTES device, which is filled with thermal storage materials to store energy, is shown in Fig. 1. In this device, the inlet temperatures of hot and cold fluids are constant. In the thermal storage process, the hot fluid with temperature T1 flows into the PBTES to exchange heat with the thermal storage material. As the temperature of the thermal storage material increases, the outlet temperature of hot fluid becomes T2. The thermal storage process ends in t hours. In the thermal release process, the cold fluid with temperature T3 flows into the PBTES to exchange heat with the thermal storage material, the temperature of thermal storage material decreases, and the outlet temperature of cold fluid becomes T4. The thermal release process ends when the thermal energy stored in the PBTES returns to the original value.

In this study, the PBTES of two-side constant temperature type was analysed and the influence factors of unstable operation of the PBTES were explored; on this basis, a steady operating model was proposed. The PBTES may undergo the same process in all cycles; and for the two-side constant-temperature type, the outlet temperature of the hot fluid is the same approximately as the inlet temperature of cold fluid for the hot side, and the same situation is for the cold side.

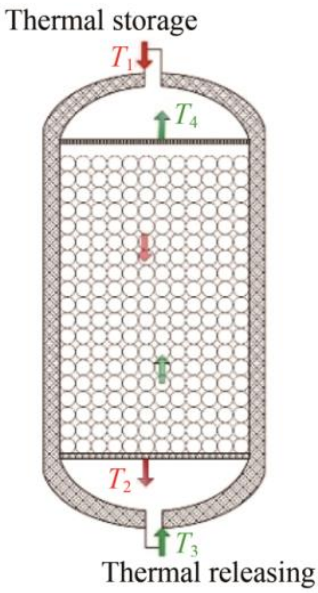


Figure 1 A conventional PBTES device

3. Steady Heat Transfer Model

3.1 Simplified steady heat transfer model

The proposed PBTES model of two-side constant temperature type is assumed to be one-dimensional and have no pressure drop, the heat transferred with surroundings is assumed to be zero. e. The heat capacity of fluid and thermal storage material is assumed constant. The mass flow rates of hot and cold fluids are the same as m_{air} & . Air is chosen as heat transfer fluid, which is considered as an ideal gas, and pebble is chosen as the thermal storage material. The initial temperature of pebbles is Tlow. Thermal storage starts at time 0. At this moment, the hot air with temperature Thigh flows into the PBTES, and the temperature decreases drastically to Tlow. Thus, a steep thermocline emerges. The thermocline moves to the cold side during the thermal storage process. The thermal storage ends at t0. Thermal release also starts at time 0, which is the same time when the cold air with temperature Tlow and the same mass flow rate as that during the thermal storage process flows into the PBTES and is heated by the hot pebbles. A thermocline also emerges and moves to the hot side during the thermal release process. The thermal release ends at t0. The time duration of thermal storage and release processes are the same because the mass flow rate during thermal storage and thermal release process are the same, and the total air mass is constant.

As both the hot and cold air exchange heat with pebbles, it can be assumed that the hot air and cold air exchange heat directly with each other through a simple heat transfer model, in which the thermal storage material, pebbles, is ignored. time of the thermal storage and thermal release can be corresponded: time, 0 (beginning of thermal storage) of the thermal storage process corresponds to time, t0 (end of thermal release) of the thermal release process, meanwhile, time, t0 (end of thermal storage) of the thermal storage process corresponds to time, 0 (initial of thermal release) of the thermal release process. Then time t1 of the thermal storage process corresponds to time, t01 of the thermal release process, and the time, t2 of the thermal storage process corresponds to time, t02 of the thermal release process, where

$$t1 = t0 - t\,01, \qquad t2 = t0 - t02$$

As mentioned, the heat transfer in the PBTES can be considered as the counterflow heat transfer between hot and cold air at a corresponding time with temperature difference δT based on the energy balance:

$$Cp_{hot} * m_{hot} * \ \Delta T_{hot} = \ Cp_{cold} * \ m_{cold} * \ \Delta T_{cold}$$

where $cp,_{cold}$, $cp,_{hot}$ represents the specific heat capacity of cold air and hot air, respectively; mcold & and mhot & are the mass flow rate of cold and hot air, respectively; and ΔTcold and ΔThot are the local temperature change of cold and hot air, respectively. Based on the preceding assumption, cp,hot is equal to cp,cold. mhot & and mcold & are the same as mair & . Thus, the local temperature changes of cold air and hot air are the same, and the temperature difference, δT, does not change along the axial direction (or thermocline direction) during the heat transfer process at corresponding time.

3.2 Steady thermodynamic model of PBTES

3.2.1 Balance of thermal energy and exergy

From t_1 in thermal storage to t_{01} in thermal release process, according to the balance of energy,

$$\Delta Usto = Hhot - \ \ Hcold$$

$$cp, air * m\ air\ (\ t0 - t1) * \ \Delta T - Cp, air * m\ air(t01 - \ 0)$$

where ΔUsto represents the change of thermal energy stored in pebbles in this process.
Hhot is the input of

△T is the temperature change of cold and hot air, which is also the temperature change of pebbles:

$$\Delta T = \ T_{high} - T_{low}$$

where Thigh represents the inlet temperature of hot air. Tlow represents the inlet temperature of cold air. The thermal energy stored in region 1 (ABCDA) is transferred equivalently to region 2 (CEFGC), as shown in Fig. 2.

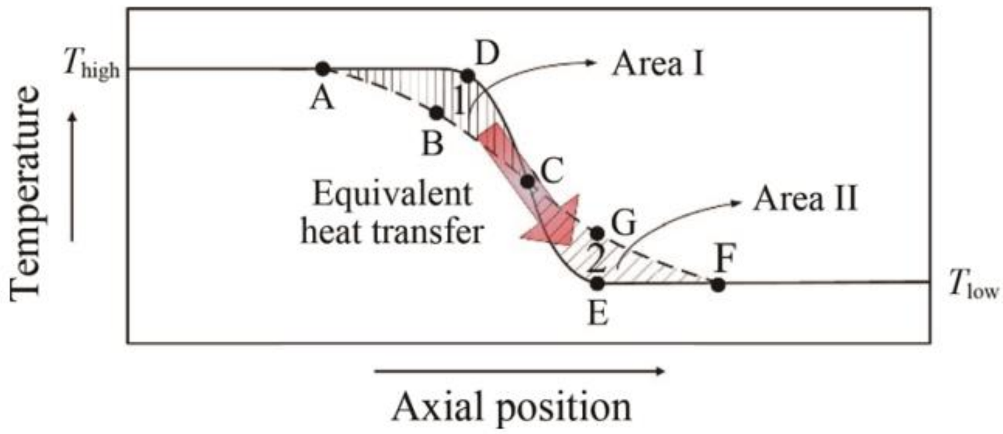


Figure 2 Shape of thermocline at corresponding time

The exergy balance of the thermal storage and thermal release can be respectively shown:

$$\Delta Es, sto = \Delta Ehot - Is$$

$$= m_{air} * (t0 - t1) * (e_{in}, hot - e_{out}, hot) - Is$$

$$\Delta En, sto = -\Delta Ecold - In$$

$$= -mair * (t01 - 0) * (eout, cold - ein, cold) - In$$

where ΔEs,sto , ΔEn,sto is the change of exergy stored in the pebbles during thermal storage and that during the thermal release process, respectively. ΔEhot is the exergy change of hot air during the thermal storage process. ΔEcold represents the exergy change of cold air during the thermal release process. Is and In respectively represent the exergy destruction because of the temperature difference between air and pebbles during the thermal storage and the thermal release process. ein,hot, eout,hot is the inlet exergy and outlet exergy of hot air, respectively. ein,cold, eout,cold is the inlet exergy and outlet exergy of cold air, respectively.

$$\Delta E_{\text{sto}} = \Delta E_{\text{n,sto}} + \Delta E_{\text{s,sto}} = -I_{\text{s}} - I_{\text{n}} = -I_{\text{sn}}$$

Isn represents the exergy destruction in the heat transfer process between cold air and hot air under the temperature difference, δT.

The change of exergy stored in pebbles indicates the change of the temperature distribution in the pebbles, the heat transfer process can be considered as a superficial reversible process because of the zero-temperature difference at two ends of the thermocline. As the process of thermal storage and release proceeds, the thermocline thickens, and the area of the curve decreases.

In the beginning, A-B is the reserved part with temperature Thigh. The temperature of other parts is Tlow, which is not in a full load of the PBTES to store thermal energy in the first thermal storage process, and the stored thermal energy is only equal to that in part B-F. C-D is the reserved part accordingly.

(1) Thermal storage capacity and thermal storage/ release time The constant thermal storage capacity during several cycles.

$$Q = c_{\mathrm{p,sto}} m_{\mathrm{sto}} \Delta T = c_{\mathrm{p,sto}} L_{\mathrm{B-F}} \rho_{\mathrm{m,sto}} \Delta T$$

where msto represents the total mass of pebbles from point B to point F. LB-F is the length of point B to point F. ρm,sto is the mass of pebbles contained per unit length.

$$M_{\mathrm{air}} = \frac{Q}{c_{\mathrm{p,air}} \Delta T} = \frac{c_{\mathrm{p.sto}}}{c_{\mathrm{p,air}}} L_{\mathrm{B-F}} \rho_{\mathrm{m,sto}}$$

The thermal storage/release time in one cycle is

$$t_{\mathrm{cycle}} = \frac{M_{\mathrm{air}}}{\dot{m}_{\mathrm{air}}}$$

(2) Exergy destruction of heat transfer per unit of time At the corresponding time, the temperature difference, δT, between cold and hot air leads to exergy destruction.

The entropy change of hot air per unit of time is

$$\Delta \dot{s}_{\mathrm{high}} = c_{\mathrm{p,air}} \dot{m}_{\mathrm{air}} \ln \frac{T_{\mathrm{low}} + \delta T}{T_{\mathrm{high}}}$$

The entropy change of cold air per unit of time is

$$\Delta \dot{s}_{\mathrm{low}} = c_{\mathrm{p,air}} \dot{m}_{\mathrm{air}} \ln \frac{T_{\mathrm{high}} - \delta T}{T_{\mathrm{low}}}$$

The exergy destruction per unit of time is

$$\begin{aligned} \dot{I}_{\mathrm{transfer}} &= T_0 \dot{s}_{\mathrm{gen,transfer}} = T_0 \left(\Delta \dot{s}_{\mathrm{high}} + \Delta \dot{s}_{\mathrm{low}} \right) \\ &= c_{\mathrm{p,air}} \dot{m}_{\mathrm{air}} T_0 \ln \frac{\left(T_{\mathrm{high}} - \delta T \right)\left(T_{\mathrm{low}} + \delta T \right)}{T_{\mathrm{high}} T_{\mathrm{low}}} \end{aligned}$$

(3) Exergy destruction rate Exergy destruction rate is the ratio of the total exergy destruction in one cycle to the maximum amount of stored exergy when the thermocline is straight.

$$\eta_{\mathrm{gen}} = \frac{\dot{I}_{\mathrm{transfer}} t_{\mathrm{cycle}}}{c_{\mathrm{p,sto}} m_{\mathrm{sto}} \left[\left(T_{\mathrm{high}} - T_{\mathrm{low}} \right) - T_0 \ln \left(T_{\mathrm{high}} / T_{\mathrm{low}} \right) \right]}$$

$$= \frac{T_0}{\left(T_{\mathrm{high}} - T_{\mathrm{low}} \right) - T_0 \ln \left(T_{\mathrm{high}} / T_{\mathrm{low}} \right)}$$

$$\ln \frac{\left(T_{\mathrm{high}} - \delta T \right) \left(T_{\mathrm{low}} + \delta T \right)}{T_{\mathrm{high}} T_{\mathrm{low}}}$$

(4) Thickness of thermocline, the change of entropy in zone 1 is

$$\Delta S_1 = \int_0^{m_{\mathrm{B\text{-}H}}} c_{\mathrm{p,sto}} \ln \frac{T_{\mathrm{mid}} + m \left(T_{\mathrm{high}} - T_{\mathrm{mid}} \right) / m_{\mathrm{B-H}}}{T_{\mathrm{high}}} \mathrm{d}m$$

$$= c_{\mathrm{p,sto}} L_{\mathrm{B\text{-}H}} \rho_{\mathrm{m,sto}} \left(\frac{T_{\mathrm{mid}}}{T_{\mathrm{high}} - T_{\mathrm{mid}}} \ln \frac{T_{\mathrm{high}}}{T_{\mathrm{mid}}} - 1 \right)$$

The change of entropy in zone 2 is

$$\Delta S_2 = \int_0^{m_{\mathrm{B\text{-}H}}} c_{\mathrm{p,sto}} \ln \frac{T_{\mathrm{low}} + m \left(T_{\mathrm{mid}} - T_{\mathrm{low}} \right) / m_{\mathrm{B\text{-}H}}}{T_{\mathrm{low}}} \mathrm{d}m$$

$$= c_{\mathrm{p,sto}} L_{\mathrm{B\text{-}H}} \rho_{\mathrm{m,sto}} \left(\frac{T_{\mathrm{mid}}}{T_{\mathrm{mid}} - T_{\mathrm{low}}} \ln \frac{T_{\mathrm{mid}}}{T_{\mathrm{low}}} - 1 \right)$$

The total exergy destruction in one cycle is

$$\begin{aligned} I_{\mathrm{sto}} &= T_0 S_{\mathrm{gen,sto}} = T_0 \left(\Delta S_1 + \Delta S_2 \right) \\ &= c_{\mathrm{p,sto}} T_0 \rho_{\mathrm{m,sto}} L_{\mathrm{B-H}} \left(\frac{T_{\mathrm{mid}}}{T_{\mathrm{high}} - T_{\mathrm{mid}}} \ln \frac{T_{\mathrm{high}}}{T_{\mathrm{mid}}} \right. \\ &\quad \left. + \frac{T_{\mathrm{mid}}}{T_{\mathrm{mid}} - T_{\mathrm{low}}} \ln \frac{T_{\mathrm{mid}}}{T_{\mathrm{low}}} - 2 \right) \end{aligned}$$

the exergy destruction caused by the heat transfer between cold and hot air is equal to the exergy destruction caused by heat transfer from the hot to the cold side of the pebbles, which is

$$I_{\mathrm{sto}} = \dot{I}_{\mathrm{transfer}} t_{\mathrm{cycle}}$$

4 Stable Operation of PBTES

The transfer process of exergy destruction of the PBTES is divided into two parts. First, the exergy destruction of heat transfer of hot air and cold air is transferred to be the exergy destruction of equivalent heat transfer of pebbles. Second, a exergy supplement is made for offsetting the exergy destruction in the pebbles, which means that the exergy destruction in pebbles is reflected on the exergy supplement by outside.

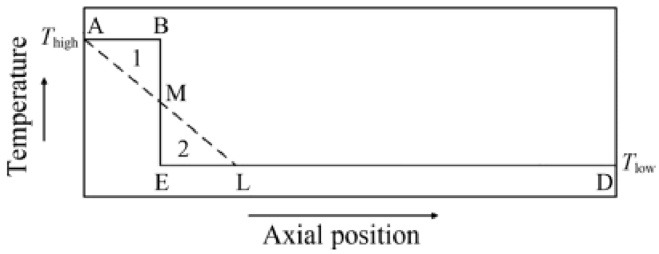


Figure 3 Limited thickness of thermocline after operation of several cycles

the original shape of the thermocline is B-E (A-B is the reserved part of hot side, cold side has a reserved part of the same length too), and after several cycles, this shape changes to its ultimate state, A-L. The total exergy destruction generated (i.e., the supplement exergy needed from surroundings) during the time when the shape of thermocline, B-E, changes to A-L is

$$I_{\text{sto}} = c_{\text{p,sto}} T_0 \rho_{\text{m,sto}} L_{\text{A-B}} \left(\frac{T_{\text{mid}}}{T_{\text{high}} - T_{\text{mid}}} \ln \frac{T_{\text{high}}}{T_{\text{mid}}} + \frac{T_{\text{mid}}}{T_{\text{mid}} - T_{\text{low}}} \ln \frac{T_{\text{mid}}}{T_{\text{low}}} - 2 \right)$$

The thermal storage/release time of the stable operation of the PBTES is as follows:

$$t = \frac{I_{\text{sto}}}{\dot{I}_{\text{transfer}}}$$

The cycle number of operation can be calculated as follows:

$$n = \frac{t}{t_{\text{cycle}}}$$

$$= \frac{L_{\text{A-B}} \left(\frac{T_{\text{mid}}}{T_{\text{high}} - T_{\text{mid}}} \ln \frac{T_{\text{high}}}{T_{\text{mid}}} + \frac{T_{\text{mid}}}{T_{\text{mid}} - T_{\text{low}}} \ln \frac{T_{\text{mid}}}{T_{\text{low}}} - 2 \right)}{L_{\text{B-F}} \ln \frac{\left(T_{\text{high}} - \delta T\right)\left(T_{\text{low}} + \delta T\right)}{T_{\text{high}} T_{\text{low}}}}$$

(1) Typical working condition:

As shown in Fig. 3, the total length of the PBTES is 15 m; the lengths of reserved parts, the part from point A to point B, and the part from point C to point D are all 5 m. The length of the part from point B to point F is also 5 m. The total mass of a pebble is 6×104 kg. The mass flow rate of the cold and hot air is 3 kg/s. The inlet temperature of hot air, Thigh, is 600 K, and the inlet temperature of cold air, Tlow, is 298 K. The environment temperature, T0, is 298 K. The heat transfer temperature difference between the cold and hot air, δT, is 10 K (i.e., the average value in a stable operating cycle). The heat capacity of air, cp,air, is 1.08 kJ/(kg·K), and the heat capacity of pebble, cp,sto, is 0.780 kJ/(kg·K). The calculated results are

Parameters	Value
Q/kJ	4.71×10^{6}
η_{gen}/%	5.17
t_{cycle}/h	1.33
t/h	6.68
n	5

(2) Variable working conditions:

The effect of Thigh and δT on the performance of the PBTES is analysed in this section, keeping other basic parameters unchanged. The exergy destruction rate, ηgen, increases with δT and decreases with Thigh. Meanwhile, ηgen is more affected by Thigh and tcycle when Thigh is lower. The reason is that the maximum stored exergy is invariable when Thigh is constant, whereas the exergy destruction of heat transfer between cold and hot air per unit of time, transfer I & , increases with δT. Meanwhile, the thermal storage/release time of one cycle, tcycle, is constant. The exergy destruction rate, ηgen, increases with δT. When δT is invariable, transfer I & and the maximum stored exergy both decrease with Thigh, but the former is more pronounced.

The cycle number, n, decreases with δT and increases with Thigh. The reason is that when Thigh is invariable, the stable operation time of thermal storage/release, t, decreases with δT, whereas the thermal storage/release time of one cycle, tcycle, is irrelevant to δT. The cycle number, n, decreases with δT. When δT is invariable, the total exergy destruction of the pebbles, Isto, and the exergy destruction of the heat transfer between cold and hot air per unit of time, transfer I & , both decrease with Thigh. Being affected by the two factors, the stable operation time of thermal storage/release, t, increases with Thigh. Thus, the cycle number, n, rises with $T_{high.}$

Therefore, in the PBTES operation, when the inlet temperature of hot air, Thigh, is high (Tlow is invariable), the temperature difference, δT, is low and the performance of the PBTES is significant. This condition also produces less exergy destruction and a larger cycle number.

5. Conclusion

When the outlet temperature of cold and hot fluids, and thermal storage capacity are strictly required by a thermodynamic system, a conventional PBTES encounters problem, such as unstable working condition, and the calculation of the unstable process becomes complex. To solve these problems, an idea was proposed to convert the unsteady heat transfer process of the PBTES with fixed outlet temperatures of cold and hot fluids to a steady process for a counterflow heat transfer. A thermodynamic PBTES model was developed based on the steady process at a corresponding time, which can be used to calculate the key performance parameters of the PBTES, including thermal storage capacity, thermal storage/release time, exergy destruction of heat transfer per unit of time, exergy destruction rate, and thickness of thermocline.

For a given inlet temperature of hot air, the decrease of exergy destruction rate and cycle number got slow with the increase of temperature difference. For a given temperature difference, the decrease of exergy destruction also got slow, while the increase rate of cycle number almost keeps unchanged.

Output from the code for verification by given data in the paper

Temperature high, δT	600°C , 10K
Thermal storage capacity, Q	4711200.0
Cycle time, t cycle/hr	1.337448559670782
The thermal storage/release time, t/hr	6.685088647040901
Exergy destruction rate, ηgen/%	5.165774164044877
The cycle number of operation, n	4.998389357633658

Code of Assignment 1: ME-686A

- Name: ***Prashant Anand Ranjan***
- Roll no.: ***21105066***

In [1]:

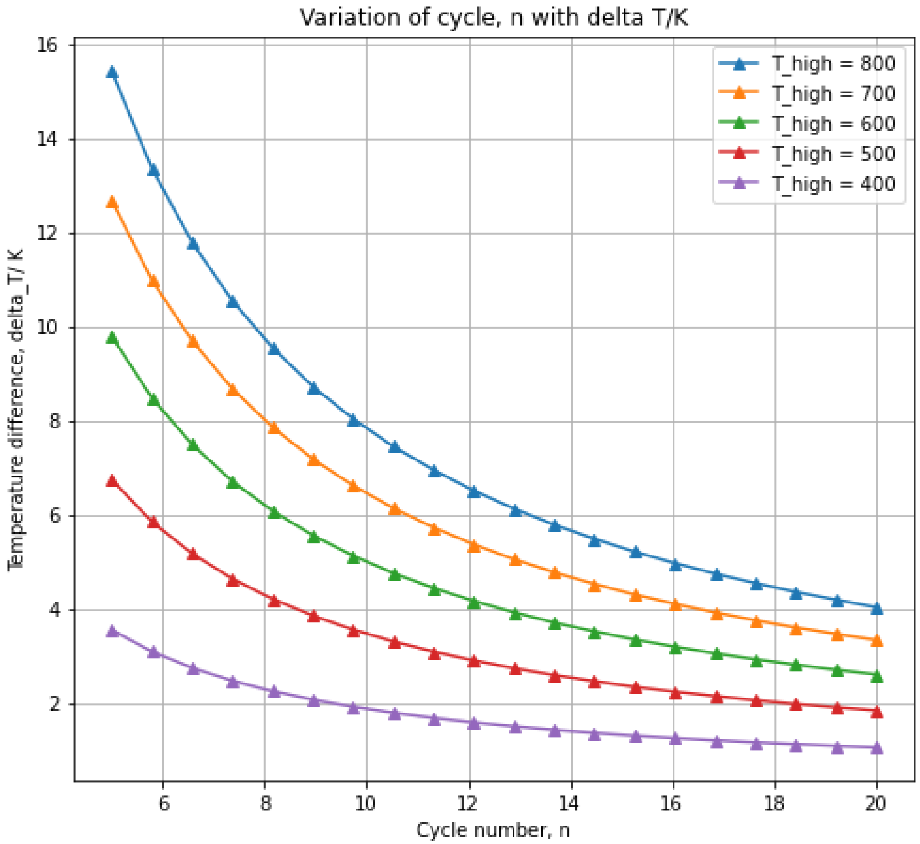
```
#.....Importing libraries
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline

#.....Declaring variables
n = 20                                                                  # Number of points to be plotted
Thigh = np.array([800, 700, 600, 500, 400])
T_low = 298
T0 = T_low
dT = np.linspace(5, 20, n)
n = np.empty(n)
η = n.copy()

#.....Properties of the working materials
cp_sto = 0.78                                                           # The heat capacity of pebble
cp_air = 1.08                                                           # The heat capacity of air

m_air = 3                                                               # The mass flow rate of the cold and hot air
m_sto = 60e3 / 3                                                        # The total mass of pebbles from point B to point F

#.....Main Code
plt.figure(figsize = (8, 16))
for T_high in Thigh:

    T_mid = (T_high + T_low) / 2
    delta_T = T_high - T_low

    Q = cp_sto * m_sto * delta_T                                         # The constant thermal storage capacity during several cycles

    M_air = Q / (cp_air * delta_T)                                       # The mass of air flowed through the PBTES

    t_cycle = M_air / m_air                                              # Cycle time in seconds

    delta_s_high = cp_air * m_air * np.log((T_low + dT) / T_high)        # The entropy change of hot air per unit of time
    delta_s_low = cp_air * m_air * np.log((T_high - dT) / T_low)         # The entropy change of cold air per unit of time
```

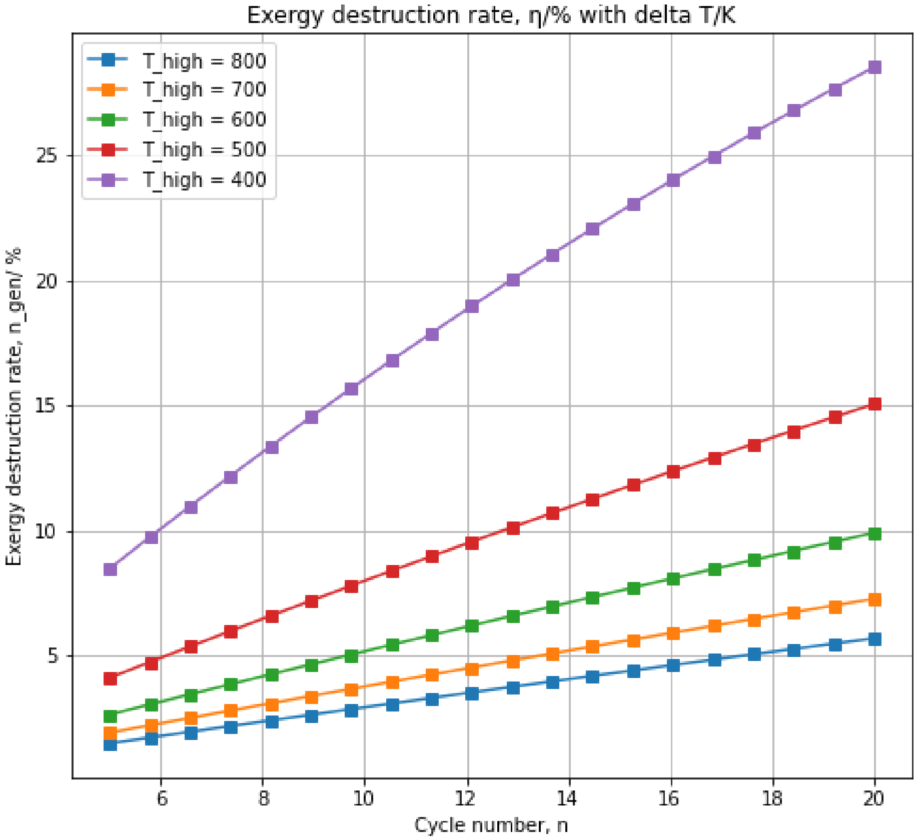
```python
I_trasfer = T0 * (delta_s_high + delta_s_low)                    # The exergy destruction per unit of time

η = (I_trasfer * t_cycle) / (cp_sto * m_sto *
                             (delta_T - T0 * np.log(T_high / T_low))) # Exergy destruction rate, ηgen,

delta_s1 = cp_sto * m_sto * ((T_mid / (T_high - T_mid)) * np.log(T_high / T_mid) - 1) # The change of entropy in zone 1
delta_s2 = cp_sto * m_sto * ((T_mid / (T_mid - T_low)) * np.log(T_mid / T_low) - 1)   # The change of entropy in zone 2

I_sto = T0 * (delta_s1 + delta_s2)                                 # The total exergy destruction in one cycle

t = I_sto / I_trasfer                                              # The thermal storage/release time of the stable
                                                                   # operation of the PBTES

n = t / t_cycle                                                    # The cycle number of operation

Label = "T_high = {}".format(T_high)

#.....Generating the plots for Variation of cycle with delta T
#     under different T_high
plt.subplot(2, 1, 1)
plt.plot(dT, n, marker = '^', label=Label)
plt.title('Variation of cycle, n with delta T/K')
plt.xlabel('Cycle number, n')
plt.ylabel('Temperature difference, delta_T/ K')
plt.grid()
plt.legend()

#.....Generating the plots for Exergy destruction rate with delta T
#     under different T_high
plt.subplot(2, 1, 2)
plt.plot(dT, η * 100, marker = 's', label=Label)
plt.title('Exergy destruction rate, η/% with delta T/K')
plt.xlabel('Cycle number, n')
plt.ylabel('Exergy destruction rate, n_gen/ %')
plt.grid()
plt.legend()
print('_________________________________Temperature_high: {}__________________________________________'.format(T_high))
print('Thermal storage capacity, Q:\t\t', Q)
print('-------------------------------------------------------------------')
print('Cycle time, t_cycle/hr:\t\t\t', t_cycle/3600)
print('-------------------------------------------------------------------')
print('The thermal storage/release time, t/hr:\n',t/3600)
print('-------------------------------------------------------------------')
print('Exergy destruction rate, ηgen/%:\n',η * 100)
print('-------------------------------------------------------------------')
print('The cycle number of operation, n:\n',n)
```

```
________________________________Temperature_high: 800_________________________________________
Thermal storage capacity, Q:             7831200.0
-------------------------------------------------------------------
Cycle time, t_cycle/hr:                  1.3374485596707817
-------------------------------------------------------------------
The thermal storage/release time, t/hr:
 [20.62982697 17.85940037 15.7539485  14.09972987 12.76574162 11.6672172
 10.74688193  9.96464351  9.29159822  8.70638241  8.19286436  7.73863507
  7.33399294  6.9712436   6.64420634  6.34785933  6.07808016  5.83145313
  5.60512402  5.3966893 ]
-------------------------------------------------------------------
Exergy destruction rate, ηgen/%:
 [1.48766554 1.71843859 1.948101   2.1766575  2.4041128  2.63047154
 2.85573834 3.07991778 3.30301441 3.52503271 3.74597716 3.96585218
 4.18466216 4.40241146 4.6191044  4.83474526 5.04933827 5.26288767
 5.47539763 5.68687228]
-------------------------------------------------------------------
The cycle number of operation, n:
 [15.42476293 13.35333628 11.77910611 10.54225956  9.54484681  8.72348856
  8.03536095  7.4504873   6.94725651  6.50969515  6.12574166  5.78611791
  5.48357011  5.21234522  4.96782197  4.74624559  4.54453378  4.36013264
  4.19090812  4.03506308]
________________________________Temperature_high: 700_________________________________________
Thermal storage capacity, Q:             6271200.0
-------------------------------------------------------------------
Cycle time, t_cycle/hr:                  1.337448559670782
-------------------------------------------------------------------
The thermal storage/release time, t/hr:
 [16.95977768 14.68704262 12.95986144 11.60287812 10.50861639  9.60753279
  8.85263849  8.21104131  7.6590283   7.1790725   6.75793924  6.38544805
  6.05363962  5.75620141  5.4880627   5.24510352  5.02394182  4.82177532
  4.63626239  4.46543115]
-------------------------------------------------------------------
Exergy destruction rate, ηgen/%:
 [1.913274   2.20934211 2.50378462 2.796608   3.08781865 3.37742295
 3.66542718 3.95183759 4.23666037 4.51990166 4.80156754 5.08166404
 5.36019713 5.63717275 5.91259676 6.18647498 6.45881319 6.72961712
 6.99889242 7.26664473]
-------------------------------------------------------------------
The cycle number of operation, n:
 [12.68069531 10.98138879  9.68998871  8.67538272  7.85721164  7.18347836
  6.6190497   6.13933243  5.72659655  5.36773728  5.05285919  4.77435039
  4.52625977  4.30386752  4.10338227  3.92172356  3.75636265  3.60520432
  3.46649773  3.33876852]
________________________________Temperature_high: 600_________________________________________
Thermal storage capacity, Q:             4711200.0
```

```
------------------------------------------------------------------
Cycle time, t_cycle/hr:                  1.337448559670782
------------------------------------------------------------------
The thermal storage/release time, t/hr:
 [13.09297959 11.3449482  10.01658283  8.97299186  8.1314998   7.43861075
  6.85817884  6.36490198  5.94053912  5.57160776  5.24792724  4.96166629
  4.7067023   4.47817938  4.27219695  4.08558574  3.91574417  3.7605166
  3.61810179  3.48698288]
------------------------------------------------------------------
Exergy destruction rate, ηgen/%:
 [2.63757061 3.04396791 3.44764864 3.84862248 4.24689898 4.64248761
 5.03539774 5.42563865 5.81321956 6.19814957 6.58043769 6.96009287
 7.33712396 7.71153972 8.08334884 8.4525599  8.81918143 9.18322185
 9.54468952 9.9035927 ]
------------------------------------------------------------------
The cycle number of operation, n:
 [9.78952012 8.4825305  7.48932193 6.70903699 6.07985985 5.56179204
 5.12780757 4.75898825 4.4416954  4.16584826 3.92383483 3.70979972
 3.5191651  3.34830028 3.19428879 3.05476103 2.92777179 2.81170934
 2.70522688 2.60719028]
________________________________Temperature_high: 500_________________________________________
Thermal storage capacity, Q:             3151200.0
------------------------------------------------------------------
Cycle time, t_cycle/hr:                  1.337448559670782
------------------------------------------------------------------
The thermal storage/release time, t/hr:
 [9.02032348 7.82556416 6.91776806 6.20469944 5.62982673 5.15657073
 4.7602158  4.42346099 4.13383359 3.88211465 3.66134293 3.46616368
 3.29239048 3.13670307 2.99643439 2.86941748 2.7538735  2.6483286
 2.55155119 2.4625042 ]
------------------------------------------------------------------
Exergy destruction rate, ηgen/%:
 [ 4.10944003  4.73684422  5.35844481  5.9742585   6.58430182  7.18859108
  7.78714243  8.3799718   8.96709496  9.54852748 10.12428474 10.69438196
 11.25883416 11.81765618 12.37086269 12.91846818 13.46048695 13.99693316
 14.52782075 15.05316353]
------------------------------------------------------------------
The cycle number of operation, n:
 [6.74442648 5.85111413 5.17236197 4.63920604 4.20937814 3.85552827
 3.55917673 3.30738776 3.09083558 2.90262726 2.73755795 2.59162392
 2.46169503 2.34528875 2.24041094 2.14544138 2.05905004 1.98013492
 1.9077752  1.84119545]
________________________________Temperature_high: 400_________________________________________
Thermal storage capacity, Q:             1591200.0
------------------------------------------------------------------
Cycle time, t_cycle/hr:                  1.337448559670782
```

```
------------------------------------------------------------------
The thermal storage/release time, t/hr:
 [4.750138   4.1372998  3.67203175 3.30691151 3.01287413 2.77111319
 2.56892193 2.39740594 2.25015323 2.1224248  2.01064247 1.91205409
 1.82450822 1.74629881 1.67605569 1.61266586 1.55521592 1.50294931
 1.45523409 1.41153839]
------------------------------------------------------------------
Exergy destruction rate, ηgen/%:
 [ 8.47519812  9.7305882  10.96351104 12.17400601 13.36211167 14.52786585
 15.67130561 16.79246724 17.8913863  18.96809758 20.02263513 21.05503229
 22.06532161 23.05353495 24.01970342 24.9638574  25.88602656 26.78623984
 27.66452545 28.52091091]
------------------------------------------------------------------
The cycle number of operation, n:
 [3.55164164 3.09342724 2.74554989 2.4725523  2.25270281 2.07194001
 1.92076317 1.79252198 1.68242226 1.58692069 1.50334191 1.42962814
 1.36417076 1.30569419 1.25317395 1.20577786 1.16282298 1.12374364
 1.08806734 1.0553964 ]
```





Exergy destruction rate, η/% with delta T/K
T_high = 800
T_high = 700
T_high = 600
T_high = 500
T_high = 400
Exergy destruction rate, n_gen/ %
Cycle number, n
5
10
15
20
25
6
8
10
12
14
16
18
20

In [ ]: