Using Spreadsheets for Analysing the Influence of Bleed Pressure on Rankine Cycle Performance

Pankaj Dumka[1,*], Rishika Chauhan[2], Kritik Rana[1], Krishana Gajula[1], Ashutosh Mishra[3], Amit Kumar Srivastava[3], Dhananjay R. Mishra[1,*]

[1]Department of Mechanical Engineering, Jaypee University of Engineering and Technology, Guna, India

[2]Department of Electronics and Communication Engineering, Jaypee University of Engineering and Technology, Guna, India

[3]Department of Computer Science and Engineering, Jaypee University of Engineering and Technology, Guna, India

([*]Email: p.dumka.ipec@gmail.com, dm30680@gmail.com)

Abstract

The objective of this article is to showcase the capabilities of Microsoft Excel package in simulating the performance of the Rankine cycle with a single bleed point. Thermodynamic properties are derived using specialized Excel tools designed for thermodynamics, with Microsoft Excel serving as the platform for these tools. The obtained properties undergo thorough testing to ensure accuracy, and the results demonstrate strong agreement with those found in other existing literature. Energy balance calculations on each component of the Rankine cycle are conducted to determine the thermodynamic properties at different points. The extraction pressure and the respective mass fraction is being evaluated and analysed to understand the behaviour of the cycle.

Keywords: Rankine cycle, Steam power plant, Steam power cycle, Excel worksheet, thermodynamic analysis, Spreadsheets, Regenerative Rankine cycle, Optimisation

Nomenclature

p	Pressure (kPa)
T	Temperature (°C)
η	Efficiency (%)
Q	Rate of heat interaction (kW)
q	Specific heat interaction (kJ/kg)
x	Fraction of bleed steam
Abbreviations	
MW	Mega watt power output
CEP	Condensate extraction pump
BFP	Boiler feed pump
FWH	Feedwater heater

1. Introduction

The Rankine Cycle stands as a fundamental thermodynamic process extensively applied in power plants for the conversion of heat into mechanical work, thereby generating electricity. Engineers frequently explore various factors impacting the Rankine Cycle's performance in the quest for optimal energy efficiency. Bleed pressure, which involves the extraction of steam at intermediate stages, is a significant consideration [1], [2].

The Rankine Cycle, foundational in steam power generation, encompasses four primary processes: pumping, heat addition, expansion, and heat rejection. Steam turbines play a pivotal role by transforming steam's thermal energy into mechanical work. The introduction of bleed pressure, involving the extraction of steam at specific points, adds a layer of complexity that influences the overall efficiency and productivity of the power plant [3]. The process of heating feed water by the extracted steam prior to the boiler is called regeneration. This technique helps improve the overall efficiency of the power plant by utilizing the bleed steam’s energy to preheat the feed water, reducing the amount of fuel needed to reach the desired temperature in the boiler.

Spreadsheets present a versatile and user-friendly platform for engineers to construct intricate models of complex thermodynamic systems like the Rankine Cycle. Applications such as Microsoft Excel and Google Sheets provide robust computational tools, simplifying the simulation and analysis of how bleed pressure affects key performance parameters [4]. Several researchers have contributed to develop tools for modelling the complex engineering problems in Spreadsheets.

El-hajj et al. [5] introduced a technique for approximating numerical solutions to systems of nonlinear differential equations with a single variable using spreadsheets. Al-Awad [6] developed and reported an Excel Add-In for obtaining Refrigerants Properties and demonstrated their use for the Optimization of Multi-Stage Compression Refrigeration Cycles. Arganbright [7] presented instructional methods that empower educators to incorporate animated graphical displays into their spreadsheet constructions, enhancing mathematical comprehension through compelling demonstrations. Sastry et al. [8] demonstrated the creation of a Microsoft Excel-based Power System Load Flow Analysis tool for system planning and operation. In a separate work, Musti et al. [9] designed a Microsoft Excel-based tool for Power System Static State Estimation. El-Awad [10] introduced an Add-Ins for Microsoft Excel that determines thermodynamic properties for various fluids. Another contribution by El-Awad [11] involved the development of a spreadsheet model using the effectiveness-NTU method. Fellah [12] reported the use of spreadsheets to model a plant on the basis of exergy destruction. This model explicitly considers regenerator design aspects, such as size and overall heat-transfer coefficient. Usage of Excel for the development of Thermal Endurance Test Report has been reported by Tan et al. [13]. Sun eta al. [14] have examined the impact of thermal mass on overheating along with the role of night ventilation using Excel application. Sambaraju [15] presented a detailed methodology to model Gauss-Newton Method for Non-Linear Data with the help of Microsoft Excel.

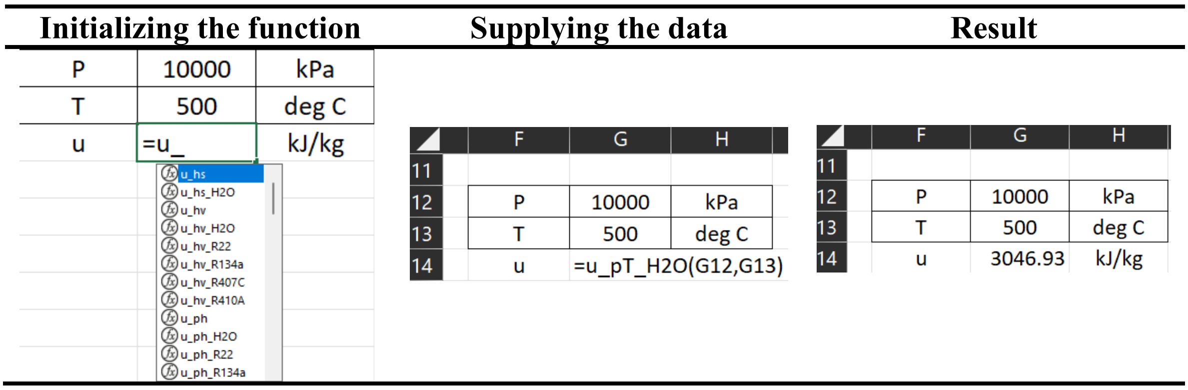
This article explores the practical application of spreadsheets in modelling the consequences of bleed pressure on Rankine Cycle performance, offering an accessible approach for comprehending and refining power plant operations.

2. Steam table Add-In in Excel

To model Rankine cycle, one need to have access of steam tables or properties of pure substances. However, the Microsoft Excel does not inherently contain the thermodynamic properties of water. To include these essential properties for thermodynamic analysis, Add-Ins files must be utilized. The Add-Ins for water properties, called **Thermotables**, can easily be obtained from Excel in ME [16]. Once installed, one can flawlessly utilize the thermodynamic properties of water (or any substance present there).

To verify that the Add-In is functioning as expected, one can check it by evaluating the internal energy of water at a particular temperature and pressure. By writing "= u" in any cell, many functions will automatically come, starting with “u”. Select the one which is having “PT” in it, such as u_PT_H2O (P : for pressure and T: temperature). Then, in the parenthesis, type the appropriate numerical values of P and T (P: kPa and T: °C). Figure 1 demonstrate the use of the Thermotables Add-In.

Figure1: Using the Thermotables Add-In to access steam table data



Initializing the function

P	10000	kPa
T	500	deg C
u	=u_	kJ/kg

Supplying the data

	F	G	H
11			
12	P	10000	kPa
13	T	500	deg C
14	u	=u_pT_H2O(G12,G13)	

Result

	F	G	H
11			
12	P	10000	kPa
13	T	500	deg C
14	u	3046.93	kJ/kg

Remember, for the steam in superheated phase, two property inputs must be taken as in single phase, the degree of freedoms is two. To know the saturation states, only one property will be required, whereas for subcritical liquid, always try to search for the property in based on temperature [2], [17].

3. Plant layout and input data

The Rankine cycle that will be solved in this article will be based on the plant layout as shown in Figure 2. Here in the layout, single bleed is considered, namely the deaerator.

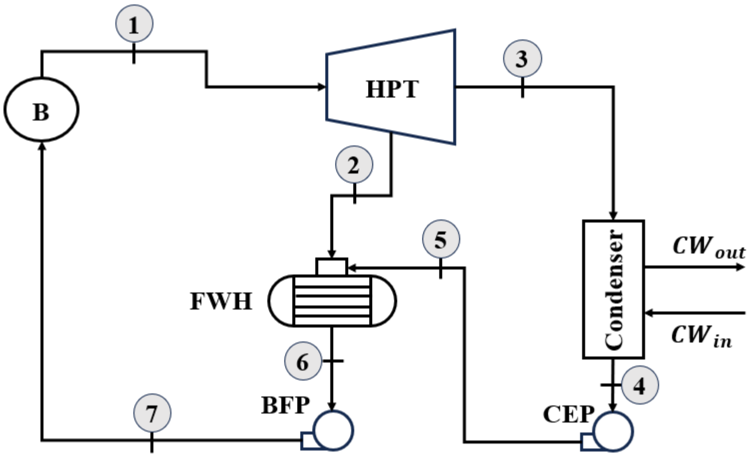


Figure 2: Thermal Power Plant layout

The plant parameters needed to model the plant are shown in Table 1. Here, one can see that the extraction pressure p_2 is given. This is necessary to start the simulation and establish the initial model for the Rankine cycle. Later, the bleed pressure will be varied between the boiler and condenser pressure, and the optimum value of the bleed pressure will be evaluated.

Table 1: TPP operation parameters

Parameter	Numerical value	unit
Turbine inlet pressure (p_1)	12000	kPa
Turbine inlet temperature (T_1)	550	°C
Bleed pressure (p_2)	2000	kPa
Condenser pressure ($p_3 = p_4$)	10	kPa
Turbine efficiency η_t	100	%
Pump efficiency η_p	100	%

4. Mathematical background

The components of the power plant are modelled considering them to be in a steady state, with no changes in the potential and kinetic energy of the fluid across them. Also, there has been no pressure drop across the components. The turbine and deaerator work adiabatically.

- **Boiler**

The boiler receives water from the deaerator and supplies steam to the turbine. Figure 3 shows the schematic of the boiler. In the figure, “1” written along the enthalpies represents the mass fraction of feedwater and steam entering and leaving the boiler.

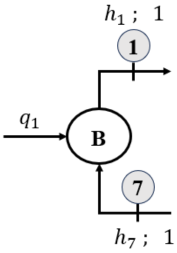


Figure 3: Mass and energy flow across boiler

By applying the first law of thermodynamics (steady flow energy equation -SFEE [2]), one can get the heat transfer to the boiler as shown in Eqn. 1.

$$q_1 = 1 \times (h_1 - h_7) \tag{1}$$

- **Condenser**

Assuming x to be the fraction of steam bleed from the turbine, then the mass fraction of steam received by the condenser will be $(1 - x)$.

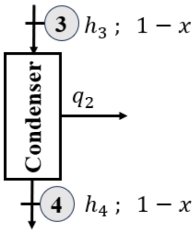


Figure 4: Mass and energy flow across Condenser

Figure 4 shows the schematic of condenser along with mass fractions and enthalpies. By applying the SFEE, the heat loss from the condenser can be obtained as shown in Eqn. 2.

$$Q_2 = (1 - x) \times (h_4 - h_3) \tag{2}$$

- **Turbine**

Figure 5 shows the schematic of mass and energy interactions across the turbine. By applying the SFEE, the work output of the turbine can be obtained as shown in Eqn. 3.

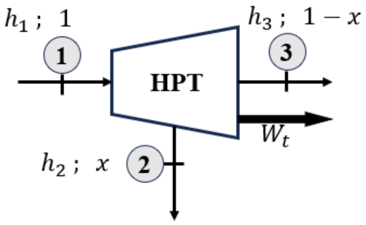


Figure 5: Mass and energy flow across turbine

$$W_t = h_1 - h_2 + (1 - x)(h_2 - h_3) \tag{3}$$

Now, one must be wondering how this expression has come about. The catch to understand this lies in fact that the unit fraction is extracting between points 1 and 2, and from points 2 and 3, $(1 - x)$ is the fraction which expands. Hence, one can think of it as a combination of two HPT turbines, i.e., HPT-1 and HPT-2, as shown in Figure 6.

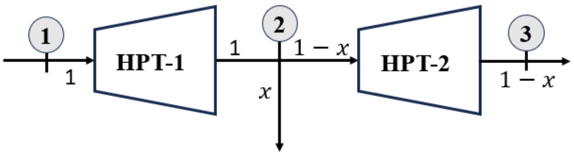


Figure 6: Splitting the turbine based on varying mass fractions

- **Feedwater heater**

Figure 7 shows the schematic of the deaerator (FWH). Applying the energy balance equation, i.e., SFEE, will result in Eqn. 4.

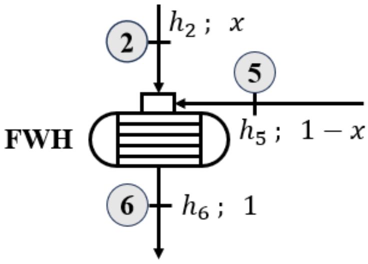


Figure 7: Mass and energy flow across the deaerator

$$xh_2 + (1-x)h_5 = h_6 \tag{4}$$

On simplification, this will result in Eqn. 5, which will be the equation based on which the mass fraction of extraction will be evaluated.

$$x = \frac{h_6 - h_5}{h_2 - h_5} \tag{5}$$

- **Boiler feed pump (BFP) and condensate extraction pump (CEP)**

Figure 8 shows the mass and energy balance across the BFP and CEP. The work input required by them is shown in Eqn. 6 and 7, respectively.

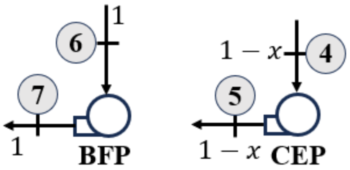


Figure 8: Mass and energy flow across BFP and CEP

$$W_{cep} = (1-x)(h_4 - h_5) \tag{6}$$

$$W_{bfp} = 1 \times (h_6 - h_7) \tag{7}$$

5. Algorithm and data analysis using Excel

Following is the algorithm one should follow to model the Rankine cycle in Excel:

i. Make a table of input data in Excel and label them.
ii. Create columns of states and then assign these states the input data (utilizing Table 1 data in this article).
iii. Step by step, starting from the turbine input to the boiler input, evaluate the enthalpy, entropy, and temperature & pressure (if unknown).
iv. Once the enthalpy and entropy at each point is known, obtain the mass fraction of bleed steam using Eqn. 5.

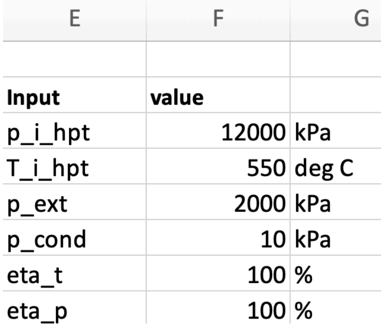
v. Evaluate specific work and heat interactions for the turbine, pumps, condenser, and boiler.

vi. From the given plant capacity (MW power output) evaluate the total mass flow rate of steam ($\dot{m}_s$) exiting the boiler by using Eqn. 8.

vii. Obtain the extraction mass by multiplying $\dot{m}_s$ with the extracted steam fraction. Also, determine the work and heat rates by multiplying the specific quantities with $\dot{m}_s$.

viii. Finally, optimize the extraction mass based on the procedure listed in the next section.

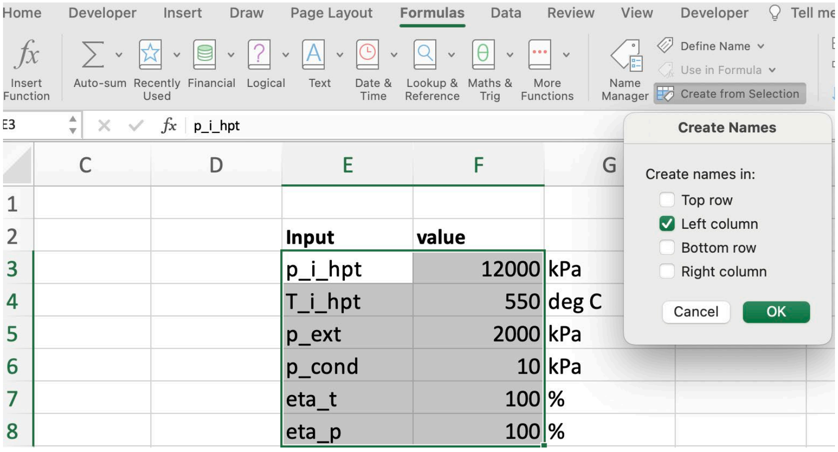
Now, based on the point number (i), a labelled input data is being created. First, write the names of variables (column E) and against them write their numerical values (column F). If one want, units can be included in the next column for better understanding, as shown in Figure 9. Here, p_i_hpt, T_i_hpt, p_ext, p_cond, eta_t, and eta_p represents the turbine inlet pressure, turbine inlet temperature, extraction pressure, condenser pressure, turbine efficiency, and pump efficiency, respectively.



E	F	G
Input	**value**	
p_i_hpt	12000	kPa
T_i_hpt	550	deg C
p_ext	2000	kPa
p_cond	10	kPa
eta_t	100	%
eta_p	100	%

Figure 9: Variable names and the numerical data against them

Now, to label the cells in columns E and F, choose both columns as depicted in Figure 8. Next, navigate to **Formulas,** and in the **Name Manager**, opt for **Create from Selection**. When the form illustrated in Figure 10 appears, check the 'Left column' option. Clicking the 'OK' button will prompt Excel to generate names for the various values in the selection box based on the labels in the left column. Once this is done, then the variables' value can be accesses simply by typing their names after "=".



E3 | fx p_i_hpt

E	F	G
Input	**value**	
p_i_hpt	12000	kPa
T_i_hpt	550	deg C
p_ext	2000	kPa
p_cond	10	kPa
eta_t	100	%
eta_p	100	%

Create Names

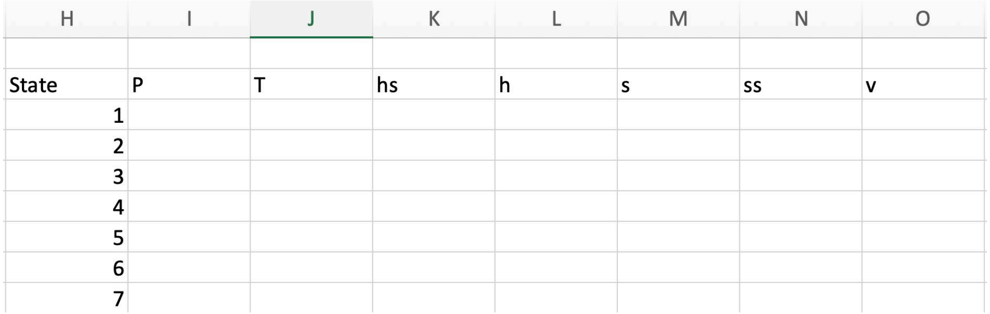
Create names in:

☐ Top row
☑ Left column
☐ Bottom row
☐ Right column

Cancel OK

Figure 10: Label creation by selecting cells

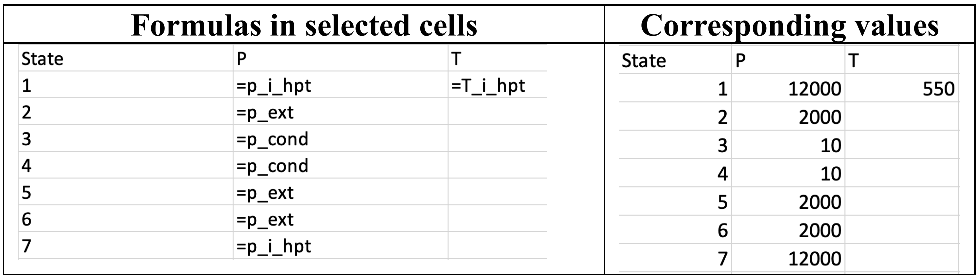
Once the variables are created, in the separate columns, create a list of state numbers as shown in Figure 1 and name the column as “States”. Then, in the next column, give the names of the other parameters such as P, T, hs, h, s, ss, and v. Here, P, T, hs, h, s, ss, and v stands for pressure, temperature, isentropic enthalpy, enthalpy, entropy, isentropic entropy and volume, respectively, as shown in Figure 11.



H	I	J	K	L	M	N	O
State	P	T	hs	h	s	ss	v
1							
2							
3							
4							
5							
6							
7							

Figure 11: Creating state and parameter columns.

Then, as mentioned in point (ii), the input data is assigned to the state (the one which is known), as shown in Figure 12.



Formulas in selected cells

State	P	T
1	=p_i_hpt	=T_i_hpt
2	=p_ext	
3	=p_cond	
4	=p_cond	
5	=p_ext	
6	=p_ext	
7	=p_i_hpt	

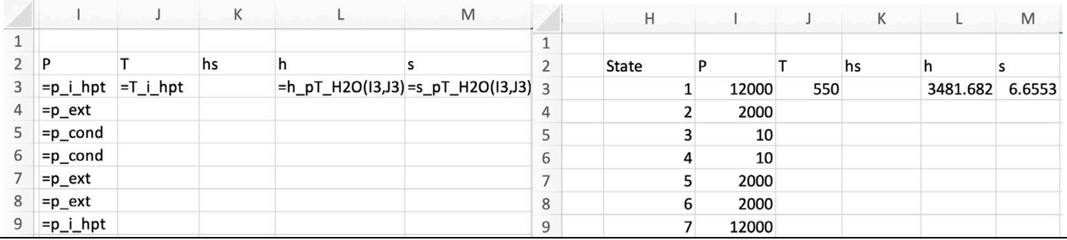
Corresponding values

State	P	T
1	12000	550
2	2000	
3	10	
4	10	
5	2000	
6	2000	
7	12000	

Figure 12: Assigning data to the states.

Then, step by step, one should move from state 1 to state 7 and evaluate the other state variables. Table 2 will explain the process of evaluating missing parameters.

Table 2: Evaluation of missing parameters

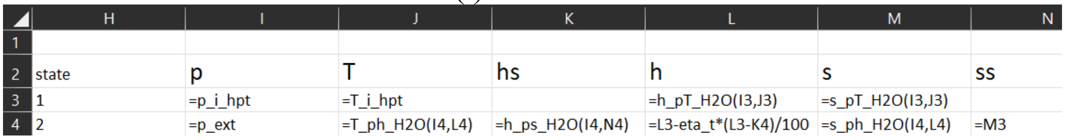
<table>
<tr><th>State</th><th>Parameter evaluation</th></tr>
<tr><td>1</td><td>At this state both the pressure and temperatures are known so the properties are evaluated using Thermotables Add-In with PT as variables.

<table>
<tr><th></th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>P</td><td>T</td><td>hs</td><td>h</td><td>s</td></tr>
<tr><td>3</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td></tr>
<tr><td>4</td><td>=p_ext</td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>=p_cond</td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>=p_cond</td><td></td><td></td><td></td><td></td></tr>
<tr><td>7</td><td>=p_ext</td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>=p_ext</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>=p_i_hpt</td><td></td><td></td><td></td><td></td></tr>
</table>
<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>State</td><td>P</td><td>T</td><td>hs</td><td>h</td><td>s</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.6553</td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>3</td><td>10</td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>4</td><td>10</td><td></td><td></td><td></td><td></td></tr>
<tr><td>7</td><td>5</td><td>2000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>6</td><td>2000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>7</td><td>12000</td><td></td><td></td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>2</td><td>Point 2 is the extraction point. Until this point, the mass fraction will be one. The expiation process has been assumed to be adiabatic and isentropic. The general procedure has been used so that the same spreadsheet can be applied to other values of efficiencies. The procedure to evaluate h, s, and T is as follows:
(a) Set the isentropic entropy at state 2 (ss_2) equal to the entropy of state 1(s_1).
(b) Based on ss_2, evaluate the isentropic enthalpy hs_2.
(c) Use formula for the isentropic efficiency of the turbine to evaluate the actual enthalpy at sate 2. The formula is as follows:</td></tr>
</table>

<table>
<tr><th>State</th><th>Parameter evaluation</th></tr>
<tr><td></td><td>

$$h_2 = h_1 - \eta_t(h_1 - hs_2)/100$$

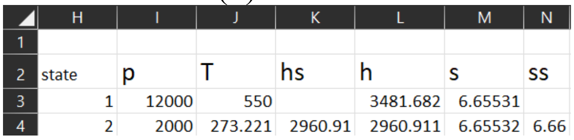
(d) Based on p2 and h2, other parameters will be evaluated as follows:

(i) Formulas



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td></tr>
<tr><td>3</td><td>1</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td><td></td></tr>
<tr><td>4</td><td>2</td><td>=p_ext</td><td>=T_ph_H2O(I4,L4)</td><td>=h_ps_H2O(I4,N4)</td><td>=L3-eta_t*(L3-K4)/100</td><td>=s_ph_H2O(I4,L4)</td><td>=M3</td></tr>
</table>

(ii) Results



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.65531</td><td></td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td>273.221</td><td>2960.91</td><td>2960.911</td><td>6.65532</td><td>6.66</td></tr>
</table>

</td></tr>
<tr><td>3</td><td>

As previously discussed, two turbines will be assumed between points 1 and 3, with separation by the extraction point (refer to Figure 5). Therefore, the procedure will be the same as that for the previous state at point 2. The procedure is as follows:

(a) Set the isentropic entropy at state 3 (ss_3) equal to the entropy of state 2(s_2).

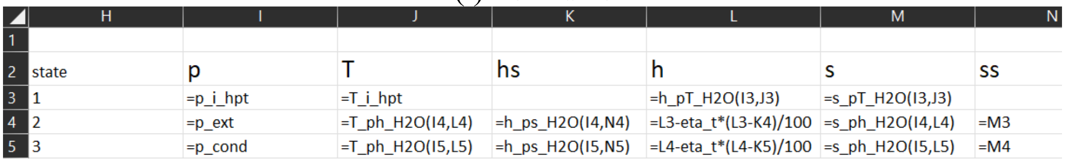
(b) Based on ss_3, evaluate the isentropic enthalpy hs_3.

(c) Use formula for the isentropic efficiency of the turbine to evaluate the actual enthalpy at sate 3. The formula is as follows:

$$h_3 = h_2 - \eta_t(h_2 - hs_3)/100$$

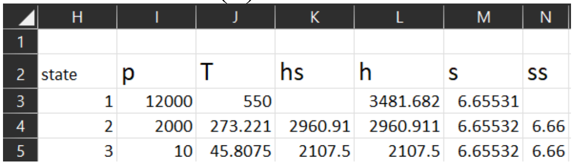
(d) Based on p3 and h3, the other parameters will be evaluated as follows:

(i) Formulas



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td></tr>
<tr><td>3</td><td>1</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td><td></td></tr>
<tr><td>4</td><td>2</td><td>=p_ext</td><td>=T_ph_H2O(I4,L4)</td><td>=h_ps_H2O(I4,N4)</td><td>=L3-eta_t*(L3-K4)/100</td><td>=s_ph_H2O(I4,L4)</td><td>=M3</td></tr>
<tr><td>5</td><td>3</td><td>=p_cond</td><td>=T_ph_H2O(I5,L5)</td><td>=h_ps_H2O(I5,N5)</td><td>=L4-eta_t*(L4-K5)/100</td><td>=s_ph_H2O(I5,L5)</td><td>=M4</td></tr>
</table>

(ii) Results

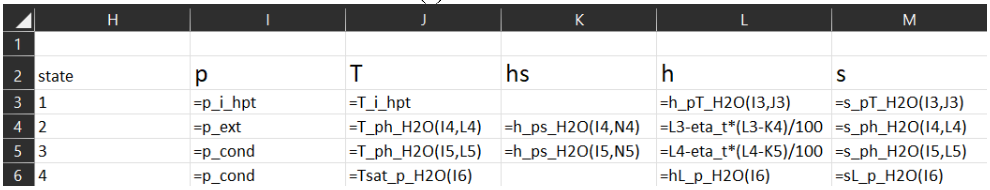


<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.65531</td><td></td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td>273.221</td><td>2960.91</td><td>2960.911</td><td>6.65532</td><td>6.66</td></tr>
<tr><td>5</td><td>3</td><td>10</td><td>45.8075</td><td>2107.5</td><td>2107.5</td><td>6.65532</td><td>6.66</td></tr>
</table>

</td></tr>
<tr><td>4</td><td>

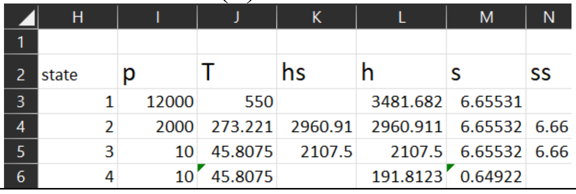
The state 4 is assumed to be saturated liquid, i.e., having dryness fraction zero. So, all the properties at state 4 will be the properties corresponding to saturated liquid state, and the temperature will be the saturation temperature corresponding to the condenser pressure. The applied formulas and results for the state 4 are as follows:

(i) Formulas



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td></tr>
<tr><td>3</td><td>1</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td></tr>
<tr><td>4</td><td>2</td><td>=p_ext</td><td>=T_ph_H2O(I4,L4)</td><td>=h_ps_H2O(I4,N4)</td><td>=L3-eta_t*(L3-K4)/100</td><td>=s_ph_H2O(I4,L4)</td></tr>
<tr><td>5</td><td>3</td><td>=p_cond</td><td>=T_ph_H2O(I5,L5)</td><td>=h_ps_H2O(I5,N5)</td><td>=L4-eta_t*(L4-K5)/100</td><td>=s_ph_H2O(I5,L5)</td></tr>
<tr><td>6</td><td>4</td><td>=p_cond</td><td>=Tsat_p_H2O(I6)</td><td></td><td>=hL_p_H2O(I6)</td><td>=sL_p_H2O(I6)</td></tr>
</table>

(ii) Results



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.65531</td><td></td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td>273.221</td><td>2960.91</td><td>2960.911</td><td>6.65532</td><td>6.66</td></tr>
<tr><td>5</td><td>3</td><td>10</td><td>45.8075</td><td>2107.5</td><td>2107.5</td><td>6.65532</td><td>6.66</td></tr>
<tr><td>6</td><td>4</td><td>10</td><td>45.8075</td><td></td><td>191.8123</td><td>0.64922</td><td></td></tr>
</table>

</td></tr>
</table>

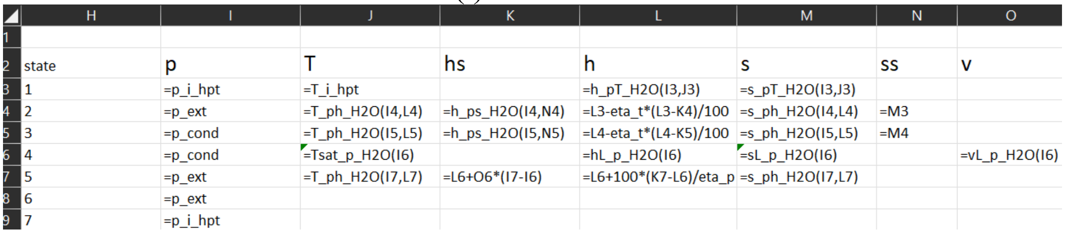
<table>
<tr><th>State</th><th>Parameter evaluation</th></tr>
<tr><td>5</td><td>
State 5 represents the exit of the CEP, characterized by subcooled liquid. However, the issue arises as only the pressure is known, and the pump efficiency must also be considered. The procedure to evaluate the final h, s, and T for the pump exit is as follows:
(a) Evaluate the specific volume of the saturated liquid at point 4 (v_4).
(b) Evaluate the isentropic enthalpy (h_{s5}) at the exit of CEP by using the formula shown below:

$$h_{s5} = h_4 + \eta_p(p_5 - p_4)$$

(c) Then evaluate the actual enthalpy considering pump efficiency based on the following formula:

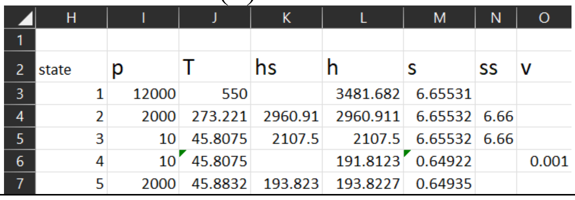
$$h_5 = h_4 + (h_{s5} - h_4)/\eta_p$$

(d) Based on p5 and h5, the other parameters will be evaluated as follows:
(i) Formulas

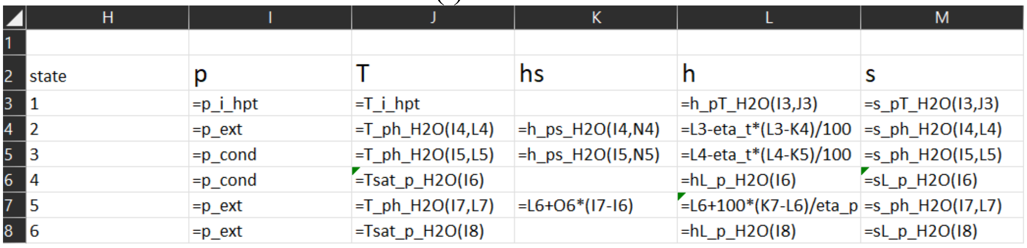


<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th><th>O</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td><td>v</td></tr>
<tr><td>3</td><td>1</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td><td></td><td></td></tr>
<tr><td>4</td><td>2</td><td>=p_ext</td><td>=T_ph_H2O(I4,L4)</td><td>=h_ps_H2O(I4,N4)</td><td>=L3-eta_t*(L3-K4)/100</td><td>=s_ph_H2O(I4,L4)</td><td>=M3</td><td></td></tr>
<tr><td>5</td><td>3</td><td>=p_cond</td><td>=T_ph_H2O(I5,L5)</td><td>=h_ps_H2O(I5,N5)</td><td>=L4-eta_t*(L4-K5)/100</td><td>=s_ph_H2O(I5,L5)</td><td>=M4</td><td></td></tr>
<tr><td>6</td><td>4</td><td>=p_cond</td><td>=Tsat_p_H2O(I6)</td><td></td><td>=hL_p_H2O(I6)</td><td>=sL_p_H2O(I6)</td><td></td><td>=vL_p_H2O(I6)</td></tr>
<tr><td>7</td><td>5</td><td>=p_ext</td><td>=T_ph_H2O(I7,L7)</td><td>=L6+O6*(I7-I6)</td><td>=L6+100*(K7-L6)/eta_p</td><td>=s_ph_H2O(I7,L7)</td><td></td><td></td></tr>
<tr><td>8</td><td>6</td><td>=p_ext</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>7</td><td>=p_i_hpt</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

(ii) Results

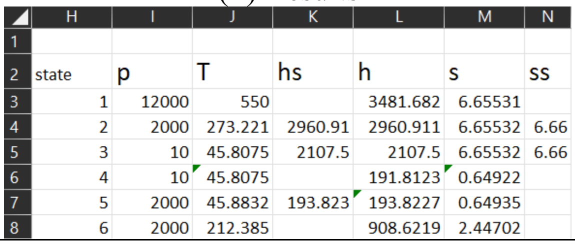


<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th><th>O</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td><td>v</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.65531</td><td></td><td></td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td>273.221</td><td>2960.91</td><td>2960.911</td><td>6.65532</td><td>6.66</td><td></td></tr>
<tr><td>5</td><td>3</td><td>10</td><td>45.8075</td><td>2107.5</td><td>2107.5</td><td>6.65532</td><td>6.66</td><td></td></tr>
<tr><td>6</td><td>4</td><td>10</td><td>45.8075</td><td></td><td>191.8123</td><td>0.64922</td><td></td><td>0.001</td></tr>
<tr><td>7</td><td>5</td><td>2000</td><td>45.8832</td><td>193.823</td><td>193.8227</td><td>0.64935</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>6</td><td>
Point 6 is the exit of deaerator, which is saturated liquid corresponding to the bleed pressure ($p_2 = p_6$). Therefore, all the properties will be evaluated as the saturation liquid properties based on the bleed pressure. The formulas and values are as follows:
(i) Formulas



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td></tr>
<tr><td>3</td><td>1</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td></tr>
<tr><td>4</td><td>2</td><td>=p_ext</td><td>=T_ph_H2O(I4,L4)</td><td>=h_ps_H2O(I4,N4)</td><td>=L3-eta_t*(L3-K4)/100</td><td>=s_ph_H2O(I4,L4)</td></tr>
<tr><td>5</td><td>3</td><td>=p_cond</td><td>=T_ph_H2O(I5,L5)</td><td>=h_ps_H2O(I5,N5)</td><td>=L4-eta_t*(L4-K5)/100</td><td>=s_ph_H2O(I5,L5)</td></tr>
<tr><td>6</td><td>4</td><td>=p_cond</td><td>=Tsat_p_H2O(I6)</td><td></td><td>=hL_p_H2O(I6)</td><td>=sL_p_H2O(I6)</td></tr>
<tr><td>7</td><td>5</td><td>=p_ext</td><td>=T_ph_H2O(I7,L7)</td><td>=L6+O6*(I7-I6)</td><td>=L6+100*(K7-L6)/eta_p</td><td>=s_ph_H2O(I7,L7)</td></tr>
<tr><td>8</td><td>6</td><td>=p_ext</td><td>=Tsat_p_H2O(I8)</td><td></td><td>=hL_p_H2O(I8)</td><td>=sL_p_H2O(I8)</td></tr>
</table>

(ii) Results



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.65531</td><td></td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td>273.221</td><td>2960.91</td><td>2960.911</td><td>6.65532</td><td>6.66</td></tr>
<tr><td>5</td><td>3</td><td>10</td><td>45.8075</td><td>2107.5</td><td>2107.5</td><td>6.65532</td><td>6.66</td></tr>
<tr><td>6</td><td>4</td><td>10</td><td>45.8075</td><td></td><td>191.8123</td><td>0.64922</td><td></td></tr>
<tr><td>7</td><td>5</td><td>2000</td><td>45.8832</td><td>193.823</td><td>193.8227</td><td>0.64935</td><td></td></tr>
<tr><td>8</td><td>6</td><td>2000</td><td>212.385</td><td></td><td>908.6219</td><td>2.44702</td><td></td></tr>
</table>
</td></tr>
<tr><td>7</td><td>
State 7 is the exit of BFP. Here also the same methodology will be used as that of point 5. Therefore, the procedure is as follows:
(a) Evaluate the specific volume of the saturated liquid at point 6 (v_6).
(b) Evaluate the isentropic enthalpy (h_{s7}) at the exit of BFP by using the formula shown below:
</td></tr>
</table>

<table>
<tr><th>State</th><th>Parameter evaluation</th></tr>
<tr><td></td><td>

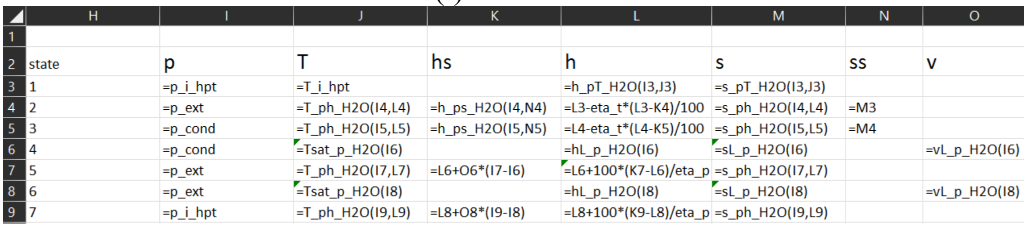
$$h_{s7} = h_6 + \eta_p (p_7 - p_6)$$

(c) Then evaluate the actual enthalpy considering pump efficiency based on the following formula:

$$h_7 = h_6 + (h_{s7} - h_6)/\eta_p$$

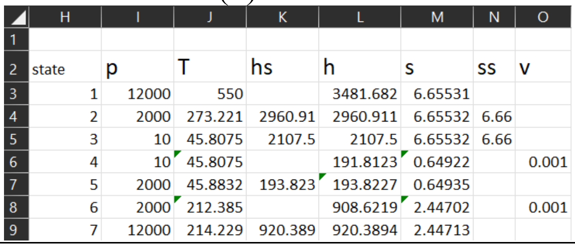
(d) Based on p7 and h7, the other parameters will be evaluated as follows:

(i) Formulas



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th><th>O</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td><td>v</td></tr>
<tr><td>3</td><td>1</td><td>=p_i_hpt</td><td>=T_i_hpt</td><td></td><td>=h_pT_H2O(I3,J3)</td><td>=s_pT_H2O(I3,J3)</td><td></td><td></td></tr>
<tr><td>4</td><td>2</td><td>=p_ext</td><td>=T_ph_H2O(I4,L4)</td><td>=h_ps_H2O(I4,N4)</td><td>=L3-eta_t*(L3-K4)/100</td><td>=s_ph_H2O(I4,L4)</td><td>=M3</td><td></td></tr>
<tr><td>5</td><td>3</td><td>=p_cond</td><td>=T_ph_H2O(I5,L5)</td><td>=h_ps_H2O(I5,N5)</td><td>=L4-eta_t*(L4-K5)/100</td><td>=s_ph_H2O(I5,L5)</td><td>=M4</td><td></td></tr>
<tr><td>6</td><td>4</td><td>=p_cond</td><td>=Tsat_p_H2O(I6)</td><td></td><td>=hL_p_H2O(I6)</td><td>=sL_p_H2O(I6)</td><td></td><td>=vL_p_H2O(I6)</td></tr>
<tr><td>7</td><td>5</td><td>=p_ext</td><td>=T_ph_H2O(I7,L7)</td><td>=L6+O6*(I7-I6)</td><td>=L6+100*(K7-L6)/eta_p</td><td>=s_ph_H2O(I7,L7)</td><td></td><td></td></tr>
<tr><td>8</td><td>6</td><td>=p_ext</td><td>=Tsat_p_H2O(I8)</td><td></td><td>=hL_p_H2O(I8)</td><td>=sL_p_H2O(I8)</td><td></td><td>=vL_p_H2O(I8)</td></tr>
<tr><td>9</td><td>7</td><td>=p_i_hpt</td><td>=T_ph_H2O(I9,L9)</td><td>=L8+O8*(I9-I8)</td><td>=L8+100*(K9-L8)/eta_p</td><td>=s_ph_H2O(I9,L9)</td><td></td><td></td></tr>
</table>

(ii) Results



<table>
<tr><th></th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th><th>M</th><th>N</th><th>O</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>state</td><td>p</td><td>T</td><td>hs</td><td>h</td><td>s</td><td>ss</td><td>v</td></tr>
<tr><td>3</td><td>1</td><td>12000</td><td>550</td><td></td><td>3481.682</td><td>6.65531</td><td></td><td></td></tr>
<tr><td>4</td><td>2</td><td>2000</td><td>273.221</td><td>2960.91</td><td>2960.911</td><td>6.65532</td><td>6.66</td><td></td></tr>
<tr><td>5</td><td>3</td><td>10</td><td>45.8075</td><td>2107.5</td><td>2107.5</td><td>6.65532</td><td>6.66</td><td></td></tr>
<tr><td>6</td><td>4</td><td>10</td><td>45.8075</td><td></td><td>191.8123</td><td>0.64922</td><td></td><td>0.001</td></tr>
<tr><td>7</td><td>5</td><td>2000</td><td>45.8832</td><td>193.823</td><td>193.8227</td><td>0.64935</td><td></td><td></td></tr>
<tr><td>8</td><td>6</td><td>2000</td><td>212.385</td><td></td><td>908.6219</td><td>2.44702</td><td></td><td>0.001</td></tr>
<tr><td>9</td><td>7</td><td>12000</td><td>214.229</td><td>920.389</td><td>920.3894</td><td>2.44713</td><td></td><td></td></tr>
</table>

</td></tr>
</table>

Before proceeding to the next phase of analysis, one may be interested in drawing T-s diagram of the cycle. To draw it, three more points will be required: saturated vapour state corresponding to the extraction pressure and saturated liquid and vapour states corresponding to the turbine inlet (or boiler) pressures. Figure 13 shows how this T-s diagram should look ideally.

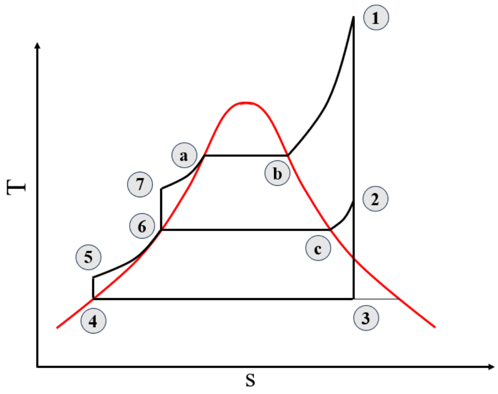
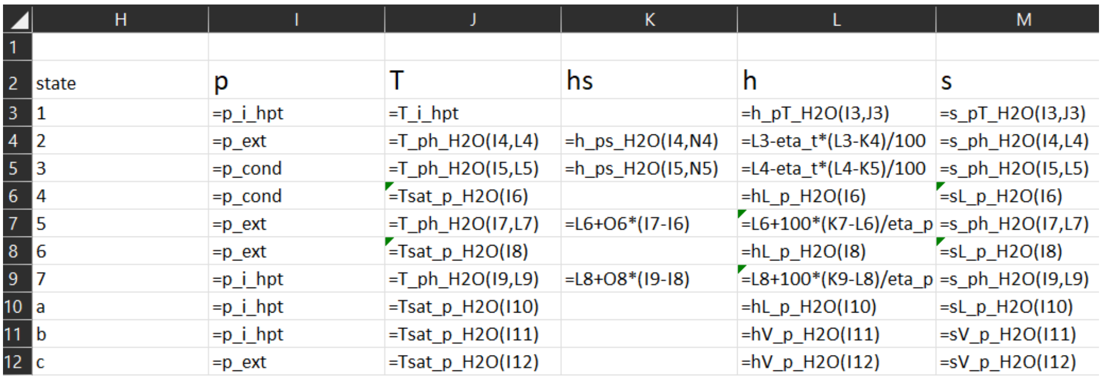


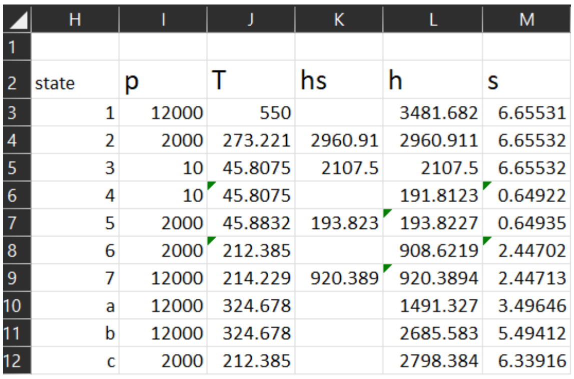
Figure 13: Theoretical T-s diagram.

In the diagram, one can observe those extra points, namely a, b, and c. Therefore, in the main Excel sheet, these points are added, and the corresponding state variables are evaluated, as shown in Figure 14 (a) and 14 (b).



	H	I	J	K	L	M
1						
2	state	p	T	hs	h	s
3	1	=p_i_hpt	=T_i_hpt		=h_pT_H2O(I3,J3)	=s_pT_H2O(I3,J3)
4	2	=p_ext	=T_ph_H2O(I4,L4)	=h_ps_H2O(I4,N4)	=L3-eta_t*(L3-K4)/100	=s_ph_H2O(I4,L4)
5	3	=p_cond	=T_ph_H2O(I5,L5)	=h_ps_H2O(I5,N5)	=L4-eta_t*(L4-K5)/100	=s_ph_H2O(I5,L5)
6	4	=p_cond	=Tsat_p_H2O(I6)		=hL_p_H2O(I6)	=sL_p_H2O(I6)
7	5	=p_ext	=T_ph_H2O(I7,L7)	=L6+O6*(I7-I6)	=L6+100*(K7-L6)/eta_p	=s_ph_H2O(I7,L7)
8	6	=p_ext	=Tsat_p_H2O(I8)		=hL_p_H2O(I8)	=sL_p_H2O(I8)
9	7	=p_i_hpt	=T_ph_H2O(I9,L9)	=L8+O8*(I9-I8)	=L8+100*(K9-L8)/eta_p	=s_ph_H2O(I9,L9)
10	a	=p_i_hpt	=Tsat_p_H2O(I10)		=hL_p_H2O(I10)	=sL_p_H2O(I10)
11	b	=p_i_hpt	=Tsat_p_H2O(I11)		=hV_p_H2O(I11)	=sV_p_H2O(I11)
12	c	=p_ext	=Tsat_p_H2O(I12)		=hV_p_H2O(I12)	=sV_p_H2O(I12)

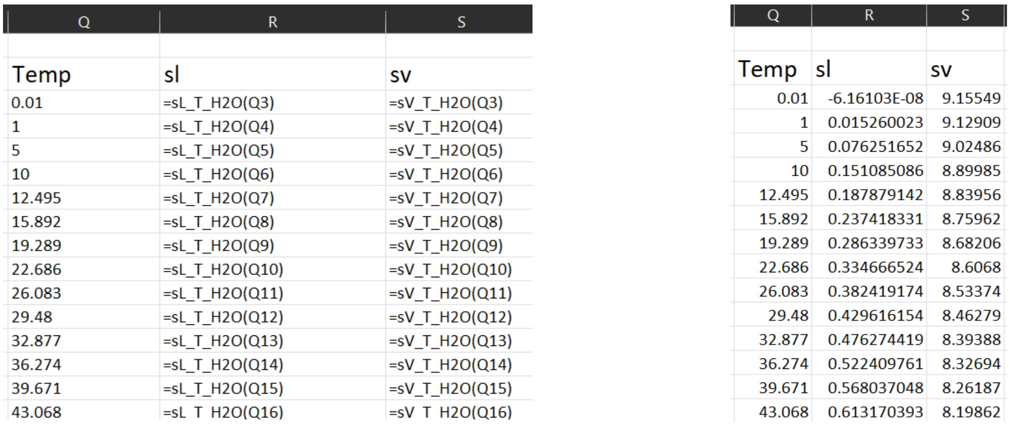
Figure 14 (a): Formulas for the states a, b, and c



	H	I	J	K	L	M
1						
2	state	p	T	hs	h	s
3	1	12000	550		3481.682	6.65531
4	2	2000	273.221	2960.91	2960.911	6.65532
5	3	10	45.8075	2107.5	2107.5	6.65532
6	4	10	45.8075		191.8123	0.64922
7	5	2000	45.8832	193.823	193.8227	0.64935
8	6	2000	212.385		908.6219	2.44702
9	7	12000	214.229	920.389	920.3894	2.44713
10	a	12000	324.678		1491.327	3.49646
11	b	12000	324.678		2685.583	5.49412
12	c	2000	212.385		2798.384	6.33916

Figure 14 (b): Numerical values corresponding to the state variables

Now, to draw the T-s diagram, first the saturation entropies are to be evaluated corresponding to the temperatures varying from the triple point to the critical point of water. Once that is done, then using Scatter plot, one can easily draw the vapour dome, as shown in Figure 15.

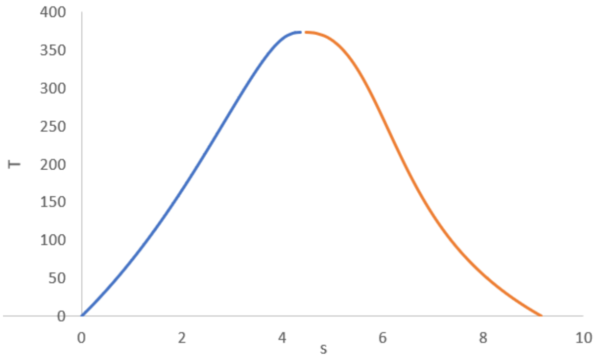


Q	R	S
Temp	sl	sv
0.01	=sL_T_H2O(Q3)	=sV_T_H2O(Q3)
1	=sL_T_H2O(Q4)	=sV_T_H2O(Q4)
5	=sL_T_H2O(Q5)	=sV_T_H2O(Q5)
10	=sL_T_H2O(Q6)	=sV_T_H2O(Q6)
12.495	=sL_T_H2O(Q7)	=sV_T_H2O(Q7)
15.892	=sL_T_H2O(Q8)	=sV_T_H2O(Q8)
19.289	=sL_T_H2O(Q9)	=sV_T_H2O(Q9)
22.686	=sL_T_H2O(Q10)	=sV_T_H2O(Q10)
26.083	=sL_T_H2O(Q11)	=sV_T_H2O(Q11)
29.48	=sL_T_H2O(Q12)	=sV_T_H2O(Q12)
32.877	=sL_T_H2O(Q13)	=sV_T_H2O(Q13)
36.274	=sL_T_H2O(Q14)	=sV_T_H2O(Q14)
39.671	=sL_T_H2O(Q15)	=sV_T_H2O(Q15)
43.068	=sL_T_H2O(Q16)	=sV_T_H2O(Q16)

(a) Saturation property formula

Q	R	S
Temp	sl	sv
0.01	-6.16103E-08	9.15549
1	0.015260023	9.12909
5	0.076251652	9.02486
10	0.151085086	8.89985
12.495	0.187879142	8.83956
15.892	0.237418331	8.75962
19.289	0.286339733	8.68206
22.686	0.334666524	8.6068
26.083	0.382419174	8.53374
29.48	0.429616154	8.46279
32.877	0.476274419	8.39388
36.274	0.522409761	8.32694
39.671	0.568037048	8.26187
43.068	0.613170393	8.19862

(b) Property values



(c) T-s diagram

Figure 15: drawing T-s diagram from the saturation properties

Now one must start adding data to this plot considering the states: 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, 7-a, a-b, b-1, 6-c, and c-2. The final T-s diagram from the data is shown in Figure 16.

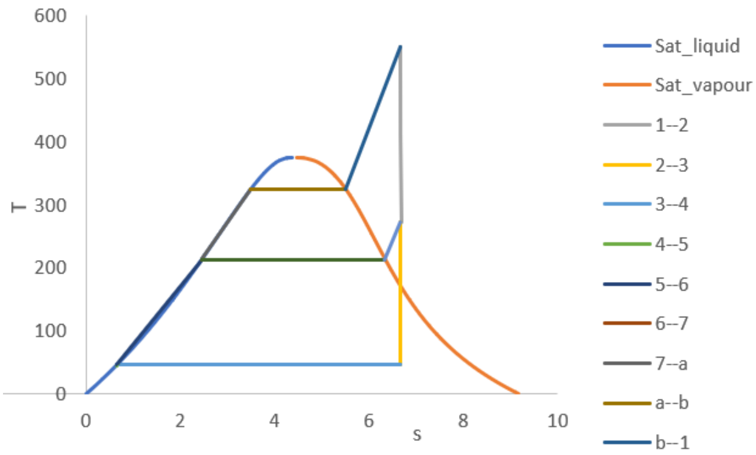


Figure 16: T-s diagram based on the evaluated data

In the T-s plot above, the CEP and BFP lines, i.e., 4-5 and 6-7, are not visible. This is since the magnitude of pump work is negligible in comparison to the turbine work and hence cannot be seen in the original T-s plot.

6. Results and discussions

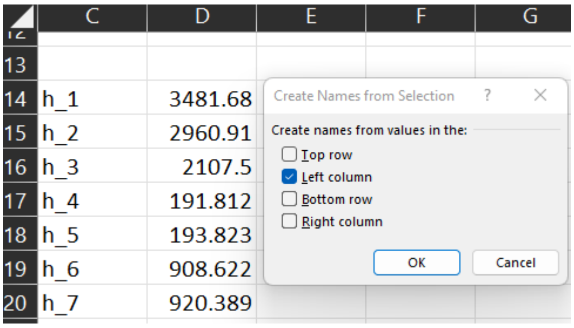
Once the pressure and temperature at every point is known, further analysis can be done. First, the full table containing all the data points is presented, as shown in Table 3.

Table 3: Properties at different state points of the cycle

State	**P**(kPa)	**T**(°C)	**h**(kJ/kg)	**s**(kJ/kg-K)
1	12000	550	3481.682	6.655311
2	2000	273.2205	2960.911	6.655316
3	10	45.80755	2107.5	6.655316
4	10	45.80755	191.8123	0.649218
5	2000	45.88317	193.8227	0.649347
6	2000	212.3845	908.6219	2.447024
7	12000	214.2288	920.3894	2.447133
a	12000	324.6783	1491.327	3.496459

State	**P**(kPa)	**T**(°C)	**h**(kJ/kg)	**s**(kJ/kg-K)
b	12000	324.6783	2685.583	5.494116
c	2000	212.3845	2798.384	6.339164

Now, as all the data points are known, the first thing to evaluate is the fraction of bleed taken for deaerator. As the enthalpy values will be required, one can the labels for enthalpies starting at h_1 and ending at h_2, as shown in Figure 17.



	C	D
13		
14	h_1	3481.68
15	h_2	2960.91
16	h_3	2107.5
17	h_4	191.812
18	h_5	193.823
19	h_6	908.622
20	h_7	920.389

Create Names from Selection

Create names from values in the:

☐ Top row
☑ Left column
☐ Bottom row
☐ Right column

Figure 17: Labelling enthalpies

Now, using Eqn. 5, the bleed fraction obtained is a shown in Figure 18. Thereafter, make a label for x as well.

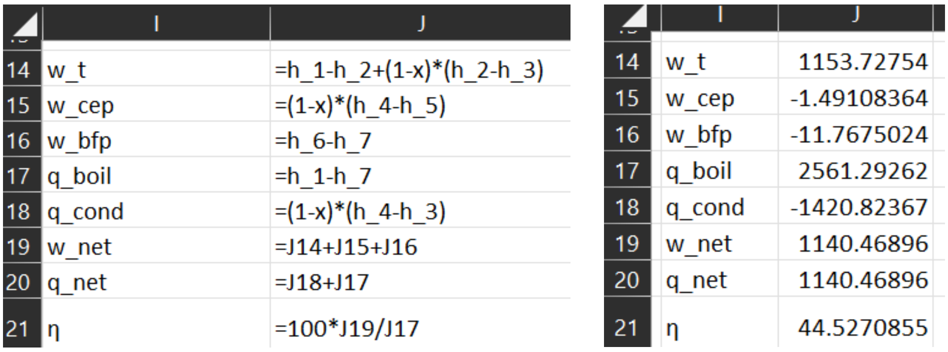
x	=(h_6-h_5)/(h_2-h_5)

x	0.25832

(a) Formula (b) Numerical magnitude

Figure 18: Evaluation of bleed to deaerator

Then, the specific work and heat interactions, along with the cycle efficiency, will be evaluated based on the formulas mentioned in the previous section. The solution procedure is shown in Figure 19.



	I	J
14	w_t	=h_1-h_2+(1-x)*(h_2-h_3)
15	w_cep	=(1-x)*(h_4-h_5)
16	w_bfp	=h_6-h_7
17	q_boil	=h_1-h_7
18	q_cond	=(1-x)*(h_4-h_3)
19	w_net	=J14+J15+J16
20	q_net	=J18+J17
21	η	=100*J19/J17

	I	J
14	w_t	1153.72754
15	w_cep	-1.49108364
16	w_bfp	-11.7675024
17	q_boil	2561.29262
18	q_cond	-1420.82367
19	w_net	1140.46896
20	q_net	1140.46896
21	η	44.5270855

(a) Formula (b) Numerical magnitude

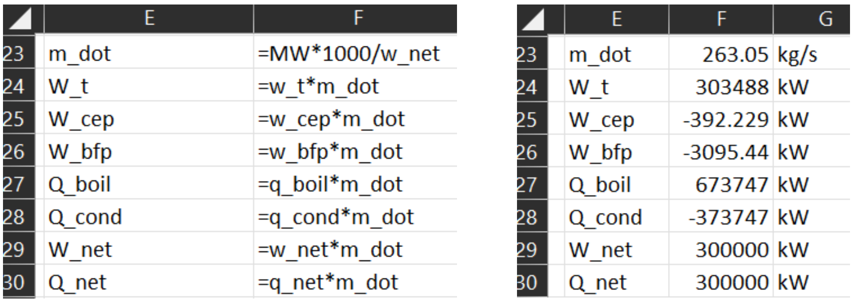
Figure 19: Solving for specific quantities

One can observe that CEP, BFP, and condenser energy interactions are negative. This is due to the sign convention which we have taken, i.e., heat added to the system and work done by the system are positive, else negative. Here, the net heat and work interactions are evaluated purposely to check whether they are equal or not. If they are not equal, that means the calculations are wrong. For further calculations, the specific quantities are also labelled.

Now, to obtain rate of heat and work interaction, one should use the net MW power output of plant. For the sake of analysis, assume it to be 300 MW. Then, the total mass flow rate of steam from the boiler can be obtained by dividing 300 MW by the net specific work output, as shown in Eqn. 8.

$$\dot{m} = MW \times \frac{10^3}{w_{net}} = 300 \times \frac{10^3}{1140.4689} = 263.05\ \text{kg/s} \tag{8}$$

The heat and work rates obtained from the cycle are shown in Figure 20 via the calculation procedure.



	E	F
23	m_dot	=MW*1000/w_net
24	W_t	=w_t*m_dot
25	W_cep	=w_cep*m_dot
26	W_bfp	=w_bfp*m_dot
27	Q_boil	=q_boil*m_dot
28	Q_cond	=q_cond*m_dot
29	W_net	=w_net*m_dot
30	Q_net	=q_net*m_dot

(a) Formula

	E	F	G
23	m_dot	263.05	kg/s
24	W_t	303488	kW
25	W_cep	-392.229	kW
26	W_bfp	-3095.44	kW
27	Q_boil	673747	kW
28	Q_cond	-373747	kW
29	W_net	300000	kW
30	Q_net	300000	kW

(b) Numerical magnitude

Figure 20: Solving for rate of energy interactions

To optimize the bleed, the best method is to use the **Solver** tool. But before that is explained, let us see how the efficiency and work output vary with the bleed pressure. For that matter, a laborious effort has been made to evaluate the efficiency and net specific work output as a function of bleed pressure. The results of the computations is shared in the Table 4.

Table 4: Tabulation of efficiency and specific work as a function of bleed pressure

S. No.	p_ext	eta	Net specific work	S. No.	p_ext	eta	Net specific work
1	12000	41.555	827.094	19	3000	44.2819	1090.38
2	11500	41.71	838.372	20	2500	44.4122	1114
3	11000	41.865	849.831	21	2000	44.5271	1140.47
4	10500	42.0198	861.493	22	1500	44.6133	1171.03
5	10000	42.1739	873.383	23	1000	44.6364	1208.13
6	9500	42.3277	885.529	24	900	44.6261	1216.74
7	9000	42.4812	897.958	25	800	44.6085	1225.92
8	8500	42.6346	910.708	26	700	44.5811	1235.8
9	8000	42.7878	923.815	27	600	44.5415	1246.55
10	7500	42.9408	937.324	28	500	44.4845	1258.44
11	7000	43.0937	951.286	29	400	44.4008	1271.81
12	6500	43.2464	965.763	30	300	44.2721	1287.29
13	6000	43.3987	980.826	31	200	44.0554	1306.02
14	5500	43.5505	996.562	32	100	43.6031	1330.69
15	5000	43.7015	1013.08	33	80	43.43832	1336.89
16	4500	43.8511	1030.51	34	60	43.21371	1343.74
17	4000	43.9986	1049.03	35	40	42.87553	1351.37
18	3500	44.1427	1068.88	36	10	41.555	1362.07

Now, once the real picture is plotted, it will come into play. Therefore, Figure 21 presents a scatter plot of the variation of cycle efficiency and net specific work output as a function of bleed pressure.

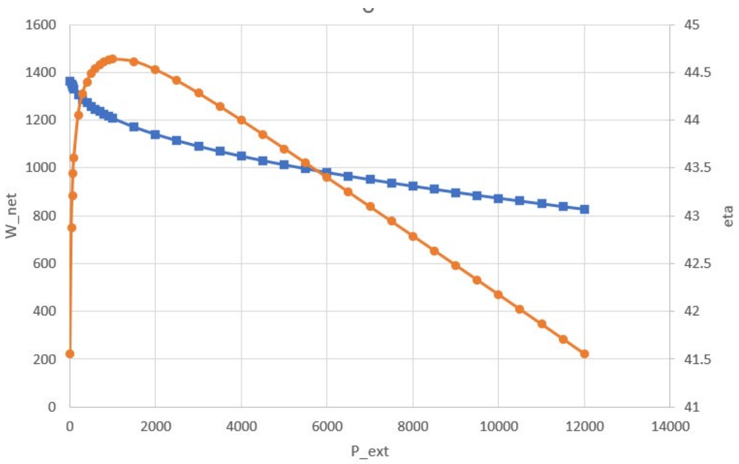


Figure 21: Variation of efficiency and specific work as a function of bleed pressure

Here, orange graph represents the efficiency, and the blue one is the representative of net specific work. One can observe that the cycle efficiency increases with the bleed pressure and attains a maximum value for a bleed pressure between 1000 and 1100 kPa. Whereas the work continuously increases with the reduction in the bleed pressure. This is due to the fact that as the bleed pressure reduces, the mass fraction of steam expanding in the turbine will increase. One can also observe that regeneration increases the cycle efficiency. However, since more steam is utilized for feedwater heating, the work output of the turbine decreases. Therefore, the gain in efficiency comes at the cost of sacrificing turbine work, as with no regeneration, the turbine work is maximum.

Now let’s dive into the real power of Excel. The same laborious task can easily be done by using **Solver**. To access **Solver**, go to **Data** tab and then **Solver** as shown in Figure 22. One can find the solver at the extreme right on this window.

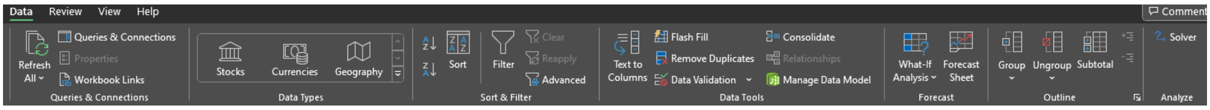
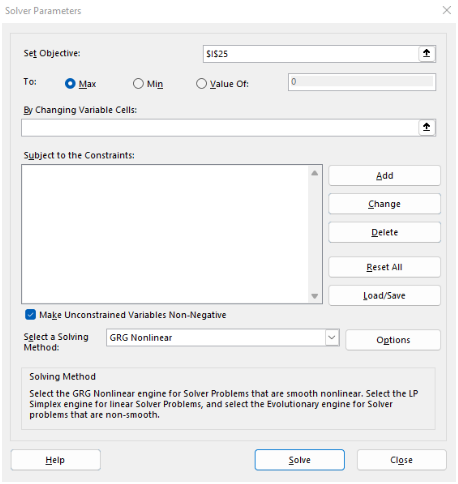


Figure 22: Solver in Data tab

The moment one clicks on **Solver**, the **Solver** Parameter window will appear, as shown in Figure 23.



Set Objective: I25

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells:

Subject to the Constraints:

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

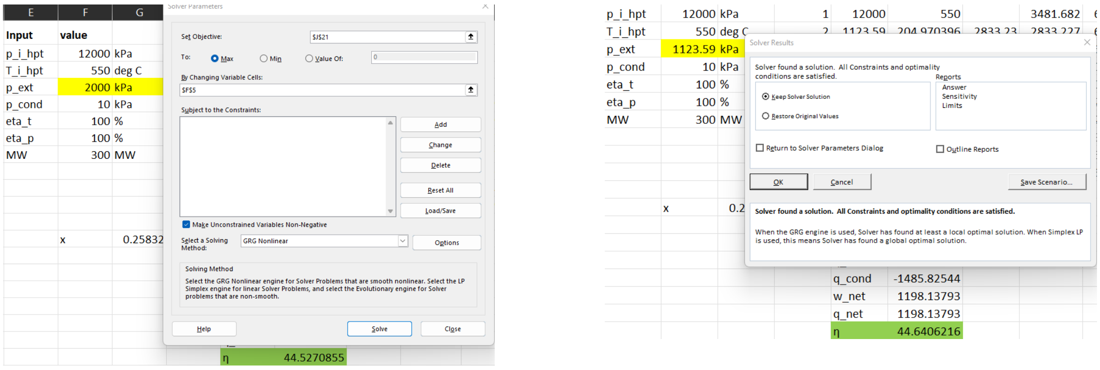
Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Figure 23: Solver parameter window

To optimize, the following steps are to be performed:

- Go to the **Set objective** portion and select the cell you want to optimize.
- Then, in the **By Changing Variable Cells** section, select the cell against which the optimization must be done, i.e., the variable you want to vary to get the optimized result.
- **Solver** must be selected, by default GRG Nonlinear is there, which is sufficient for our case.
- Click **Solve**, and the cells whose value is to be optimized and the one which is varied to do so both will be updated in no time.

In this problem of Rankine cycle optimization, the efficiency cell will be selected for **Set objective** and p_ext will be the variable whose value is being changed. Figure 24 (a) and 24 (b) demonstrates the operation of optimization. For better understanding, the efficiency and p_ext cells are highlighted with the green and yellow colour, respectively.



Input	value	
p_i_hpt	12000	kPa
T_i_hpt	550	deg C
p_ext	2000	kPa
p_cond	10	kPa
eta_t	100	%
eta_p	100	%
MW	300	MW
	x	0.25832

Set Objective: J21

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells: F5

Subject to the Constraints:

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

η	44.5270855

(a) Input phase

p_i_hpt	12000	kPa	1	12000	550		3481.682
T_i_hpt	550	deg C	2	1123.59	204.970396	2833.23	2833.227
p_ext	1123.59	kPa					
p_cond	10	kPa					
eta_t	100	%					
eta_p	100	%					
MW	300	MW					

Solver found a solution. All Constraints and optimality conditions are satisfied.

● Keep Solver Solution

○ Restore Original Values

Reports

Answer

Sensitivity

Limits

☐ Return to Solver Parameters Dialog

☐ Outline Reports

Solver found a solution. All Constraints and optimality conditions are satisfied.

When the GRG engine is used, Solver has found at least a local optimal solution. When Simplex LP is used, this means Solver has found a global optimal solution.

q_cond	-1485.82544
w_net	1198.13793
q_net	1198.13793
η	44.6406216

(b) Output phase

Figure 24: Optimizing the single bleed Rankine cycle using **Solver**

Here, one can observe that the **Solver** has done the task of optimization with less effort and very quickly. The result provided by the **Solver** is in accordance with what has been obtained by hand calculations done previously.

7. Conclusions

This article underscores the Microsoft Excel package's proficiency in simulating the Rankine cycle with a single bleed point. The thermodynamic performance of a steam power unit is meticulously assessed using Excel spreadsheets, emphasizing the following key aspects:

- Utilization of specialized Excel tools designed for thermodynamics to generate thermodynamic properties.
- Application of Solver to optimize the bleed pressure.
- Optimization of cycle performance through the Solver Excel command, aiming to maximize cycle efficiency. The extraction pressures serve as the changing variable for this optimization process.

Recognizing Excel spreadsheets as an exceptionally potent tool for simulating thermal systems, this work aligns with the broader objective of showcasing the capabilities of Microsoft Excel in simulating the Rankine cycle's performance. The energy balance calculations demonstrate good agreement with existing literature. The evaluation and analysis of extraction pressure and mass fraction further contribute to a comprehensive understanding of the Rankine cycle.

References

[1] A. R. Joshi, A. Deo, A. Parashar, D. R. Mishra, and P. Dumka, “Modelling Steam Power Cycle using Python,” *Int. J. Sci. Res. Comput. Sci. Eng. Inf. Technol.*, vol. 9, no. 1, pp. 152–162, 2023.

[2] P. K. Nag, *Engineering thermodynamics*. Tata McGraw Hill, 2013.

[3] N. H. Roge, G. Khankari, and S. Karmakar, “Waste Heat Recovery From Fly Ash of 210 MW Coal Fired Power Plant Using Organic Rankine Cycle,” *J. Energy Resour. Technol.*, vol. 144, no. 8, 2021, doi: 10.1115/1.4052949.

[4] J. M. Lindquist and C. A. Sulewski, “Microsoft Excel: The Universal Tool of Analysis,” in *Handbook of Military and Defense Operations Research*, Chapman and Hall/CRC, 2020, pp. 19–54.

[5] A. El-Hajj, “Functional Simulation Using Spreadsheets,” *Simulation*, vol. 73, pp. 80–90, 1999, [Online]. Available: https://api.semanticscholar.org/CorpusID:38215053

[6] M. M. El-Awad, “An Excel Add-In for Refrigerants Properties and its Use for Optimising Multi-Stage Compression Refrigeration Cycles,” vol. 12, no. 1, pp. 1–18, 2003, [Online]. Available: https://sie.scholasticahq.com

[7] D. Arganbright, “Enhancing Mathematical Graphical Displays in Excel through Animation,” *Spreadsheets Educ.*, vol. 2, no. 1, pp. 1–25, 2006.

[8] M. K. S. Sastry, R. Roopchand, and R. Chhetri, “Power distribution system load flow using microsoft excel,” *Proc. - 2014 4th Int. Conf. Commun. Syst. Netw. Technol. CSNT 2014*, vol. 6, no. 1, pp. 954–959, 2014, doi: 10.1109/CSNT.2014.196.

[9] M. K. S. Sastry, B. P.V., and R. R. Malireddy, “Power System State Estimation using Microsoft Excel,” *Spreadsheets Educ.*, vol. 8, p. 1, 2014, [Online]. Available: https://api.semanticscholar.org/CorpusID:53553993

[10] M. M. El-Awad, “A Multi-Substance Add-in for the Analyses of Thermo-fluid Systems using Microsoft Excel,” *Int. J. Eng. Appl. Sci.*, vol. 2, no. 3, 2015.

[11] M. Al-Awad, “Modelling the Regenerator for Multi-Objective Optimisation of the Air-Bottoming Cycle with Excel,” *Spreadsheets Educ.*, vol. 9, no. 2, pp. 1–13, 2016.

[12] G. Fellah, “Excel Spreadsheet as a Tool for Simulating the Performance of Steam Power Plants,” vol. 12, no. January, pp. 1–19, 2019.

[13] R. K. Tan, K. Önder, F. Yerisenoglu, and R. Mutlu, “Usage of an Excel Spreadsheet for a Thermal Endurance Test Report,” *Eur. J. Eng. Appl. Sci.*, vol. 3412, pp. 91–97, 2023, doi: 10.55581/ejeas.1398578.

[14] H. Sun, J. K. Calautit, and C. Jimenez-Bescos, “Examining the regulating impact of thermal mass on overheating, and the role of night ventilation, within different climates and future scenarios across China,” *Clean. Eng. Technol.*, vol. 9, no. July, p. 100534, 2022, doi: 10.1016/j.clet.2022.100534.

[15] P. Sambaraju, “Gauss-Newton Method for Non-Linear Data Using Microsoft Excel.,” *Spreadsheets Educ.*, pp. 1–9, 2023, doi: https://doi.org/10.1000/189.

[16] “Excel in ME.” [Online]. Available: https://www.excelinme.net/thermal-systems/

[17] P. K. Nag, *Power plant engineering*. Tata McGraw-Hill Education, 2002.