Modelling Steam Power Cycle using Python

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ABSTRACT

In this research article an attempt has been made to solve thermal power plant problems using Python programming. The hand calculations and use of thermodynamic property tables make it difficult sometimes to arrive at the correct solutions. But due to the PYroMAT library one can easily search for property data and solve for the Rankine cycle. Also, the python makes it so easy to plot the Rankine cycle once data at each equilibrium point is obtained. Two touch numerical problems have been used to show the capability of PYroMAT library in solving for the power plant thermodynamics problems. The results obtained from the codes matches exactly with the literature.

Keywords: Power plant, Rankine Cycle, Python Programming, PYroMAT

Nomenclature

c_P	Specific heat at constant pressure, kJ/kgK
h	Specific enthalpy, kJ/kg
s	Specific entropy, kJ/kg
V_f	Specific volume, m³/kg
x	Quality, dryness fraction
C_v	Calorific value
h_f	Enthaply on saturated liquid line
h_g	Enthaply on saturated vapour line
s_f	Entropy on saturated liquid line
s_g	Entropy on saturated vapour line

Subscripts

f	Saturated liquid
fg	Difference in property between saturated liquid and saturated vapour
g	Saturated vapour
η	Efficiency

I. INTRODUCTION

Steam power plant is a steam driven plant which continuously converts fuel energy into shaft work and ultimately for generating electricity. It is simply runs on the Rankine cycle[1]. Water is used as the working fluid in liquid and vapour phase during the operational cycles. Despite of its corrosive properties,

water is notable for its high specific heat and latent heat of vapourization. A Steam power plant consists of some main and common components such as boiler (B), steam turbine (T), generating unit, condenser (C), Pump (P) and other auxiliaries to run the plant[2].Fig. 1 shows the schematic of a simple power plant.
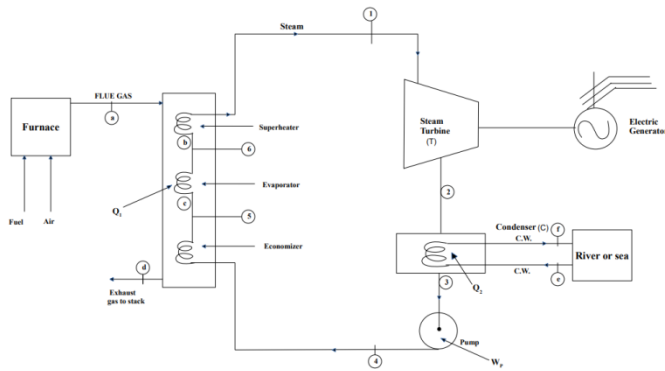

Fig. 1: Simple Steam Plant

Rankine cycle analysis in addition to driving the industrial revolution, supplying the rise of rail around the world and energizing the first ships to be sailed into the wind, Rankine cycle still provides most of the world's electricity in nuclear, coal and even in the combined cycle gas turbine plants. The energy gained by burning of the fuel is supplied to the water in the boiler(B) which where the water is heated in reversible constant pressure process in the economizer, then to the evaporator and following the superheater generating steam at a high temperature and pressure. The steam is then passed into the turbine (T)where the steam expands to low pressure to produce shaft work used to turn a generator. The steam then proceeds to the condenser(C) where it is condensed into water where the cooling water from sea or river takes away the heat released by the steam. The condensate is now fed back to the boiler using pump (P) and the cycle goes on[2,3].

To perform hand calculations and to look every data from steam table is not only tedious but also very error prone[4]. The possibility of hand calculations can be eliminated permanently if one automates the process by writing codes[5–7]. Here comes the importance of programming in core mechanical field. The easiest language to pick up is Python as it have a powerful library for performing numeric or symbolic computations[8–10]. The symbolic calculations are done with the help of the SymPy [11–14] module, whereas for numerical computations, NumPy [15–18] is used. Matplotlib [19,20] is a powerful tool for data visualization. These modules are open source and can be used freely for scientific computations. Both NumPy and Sympy are very powerful in algebra, discrete mathematics, calculus etc. [8], [9]. Apart from these modules PYroMAT[21] is a very good tool when it comes to the evaluation of the thermodynamic properties of different substances.

PYroMAT is an open source program that is used for retrieving thermodynamic properties of substances conveniently. It is user- friendly package with access of data over 1000 substances that includes liquids, gases and plasmas exposed in an intuitively designed object interface. It is written in plain PYTHON language and the core algorithms depend solely on Numpy package for back-end numerical and array support. Using PYroMAT instead of other alternatives is more competent as it minimizes the number of licks and keystrokes to acquire required data[22].The property models provided by the package for ideal gases, gases mixtures and multiphase pure substances includes: cp (Isobaric specific heat), cv (Isochoric specific heat), d (density), e (Internal energy), gam (Specific heat ratio), h (Enthalpy), mw (Molecular Weight), R (Ideal gas constant), s (Entropy).

Quality (dryness fraction) is supported by inverse properties. In PYroMAT, keyword parameter named 'quality', if set 'Time' it prompts T_h(temperature from enthalpy) and T_s (temperature from entropy) to return both temperature and quality.
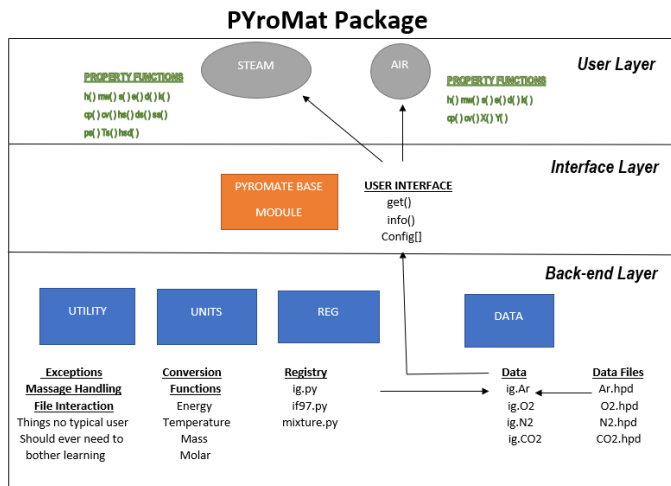
PYroMat Package

Figure 2: The PYroMAT package structure

The PYroMAT package is built in two layers with user layer at the top and most powerful. The PYroMAT base module provides a minimalist interface to more sophisticated back end. PYroMAT is primarily concerned with thermodynamics properties with no single set of units used to express since PYroMAT uses a user- configurable unit system. The configuration object Config[ ], manages all of the user configurable behaviours that how data are loaded, which units to use, what temperature-pressure defaults should be used. Fig. 2 shows the package structure of PYroMAT module.

In the research article PYroMAT along with Pylab has been used to model the Rankine cycle. The power of these libraries are demonstrated with the help of two real life power plant problems.

II. Implementation of Python programming

Example 1

For the analysis, a cogeneration plant is taken with a power load of 5.6 MW and heating load of 1.163 MW is taken. At 4000 kPa and 500°C, steam is generated and expanded isentropically in the turbine to the condenser at 6 kPa. From the turbine steam is bleeded at 200 kPa which is condensed in the process heater to saturated liquid and is pumped back to the boiler. Examine (a) the steam generation capacity of the boiler, (b) the heat input to the boiler, (c) fuel burning rate if calorific value of coal is 25 MJ/kg is burned with the boiler efficiency of 88%, (d) heat rejected to the condenser, (e) water flow rate in the condenser if temperature rise is 6°C neglecting the pump work.

Analytical approach

From the steam table, $h_1 = 3445.3$ KJ/kg and $s_1 = 7.0901$ KJ/kg-K

As, steam is expanded isentropically through the turbine, so $s_3 = s_2 = s_1 = 7.0901$ KJ/kg-K

Steam is extracted at 200 kPa for process heating, so getting properties from the steam table at $p_2 = 200$kPa :
$s_f = 1.5301$ KJ/kg-K and $s_{fg} = 5.5970$ KJ/kg-K

$$s_2 = s_f + x_2 \times s_{fg} \tag{1}$$

So, x_2 can be written as,

$$x_2 = \frac{s_2 - s_f}{s_{fg}} \tag{2}$$

Now replacing the values of the entities to get x_2.

$$x_2 = \frac{7.0901 - 1.5301}{5.5970} \tag{3}$$

or,

$$x_2 = 0.99 \tag{4}$$

Therefore, from this we can deduce that point 2 is on the saturated vapour line as the dryness fraction is approximately equal to 1. Hence,

$$h_2 = h_g \text{ (at 200 kPa)} = 2706.7 \text{ kJ/kg} \qquad (5)$$

and from the problem we know that, the steam extracted is condensed in the pro¬cess heater at 200 kPa. So,

$$h_2 - h_6 = h_{fg} = 2201.9 \text{ kJ/kg} \qquad (6)$$

Let 'm' be the rate of steam extraction for process heater.So, by Steady Flow Energy Equation (SFEE) for process heater:

Heating load can be written as:

$$Q_2 = m(h_2 - h_6) \qquad (7)$$

It is given that $Q_2 = 1.63 \times 10^3$ kW

$$m = \frac{1.63 \times 10^3}{2201.9} \qquad (8)$$

$$m = 0.528 \text{ kg/s} \qquad (9)$$

at condenser inlet $(p_2 = 6 \text{ kPa})$,

$$s_3 = s_f + x_3 s_{fg} \qquad (10)$$

So, x_3 can be written as,

$$x_3 = \frac{s_3 - s_f}{s_{fg}} \qquad (11)$$

Now replacing the values of the entities to get x_3.

$$x_3 = \frac{7.0901 - 0.52}{7.815} \qquad (12)$$
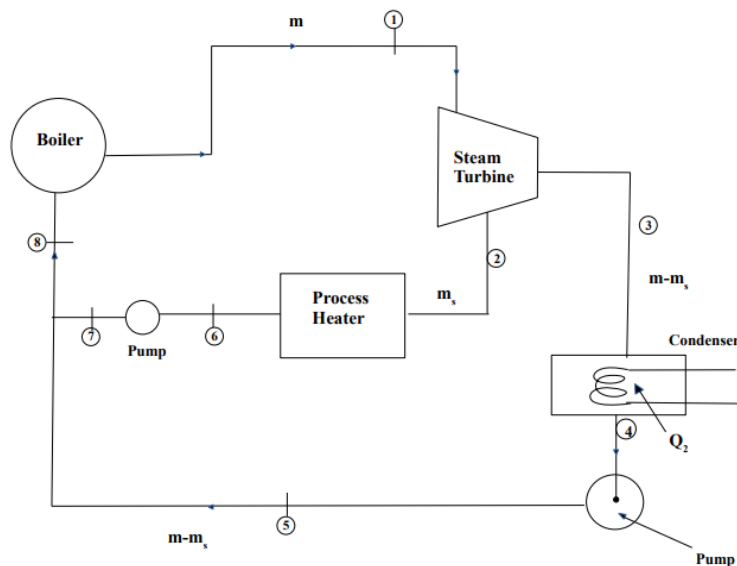
Or,

$$x_3 = 0.84 \qquad (13)$$

Figure 3: Co-generation plant with a pass-out turbine

from the steam table, the values of h_f and h_{fg} are 149.79 kJ/kg and 2416.0 kJ/kg respectively.

Now, h_3 can be calculated as:

$$h_3 = h_f + x_3 h_{fg} \tag{14}$$

by substituting values we get:

$$h_3 = 149.79 + 0.84 \times 2416 \tag{15}$$

or,

$$h_3 = 2180.59 \text{ kJ/kg} \tag{16}$$

(a) Let m_s be the mass of the steam present at the turbine inlet, then, the total work outputbytheturbine can be written as :

$$W_T = m_s(h_1 - h_2) + (m_s - m)(h_2 - h_3) \tag{17}$$

since, power load is given as $W_T = 5.6 \times 10^3$ KW and substituting the values,

$$m_s(3445.3 - 2706.7) + (m_s - 0.528)(2706.70 - 2180.59) = 5.6 \times 10^3 \tag{18}$$

$$m_s \times 738.6 + (m_s - 0.528) \times 526.11 = 5.6 \times 10^3 \tag{19}$$

$$m_s \times 738.6 + m_s \times 526.11 - 0.528 \times 526.11 = 5.6 \times 10^3 \tag{20}$$

By re-arranging and simplifying the above equation m_s can be calculated as,

$$m_s = \frac{5877.8}{1264.7} = 4.684 \text{ kg/s} \tag{21}$$

At $p_2 = 200$ kPa; $h_6 = h_f = 504.7$ kJ/kg and $V_{f6} = 1.061 \times 10^{-3} \text{m}^3/\text{kg}$

For Drip pump,

$$h_7 = h_6 + V_{f6}(p_1 - p_2) \tag{22}$$

$$h_7 = 504.7 + 1.061 \times 10^{-3}(4000 - 200) \tag{23}$$

or,

$$h_7 = 508.73 \text{kJ/kg} \tag{24}$$

similarly,

$$h_5 = h_6 + V_{f4}(4000 - 6) \tag{25}$$

$$h_5 = 149.79 + 1.006 \times 10^{-3} \times 3994 \tag{26}$$

$$h_5 = 153.8 \text{kJ/kg} \tag{27}$$

(a) In the boiler, the heat added can be calculated by,

$$Q_1 = (m_s - m)(h_1 - h_5) + m(h_1 - h_7) \tag{28}$$

putting all the required values in the above equation ,

$$Q_1 = (4.648 - 0.528)(3445.3 - 153.8) + 0.528(3445.3 - 50.73) \tag{29}$$

By simplifying and solving ,

$$Q_1 = 15.11 \text{ MW} \tag{30}$$

(b) If m_f is the fuel burning rate then the efficiency of the boiler can be written as,

$$\eta_{boiler} = \frac{Q_1}{m_f \times C_v} \tag{31}$$

Then, m_f is calculated as,

$$m_f = \frac{Q_1}{\eta_{boiler} \times C_v} \tag{32}$$

$$m_f = \frac{15.11}{0.88 \times 25} \tag{33}$$

Hence, the fuel burning rate m_f = 0.687 kg/s.

(c) With Q_2 as the heat rejected through the condenser and $h_4 = h_f$(at p_4= 6kPa) = 151.47 kJ/kg

$$Q_2=(m_s - m)(h_3 - h_4) \tag{34}$$

$$Q_2 = (4.648 - 0.528) (2180.59 - 151.47) \tag{35}$$

Hence, the heat rejected through the condenser is Q_2 = 8.36 MW

(d) If m_c is the flow rate of water in the condenser,

$$Q_2 = m_c c_P(\Delta t) \tag{36}$$

So, m_c can be calculated as,

$$m_c = \frac{Q_2}{c_p \times \Delta t} \tag{37}$$

$$m_c = \frac{8.36 \times 10^3}{4.187 \times 6} \tag{38}$$

Therefore, water flow rate in the condenser m_c = 332.77 kg/s.

On the basis of the data obtained from the code the Rankine cycle for the co-generation plant has been successfully developed using Pylab as shown in Fig. 4 (code is in Appendix). Tab. 1 lists the output according to the data points mentioned in the plot.
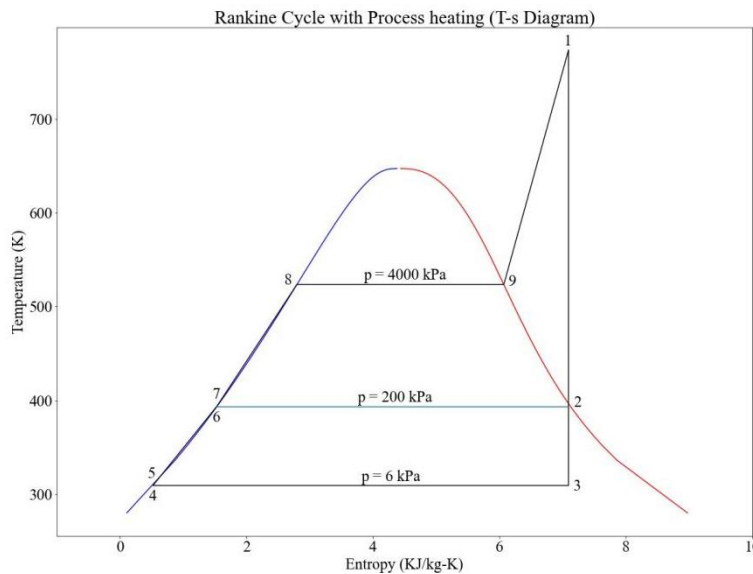

Figure 4: T-s diagram

Tab. 1: Thermodynamic properties at different state points on the T-S diagram.

State	Temperature (K)	Entropy (kJ/kg-K)	Enthalpy (kJ/kg)
1	773.150	7.092	3446.059
2	393.361	7.092	2706.263
3	309.309	7.092	2184.084
4	309.309	0.521	151.469
5	309.413	0.521	155.489
6	393.361	1.530	504.712
7	393.681	1.530	508.743

| 8 | 523.503 | 2.797 | 1087.498 |
| 9 | 523.503 | 6.069 | 2800.859 |

Example 2

In a steam turbine, steam is supplied at a pressure of 7 MPa and 450 ℃. It is then expanded at 2.5 MPa and reheated to a temperature of 420 ℃ at constant pressure. It is further expanded in intermediate pressure turbine to a minimum pressure such that the steam bleeded at this pressure is used for feedwater heating to 180° C. The rest of the steam expands from that pressure to condenser at 70 kPa. The h.p turbine has its isentropic efficiency as 78.5% and i.p. and and l.p. as 83 %each. Determine (a) minimum pressure necessary for bleeding (b) at turbine inlet, the quantity of the steam bled per kg of the flow, and (c) the cycle efficiency, neglecting the pump work.

Analytical approach

Feedwater heater is heated to 180 ℃. So p_{sat} at 180℃ = 10 bar is the pressure at which the heater operates.

Now, with reference to the superheated steam table we know that atp_1 = 70 MPa, T_1 = 450 ℃ :

$h_1 = 3287.94$ kJ/kg, and

The outlet of the h.p turbine is assumed to be on saturated vapour line so, from the saturated steam table at p_2=2.5MPa :
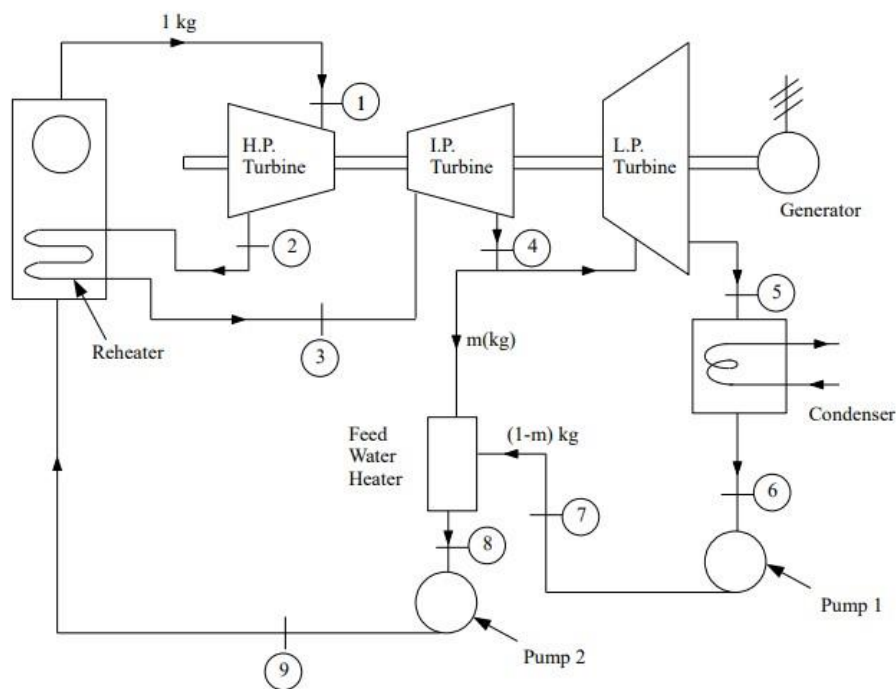

Figure 5: Steam power plant with different pressure stages and feedwater heating

h_{2s}= 2801.93 kJ/kg

From the superheated steam table at p_3 = 2.5 MPa, T_3 = 420 ℃ : h_3 = 3284.44 kJ/kg,

Andfor the steam bleeded from the i.p turbine, at p_4 = 1 MPa from the saturated steam table on saturated vapour line, we get h_{4s}= 2777.10 kJ/kg.

Now, work output of i.p. turbine is given as ;

$$W_{ip}= h_3-h_4 \tag{39}$$

and efficiency of the turbine is provided as ;

$$\eta_{ip}= \frac{h_3-h_4}{h_3-h_{4s}} \tag{40}$$

from this we get :

$$h_4= h_3-\eta_{ip}\times(h_3-h_{4s}) \tag{41}$$

after replacing the values, we get

$$h_4= 2863.35\text{kJ/kg} \tag{42}$$

Now, for steam at the outlet of l.p. turbine at pressure p_5 = 7 kPa, from saturated steam table we get,

$$h_{5s}= 2571.74 \text{ kJ/kg}$$

Now, as the efficiency of the h.p. turbine is provided,

$$\eta_{lp}= 0.83=\frac{h_4-h_5}{h_4-h_{5s}} \tag{43}$$

By re-arranging the above equation 'h_5' can be calculated as,

$$h_5= h_4-\eta_{lp}(h_4-h_{5s}) \tag{44}$$

Putting the values of the known terms and solving,

$$h_5= 2621.29\text{kJ/kg} \tag{45}$$

Now, the steam at the exit of the condenser at pressure p_c= 7 kPa, using the saturated steam table on the saturated liquid line, h_6 = 162.7 kJ/kg , and, $h_7 = h_6$

Similarly, the steam at the exit of the feedwater heater at pressure p_{rh2} = 1 MPa, using steam table on the saturated liquid line, h_8 = 762.81 kJ/kg

Now, as the efficiency of the h.p. turbine is provided

$$\eta_{hp}=0.785 =\frac{h_1-h_2}{h_1-h_{2s}} \tag{46}$$

from that,

$$h_2= h_1-\eta_{hp}\times(h_1-h_{2s}) \tag{47}$$

Putting the values and solving for h_2,

$$h_2= 2906.42\text{kJ/kg} \tag{48}$$

Energy balance of the heater gives,

$$m\times h_4 + (1-m)\times h_7= 1\times h_8 \tag{49}$$

$$m\times2863.35+ (1-m)\times162.7 = 1\times762.81 \tag{50}$$

$$m=\frac{600.11}{2700.65} = 0.222 \text{ kg/s} \tag{51}$$

Hence, m = 0.222 kg/s is the steam flow of at turbine inlet.

Efficiency of the cycle can be represented as :

$$\eta_{cycle} = \frac{(h_1 - h_2) + (h_3 - h_4) + (1-m) \times (h_4 - h_5)}{(h_1 - h_8) + (h_3 - h_2)} \qquad (52)$$

Now, substituting the values and solving for η_{cycle},

$$\eta_{cycle} = \frac{(381.49 + 421.09 + 0.778 \times 242.06)}{(2525.4 + 378.02)} \qquad (53)$$

$$\eta_{cycle} = \frac{990.90}{2903.42} \times 100 = 34.12\% \qquad (54)$$

Based on the data obtained from the code the Rankine cycle for the plant has been successfully developed using Pylab as shown in Fig. 6. Tab. 2 lists the output according to the data points mentioned in the plot.
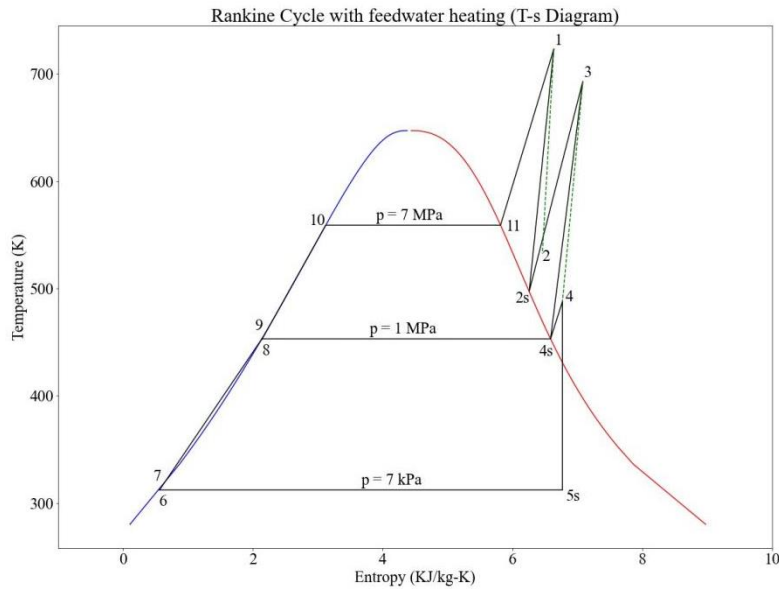

Figure 6: T-s diagram

Tab. 2: thermodynamic properties at different state of processes

State	Temperature (K)	Entropy (kJ/kg-K)	Enthalpy (kJ/kg)
1	773.150	6.635	3287.949
2s	497.099	6.256	2801.964
2	532.481	6.459	2906.451
3	693.150	7.082	3284.477
4s	453.15	6.585	2777.139
4	487.912	6.768	2863.386
5s	312.149	6.768	2571.747
6	312.149	0.559	163.342
7	311.935	0.559	163.342
8	453.028	2.138	762.525
9	452.328	2.138	762.525
10	558.979	3.122	1267.604
11	558.979	5.815	2772.657

III.CONCLUSION

The research article aims at automating the process of modelling Rankine cycle using Python programming. To perform this task PYroMAT module has been used. Detailed algorithm for solving the properties at different states has been mentioned along with its python counterpart. The codes were tested against real power plant problem, and it has been observed that there has been a exact match between the literature and code outcomes. Moreover, the data obtained by codes were also plotted with the help of Pylab to produce the Rankine cycle. This research article will help practice engineers and undergraduate students to understand the Rankine cycle and will also help them in solving complex power plant problems.

IV. REFERENCES

[1]. Nag PK. Engineering thermodynamics. Tata McGraw Hill; 2013.

[2]. Nag PK. Power plant engineering. Tata McGraw-Hill Education; 2002.

[3]. Ma X, Zhao X, Zhang Y, Liu K, Yang H, Li J, et al. Combined Rankine Cycle and dew point cooler for energy efficient power generation of the power plants - A review and perspective study. Energy 2022;238:121688. doi:https://doi.org/10.1016/j.energy.2021.121688.

[4]. Pawar PS, Mishra DR, Dumka P, Pradesh M. OBTAINING EXACT SOLUTIONS OF VISCO-INCOMPRESSIBLE PARALLEL FLOWS USING PYTHON. Int J Eng Appl Sci Technol 2022;6:213–7.

[5]. Dumka P, Singh A, Singh GP, Mishra DR. Kinematics of Fluid : A Python Approach. Int J Res Anal Rev 2022;9:131–5.

[6]. Pawar PS, Mishra DR, Dumka P. Solving First Order Ordinary Differential Equations using Least Square Method : A comparative study. Int J Innov Sci Res Technol 2022;7:857–64.

[7]. Huei YC. Benefits and introduction to python programming for freshmore students using inexpensive robots. Proc. IEEE Int. Conf. Teaching, Assess. Learn. Eng. Learn. Futur. Now, TALE 2014, 2015, p. 12–7. doi:10.1109/TALE.2014.7062611.

[8]. Lin JWB. Why python is the next wave in earth sciences computing. Bull Am Meteorol Soc 2012;93:1823–4. doi:10.1175/BAMS-D-12-00148.1.

[9]. Moruzzi G. Python Basics and the Interactive Mode. Essent. Python Phys., Cham: Springer International Publishing; 2020, p. 1–39. doi:10.1007/978-3-030-45027-4_1.

[10]. Huang C. Python Solver for Stochastic Differential Equations 2011;34:1–13.

[11]. Meurer A, Smith CP, Paprocki M, Čertík O, Kirpichev SB, Rocklin M, et al. SymPy: Symbolic computing in python. PeerJ Comput Sci 2017;2017:1–27. doi:10.7717/peerj-cs.103.

[12]. Cywiak M, Cywiak D. SymPy. Multi-Platform Graph. Program. with Kivy Basic Anal. Program. 2D, 3D, Stereosc. Des., Berkeley, CA: Apress; 2021, p. 173–90. doi:10.1007/978-1-4842-7113-1_11.

[13]. Dumka P, Chauhan R, Singh A, Singh G, Mishra D. Implementation of Buckingham ' s Pi theorem using Python. Adv Eng Softw 2022;173:103232. doi:10.1016/j.advengsoft.2022.103232.

[14]. Dumka P, Pawar PS, Sauda A, Shukla G, Mishra DR. Application of He's homotopy and perturbation method to solve heat transfer equations: A python approach. Adv Eng Softw 2022;170:103160. doi:10.1016/j.advengsoft.2022.103160.

[15]. Johansson R. Numerical python: Scientific computing and data science applications with numpy, SciPy and matplotlib, Second edition.

Apress, Berkeley, CA; 2018. doi:10.1007/978-1-4842-4246-9.

[16]. Dumka P, Rana K, Pratap S, Tomar S, Pawar PS, Mishra DR. Modelling air standard thermodynamic cycles using python. Adv Eng Softw 2022;172:103186. doi:10.1016/j.advengsoft.2022.103186.

[17]. Dumka P, Sharma S, Gautam H, Mishra DR. Finite Volume Modelling of an Axisymmetric Cylindrical Fin using Python. Res Appl Therm Eng 2021;4:1–11.

[18]. Bäcker A. Computational physics education with python. Comput Sci Eng 2007;9:30–3. doi:10.1109/MCSE.2007.48.

[19]. Porcu V. Matplotlib. Python Data Min. Quick Syntax Ref., Berkeley, CA: Apress; 2018, p. 201–34. doi:10.1007/978-1-4842-4113-4_10.

[20]. Dumka P, Deo A, Gajula K, Sharma V, Chauhan R, Mishra DR. Load and Load Duration Curves Using Python. Int J All Res Educ Sci Methods 2022;10:2127–34.

[21]. Martin CR. The PYroMat User and Developer Handbook. 2022.

[22]. Roge NH, Khankari G, Karmakar S. Waste Heat Recovery From Fly Ash of 210 MW Coal Fired Power Plant Using Organic Rankine Cycle. J Energy Resour Technol 2021;144. doi:10.1115/1.4052949.

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