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Applied Thermodynamics: Software Solutions

Vapor Power cycles (Rankine cycle) + Problems (Mathcad)

Dr. M. Thirumaleshwar

DR. M. THIRUMALESHWAR

APPLIED THERMODYNAMICS: SOFTWARE SOLUTIONS

VAPOR POWER CYCLES (RANKINE CYCLE) + PROBLEMS (MATHCAD)

Applied Thermodynamics: Software Solutions:
Vapor Power cycles (Rankine cycle) + Problems (Mathcad)
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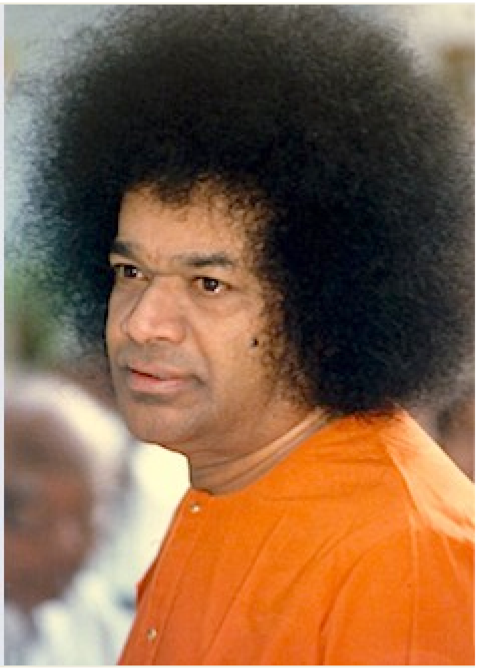
DEDICATION

This work is lovingly dedicated at the lotus feet of:
Bhagavan Sri Sathya Sai Baba



Engage always in good deeds and beneficial activities. Speak the truth, do not inflict pain by word or deed – or, even by thought. That is the way to gain true peace, and that is the highest gain you can earn in this life.

– Bhagavan Sri Sathya Sai Baba

PREFACE

This book, viz. "**Applied Thermodynamics: Software solutions – Vapor Power cycles (Rankine cycle)**" is a supplement to the Part-II of the popular, free ebook series on **Applied Thermodynamics: Software Solutions** by the same author, published by Bookboon.

In this book, as with other books of this series, the focus is on the solutions of problems using computer software. Only the essential theory and summary of equations required for calculations are given at the beginning of the chapter.

Here**, we have particularly focused on solving problems with the very useful software, Mathcad**. Since Mathcad does not have built-in functions to determine the properties water/steam, we have first written useful functions for properties of water/steam using data from NIST. Then, we demonstrate the ease with which one can do calculations, produce tables and graphs of results, and perform 'what-if analysis' with Mathcad, by solving a variety of problems.

Advantages of using computer software to solve problems are reiterated:

1. It helps in solving the problems fast and accurately
ii. Parametric analysis (what-if analysis) and graphical visualization is done very easily. This helps in an in-depth analysis of the problem.
iii. Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
iv. In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
v. These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

Useful data for water/steam are generated from NIST website, i.e.
http://webbook.nist.gov/chemistry/fluid/.

And, using the NIST data, Mathcad Functions are written for both saturation properties of water and superheated steam properties. These Functions are then used in solving problems, illustrating the ease of using Mathcad in calculations and graphing. Further, the Mathcad programs are given clearly and transparently, so that the students, teachers, researchers and professionals can reproduce them for their works.

Several Functions are written in Mathcad to simplify the standard and most often required calculations for Rankine cycle and its variations, which, the students, teachers and researchers may find very useful.

S.I. Units are used throughout this book. Wide variety of worked examples presented in the book should be useful for those appearing for University, AMIE and Engineering Services examinations.

Acknowledgements: Firstly, I would like to **thank all my students**, who have been an inspiration to me in all my academic efforts.

Sincere thanks are due to **Rev. Fr. Joseph Lobo**, Director, St. Joseph Engineering College, Mangalore, for his kindness, regard and words of encouragement.

I am also thankful to **Dr. Thirumaleshwara Bhat**, Principal, Sri Madhwa Vadiraja Institute of Technology and Management, Bantakal, Udupi, for giving me support in my academic activities.

My special thanks to **Bookboon.com** for publishing this free ebook. **Ms Karin Jakobsen and Ms Sophie Tergeist** and their editorial staff have been most patient, encouraging and helpful.

Finally, I would like to express my sincere thanks and appreciation to my **wife, Kala,** who, as usual, has given me continuous support, help and support in all my academic activities, making many silent sacrifices.

M. Thirumaleshwar
May 2016
Email: tmuliya@rediffmail.com

ABOUT THE AUTHOR

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenics) from University of Southampton, U.K. and Ph.D(cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryo-pumping etc.

He worked as Head of Cryogenics Section in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.

He worked as Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.

He also worked at the Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.

He was Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.

He also worked as Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.

He was Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by Ms. Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

Link to this Google book:

https://books.google.co.in/books?id=b2238B-AsqcC&printsec=frontcover&source=gbs_atb#v=onepage&q&f=false

He has authored a free e-book series entitled **"Software Solutions to Problems on Heat Transfer"** wherein problems are solved using 4 software viz. Mathcad, EES, FEHT and EXCEL. This book, containing about 2750 pages, is presented in 9 parts and all the 9 parts can be downloaded for free from www.bookboon.com

He has also authored free e-books on **Thermodynamics** entitled **"Basic Thermodynamics: Software Solutions"** and **"Applied Thermodynamics: Software Solutions"** wherein problems are solved using 3 software viz. Mathcad, EES, and TEST. Each of these titles is presented in 5 parts and all the books can be downloaded for free from www.bookboon.com

His another free ebook, viz. Cry**ogenic Engineering: Software Solutions – Part-I** was published by Bookboon about an year ago.

He has also authored three motivational, free ebooks, published by www.bookboon.com, entitled as follows:

1. Towards Excellence… How to Study (A Guide book to Students)
2. Towards Excellence… How to teach (A guide book to Teachers)
3. Towards Excellence… Seminars, GD's and Personal Interviews

Dr. M. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

ABOUT THE SOFTWARE USED

Following software is used while solving problems in this book:

Mathcad 7 and Mathcad 15 (Ref: www.ptc.com)

For a brief introduction to Mathcad, EES and EXCEL see the chapter 1 of the following free ebook by the author:

“Software Solutions to Problems on Heat Transfer – CONDUCTION-Part-I”:

http://bookboon.com/en/software-solutions-to-problems-on-heat-transfer-ebook

VAPOR POWER CYCLES

Learning objectives:

1. In this chapter, 'Vapor Power cycles' are analyzed with particular reference to Rankine cycle and its variations, used in Steam Power Plants.
2. Cycles dealt with are: Ideal Rankine cycle, Practical Rankine cycle with the isentropic efficiencies of turbine and pump considered, Reheat Rankine cycle (with both ideal and actual processes), Regenerative Rankine cycle and Reheat-Regenerative Rankine cycle.
3. Several useful Mathcad Functions are written for properties of water/steam in superheated and two-phase regions using data generated from NIST website, since Mathcad does not have built-in Functions for water/steam, and these Functions are used in solving a variety of problems.
4. Problems from University question papers and standard Text books are solved with Mathcad.

1 INTRODUCTION

Mathcad does not have built-in functions for properties of Water/steam.

So, we have written Mathcad Functions for properties of Water/Steam, that are essential for problem solving.

H2O/Steam properties are generated from NIST website [1], i.e.
http://webbook.nist.gov/chemistry/fluid/

Procedure to use the above NIST website to get both the saturation properties and superheat gas properties for different fluids is explained in detail in the earlier free ebook by this author (See pp. 40–48 and pp. 60–66 of that book), published by Bookboon:

Cryogenic Engineering: Software Solutions: Part-I

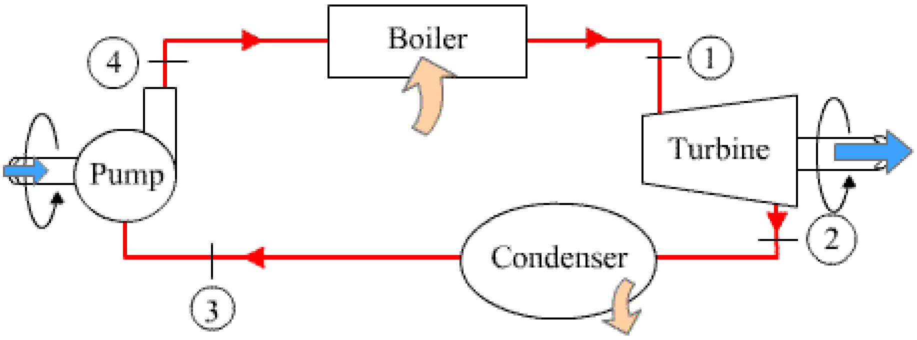
http://bookboon.com/en/cryogenic-engineering-software-solutions-part-i-ebook

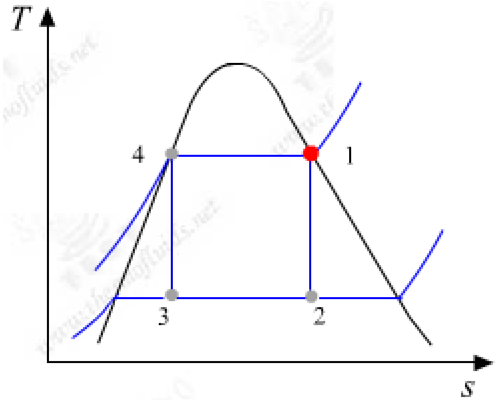
2 DEFINITIONS, STATEMENTS AND FORMULAS USED [2–8]

While analyzing the following cycles, quantities of interest are: heat supplied in boiler (q_{in}, in kJ/kg), heat rejected in condenser (q_{out}, in kJ/kg), work output of turbine (w_t, in kJ/kg), work required by pump (w_{pump}, in kJ/kg), net work (w_{net}, in kJ/kg), thermal efficiency (η), Specific Steam consumption (SSC, in kg/kWh), and Work ratio.

In the following sections, most of the block diagrams are taken from Ref. [8].

2.1 CARNOT CYCLE FOR STEAM





For Carnot cycle:

Process 1-2: Isentropic expansion in turbine
Process 2-3: Isothermal heat rejection in condenser
Process 3-4: Isentropic compression in pump
Process 4-1: Isothermal heat addition in boiler

Then, per unit mass of steam circulating, we have, in units of kJ/kg:

$q_{in} := h1 - h4$

$\eta_{carnot} = \frac{T1 - T2}{T1} = 1 - \frac{q_{out}}{q_{in}}$ With temp in Kelvin

$q_{out} := h2 - h3$

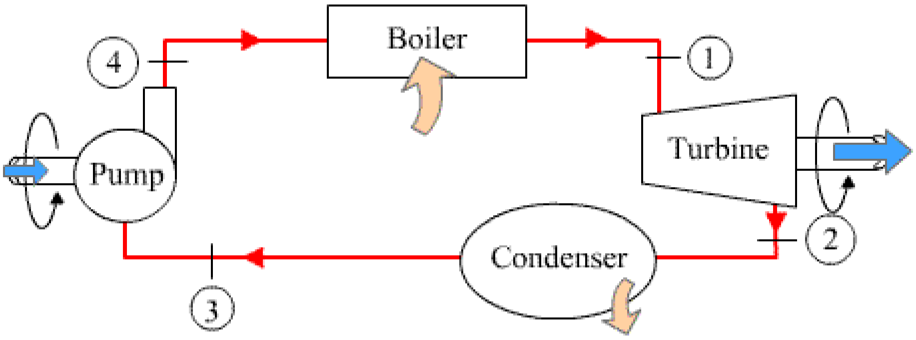
$\eta := \frac{w_{net}}{q_{in}} \cdot 100$

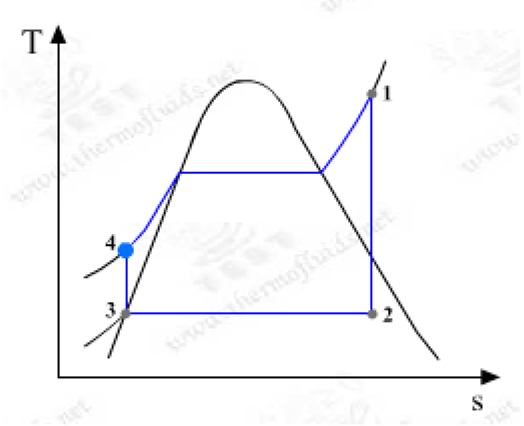
$w_T := h1 - h2$

$SSC := \frac{3600}{w_{net}}$ Work Ratio: $WR := \frac{w_{net}}{w_T}$

$w_{net} := w_T - w_p$

2.2 IDEAL RANKINE CYCLE FOR STEAM





Here, we have, per kg of steam circulating:

$q_{in} := h1 - h4$

$q_{out} := h2 - h3$

$w_T := h1 - h2$

$w_{net} := w_T - w_p$

$\eta := \frac{w_{net}}{q_{in}} \cdot 100$

Pump work: (with sp. vol = vf3 in m^3/kg, P1, P2 in kPa):

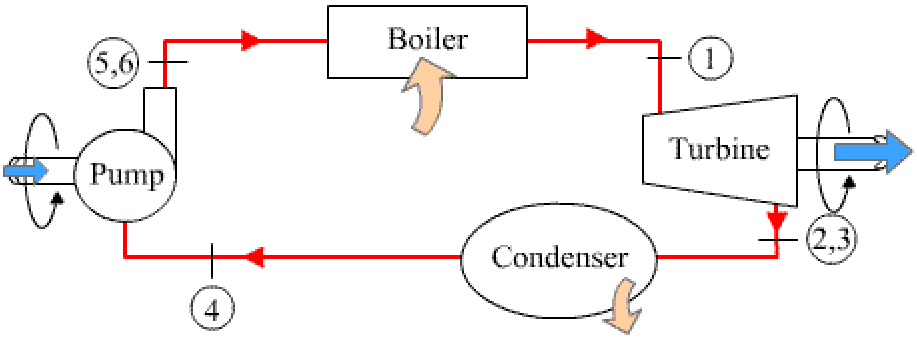
$w_p := vf3 \cdot (P1 - P2)$ kJ...pump work

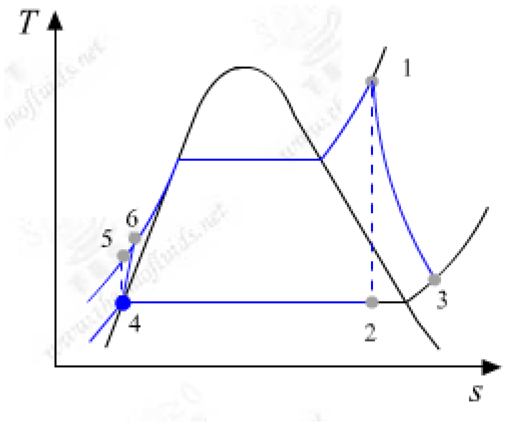
$h4 := h3 + w_p$

$SSC := \frac{3600}{w_{net}}$

Work Ratio: $WR := \frac{w_{net}}{w_T}$

2.3 ACTUAL RANKINE CYCLE FOR STEAM





Here:
Process 1-2: Ideal isentropic expansion in turbine
Process 1-3: Actual expansion in turbine
Process 4-5: Ideal isentropic compression in pump
Process 4-6: Actual compression in pump

$$\eta_{turb} := \frac{h1 - h3}{h1 - h2}$$

$$\eta_{pump} = \frac{h5 - h4}{h6 - h4}$$

$$q_{in} = h1 - h6$$

$$q_{out} = h3 - h4$$

$$w_T = h1 - h3$$

Pump work: (with sp. vol = vf3 in m^3/kg, P1, P2 in kPa):

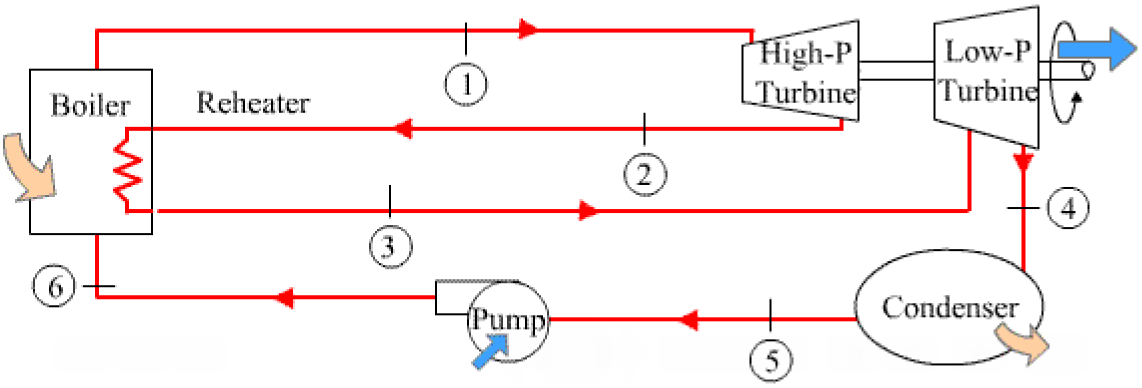
$$w_{p\_ideal} = vf4 \cdot (P1 - P2) \cdot \quad \text{kJ/kg}$$

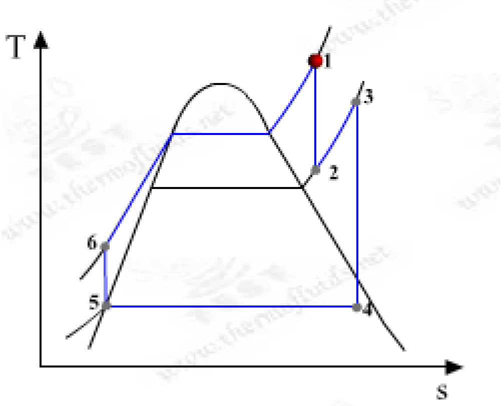
$$h5 = h4 + w_{p\_ideal} \qquad h6 = h4 + \frac{(h5 - h4)}{\eta_{pump}} \qquad w_{p\_actual} = h6 - h4$$

$$\eta = \frac{w_{net}}{q_{in}} \cdot 100$$

$$SSC = \frac{3600}{w_{net}} \quad \text{kg/kWh}$$

2.4 REHEAT RANKINE CYCLE, WITH IDEAL PROCESSES FOR STEAM





For this case, we have:

$Q_{in} := (h1 - h6) + (h3 - h2)$

$Q_{out} := h4 - h5$

$W_P := vf5 \cdot (P6 - P5)$ kJ/kg

$h6 := h5 + W_P$

$W_T := (h1 - h2) + (h3 - h4)$

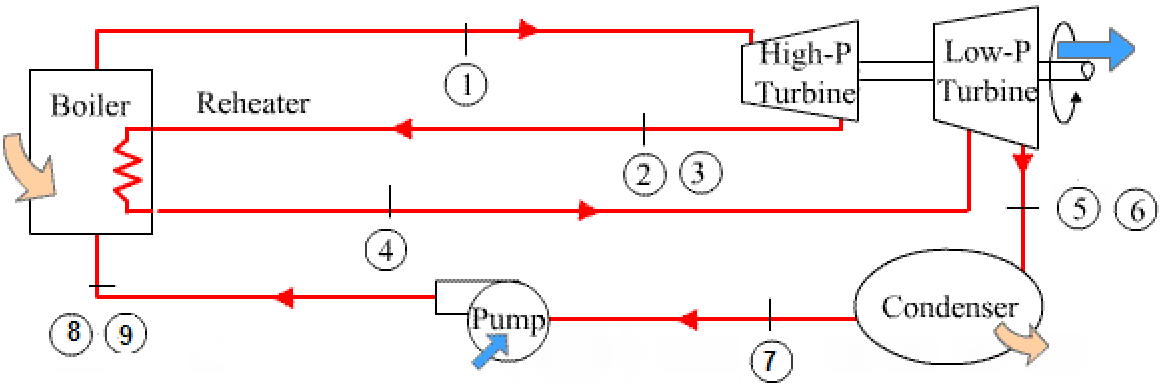
$W_{net} := W_T - W_P$

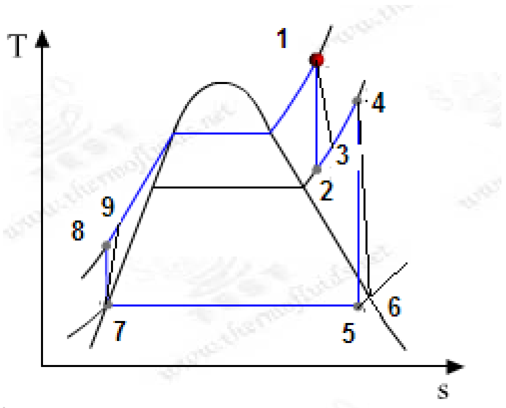
$\eta := \frac{W_{net}}{Q_{in}} \cdot 100$

$SSC := \frac{3600}{W_{net}}$

Work Ratio: $WR := \frac{W_{net}}{W_T}$

2.5 ACTUAL, REHEAT RANKINE CYCLE FOR STEAM





Various parameters are calculated as:

$$q_{in} = (h1 - h9) + (h4 - h3)$$

$$q_{out} = h6 - h7$$

$$w_{turb} = (h1 - h3) + (h4 - h6)$$

$$h8 = h7 + vf7 \cdot (P1 - P5)$$

$$w_p = h9 - h7$$

$$w_{net} = W_{turb} - w_p$$

Work Ratio: $WR = \frac{w_{net}}{w_{turb}}$

$$\eta_{pump} = \frac{h8 - h7}{h9 - h7}$$

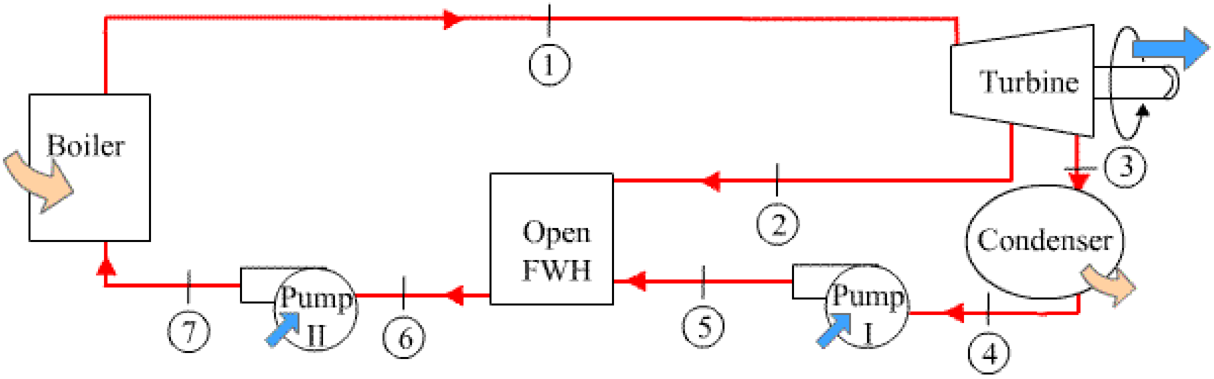
$$\eta_{turb1} = \frac{h1 - h3}{h1 - h2}$$

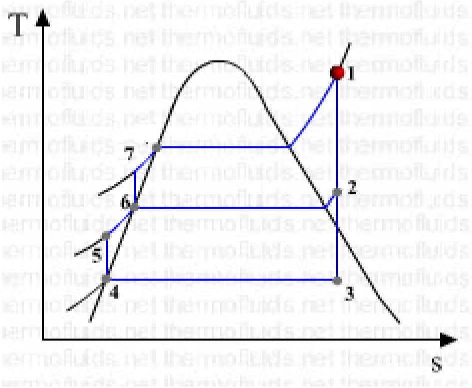
$$\eta_{turb2} = \frac{h4 - h6}{h4 - h5}$$

$$\eta = \frac{W_{net}}{Q_{in}} \cdot 100$$

$$SSC = \frac{3600}{W_{net}}$$

2.6 REGENERATIVE RANKINE CYCLE, WITH ONE OPEN FEED WATER HEATER (FWH), WITH IDEAL PROCESSES FOR STEAM





Various parameters are calculated as:

$$q_{in} = h1 - h7$$

$$q_{out} = (h3 - h4)\cdot(1 - y)$$

$$w_T = (h1 - h2) + (h2 - h3)\cdot(1 - y)$$

$$w_{P1} = (h5 - h4)\cdot(1 - y)$$

$$w_{P2} = h7 - h6$$

$$w_{net} = w_T - \left(w_{P1} + w_{P2}\right)$$

$$y = \frac{h6 - h5}{h2 - h5}$$

$$h7 = h6 + vf6\cdot(P7 - P6)$$

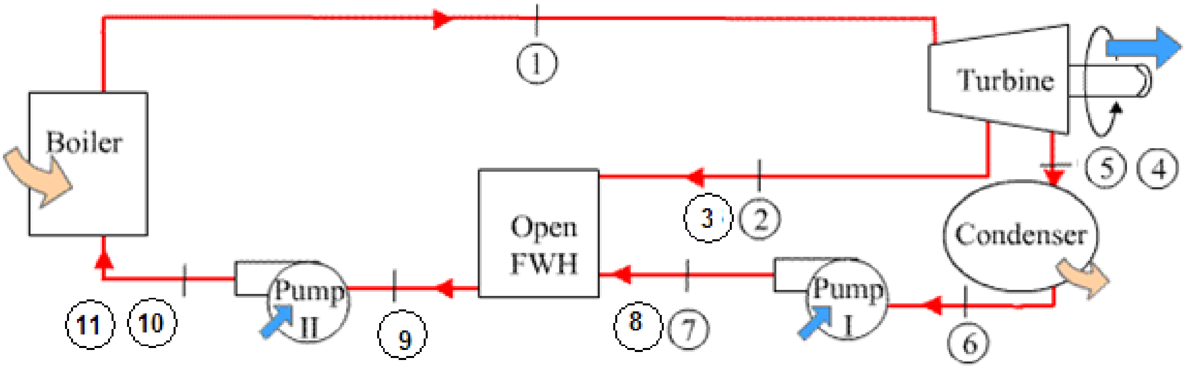
$$h5 = h4 + vf4\cdot(P5 - P4)$$

$$\eta = \frac{w_{net}}{q_{in}}\cdot 100$$

$$SSC = \frac{3600}{w_{net}}$$

Work Ratio: $WR = \dfrac{w_{net}}{w_T}$

2.7 ACTUAL, REGENERATIVE RANKINE CYCLE, WITH ONE OPEN FEED WATER HEATER (FWH), FOR STEAM



Various quantities are calculated as:

$$q_{in} = h1 - h11$$

$$q_{out} = (h5 - h6)\cdot(1 - y)$$

$$w_T = (h1 - h3) + (h3 - h5)\cdot(1 - y)$$

$$w_{P1} = (h8 - h6)\cdot(1 - y)$$

$$w_{P2} = h11 - h9$$

$$w_{net} = w_T - \left(w_{P1} + w_{P2}\right)$$

$$y = \frac{h9 - h8}{h3 - h8}$$

$$h7 = h6 + vf6\cdot(P7 - P6)$$

$$h10 = h9 + vf9\cdot(P10 - P9)$$

$$\eta = \frac{w_{net}}{q_{in}}\cdot 100$$

$$SSC = \frac{3600}{w_{net}}$$

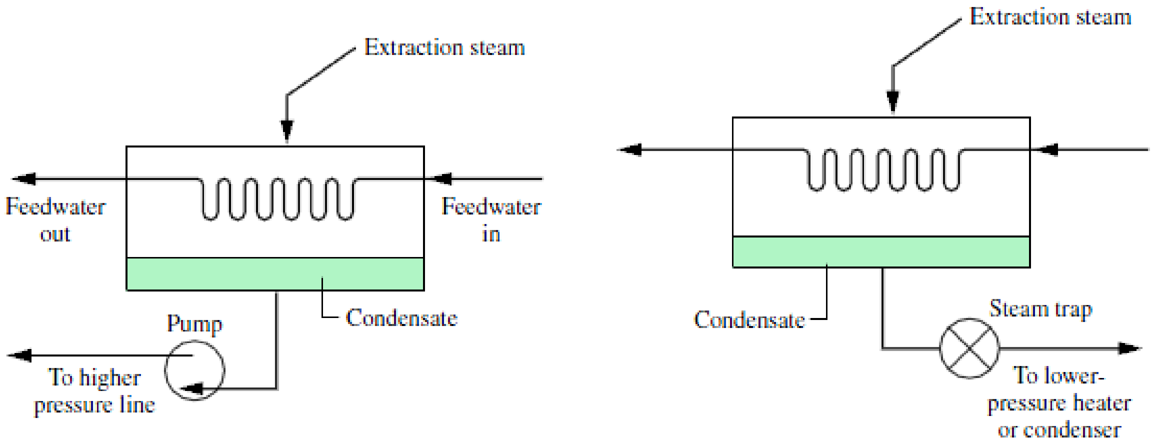
Work Ratio: $WR = \frac{w_{net}}{w_T}$

2.8 REGENERATIVE RANKINE CYCLE, WITH ONE CLOSED FEED WATER HEATER (FWH), WITH IDEAL PROCESSES FOR STEAM:

Another type of feed water heater is the 'closed' type. Generally, this heater is of a shell and tube arrangement, where the extracted steam condenses over the tubes inside which the feed water to be heated flows. The condensate is dealt with in one of the following ways:

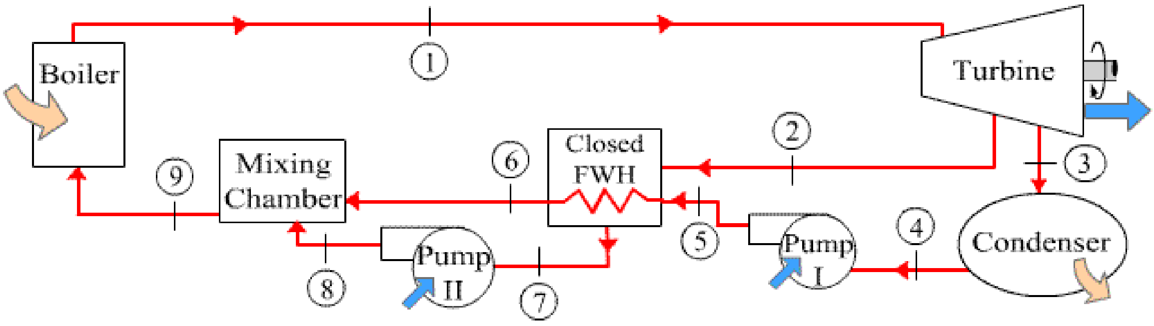
a) The condensate is pumped to a higher pressure and is *sent forward* to mix with the feed water in a mixing chamber, or
b) The condensate is throttled to a lower pressure in a 'trap' and *sent back* to the condenser or to one of the previous heaters.

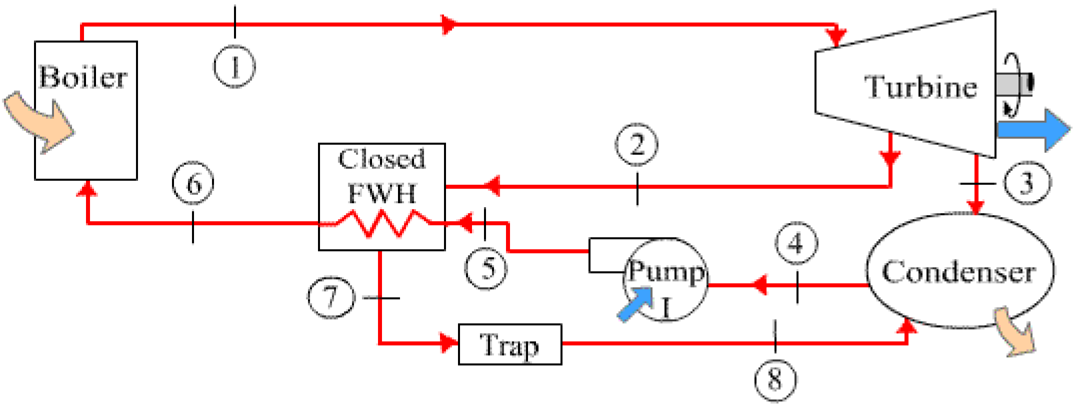
Both the arrangements are shown schematically below [4]:



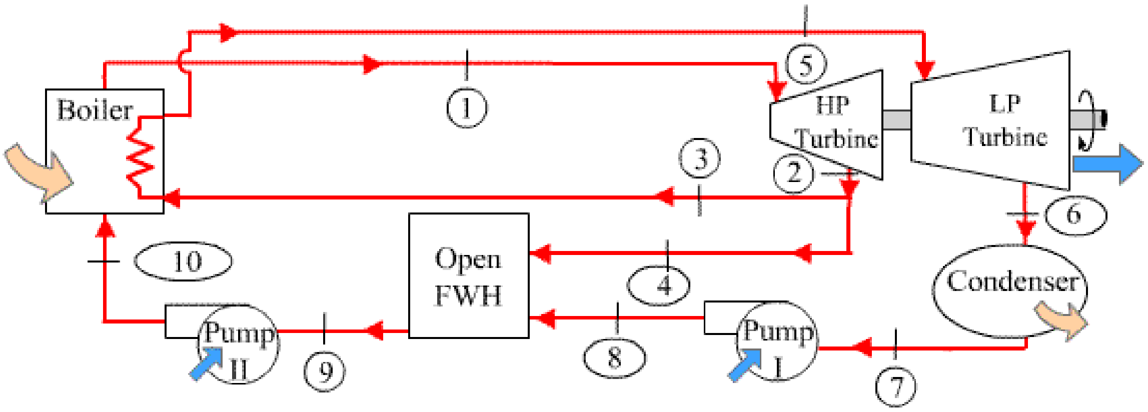
(*a*) (*b*)

Following are the respective schematic diagrams of these two types [8]:

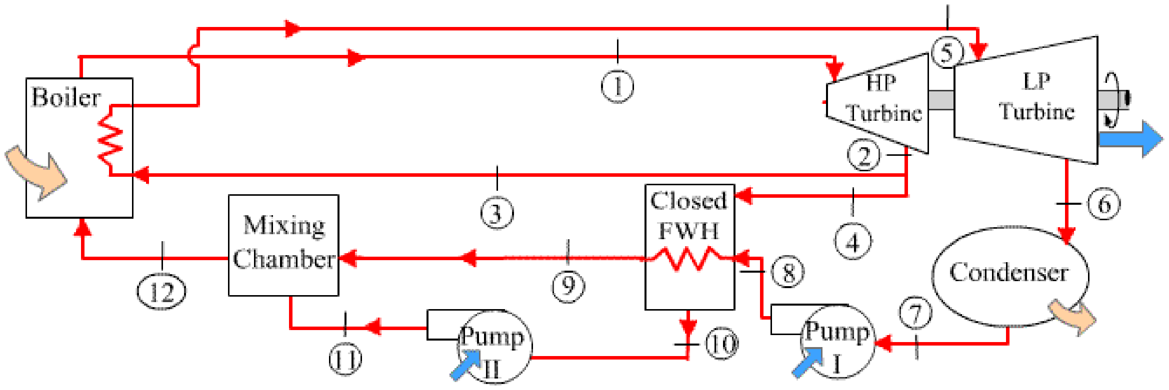




2.9A REHEAT-REGENERATIVE RANKINE CYCLE, WITH ONE OPEN FEED WATER HEATER (FWH), WITH IDEAL PROCESSES FOR STEAM:



2.9B REHEAT-REGENERATIVE RANKINE CYCLE, WITH ONE CLOSED FEED WATER HEATER (FWH), WITH IDEAL PROCESSES FOR STEAM:



Note: There are several other variations possible, with a combination of open and closed FWH, taking in to account the isentropic efficiencies of turbines and pumps etc.

2.10 SECOND LAW ANALYSIS (OR, EXERGY ANALYSIS) OF VAPOR POWER CYCLES [3]:

Second law analysis enables us to find out where in the cycle the irreversibilities occur and what their magnitudes are.

Exergy destruction for a steady flow system is given by:

$$X_{dest} = T_0 \cdot S_{gen} = T_0 \cdot \left(S_{out} - S_{in}\right) = T_0 \cdot \left[\sum_{out} (mdot \cdot s) + \frac{Q_{out}}{Tb_{out}} - \sum_{in} (mdot \cdot s) - \frac{Q_{in}}{Tb_{in}}\right] \quad \text{kW}$$

On a ***unit mass basis***, for a one inlet, one exit, **steady flow device**, we have:

$$x_{dest} = T_0 \cdot s_{gen} = T_0 \cdot \left(s_e - s_i + \frac{q_{out}}{Tb_{out}} - \frac{q_{in}}{Tb_{in}}\right) \quad \text{kJ/kg}$$

where Tb_{in} and Tb_{out} are the temps at system boundary where heat is transferred in to and out of the system respectively.

For a cycle with heat transfers at a source temp TH and sink temp TL, exergy destruction is given by:

$$x_{dest} = T_0 \cdot \left(\frac{q_{out}}{TL} - \frac{q_{in}}{TH}\right) \quad \text{kJ/kg}$$

And exergy of flow for a fluid stream at a state (P, T) is determined from:

$$\psi = \left(h - h_0\right) - T_0 \cdot \left(s - s_0\right) + \frac{V^2}{2 \cdot 1000} + \frac{g \cdot Z}{1000} \qquad \text{kJ/kg}$$

where (h, s) are enthalpy and entropy at state (P,T), and (h_0, s_0) are enthalpy and entropy at ambient conditions of (P0, T0). Temp should be in Kelvin. V is the velocity in m/s and Z is the elevation in meters. Generally, for the cases we come across, V and Z are taken as zero.

2.11 SECOND LAW EFFICIENCY, η_{II}[9]:

Thermal efficiency for heat engines and coefficient of performance for refrigerators are based on the first law of thermodynamics and referred to as *the first-law efficiencies.*

Second-law efficiency is defined based on II Law:

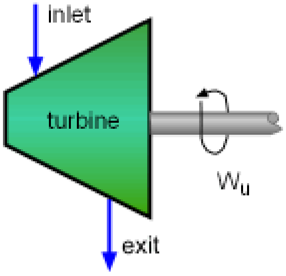
The second-law efficiency *for a heat engine* is defined as the ratio of the useful work output to the maximum possible work output (for work-producing device, such as turbine), or the ratio of the minimum work input to the actual useful work input (for work-consuming device, such as compressor).

For refrigerators or heat Pumps, it is defined as the ratio of the actual COP to the COP of reversible process. For mixing chambers, the second-law efficiency is defined as the ratio of the exergy recovered to the exergy supplied.

Summarizing:

Device	**Second Law efficiency, η_{II}**
Heat engine	η_{th} / η_{rev}
Work producing device (ex: Turbine)	W_u / W_{rev}
Work consuming device (ex: Compressor)	W_{rev} / W_u
Refrigerators/Heat pumps	COP / COP_{rev}
Mixing chambers/heat exchangers	Exergy recovered/Exergy supplied

For an adiabatic turbine:



For a turbine the second-law efficiency is defined as:

$$\eta_{II}=\frac{W_u}{W_{rev}}$$

where W_u is the actual useful work and W_{rev} is the reversible work.

From an energy balance, neglecting kinetic and potential energy differences compared to the enthalpy change of the fluid, we get:

$$W_u = m \cdot (h_i - h_e)$$

The reversible work for adiabatic turbine, the reversible work equals the difference of the flow exergies at the inlet and the exit:

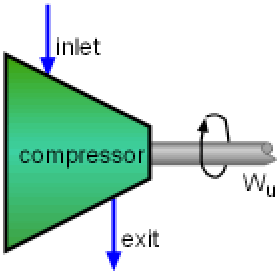
$$W_{rev} = m \cdot (ef_i - ef_e)$$

Then, *second-law efficiency of an adiabatic turbine* is given by:

$$\eta_{II} = \frac{h_i - h_e}{ef_i - ef_e}$$

Similarly, *second-law efficiency of a mixing chamber* is:

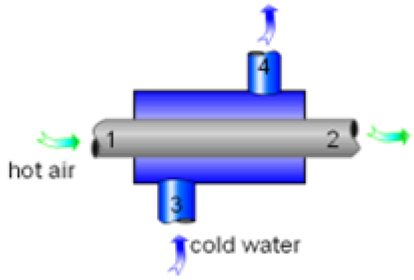
Similarly, *second-law efficiency of a compressor* is:



$\eta II = (ef_i - ef_e) / (h_i - h_e)$

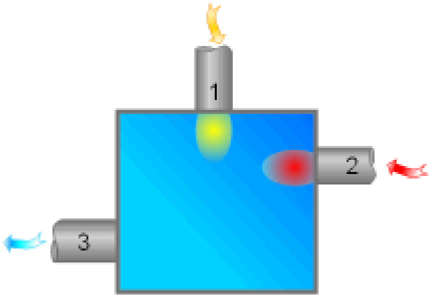
For *heat exchangers* and *mixing chambers*, their second-law efficiencies are given as the ratio of exergy recovered to exergy supplied.

For a heat exchanger: the second-law efficiency is:



$$\eta_{II} = \frac{m_{cold} \cdot (ef_4 - ef_3)}{m_{hot} \cdot (ef_1 - ef_2)}$$

where m_{cold} and m_{hot} are mass flow rates of cold and hot fluids respectively. And, ef stands for exergy of flow.



Adiabatic Mixing Chamber

Here, m_1 and m_2 are mass flow rates of hot and cold fluids respectively. And, ef stands for exergy of flow, as usual. Then, second Law efficiency is:

$$\eta_{II} = \frac{m_2 \cdot (ef_3 - ef_2)}{m_1 \cdot (ef_1 - ef_3)}$$

Summarizing:

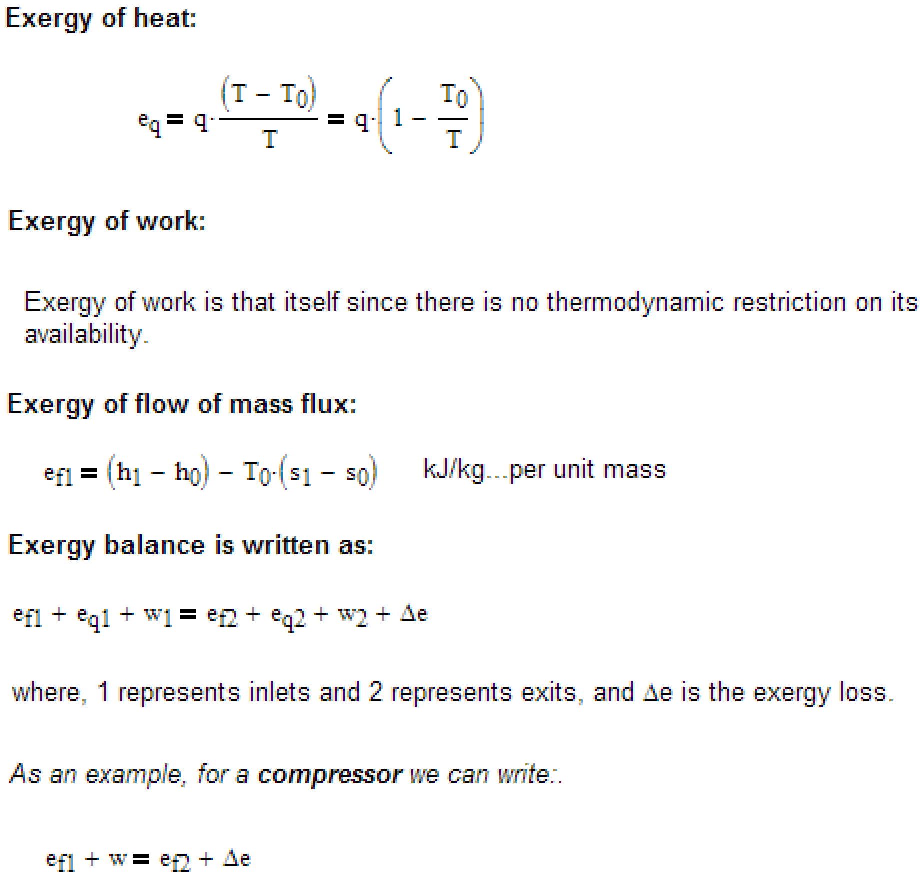
Device	Second Law efficiency, η_{II}
Adiabatic turbine	$\eta_{II} = \dfrac{h_i - h_e}{ef_i - ef_e}$
Adiabatic compressor	$\eta_{II} = \dfrac{ef_i - ef_e}{h_i - h_e}$
Heat Exchanger (non-mixing)	$\eta_{II} = \dfrac{m_{cold} \cdot \left(ef_4 - ef_3\right)}{m_{hot} \cdot \left(ef_1 - ef_2\right)}$
Adiabatic Mixing chamber	$\eta_{II} = \dfrac{m_2 \cdot \left(ef_3 - ef_2\right)}{m_1 \cdot \left(ef_1 - ef_3\right)}$

Exergy balance: Exergy losses can be found out for a given component by making an exergy balance for that component.

Exergy balance is written for each component of a system to find out the relative magnitudes of **'exergy losses'** in those components so that corrective action can be taken to reduce the losses.

Writing the exergy balance for components of a steady flow system, such as compressors, turbines, throttle valves, heat exchangers etc is as follows[6]:

Remember:



Exergy of heat:

$$e_q = q \cdot \frac{(T - T_0)}{T} = q \cdot \left(1 - \frac{T_0}{T}\right)$$

Exergy of work:

Exergy of work is that itself since there is no thermodynamic restriction on its availability.

Exergy of flow of mass flux:

$e_{f1} = (h_1 - h_0) - T_0 \cdot (s_1 - s_0)$ kJ/kg...per unit mass

Exergy balance is written as:

$$e_{f1} + e_{q1} + w_1 = e_{f2} + e_{q2} + w_2 + \Delta e$$

where, 1 represents inlets and 2 represents exits, and Δe is the exergy loss.

*As an example, for a **compressor** we can write:.*

$$e_{f1} + w = e_{f2} + \Delta e$$

If the compression is adiabatic: q = 0, and eq =0; and **if it is reversible**, Δe = 0

Therefore:

$$w = e_{f2} - e_{f1}$$

If the compression is adiabatic, but irreversible, then:

$$w = (e_{f2} - e_{f1}) + \Delta e$$

For an isothermal compression at ambient temp T0, we can write:

$$w = e_{f2} - e_{f1}$$

since though an amount of heat q is evolved during compression, its exergy eq = 0, compression being at T0.

Similarly:

For an expander, insulated, and with inlet at 3 and exit at 4, we can write:

$$e_3 = e_4 + w + \Delta e_{exp}$$

i.e. $\Delta e_{exp} = (e_3 - e_4) - w$

And, if expansion is isentropic:

$$\Delta e_{exp} = 0$$

3 PROBLEMS SOLVED WITH MATHCAD

Note:

Generally, while solving problems on vapor power cycles which use Water/Steam as working substance, we have to refer to tables often to get properties of water/steam at various state points.

Instead of using property tables, here, we shall first develop few simple Mathcad Functions for water/steam based on NIST data:

Ref: http://webbook.nist.gov/chemistry/fluid/, and then use them in solving problems. These Functions use the built-in linear interpolation function 'linterp' in Mathcad to get interpolated properties.

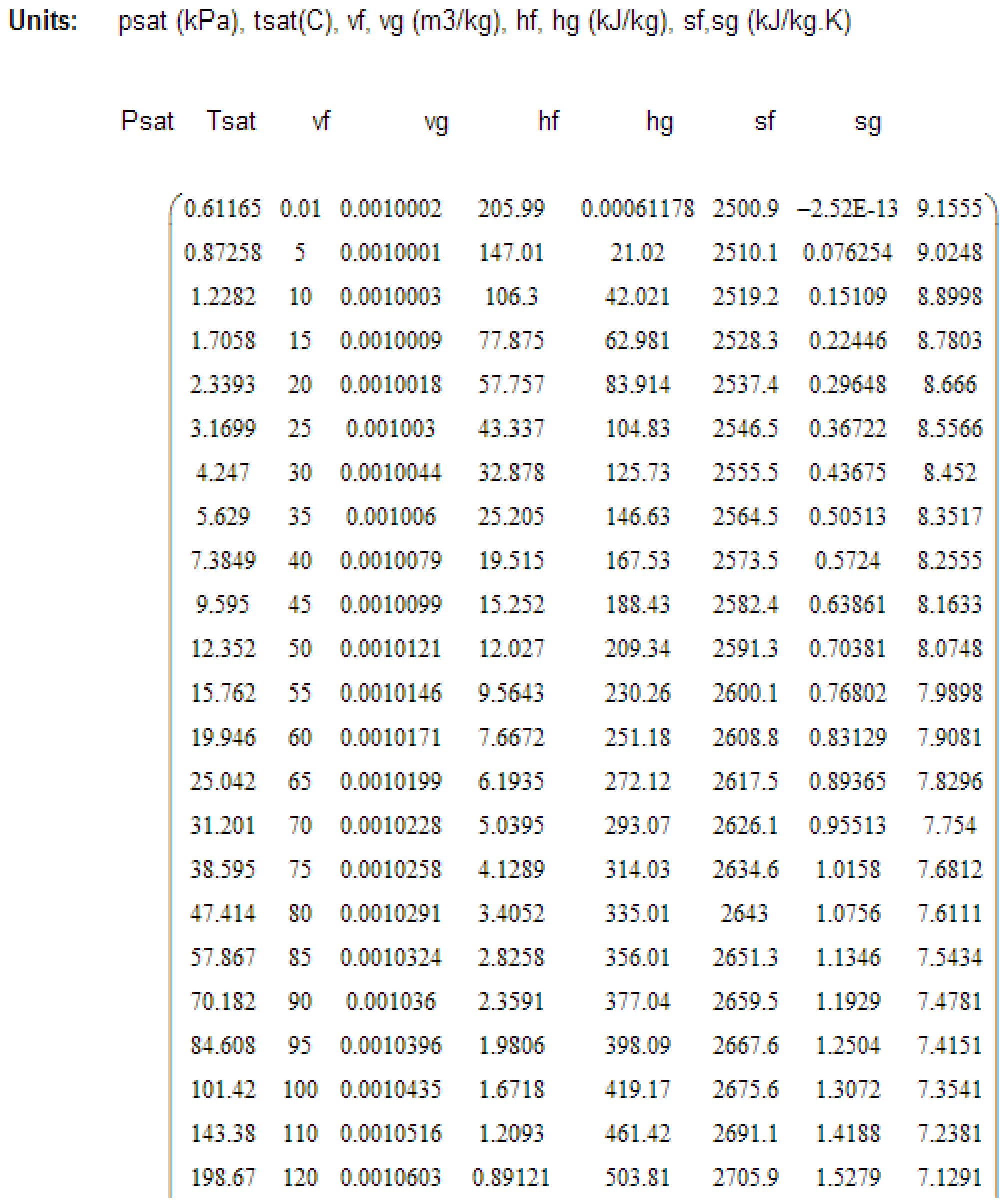
Mathcad Functions for properties of water/steam:

First, Tables are prepared for Saturated and Superheated H2O based on data tables generated from NIST website, i.e. http://webbook.nist.gov/chemistry/fluid/

Next, we write Functions for sat. properties of H2O and also in the two-phase region:

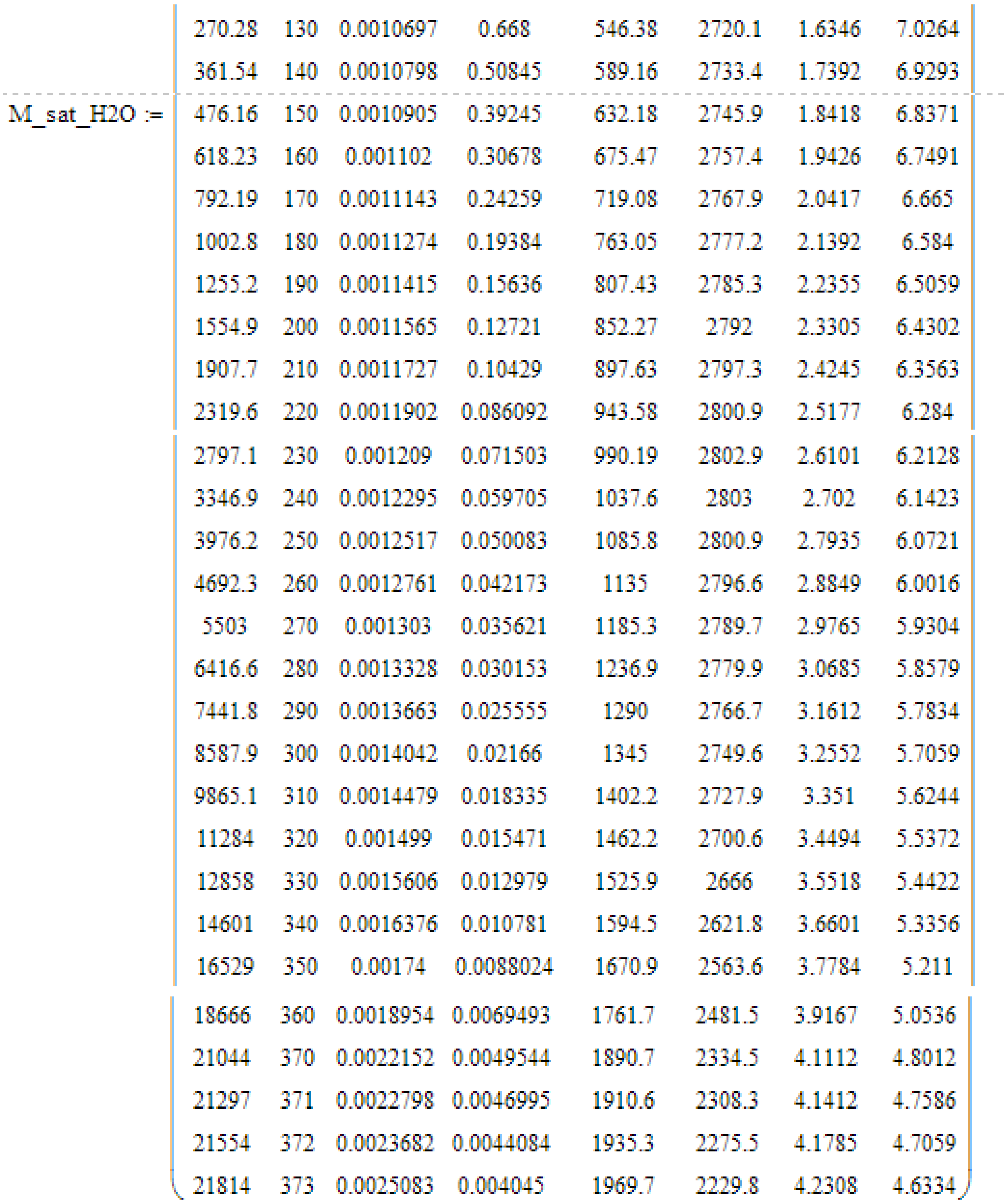
Here, the Sat. pressure Table is generated from NIST website, and is copied as a Matrix in to Mathcad:

Properties of Water-Steam: Ref: NIST



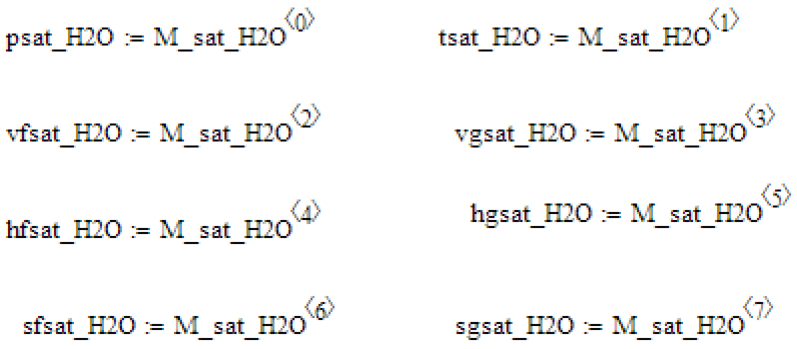
Units: psat (kPa), tsat(C), vf, vg (m3/kg), hf, hg (kJ/kg), sf,sg (kJ/kg.K)

Psat	Tsat	vf	vg	hf	hg	sf	sg
0.61165	0.01	0.0010002	205.99	0.00061178	2500.9	−2.52E-13	9.1555
0.87258	5	0.0010001	147.01	21.02	2510.1	0.076254	9.0248
1.2282	10	0.0010003	106.3	42.021	2519.2	0.15109	8.8998
1.7058	15	0.0010009	77.875	62.981	2528.3	0.22446	8.7803
2.3393	20	0.0010018	57.757	83.914	2537.4	0.29648	8.666
3.1699	25	0.001003	43.337	104.83	2546.5	0.36722	8.5566
4.247	30	0.0010044	32.878	125.73	2555.5	0.43675	8.452
5.629	35	0.001006	25.205	146.63	2564.5	0.50513	8.3517
7.3849	40	0.0010079	19.515	167.53	2573.5	0.5724	8.2555
9.595	45	0.0010099	15.252	188.43	2582.4	0.63861	8.1633
12.352	50	0.0010121	12.027	209.34	2591.3	0.70381	8.0748
15.762	55	0.0010146	9.5643	230.26	2600.1	0.76802	7.9898
19.946	60	0.0010171	7.6672	251.18	2608.8	0.83129	7.9081
25.042	65	0.0010199	6.1935	272.12	2617.5	0.89365	7.8296
31.201	70	0.0010228	5.0395	293.07	2626.1	0.95513	7.754
38.595	75	0.0010258	4.1289	314.03	2634.6	1.0158	7.6812
47.414	80	0.0010291	3.4052	335.01	2643	1.0756	7.6111
57.867	85	0.0010324	2.8258	356.01	2651.3	1.1346	7.5434
70.182	90	0.001036	2.3591	377.04	2659.5	1.1929	7.4781
84.608	95	0.0010396	1.9806	398.09	2667.6	1.2504	7.4151
101.42	100	0.0010435	1.6718	419.17	2675.6	1.3072	7.3541
143.38	110	0.0010516	1.2093	461.42	2691.1	1.4188	7.2381
198.67	120	0.0010603	0.89121	503.81	2705.9	1.5279	7.1291



$$M\_sat\_H2O := \begin{pmatrix}
270.28 & 130 & 0.0010697 & 0.668 & 546.38 & 2720.1 & 1.6346 & 7.0264 \\
361.54 & 140 & 0.0010798 & 0.50845 & 589.16 & 2733.4 & 1.7392 & 6.9293 \\
476.16 & 150 & 0.0010905 & 0.39245 & 632.18 & 2745.9 & 1.8418 & 6.8371 \\
618.23 & 160 & 0.001102 & 0.30678 & 675.47 & 2757.4 & 1.9426 & 6.7491 \\
792.19 & 170 & 0.0011143 & 0.24259 & 719.08 & 2767.9 & 2.0417 & 6.665 \\
1002.8 & 180 & 0.0011274 & 0.19384 & 763.05 & 2777.2 & 2.1392 & 6.584 \\
1255.2 & 190 & 0.0011415 & 0.15636 & 807.43 & 2785.3 & 2.2355 & 6.5059 \\
1554.9 & 200 & 0.0011565 & 0.12721 & 852.27 & 2792 & 2.3305 & 6.4302 \\
1907.7 & 210 & 0.0011727 & 0.10429 & 897.63 & 2797.3 & 2.4245 & 6.3563 \\
2319.6 & 220 & 0.0011902 & 0.086092 & 943.58 & 2800.9 & 2.5177 & 6.284 \\
2797.1 & 230 & 0.001209 & 0.071503 & 990.19 & 2802.9 & 2.6101 & 6.2128 \\
3346.9 & 240 & 0.0012295 & 0.059705 & 1037.6 & 2803 & 2.702 & 6.1423 \\
3976.2 & 250 & 0.0012517 & 0.050083 & 1085.8 & 2800.9 & 2.7935 & 6.0721 \\
4692.3 & 260 & 0.0012761 & 0.042173 & 1135 & 2796.6 & 2.8849 & 6.0016 \\
5503 & 270 & 0.001303 & 0.035621 & 1185.3 & 2789.7 & 2.9765 & 5.9304 \\
6416.6 & 280 & 0.0013328 & 0.030153 & 1236.9 & 2779.9 & 3.0685 & 5.8579 \\
7441.8 & 290 & 0.0013663 & 0.025555 & 1290 & 2766.7 & 3.1612 & 5.7834 \\
8587.9 & 300 & 0.0014042 & 0.02166 & 1345 & 2749.6 & 3.2552 & 5.7059 \\
9865.1 & 310 & 0.0014479 & 0.018335 & 1402.2 & 2727.9 & 3.351 & 5.6244 \\
11284 & 320 & 0.001499 & 0.015471 & 1462.2 & 2700.6 & 3.4494 & 5.5372 \\
12858 & 330 & 0.0015606 & 0.012979 & 1525.9 & 2666 & 3.5518 & 5.4422 \\
14601 & 340 & 0.0016376 & 0.010781 & 1594.5 & 2621.8 & 3.6601 & 5.3356 \\
16529 & 350 & 0.00174 & 0.0088024 & 1670.9 & 2563.6 & 3.7784 & 5.211 \\
18666 & 360 & 0.0018954 & 0.0069493 & 1761.7 & 2481.5 & 3.9167 & 5.0536 \\
21044 & 370 & 0.0022152 & 0.0049544 & 1890.7 & 2334.5 & 4.1112 & 4.8012 \\
21297 & 371 & 0.0022798 & 0.0046995 & 1910.6 & 2308.3 & 4.1412 & 4.7586 \\
21554 & 372 & 0.0023682 & 0.0044084 & 1935.3 & 2275.5 & 4.1785 & 4.7059 \\
21814 & 373 & 0.0025083 & 0.004045 & 1969.7 & 2229.8 & 4.2308 & 4.6334
\end{pmatrix}$$

To write the Functions, we extract each column from the Table as a vector:



$$psat\_H2O := M\_sat\_H2O^{\langle 0\rangle} \qquad tsat\_H2O := M\_sat\_H2O^{\langle 1\rangle}$$

$$vfsat\_H2O := M\_sat\_H2O^{\langle 2\rangle} \qquad vgsat\_H2O := M\_sat\_H2O^{\langle 3\rangle}$$

$$hfsat\_H2O := M\_sat\_H2O^{\langle 4\rangle} \qquad hgsat\_H2O := M\_sat\_H2O^{\langle 5\rangle}$$

$$sfsat\_H2O := M\_sat\_H2O^{\langle 6\rangle} \qquad sgsat\_H2O := M\_sat\_H2O^{\langle 7\rangle}$$

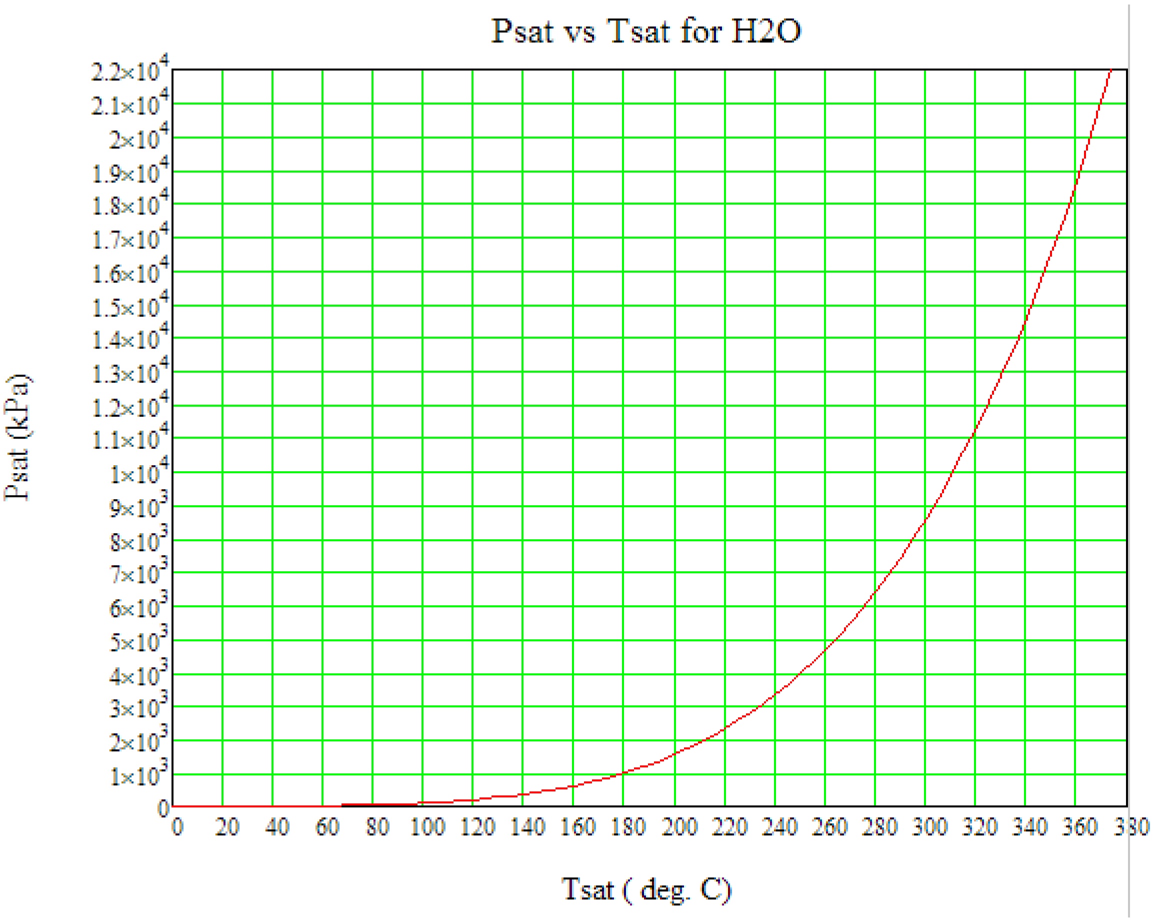
Now, use these data vectors to get interpolated values, in conjunction with the linear interpolation function 'linterp' in Mathcad.

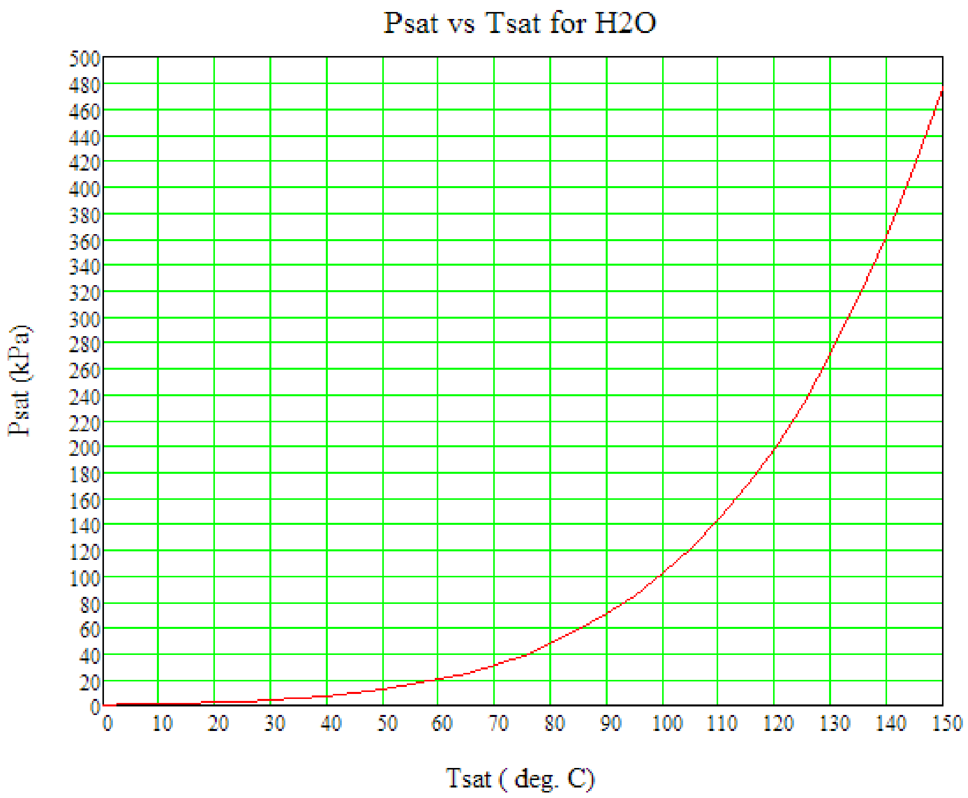
```
TSAT_H2O(P) := interp(cspline(psat_H2O,tsat_H2O),psat_H2O,tsat_H2O,P)

PSAT_H2O(T) := interp(cspline(tsat_H2O,psat_H2O),tsat_H2O,psat_H2O,T)

HFSATP_H2O(P) := linterp(psat_H2O,hfsat_H2O,P)

HFSATT_H2O(T) := linterp(tsat_H2O,hfsat_H2O,T)

HGSATP_H2O(P) := linterp(psat_H2O,hgsat_H2O,P)

HGSATT_H2O(T) := linterp(tsat_H2O,hgsat_H2O,T)

HFGSATP_H2O(P) := HGSATP_H2O(P) − HFSATP_H2O(P)

HFGSATT_H2O(T) := HGSATT_H2O(T) − HFSATT_H2O(T)
```

```
SFSATP_H2O(P) := linterp(psat_H2O, sfsat_H2O, P)

SFSATT_H2O(T) := linterp(tsat_H2O, sfsat_H2O, T)

SGSATP_H2O(P) := linterp(psat_H2O, sgsat_H2O, P)

SGSATT_H2O(T) := linterp(tsat_H2O, sgsat_H2O, T)

SFGSATP_H2O(P) := SGSATP_H2O(P) − SFSATP_H2O(P)

SFGSATT_H2O(T) := SGSATT_H2O(T) − SFSATT_H2O(T)

VGSATP_H2O(P) := linterp(psat_H2O, vgsat_H2O, P)

VGSATT_H2O(T) := linterp(tsat_H2O, vgsat_H2O, T)

VFSATP_H2O(P) := linterp(psat_H2O, vfsat_H2O, P)

VFSATT_H2O(T) := linterp(tsat_H2O, vfsat_H2O, T)

VFGSATP_H2O(P) := VGSATP_H2O(P) − VFSATP_H2O(P)

VFGSATT_H2O(T) := VGSATT_H2O(T) − VFSATT_H2O(T)

UGSATP_H2O(P) := HGSATP_H2O(P) − P·VGSATP_H2O(P)

UFSATP_H2O(P) := HFSATP_H2O(P) − P·VFSATP_H2O(P)

UFGSATP_H2O(P) := UGSATP_H2O(P) − UFSATP_H2O(P)

UGSATT_H2O(T) := HGSATT_H2O(T) − PSAT_H2O(T)·VGSATT_H2O(T)

UFSATT_H2O(T) := HFSATT_H2O(T) − PSAT_H2O(T)·VFSATT_H2O(T)

UFGSATT_H2O(T) := UGSATT_H2O(T) − UFSATT_H2O(T)

SFSATHF_H2O(hf) := linterp(hfsat_H2O, sfsat_H2O, hf)      ...finds sf when hf is given
```

Plot the P-T curve (vapor pressure curve). Note that here 'spline interpolation' is used:

$T := 0, 5 .. 375$ define a range variable

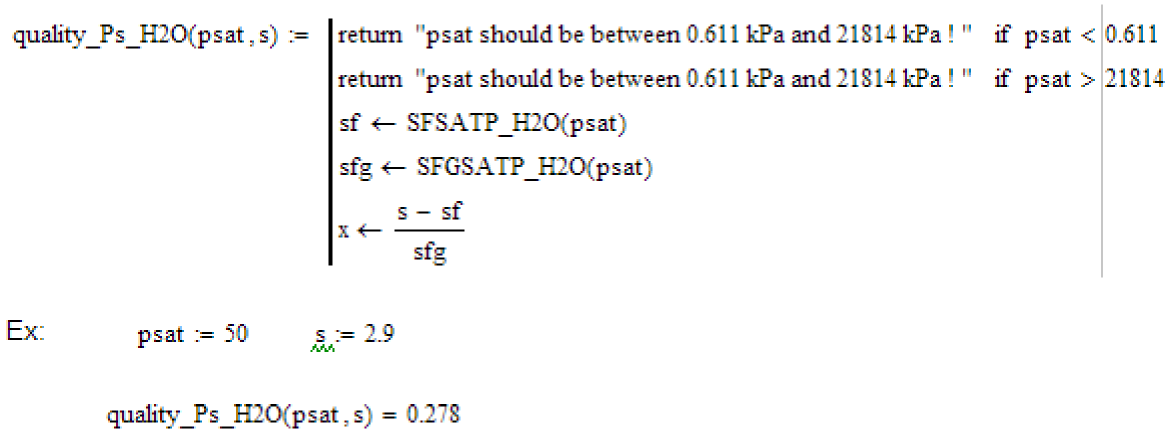



Psat vs Tsat for H2O
Psat (kPa)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Tsat (deg. C)

===

Further, following *additional functions* for finding out the quality, entropy and enthalpy in the two-phase region are written. They are very useful in calculations related to vapor power cycles (Rankine cycle), using H2O/Steam.

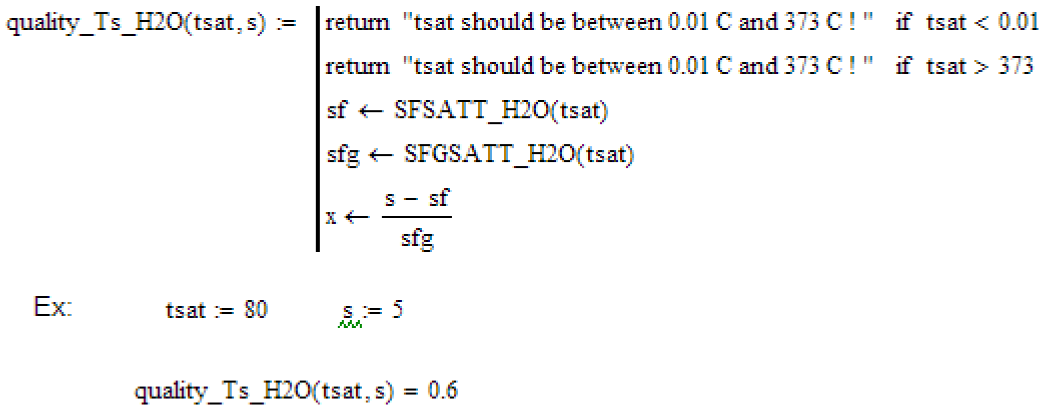
In the following programs: psat = sat. pr.(kPa), tsat = sat. temp (C), s = entropy (kJ/kg.C), h = enthalpy (kJ/kg), x = quality:



quality_Ps_H2O(psat, s) :=
- return "psat should be between 0.611 kPa and 21814 kPa ! " if psat < 0.611
- return "psat should be between 0.611 kPa and 21814 kPa ! " if psat > 21814
- sf ← SFSATP_H2O(psat)
- sfg ← SFGSATP_H2O(psat)
- $x \leftarrow \frac{s - sf}{sfg}$

Ex: psat := 50 s := 2.9

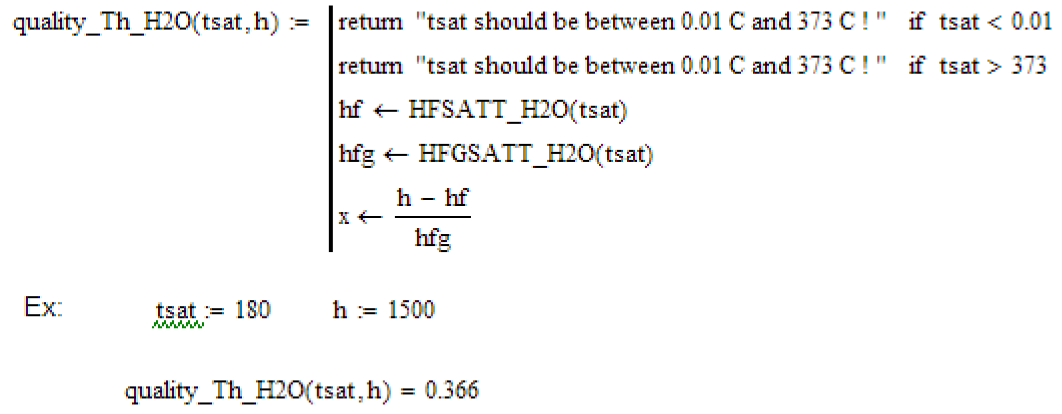
quality_Ps_H2O(psat, s) = 0.278



quality_Ts_H2O(tsat, s) :=
- return "tsat should be between 0.01 C and 373 C ! " if tsat < 0.01
- return "tsat should be between 0.01 C and 373 C ! " if tsat > 373
- sf ← SFSATT_H2O(tsat)
- sfg ← SFGSATT_H2O(tsat)
- $x \leftarrow \frac{s - sf}{sfg}$

Ex: tsat := 80 s := 5

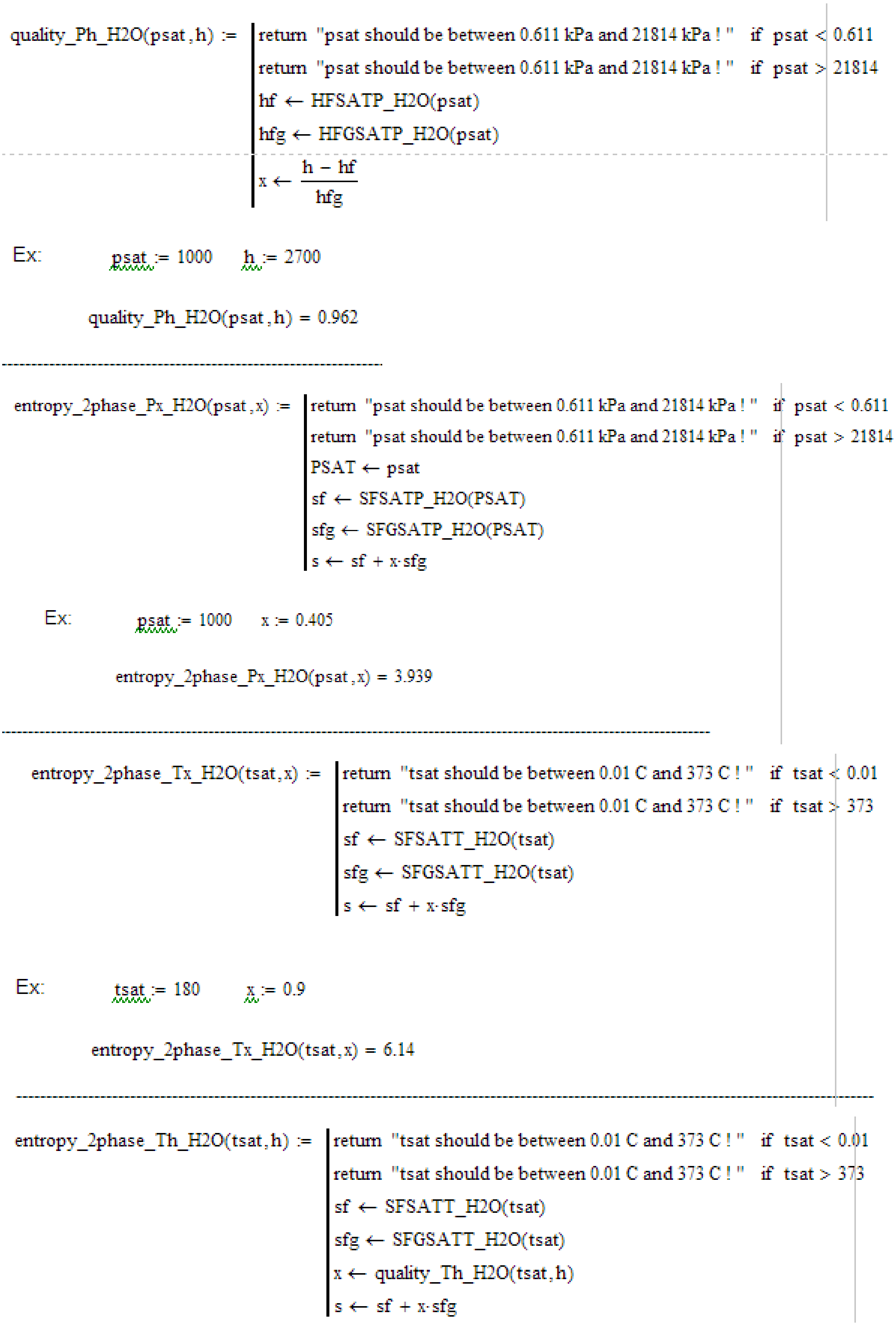
quality_Ts_H2O(tsat, s) = 0.6



quality_Th_H2O(tsat, h) :=
- return "tsat should be between 0.01 C and 373 C ! " if tsat < 0.01
- return "tsat should be between 0.01 C and 373 C ! " if tsat > 373
- hf ← HFSATT_H2O(tsat)
- hfg ← HFGSATT_H2O(tsat)
- $x \leftarrow \frac{h - hf}{hfg}$

Ex: tsat := 180 h := 1500

quality_Th_H2O(tsat, h) = 0.366



```
quality_Ph_H2O(psat,h) := | return "psat should be between 0.611 kPa and 21814 kPa ! "  if psat < 0.611
                          | return "psat should be between 0.611 kPa and 21814 kPa ! "  if psat > 21814
                          | hf ← HFSATP_H2O(psat)
                          | hfg ← HFGSATP_H2O(psat)
                          | x ← (h − hf)/hfg
```

Ex: psat := 1000   h := 2700

quality_Ph_H2O(psat,h) = 0.962

```
entropy_2phase_Px_H2O(psat,x) := | return "psat should be between 0.611 kPa and 21814 kPa ! "  if psat < 0.611
                                 | return "psat should be between 0.611 kPa and 21814 kPa ! "  if psat > 21814
                                 | PSAT ← psat
                                 | sf ← SFSATP_H2O(PSAT)
                                 | sfg ← SFGSATP_H2O(PSAT)
                                 | s ← sf + x·sfg
```

Ex: psat := 1000   x := 0.405

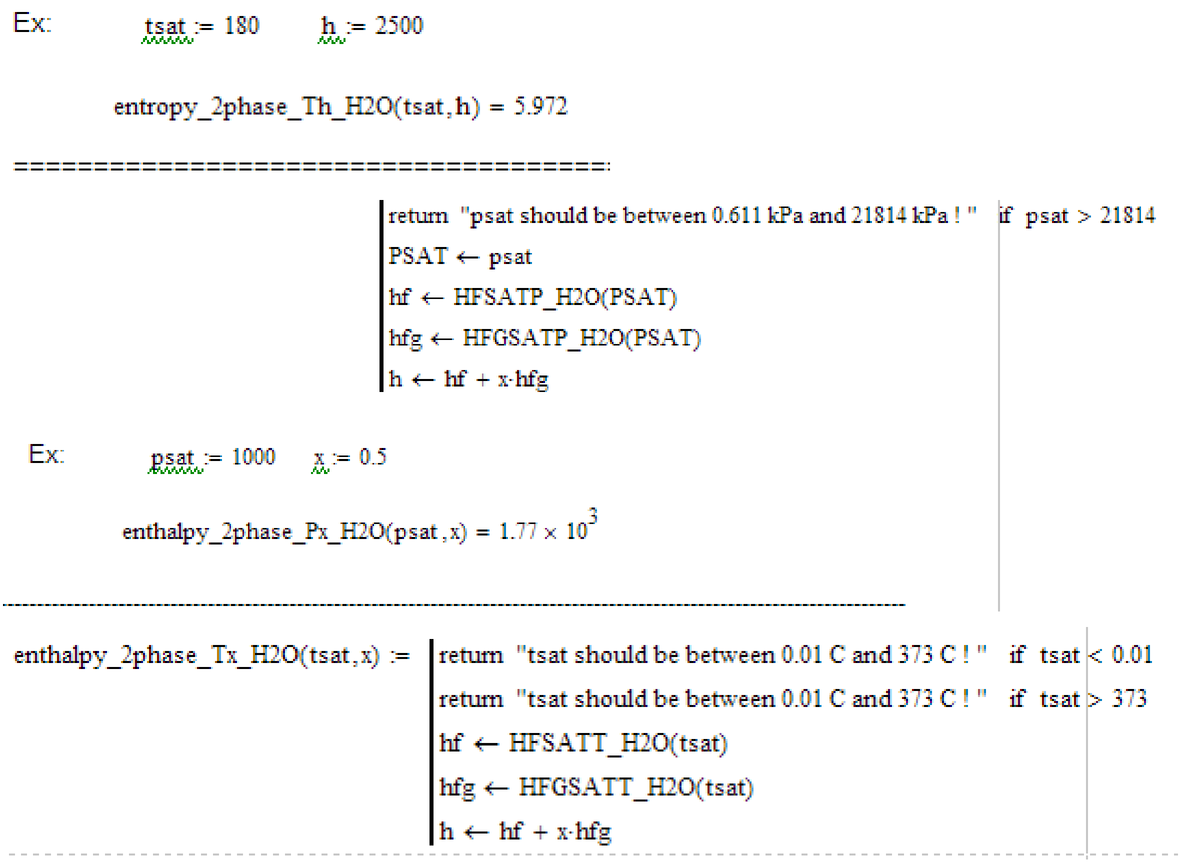
entropy_2phase_Px_H2O(psat,x) = 3.939

```
entropy_2phase_Tx_H2O(tsat,x) := | return "tsat should be between 0.01 C and 373 C ! "  if tsat < 0.01
                                 | return "tsat should be between 0.01 C and 373 C ! "  if tsat > 373
                                 | sf ← SFSATT_H2O(tsat)
                                 | sfg ← SFGSATT_H2O(tsat)
                                 | s ← sf + x·sfg
```

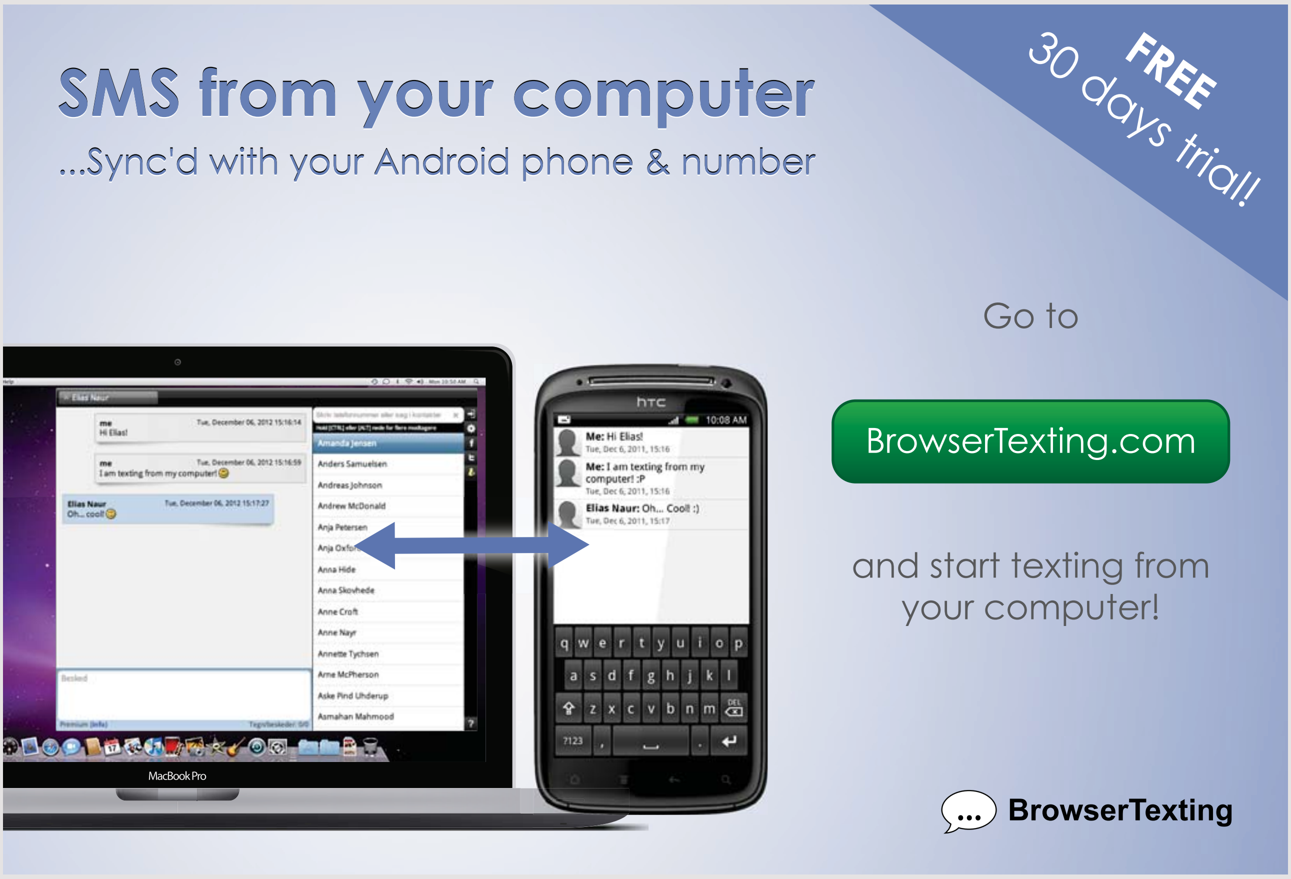
Ex: tsat := 180   x := 0.9

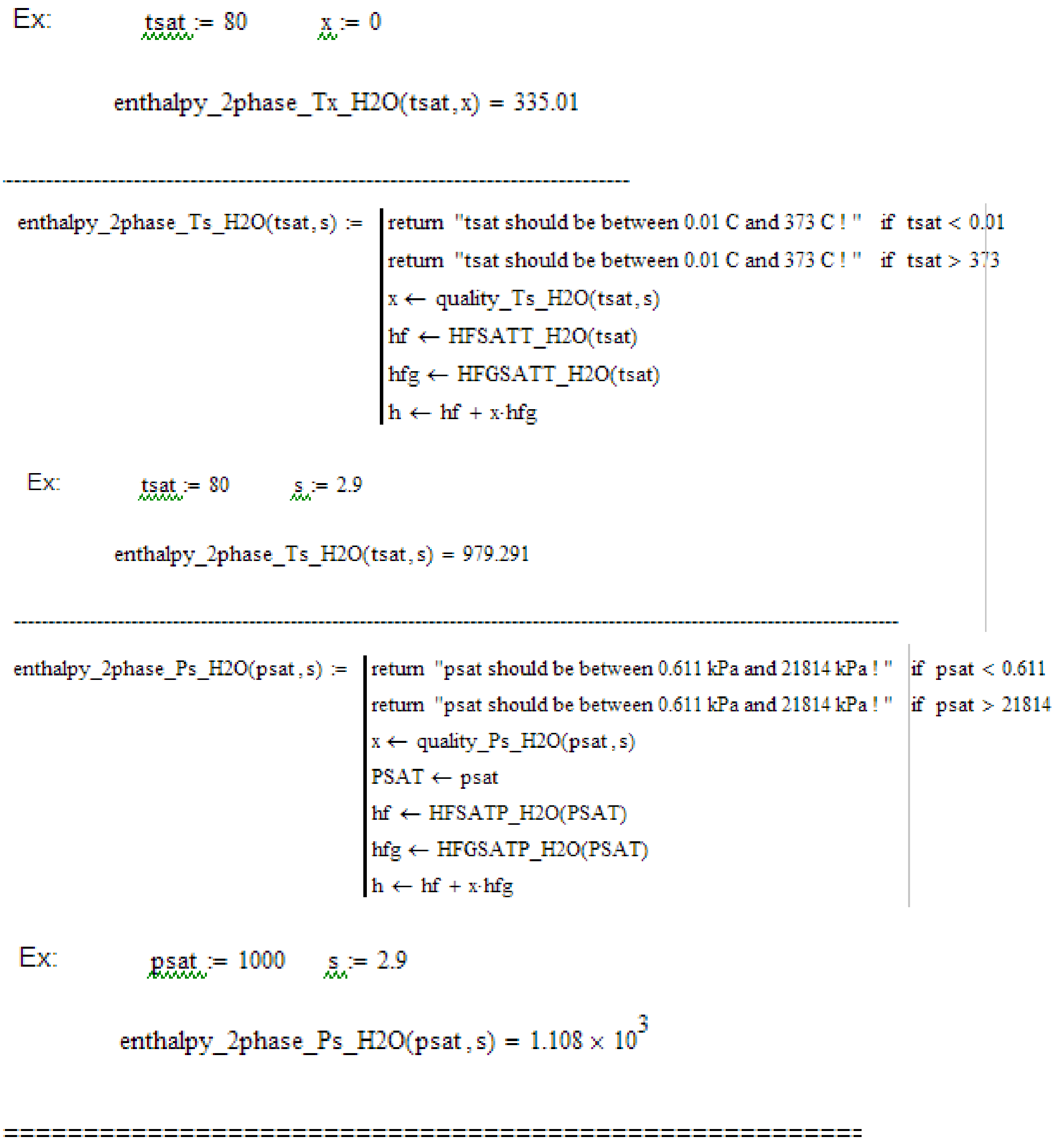
entropy_2phase_Tx_H2O(tsat,x) = 6.14

```
entropy_2phase_Th_H2O(tsat,h) := | return "tsat should be between 0.01 C and 373 C ! "  if tsat < 0.01
                                 | return "tsat should be between 0.01 C and 373 C ! "  if tsat > 373
                                 | sf ← SFSATT_H2O(tsat)
                                 | sfg ← SFGSATT_H2O(tsat)
                                 | x ← quality_Th_H2O(tsat,h)
                                 | s ← sf + x·sfg
```



```
Ex:        tsat := 180       h := 2500

       entropy_2phase_Th_H2O(tsat,h) = 5.972

========================================

                         | return  "psat should be between 0.611 kPa and 21814 kPa ! "  if  psat > 21814
                         | PSAT ← psat
                         | hf ← HFSATP_H2O(PSAT)
                         | hfg ← HFGSATP_H2O(PSAT)
                         | h ← hf + x·hfg

 Ex:        psat := 1000     x := 0.5

       enthalpy_2phase_Px_H2O(psat,x) = 1.77 × 10^3

------------------------------------------------------------------

enthalpy_2phase_Tx_H2O(tsat,x) :=  | return  "tsat should be between 0.01 C and 373 C ! "  if  tsat < 0.01
                                   | return  "tsat should be between 0.01 C and 373 C ! "  if  tsat > 373
                                   | hf ← HFSATT_H2O(tsat)
                                   | hfg ← HFGSATT_H2O(tsat)
                                   | h ← hf + x·hfg
------------------------------------------------------------------
```





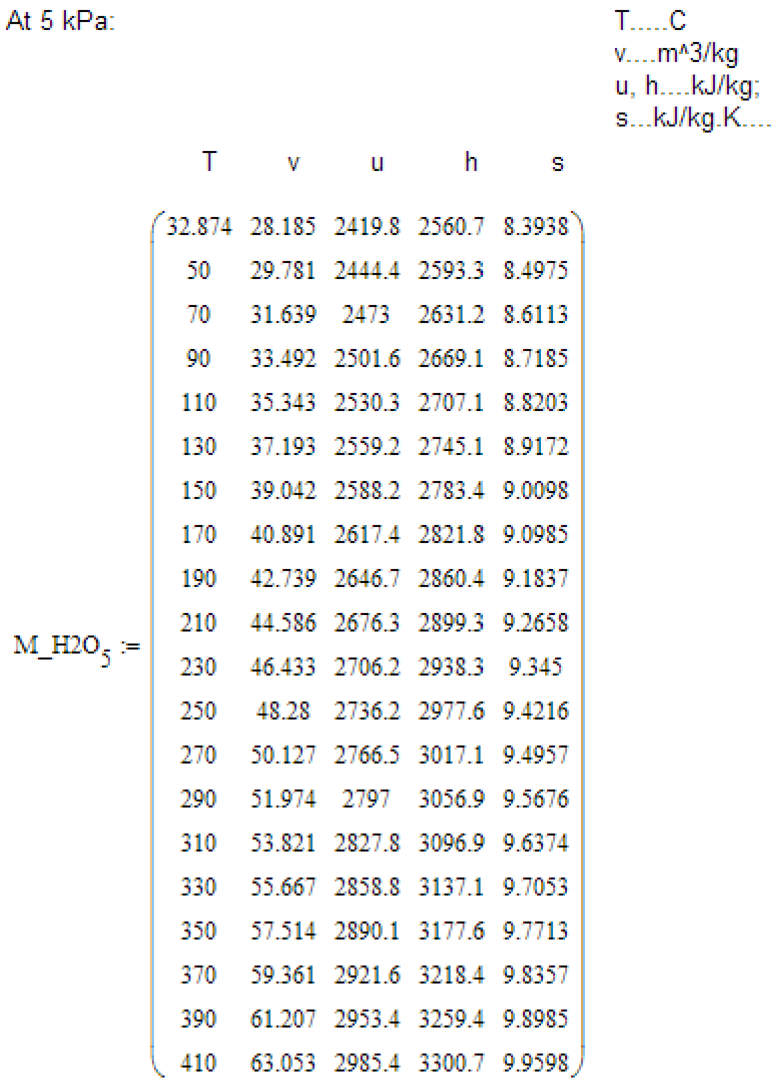
```
Ex:        tsat := 80        x := 0

        enthalpy_2phase_Tx_H2O(tsat,x) = 335.01

--------------------------------------------------------------------------------
enthalpy_2phase_Ts_H2O(tsat,s) := | return "tsat should be between 0.01 C and 373 C ! "  if tsat < 0.01
                                  | return "tsat should be between 0.01 C and 373 C ! "  if tsat > 373
                                  | x ← quality_Ts_H2O(tsat,s)
                                  | hf ← HFSATT_H2O(tsat)
                                  | hfg ← HFGSATT_H2O(tsat)
                                  | h ← hf + x·hfg

Ex:        tsat := 80        s := 2.9

        enthalpy_2phase_Ts_H2O(tsat,s) = 979.291

------------------------------------------------------------------------------------------------------------
enthalpy_2phase_Ps_H2O(psat,s) := | return "psat should be between 0.611 kPa and 21814 kPa ! "  if psat < 0.611
                                  | return "psat should be between 0.611 kPa and 21814 kPa ! "  if psat > 21814
                                  | x ← quality_Ps_H2O(psat,s)
                                  | PSAT ← psat
                                  | hf ← HFSATP_H2O(PSAT)
                                  | hfg ← HFGSATP_H2O(PSAT)
                                  | h ← hf + x·hfg

Ex:        psat := 1000      s := 2.9

        enthalpy_2phase_Ps_H2O(psat,s) = 1.108 × 10^3

==============================================================
```

Next, for Superheated steam:

For each pressure, the Table is copied as a matrix in Mathcad, where the columns give data on P (kPa), T (deg.C), v (m^3/kg), u (kJ/kg), h (kJ/kg) and s (kJ/kg.C). Linear interpolation is done to get intermediate values.

Data Matrices are written for the following pressures: 5, 10, 50, 100, 200, 300, 400, 500, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 6000, 7000, 8000, 9000, 10000, 12500, 15000, 17500, 20000 kPa.

A sample set of data written for a pressure of 5 kPa are shown below:



At 5 kPa:

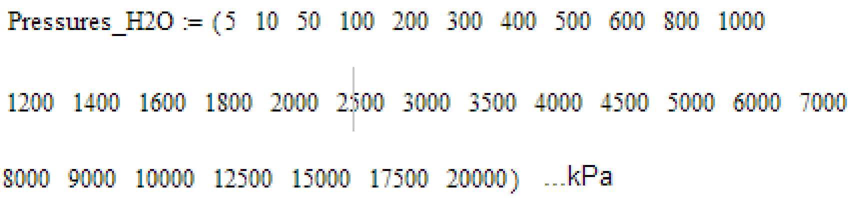
T.....C
v....m^3/kg
u, h....kJ/kg;
s...kJ/kg.K....

$$M\_H2O_{5} := \begin{array}{c} \begin{matrix} T & v & u & h & s \end{matrix} \\ \begin{pmatrix} 32.874 & 28.185 & 2419.8 & 2560.7 & 8.3938 \\ 50 & 29.781 & 2444.4 & 2593.3 & 8.4975 \\ 70 & 31.639 & 2473 & 2631.2 & 8.6113 \\ 90 & 33.492 & 2501.6 & 2669.1 & 8.7185 \\ 110 & 35.343 & 2530.3 & 2707.1 & 8.8203 \\ 130 & 37.193 & 2559.2 & 2745.1 & 8.9172 \\ 150 & 39.042 & 2588.2 & 2783.4 & 9.0098 \\ 170 & 40.891 & 2617.4 & 2821.8 & 9.0985 \\ 190 & 42.739 & 2646.7 & 2860.4 & 9.1837 \\ 210 & 44.586 & 2676.3 & 2899.3 & 9.2658 \\ 230 & 46.433 & 2706.2 & 2938.3 & 9.345 \\ 250 & 48.28 & 2736.2 & 2977.6 & 9.4216 \\ 270 & 50.127 & 2766.5 & 3017.1 & 9.4957 \\ 290 & 51.974 & 2797 & 3056.9 & 9.5676 \\ 310 & 53.821 & 2827.8 & 3096.9 & 9.6374 \\ 330 & 55.667 & 2858.8 & 3137.1 & 9.7053 \\ 350 & 57.514 & 2890.1 & 3177.6 & 9.7713 \\ 370 & 59.361 & 2921.6 & 3218.4 & 9.8357 \\ 390 & 61.207 & 2953.4 & 3259.4 & 9.8985 \\ 410 & 63.053 & 2985.4 & 3300.7 & 9.9598 \end{pmatrix} \end{array}$$

Then, all the data matrices written for the different pressures are combined into a single program with linear interpolation applied for any desired pressure and temperature:

This Function returns enthalpy (h, kJ/kg) and entropy (s, kJ/kg.C) when pressure (P, in kPa) and temp (T, in C) are input.

First, a data vector is created for all the pressures for which we have collected data:



Pressures_H2O := (5 10 50 100 200 300 400 500 600 800 1000

1200 1400 1600 1800 2000 2500 3000 3500 4000 4500 5000 6000 7000

8000 9000 10000 12500 15000 17500 20000) ...kPa

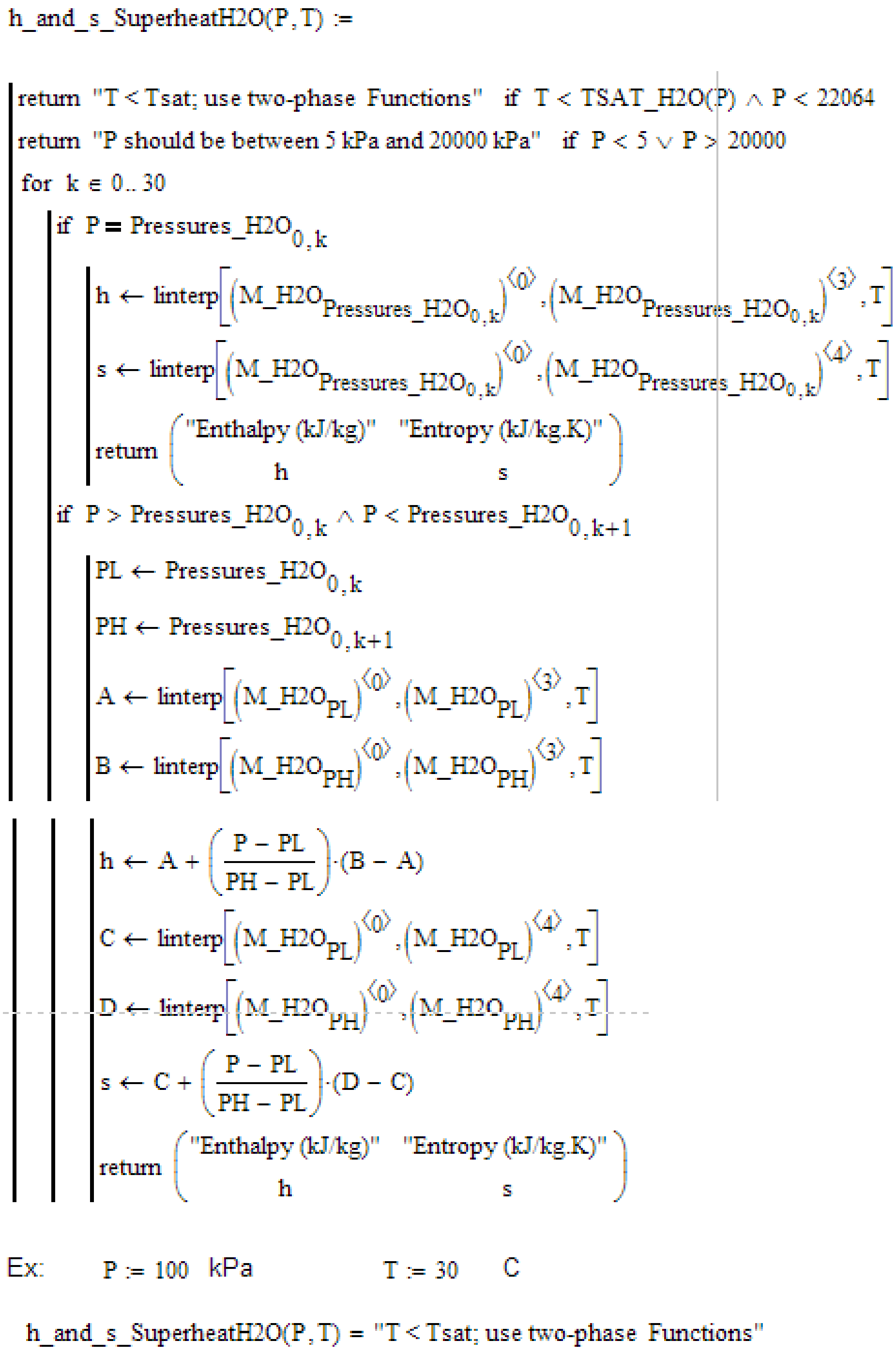
Explanation of the Function:

In the Function below, P and T are the inputs, and h and s are the outputs.

If the input P value exactly matches with one of the values in the Pressures_H2O data vector, that particular Matrix is accessed and the h and s are found out by linear interpolation.

However, if the input P does not exactly match with any of the values in the Pressures_H2O data vector, then the pressures PL and PH which bracket P are found out, and the h and s are first calculated for pressures corresponding to PL and PH, and then the h and s values at the required P are found out by linear interpolation:

Now, write the function:

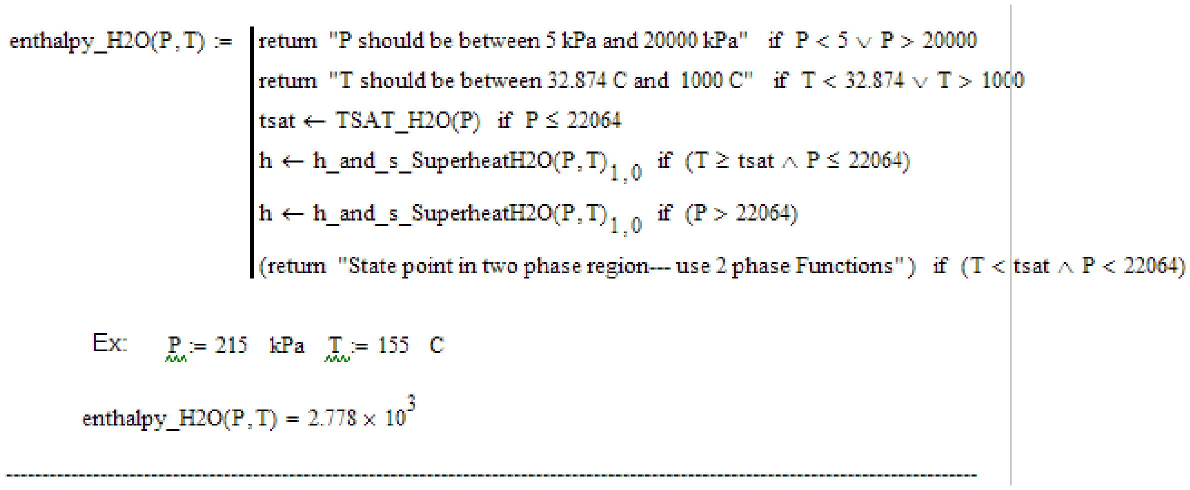


```
h_and_s_SuperheatH2O(P, T) :=
    return "T < Tsat; use two-phase  Functions"   if  T < TSAT_H2O(P) ∧ P < 22064
    return "P should be between 5 kPa and 20000 kPa"   if  P < 5 ∨ P > 20000
    for  k ∈ 0..30
        if  P = $Pressures\_H2O_{0,k}$
            h ← linterp[$(M\_H2O_{Pressures\_H2O_{0,k}})^{\langle 0\rangle}$, $(M\_H2O_{Pressures\_H2O_{0,k}})^{\langle 3\rangle}$, T]
            s ← linterp[$(M\_H2O_{Pressures\_H2O_{0,k}})^{\langle 0\rangle}$, $(M\_H2O_{Pressures\_H2O_{0,k}})^{\langle 4\rangle}$, T]
            return ("Enthalpy (kJ/kg)"  "Entropy (kJ/kg.K)"; h  s)
        if  P > $Pressures\_H2O_{0,k}$ ∧ P < $Pressures\_H2O_{0,k+1}$
            PL ← $Pressures\_H2O_{0,k}$
            PH ← $Pressures\_H2O_{0,k+1}$
            A ← linterp[$(M\_H2O_{PL})^{\langle 0\rangle}$, $(M\_H2O_{PL})^{\langle 3\rangle}$, T]
            B ← linterp[$(M\_H2O_{PH})^{\langle 0\rangle}$, $(M\_H2O_{PH})^{\langle 3\rangle}$, T]
            h ← $A + \left(\frac{P - PL}{PH - PL}\right)\cdot(B - A)$
            C ← linterp[$(M\_H2O_{PL})^{\langle 0\rangle}$, $(M\_H2O_{PL})^{\langle 4\rangle}$, T]
            D ← linterp[$(M\_H2O_{PH})^{\langle 0\rangle}$, $(M\_H2O_{PH})^{\langle 4\rangle}$, T]
            s ← $C + \left(\frac{P - PL}{PH - PL}\right)\cdot(D - C)$
            return ("Enthalpy (kJ/kg)"  "Entropy (kJ/kg.K)"; h  s)
```

Ex: P := 100 kPa   T := 30 C

h_and_s_SuperheatH2O(P, T) = "T < Tsat; use two-phase Functions"

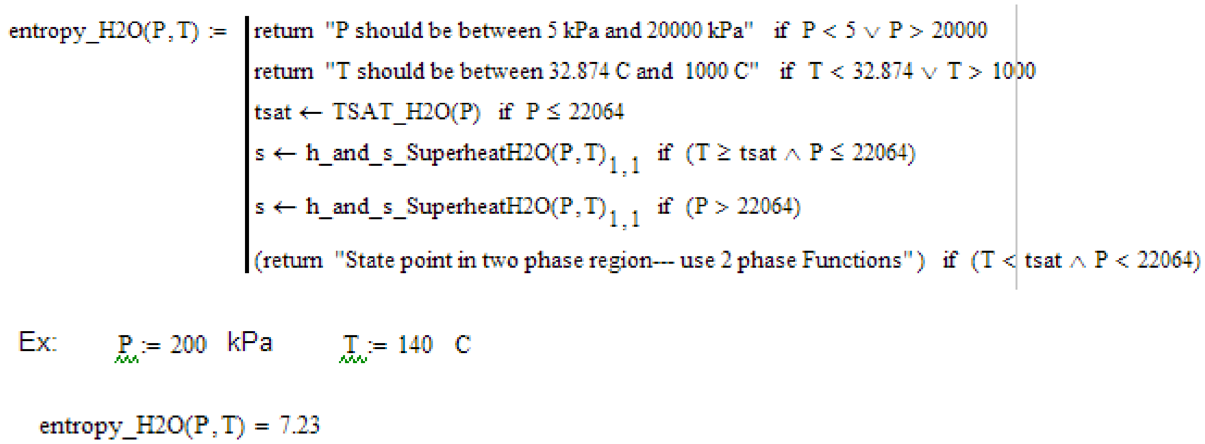
Further, for convenience and uniformity, we write the following programs to get enthalpy and entropy of H2O/Steam when P and T are given in kPa and deg.C respectively:



```
enthalpy_H2O(P,T) := | return "P should be between 5 kPa and 20000 kPa"  if P < 5 ∨ P > 20000
                     | return "T should be between 32.874 C and 1000 C"  if T < 32.874 ∨ T > 1000
                     | tsat ← TSAT_H2O(P)  if P ≤ 22064
                     | h ← h_and_s_SuperheatH2O(P,T)1,0  if (T ≥ tsat ∧ P ≤ 22064)
                     | h ← h_and_s_SuperheatH2O(P,T)1,0  if (P > 22064)
                     | (return "State point in two phase region--- use 2 phase Functions")  if (T < tsat ∧ P < 22064)
```

Ex: P := 215 kPa T := 155 C

enthalpy_H2O(P,T) = 2.778×10^3

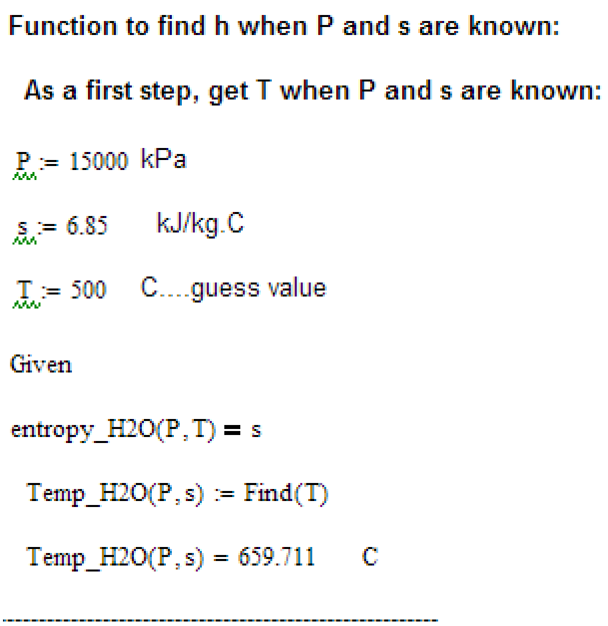


```
entropy_H2O(P,T) := | return "P should be between 5 kPa and 20000 kPa"  if P < 5 ∨ P > 20000
                    | return "T should be between 32.874 C and 1000 C"  if T < 32.874 ∨ T > 1000
                    | tsat ← TSAT_H2O(P)  if P ≤ 22064
                    | s ← h_and_s_SuperheatH2O(P,T)1,1  if (T ≥ tsat ∧ P ≤ 22064)
                    | s ← h_and_s_SuperheatH2O(P,T)1,1  if (P > 22064)
                    | (return "State point in two phase region--- use 2 phase Functions")  if (T < tsat ∧ P < 22064)
```

Ex: P := 200 kPa T := 140 C

entropy_H2O(P,T) = 7.23

==



Function to find h when P and s are known:

As a first step, get T when P and s are known:

P := 15000 kPa

s := 6.85 kJ/kg.C

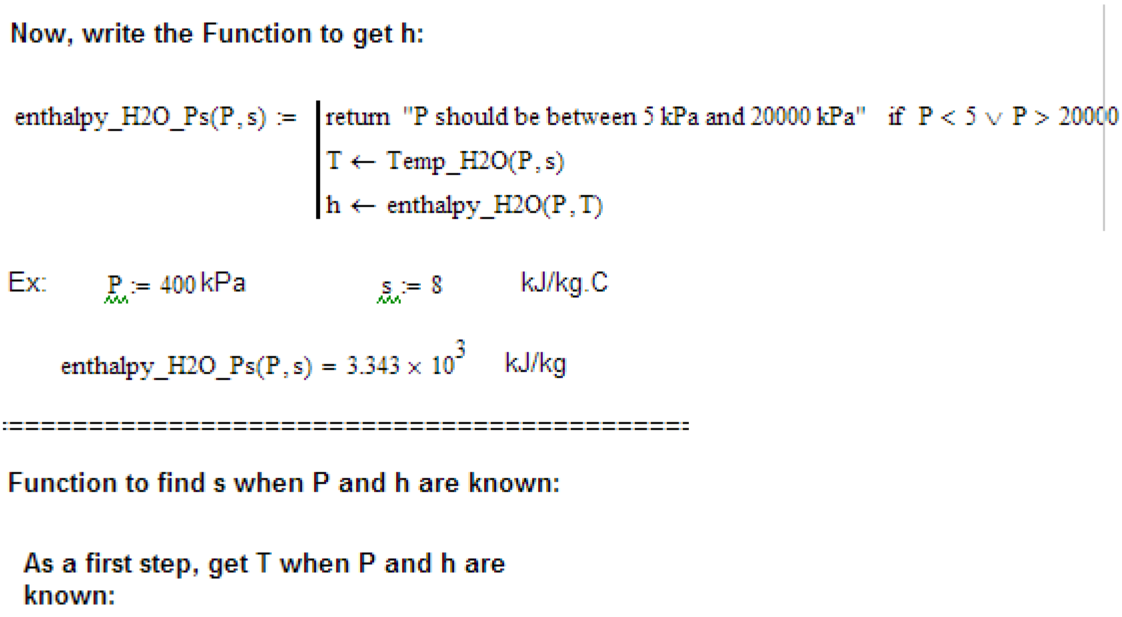
T := 500 C....guess value

Given

entropy_H2O(P,T) = s

Temp_H2O(P,s) := Find(T)

Temp_H2O(P,s) = 659.711 C



Now, write the Function to get h:

```
enthalpy_H2O_Ps(P, s) := | return "P should be between 5 kPa and 20000 kPa"  if  P < 5 ∨ P > 20000
                         | T ← Temp_H2O(P, s)
                         | h ← enthalpy_H2O(P, T)
```

Ex: $P := 400\,\mathrm{kPa}$ $s := 8$ kJ/kg.C

$\text{enthalpy\_H2O\_Ps}(P, s) = 3.343 \times 10^{3}$ kJ/kg

===

Function to find s when P and h are known:

As a first step, get T when P and h are known:

$P := 15000$ kPa $h := 3737$ kJ/kg

$T := 600$ C....guess value

Given

$\text{enthalpy\_H2O}(P,T) = h$

$\text{Temp\_H2O\_Ph}(P,h) := \text{Find}(T)$

$\text{Temp\_H2O\_Ph}(P,h) = 659.765$ C

Now, write the Function to get s:

```
entropy_H2O_Ph(P,h) := | return "P should be between 50 kPa and 20000 kPa"  if P < 50 ∨ P > 20000
                       | T ← Temp_H2O_Ph(P,h)
                       | s ← entropy_H2O(P,T)
```

Ex: $P := 200$ kPa $h := 2850$ kJ/kg $\text{Temp\_H2O\_Ph}(P,h) = 189.704$

$\text{entropy\_H2O\_Ph}(P,h) = 7.464$

:==

Function to determine Exergy of mass flow:

This function returns the specific availability of H2O in kJ/kg as a function of

T [C], P [kPa], and 'dead state' P0 (kPa), T0 (C)

```
Exergy_flow_H2O(h,s,T0,P0) := | h0 ← HFSATT_H2O(T0)
                              | s0 ← SFSATT_H2O(T0)
                              | return 0  if h = h0 ∧ s = s0
                              | (h − h0) − (T0 + 273)(s − s0)
```

Ex: $P := 3000$ kPa $T := 350$ C $P0 := 101.3$ kPa $T0 := 17$ C

Then:

$\text{Exergy\_flow\_H2O}(h,s,T0,P0) = 532.094$ **kJ/kg .... exergy of mass flow**

Now, let us work out some problems using the above written Mathcad Functions for H2O/Steam:

Note: Diagrams for Rankine cycle and its variations are from Ref: [8]

Prob.3.1 A steam power plant works on Rankine cycle between pressure ratio 20 bar and 0.05 bar. Steam supplied to the turbine is dry, saturated. Find thermal efficiency, work ratio and Specific Steam Consumption (SSC). What would be the efficiency and work ratio in case of Carnot cycle operating in the same pressure limits? [M.U.]

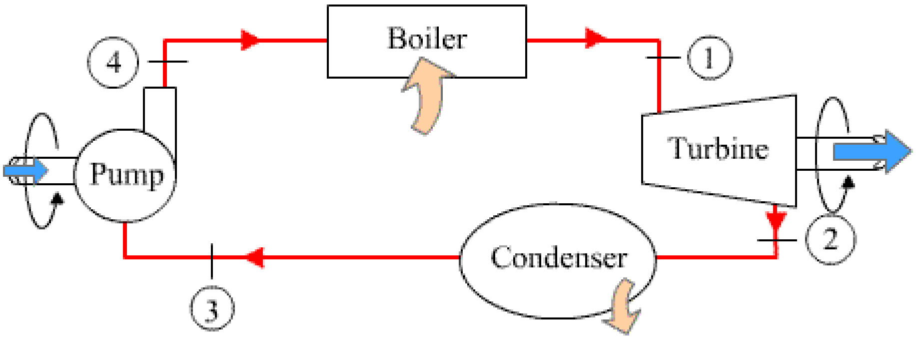


Fig.Prob.3.1 (a). Schematic diagram of simple, ideal Rankine cycle

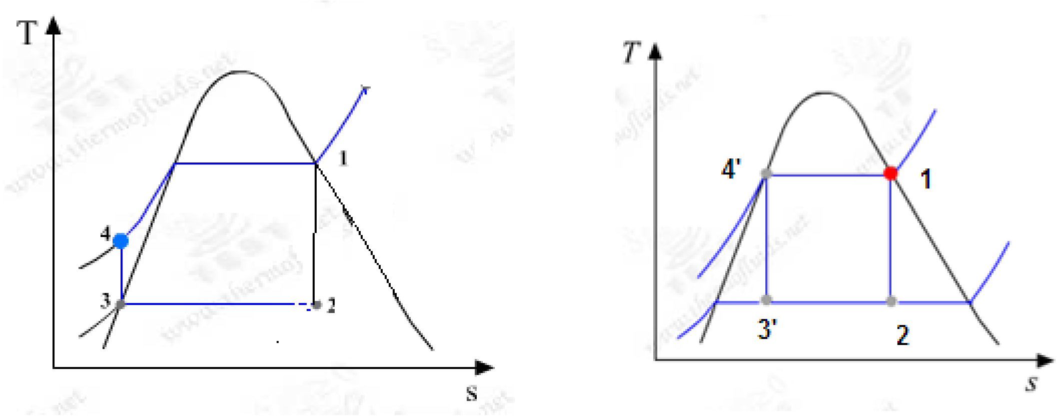


Fig.Prob.3.1 (b) and (c). T-s diagram of simple, ideal Rankine cycle, and of Carnot cycle

Solution:

Data:

$P_{boiler} := 2000$ kPa $P_{cond} := 5$ kPa

$x1 := 1$ ...steam supplied to turbine is sat. and dry.

First, calculate the properties at salient points in cycle:

State 1:

$h1 := \mathrm{HGSATP\_H2O}(\mathrm{P\_boiler})$ i.e. $h1 = 2.798 \times 10^{3}$ **kJ/kg ... enthalpy at entry to turbine**

$s1 := \mathrm{SGSATP\_H2O}(\mathrm{P\_boiler})$ i.e. $s1 = 6.34$ kJ/kg.K

State 2:

$s2 := s1$ ..for isentropic expn in turbine

$x2 := \mathrm{quality\_Ps\_H2O}(\mathrm{P\_cond}, s2)$

i.e. $x2 = 0.74$ ...quality of steam after expn in turbine

$h2 := \mathrm{enthalpy\_2phase\_Px\_H2O}(\mathrm{P\_cond}, x2)$

i.e. $h2 = 1.931 \times 10^{3}$ **kJ/kg .... enthalpy at the end of expn in turbine**

State 3:

$h3 := HFSATP\_H2O(P\_cond)$

i.e. $h3 = 137.118$ **kJ/kg ... enthalpy of sat. liq. at entry to the Pump**

$s3 := SFSATP\_H2O(P\_cond)$

i.e. $s3 = 0.474$ kJ/kg.K ... entropy of sat. liq. at entry to the Pump

$vf3 := VFSATP\_H2O(P\_cond)$

i.e. $vf3 = 1.005 \times 10^{-3}$ m^3/kg ...sp. vol. of sat. liq. at entry to the Pump

Therefore, Pump work:

$w\_P := vf3 \cdot (P\_boiler - P\_cond)$

i.e. $w\_P = 2.006$ **kJ/kg .... Ans.**

State 4:

$h4 := h3 + w\_P$ i.e. $h4 = 139.123$ **kJ/kg .... enthalpy at exit of pump**

$s4 := s3$ ...for isentropic compression in Pump

Now, find out the parameters required:

Turbine work:

$w\_T := h1 - h2$ i.e. $w\_T = 866.896$ **kJ/kg ... Ans.**

Net work:

$w\_net := w\_T - w\_P$ i.e. $w\_net = 864.89$ **kJ/kg ... Ans.**

Heat supplied in boiler:

$q\_in := h1 - h4$ i.e. $q\_in = 2.659 \times 10^{3}$ **kJ/kg ... Ans.**

Heat rejected in condenser:

$q\_out := h2 - h3$ i.e. $q\_out = 1.794 \times 10^{3}$ **kJ/kg ... Ans.**

Thermal efficiency:

$eta := \frac{w\_net}{q\_in}$ i.e. $eta = 0.325$ **= 32.5 % ..... Ans.**

Work Ratio:

$WR := \frac{w\_net}{w\_T}$ i.e. $WR = 0.998$ **...work ratio .... Ans.**

Specific Steam Consumption:

$SSC := \frac{3600}{w\_net}$ i.e. $SSC = 4.162$ **kg/kWh .... Ans.**

For a Carnot cycle, working between same temp. limits:

State 1 and State 2 remain the same. State 4 is dry, sat. at boiler pressure, and state 3 is such that s3 = s4. So, problem is to find out corresponding h3 and h4 for Carnot cycle, i.e, find h3_prime and h4_prime:

State 4-prime:

$h4\_prime := HFSATP\_H2O(P\_boiler)$

i.e. $h4\_prime = 907.927$ **kJ/kg ... enthalpy at state 4 for Carnot cycle**

$s4\_prime := SFSATP\_H2O(P\_boiler)$

i.e. $s4\_prime = 2.445$ **kJ/kg ... entropy at state 4 for Carnot cycle**

State 3-prime:

$s3\_prime := s4\_prime$ ....for isentropic compression in pump

$h3\_prime := enthalpy\_2phase\_Ps\_H2O(P\_cond, s3\_prime)$

i.e. $h3\_prime = 740.046$ **kJ/kg ... enthalpy at state 3 for Carnot cycle**

$x3\_prime := quality\_Ph\_H2O(P\_cond, h3\_prime)$

i.e. $x3\_prime = 0.249$ ...quality of steam at point 3_prime for Carnot cycle ... entry to pump

Now, calculate the required parameters for Carnot cycle:

Pump work:

$w\_P\_Carnot := h4\_prime - h3\_prime$

i.e. $w\_P\_Carnot = 167.88$ **kJ/kg .... Ans.**

Turbine work:

$$w\_T\_Carnot := h1 - h2$$

i.e. $w\_T\_Carnot = 866.896$ **kJ/kg .... Ans.**

Net work:

$$w\_net\_Carnot := w\_T - w\_P\_Carnot$$

i.e. $w\_net\_Carnot = 699.015$ **kJ/kg ... Ans.**

Work Ratio:

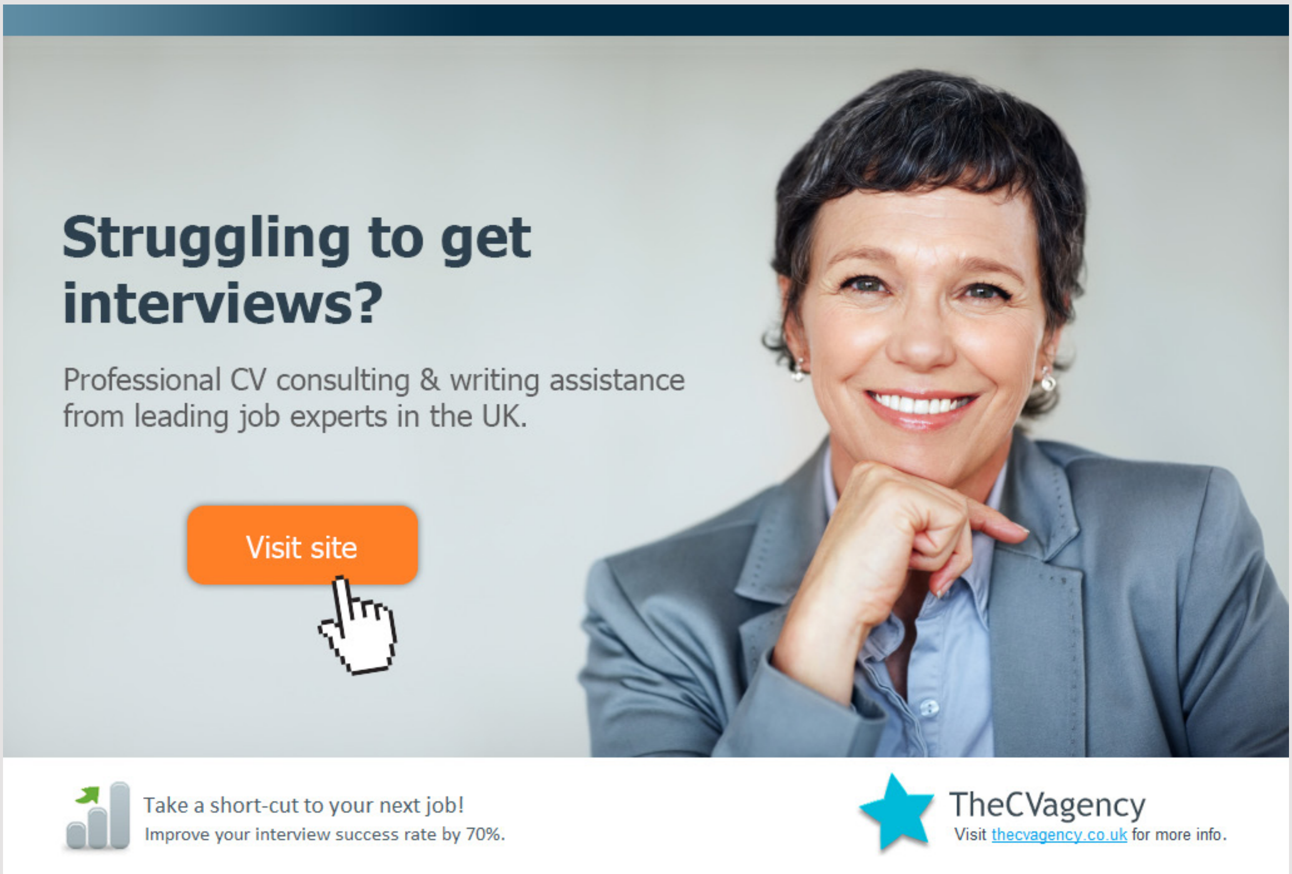
$$WR\_Carnot := \frac{w\_net\_Carnot}{w\_T\_Carnot}$$

i.e. $WR\_Carnot = 0.806$ **...Ans.**

Efficiency:

$$eta\_Carnot = \frac{T\_boiler - T\_cond}{T\_boiler + 273}$$

$T\_boiler := TSAT\_H2O(P\_boiler)$ i.e. $T\_boiler = 212.377$ C



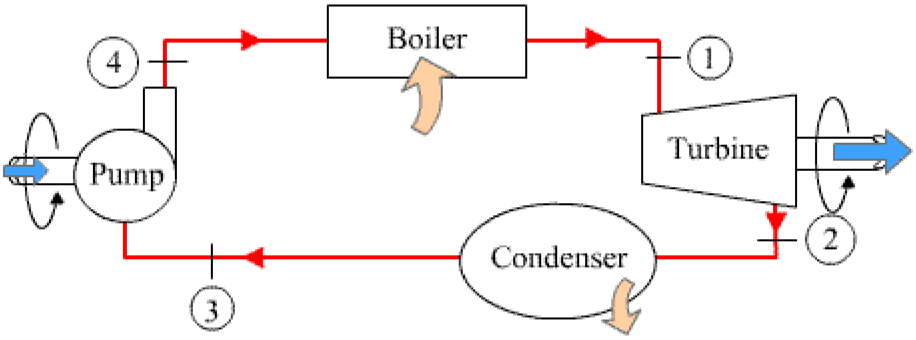
T_cond := TSAT_H2O(P_cond)   i.e.   T_cond = 32.875   C

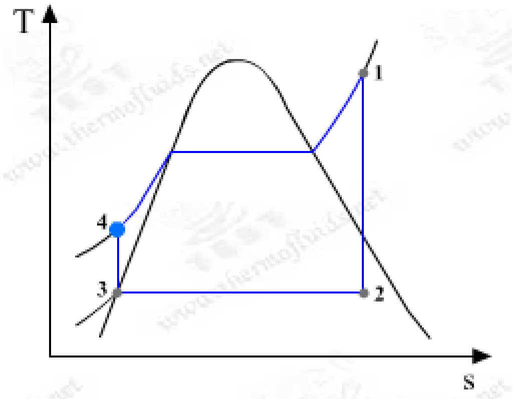
Therefore:

$$\text{eta\_Carnot} := \frac{\text{T\_boiler} - \text{T\_cond}}{\text{T\_boiler} + 273}$$

i.e.   eta_Carnot = 0.37   **= 37 % ...Thermal effcy.. Ans.**

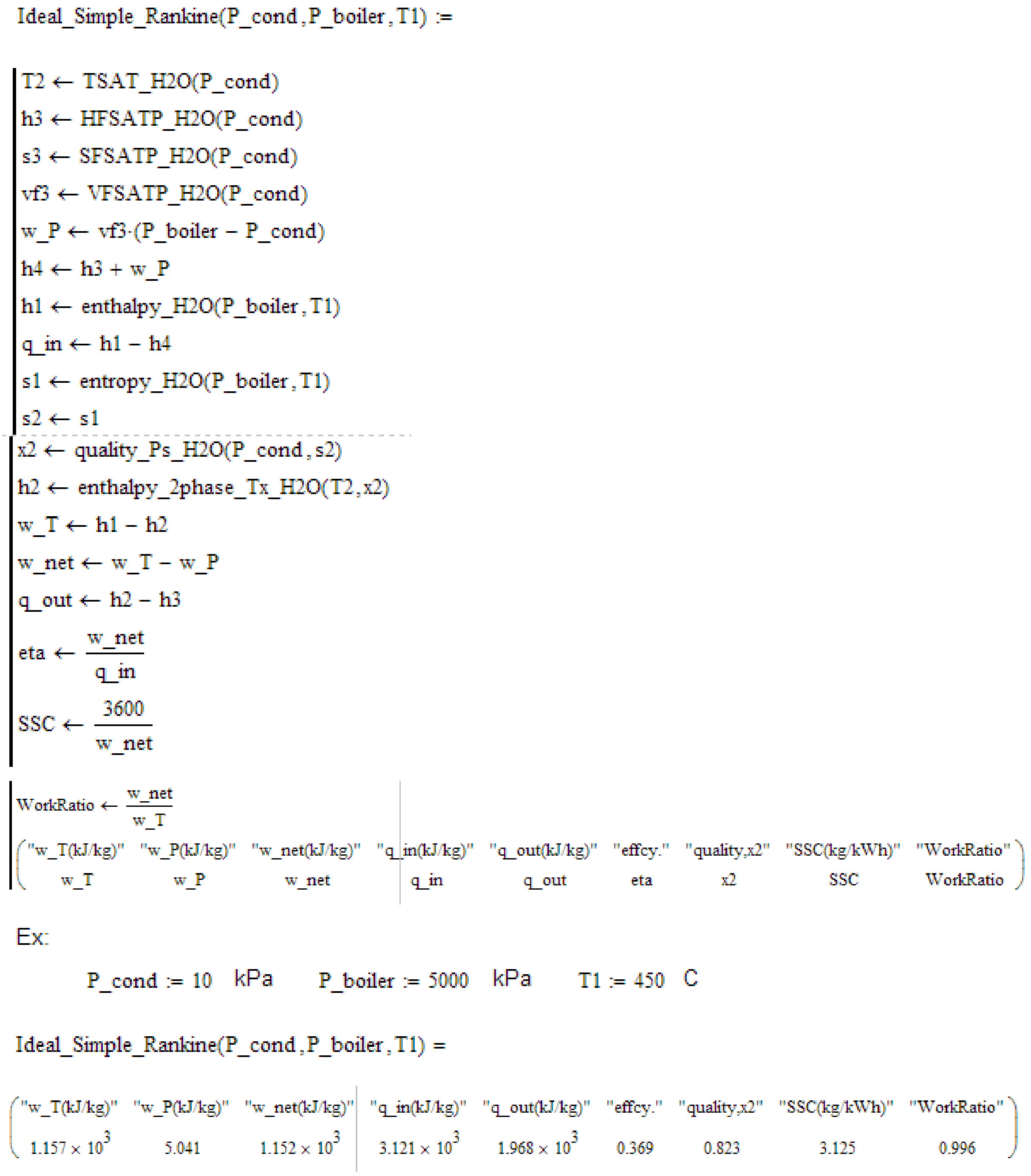
Prob. 3.2 Write a Mathcad program to find out the parameters of interest for an Ideal Rankine cycle operating between a condenser pressure P_cond, Turbine inlet temp T1, and boiler pressure of P_boiler.





Solution:

Here, pressures are in kPa, temp in deg.C.



```
Ideal_Simple_Rankine(P_cond, P_boiler, T1) :=

   T2 ← TSAT_H2O(P_cond)
   h3 ← HFSATP_H2O(P_cond)
   s3 ← SFSATP_H2O(P_cond)
   vf3 ← VFSATP_H2O(P_cond)
   w_P ← vf3·(P_boiler − P_cond)
   h4 ← h3 + w_P
   h1 ← enthalpy_H2O(P_boiler, T1)
   q_in ← h1 − h4
   s1 ← entropy_H2O(P_boiler, T1)
   s2 ← s1
   x2 ← quality_Ps_H2O(P_cond, s2)
   h2 ← enthalpy_2phase_Tx_H2O(T2, x2)
   w_T ← h1 − h2
   w_net ← w_T − w_P
   q_out ← h2 − h3
   eta ← w_net / q_in
   SSC ← 3600 / w_net
   WorkRatio ← w_net / w_T
   ( "w_T(kJ/kg)"  "w_P(kJ/kg)"  "w_net(kJ/kg)"  "q_in(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "quality,x2"  "SSC(kg/kWh)"  "WorkRatio" )
   (    w_T           w_P            w_net            q_in           q_out          eta          x2            SSC          WorkRatio  )

Ex:

      P_cond := 10   kPa     P_boiler := 5000   kPa     T1 := 450   C

Ideal_Simple_Rankine(P_cond, P_boiler, T1) =

( "w_T(kJ/kg)"   "w_P(kJ/kg)"  "w_net(kJ/kg)"  "q_in(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "quality,x2"  "SSC(kg/kWh)"  "WorkRatio" )
(  1.157 × 10^3     5.041       1.152 × 10^3    3.121 × 10^3   1.968 × 10^3    0.369      0.823          3.125          0.996    )
```

Explanation for the above Function:

This function gives all the important parameters of performance of Ideal Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where temperature T1 is in deg.C and pressures P_cond and P_boiler are in kPa. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump work (w_P), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), quality of steam at turbine exit (x2), Specific Steam Consumption (SSC) and Work Ratio. Units of each quantity are also given in output.

The line structure is the RHS of the Function.

Each step therein is explained below in the same order:

- Sat. temp T2 in condenser is calculated, knowing the P_cond
- h3, the sat. liq. enthalpy at point 3, i.e. at entry to pump is calculated
- s3, the sat. liq. entropy at entry to pump is calculated
- vf3, the sp. vol. of sat. liq. at entry to pump is calculated

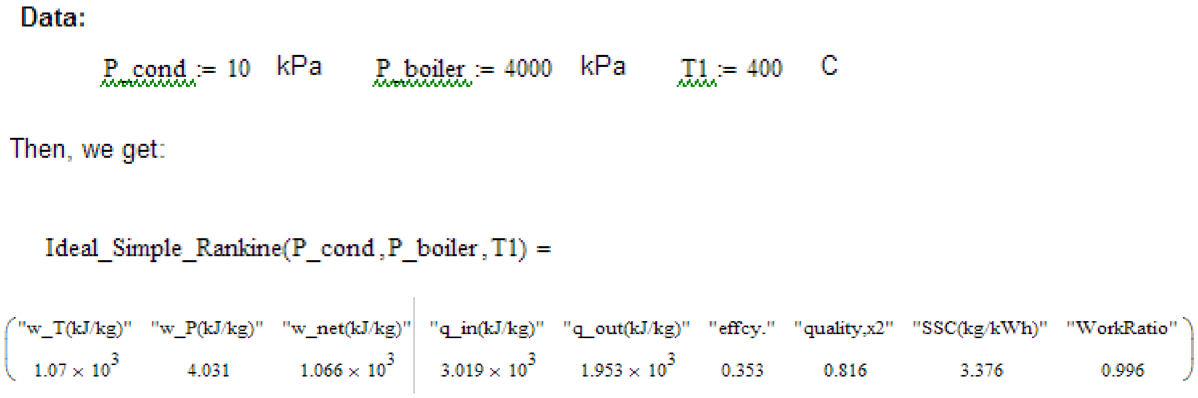
- Isentropic work of compression in Pump w_P is calculated as w_p = vf. ΔP
- h4, enthalpy at the exit of pump is calculated
- h1, enthalpy at the turbine inlet, is calculated
- q_in, heat supplied in boiler is calculated
- s1, the entropy at entry to turbine is calculated
- s2 = s1, for isentropic expansion in the turbine
- x2, the quality at exit of turbine is calculatedated
- h2, the enthalpy at turbine exit is calculated
- w_P, the Pump work is calculated as vf.ΔP = vf3. (P_boiler – P_cond)
- w_net, the net work output is calculated
- q_out, the heat rejected in condenser is calculated
- eta, the thermal effcy is calculated
- Specific Steam Consumption is calculated
- Work Ratio is calculated
- Finally, output Matrix contains all the calculated parameters of interest in a compact table

Prob. 3.3 In an Ideal Rankine cycle, steam enters the turbine at a temp 400 C and pressure of 4 MPa, and condenser pressure is 10 kPa. Determine the cycle efficiency and other parameters.[3]

Investigate the effect of changing the condenser pressure, boiler pressure and turbine inlet temperatures on the cycle efficiency, SSC and the quality (x2) at the turbine exit.

Solution:

We use the above written Mathcad Function straightaway:



Data:

P_cond := 10 kPa   P_boiler := 4000 kPa   T1 := 400 C

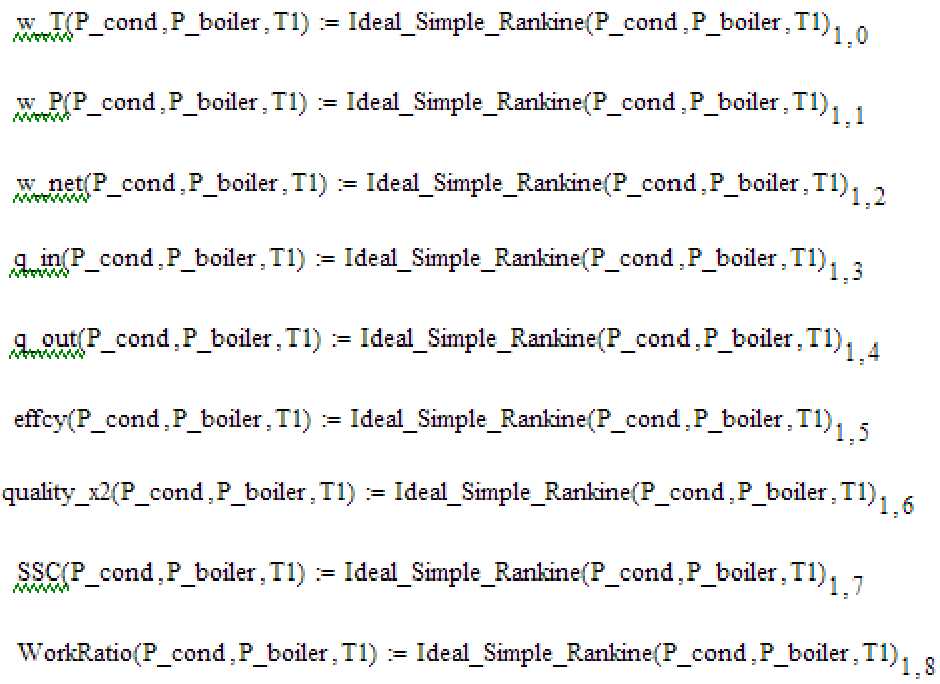
Then, we get:

Ideal_Simple_Rankine(P_cond, P_boiler, T1) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x2"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.07 \times 10^{3} & 4.031 & 1.066 \times 10^{3} & 3.019 \times 10^{3} & 1.953 \times 10^{3} & 0.353 & 0.816 & 3.376 & 0.996 \end{pmatrix}$$

Note that cycle efficiency = eta = 0.353 = 35.3%…Ans.

Let us write the different quantities as functions of P_cond, P_boiler and T1 so that we can easily plot the results later:



$\text{w\_T}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,0}$

$\text{w\_P}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,1}$

$\text{w\_net}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,2}$

$\text{q\_in}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,3}$

$\text{q\_out}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,4}$

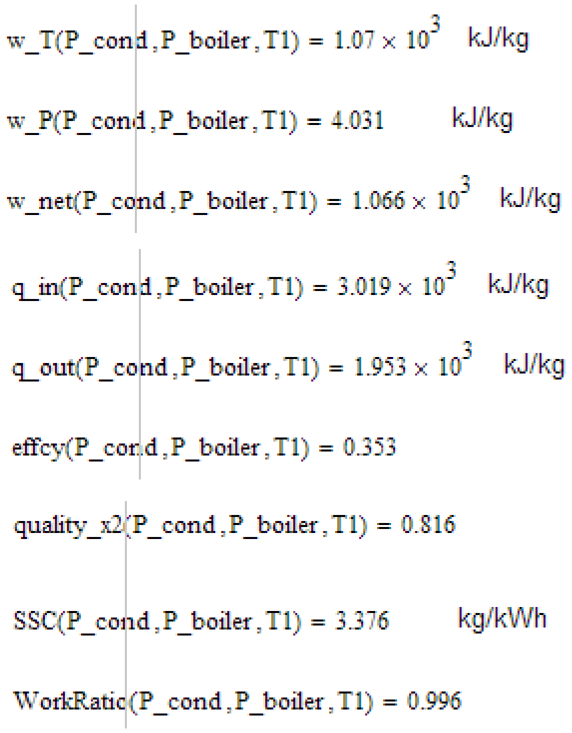
$\text{effcy}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,5}$

$\text{quality\_x2}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,6}$

$\text{SSC}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,7}$

$\text{WorkRatio}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) := \text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,8}$

i.e. we get:



$\text{w\_T}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 1.07 \times 10^{3}$ kJ/kg

$\text{w\_P}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 4.031$ kJ/kg

$\text{w\_net}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 1.066 \times 10^{3}$ kJ/kg

$\text{q\_in}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 3.019 \times 10^{3}$ kJ/kg

$\text{q\_out}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 1.953 \times 10^{3}$ kJ/kg

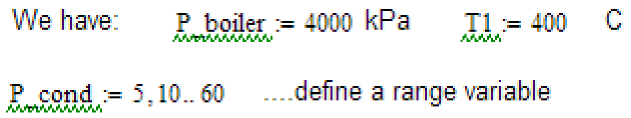
$\text{effcy}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 0.353$

$\text{quality\_x2}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 0.816$

$\text{SSC}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 3.376$ kg/kWh

$\text{WorkRatio}(\text{P\_cond}, \text{P\_boiler}, \text{T1}) = 0.996$

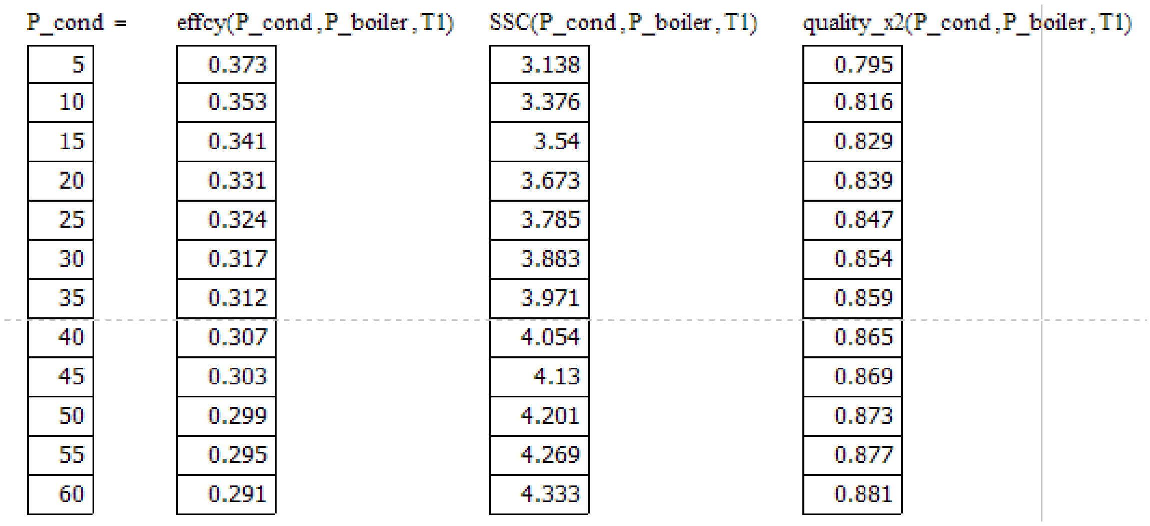
Now, plot the effect of changing condensing pressure on performance parameters, keeping P_boiler and T1 constant:



We have: P_boiler := 4000 kPa T1 := 400 C

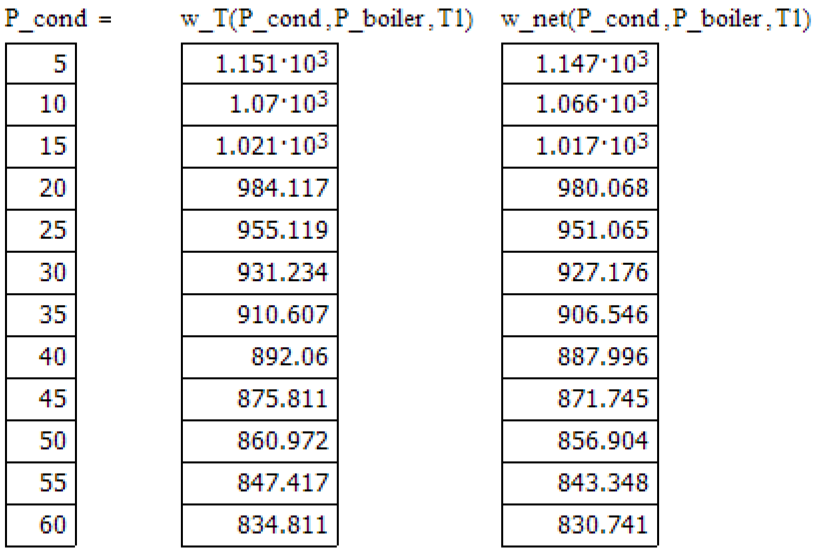
P_cond := 5, 10.. 60 ....define a range variable

We get:



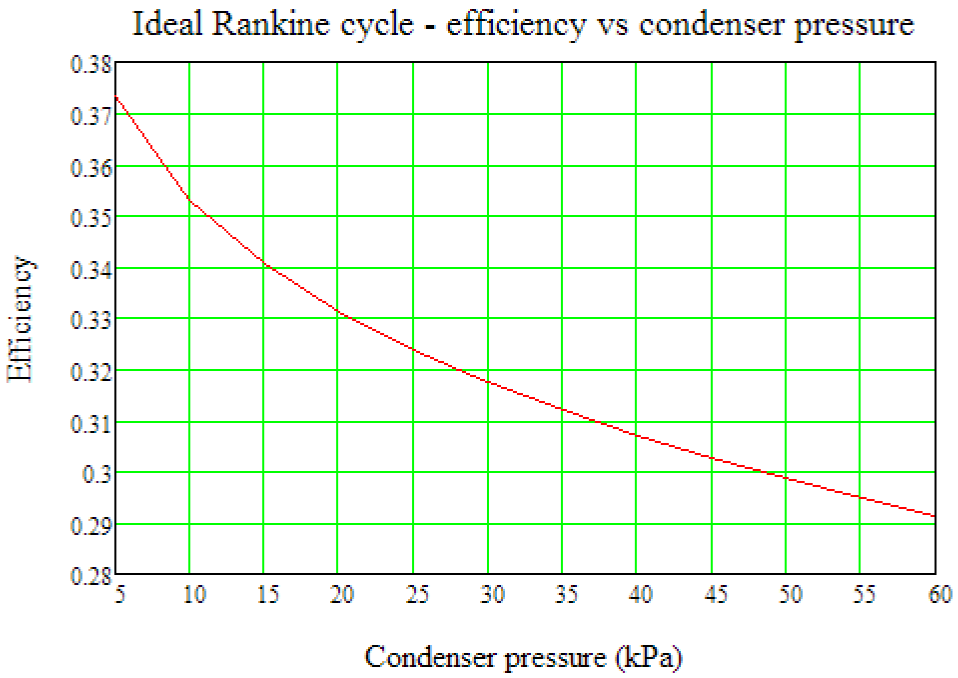
P_cond =	effcy(P_cond, P_boiler, T1)	SSC(P_cond, P_boiler, T1)	quality_x2(P_cond, P_boiler, T1)
5	0.373	3.138	0.795
10	0.353	3.376	0.816
15	0.341	3.54	0.829
20	0.331	3.673	0.839
25	0.324	3.785	0.847
30	0.317	3.883	0.854
35	0.312	3.971	0.859
40	0.307	4.054	0.865
45	0.303	4.13	0.869
50	0.299	4.201	0.873
55	0.295	4.269	0.877
60	0.291	4.333	0.881

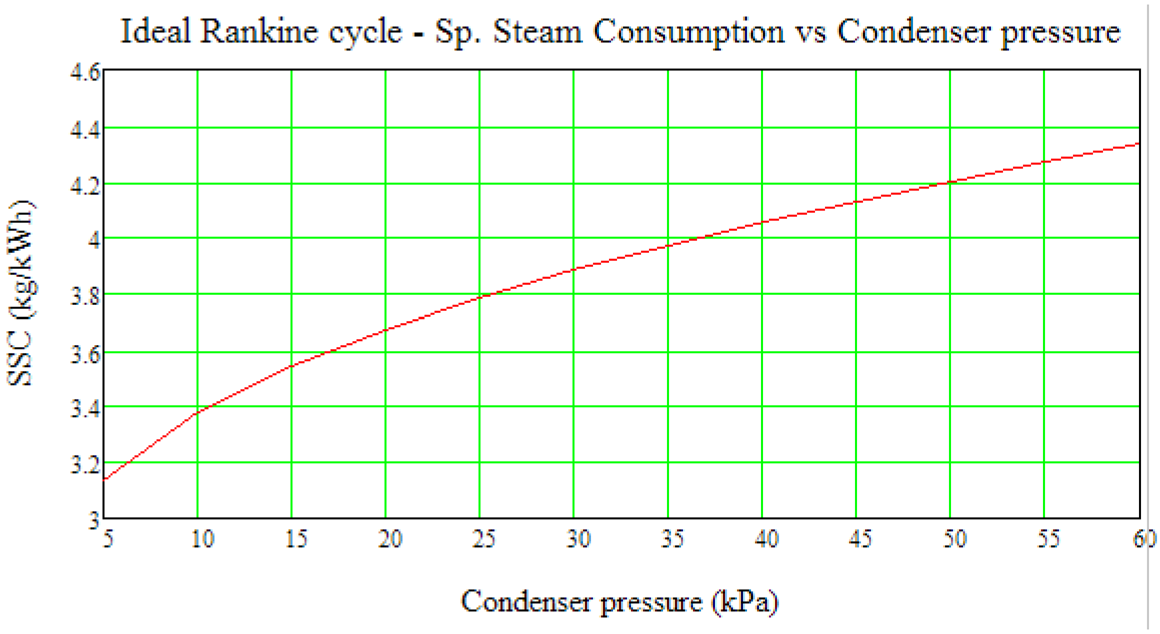
Also:

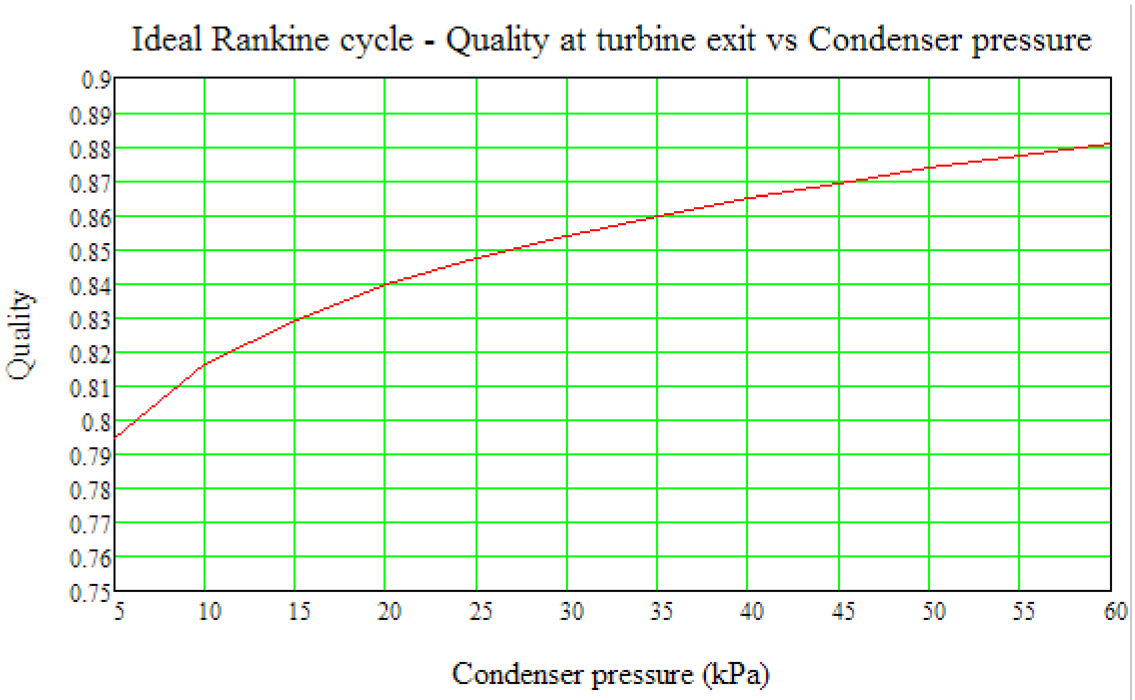


P_cond =	w_T(P_cond, P_boiler, T1)	w_net(P_cond, P_boiler, T1)
5	$1.151\cdot10^3$	$1.147\cdot10^3$
10	$1.07\cdot10^3$	$1.066\cdot10^3$
15	$1.021\cdot10^3$	$1.017\cdot10^3$
20	984.117	980.068
25	955.119	951.065
30	931.234	927.176
35	910.607	906.546
40	892.06	887.996
45	875.811	871.745
50	860.972	856.904
55	847.417	843.348
60	834.811	830.741

Plots:



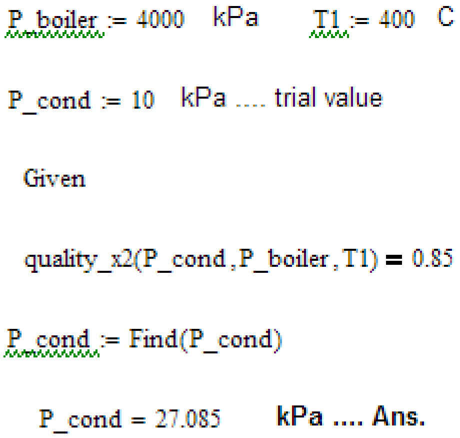




If the quality at turbine exit should be limited to 0.85 (i.e. moisture should not be more than 15%), what should be the lowest permitted condenser pressure?

Condenser pressure can be found out from the above graph.

Alternatively, use the 'Solve block' of Mathcad:



P_boiler := 4000 kPa   T1 := 400 C

P_cond := 10 kPa .... trial value

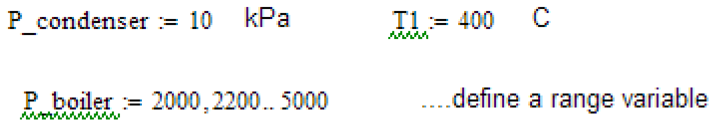
Given

quality_x2(P_cond, P_boiler, T1) = 0.85

P_cond := Find(P_cond)

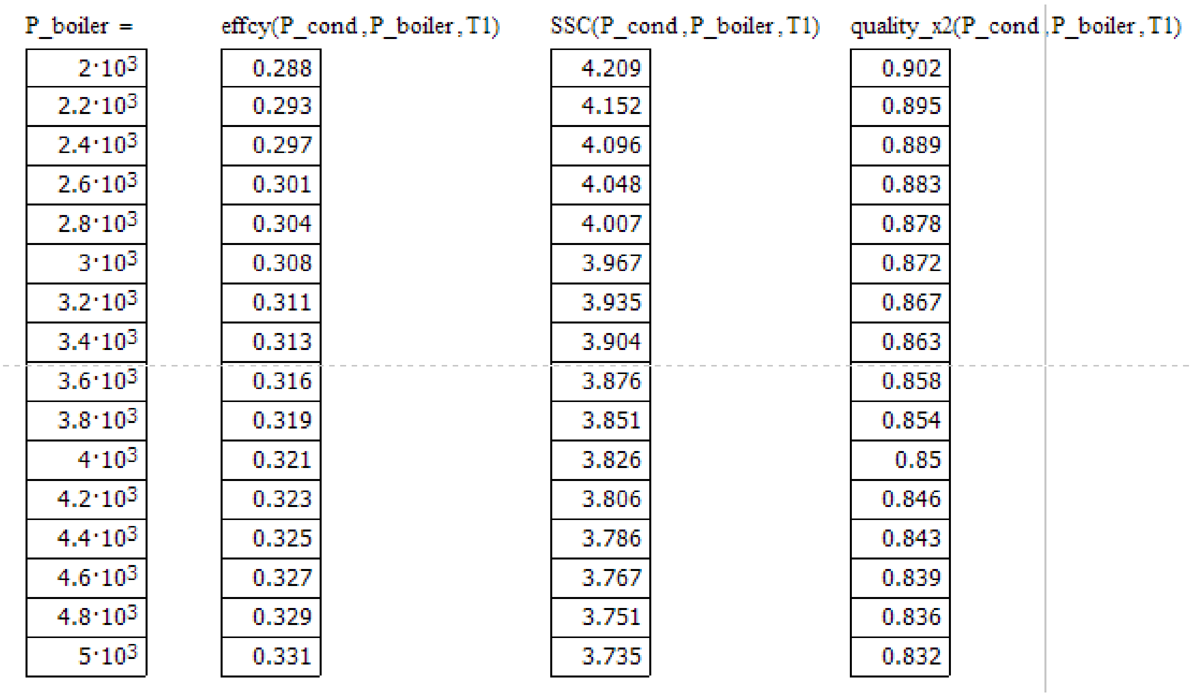
P_cond = 27.085 kPa .... Ans.

Plot the effect of changing boiler pressure on performance parameters, keeping P_ condenser and T1 constant:



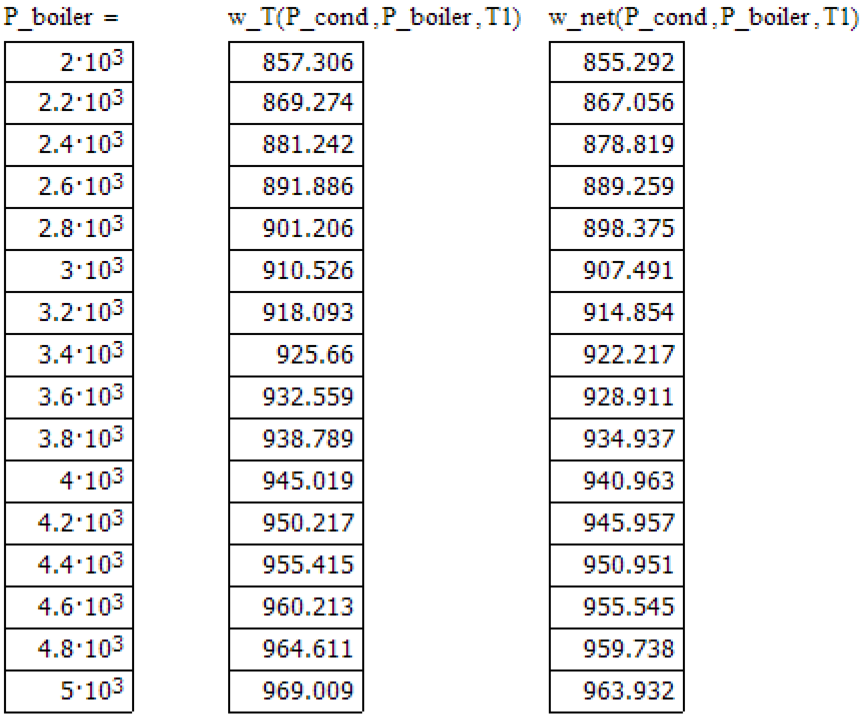
P_condenser := 10 kPa   T1 := 400 C

P_boiler := 2000, 2200 .. 5000   ....define a range variable



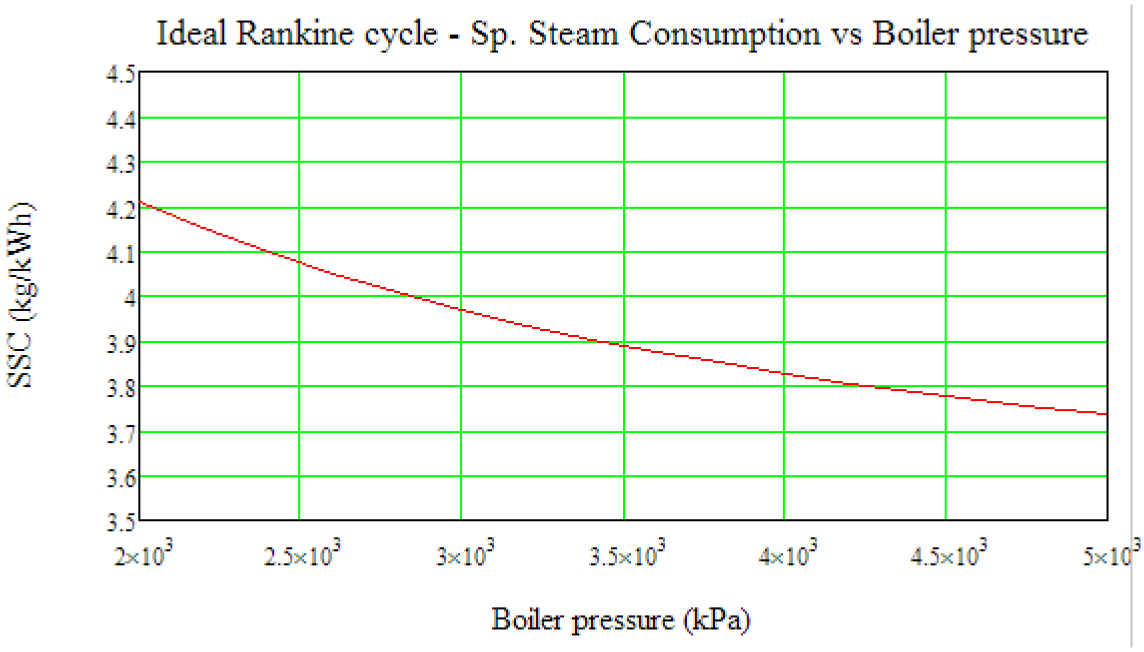
P_boiler =	effcy(P_cond, P_boiler, T1)	SSC(P_cond, P_boiler, T1)	quality_x2(P_cond, P_boiler, T1)
$2\cdot10^3$	0.288	4.209	0.902
$2.2\cdot10^3$	0.293	4.152	0.895
$2.4\cdot10^3$	0.297	4.096	0.889
$2.6\cdot10^3$	0.301	4.048	0.883
$2.8\cdot10^3$	0.304	4.007	0.878
$3\cdot10^3$	0.308	3.967	0.872
$3.2\cdot10^3$	0.311	3.935	0.867
$3.4\cdot10^3$	0.313	3.904	0.863
$3.6\cdot10^3$	0.316	3.876	0.858
$3.8\cdot10^3$	0.319	3.851	0.854
$4\cdot10^3$	0.321	3.826	0.85
$4.2\cdot10^3$	0.323	3.806	0.846
$4.4\cdot10^3$	0.325	3.786	0.843
$4.6\cdot10^3$	0.327	3.767	0.839
$4.8\cdot10^3$	0.329	3.751	0.836
$5\cdot10^3$	0.331	3.735	0.832

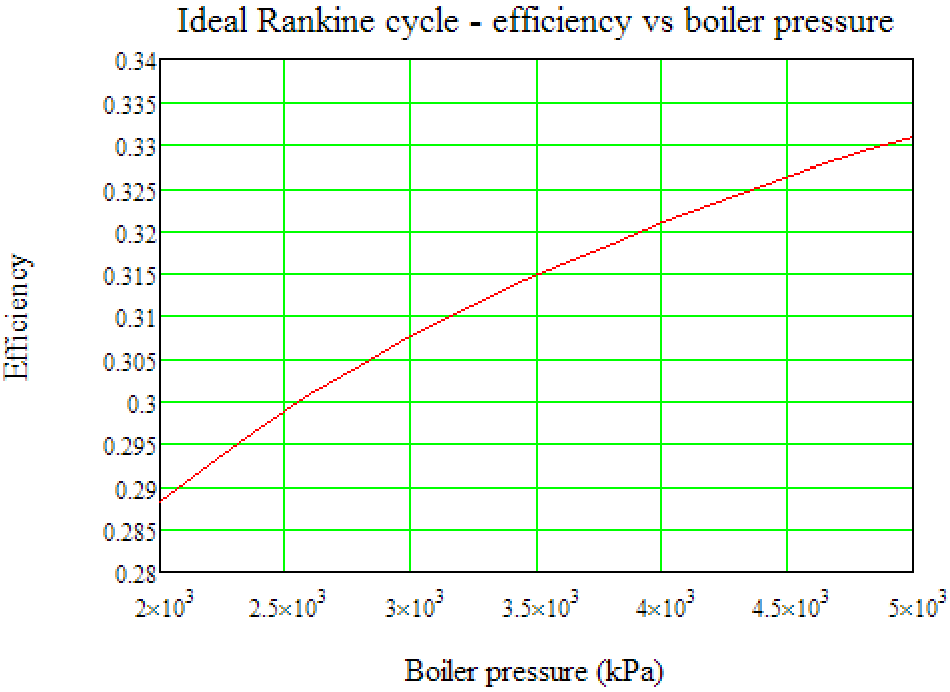
Also:

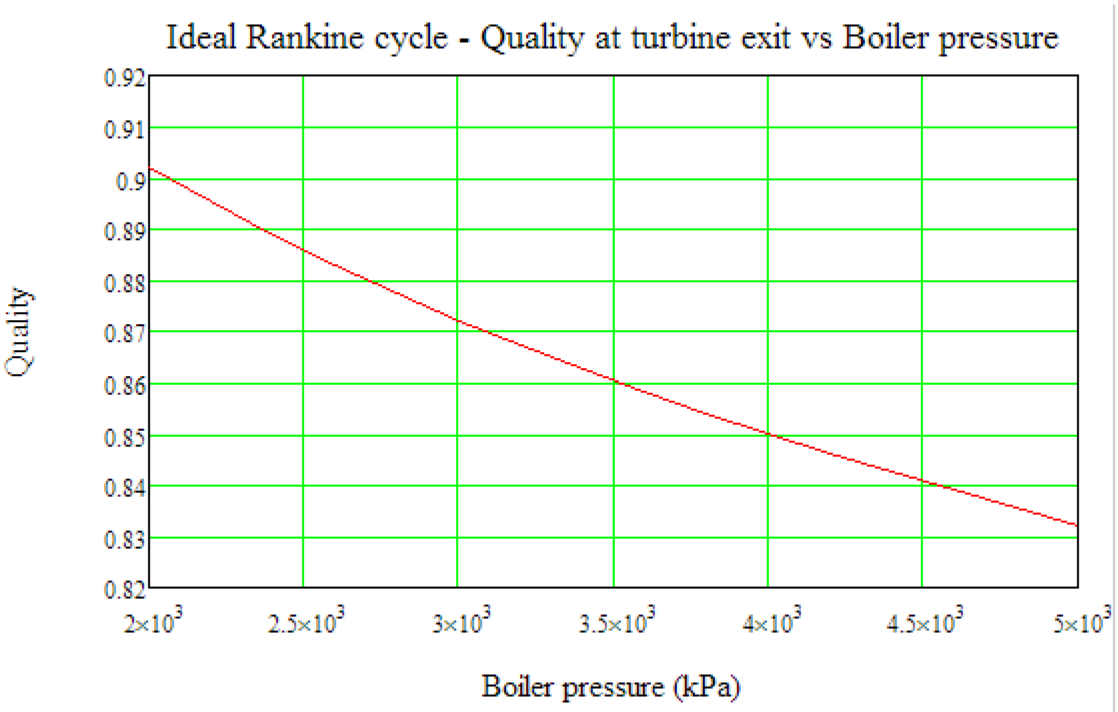


P_boiler =	w_T(P_cond, P_boiler, T1)	w_net(P_cond, P_boiler, T1)
$2\cdot10^3$	857.306	855.292
$2.2\cdot10^3$	869.274	867.056
$2.4\cdot10^3$	881.242	878.819
$2.6\cdot10^3$	891.886	889.259
$2.8\cdot10^3$	901.206	898.375
$3\cdot10^3$	910.526	907.491
$3.2\cdot10^3$	918.093	914.854
$3.4\cdot10^3$	925.66	922.217
$3.6\cdot10^3$	932.559	928.911
$3.8\cdot10^3$	938.789	934.937
$4\cdot10^3$	945.019	940.963
$4.2\cdot10^3$	950.217	945.957
$4.4\cdot10^3$	955.415	950.951
$4.6\cdot10^3$	960.213	955.545
$4.8\cdot10^3$	964.611	959.738
$5\cdot10^3$	969.009	963.932

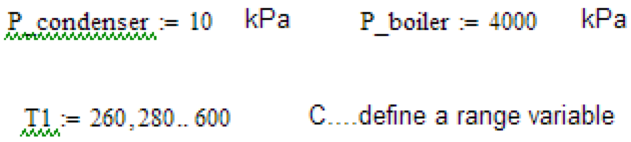
Plots:


Ideal Rankine cycle - Sp. Steam Consumption vs Boiler pressure
SSC (kg/kWh)
4.5
4.4
4.3
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
2×10^3
2.5×10^3
3×10^3
3.5×10^3
4×10^3
4.5×10^3
5×10^3
Boiler pressure (kPa)


Ideal Rankine cycle - efficiency vs boiler pressure
Efficiency
0.34
0.335
0.33
0.325
0.32
0.315
0.31
0.305
0.3
0.295
0.29
0.285
0.28
2×10^3
2.5×10^3
3×10^3
3.5×10^3
4×10^3
4.5×10^3
5×10^3
Boiler pressure (kPa)


Ideal Rankine cycle - Quality at turbine exit vs Boiler pressure
Quality
0.92
0.91
0.9
0.89
0.88
0.87
0.86
0.85
0.84
0.83
0.82
2×10^3
2.5×10^3
3×10^3
3.5×10^3
4×10^3
4.5×10^3
5×10^3
Boiler pressure (kPa)

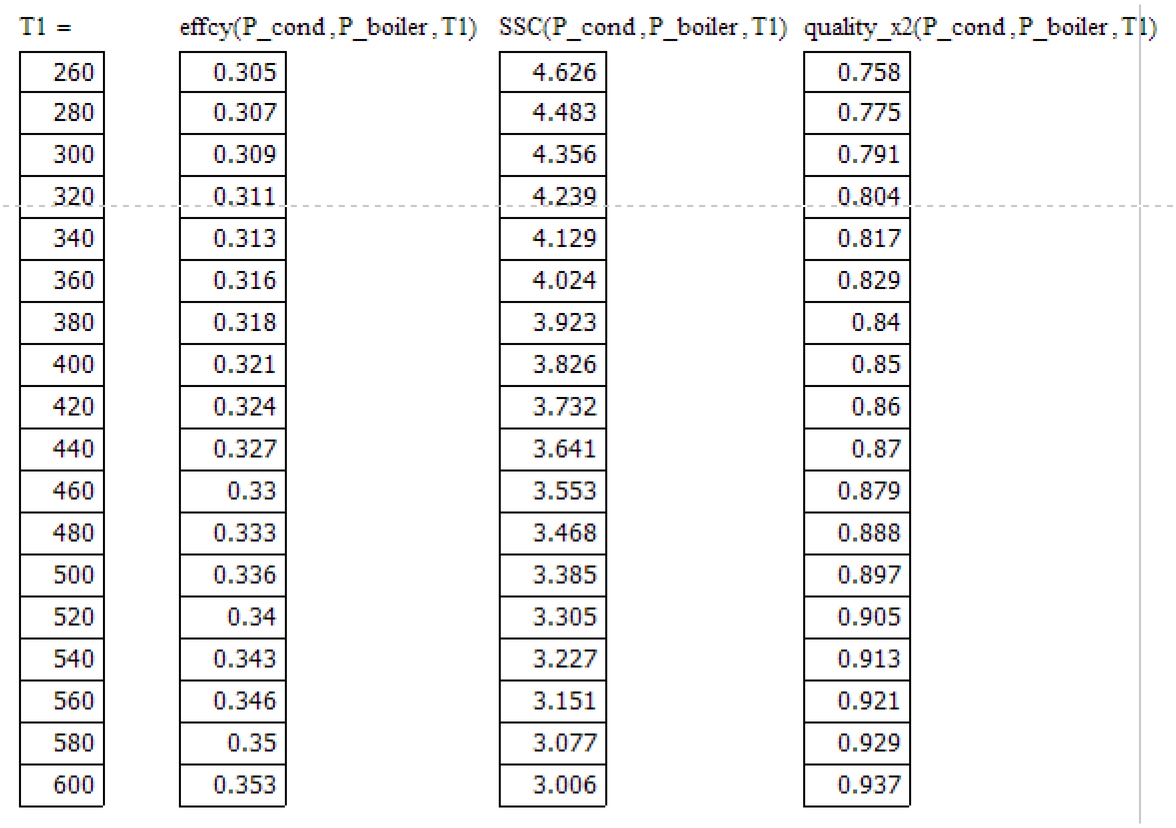
Plot the effect of changing turbine inlet temp (T1) on performance parameters, keeping P_condenser and P_boiler constant:



P_condenser := 10 kPa   P_boiler := 4000 kPa

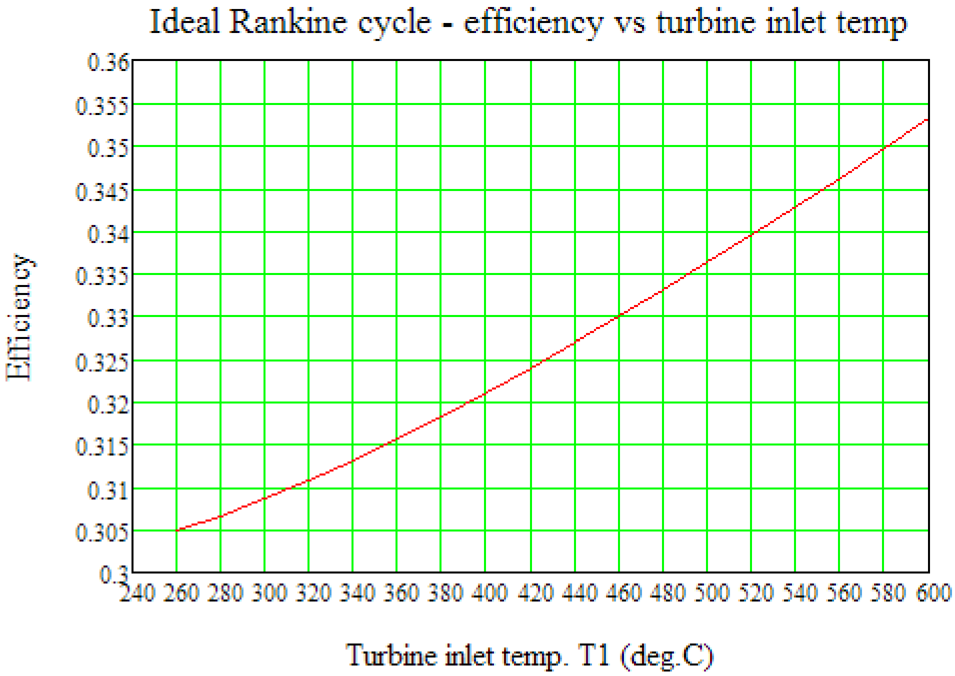
T1 := 260, 280 .. 600   C....define a range variable

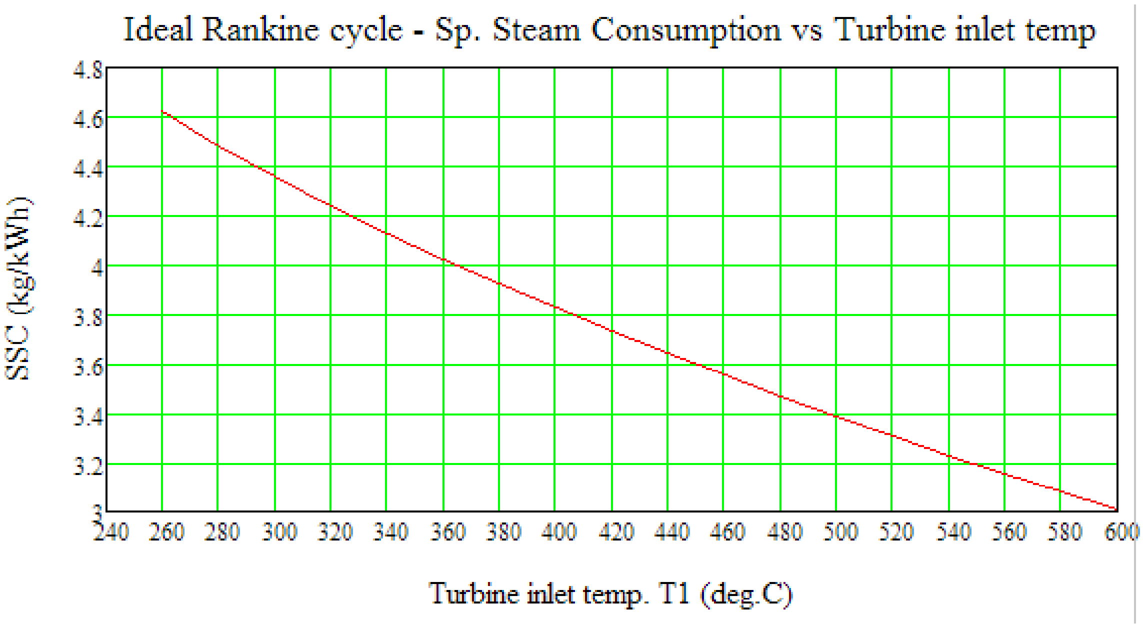
We get:

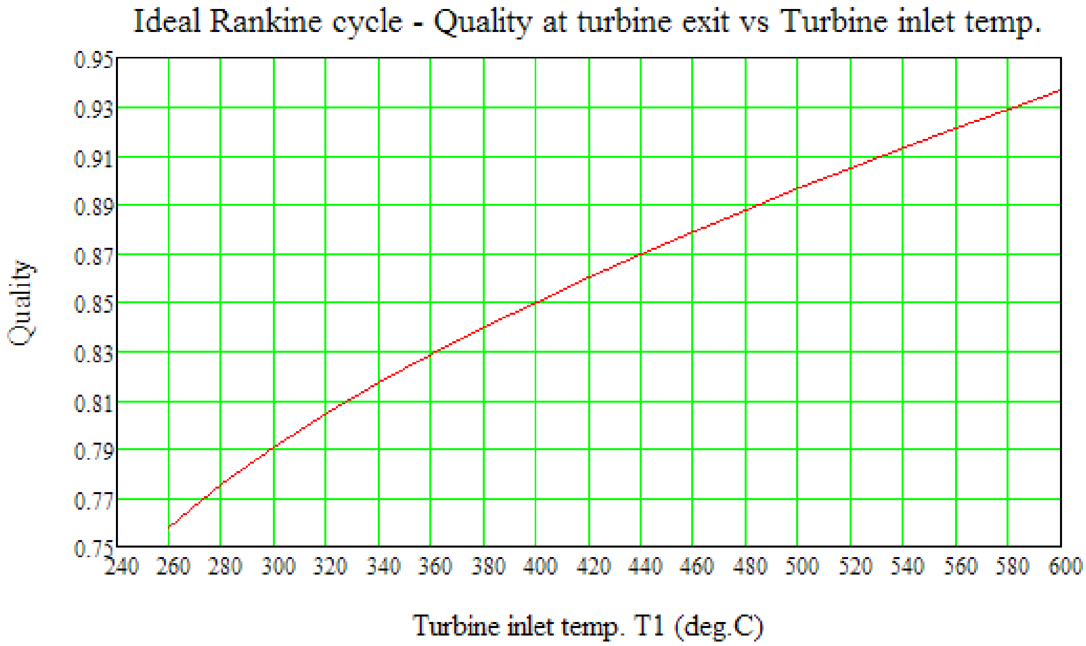


T1 =	effcy(P_cond, P_boiler, T1)	SSC(P_cond, P_boiler, T1)	quality_x2(P_cond, P_boiler, T1)
260	0.305	4.626	0.758
280	0.307	4.483	0.775
300	0.309	4.356	0.791
320	0.311	4.239	0.804
340	0.313	4.129	0.817
360	0.316	4.024	0.829
380	0.318	3.923	0.84
400	0.321	3.826	0.85
420	0.324	3.732	0.86
440	0.327	3.641	0.87
460	0.33	3.553	0.879
480	0.333	3.468	0.888
500	0.336	3.385	0.897
520	0.34	3.305	0.905
540	0.343	3.227	0.913
560	0.346	3.151	0.921
580	0.35	3.077	0.929
600	0.353	3.006	0.937

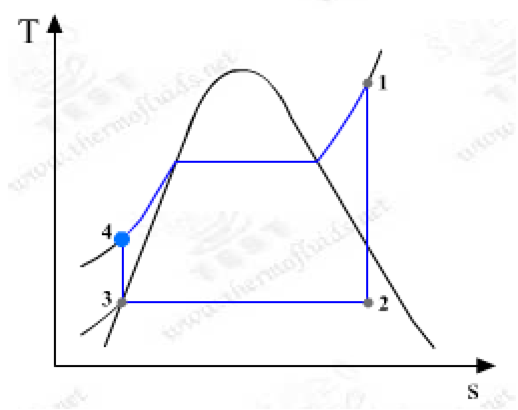
Plots:

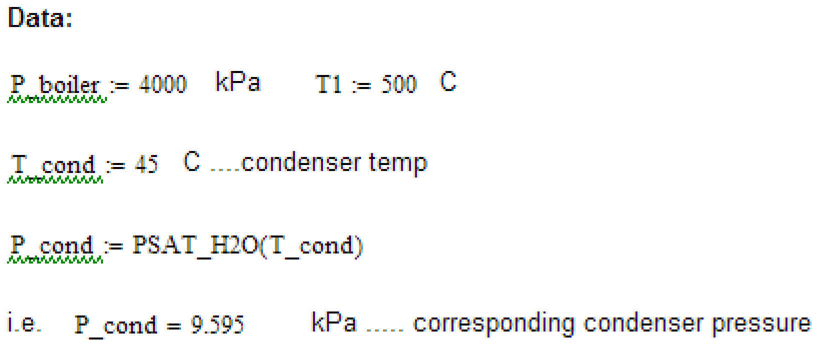

Ideal Rankine cycle - efficiency vs turbine inlet temp
Efficiency
0.36
0.355
0.35
0.345
0.34
0.335
0.33
0.325
0.32
0.315
0.31
0.305
0.3
240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600
Turbine inlet temp. T1 (deg.C)


Ideal Rankine cycle - Sp. Steam Consumption vs Turbine inlet temp
SSC (kg/kWh)
4.8
4.6
4.4
4.2
4
3.8
3.6
3.4
3.2
3
240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600
Turbine inlet temp. T1 (deg.C)


Ideal Rankine cycle - Quality at turbine exit vs Turbine inlet temp.
Quality
0.95
0.93
0.91
0.89
0.87
0.85
0.83
0.81
0.79
0.77
0.75
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
540
560
580
600
Turbine inlet temp. T1 (deg.C)

Prob. 3.4 A steam power plant has a steam generator exit at 4 MPa, 500 C and a condenser exit temp of 45 C. Assume all components are ideal and find the cycle efficiency, turbine and pump works, heat transfer in boiler and condenser and the SSC.[3]





Data:

P_boiler := 4000 kPa T1 := 500 C

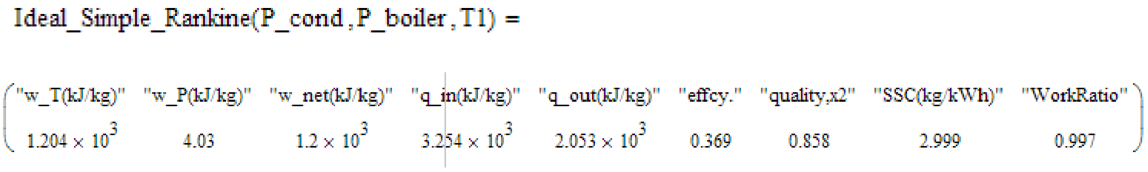
T_cond := 45 C ....condenser temp

P_cond := PSAT_H2O(T_cond)

i.e. P_cond = 9.595 kPa ..... corresponding condenser pressure

Now, apply the Mathcad Function for Ideal Simple Rankine cycle, and get all parameters immediately:

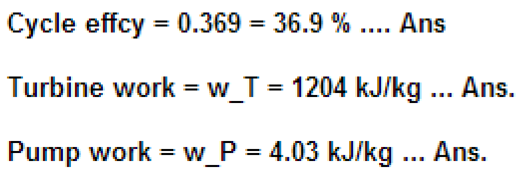
And, we get:



Ideal_Simple_Rankine(P_cond, P_boiler, T1) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x2"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.204 \times 10^{3} & 4.03 & 1.2 \times 10^{3} & 3.254 \times 10^{3} & 2.053 \times 10^{3} & 0.369 & 0.858 & 2.999 & 0.997 \end{pmatrix}$$

Thus, we get:



Cycle effcy = 0.369 = 36.9 % .... Ans

Turbine work = w_T = 1204 kJ/kg ... Ans.

Pump work = w_P = 4.03 kJ/kg ... Ans.

Net work = w_net = 1200 kJ/kg ... Ans.

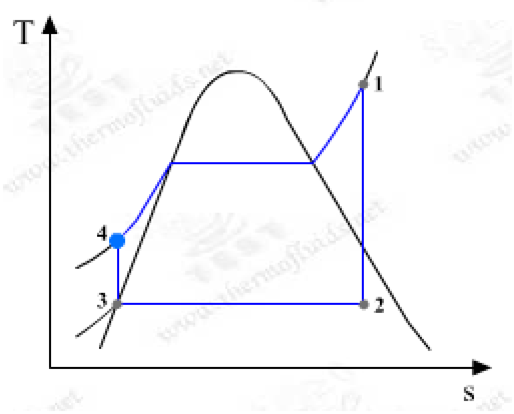
Heat supplied in boiler = q_in = 3254 kJ/kg ... Ans.

Heat rej. in condenser = q_out = 2053 kJ/kg ... Ans.

Specific Steam Consumption = SSC = 2.999 kg/kWh ... Ans.

Quality of steam at exit of turbine = x2 = 0.858 ... Ans.

Prob. 3.5 Net power output of a steam power plant operating on an ideal Rankine cycle is 100 MW. Steam enters the turbine at 8 MPa, 600 C and the condenser exit pressure is 8 kPa. Assume all components are ideal and find the cycle efficiency, SSC, mass flow rate of steam in kg/h, turbine and pump works, heat transfer in boiler and condenser.



Data:

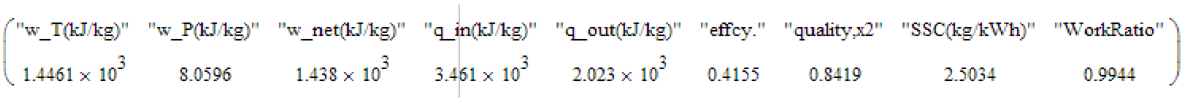
P_boiler := 8000 kPa   T1 := 600 C   Power := 100 MW

P_cond := 8 kPa .

Now, apply the Mathcad Function for Ideal Simple Rankine cycle, and get all parameters immediately:

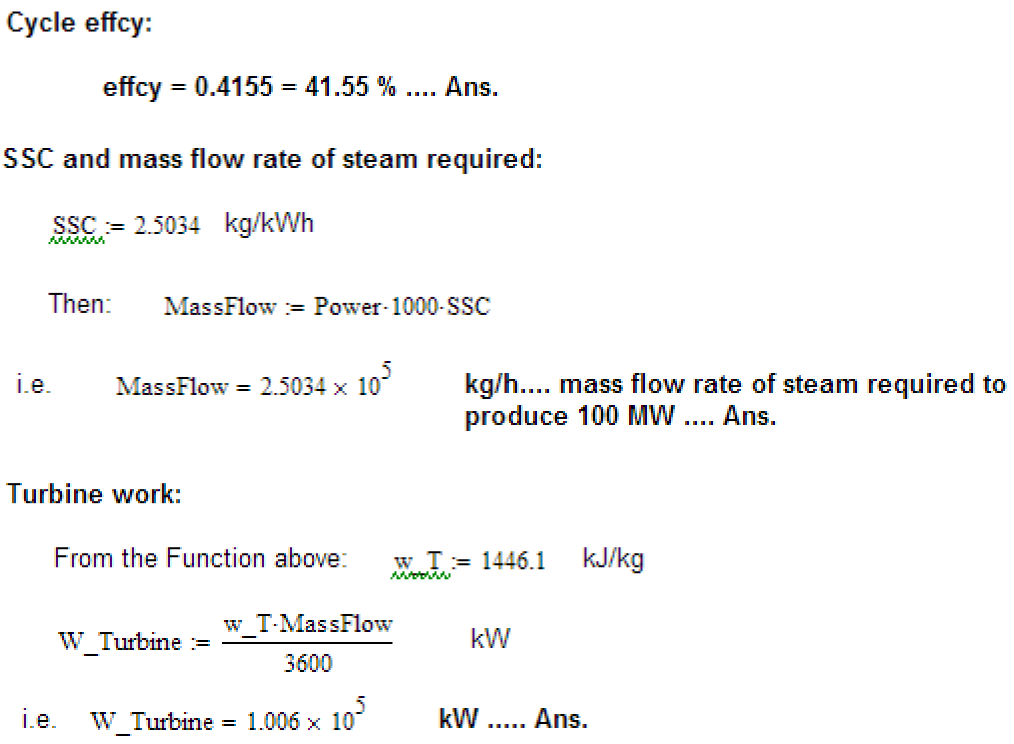
And, we get:

Ideal_Simple_Rankine(P_cond, P_boiler, T1) =



$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x2"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.4461 \times 10^3 & 8.0596 & 1.438 \times 10^3 & 3.461 \times 10^3 & 2.023 \times 10^3 & 0.4155 & 0.8419 & 2.5034 & 0.9944 \end{pmatrix}$$

Thus, we see that:



Cycle effcy:

effcy = 0.4155 = 41.55 % .... Ans.

SSC and mass flow rate of steam required:

$SSC := 2.5034$ kg/kWh

Then: $MassFlow := Power \cdot 1000 \cdot SSC$

i.e. $MassFlow = 2.5034 \times 10^{5}$ **kg/h.... mass flow rate of steam required to produce 100 MW .... Ans.**

Turbine work:

From the Function above: $w\_T := 1446.1$ kJ/kg

$$W\_Turbine := \frac{w\_T \cdot MassFlow}{3600}$$ kW

i.e. $W\_Turbine = 1.006 \times 10^{5}$ **kW ..... Ans.**

Pump work:

From the Function above: $w\_P := 8.0596$ kJ/kg

$$W\_Pump := \frac{w\_P \cdot MassFlow}{3600} \quad \text{kW}$$

i.e. $W\_Pump = 560.456$ **kW ..... Ans.**

Heat transfer in boiler:

From the Function above: $q\_in := 3461$ kJ/kg

$$Q\_boiler := \frac{q\_in \cdot MassFlow}{3600} \quad \text{kW}$$

i.e. $Q\_boiler = 2.407 \times 10^{5}$ **kW ..... Ans.**

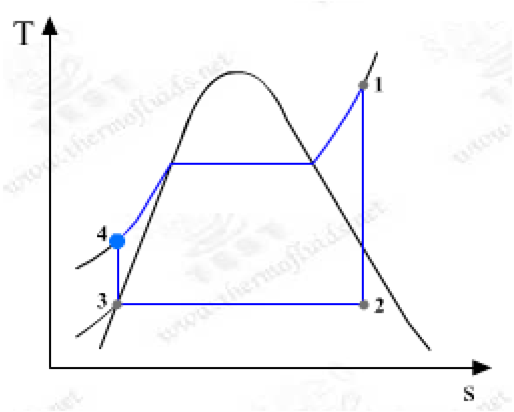
Heat transfer in condenser:

From the Function above: $q\_out := 2023$ kJ/kg

$$Q\_condenser := \frac{q\_out \cdot MassFlow}{3600} \quad \text{kW}$$

i.e. $Q\_condenser = 1.407 \times 10^{5}$ **kW ..... Ans.**

Prob.3.6 A steam power plant operating with an ideal Rankine cycle has a high pressure of 5 MPa and a low pressure of 15 kPa. The turbine exhaust state should have a quality of at least 95% and the turbine power generated should be 7.5 MW. Find the necessary boiler exit temp and the total mass flow rate. [3]



Solution:

Data:

P_boiler := 5000 kPa   P_cond := 15 kPa

Power_output := 7500 kW

To find T1 such thast x2 = 0.95

Take a trial value for the turbine inlet temp, T1, i.e. T1 := 400 C .... trial value

Using this trial value of T1, apply Mathcad Function for Ideal Simple Rankine cycle:

Ideal_Simple_Rankine(P_cond, P_boiler, T1) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x2"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.043 \times 10^{3} & 5.055 & 1.038 \times 10^{3} & 2.966 \times 10^{3} & 1.928 \times 10^{3} & 0.35 & 0.812 & 3.467 & 0.995 \end{pmatrix}$$

Now, of course, the quality is not 0.95, but it is 0.812.

We now, use the 'Solve block of Mathcad to get exact value of T1 required:

Given

$$\text{Ideal\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1})_{1,6} = 0.95$$

T1 := Find(T1)

i.e. T1 = 756.103 **C .... value of T1 required to get turbine exhaust 0.95 dry..... Ans.**

So, with this value of T1, again use the above Mathcad Function to get other parameters:

Ideal_Simple_Rankine(P_cond, P_boiler, T1) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x2"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.553 \times 10^{3} & 5.055 & 1.548 \times 10^{3} & 3.802 \times 10^{3} & 2.254 \times 10^{3} & 0.407 & 0.95 & 2.325 & 0.997 \end{pmatrix}$$

We note that:

Thermal effcy. = 0.407 = 40.7 % .... Ans.

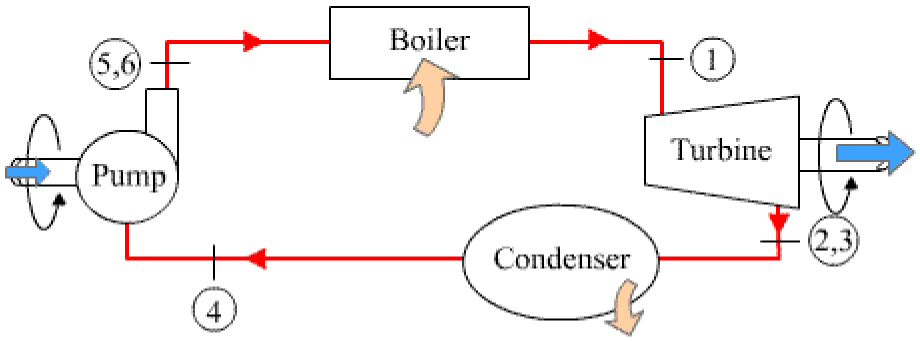
$SSC := 2.325$ kg/kWh

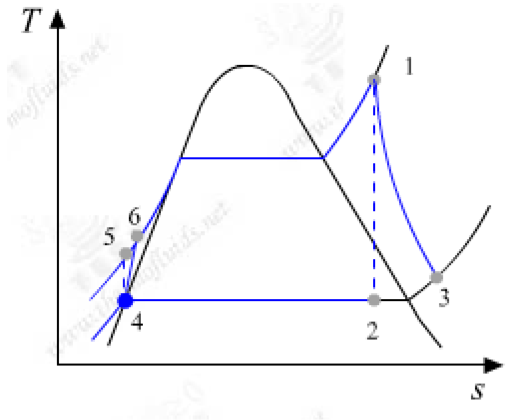
Therefore, mass flow rate of steam required to get a power output of 7500 kW:

$MassFlow := Power\_output \cdot SSC$ kg/h

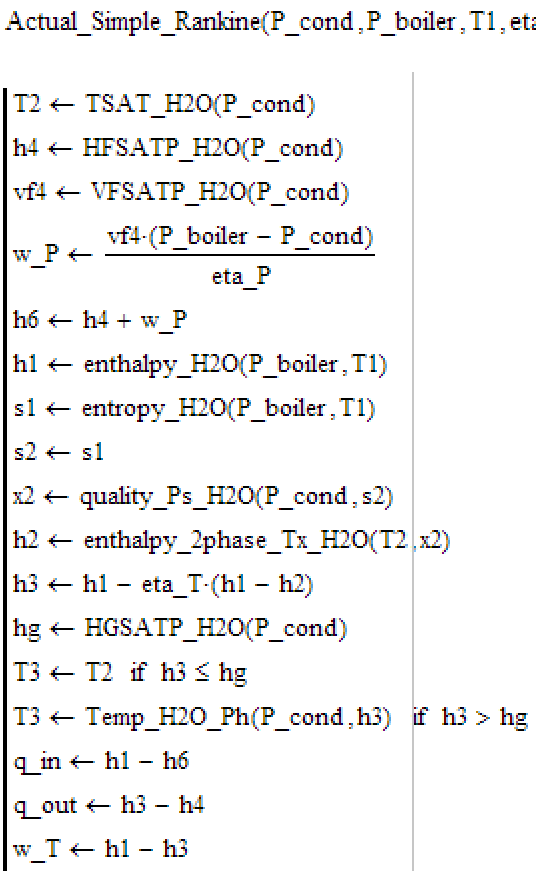
i.e. $MassFlow = 1.744 \times 10^{4}$ **kg/h ...= 4.844 kg/s .... Ans.**

Prob.3.7 Write a Mathcad Function to calculate the parameters of interest for an actual, simple Rankine cycle, i.e. taking in to account the isentropic efficiencies of turbine and pump.

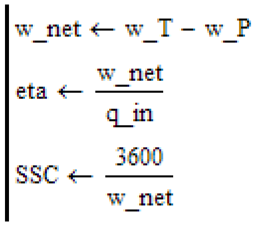




Mathcad Function:



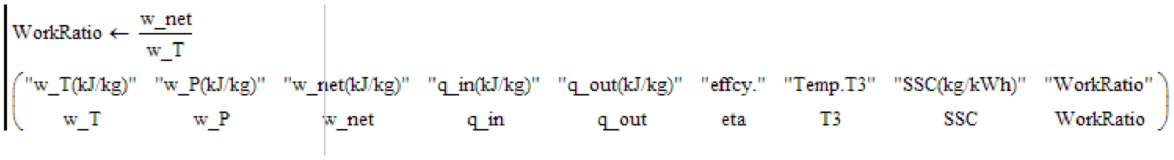
```
Actual_Simple_Rankine(P_cond, P_boiler, T1, eta_T, eta_P) :=

T2 ← TSAT_H2O(P_cond)
h4 ← HFSATP_H2O(P_cond)
vf4 ← VFSATP_H2O(P_cond)
w_P ← $\frac{vf4\cdot(P\_boiler - P\_cond)}{eta\_P}$
h6 ← h4 + w_P
h1 ← enthalpy_H2O(P_boiler, T1)
s1 ← entropy_H2O(P_boiler, T1)
s2 ← s1
x2 ← quality_Ps_H2O(P_cond, s2)
h2 ← enthalpy_2phase_Tx_H2O(T2, x2)
h3 ← h1 − eta_T·(h1 − h2)
hg ← HGSATP_H2O(P_cond)
T3 ← T2  if  h3 ≤ hg
T3 ← Temp_H2O_Ph(P_cond, h3)  if  h3 > hg
q_in ← h1 − h6
q_out ← h3 − h4
w_T ← h1 − h3
```



$$\text{w\_net} \leftarrow \text{w\_T} - \text{w\_P}$$

$$\text{eta} \leftarrow \frac{\text{w\_net}}{\text{q\_in}}$$

$$\text{SSC} \leftarrow \frac{3600}{\text{w\_net}}$$



$$\text{WorkRatio} \leftarrow \frac{\text{w\_net}}{\text{w\_T}}$$

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"Temp.T3"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ \text{w\_T} & \text{w\_P} & \text{w\_net} & \text{q\_in} & \text{q\_out} & \text{eta} & \text{T3} & \text{SSC} & \text{WorkRatio} \end{pmatrix}$$

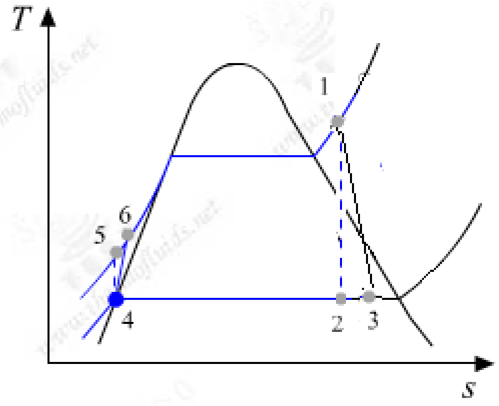
Explanation for the above Function:

This function gives all the important parameters of performance of an actual, simple Rankine cycle.

This function is similar to the Function written earlier for parameters of Ideal Rankine cycle, except that now, while calculating turbine and pump works, their isentropic efficiencies are also considered.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where temperature T1 is in deg.C and pressures P_cond and P_boiler are in kPa, and eta_T and eta_P are the isentropic efficiencies of the turbine and pump respectively. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump work (w_P), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), Temp of steam at turbine exit (T3), Specific Steam Consumption (SSC) and Work Ratio. Units of each quantity are also given in output.

Prob. 3.8 A steam power plant operates on Rankine cycle, with boiler pressure of 15 MPa and condenser pressure of 10 kPa. Steam enters the turbine at 600 C. For turbine, isentropic effcy = 0.87 and for pump, isentropic effcy = 0.85, find the thermal effcy of the plant. Also find the power output if the mass flow rate of steam = 15 kg/s.



Solution:

Data:

P_boiler := 15000 kPa   T1 := 600 C   MassFlow := 15 kg/s

P_cond := 10 kPa .   eta_T := 0.87   eta_P := 0.85

Then: T_cond := TSAT_H2O(P_cond)   i.e.   T_cond = 45.806   C .. condenser temp.

Using the Mathcad Function written above:

$\text{Actual\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1}, \text{eta\_T}, \text{eta\_P}) =$

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"Temp.T3"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.2773 \times 10^{3} & 17.8156 & 1.2595 \times 10^{3} & 3.3738 \times 10^{3} & 2.1143 \times 10^{3} & 0.3733 & 45.8065 & 2.8582 & 0.9861 \end{pmatrix}$$

We see that:

Thermal effcy. = 0.3733 = 37.33 % ... Ans.

And:

$\text{w\_net} := 1259.5$ kJ/kg .... net work output

Therefore, Power output:

$\text{Power} := \text{MassFlow} \cdot \text{w\_net}$ kW

i.e. $\text{Power} = 1.889 \times 10^{4}$ **kW .... Ans.**

Plot the thermal effcy and power output as isentropic effcy of turbine varies from 0.6 to 1, other conditions remaining unchanged:

First, write the relevant quantities as functions of eta_T:

$\text{Effcy}(\text{eta\_T}) := \text{Actual\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1}, \text{eta\_T}, \text{eta\_P})_{1,5}$ i.e. $\text{Effcy}(\text{eta\_T}) = 0.373$

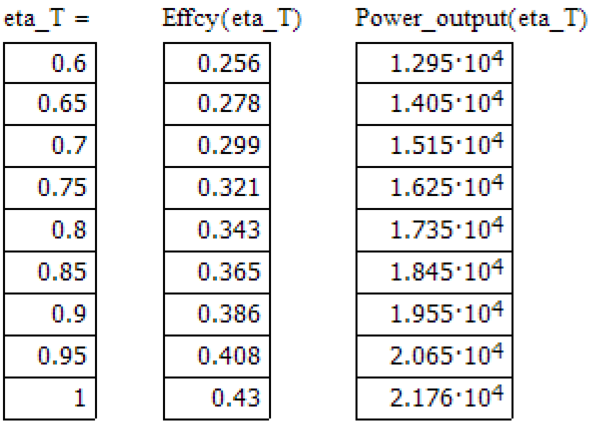
$\text{W\_net}(\text{eta\_T}) := \text{Actual\_Simple\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{T1}, \text{eta\_T}, \text{eta\_P})_{1,2}$ i.e. $\text{W\_net}(\text{eta\_T}) = 1.26 \times 10^{3}$

$\text{Power\_output}(\text{eta\_T}) := \text{W\_net}(\text{eta\_T}) \cdot \text{MassFlow}$ i.e. $\text{Power\_output}(\text{eta\_T}) = 1.889 \times 10^{4}$

Now, we have:

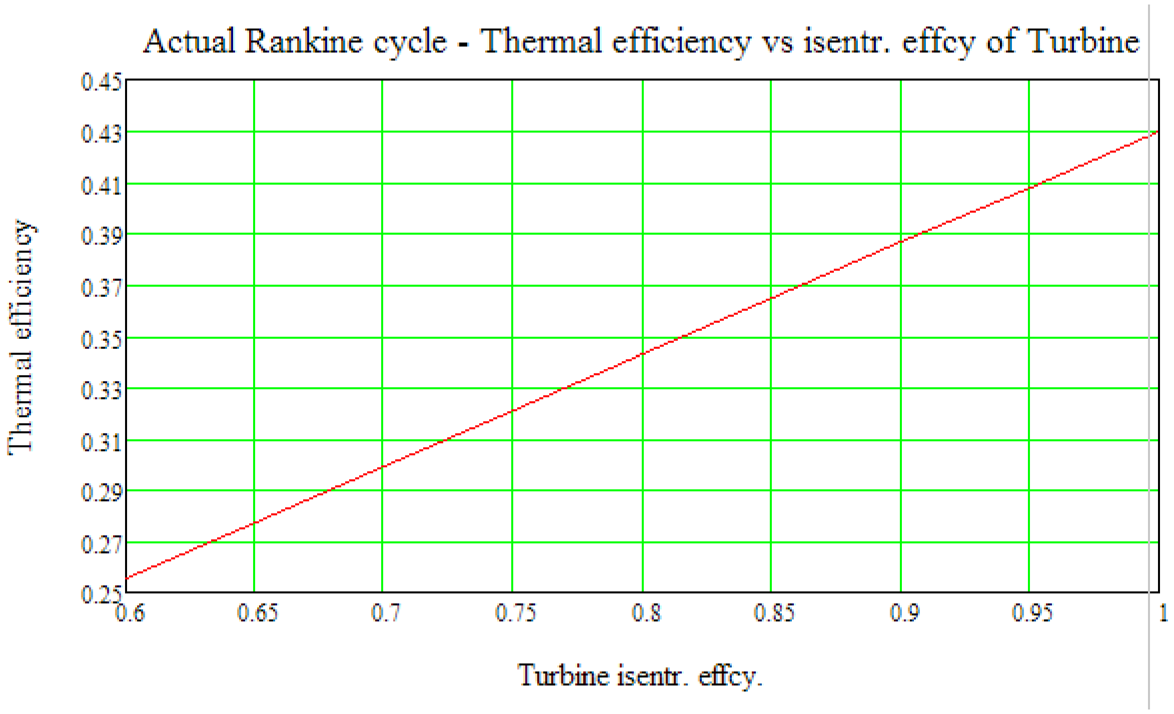
$\text{eta\_T} := 0.6, 0.65 .. 1$ ...define a range variable

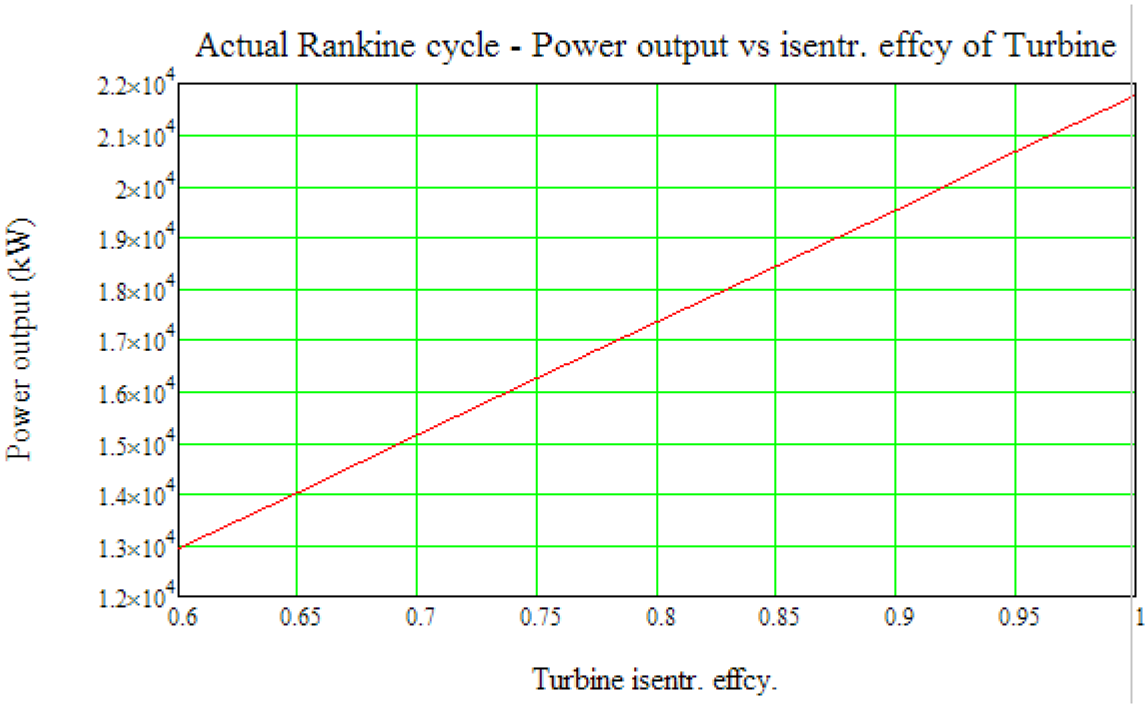
And, we get:



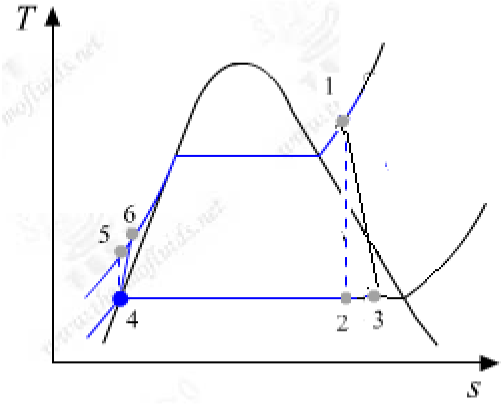
eta_T =	Effcy(eta_T)	Power_output(eta_T)
0.6	0.256	$1.295\cdot10^4$
0.65	0.278	$1.405\cdot10^4$
0.7	0.299	$1.515\cdot10^4$
0.75	0.321	$1.625\cdot10^4$
0.8	0.343	$1.735\cdot10^4$
0.85	0.365	$1.845\cdot10^4$
0.9	0.386	$1.955\cdot10^4$
0.95	0.408	$2.065\cdot10^4$
1	0.43	$2.176\cdot10^4$

And, plot the results:




Actual Rankine cycle - Power output vs isentr. effcy of Turbine
Power output (kW)
2.2×10^4
2.1×10^4
2×10^4
1.9×10^4
1.8×10^4
1.7×10^4
1.6×10^4
1.5×10^4
1.4×10^4
1.3×10^4
1.2×10^4
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Turbine isentr. effcy.

Prob. 3.9 Steam enters the turbine of a power plant at 5 MPa and 400 C, and exhausts to a condenser at 10 kPa. The turbine produces a power output of 20 000 kW with an isentropic efficiency of 85%. What is the mass flow rate of steam and the rate of heat rejection to the condenser? Find the thermal effcy of the power plant. How does this compare with a Carnot cycle? [3]



Solution:

Data:

P_boiler := 5000 kPa   T1 := 400 C   Power_output := 20000 kW

P_cond := 10 kPa .   eta_T := 0.85   eta_P := 1

Then: T_cond := TSAT_H2O(P_cond)   i.e. T_cond = 45.806 C .. condenser temp.

Using the Mathcad Function written above:

Actual_Simple_Rankine(P_cond, P_boiler, T1, eta_T, eta_P) =

"w_T(kJ/kg)"	"w_P(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"Temp.T3"	"SSC(kg/kWh)"	"WorkRatio"
928.0158	5.041	922.9748	3×10^3	2.077×10^3	0.3077	45.8065	3.9004	0.9946

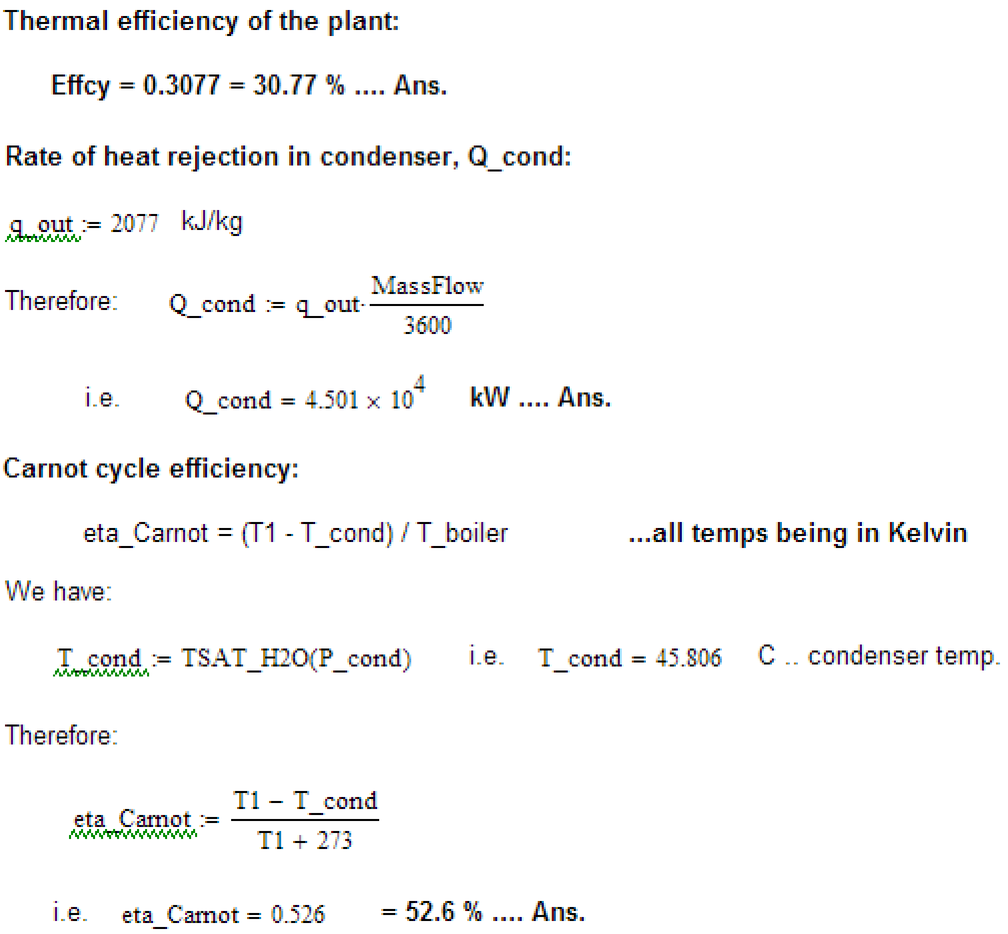
Thus, we see that:

SSC := 3.9004 kg/kWh

Therefore, Mass flow rate of steam to get a power output of 20000 kW:

MassFlow := SSC·Power_output kg/h

i.e. MassFlow = 7.801×10^4 **kg/h ... = 21.669 kg/s .... Ans.**



Thermal efficiency of the plant:

Effcy = 0.3077 = 30.77 % .... Ans.

Rate of heat rejection in condenser, Q_cond:

q_out := 2077 kJ/kg

Therefore: $Q\_cond := q\_out \cdot \frac{MassFlow}{3600}$

i.e. $Q\_cond = 4.501 \times 10^{4}$ **kW .... Ans.**

Carnot cycle efficiency:

eta_Carnot = (T1 - T_cond) / T_boiler **...all temps being in Kelvin**

We have:

T_cond := TSAT_H2O(P_cond) i.e. T_cond = 45.806 C .. condenser temp.

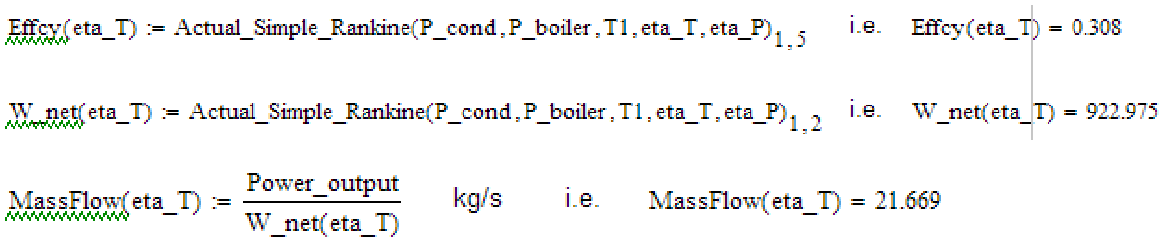
Therefore:

$$eta\_Carnot := \frac{T1 - T\_cond}{T1 + 273}$$

i.e. eta_Carnot = 0.526 **= 52.6 % .... Ans.**

Keeping the power output constant at 20000 kW, plot mass flow rate of steam and thermal effcy of the plant as the turbine isentropic effcy changes from 0.6 to 1:

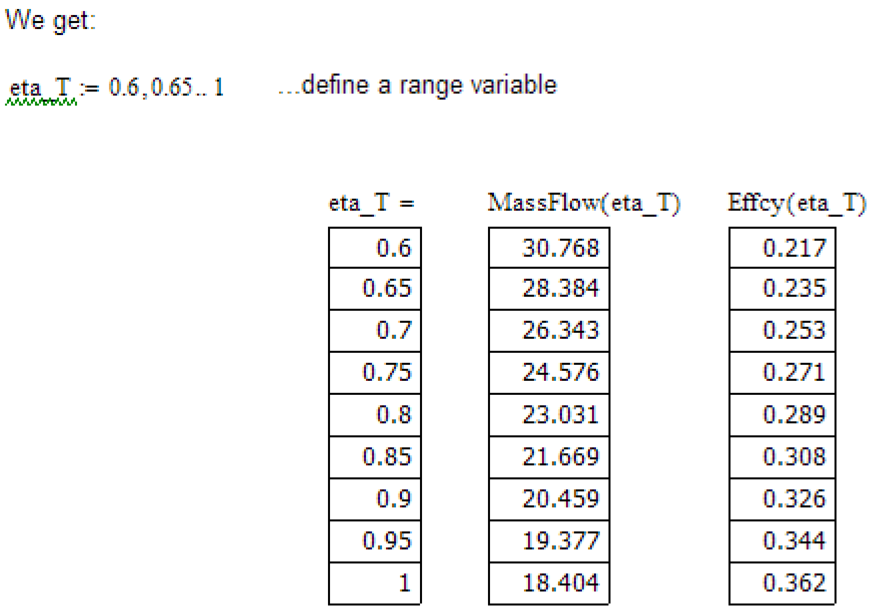
First, write the relevant quantities as functions of eta_T:



$Effcy(eta\_T) := Actual\_Simple\_Rankine(P\_cond, P\_boiler, T1, eta\_T, eta\_P)_{1,5}$ i.e. Effcy(eta_T) = 0.308

$W\_net(eta\_T) := Actual\_Simple\_Rankine(P\_cond, P\_boiler, T1, eta\_T, eta\_P)_{1,2}$ i.e. W_net(eta_T) = 922.975

$MassFlow(eta\_T) := \frac{Power\_output}{W\_net(eta\_T)}$ kg/s i.e. MassFlow(eta_T) = 21.669

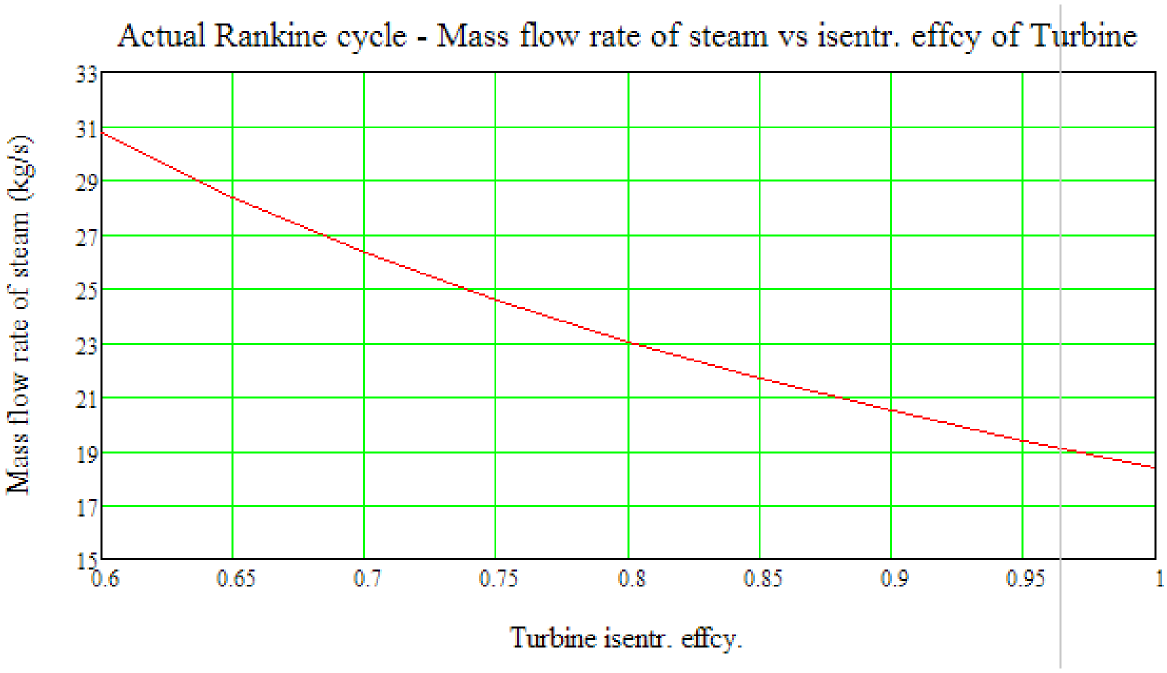


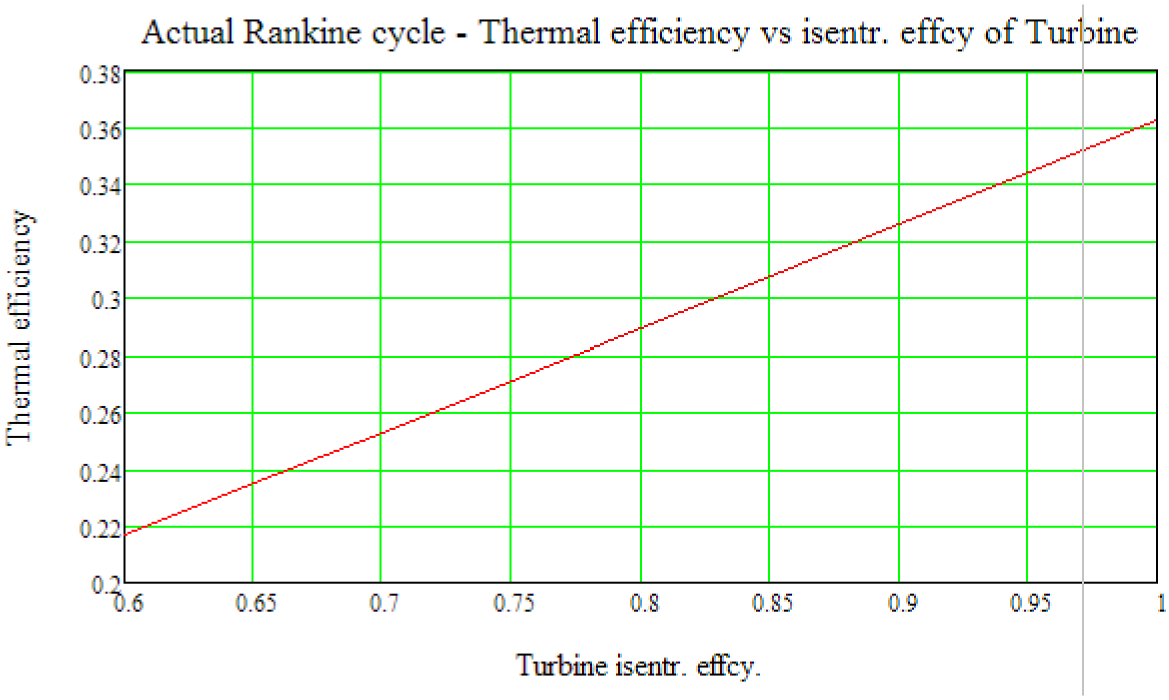
We get:

eta_T := 0.6,0.65..1 ...define a range variable

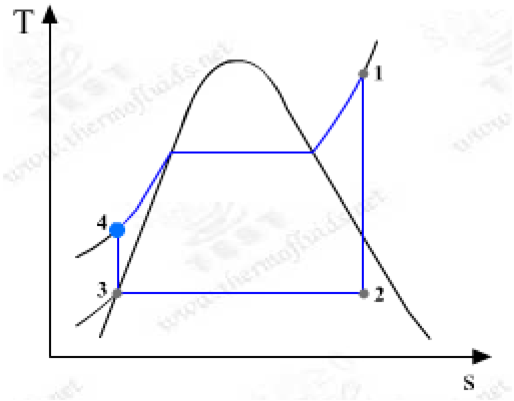
eta_T =	MassFlow(eta_T)	Effcy(eta_T)
0.6	30.768	0.217
0.65	28.384	0.235
0.7	26.343	0.253
0.75	24.576	0.271
0.8	23.031	0.289
0.85	21.669	0.308
0.9	20.459	0.326
0.95	19.377	0.344
1	18.404	0.362

Plot the results:





Prob. 3.10 Consider a 210-MW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the quality of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam. [2]



First, let us consider the Ideal, Simple Rankine cycle, and use the Mathcad Function written to calculate various parameters for that cycle:

Data:

Power_output := 210000 kW

P_boiler := 10000 kPa   T1 := 500 C   P_cond := 10 kPa

Using the Mathcad Function for Ideal, Simple Rankine cycle:

Ideal_Simple_Rankine(P_cond, P_boiler, T1) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x2"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.2858 \times 10^3 & 10.0921 & 1.2757 \times 10^3 & 3.1734 \times 10^3 & 1.8977 \times 10^3 & 0.402 & 0.7932 & 2.822 & 0.9922 \end{pmatrix}$$

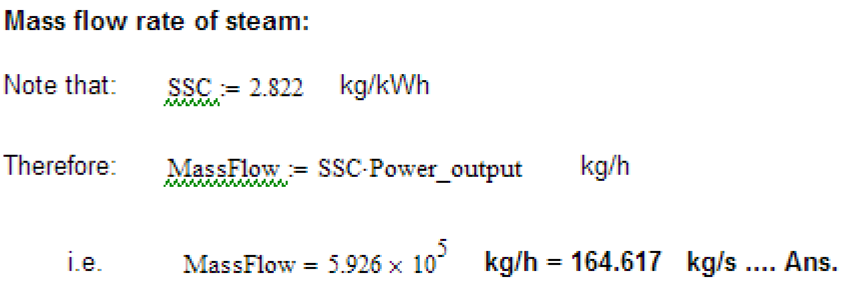
We see from the Function output that:

Quality of steam at turbine exit, x2:

quality, x2 = 0.793 .... Ans.

Thermal effcy. of cycle:

efffcy = 0.402   **= 40.2 % .... Ans.**



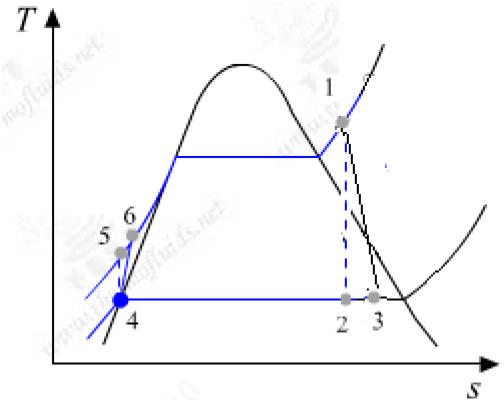
Mass flow rate of steam:

Note that: $SSC := 2.822$ kg/kWh

Therefore: $MassFlow := SSC \cdot Power\_output$ kg/h

i.e. $MassFlow = 5.926 \times 10^{5}$ **kg/h = 164.617 kg/s .... Ans.**

Prob. 3.11 Repeat the above problem assuming an isentropic efficiency of 85 percent for both the turbine and the pump. [2]



Now, use the Mathcad Function written for Actual, Simple Rankine cycle:

Data:

$\text{Power\_output} := 210000$ kW $\quad \text{P\_cond} := 10$ kPa $\quad \text{P\_boiler} := 10000$ kPa

$\text{T1} := 500$ C $\quad \text{T\_cond} := \text{TSAT\_H2O(P\_cond)}$ i.e. $\text{T\_cond} = 45.806$ C

$\text{eta\_T} := 0.85 \quad \text{eta\_P} := 0.85$

Using the Mathcad Function for Actual, Simple Rankine cycle:

$\text{Actual\_Simple\_Rankine(P\_cond, P\_boiler, T1, eta\_T, eta\_P)} =$

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"Temp.T3"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.093 \times 10^{3} & 11.873 & 1.081 \times 10^{3} & 3.172 \times 10^{3} & 2.091 \times 10^{3} & 0.341 & 45.806 & 3.33 & 0.989 \end{pmatrix}$$

We see from the Function output that:

Thermal effcy. of cycle:

$\text{efffcy} = 0.341$ **= 34.1 % .... Ans.**

Mass flow rate of steam:

Note that: $\text{SSC} := 3.33$ kg/kWh

Therefore: $\text{MassFlow} := \text{SSC} \cdot \text{Power\_output}$ kg/h

i.e. $\text{MassFlow} = 6.993 \times 10^{5}$ **kg/h = 194.25 kg/s .... Ans.**

Quality of steam at turbine exit, x2:

From the Function output: $\text{w\_T} := 1093$ kJ/kg

We have: $\text{h1} := \text{enthalpy\_H2O(P\_boiler, T1)}$

i.e. $\text{h1} = 3.375 \times 10^{3}$ kJ/kg

Since turbine work, w_T = (h1 - h3), we have:

$\text{h3} := \text{h1} - \text{w\_T}$

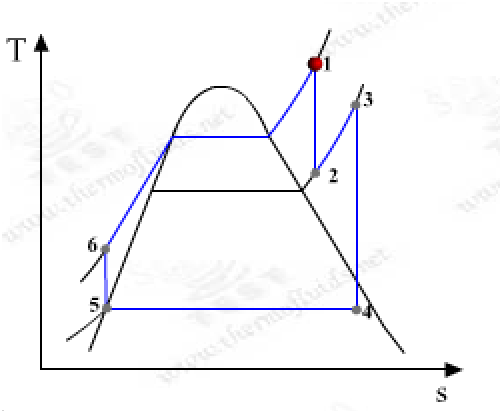
i.e. $\text{h3} = 2.282 \times 10^{3}$ kJ/kg

Also, note from the Function output that temp T3 = 45.806 C, the sat. temp at the condenser pressure of 10 kPa, i.e. turbine exit is in the two phase region. Let the quality of steam at turbine exit be x3.

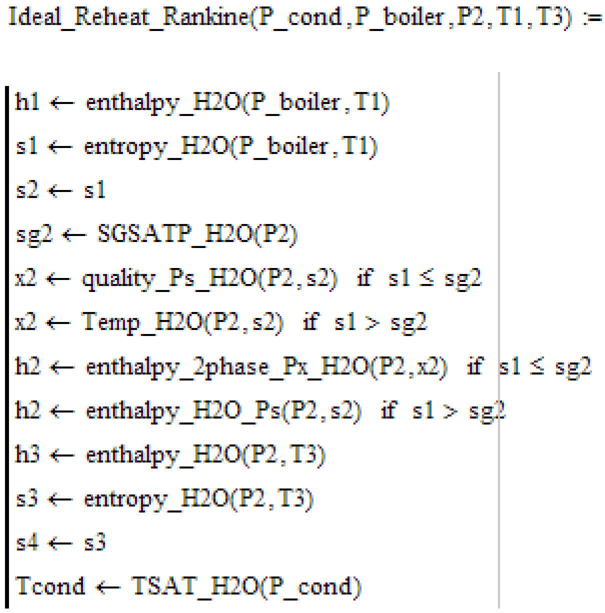
Then: x3 := quality_Ph_H2O(P_cond,h3)

i.e. x3 = 0.874 **...quality at point 3, the exit of 'actual' turbine .... Ans.**

Prob. 3.12 Write a Mathcad program to find out the parameters of interest in an ideal, reheat Rankine cycle.



Mathcad Function:



```
Ideal_Reheat_Rankine(P_cond,P_boiler,P2,T1,T3) :=

| h1 ← enthalpy_H2O(P_boiler,T1)
| s1 ← entropy_H2O(P_boiler,T1)
| s2 ← s1
| sg2 ← SGSATP_H2O(P2)
| x2 ← quality_Ps_H2O(P2,s2)  if  s1 ≤ sg2
| x2 ← Temp_H2O(P2,s2)  if  s1 > sg2
| h2 ← enthalpy_2phase_Px_H2O(P2,x2)  if  s1 ≤ sg2
| h2 ← enthalpy_H2O_Ps(P2,s2)  if  s1 > sg2
| h3 ← enthalpy_H2O(P2,T3)
| s3 ← entropy_H2O(P2,T3)
| s4 ← s3
| Tcond ← TSAT_H2O(P_cond)
```

```
x4 ← quality_Ps_H2O(P_cond, s4)
h4 ← enthalpy_2phase_Tx_H2O(Tcond, x4)
h5 ← HFSATP_H2O(P_cond)
vf5 ← VFSATP_H2O(P_cond)
w_P ← vf5·(P_boiler − P_cond)
h6 ← h5 + w_P
q_in ← (h1 − h6) + (h3 − h2)
w_T ← (h1 − h2) + (h3 − h4)
w_net ← w_T − w_P
q_out ← h4 − h5
```

$$\text{eta} \leftarrow \frac{\text{w\_net}}{\text{q\_in}}$$

$$\text{SSC} \leftarrow \frac{3600}{\text{w\_net}}$$

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"x2 or T2 (C)"} & \text{"SSC(kg/kWh)"} \\ \text{w\_T} & \text{w\_P} & \text{w\_net} & \text{q\_in} & \text{q\_out} & \text{eta} & \text{x4} & \text{x2} & \text{SSC} \end{pmatrix}$$

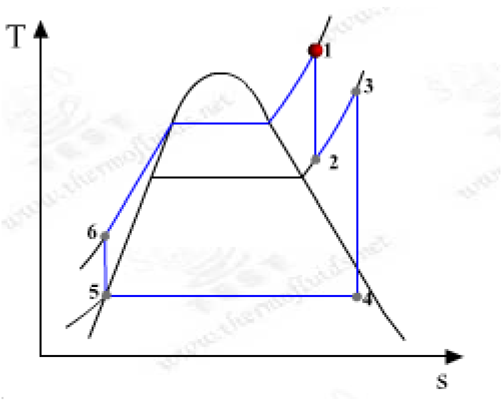
Explanation for the above Function:

This function gives all the important parameters of performance of an Ideal, Reheat Rankine cycle.

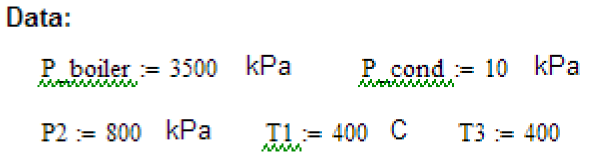
This function is similar to the Function written earlier for parameters of Ideal Rankine cycle, except that now, we check if the exit of HP turbine is in two phase region or superheat region, and determine the enthalpy accordingly.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where Turbine inlet temperature T1 and reheat temp T3 are in deg.C and pressures P_cond, P_boiler and reheat pressure P2 are in kPa. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump work (w_P), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), quality of steam at LP turbine exit (x4), quality of steam at HP turbine exit (x2) or its Temp (T2), and Specific Steam Consumption (SSC). Units of each quantity are also given in output.

Prob.3.13 In an ideal steam reheat cycle, steam enters the high pressure turbine at 3.5 MPa, 400 C and expands to 0.8 MPa. It is then reheated to 400 C and expands to 10 kPa in the low pressure turbine. Calculate the cycle thermal efficiency and the moisture content of the steam leaving the low pressure turbine. Also, plot the variation of efficiency and dryness fraction, x4 as reheat pressure P2 varies from 600 kPa to 1500 kPa, other conditions remaining the same.[3]



Solution:


Data:

P_boiler := 3500 kPa P_cond := 10 kPa

P2 := 800 kPa T1 := 400 C T3 := 400 C

Applying the Mathcad Function written above straightaway:

We get:

Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"x2 or T2 (C)"} & \text{"SSC(kg/kWh)"} \\ 1.239 \times 10^{3} & 3.526 & 1.236 \times 10^{3} & 3.444 \times 10^{3} & 2.208 \times 10^{3} & 0.359 & 0.923 & 205.298 & 2.913 \end{pmatrix}$$

i.e.

Cycle efficiency = 0.359 = 35.9% .... Ans.

Moisture content of steam at low pressure turbine exit:

We have, quality, x4 = 0.923.

i.e. moisture content = 1 - 0.923 = 0.077 = 7.7 % .... Ans.

Plot the variation of efficiency and x4 as reheat pressure P2 varies from 600 kPa to 1500 kPa, other conditions remaining the same:

First, write effcy and dryness fraction x4 as functions of P2:

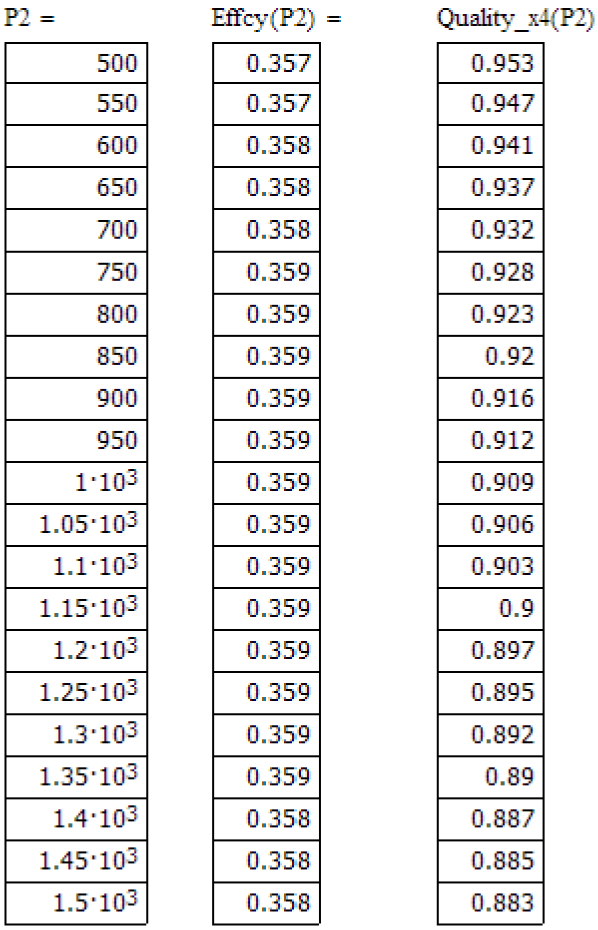
$\text{Effcy(P2)} := \text{Ideal\_Reheat\_Rankine(P\_cond, P\_boiler, P2, T1, T3)}_{1,5}$ $\text{Effcy(P2)} = 0.359$

$\text{Quality\_x4(P2)} := \text{Ideal\_Reheat\_Rankine(P\_cond, P\_boiler, P2, T1, T3)}_{1,6}$ $\text{Quality\_x4(P2)} = 0.923$

To plot the results:

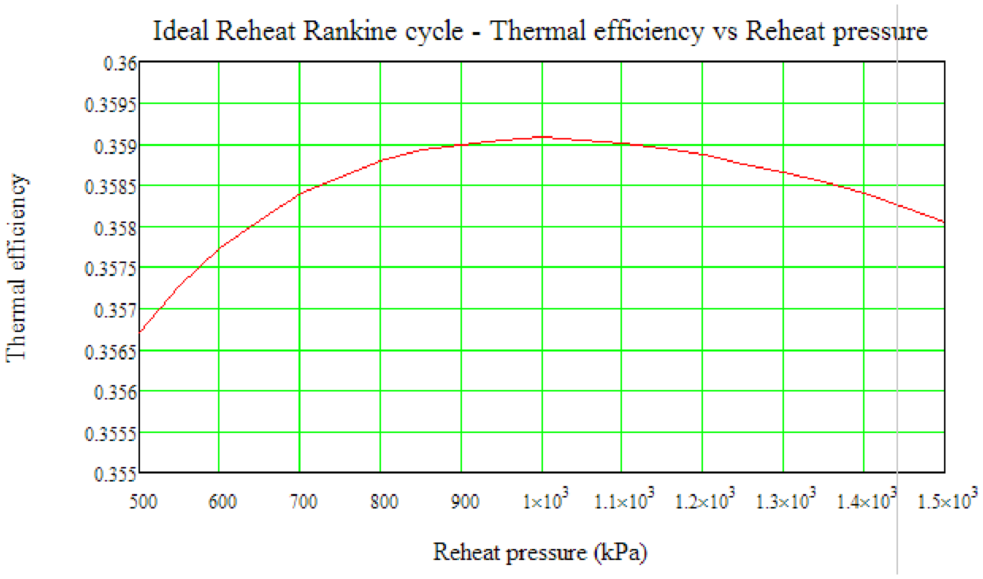
$P2 := 500, 550 .. 1500$ ....define a range variable

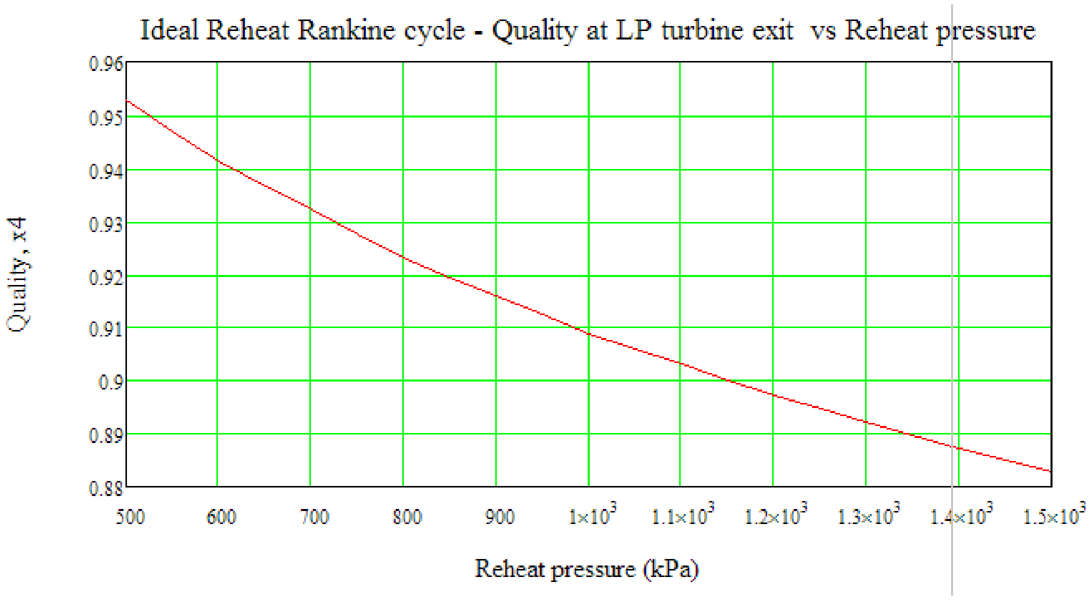
And, we get:



P2 =	Effcy(P2) =	Quality_x4(P2)
500	0.357	0.953
550	0.357	0.947
600	0.358	0.941
650	0.358	0.937
700	0.358	0.932
750	0.359	0.928
800	0.359	0.923
850	0.359	0.92
900	0.359	0.916
950	0.359	0.912
$1\cdot10^3$	0.359	0.909
$1.05\cdot10^3$	0.359	0.906
$1.1\cdot10^3$	0.359	0.903
$1.15\cdot10^3$	0.359	0.9
$1.2\cdot10^3$	0.359	0.897
$1.25\cdot10^3$	0.359	0.895
$1.3\cdot10^3$	0.359	0.892
$1.35\cdot10^3$	0.359	0.89
$1.4\cdot10^3$	0.358	0.887
$1.45\cdot10^3$	0.358	0.885
$1.5\cdot10^3$	0.358	0.883

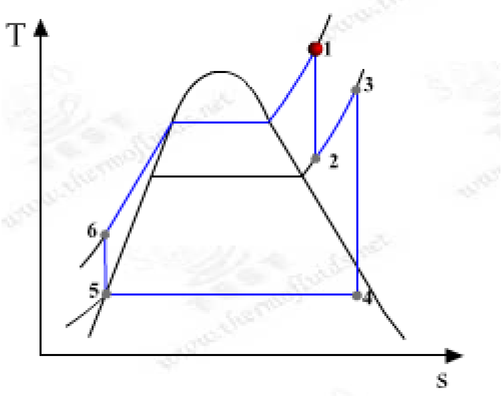
Plots:




Ideal Reheat Rankine cycle - Quality at LP turbine exit vs Reheat pressure
Quality , x4
0.96
0.95
0.94
0.93
0.92
0.91
0.9
0.89
0.88
500
600
700
800
900
1×10³
1.1×10³
1.2×10³
1.3×10³
1.4×10³
1.5×10³
Reheat pressure (kPa)

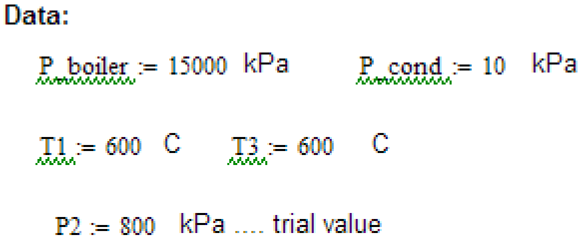
Prob.3.14 A steam power plant operates on an ideal reheat Rankine cycle. Steam enters the HP turbine at 15 MPa, 600 C, and is condensed in the condenser at 10 kPa. If the moisture content of steam at the exit of LP turbine is not to exceed 10%, determine the reheat pressure and the thermal efficiency of the cycle. Assume that the steam is reheated to 600 C.[2]

Solution:



We shall assume a trial value for reheat pressure P2 and apply the Mathcad Function written earlier.

Obviously, quality_x4 in the output will not be 0.9 as required. Then we shall use the 'Solve block' of Mathcad to determine P2 such that quality_x4 is 0.9:



Data:

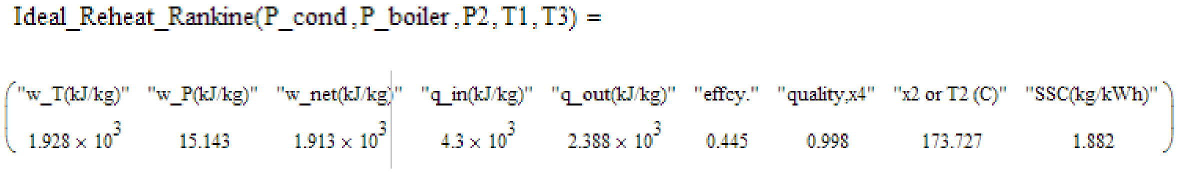
P_boiler := 15000 kPa P_cond := 10 kPa

T1 := 600 C T3 := 600 C

P2 := 800 kPa .... trial value

Applying the Mathcad Function written above straightaway:

We get:



Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"x2 or T2 (C)"} & \text{"SSC(kg/kWh)"} \\ 1.928 \times 10^{3} & 15.143 & 1.913 \times 10^{3} & 4.3 \times 10^{3} & 2.388 \times 10^{3} & 0.445 & 0.998 & 173.727 & 1.882 \end{pmatrix}$$

Note that quality, x4 = 0.998

Use 'Solve block' of Mathcad to get the value of P2 which will make x4 equal to 0.9:

$$\text{Quality\_x4}(P2) := \text{Ideal\_Reheat\_Rankine}(P\_cond, P\_boiler, P2, T1, T3)_{1,6}$$

Given

$$\text{Quality\_x4}(P2) = 0.9$$

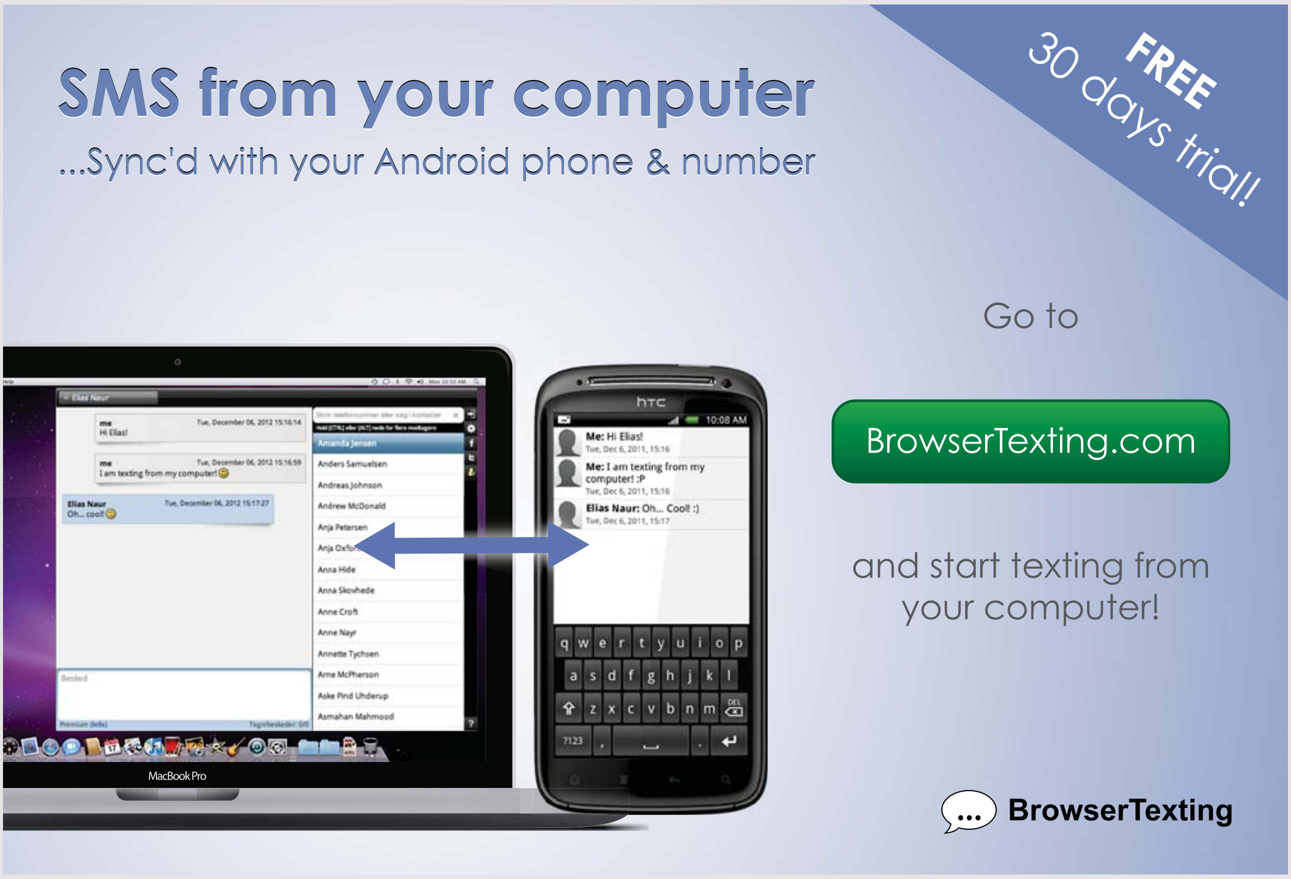
$$P2 := \text{Find}(P2)$$

i.e. $P2 = 3.772 \times 10^{3}$ **kPa....Reheat pressure.... Ans.**

Now, with this value of P2, again use the Mathcad Function for ideal reheat Rankine cycle, and get effcy etc:

$$\text{Ideal\_Reheat\_Rankine}(P\_cond, P\_boiler, P2, T1, T3) =$$

"w_T(kJ/kg)"	"w_P(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"quality,x4"	"x2 or T2 (C)"	"SSC(kg/kWh)"
1.778×10^{3}	15.143	1.763×10^{3}	3.916×10^{3}	2.153×10^{3}	0.45	0.9	365.814	2.042



We see that:

Thermal effcy of the plant = 0.45 = 45 % .... Ans.

Plot the reheat pressure, P2 as the quality of steam at exit of LP turbine varies from 0.85 to 0.99:

Now, re-write the Solve block as follows:

$x4 := 0.9$ ... quality required at LP turbine exit

$Quality\_x4(P2) := Ideal\_Reheat\_Rankine(P\_cond, P\_boiler, P2, T1, T3)_{1,6}$

Given

$Quality\_x4(P2) = x4$

$P2(x4) := Find(P2)$ ...write P2 as a function of x4, so that we can get P2 for various values of x4, and plot the results.

i.e. $P2(x4) = 3.772 \times 10^3$ **kPa....Reheat pressure.... Ans.**

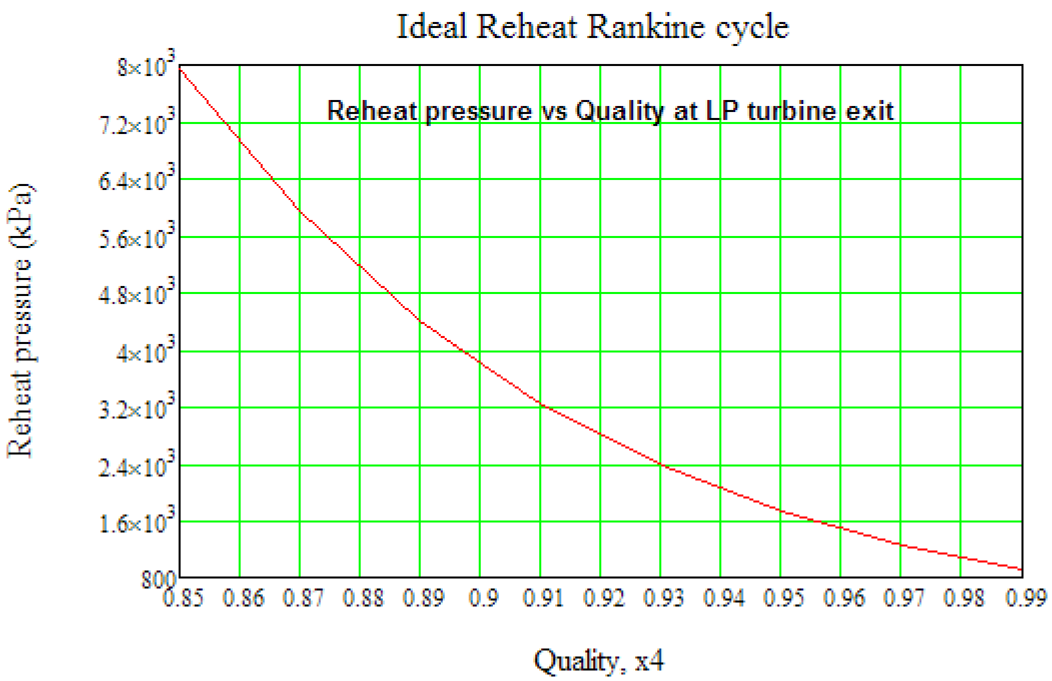
Now, to plot:

$x4 := 0.85, 0.87 .. 0.99$ ...define a range variable

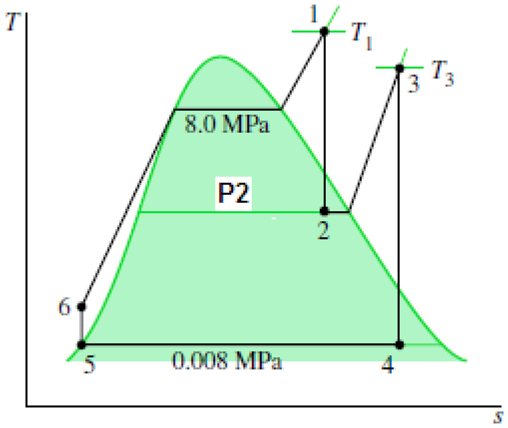
And, we get:

x4 =	P2(x4) =
0.85	$7.955 \cdot 10^3$
0.87	$5.935 \cdot 10^3$
0.89	$4.392 \cdot 10^3$
0.91	$3.235 \cdot 10^3$
0.93	$2.371 \cdot 10^3$
0.95	$1.725 \cdot 10^3$
0.97	$1.256 \cdot 10^3$
0.99	915.039

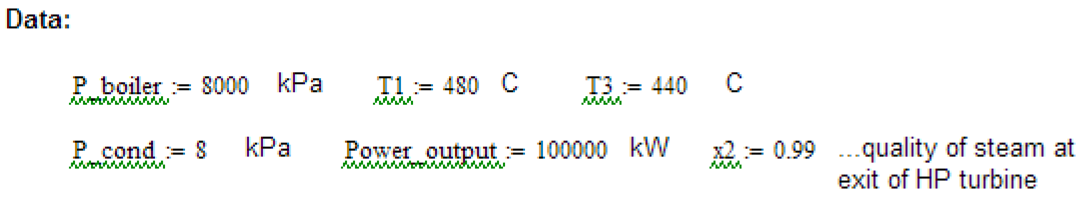
Now, plot:



Prob.3.15 A steam power plant with a 100 MW output, operates on an ideal reheat Rankine cycle. Steam enters the HP turbine at 8 MPa, 480 C, and is condensed in the condenser at 8 kPa. If the moisture content of steam at the exit of HP turbine is 1%, and the steam is reheated to 440 C, determine the reheat pressure, thermal efficiency of the cycle, mass flow rate of steam and heat transfer in condenser. [4]



Note that here, exit of the HP turbine (i.e. state 2) falls in the two-phase region.



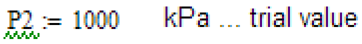
Data:

P_boiler := 8000 kPa T1 := 480 C T3 := 440 C

P_cond := 8 kPa Power_output := 100000 kW x2 := 0.99 ...quality of steam at exit of HP turbine

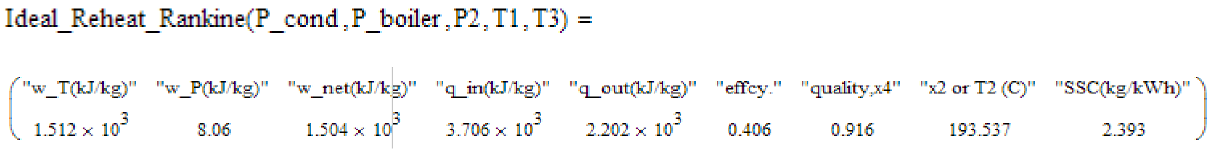
Assume a reheat pressure, say 1000 kPa, and calculate. Obviously, x2 will not be 99%;

So, use the 'Solve block of Mathcad to get the value of P2 to make x2 = 0.99. See below:



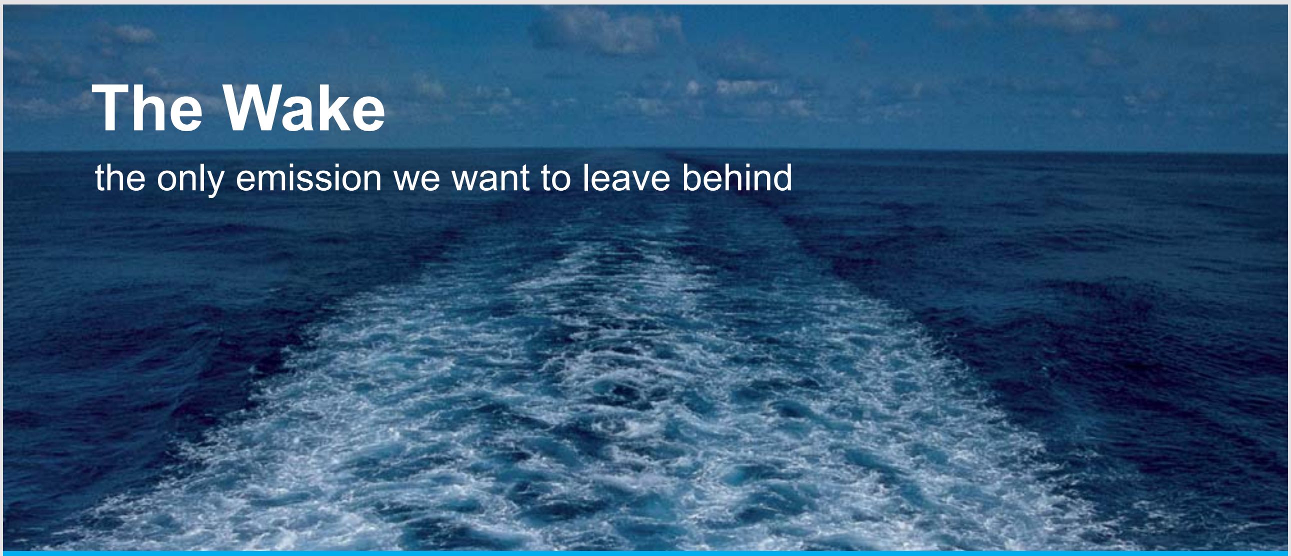
P2 := 1000 kPa ... trial value

And, applying the Mathcad Function,



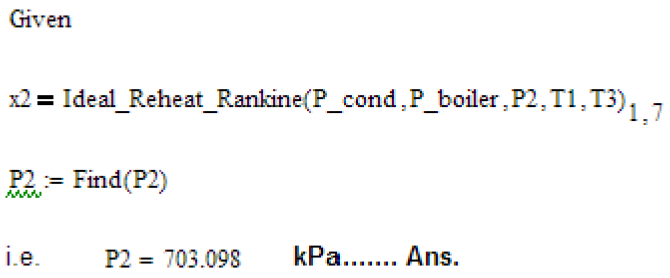
Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

"w_T(kJ/kg)"	"w_P(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"quality,x4"	"x2 or T2 (C)"	"SSC(kg/kWh)"
1.512×10^3	8.06	1.504×10^3	3.706×10^3	2.202×10^3	0.406	0.916	193.537	2.393



We see that x2 = 193.57, which means that with our assumed value of P2 (= 1000 kPa), the HP turbine exit is in superheat region, and the temp T is 193.57 deg. C.

Now, let us apply the "Solve block" of Mathcad:



Given

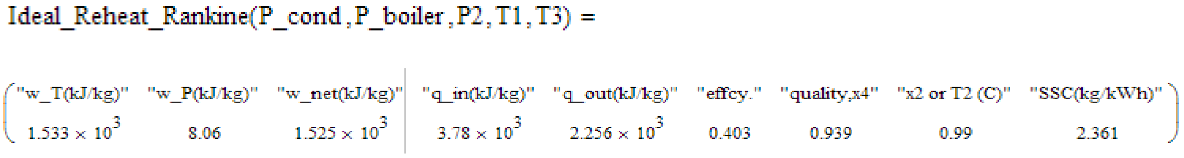
$x2 = \text{Ideal\_Reheat\_Rankine}(P\_cond, P\_boiler, P2, T1, T3)_{1,7}$

$P2 := \text{Find}(P2)$

i.e. $P2 = 703.098$ **kPa....... Ans.**

So, correct value of P2 is 703.098 kPa.

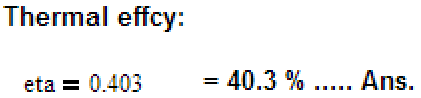
Now, apply the same Mathcad Function again, with the updated value of P2, to get correct performance parameters:



$\text{Ideal\_Reheat\_Rankine}(P\_cond, P\_boiler, P2, T1, T3) =$

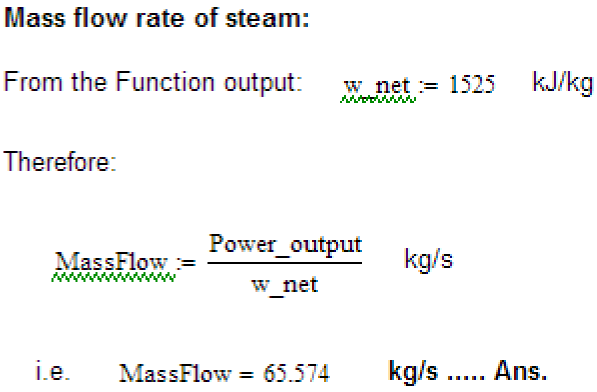
$$\left(\begin{array}{ccc|cccccc} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"x2 or T2 (C)"} & \text{"SSC(kg/kWh)"} \\ 1.533 \times 10^{3} & 8.06 & 1.525 \times 10^{3} & 3.78 \times 10^{3} & 2.256 \times 10^{3} & 0.403 & 0.939 & 0.99 & 2.361 \end{array}\right)$$

Therefore, we have:



Thermal effcy:

$eta = 0.403$ **= 40.3 % ..... Ans.**



Mass flow rate of steam:

From the Function output: $w\_net := 1525$ kJ/kg

Therefore:

$$MassFlow := \frac{Power\_output}{w\_net} \quad \text{kg/s}$$

i.e. $MassFlow = 65.574$ **kg/s ..... Ans.**

Heat transfer in condenser:

We see that: $q\_out := 2256$ kJ/kg

Therefore:

$$Q\_cond := MassFlow \cdot q\_out$$ kW

i.e. $Q\_cond = 1.4793 \times 10^{5}$ **kW ...= 147.93 MW...... Ans.**

Investigate the effect of changing reheat pressure, P2 on the thermal effcy and condenser heat transfer:

First, write effcy and condenser heat transfer (q_out) as functions of P2:

$$effcy(P2) := Ideal\_Reheat\_Rankine(P\_cond, P\_boiler, P2, T1, T3)_{1,5}$$

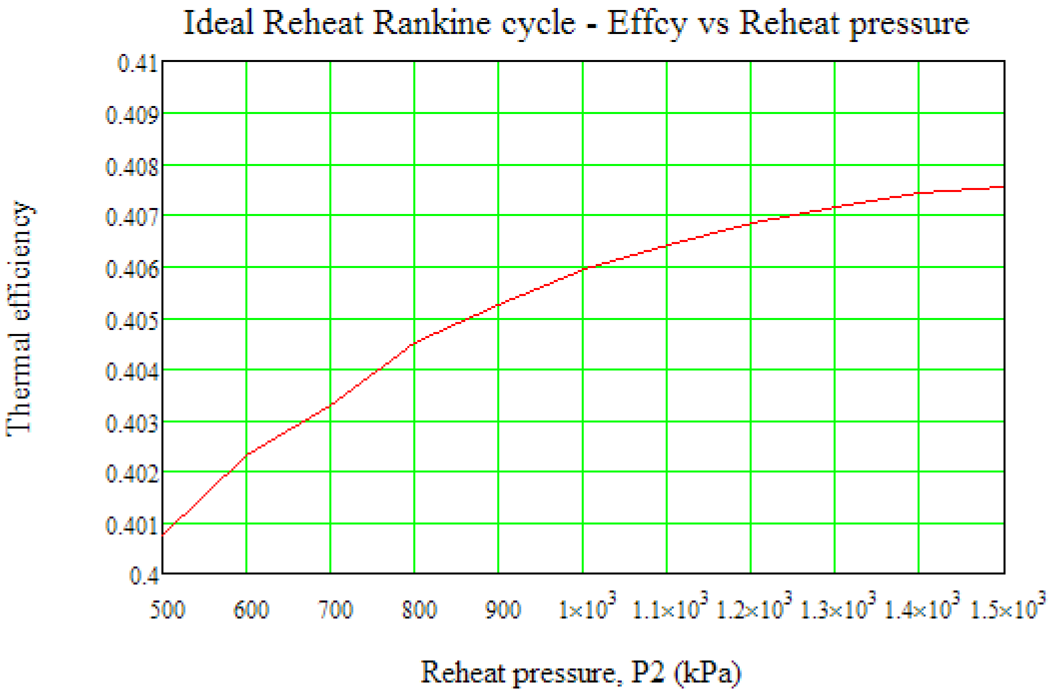
$$q\_out(P2) := Ideal\_Reheat\_Rankine(P\_cond, P\_boiler, P2, T1, T3)_{1,4}$$

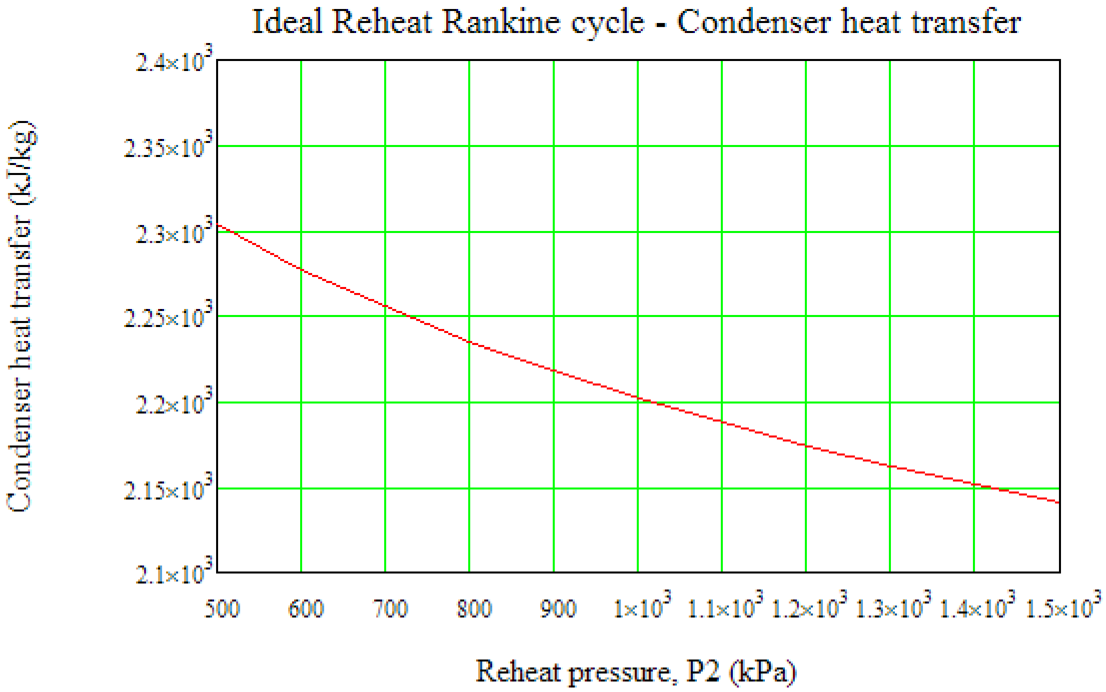
Now:

$P2 := 500, 600 .. 1500$ kPa .... define a range variable

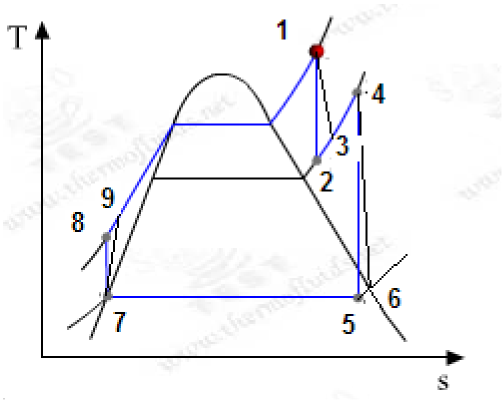
P2 =	effcy(P2) =	q_out(P2) =
500	0.401	$2.304 \cdot 10^{3}$
600	0.402	$2.278 \cdot 10^{3}$
700	0.403	$2.256 \cdot 10^{3}$
800	0.405	$2.235 \cdot 10^{3}$
900	0.405	$2.218 \cdot 10^{3}$
$1 \cdot 10^{3}$	0.406	$2.202 \cdot 10^{3}$
$1.1 \cdot 10^{3}$	0.406	$2.188 \cdot 10^{3}$
$1.2 \cdot 10^{3}$	0.407	$2.174 \cdot 10^{3}$
$1.3 \cdot 10^{3}$	0.407	$2.163 \cdot 10^{3}$
$1.4 \cdot 10^{3}$	0.407	$2.151 \cdot 10^{3}$
$1.5 \cdot 10^{3}$	0.408	$2.141 \cdot 10^{3}$

Plots:

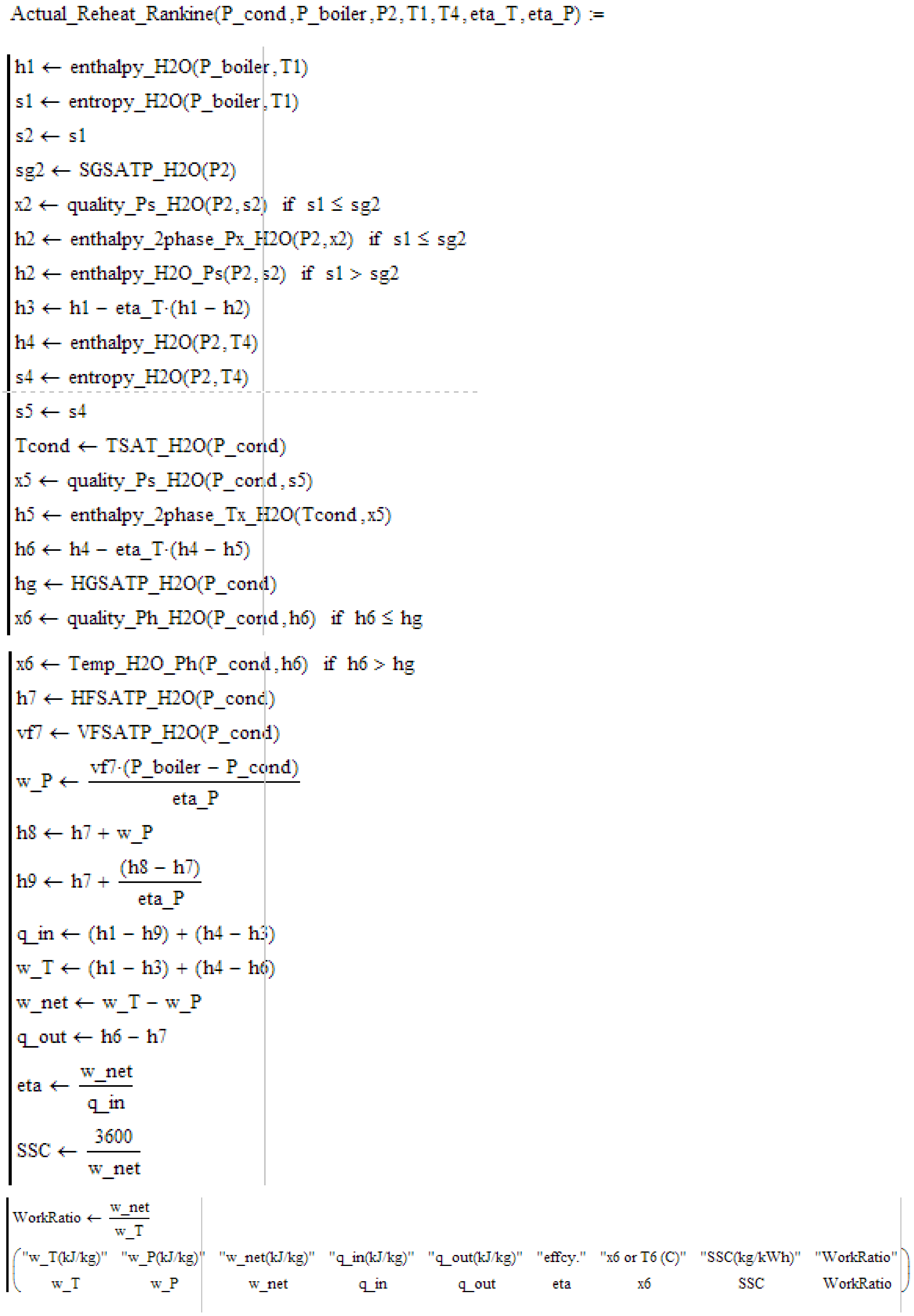

Ideal Reheat Rankine cycle - Effcy vs Reheat pressure
Thermal efficiency
0.41
0.409
0.408
0.407
0.406
0.405
0.404
0.403
0.402
0.401
0.4
500
600
700
800
900
1×10^3
1.1×10^3
1.2×10^3
1.3×10^3
1.4×10^3
1.5×10^3
Reheat pressure, P2 (kPa)



Prob.3.16 Write a Mathcad Function to determine parameters of interest for an actual, reheat Rankine cycle.



Mathcad Function:



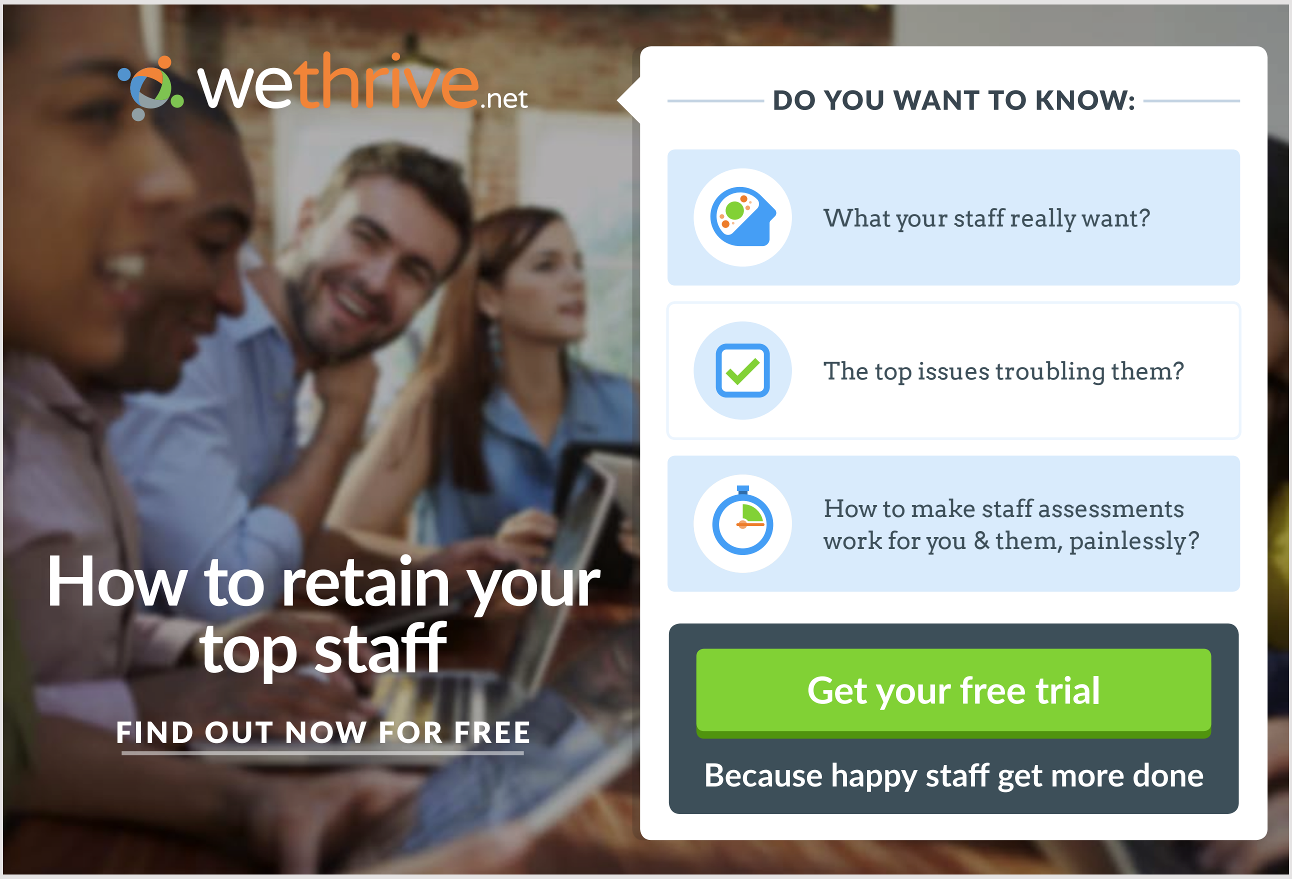
```
Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P) :=
    h1 ← enthalpy_H2O(P_boiler, T1)
    s1 ← entropy_H2O(P_boiler, T1)
    s2 ← s1
    sg2 ← SGSATP_H2O(P2)
    x2 ← quality_Ps_H2O(P2, s2)  if  s1 ≤ sg2
    h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s1 ≤ sg2
    h2 ← enthalpy_H2O_Ps(P2, s2)  if  s1 > sg2
    h3 ← h1 − eta_T·(h1 − h2)
    h4 ← enthalpy_H2O(P2, T4)
    s4 ← entropy_H2O(P2, T4)
    s5 ← s4
    Tcond ← TSAT_H2O(P_cond)
    x5 ← quality_Ps_H2O(P_cond, s5)
    h5 ← enthalpy_2phase_Tx_H2O(Tcond, x5)
    h6 ← h4 − eta_T·(h4 − h5)
    hg ← HGSATP_H2O(P_cond)
    x6 ← quality_Ph_H2O(P_cond, h6)  if  h6 ≤ hg
    x6 ← Temp_H2O_Ph(P_cond, h6)  if  h6 > hg
    h7 ← HFSATP_H2O(P_cond)
    vf7 ← VFSATP_H2O(P_cond)
    w_P ← $\frac{vf7\cdot(P\_boiler - P\_cond)}{eta\_P}$
    h8 ← h7 + w_P
    h9 ← h7 + $\frac{(h8 - h7)}{eta\_P}$
    q_in ← (h1 − h9) + (h4 − h3)
    w_T ← (h1 − h3) + (h4 − h6)
    w_net ← w_T − w_P
    q_out ← h6 − h7
    eta ← $\frac{w\_net}{q\_in}$
    SSC ← $\frac{3600}{w\_net}$
    WorkRatio ← $\frac{w\_net}{w\_T}$
    ( "w_T(kJ/kg)"  "w_P(kJ/kg)"  "w_net(kJ/kg)"  "q_in(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "x6 or T6 (C)"  "SSC(kg/kWh)"  "WorkRatio" )
    (  w_T           w_P           w_net           q_in           q_out           eta       x6              SSC            WorkRatio   )
```

Explanation for the above Function:

This function gives all the important parameters of performance of an Actual, Reheat Rankine cycle.

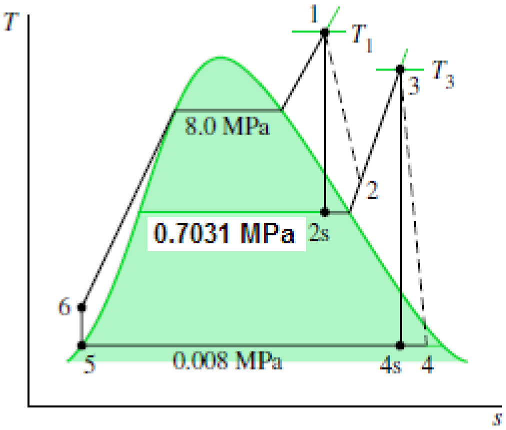
This function is similar to the Function written earlier for parameters of Ideal Reheat Rankine cycle, except that now, we check if the exits of both the HP and LP turbines are in two phase region or superheat region, and determine the enthalpies accordingly.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where Turbine inlet temperature T1 and reheat temp T4 are in deg.C and pressures P_cond, P_boiler and reheat pressure P2 are in kPa. Eta_T and eta_P are the isentropic efficiencies of the turbines and of the pump respectively. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump work (w_P), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), quality of steam at LP turbine exit (x6) or if the exit is in the superheat region, its Temp (T6), Specific Steam Consumption (SSC), and the WorkRatio. Units of each quantity are also given in output.

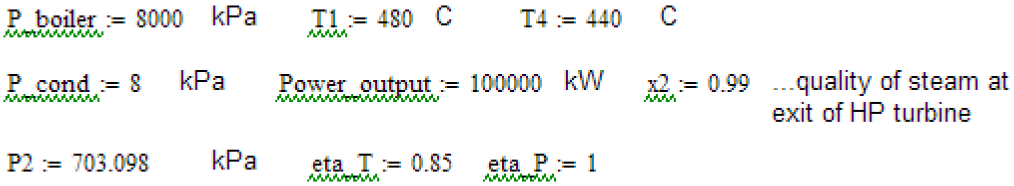


Prob.3.17 In Prob.3.15, let each turbine stage have an isentropic efficiency of 85%, all other conditions remaining the same.Then, determine the thermal efficiency of the plant.

Also, plot the thermal efficiency as each turbine stage isentropic efficiency varies from 85% to 100%. [4]



Data:

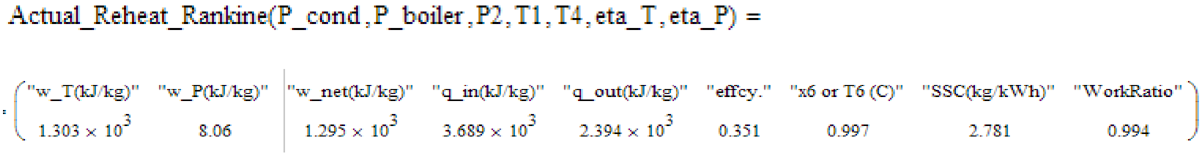


P_boiler := 8000 kPa   T1 := 480 C   T4 := 440 C

P_cond := 8 kPa   Power_output := 100000 kW   x2 := 0.99 ...quality of steam at exit of HP turbine

P2 := 703.098 kPa   eta_T := 0.85   eta_P := 1

Using the Mathcad Function for Actual Reheat Rankine cycle, we get:



Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P) =

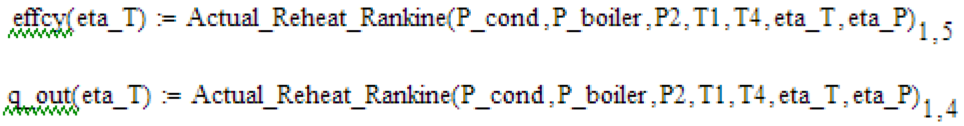
"w_T(kJ/kg)"	"w_P(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"x6 or T6 (C)"	"SSC(kg/kWh)"	"WorkRatio"
1.303×10^3	8.06	1.295×10^3	3.689×10^3	2.394×10^3	0.351	0.997	2.781	0.994

Thus, we have:

Thermal effcy: effcy = 0.351   = 35.1% .... Ans.

To plot the thermal effcy. And condenser heat transfer as each turbine stage isentropic effcy. varies from 0.85 to 1:

First, write effcy andq_out as functions of eta_T:



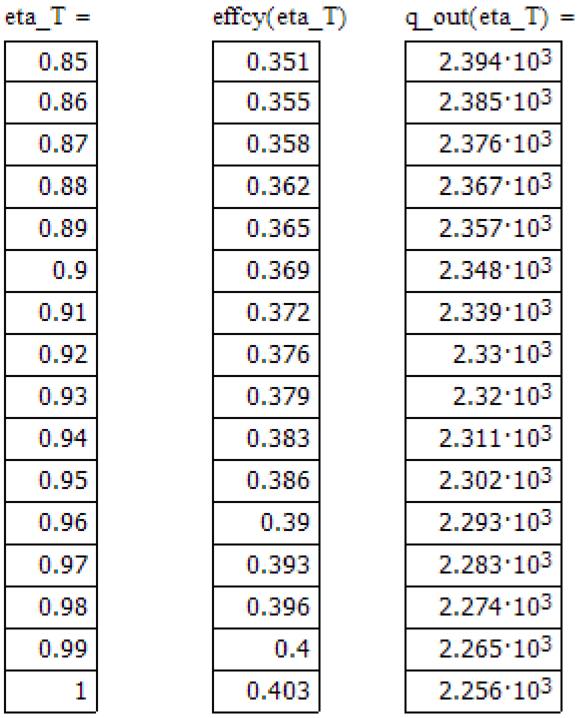
effcy(eta_T) := Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P)$_{1,5}$

q_out(eta_T) := Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P)$_{1,4}$

Now:

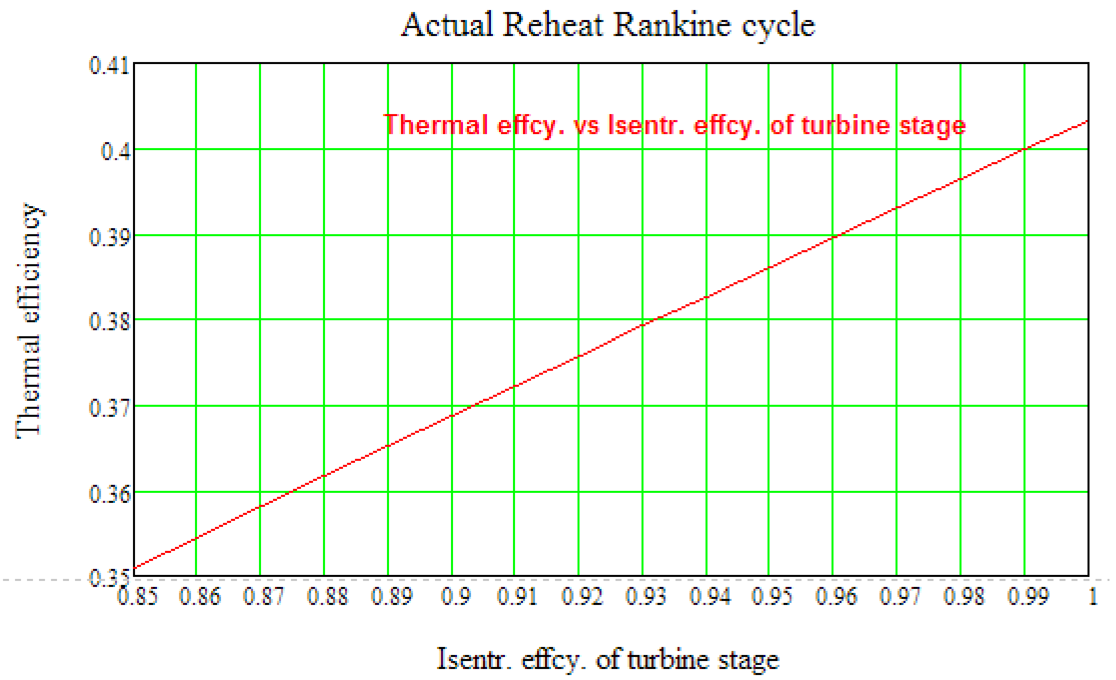
eta_T := 0.85, 0.86.. 1 ...define a range variable

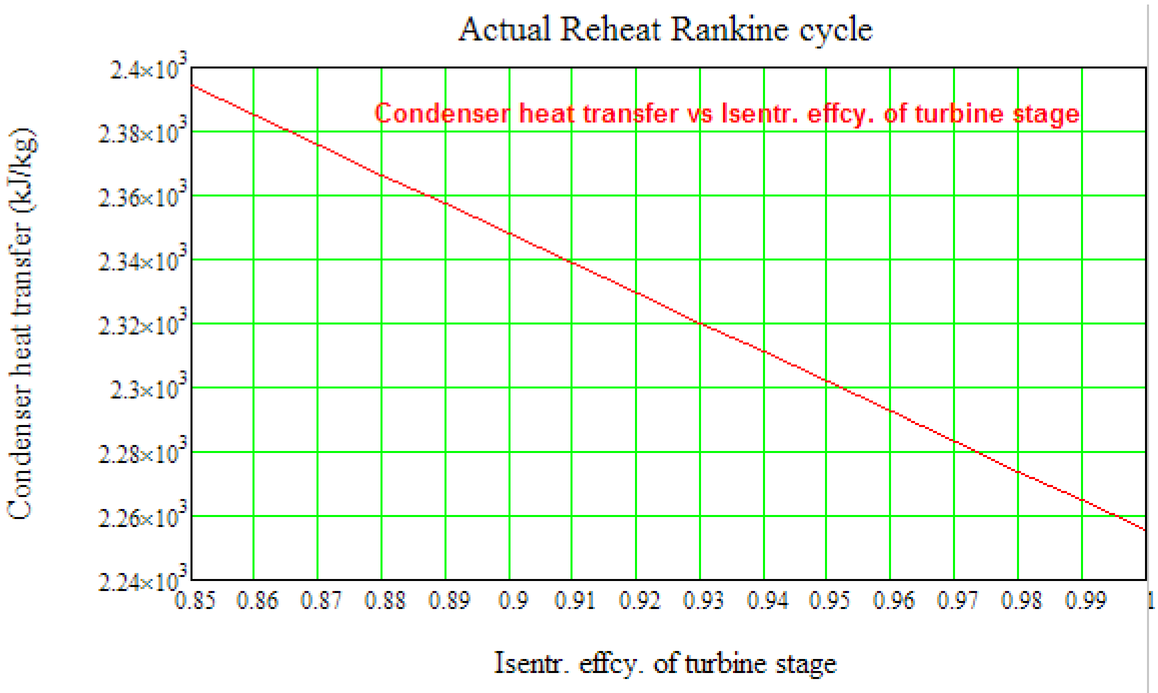
And, we get:



eta_T =	effcy(eta_T)	q_out(eta_T) =
0.85	0.351	$2.394\cdot10^{3}$
0.86	0.355	$2.385\cdot10^{3}$
0.87	0.358	$2.376\cdot10^{3}$
0.88	0.362	$2.367\cdot10^{3}$
0.89	0.365	$2.357\cdot10^{3}$
0.9	0.369	$2.348\cdot10^{3}$
0.91	0.372	$2.339\cdot10^{3}$
0.92	0.376	$2.33\cdot10^{3}$
0.93	0.379	$2.32\cdot10^{3}$
0.94	0.383	$2.311\cdot10^{3}$
0.95	0.386	$2.302\cdot10^{3}$
0.96	0.39	$2.293\cdot10^{3}$
0.97	0.393	$2.283\cdot10^{3}$
0.98	0.396	$2.274\cdot10^{3}$
0.99	0.4	$2.265\cdot10^{3}$
1	0.403	$2.256\cdot10^{3}$

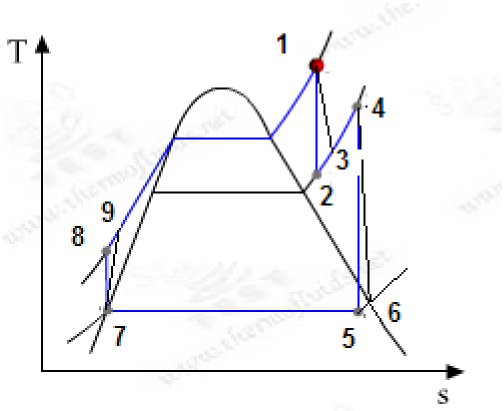
Plot:


Actual Reheat Rankine cycle
Thermal effcy. vs Isentr. effcy. of turbine stage
Thermal efficiency
0.41
0.4
0.39
0.38
0.37
0.36
0.35
0.85
0.86
0.87
0.88
0.89
0.9
0.91
0.92
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1
Isentr. effcy. of turbine stage



==

Prob. 3.18 In a reheat cycle power plant, steam enters the HP turbine at 5 MPa, 450 C and expands to 0.5 MPa, after which it is reheated to 450 C. The steam is then expanded through the LP turbine to 7.5 kPa. Liquid water leaving the condenser is pumped to 5 MPa and returned to steam generator. Each turbine has an isentropic effcy of 87% and a pump effcy of 82%. If the total power output of turbine is 10 MW, determine the mass flow rate of steam, the pump power input, and the thermal effcy of the power plant. [3]



Solution:

Data:

$P\_boiler := 5000$ kPa $T1 := 450$ C

$P2 := 500$ kPa $T4 := 450$ C

$P\_cond := 7.5$ kPa $eta\_T := 0.87$ $eta\_P := 0.82$

$T\_cond := TSAT\_H2O(P\_cond)$ i.e. $T\_cond = 40.29$ C

$Turbine\_Power := 10000$ kW

Applying the Mathcad Function written above:

$Actual\_Reheat\_Rankine(P\_cond, P\_boiler, P2, T1, T4, eta\_T, eta\_P) =$

$$\left(\begin{array}{c|cccccccc} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"x6 or T6 (C)"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.278 \times 10^{3} & 6.1371 & 1.2719 \times 10^{3} & 3.6974 \times 10^{3} & 2.4269 \times 10^{3} & 0.344 & 51.5246 & 2.8305 & 0.9952 \end{array}\right)$$

Note: T6 = 51.5246 C in the above Function output means that the state of steam at the exit of Turbine is in the superheated region.

We see that, total turbine work is: $w\_T := 1278$ kJ/kg

Therefore, mass flow rate of steam:

$$MassFlow := \frac{Turbine\_Power}{w\_T}$$

i.e. $MassFlow = 7.825$ **kg/s ..... Ans.**

Pump work: $w\_P := 6.1371$ kJ/kg

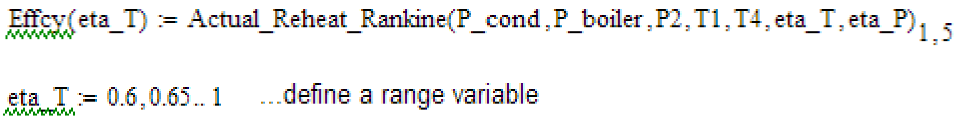
Therefore, Power input to Pump: $Pump\_Power := w\_P \cdot MassFlow$

i.e. $Pump\_Power = 48.021$ **kW .... Ans.**

Thermal effcy. of the plant:

$Efffcy = 0.344$ **= 34.4% .... Ans.**

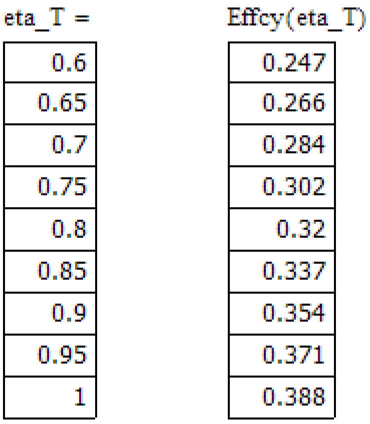
Plot the thermal effcy as eta_T varies from 0.6 to 1:



Effcy(eta_T) := Actual_Reheat_Rankine(P_cond,P_boiler,P2,T1,T4,eta_T,eta_P)$_{1,5}$

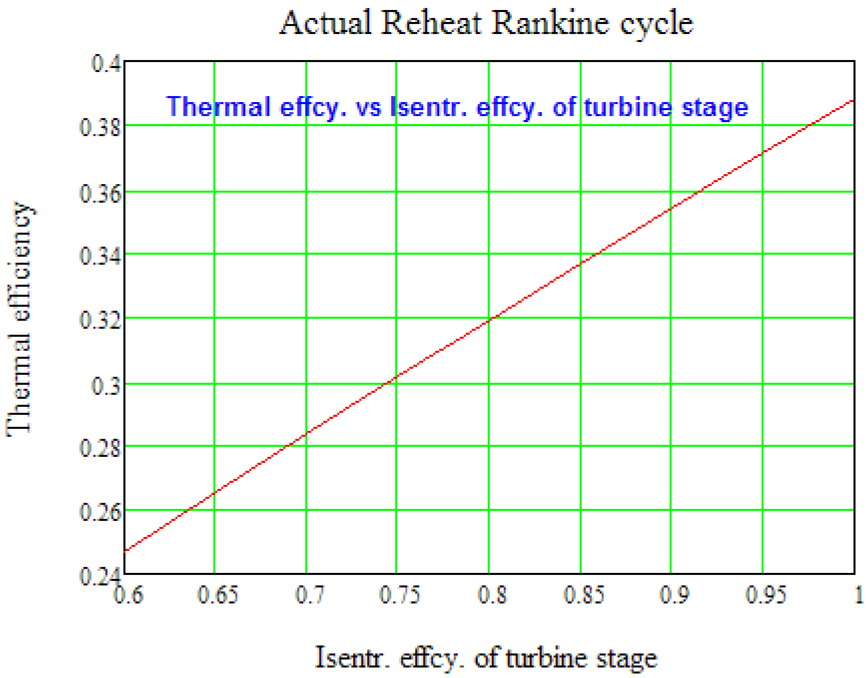
eta_T := 0.6,0.65.. 1   ...define a range variable

We get:



eta_T =	Effcy(eta_T)
0.6	0.247
0.65	0.266
0.7	0.284
0.75	0.302
0.8	0.32
0.85	0.337
0.9	0.354
0.95	0.371
1	0.388

Plot:



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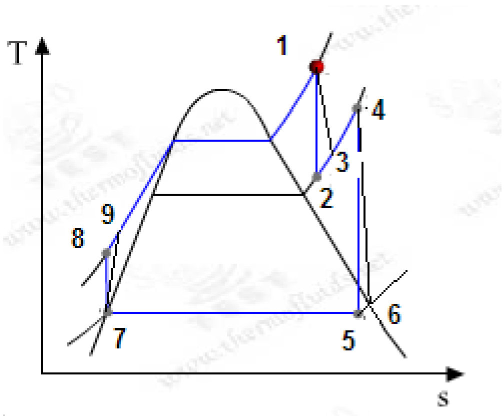
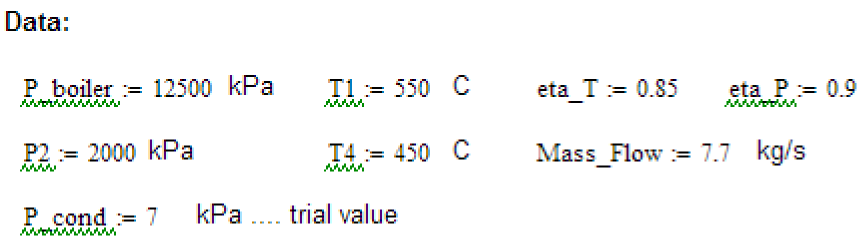
Prob. 3.19 A steam power plant operates on the reheat Rankine cycle. Steam enters the high-pressure turbine at 12.5 MPa and 550°C at a rate of 7.7 kg/s and leaves at 2 MPa. Steam is then reheated at constant pressure to 450°C before it expands in the low-pressure turbine. The isentropic efficiencies of the turbine and the pump are 85 percent and 90 percent, respectively. Steam leaves the condenser as a saturated liquid. If the moisture content of the steam at the exit of the turbine is not to exceed 5 percent, determine (*a*) the condenser pressure, (*b*) the net power output, and (*c*) the thermal efficiency. [2]



Note: Start with a trial value for P_cond and apply the Function; obviously, the quality at exit of turbine, x6 will not be 0.9. So, apply the 'Solve block' of Mathcad to get the correct value of P_cond to have x6 = 0.9. Then, with this new value of P_cond, apply the Function again:



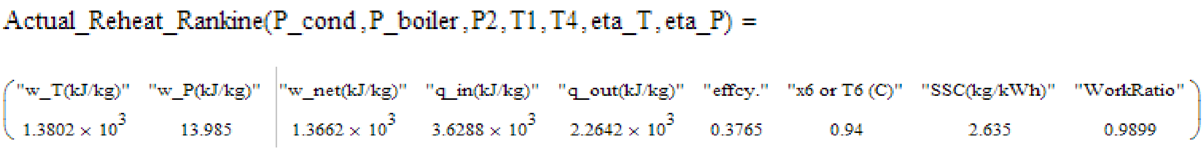
Data:

P_boiler := 12500 kPa   T1 := 550 C   eta_T := 0.85   eta_P := 0.9

P2 := 2000 kPa   T4 := 450 C   Mass_Flow := 7.7 kg/s

P_cond := 7 kPa .... trial value

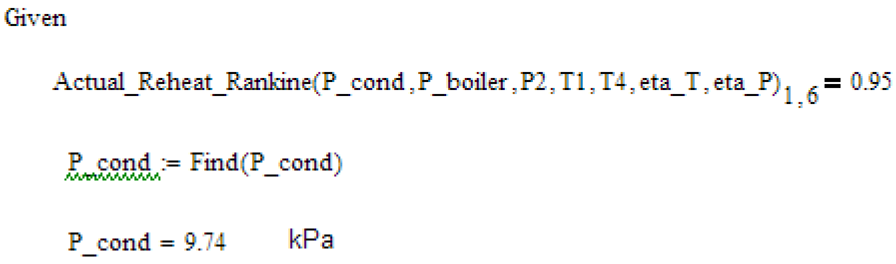
Applying the Mathcad Function written above:



Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"x6 or T6 (C)"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.3802 \times 10^3 & 13.985 & 1.3662 \times 10^3 & 3.6288 \times 10^3 & 2.2642 \times 10^3 & 0.3765 & 0.94 & 2.635 & 0.9899 \end{pmatrix}$$

Now, the quality x6 is 0.94. So, apply the "solve block' of Mathcad to get x6 = 0.95:



Given

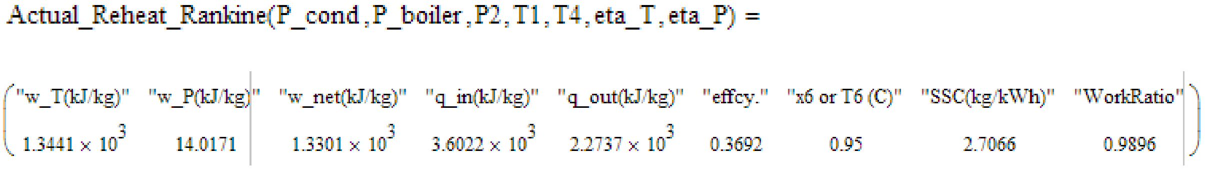
$\text{Actual\_Reheat\_Rankine}(P\_cond, P\_boiler, P2, T1, T4, eta\_T, eta\_P)_{1,6} = 0.95$

P_cond := Find(P_cond)

P_cond = 9.74 kPa

i.e. the value of P_cond = 9.74 kPa, to get x6 = 0.95…Ans.

Applying the Function again, we get other parameters:

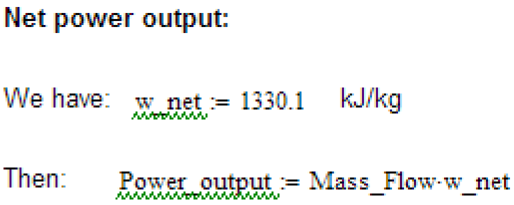


Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"x6 or T6 (C)"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.3441 \times 10^3 & 14.0171 & 1.3301 \times 10^3 & 3.6022 \times 10^3 & 2.2737 \times 10^3 & 0.3692 & 0.95 & 2.7066 & 0.9896 \end{pmatrix}$$

Thus:

Condenser pressure: P_cond = 9.74 **kPa .... Ans.**



Net power output:

We have: w_net := 1330.1 kJ/kg

Then: Power_output := Mass_Flow·w_net

i.e. $\text{Power\_output} = 1.024 \times 10^{4}$ kW ...= 10.24 MW ... Ans.

Thermal efficiency:

Effcy = 0.3692 = 36.92% .... Ans.

:===

Plot Thermal effcy. and quality at turbine exit, x6 vs turbine effcy. for eta_T = 0.6 to 1:

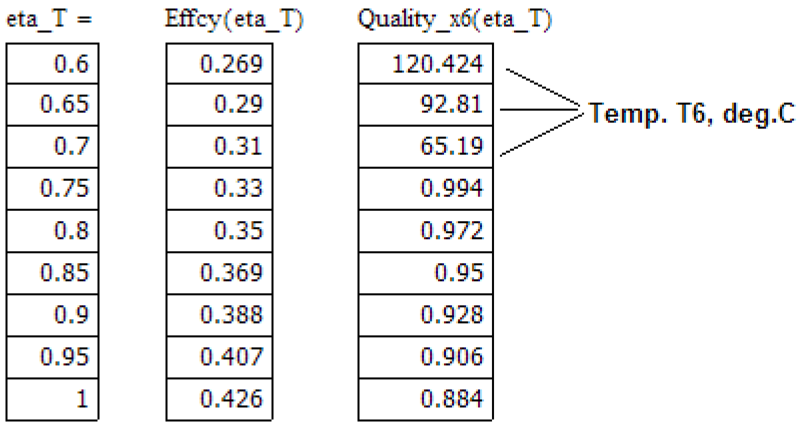
First, write themal effcy. and quality as a functions of eta_T:

$\text{Effcy}(\text{eta\_T}) := \text{Actual\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{P2}, \text{T1}, \text{T4}, \text{eta\_T}, \text{eta\_P})_{1,5}$

$\text{Quality\_x6}(\text{eta\_T}) := \text{Actual\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{P2}, \text{T1}, \text{T4}, \text{eta\_T}, \text{eta\_P})_{1,6}$

$\text{eta\_T} := 0.6, 0.65 .. 1$ .... define a range variable

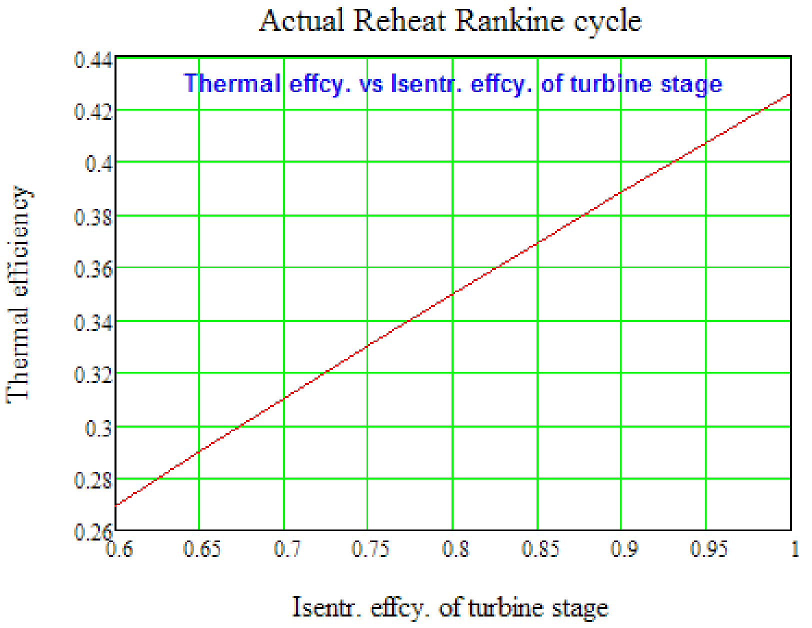
We get:

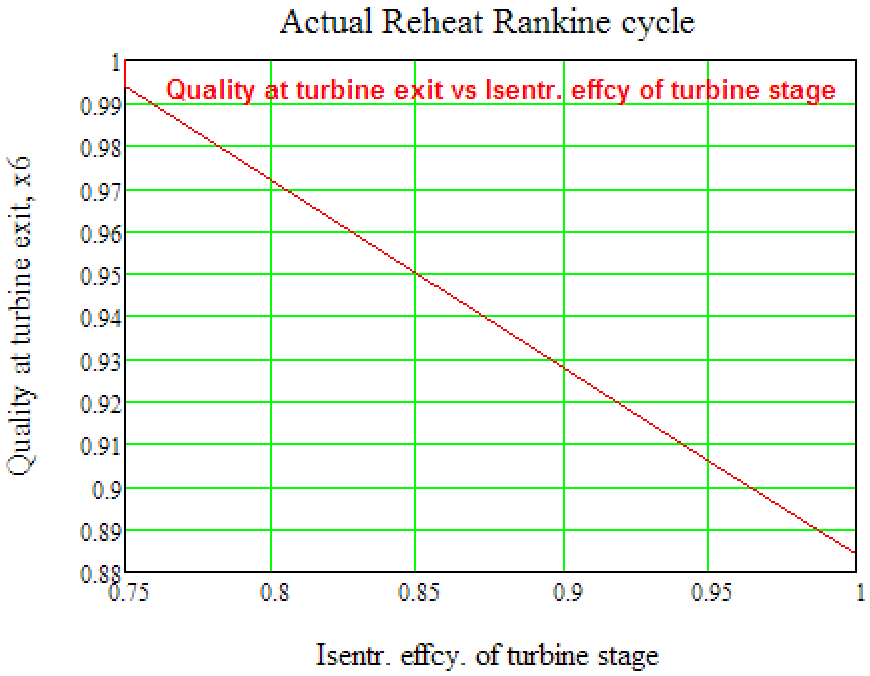


eta_T =	Effcy(eta_T)	Quality_x6(eta_T)
0.6	0.269	120.424
0.65	0.29	92.81
0.7	0.31	65.19
0.75	0.33	0.994
0.8	0.35	0.972
0.85	0.369	0.95
0.9	0.388	0.928
0.95	0.407	0.906
1	0.426	0.884

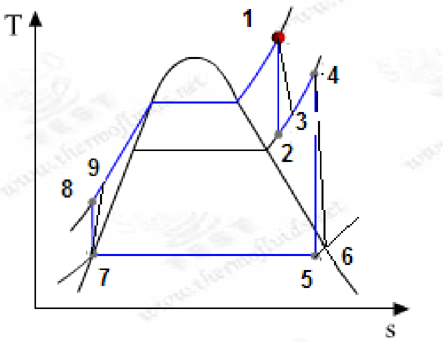
Note: In the above Table, for eta_T = 0.6, 0.65 and 0.7, the turbine exit is in *superheated region*, which is indicated by showing turbine exit temps as: 120.424, 92.81 and 65.19 C respectively.

And, plot:





Prob. 3.20 Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 500°C and the low-pressure turbine at 1 MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10 kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pump is 95 percent. Determine: (*a*) the quality (or temperature, if superheated) of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam. [2]



Data:

P_boiler := 10000 kPa

T1 := 500 C

eta_T := 0.8

eta_P := 0.95

P2 := 1000 kPa

T4 := 500 C

Power_output := 80000 kW

P_cond := 10 kPa

Applying the Mathcad Function written above:

$$\text{Actual\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{P2}, \text{T1}, \text{T4}, \text{eta\_T}, \text{eta\_P}) =$$

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"x6 or T6 (C)"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.2879 \times 10^{3} & 10.6233 & 1.2773 \times 10^{3} & 3.7496 \times 10^{3} & 2.4729 \times 10^{3} & 0.3406 & 87.875 & 2.8185 & 0.9918 \end{pmatrix}$$

We see that:

Temp at turbine exit: $T6 = 87.875$ **deg.C ..... Ans.**

Thermal effcy.: $\text{effcy} = 0.3406$ **= 34.06% ..... Ans.**

Mass flow rate of steam:

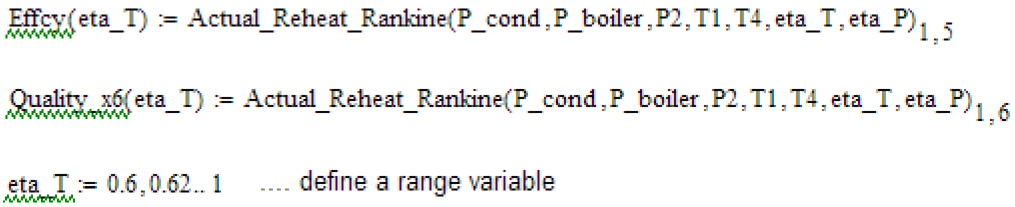
We have: $\text{w\_net} := 1277.3$ kJ/kg

Then: $\text{MassFlow} := \dfrac{\text{Power\_output}}{\text{w\_net}}$

i.e. $\text{MassFlow} = 62.632$ **kg/s ..... Ans.**

Plot Thermal effcy. and quality, x6/temp. T6 at turbine exit, vs turbine effcy. for eta_T = 0.6 to 1:

First, write themal effcy and x6/T6 as a function of eta_T:

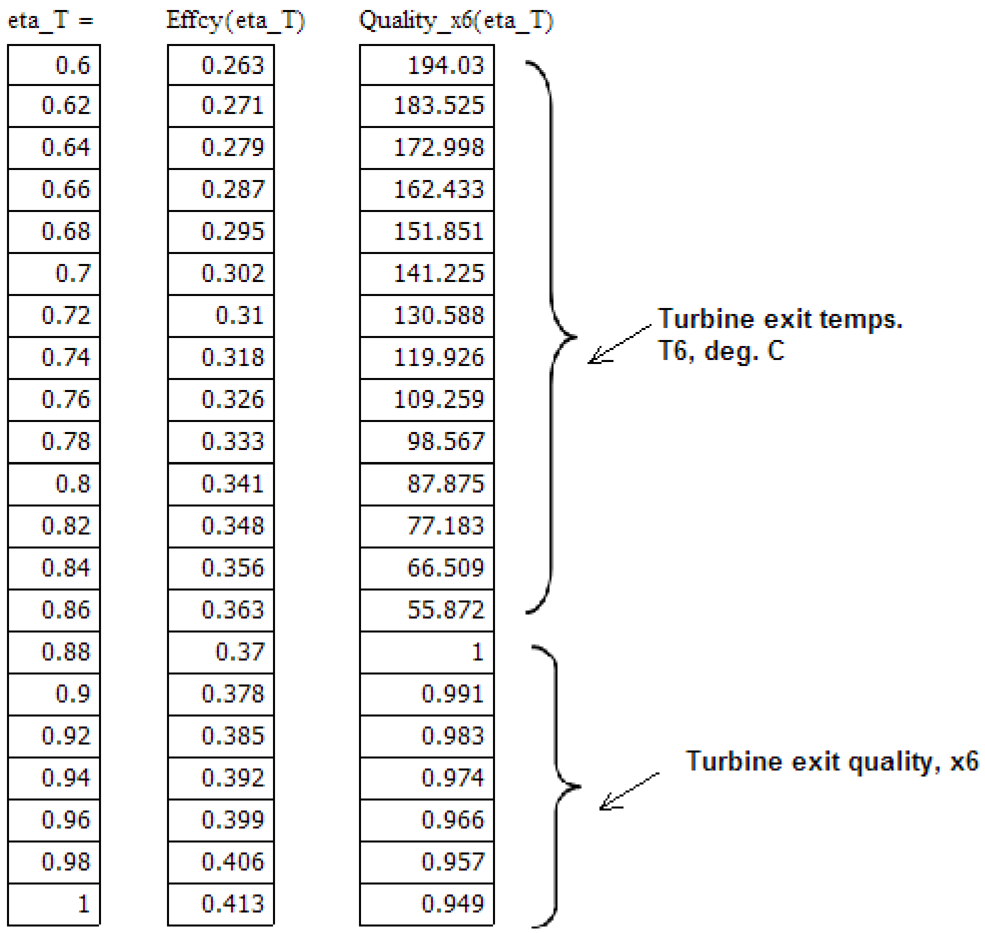


Effcy(eta_T) := Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P)$_{1,5}$

Quality_x6(eta_T) := Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P)$_{1,6}$

eta_T := 0.6, 0.62.. 1 .... define a range variable

We get:



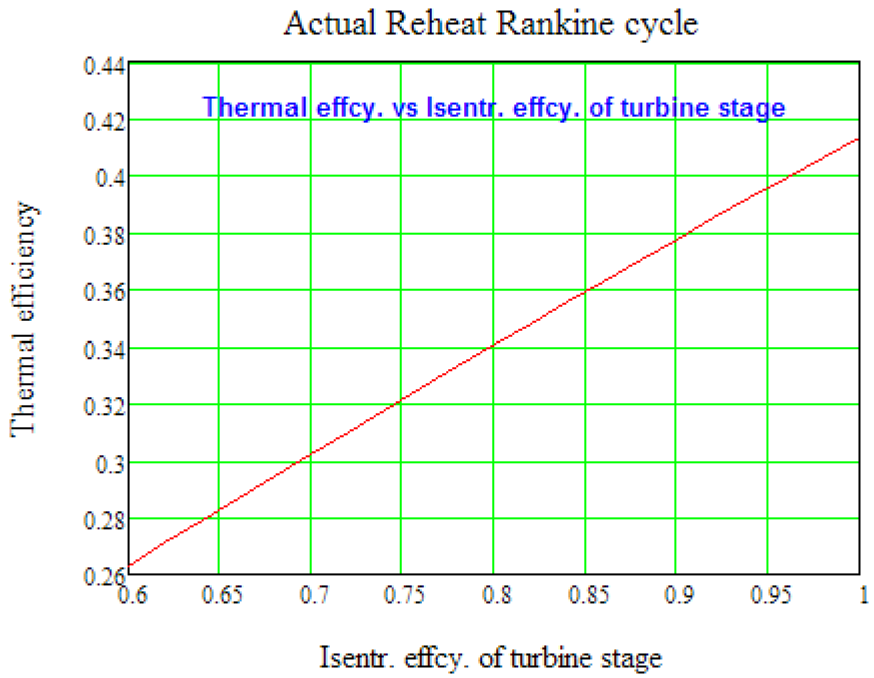
eta_T =	Effcy(eta_T)	Quality_x6(eta_T)
0.6	0.263	194.03
0.62	0.271	183.525
0.64	0.279	172.998
0.66	0.287	162.433
0.68	0.295	151.851
0.7	0.302	141.225
0.72	0.31	130.588
0.74	0.318	119.926
0.76	0.326	109.259
0.78	0.333	98.567
0.8	0.341	87.875
0.82	0.348	77.183
0.84	0.356	66.509
0.86	0.363	55.872
0.88	0.37	1
0.9	0.378	0.991
0.92	0.385	0.983
0.94	0.392	0.974
0.96	0.399	0.966
0.98	0.406	0.957
1	0.413	0.949

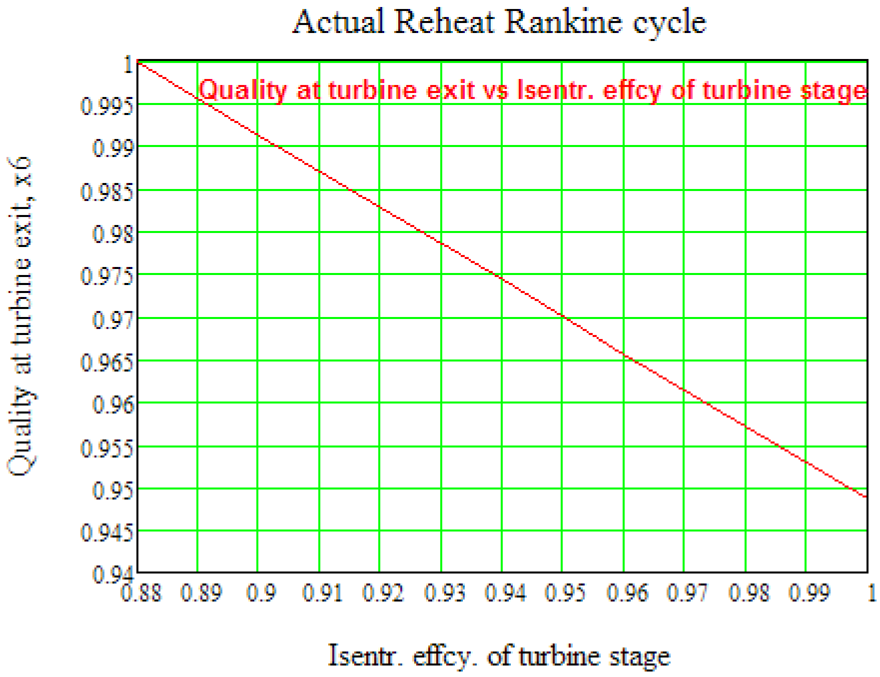
Turbine exit temps. T6, deg. C

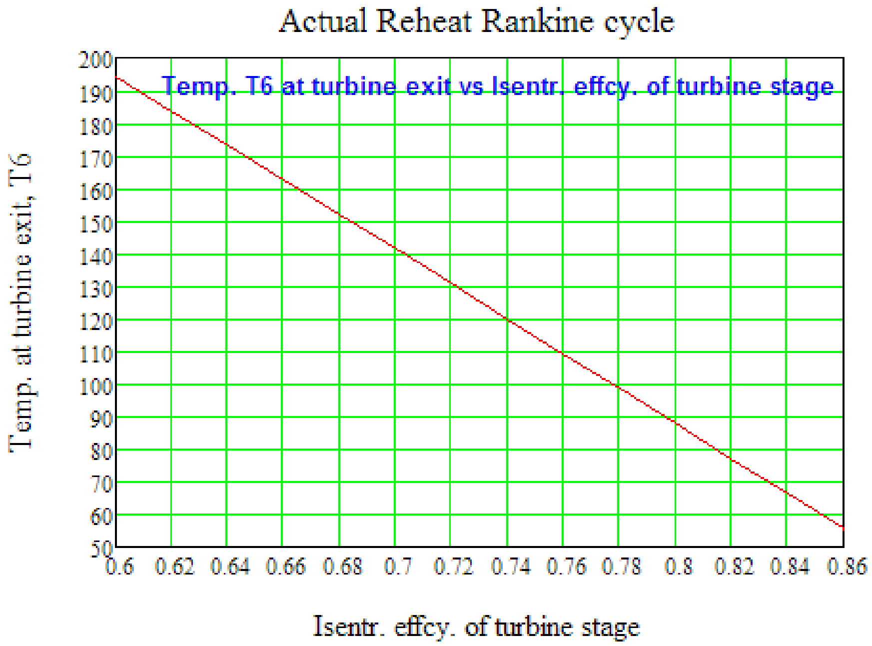
Turbine exit quality, x6

Note that for eta_T = 0.6 to 0.86, the turbine exit is in superheated region and the corresponding turbine exit temps can be read off from the above Table. For eta_T = 0.88, the turbine exit is just sat. vapor (quality x6 = 1). For eta_T > 0.9, the turbine exit is in the two-phase region and the corresponding qualities of turbine exit (x6) can be seen in the above Table.

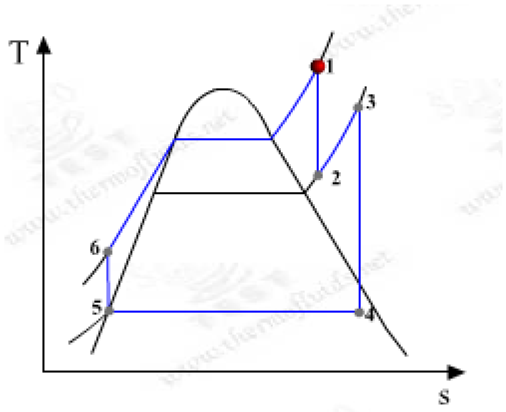
Now, plot the results:






Actual Reheat Rankine cycle
Temp. T6 at turbine exit vs Isentr. effcy. of turbine stage
Temp. at turbine exit, T6
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
0.6
0.62
0.64
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
0.82
0.84
0.86
Isentr. effcy. of turbine stage

Prob. 3.21 In a steam power plant operating on a reheat Rankine cycle, steam is supplied to the turbine at a pressure of 32 bar and a temp of 410 C. Steam is reheated at 5.5 bar to a temp of 400 C, before it is expanded down to 0.08 bar. What will be the dryness fraction at the exit of LP turbine and the efficiency of the cycle? [VTU]



Data:

P_boiler := 3200 kPa   T1 := 410 C   P_cond := 8 kPa

P2 := 550 kPa   T3 := 400 C

Applying the Mathcad Function for Ideal, reheat cycle, written earlier, we get:

Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.285 \times 10^{3} & 3.219 & 1.282 \times 10^{3} & 3.534 \times 10^{3} & 2.253 \times 10^{3} & 0.363 & 0.937 & 2.809 & 0.997 \end{pmatrix}$$

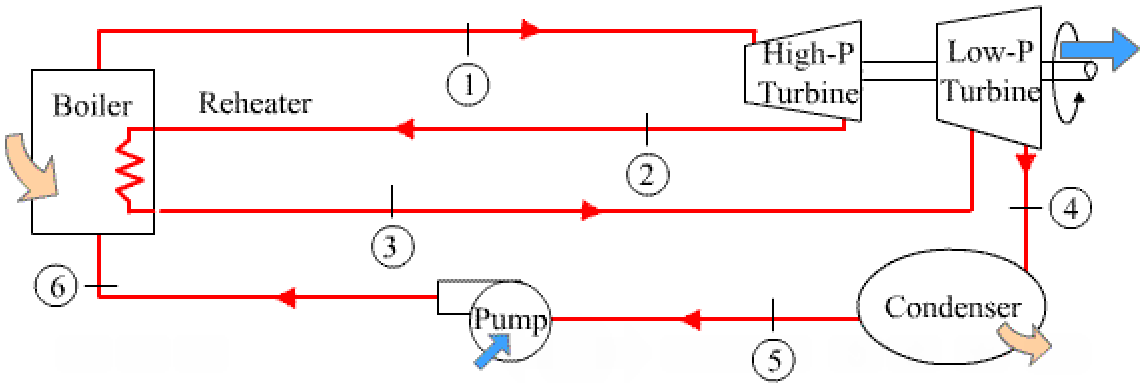
i.e.

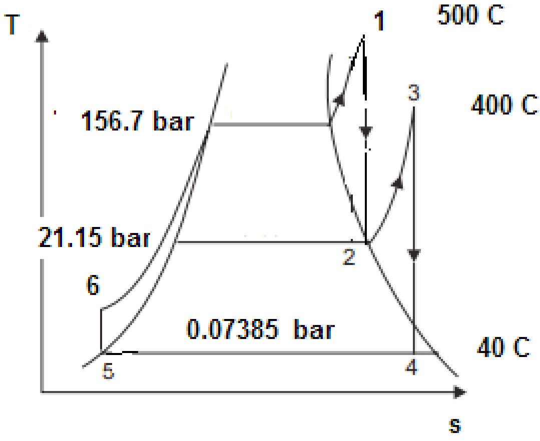
Dryness fraction at LP turbine exit = x4 = 0.937 ..... Ans.

Thermal effcy of the cycle = 0.363 = 36.3% .... Ans.

===

Prob.3.22 In a reheat Rankine cycle, steam at 500 C expands in a HP turbine till it is saturated vap. It is then reheated at constant pressure to 400 C and then expanded in a LP turbine to 40 C. If the max. moisture content at the turbine exhaust is limited to 15%, find: (i) the reheat pressure, (ii) pressure of steam at the inlet to HP turbine, (iii) net specific work output, (iv) cycle efficiency, and (v) steam rate. Assume all ideal processes. [VTU]





Data:

T1 := 500 C T3 := 400 C T4 := 40 C x4 := 0.85 x2 := 1

i.e. P_cond := PSAT_H2O(T4) i.e. P_cond = 7.385 kPa

Then, we have:

s4 := entropy_2phase_Tx_H2O(T4,x4) i.e. s4 = 7.103 kJ/kg.K

Now, we use the 'Solve block' of Mathcad to find P1 and P2, very easily:

P1 := 20000 kPa ... trial value

P2 := 4000 kPa ... trial value

Given

entropy_H2O(P2, T3) = s4 ....for isentropic expn in LP turbine

entropy_H2O(P1, T1) = SGSATP_H2O(P2) ....for isentropic expn in HP turbine

$$\text{Find}(P1, P2) = \begin{pmatrix} 1.5666 \times 10^{4} \\ 2.1153 \times 10^{3} \end{pmatrix}$$

i.e. P1 := 15666 **kPa = 156.7 bar ....boiler pressure.. Ans.**

P2 := 2115.3 **kPa = 21.15 bar ...reheat pressure .... Ans.**

Further, note that: P_boiler := P1

Now, let us apply the Mathcad Function for Ideal, reheat cycle, to get other parameters:

Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.536 \times 10^{3} & 15.782 & 1.521 \times 10^{3} & 3.566 \times 10^{3} & 2.045 \times 10^{3} & 0.426 & 0.85 & 2.367 & 0.99 \end{pmatrix}$$

Therefore, we note from the above:

Net work output: w_net = 1521 **kJ/kg .... Ans.**

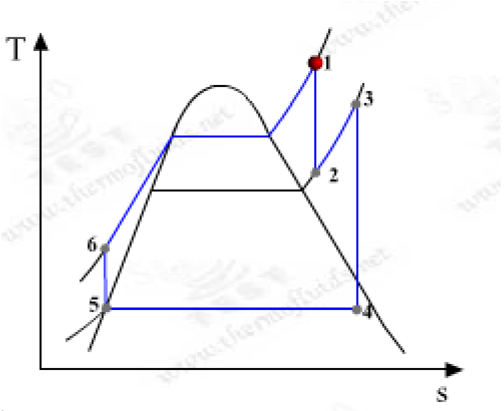
Cycle efficiency: effcy = 0.426 **= 42.6% .... Ans.**

Sp. Steam Consumption: SSC = 2.367 **kg/kWh ..... Ans.**

===:

Note: To appreciate the power and elegance of Mathcad Functions presented above, try to work out the above problem using only Water/Steam Tables.

Prob.3.23 In a reheat Rankine cycle, steam at 20 MPa, 550 C expands in a HP turbine. It is then reheated at constant pressure to 550 C and then expanded in a LP turbine to 15 kPa. If the max. moisture content at the turbine exhaust is limited to 10%, find: (i) the reheat pressure, (ii) ratio of pump work to turbine work, (iii) ratio of heat rejection to heat addition, and (iv) cycle thermal efficiency. Assume all ideal processes. [VTU]



Data:

T1 := 550 C T3 := 550 C x4 := 0.9

i.e. P_cond := 15 kPa P_boiler := 20000 kPa

We have to find reheat pressure P2:

Start with a trial value of P2, i.e. P2 := 4000 kPa

Now, apply the Mathcad Function for Ideal, reheat Rankine cycle.

In the output, observe the quality x4. Obviously, it will not be 0.9

So, use the 'Solve block' of Mathcad to get correct value of P2 to make x4 = 0.9:

Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.663 \times 10^{3} & 20.266 & 1.643 \times 10^{3} & 3.763 \times 10^{3} & 2.12 \times 10^{3} & 0.437 & 0.893 & 2.191 & 0.988 \end{pmatrix}$$

Note that in the output, we get x4 = 0.893.

Now, apply the 'Solve block' of Mathcad:

Given

$$\text{Ideal\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, \text{P2}, \text{T1}, \text{T3})_{1,6} = \text{x4}$$

P2 := Find(P2)

i.e. $\text{P2} = 3.637 \times 10^{3}$ **kPa ..... reheat pressure .... Ans.**

With this value of P2, apply the Function again to get other parameters:

Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3) =

$$\begin{pmatrix} \text{"w\_T(kJ/kg)"} & \text{"w\_P(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"quality,x4"} & \text{"SSC(kg/kWh)"} & \text{"WorkRatio"} \\ 1.673 \times 10^{3} & 20.266 & 1.653 \times 10^{3} & 3.789 \times 10^{3} & 2.135 \times 10^{3} & 0.436 & 0.9 & 2.178 & 0.988 \end{pmatrix}$$

Therefore, we get:

Pump work: $\text{w\_P} = 20.266$ **kJ/kg .... Ans.**

Turbine work: $\text{w\_T} = 1673$ **kJ/kg .... Ans.**

Their ratio: $\frac{\text{w\_P}}{\text{w\_T}} = \frac{20.266}{1673} = 0.012$ **....Ans.**

Heat rejection: $\text{q\_out} = 2135$ **kJ/kg .... Ans.**

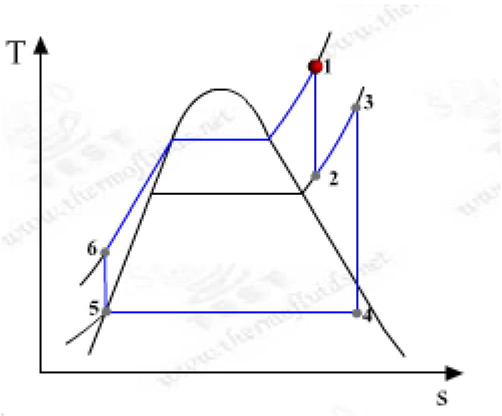
Heat added: $\text{q\_in} = 3789$ **kJ/kg .... Ans.**

Their ratio: $\frac{\text{q\_out}}{\text{q\_in}} = \frac{2135}{3789} = 0.563$ **....Ans.**

Cycle effcy.: $\text{effcy} = 0.436$ **= 43.6% .... Ans.**

==

Prob.3.24 In a reheat Rankine cycle, net power output is 80 MW. Steam at 100 bar, 500 C expands in a HP turbine. It is then reheated at 10 bar to 500 C and then expanded in a LP turbine to 10 kPa. Find: (i) quality of steam at exit of LP turbine, (ii) thermal efficiency, (iii) mass flow rate of steam. Assume all ideal processes. [VTU]



Data:

T1 := 500 C   T3 := 500 C   Power_output := 80000 kW

i.e. P_cond := 10 kPa   P_boiler := 10000 kPa   P2 := 1000 kPa

Now, apply the Mathcad Function for Ideal, reheat Rankine cycle:

We get:

```
Ideal_Reheat_Rankine(P_cond,P_boiler,P2,T1,T3) =

("w_T(kJ/kg)"  "w_P(kJ/kg)"  "w_net(kJ/kg)" | "q_in(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "quality,x4"  "SSC(kg/kWh)"  "WorkRatio")
( 1.6099 × 10^3   10.0921     1.5998 × 10^3  |  3.869 × 10^3   2.2692 × 10^3   0.4135    0.9485        2.2503         0.9937    )
```

From the Function output, we see that:

Quality of steam at exit of LP turbine = x4 = 0.9485 .... Ans.

Thermal efficiency = effcy = 0.4135 = 41.35 % .... Ans.

Mass flow rate of steam:

Now, we have: SSC := 2.2503 kg/kWh

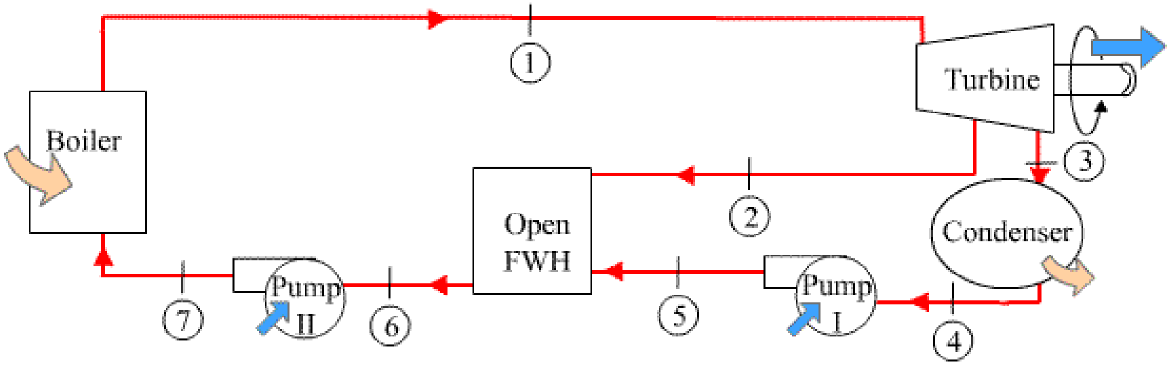
Then: MassFlow := SSC·Power_output kg/h

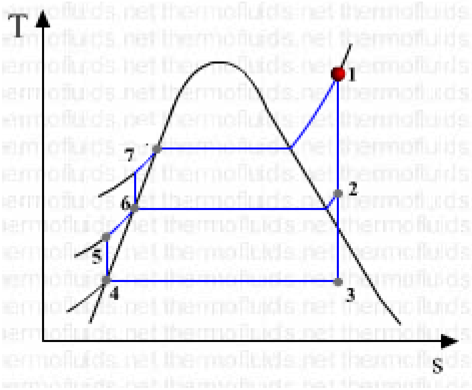
i.e. MassFlow = 1.8×10^5 **kg/h = 50.007 kg/s .... Ans.**

===

Prob. 3.25 Write a Mathcad program to find out the various parameters of interest for a Regenerative Rankine cycle, using one open Feedwater heater (FWH), with ideal processes for steam.

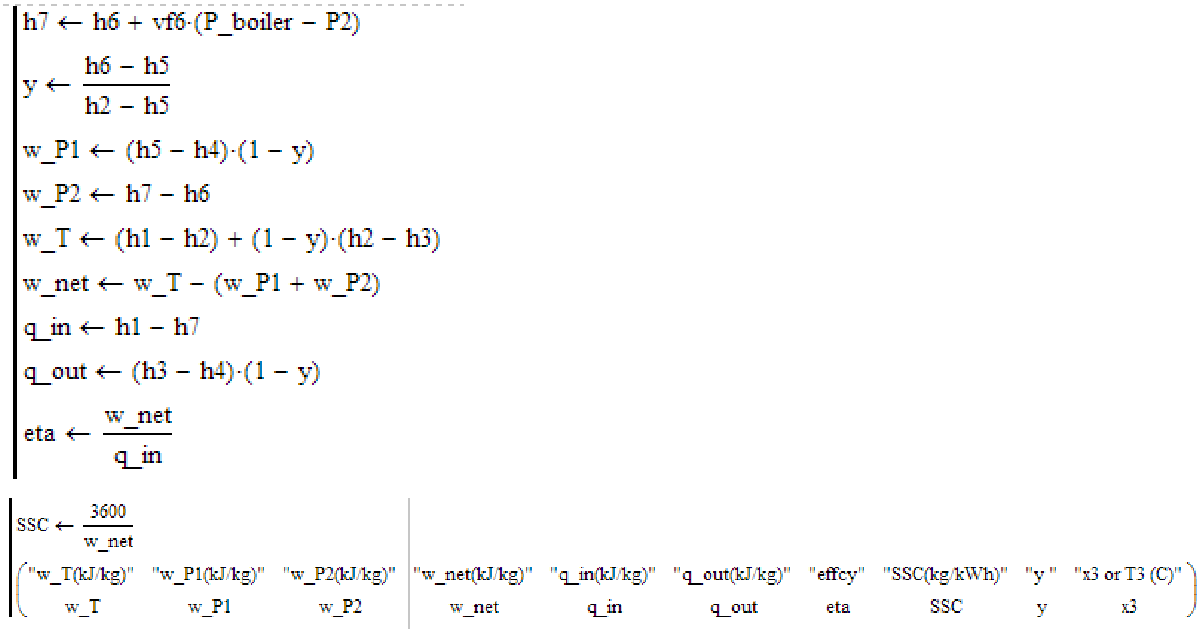
Solution:





```
Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1) :=

    h1 ← enthalpy_H2O(P_boiler, T1)
    s1 ← entropy_H2O(P_boiler, T1)
    s2 ← s1
    sg2 ← SGSATP_H2O(P2)
    x2 ← quality_Ps_H2O(P2, s2)  if  s2 ≤ sg2
    h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s2 ≤ sg2
    h2 ← enthalpy_H2O_Ps(P2, s2)  if  s2 > sg2
    s3 ← s1
    sg3 ← SGSATP_H2O(P_cond)
    Tcond ← TSAT_H2O(P_cond)
    x3 ← quality_Ps_H2O(P_cond, s3)  if  s3 ≤ sg3
    h3 ← enthalpy_2phase_Tx_H2O(Tcond, x3)  if  s3 ≤ sg3
    h3 ← enthalpy_H2O_Ps(P_cond, s3)  if  s3 > sg3
    x3 ← Temp_H2O_Ph(P_cond, h3)  if  s3 > sg3
    h4 ← HFSATP_H2O(P_cond)
    vf4 ← VFSATP_H2O(P_cond)
    h5 ← h4 + vf4·(P2 − P_cond)
    h6 ← HFSATP_H2O(P2)
    vf6 ← VFSATP_H2O(P2)
```



```
h7 ← h6 + vf6·(P_boiler − P2)
      h6 − h5
y ←  -------
      h2 − h5
w_P1 ← (h5 − h4)·(1 − y)
w_P2 ← h7 − h6
w_T ← (h1 − h2) + (1 − y)·(h2 − h3)
w_net ← w_T − (w_P1 + w_P2)
q_in ← h1 − h7
q_out ← (h3 − h4)·(1 − y)
        w_net
eta ←  -----
        q_in
        3600
SSC ←  -----
        w_net
("w_T(kJ/kg)"  "w_P1(kJ/kg)"  "w_P2(kJ/kg)"  "w_net(kJ/kg)"  "q_in(kJ/kg)"  "q_out(kJ/kg)"  "effcy"  "SSC(kg/kWh)"  "y "  "x3 or T3 (C)")
(    w_T           w_P1           w_P2           w_net           q_in           q_out        eta        SSC         y         x3      )
```

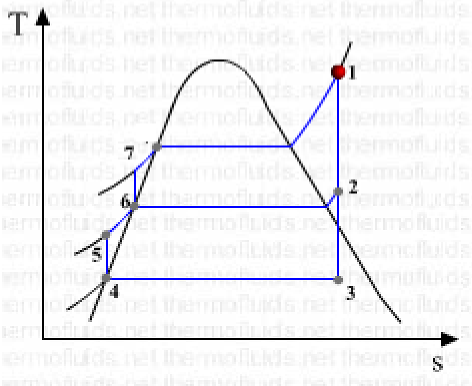
Explanation for the above Function:

This function gives all the important parameters of performance of an Ideal, Regenerative Rankine cycle.

This function is similar to the Functions written earlier for other variations of Rankine cycle, and here also we check if the exits of both stages of turbine are in two phase region or superheat region, and determine the enthalpies accordingly.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where Turbine inlet temperature is in deg.C and pressures P_cond, P_boiler and extraction pressure P2 are in kPa. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump works (w_P1 and w_P2), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), Specific Steam Consumption (SSC), fraction of extracted stream (y), and the quality of steam at turbine exit (x3) if the exit steam is in two phase region, or its temp (T3) if the exit steam is in superheat region. Units of each quantity are also given in output.

Prob. 3.26 In an ideal regenerative cycle, steam enters the turbine at 4 MPa, 400 C. After expansion to 400 kPa, some of the steam is extracted from the turbine for heating the feed water in an open feed water heater (FWH). The pressure in the FWH is 400 kPa and the water leaving it is sat. liquid at 400 kPa. The steam not extracted expands to 10 kPa. Determine the cycle efficiency. [3]



Solution:

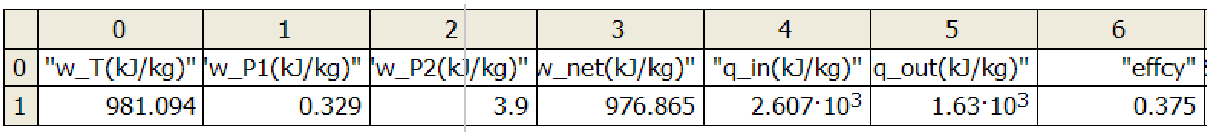
Data:

P_boiler := 4000 kPa   P_cond := 10 kPa   P2 := 400 kPa

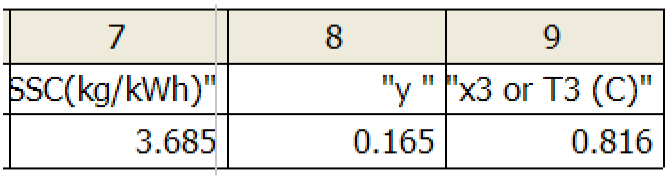
T1 := 400 C

Applying the Mathcad Function written above, we get:

Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1) =



	0	1	2	3	4	5	6
0	"w_T(kJ/kg)"	'w_P1(kJ/kg)"	'w_P2(kJ/kg)"	w_net(kJ/kg)"	"q_in(kJ/kg)"	q_out(kJ/kg)"	"effcy"
1	981.094	0.329	3.9	976.865	$2.607\cdot10^{3}$	$1.63\cdot10^{3}$	0.375



7	8	9
SSC(kg/kWh)"	"y "	"x3 or T3 (C)"
3.685	0.165	0.816

We note from the Function output that:

Cycle effcy. = 0.375 = 37.5%…Ans.
Fraction of extracted steam = y = 0.165 = 16.5%…Ans.

Plot the effect of varying extraction pressure on net work output and thermal effcy, other conditions remaining the same:

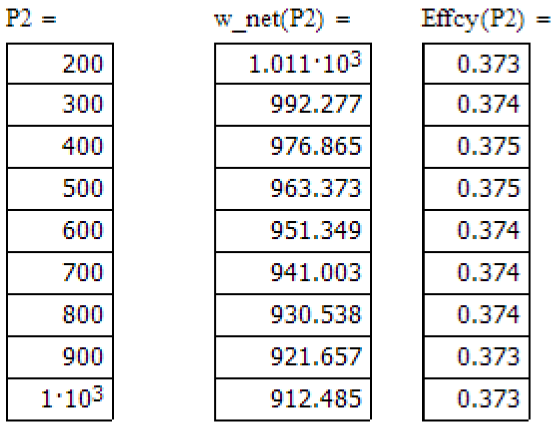
First, write the net work output and thermal effcy. as functions of P2:

$w\_net(P2) := Ideal\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1)_{1,3}$

$Effcy(P2) := Ideal\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1)_{1,6}$

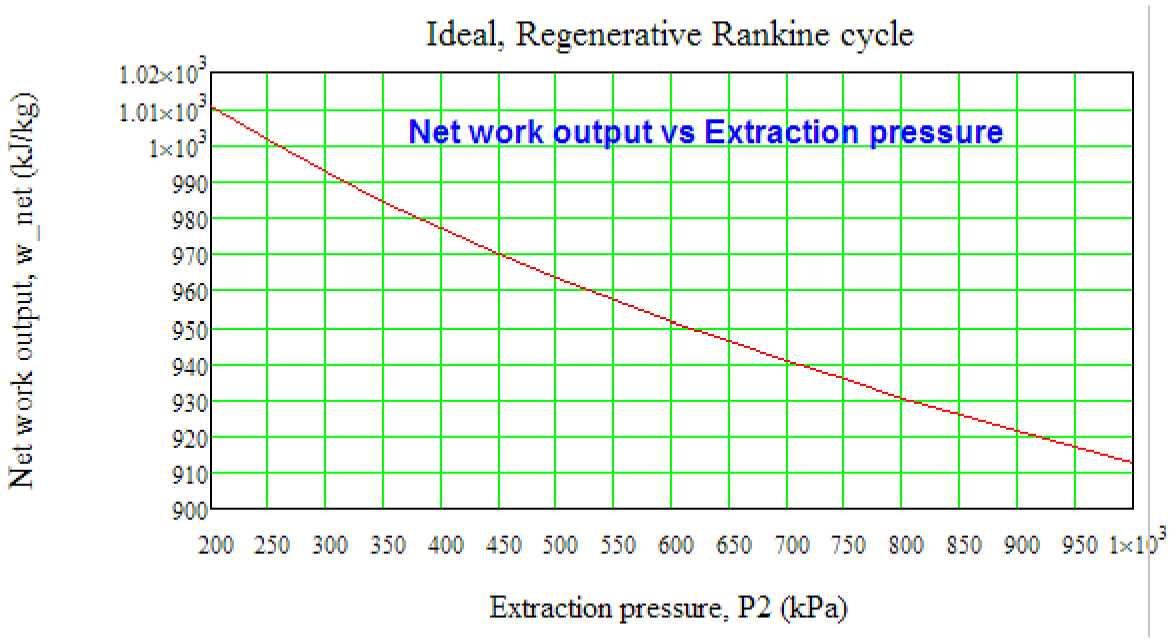
To plot the results:

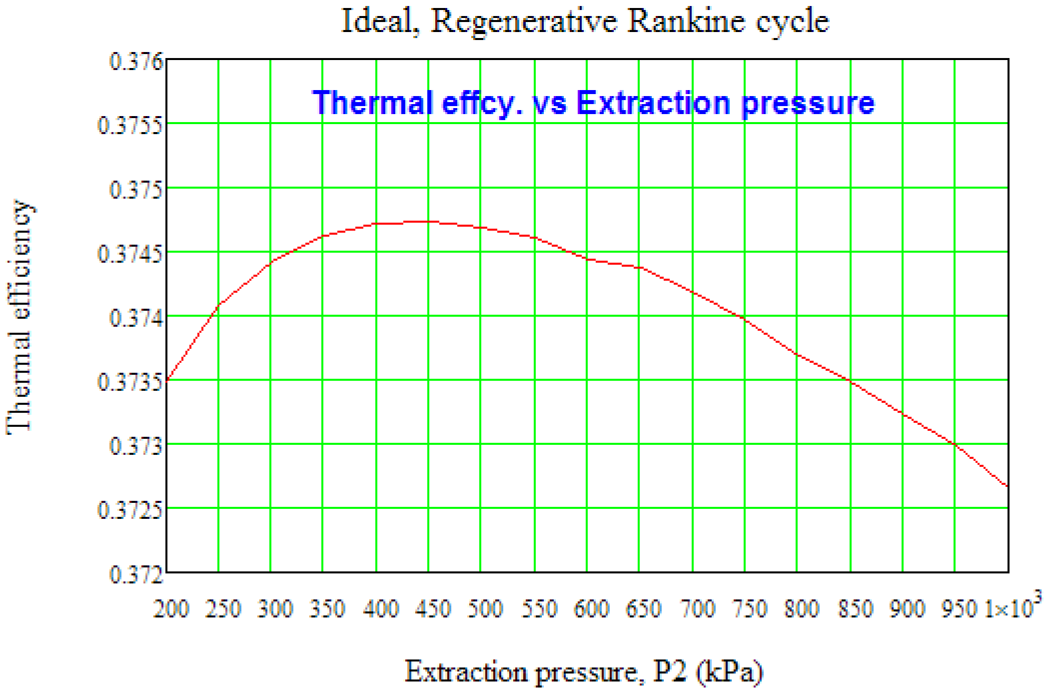
P2 := 200, 300 .. 1000 ....define a range variable



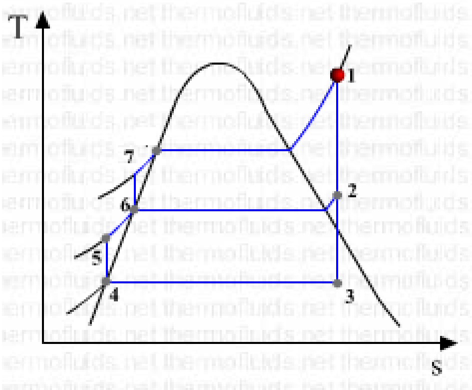
P2 =	w_net(P2) =	Effcy(P2) =
200	$1.011\cdot10^{3}$	0.373
300	992.277	0.374
400	976.865	0.375
500	963.373	0.375
600	951.349	0.374
700	941.003	0.374
800	930.538	0.374
900	921.657	0.373
$1\cdot10^{3}$	912.485	0.373

Plots:


Ideal, Regenerative Rankine cycle
Net work output vs Extraction pressure
Net work output, w_net (kJ/kg)
1.02×10^3
1.01×10^3
1×10^3
990
980
970
960
950
940
930
920
910
900
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1×10^3
Extraction pressure, P2 (kPa)



Prob. 3.27 In an ideal regenerative cycle, steam enters the turbine at 6 MPa, 450 C. After expansion to 400 kPa, some of the steam is extracted from the turbine for heating the feed water in an open feed water heater (FWH). The pressure in the FWH is 400 kPa and the water leaving it is sat. liquid at 400 kPa. The steam not extracted expands to 20 kPa. Determine: (a) net work output per kg of steam, (b) the cycle efficiency. [2]



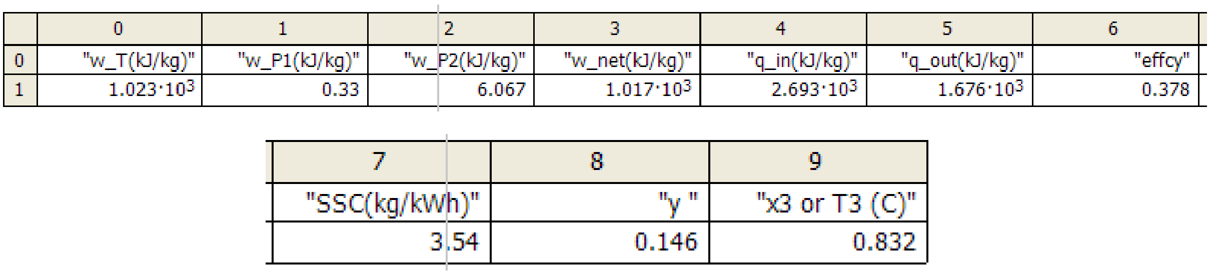
Data:

P_boiler := 6000 kPa   P_cond := 20 kPa   P2 := 400 kPa

T1 := 450 C

Applying the Mathcad Function for the ideal, regenerative Rankine cycle:

Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1) =



	0	1	2	3	4	5	6	7	8	9
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"	"SSC(kg/kWh)"	"y "	"x3 or T3 (C)"
1	$1.023 \cdot 10^3$	0.33	6.067	$1.017 \cdot 10^3$	$2.693 \cdot 10^3$	$1.676 \cdot 10^3$	0.378	3.54	0.146	0.832

We see from the Function output that:

Net work output:

w_net = 1017 **kJ/kg ..... Ans.**

Cycle efficiency:

effcy = 0.378 **= 37.8% ..... Ans.**

==

Plot cycle effcy as extraction pressure, P2 varies from 200 kPa to 1500 kPa:

First write the cycle effcy as a function of P2:

$Effcy(P2) := Ideal\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1)_{1,6}$

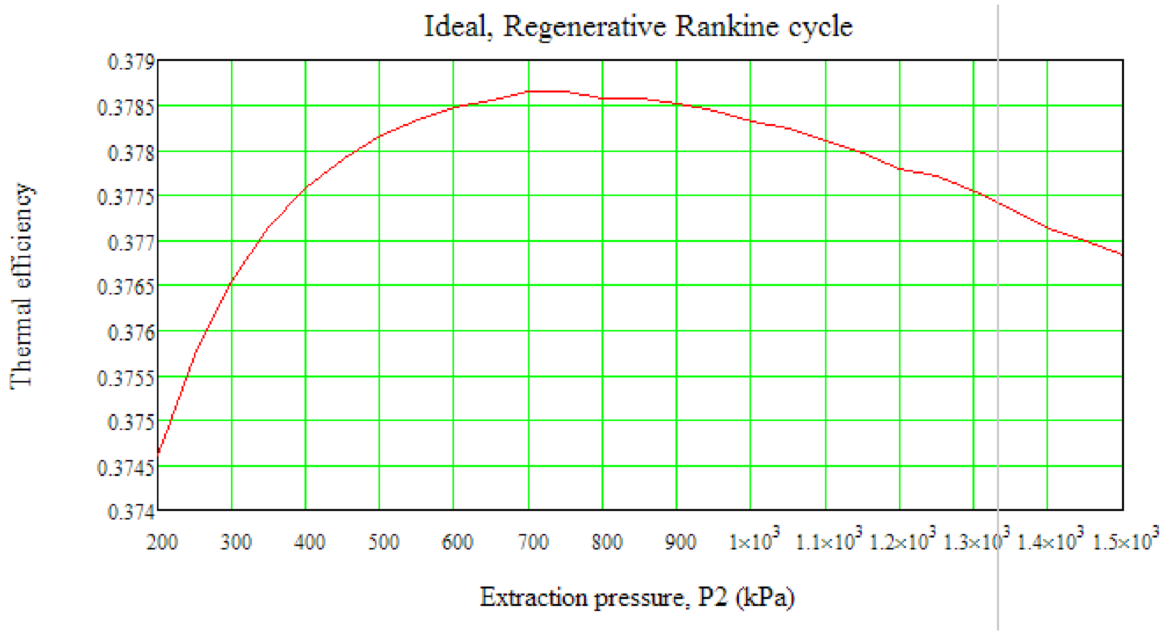
Now:

P2 := 200, 300.. 1500 kPa .... define a range variable

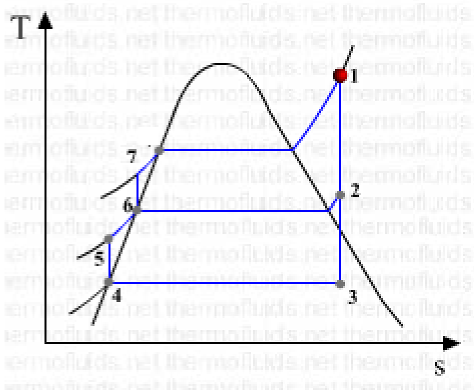
And, we get:

P2 =	Effcy(P2) =
200	0.3746
300	0.3765
400	0.3776
500	0.3782
600	0.3785
700	0.3787
800	0.3786
900	0.3785
$1\cdot10^{3}$	0.3783
$1.1\cdot10^{3}$	0.3781
$1.2\cdot10^{3}$	0.3778
$1.3\cdot10^{3}$	0.3775
$1.4\cdot10^{3}$	0.3771
$1.5\cdot10^{3}$	0.3768

Plot:



Prob. 3.28 In a single heater regenerative cycle, steam enters the turbine at 30 bar, 400 C. After expansion to 500 kPa, some of the steam is extracted from the turbine for heating the feed water in an open feed water heater (FWH). The pressure in the FWH is 500 kPa and the water leaving it is sat. liquid at 500 kPa. The steam not extracted expands to 10 kPa. Determine: (a) SSC, (b) the cycle efficiency. [VTU]

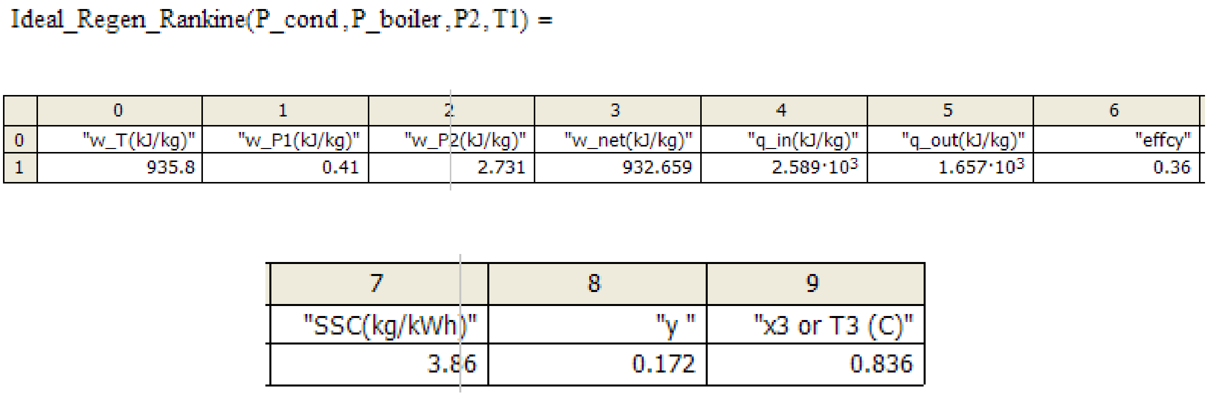


Data:

$P_{boiler} := 3000$ kPa $P_{cond} := 10$ kPa $P2 := 500$ kPa

$T1 := 400$ C

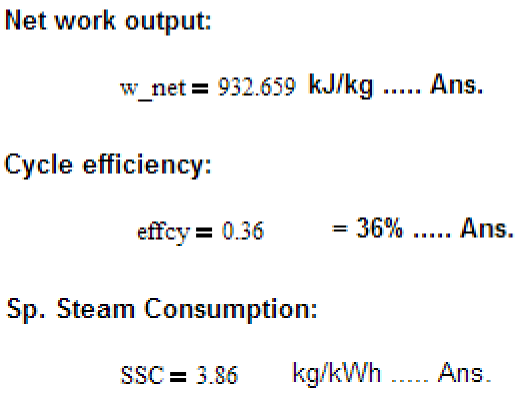
Applying the Mathcad Function for the ideal, regenerative Rankine cycle:



Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1) =

	0	1	2	3	4	5	6	7	8	9
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"	"SSC(kg/kWh)"	"y "	"x3 or T3 (C)"
1	935.8	0.41	2.731	932.659	$2.589\cdot10^{3}$	$1.657\cdot10^{3}$	0.36	3.86	0.172	0.836

We see from the Function output that:



Net work output:

w_net = 932.659 **kJ/kg ..... Ans.**

Cycle efficiency:

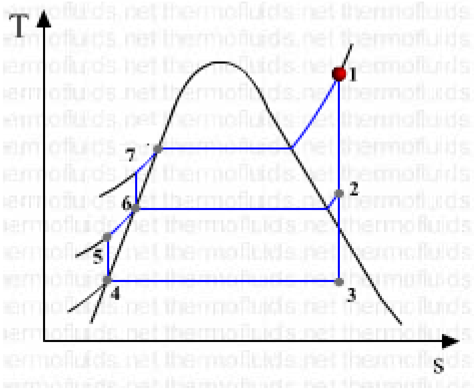
effcy = 0.36 **= 36% ..... Ans.**

Sp. Steam Consumption:

SSC = 3.86 kg/kWh ..... Ans.

===

Prob. 3.29 Investigate the effect of extraction pressure on the performance of an ideal regenerative Rankine cycle with one open feedwater heater. Steam enters the turbine at 15 MPa and 600°C and the condenser at 10 kPa. Determine the thermal efficiency of the cycle, and plot it against extraction pressures of 12.5, 10, 7, 5, 2, 1, 0.5, 0.1, and 0.05 MPa, and discuss the results. [2]



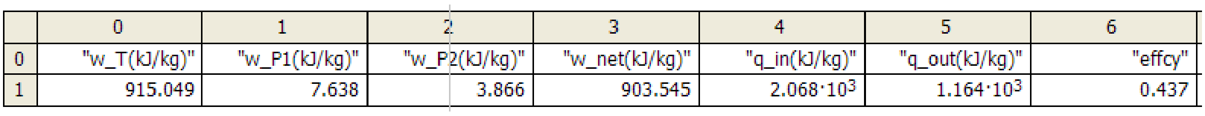
Data:

$P\_boiler := 15000$ kPa $P\_cond := 10$ kPa $P2 := 12500$ kPa

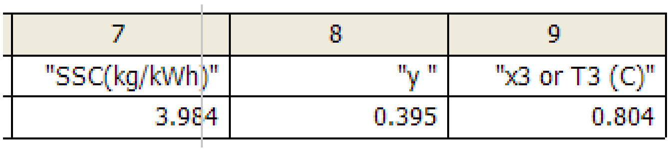
$T1 := 600$ C

Applying the Mathcad Function for the ideal, regenerative Rankine cycle:

Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1) =



	0	1	2	3	4	5	6
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"
1	915.049	7.638	3.866	903.545	$2.068 \cdot 10^3$	$1.164 \cdot 10^3$	0.437



7	8	9
"SSC(kg/kWh)"	"y "	"x3 or T3 (C)"
3.984	0.395	0.804

We see that: effcy = 0.437 = 43.7% .... Ans.

To plot the variation of effcy. as P2 varies:

First, define effcy as a function of P2:

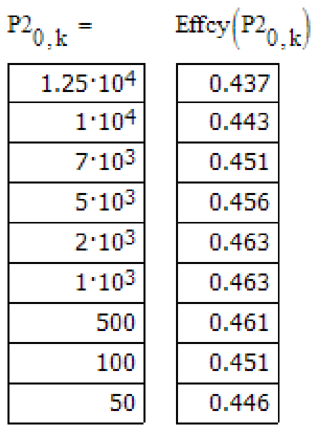
$\text{Effcy}(P2) := \text{Ideal\_Regen\_Rankine}(P\_cond, P\_boiler, P2, T1)_{1,6}$ $\text{Effcy}(P2) = 0.437$

Now, put the desired values of P2 in a vector:

$P2 := (12500 \quad 10000 \quad 7000 \quad 5000 \quad 2000 \quad 1000 \quad 500 \quad 100 \quad 50)$ ...vector of P2 values

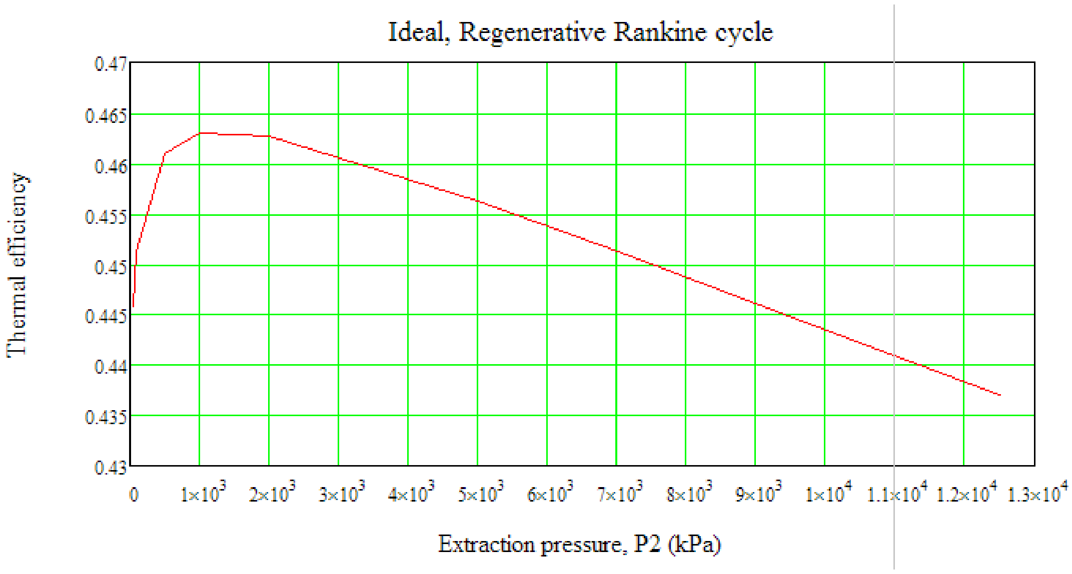
$k := 0, 1 .. 7$ ...define a range variable for index k

We get:

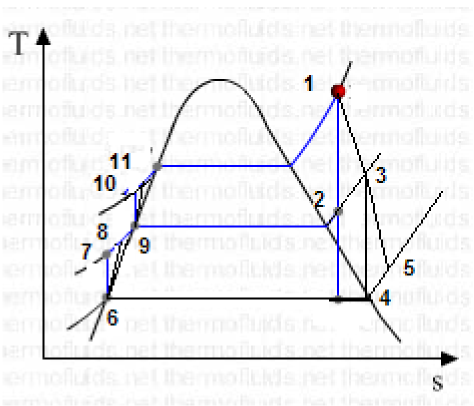


$P2_{0,k} =$	$\text{Effcy}\left(P2_{0,k}\right)$
$1.25 \cdot 10^4$	0.437
$1 \cdot 10^4$	0.443
$7 \cdot 10^3$	0.451
$5 \cdot 10^3$	0.456
$2 \cdot 10^3$	0.463
$1 \cdot 10^3$	0.463
500	0.461
100	0.451
50	0.446

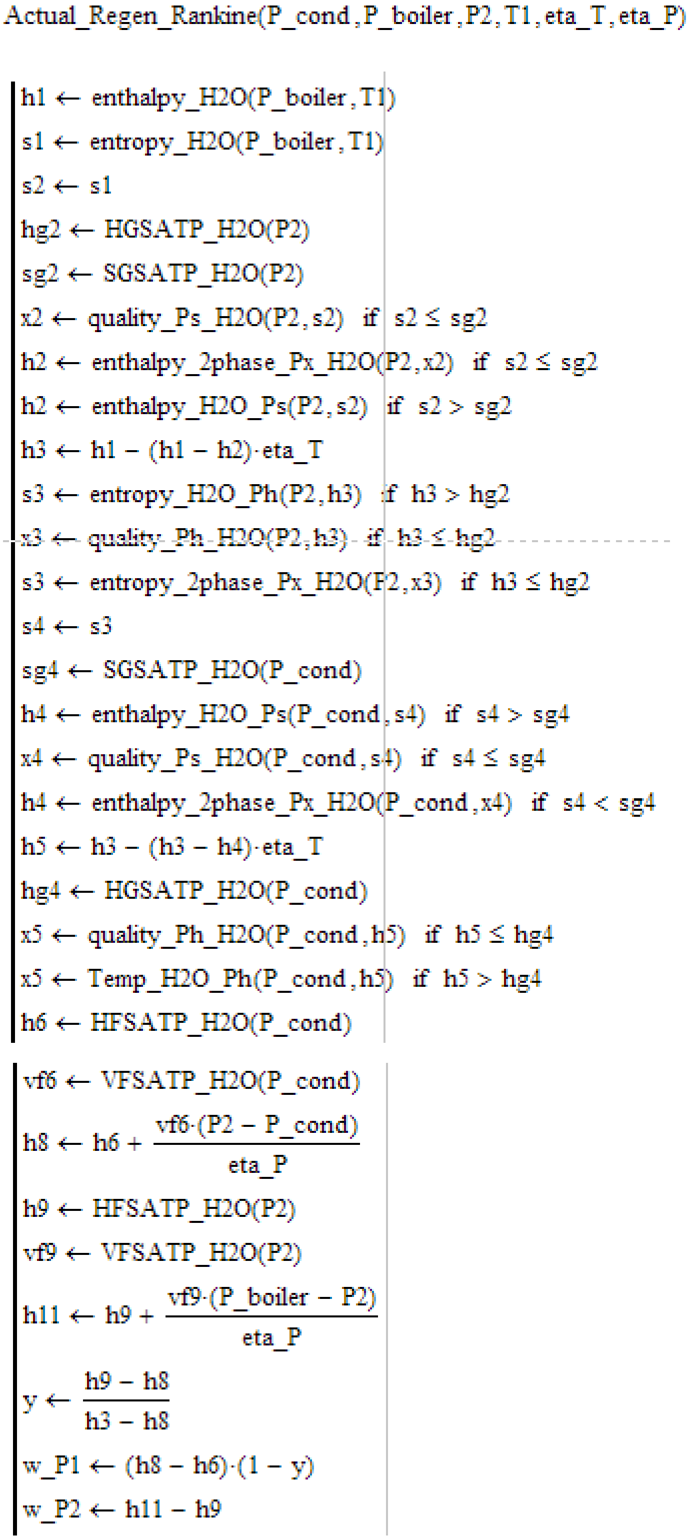
Now, plot the results:



Prob. 3.30 Write a Mathcad program to find out the various parameters of interest for an Actual, Regenerative Rankine cycle, with one open FWH. Take eta_T as the isentropic efficiencies of turbine stages, and eta_P as the isentropic efficiencies of pumps.



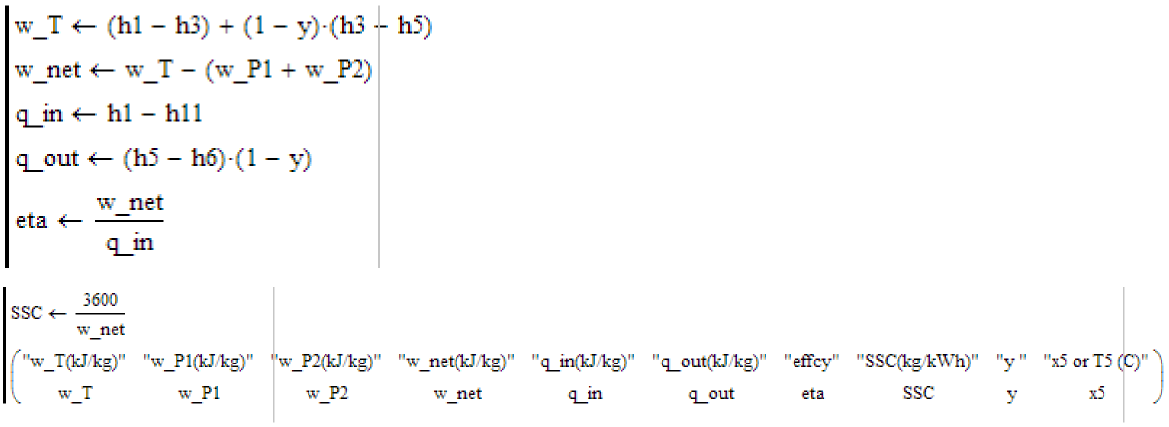
Mathcad Function:



```
Actual_Regen_Rankine(P_cond, P_boiler, P2, T1, eta_T, eta_P) :=

    h1 ← enthalpy_H2O(P_boiler, T1)
    s1 ← entropy_H2O(P_boiler, T1)
    s2 ← s1
    hg2 ← HGSATP_H2O(P2)
    sg2 ← SGSATP_H2O(P2)
    x2 ← quality_Ps_H2O(P2, s2)  if  s2 ≤ sg2
    h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s2 ≤ sg2
    h2 ← enthalpy_H2O_Ps(P2, s2)  if  s2 > sg2
    h3 ← h1 − (h1 − h2)·eta_T
    s3 ← entropy_H2O_Ph(P2, h3)  if  h3 > hg2
    x3 ← quality_Ph_H2O(P2, h3)  if  h3 ≤ hg2
    s3 ← entropy_2phase_Px_H2O(P2, x3)  if  h3 ≤ hg2
    s4 ← s3
    sg4 ← SGSATP_H2O(P_cond)
    h4 ← enthalpy_H2O_Ps(P_cond, s4)  if  s4 > sg4
    x4 ← quality_Ps_H2O(P_cond, s4)  if  s4 ≤ sg4
    h4 ← enthalpy_2phase_Px_H2O(P_cond, x4)  if  s4 < sg4
    h5 ← h3 − (h3 − h4)·eta_T
    hg4 ← HGSATP_H2O(P_cond)
    x5 ← quality_Ph_H2O(P_cond, h5)  if  h5 ≤ hg4
    x5 ← Temp_H2O_Ph(P_cond, h5)  if  h5 > hg4
    h6 ← HFSATP_H2O(P_cond)

    vf6 ← VFSATP_H2O(P_cond)
    h8 ← h6 + $\frac{vf6\cdot(P2 - P\_cond)}{eta\_P}$
    h9 ← HFSATP_H2O(P2)
    vf9 ← VFSATP_H2O(P2)
    h11 ← h9 + $\frac{vf9\cdot(P\_boiler - P2)}{eta\_P}$
    y ← $\frac{h9 - h8}{h3 - h8}$
    w_P1 ← (h8 − h6)·(1 − y)
    w_P2 ← h11 − h9
```



$$
\begin{array}{l}
w\_T \leftarrow (h1 - h3) + (1 - y)\cdot(h3 - h5)\\
w\_net \leftarrow w\_T - (w\_P1 + w\_P2)\\
q\_in \leftarrow h1 - h11\\
q\_out \leftarrow (h5 - h6)\cdot(1 - y)\\
eta \leftarrow \dfrac{w\_net}{q\_in}
\end{array}
$$

$$
\begin{array}{l}
SSC \leftarrow \dfrac{3600}{w\_net}\\
\begin{pmatrix}
\text{"w\_T(kJ/kg)"} & \text{"w\_P1(kJ/kg)"} & \text{"w\_P2(kJ/kg)"} & \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy"} & \text{"SSC(kg/kWh)"} & \text{"y "} & \text{"x5 or T5 (C)"}\\
w\_T & w\_P1 & w\_P2 & w\_net & q\_in & q\_out & eta & SSC & y & x5
\end{pmatrix}
\end{array}
$$

Explanation for the above Function:

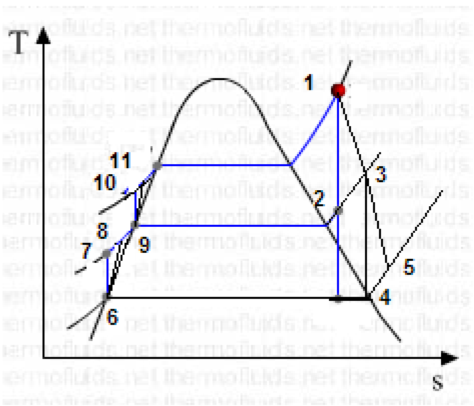
This function gives all the important parameters of performance of an Actual, Regenerative Rankine cycle.

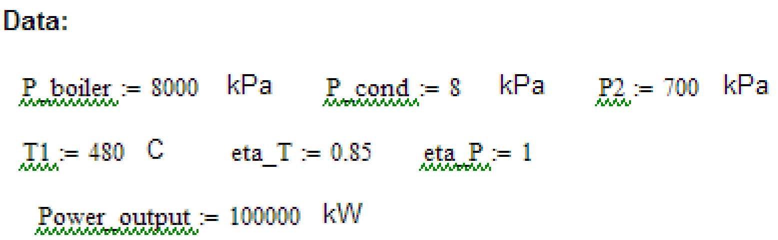
This function is similar to the Functions written earlier for other variations of Rankine cycle, and here also we check if the exits of both stages of turbine are in two phase region or superheat region, and determine the enthalpies accordingly. While calculating the works of turbines and pumps, their isentropic efficiencies are taken in to account.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where Turbine inlet temperature is in deg.C and pressures P_cond, P_boiler and extraction pressure P2 are in kPa. Isentropic efficiencies of turbine stages and of pump are eta_T and eta_P respectively. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump works (w_P1 and w_P2), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), Specific Steam Consumption (SSC), fraction of extracted stream (y), and the quality of steam at turbine exit (x5) if the exit steam is in two phase region, or its temp (T5) if the exit steam is in superheat region. Units of each quantity are also given in output.

Prob. 3.31 Consider a regenerative vapor power cycle with one open feedwater heater. Steam enters the turbine at 8.0 MPa, 480_C and expands to 0.7 MPa, where some of the steam is extracted and diverted to the open feedwater heater operating at 0.7 MPa. The remaining steam expands through the second-stage turbine to the condenser pressure of 0.008 MPa. Saturated liquid exits the open feedwater heater at 0.7 MPa. The isentropic efficiency of each turbine stage is 85% and each pump operates isentropically.

If the net power output of the cycle is 100 MW, determine:
(a) the thermal efficiency, and **(b)** the mass flow rate of steam entering the first turbine stage, in kg/h. [4]





Data:

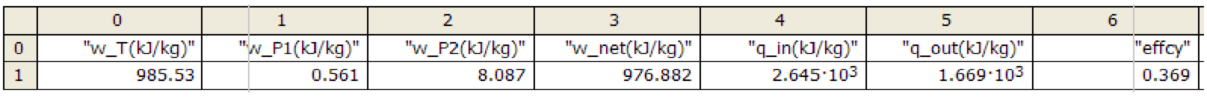
P_boiler := 8000 kPa   P_cond := 8 kPa   P2 := 700 kPa

T1 := 480 C   eta_T := 0.85   eta_P := 1

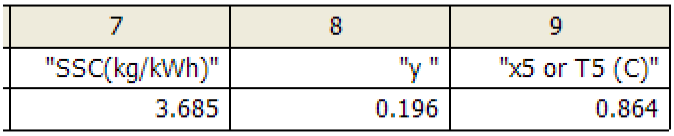
Power_output := 100000 kW

Applying the Mathcad Function for the actual, regenerative Rankine cycle:

Actual_Regen_Rankine(P_cond, P_boiler, P2, T1, eta_T, eta_P) =



	0	1	2	3	4	5	6	
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"		"effcy"
1	985.53	0.561	8.087	976.882	$2.645\cdot10^3$	$1.669\cdot10^3$		0.369



7	8	9
"SSC(kg/kWh)"	"y "	"x5 or T5 (C)"
3.685	0.196	0.864

We see from the Function output that:

Thermal effcy. = 0.369 = 36.9% ... Ans.

Mass flow rate of steam:

We have: $w\_net := 976.882$ kJ/kg

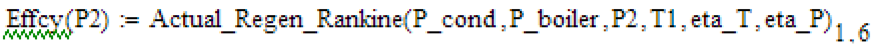
Then: $MassFlow := \frac{Power\_output}{w\_net}$ kg/s

i.e. $MassFlow = 102.367$ **kg/s = 3.685 x 10^5 kg/h ..... Ans.**

Plot Thermal effcy and net work output as feedwater heater pressure varies from 500 kPa to 3000 kPa:

First, write the relevant quantities as functions of feedwater heater pressure, P2:

$W\_net(P2) := Actual\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, eta\_T, eta\_P)_{1,3}$

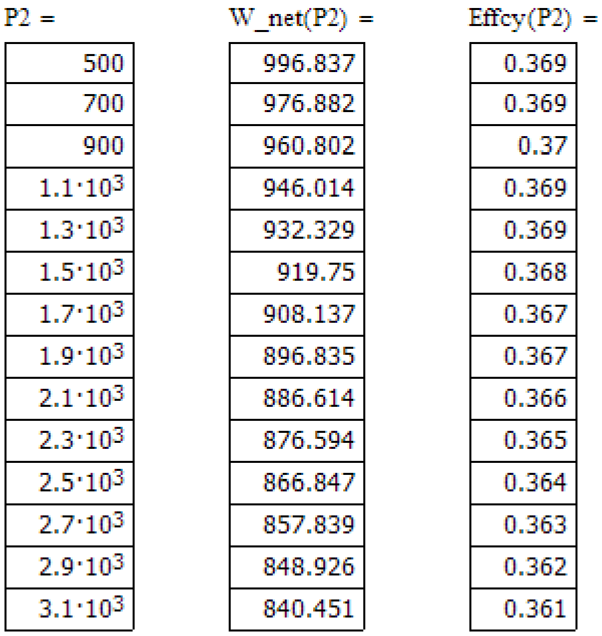


$Effcy(P2) := Actual\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, eta\_T, eta\_P)_{1,6}$

To plot the results:

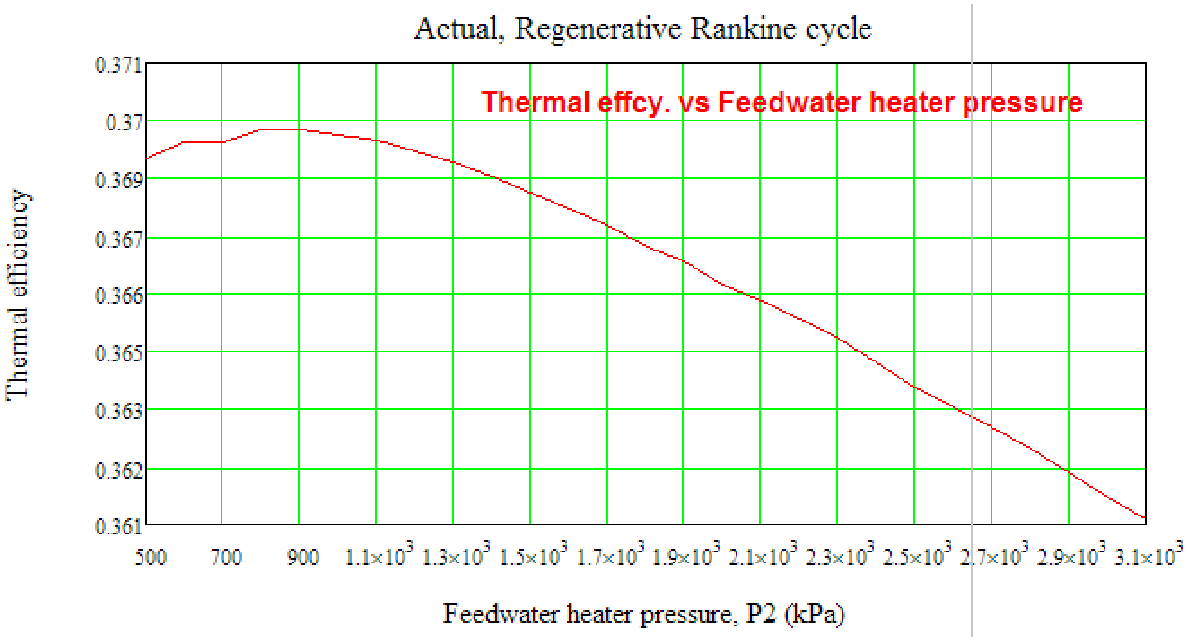
$P2 := 500, 700 .. 3100$ ....define a range variable

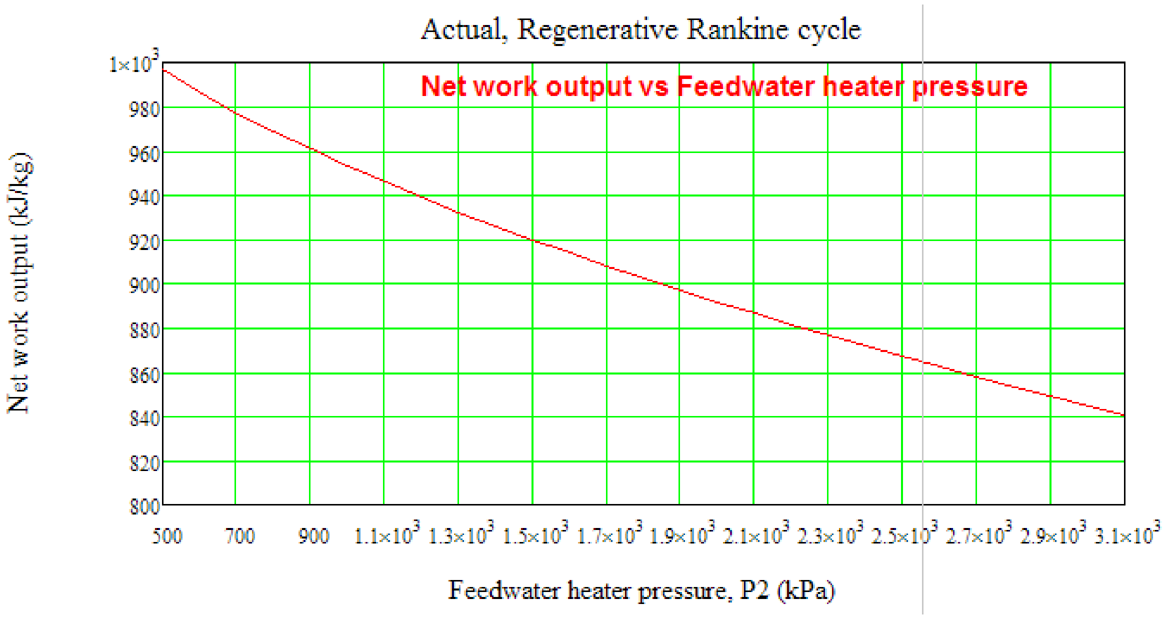
We get:



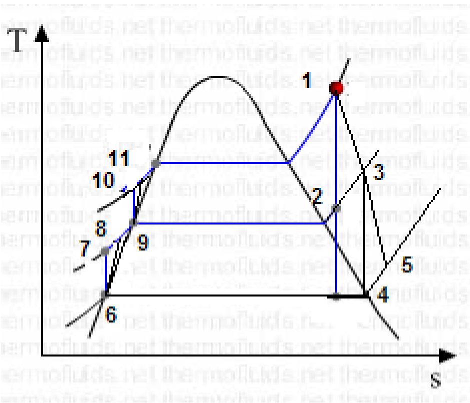
P2 =	W_net(P2) =	Effcy(P2) =
500	996.837	0.369
700	976.882	0.369
900	960.802	0.37
$1.1\cdot10^{3}$	946.014	0.369
$1.3\cdot10^{3}$	932.329	0.369
$1.5\cdot10^{3}$	919.75	0.368
$1.7\cdot10^{3}$	908.137	0.367
$1.9\cdot10^{3}$	896.835	0.367
$2.1\cdot10^{3}$	886.614	0.366
$2.3\cdot10^{3}$	876.594	0.365
$2.5\cdot10^{3}$	866.847	0.364
$2.7\cdot10^{3}$	857.839	0.363
$2.9\cdot10^{3}$	848.926	0.362
$3.1\cdot10^{3}$	840.451	0.361

Plots:





Prob. 3.32 A power plant operates on a regenerative vapor power cycle with one open feedwater heater. Steam enters the first turbine stage at 12 MPa, 520_C and expands to 1 MPa, where some of the steam is extracted and diverted to the open feedwater heater operating at 1 MPa. The remaining steam expands through the second turbine stage to the condenser pressure of 6 kPa. Saturated liquid exits the open feedwater heater at 1 MPa. For isentropic efficiencies of the turbines and pumps = 80% each, determine for the cycle: **(a)** the thermal efficiency and **(b)** the mass flow rate into the first turbine stage, in kg/h, for a net power output of 330 MW. Investigate the effects on cycle performance as the feedwater heater pressure takes on other values. [4]



Data:

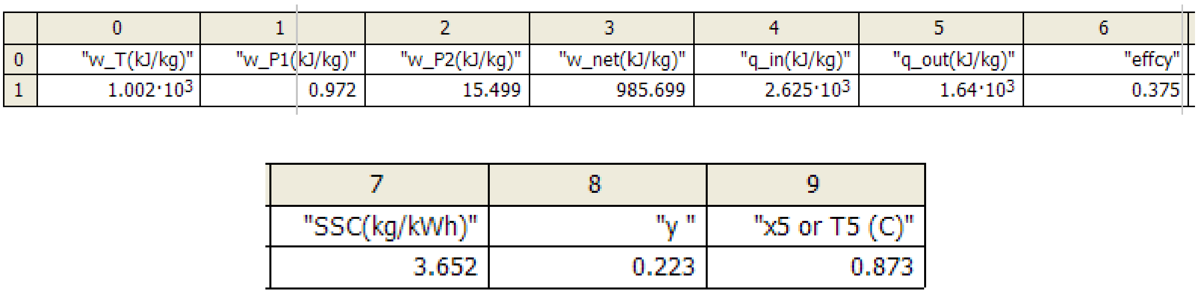
P_boiler := 12000 kPa   P_cond := 6 kPa   P2 := 1000 kPa

T1 := 520 C   eta_T := 0.8   eta_P := 0.8

Power_output := 330000 kW

Applying the Mathcad Function for the actual, regenerative Rankine cycle:

Actual_Regen_Rankine(P_cond, P_boiler, P2, T1, eta_T, eta_P) =



	0	1	2	3	4	5	6
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"
1	$1.002 \cdot 10^3$	0.972	15.499	985.699	$2.625 \cdot 10^3$	$1.64 \cdot 10^3$	0.375

7	8	9
"SSC(kg/kWh)"	"y "	"x5 or T5 (C)"
3.652	0.223	0.873

We see from the Function output that:

Thermal effcy. = 0.375 = 37.5% ... Ans.

Mass flow rate of steam:

We have: $w\_net := 985.699$ kJ/kg

Then: $MassFlow := \frac{Power\_output}{w\_net}$ kg/s

i.e. $MassFlow = 334.788$ **kg/s = 12.05 x 10^5 kg/h ..... Ans.**

Plot Thermal effcy. and net work output as feedwater heater pressure varies from 500 kPa to 5000 kPa:

First, write the relevant quantities as functions of feedwater heater pressure, P2:

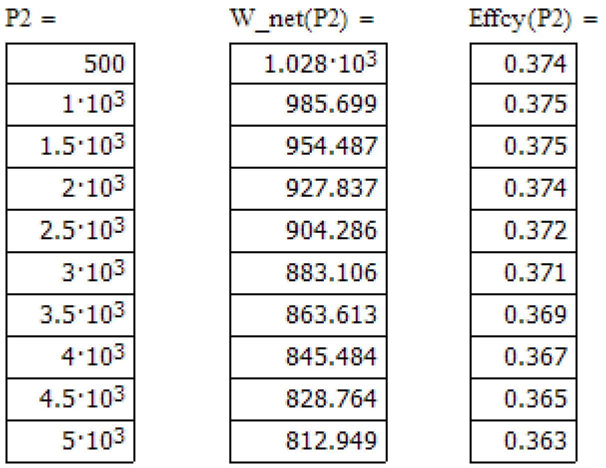
$W\_net(P2) := Actual\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, eta\_T, eta\_P)_{1,3}$

$Effcy(P2) := Actual\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, eta\_T, eta\_P)_{1,6}$

To plot the results:

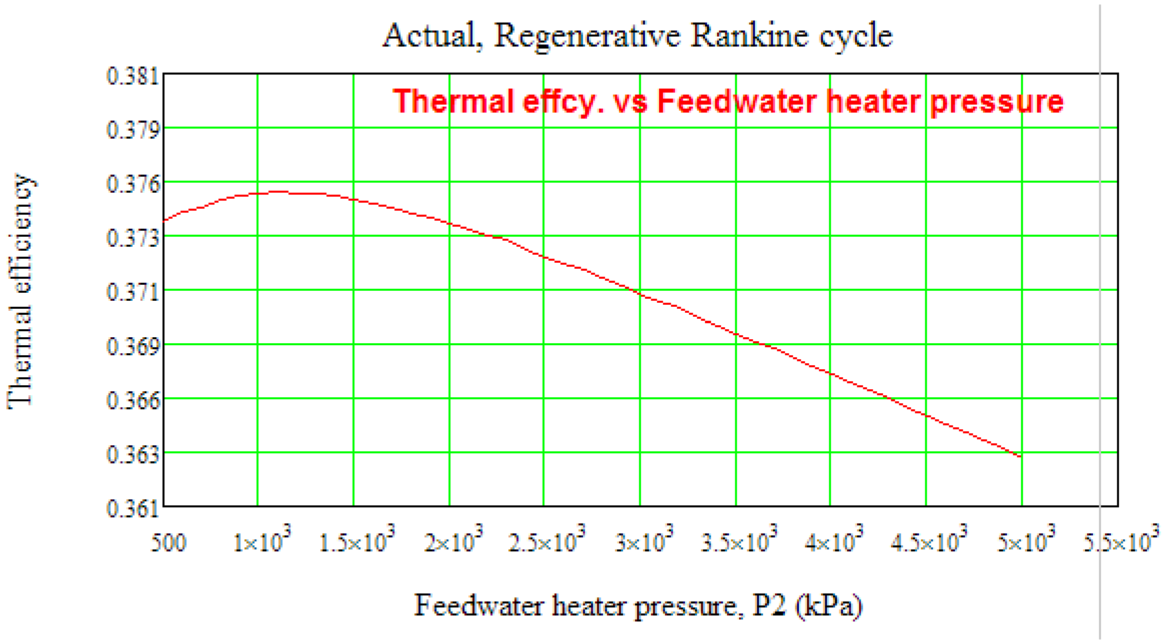
$P2 := 500, 1000 .. 5000$ ....define a range variable

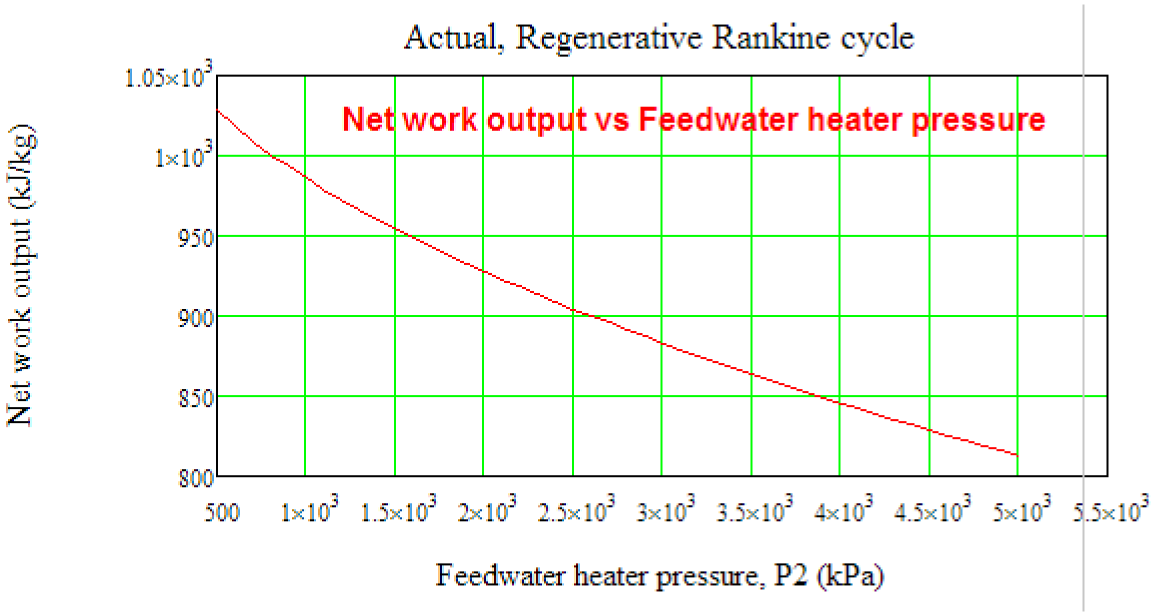
We get:

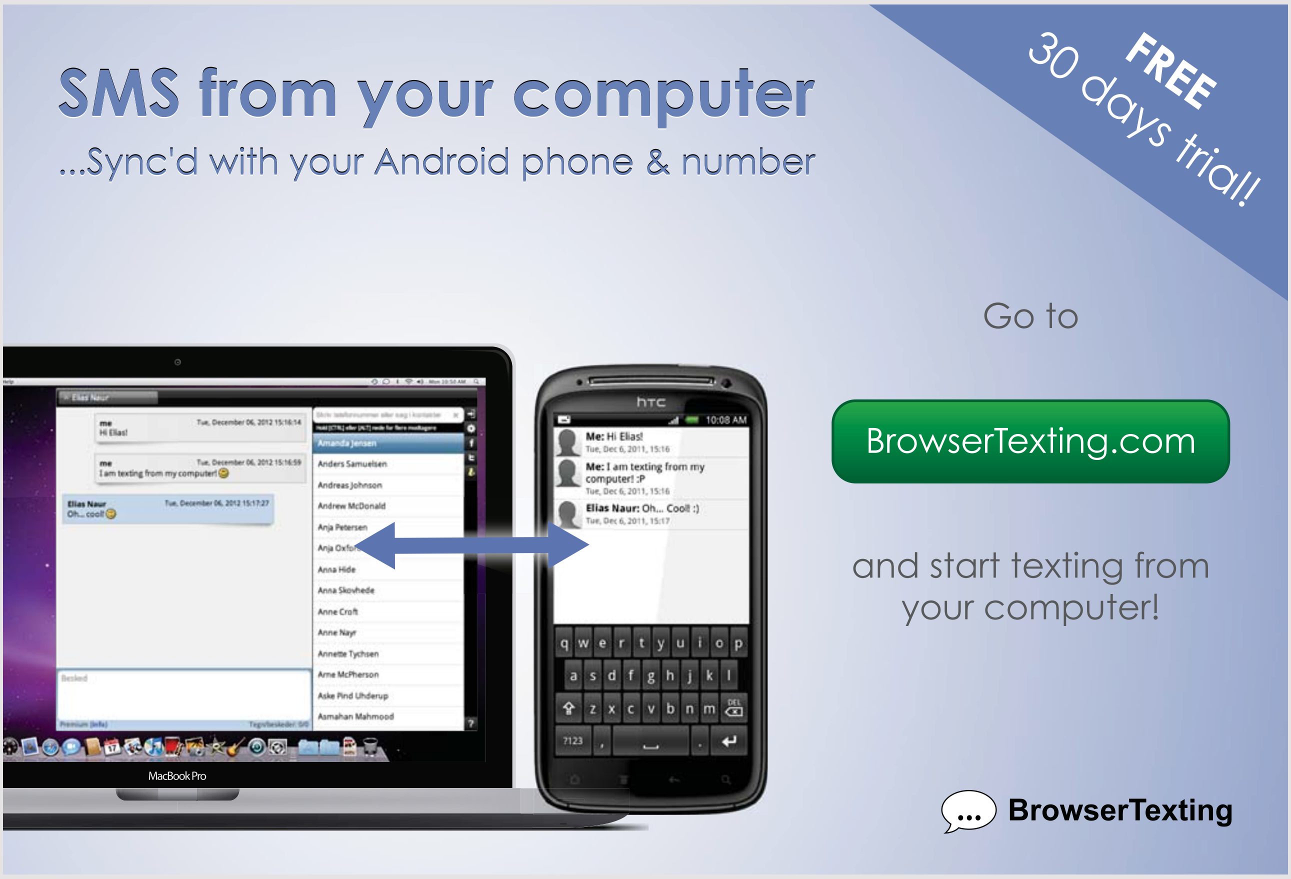


P2 =	W_net(P2) =	Effcy(P2) =
500	$1.028 \cdot 10^3$	0.374
$1 \cdot 10^3$	985.699	0.375
$1.5 \cdot 10^3$	954.487	0.375
$2 \cdot 10^3$	927.837	0.374
$2.5 \cdot 10^3$	904.286	0.372
$3 \cdot 10^3$	883.106	0.371
$3.5 \cdot 10^3$	863.613	0.369
$4 \cdot 10^3$	845.484	0.367
$4.5 \cdot 10^3$	828.764	0.365
$5 \cdot 10^3$	812.949	0.363

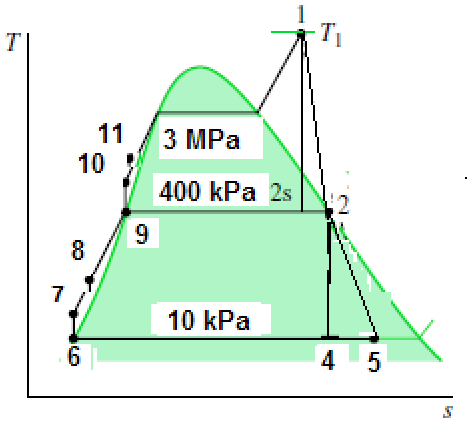
Now, plot:




Actual, Regenerative Rankine cycle
Net work output vs Feedwater heater pressure
Net work output (kJ/kg)
1.05×10^3
1×10^3
950
900
850
800
500
1×10^3
1.5×10^3
2×10^3
2.5×10^3
3×10^3
3.5×10^3
4×10^3
4.5×10^3
5×10^3
5.5×10^3
Feedwater heater pressure, P2 (kPa)



Prob. 3.33 Steam at 30 bar and 350 C is supplied to a steam turbine in a practical regenerative cycle and the steam is bled at 4 bar.The bled steam comes out as dry saturated steam and heats the feed water in an open type FWH to its saturated liquid state. The rest of the steam in the turbine expands to a condenser pressure of 0.1 bar. Assuming the turbine effcy. to be the same before and after bleeding, determine: (a) the turbine effcy (b) steam quality at inlet to condenser (c) mass flow rate of bled steam per unit mass flow rate at turbine inlet, and (d) the cycle effcy. [VTU]



Data:

P_boiler := 3000 kPa   P_cond := 10 kPa   P2 := 400 kPa

T1 := 350 C   eta_P := 1   ...assumed, since effcy of pump is not mentioned in data

First, let us calculate the Turbine stage effcy, and then we shall use the Mathcad Function for Actual, regen. Rankine cycle, written earlier:

h1 := enthalpy_H2O(P_boiler, T1)   i.e. $h1 = 3.116 \times 10^{3}$ kJ/kg

s1 := entropy_H2O(P_boiler, T1)   i.e.   s1 = 6.745   kJ/kg.K

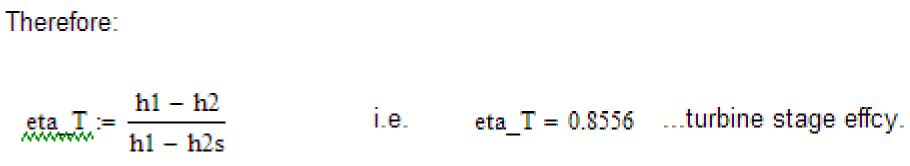
s2s := s1   ...for isentropic expn in turbine stage

x2s := quality_Ps_H2O(P2, s2s)   i.e.   x2s = 0.97

h2s := enthalpy_2phase_Px_H2O(P2, x2s)   i.e. $h2s = 2.674 \times 10^{3}$ kJ/kg

x2 := 1   ...by data

h2 := HGSATP_H2O(P2)   i.e. $h2 = 2.738 \times 10^{3}$ kJ/kg

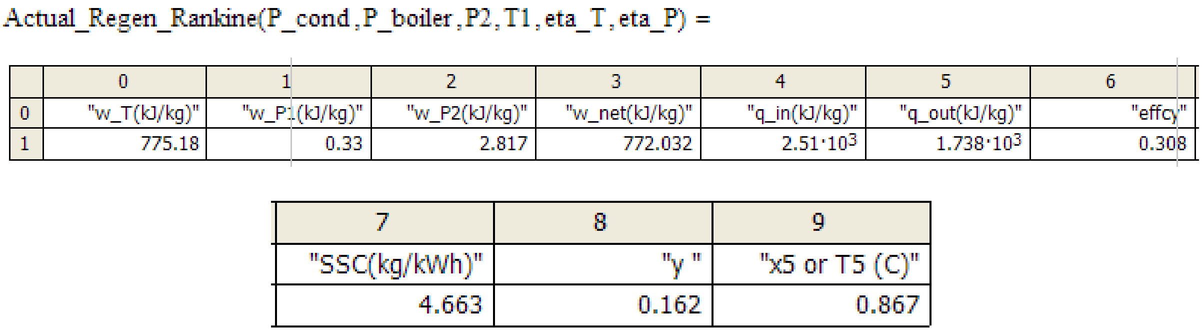


Therefore:

$eta\_T := \frac{h1 - h2}{h1 - h2s}$ i.e. $eta\_T = 0.8556$ ...turbine stage effcy.

Now, applying the Mathcad Function for the actual, regenerative Rankine cycle to get other performance parameters:

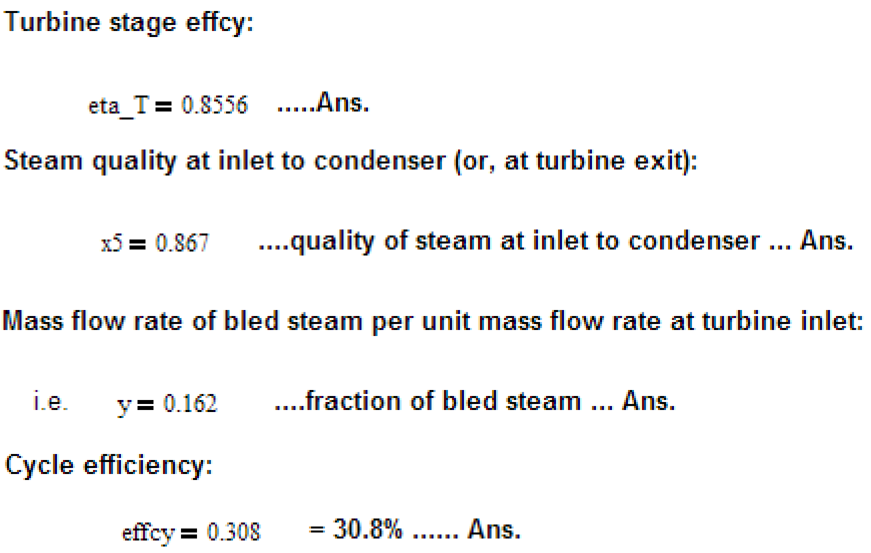
We get:



Actual_Regen_Rankine(P_cond, P_boiler, P2, T1, eta_T, eta_P) =

	0	1	2	3	4	5	6	7	8	9
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"	"SSC(kg/kWh)"	"y "	"x5 or T5 (C)"
1	775.18	0.33	2.817	772.032	$2.51 \cdot 10^3$	$1.738 \cdot 10^3$	0.308	4.663	0.162	0.867

Therefore:



Turbine stage effcy:

$eta\_T = 0.8556$ **.....Ans.**

Steam quality at inlet to condenser (or, at turbine exit):

$x5 = 0.867$ **....quality of steam at inlet to condenser ... Ans.**

Mass flow rate of bled steam per unit mass flow rate at turbine inlet:

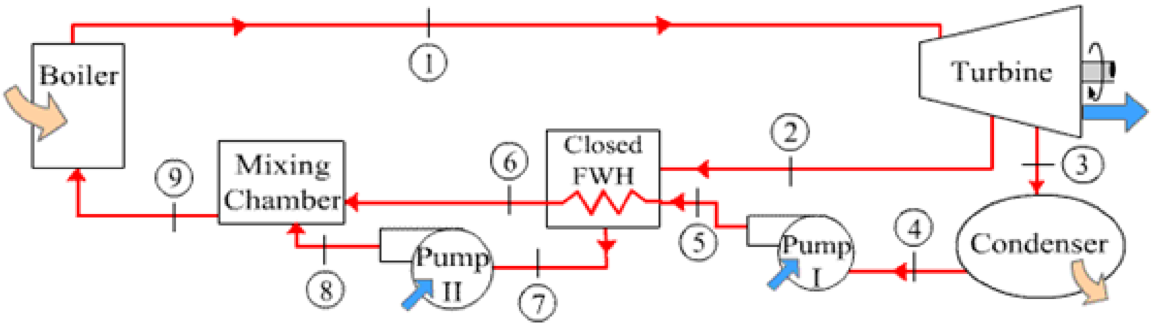
i.e. $y = 0.162$ **....fraction of bled steam ... Ans.**

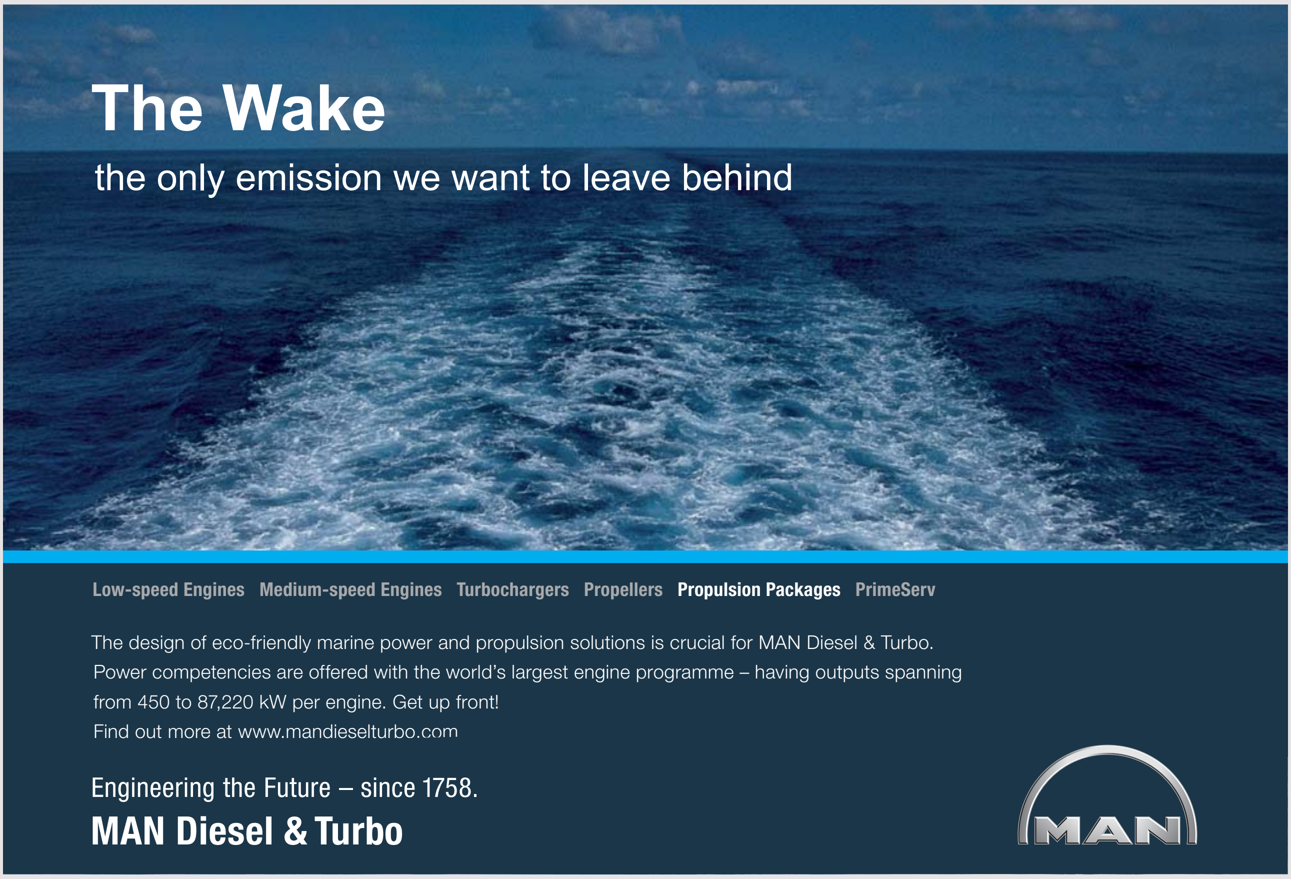
Cycle efficiency:

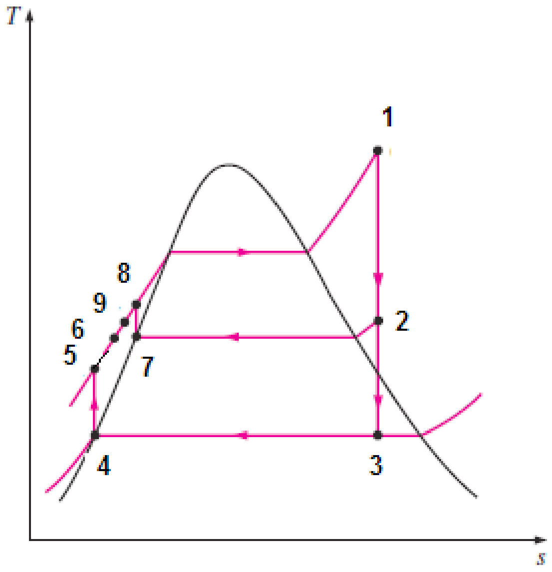
$effcy = 0.308$ **= 30.8% ...... Ans.**

===

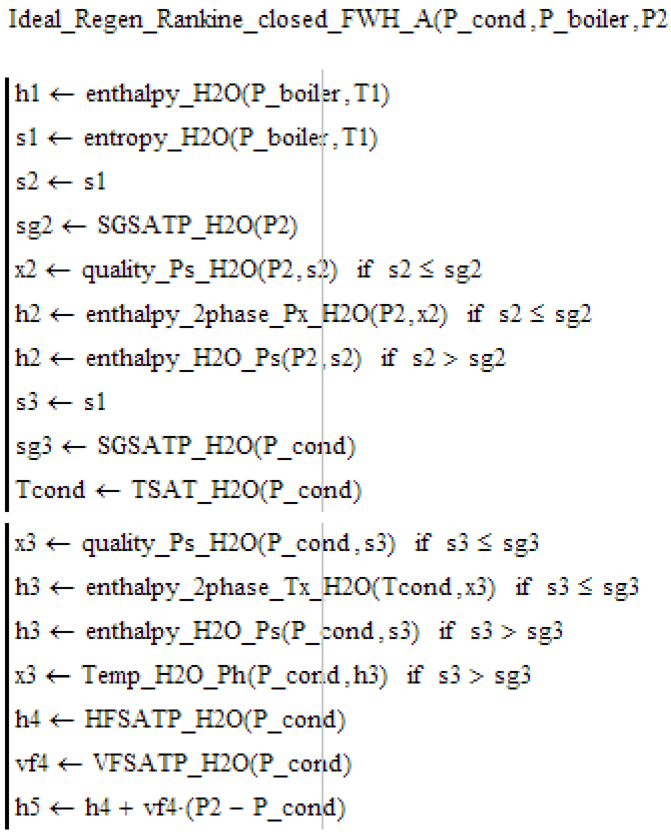
Prob. 3.34 Write a Mathcad program to find out the various parameters of interest for an Ideal, Regenerative Rankine cycle, with one *closed* FWH, from where Pump-II pumps the condensed steam to the feed water line. Take ideal processes for steam.





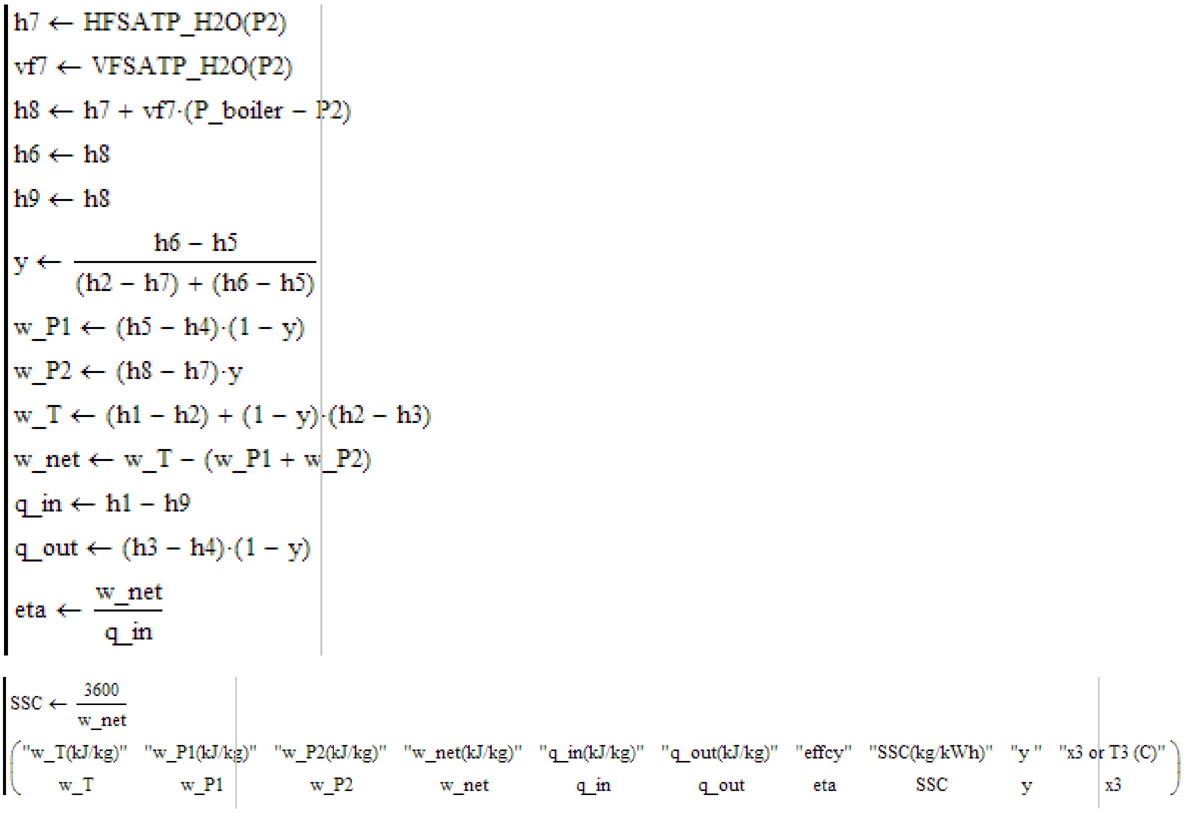


Mathcad program:



```
Ideal_Regen_Rankine_closed_FWH_A(P_cond, P_boiler, P2, T1) :=

| h1 ← enthalpy_H2O(P_boiler, T1)
| s1 ← entropy_H2O(P_boiler, T1)
| s2 ← s1
| sg2 ← SGSATP_H2O(P2)
| x2 ← quality_Ps_H2O(P2, s2)  if  s2 ≤ sg2
| h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s2 ≤ sg2
| h2 ← enthalpy_H2O_Ps(P2, s2)  if  s2 > sg2
| s3 ← s1
| sg3 ← SGSATP_H2O(P_cond)
| Tcond ← TSAT_H2O(P_cond)
| x3 ← quality_Ps_H2O(P_cond, s3)  if  s3 ≤ sg3
| h3 ← enthalpy_2phase_Tx_H2O(Tcond, x3)  if  s3 ≤ sg3
| h3 ← enthalpy_H2O_Ps(P_cond, s3)  if  s3 > sg3
| x3 ← Temp_H2O_Ph(P_cond, h3)  if  s3 > sg3
| h4 ← HFSATP_H2O(P_cond)
| vf4 ← VFSATP_H2O(P_cond)
| h5 ← h4 + vf4·(P2 − P_cond)
```



```
h7 ← HFSATP_H2O(P2)
vf7 ← VFSATP_H2O(P2)
h8 ← h7 + vf7·(P_boiler − P2)
h6 ← h8
h9 ← h8
y ← $\frac{h6 - h5}{(h2 - h7) + (h6 - h5)}$
w_P1 ← (h5 − h4)·(1 − y)
w_P2 ← (h8 − h7)·y
w_T ← (h1 − h2) + (1 − y)·(h2 − h3)
w_net ← w_T − (w_P1 + w_P2)
q_in ← h1 − h9
q_out ← (h3 − h4)·(1 − y)
eta ← $\frac{w\_net}{q\_in}$
SSC ← $\frac{3600}{w\_net}$
$\begin{pmatrix} "w\_T(kJ/kg)" & "w\_P1(kJ/kg)" & "w\_P2(kJ/kg)" & "w\_net(kJ/kg)" & "q\_in(kJ/kg)" & "q\_out(kJ/kg)" & "effcy" & "SSC(kg/kWh)" & "y\ " & "x3\ or\ T3\ (C)" \\ w\_T & w\_P1 & w\_P2 & w\_net & q\_in & q\_out & eta & SSC & y & x3 \end{pmatrix}$
```

Explanation for the above Function:

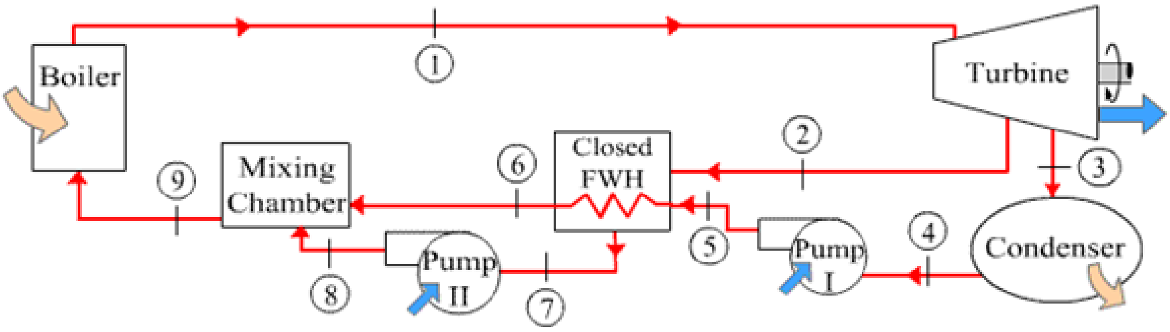
This function gives all the important parameters of performance of an Ideal Regenerative Rankine cycle with one *closed* FWH. Condensed extracted steam from the closed FWH is pumped *forward* to the feedwater line.

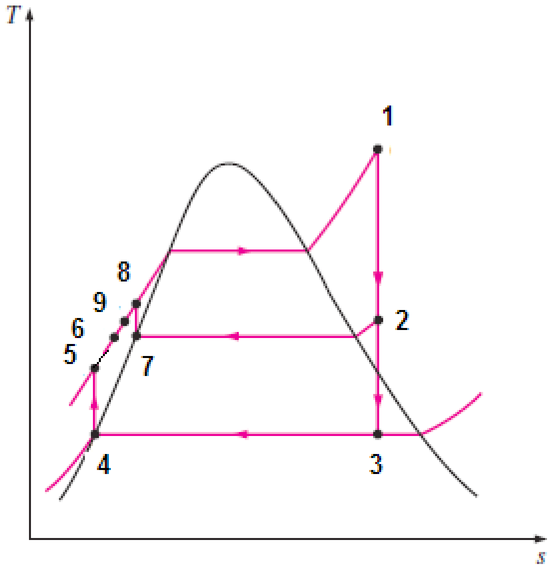
This function is similar to the Functions written earlier for other variations of Rankine cycle, and here also we check if the exits of both stages of turbine are in two phase region or superheat region, and determine the enthalpies accordingly.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where Turbine inlet temperature is in deg.C and pressures P_cond, P_boiler and extraction pressure P2 are in kPa. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump works (w_P1 and w_P2), Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficiency (effcy), Specific Steam Consumption (SSC), fraction of extracted stream (y), and the quality of steam at turbine exit (x3) if the exit steam is in two phase region, or its temp (T3) if the exit steam is in superheat region. Units of each quantity are also given in output.

Prob. 3.35 In an ideal regenerative cycle, steam enters the turbine at 6 MPa, 450 C. After expansion to 400 kPa, some of the steam is extracted from the turbine for heating the feed water in a *closed* feed water heater (FWH). The pressure in the FWH is 400 kPa and the water leaving it is sat. liquid at 400 kPa. The steam not extracted expands to 20 kPa. Determine: (a) net work output per kg of steam, (b) the cycle efficiency. [2]

Note: This is the same as Prob.3.27, which was solved for an open FWH. But, now a closed FWH is used.





Data:

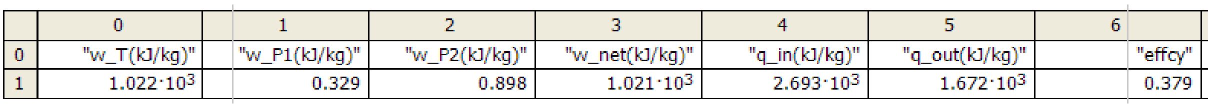
P_cond := 20 kPa P_boiler := 6000 kPa P2 := 400 kPa

T1 := 450 C

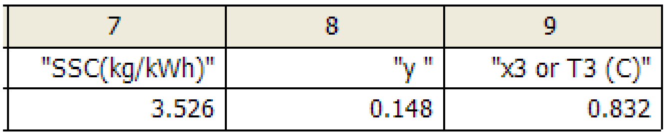
Applying the Mathcad Function for ideal, regenerative Rankine cycle with a closed feed water heater, written above:

We get:

Ideal_Regen_Rankine_closed_FWH_A(P_cond, P_boiler, P2, T1) =



	0	1	2	3	4	5	6
0	"w_T(kJ/kg)"	"w_P1(kJ/kg)"	"w_P2(kJ/kg)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"
1	$1.022 \cdot 10^3$	0.329	0.898	$1.021 \cdot 10^3$	$2.693 \cdot 10^3$	$1.672 \cdot 10^3$	0.379



7	8	9
"SSC(kg/kWh)"	"y "	"x3 or T3 (C)"
3.526	0.148	0.832

Thus:

Net work output:

w_net = 1021 **kJ/kg .... Ans.**

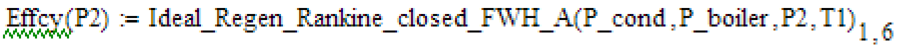
Cycle efficiency:

effcy = 0.379 **= 37.9% .... Ans.**

:==

Plot cycle effcy as extraction pressure, P2 varies from 200 kPa to 1500 kPa:

First write the cycle effcy as a function of P2:

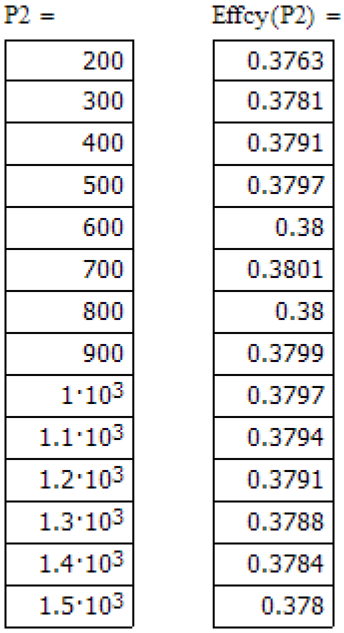


Effcy(P2) := Ideal_Regen_Rankine_closed_FWH_A(P_cond, P_boiler, P2, T1)$_{1,6}$

Now:

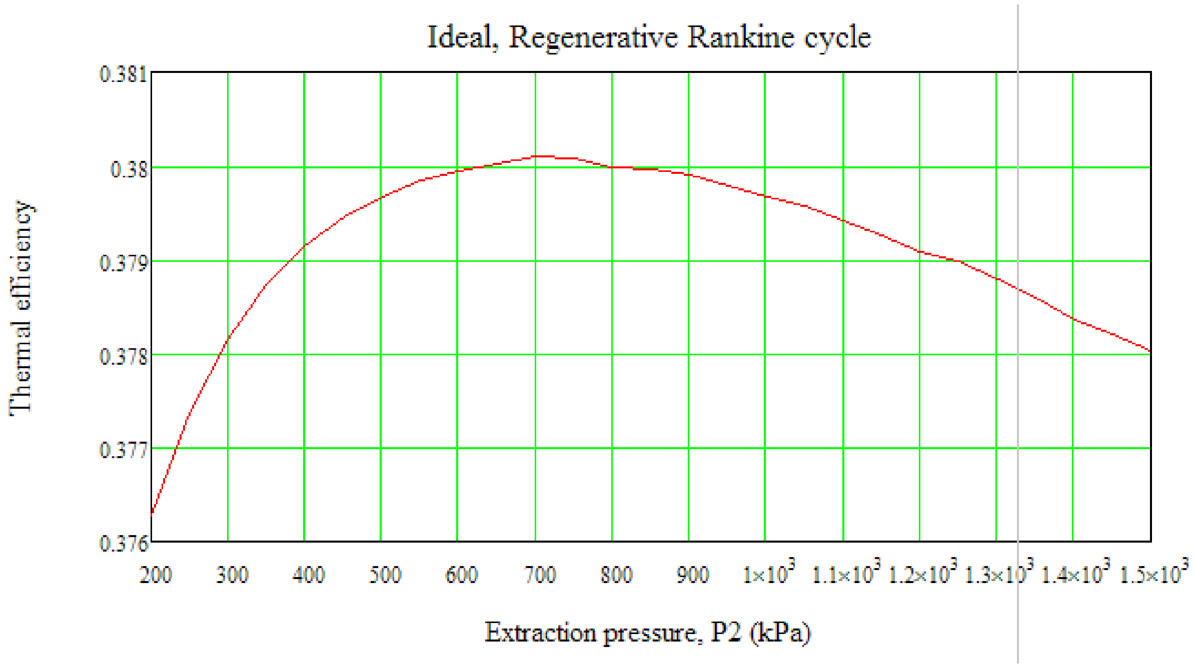
P2 := 200, 300 .. 1500 kPa .... define a range variable

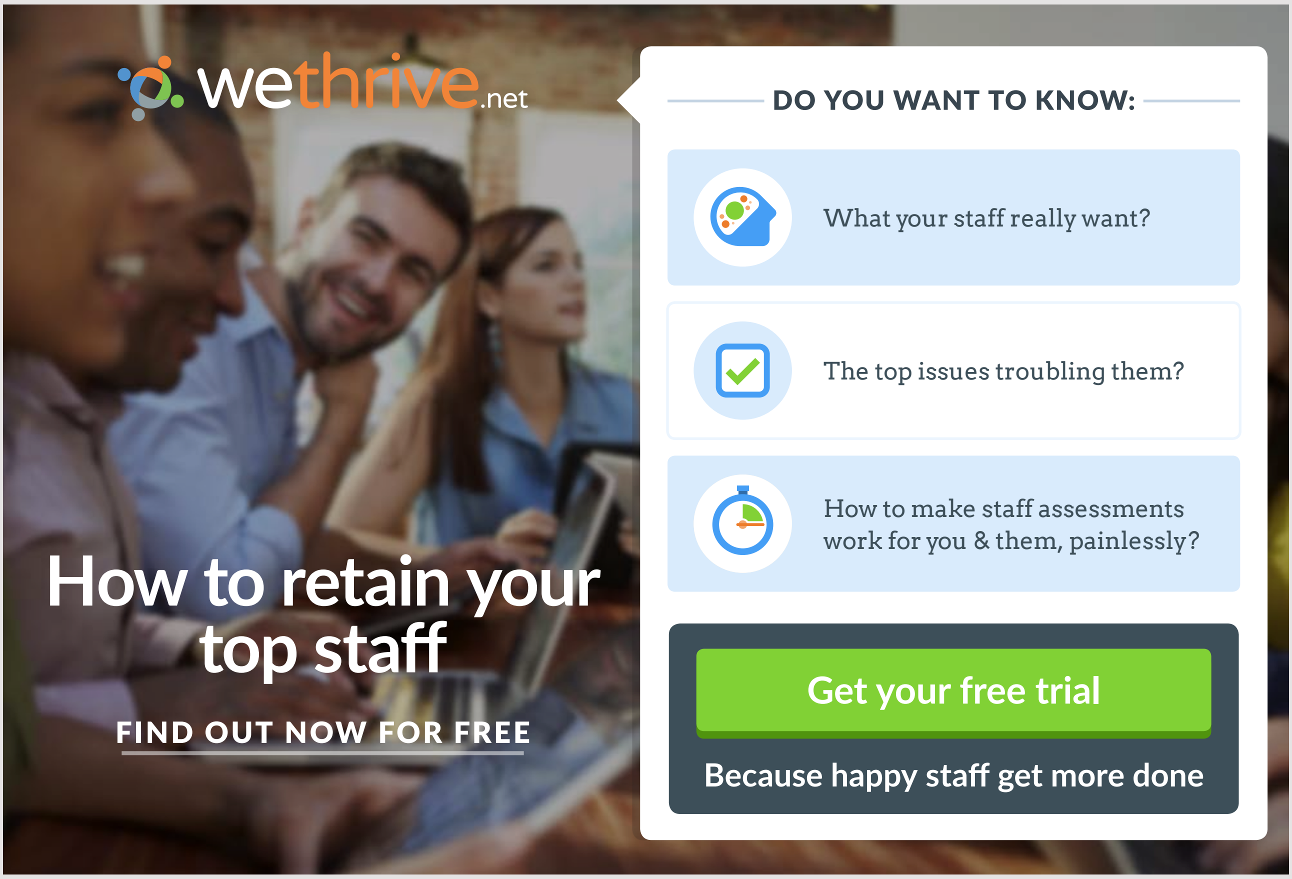
We get:



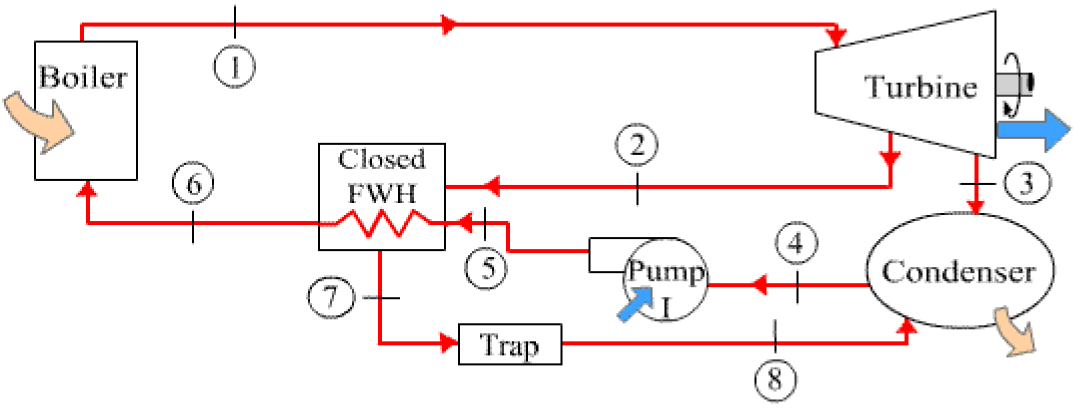
P2 =	Effcy(P2) =
200	0.3763
300	0.3781
400	0.3791
500	0.3797
600	0.38
700	0.3801
800	0.38
900	0.3799
$1\cdot10^3$	0.3797
$1.1\cdot10^3$	0.3794
$1.2\cdot10^3$	0.3791
$1.3\cdot10^3$	0.3788
$1.4\cdot10^3$	0.3784
$1.5\cdot10^3$	0.378

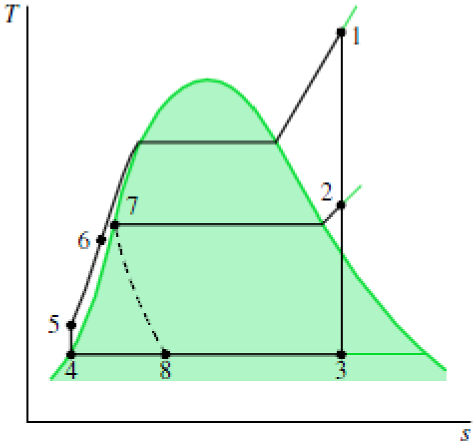
Plot:


Ideal, Regenerative Rankine cycle
Thermal efficiency
0.381
0.38
0.379
0.378
0.377
0.376
200
300
400
500
600
700
800
900
1×10³
1.1×10³
1.2×10³
1.3×10³
1.4×10³
1.5×10³
Extraction pressure, P2 (kPa)

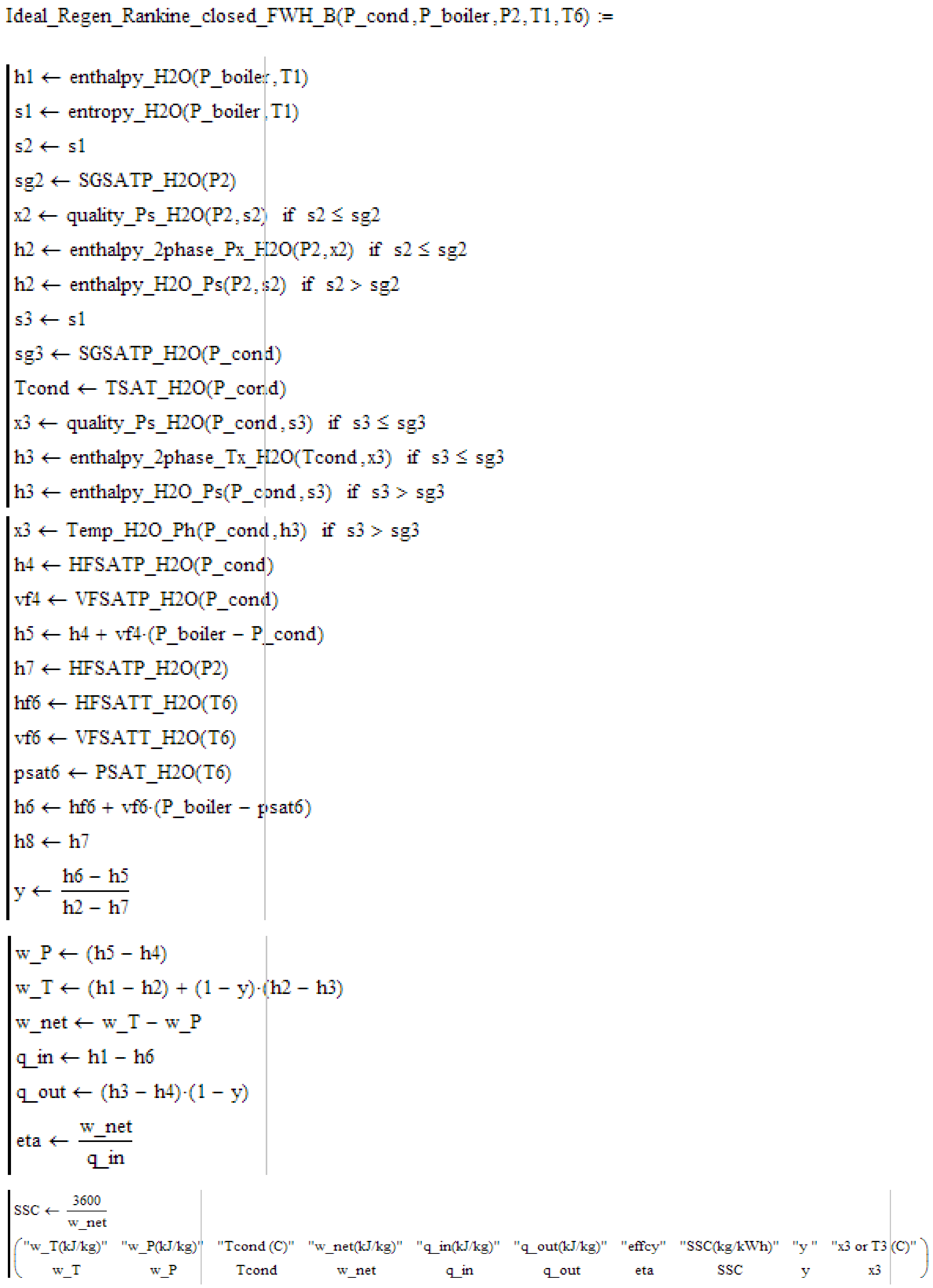


Prob. 3.36 Write a Mathcad program to find out the various parameters of interest for an Ideal, Regenerative Rankine cycle, with one *closed* FWH, from where the condensed steam is sent back to the condenser via a trap (where steam is trapped and the liquid is throttled to condenser pressure). Exit temp of feedwater stream at the feedwater heater (T6) is given. Take ideal processes for steam.





Mathcad Function:



```
Ideal_Regen_Rankine_closed_FWH_B(P_cond, P_boiler, P2, T1, T6) :=
    h1 ← enthalpy_H2O(P_boiler, T1)
    s1 ← entropy_H2O(P_boiler, T1)
    s2 ← s1
    sg2 ← SGSATP_H2O(P2)
    x2 ← quality_Ps_H2O(P2, s2)  if  s2 ≤ sg2
    h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s2 ≤ sg2
    h2 ← enthalpy_H2O_Ps(P2, s2)  if  s2 > sg2
    s3 ← s1
    sg3 ← SGSATP_H2O(P_cond)
    Tcond ← TSAT_H2O(P_cond)
    x3 ← quality_Ps_H2O(P_cond, s3)  if  s3 ≤ sg3
    h3 ← enthalpy_2phase_Tx_H2O(Tcond, x3)  if  s3 ≤ sg3
    h3 ← enthalpy_H2O_Ps(P_cond, s3)  if  s3 > sg3
    x3 ← Temp_H2O_Ph(P_cond, h3)  if  s3 > sg3
    h4 ← HFSATP_H2O(P_cond)
    vf4 ← VFSATP_H2O(P_cond)
    h5 ← h4 + vf4·(P_boiler − P_cond)
    h7 ← HFSATP_H2O(P2)
    hf6 ← HFSATT_H2O(T6)
    vf6 ← VFSATT_H2O(T6)
    psat6 ← PSAT_H2O(T6)
    h6 ← hf6 + vf6·(P_boiler − psat6)
    h8 ← h7
    y ← $\frac{h6 - h5}{h2 - h7}$
    w_P ← (h5 − h4)
    w_T ← (h1 − h2) + (1 − y)·(h2 − h3)
    w_net ← w_T − w_P
    q_in ← h1 − h6
    q_out ← (h3 − h4)·(1 − y)
    eta ← $\frac{w\_net}{q\_in}$
    SSC ← $\frac{3600}{w\_net}$
    ⎛"w_T(kJ/kg)"  "w_P(kJ/kg)"  "Tcond (C)"  "w_net(kJ/kg)"  "q_in(kJ/kg)"  "q_out(kJ/kg)"  "effcy"  "SSC(kg/kWh)"  "y "  "x3 or T3 (C)"⎞
    ⎝    w_T           w_P          Tcond         w_net           q_in           q_out          eta        SSC         y          x3       ⎠
```

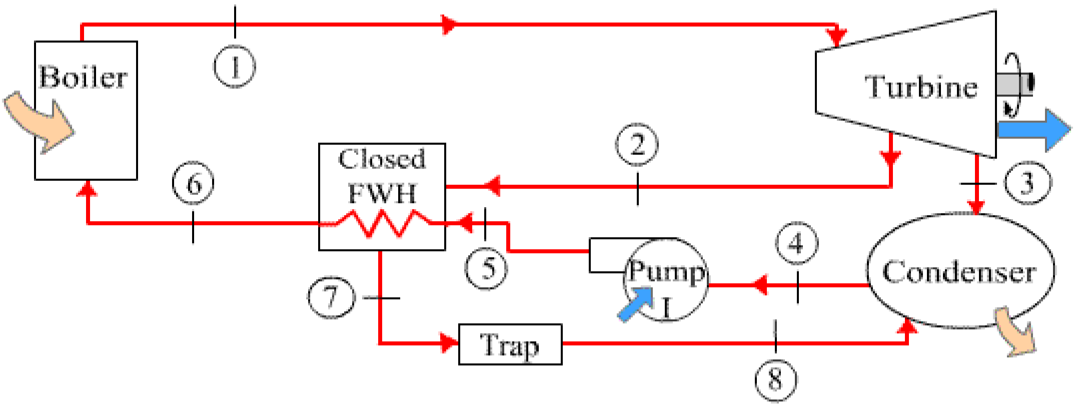
Explanation for the above Function:

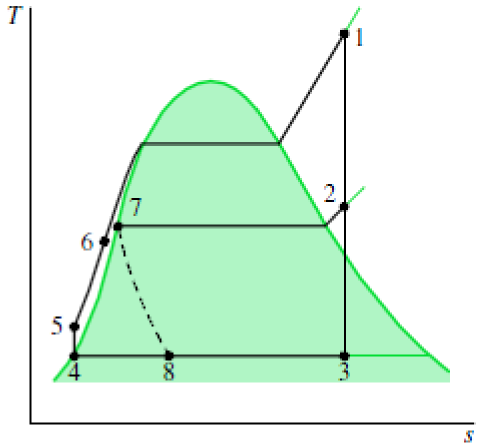
This function gives all the important parameters of performance of an Ideal Regenerative Rankine cycle with one *closed* FWH. Condensed extracted steam from the closed FWH is throttled and sent back to the condenser (or, the previous low pressure heater).

This function is similar to the Functions written earlier for other variations of Rankine cycle, and here also we check if the exits of both stages of turbine are in two phase region or superheat region, and determine the enthalpies accordingly.

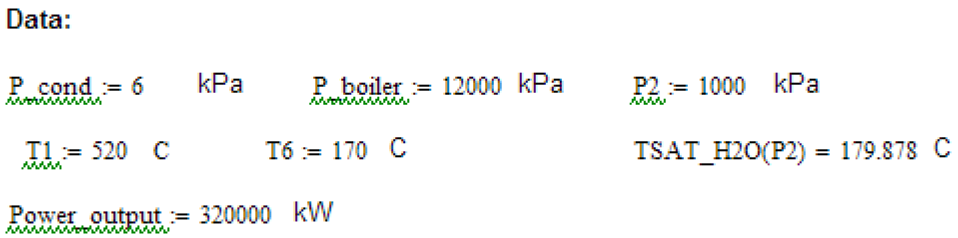
First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where Turbine inlet temperature is in deg.C and pressures P_cond, P_boiler and extraction pressure P2 are in kPa. T6 (deg.C) is the temperature of feedwater going out of the closed feedwater heater, before it enters the boiler. Outputs are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Turbine work (w_T), Pump work (w_P), Condenser temp. T_cond, Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficieny (effcy), fraction of extracted stream (y), and the quality of steam at turbine exit (x3) if the exit steam is in two phase region, or its temp (T3) if the exit steam is in superheat region. Units of each quantity are also given in output.

Prob. 3.37 A power plant operates on a regenerative vapor power cycle with one closed feedwater heater. Steam enters the first turbine stage at 120 bar, 520 C and expands to 10 bar, where some of the steam is extracted and diverted to a closed feedwater heater. Condensate exiting the feedwater heater as saturated liquid at 10 bar passes through a trap into the condenser. The feedwater exits the heater at 120 bar with a temperature of 170 C. The condenser pressure is 0.06 bar. For isentropic processes in each turbine stage and the pump, determine for the cycle **(a)** the thermal efficiency and **(b)** the mass flow rate into the first-stage turbine, in kg/h, if the net power developed is 320 MW. [4]





Solution:



Data:

P_cond := 6 kPa P_boiler := 12000 kPa P2 := 1000 kPa

T1 := 520 C T6 := 170 C TSAT_H2O(P2) = 179.878 C

Power_output := 320000 kW

Applying the Mathcad Function for ideal, regenerative Rankine cycle with a closed feed water heater, written above, we get:

Ideal_Regen_Rankine_closed_FWH_B(P_cond, P_boiler, P2, T1, T6) =

	0	1	2	3	4	5	6
0	"w_T(kJ/kg)"	"w_P(kJ/kg)"	"Tcond (C)"	"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"
1	$1.172 \cdot 10^3$	12.071	36.16	$1.16 \cdot 10^3$	$2.672 \cdot 10^3$	$1.338 \cdot 10^3$	0.434

7	8	9
"SSC(kg/kWh)"	"y "	"x3 or T3 (C)"
3.103	0.284	0.773

Therefore:

Thermal efficiency:

effcy = 0.434 **=43.4% .... Ans.**

Mass flow rate:

We see from the Function output: w_net := 1160.3 kJ/kg

Then: $\text{Mass\_Flow} := \dfrac{\text{Power\_output}}{\text{w\_net}}$

i.e. Mass_Flow = 275.791 **kg/s = 9.928 x 10^5 kg/h ..... Ans.**

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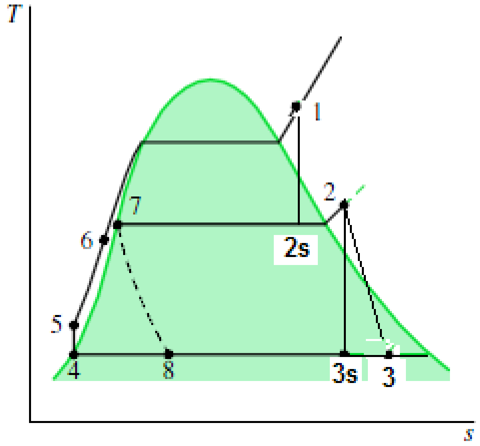
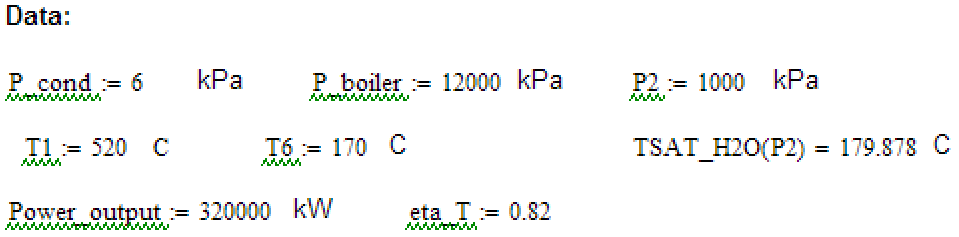
Prob. 3.38 Reconsider the cycle of Problem 3.36, but include in the analysis that each turbine stage has an isentropic efficiency of 82%. The pump efficiency remains 100%. [4]





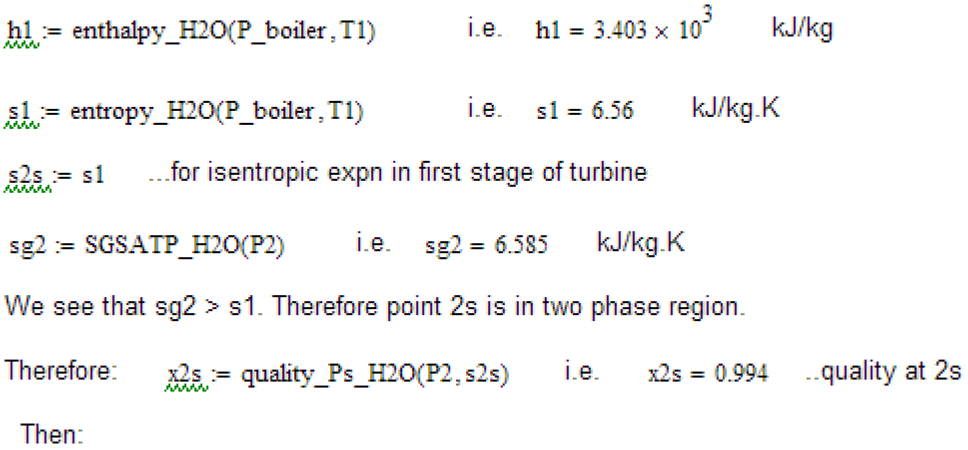
Data:

P_cond := 6 kPa   P_boiler := 12000 kPa   P2 := 1000 kPa

T1 := 520 C   T6 := 170 C   TSAT_H2O(P2) = 179.878 C

Power_output := 320000 kW   eta_T := 0.82

Let us calculate the enthalpies at various state points:



h1 := enthalpy_H2O(P_boiler, T1)   i.e. $h1 = 3.403 \times 10^{3}$ kJ/kg

s1 := entropy_H2O(P_boiler, T1)   i.e.   s1 = 6.56   kJ/kg.K

s2s := s1   ...for isentropic expn in first stage of turbine

sg2 := SGSATP_H2O(P2)   i.e.   sg2 = 6.585   kJ/kg.K

We see that sg2 > s1. Therefore point 2s is in two phase region.

Therefore: x2s := quality_Ps_H2O(P2, s2s)   i.e.   x2s = 0.994   ..quality at 2s

Then:

h2s := enthalpy_2phase_Px_H2O(P2,x2s) i.e. $h2s = 2.766 \times 10^3$ kJ/kg

Therefore:

w_T1 := (h1 − h2s)·eta_T i.e. w_T1 = 522.733 kJ/kg .... work of first stage turbine

And:

h2 := h1 − w_T1 i.e. $h2 = 2.881 \times 10^3$ kJ/kg

hg2 := HGSATP_H2O(P2) $hg2 = 2.777 \times 10^3$ kJ/kg

We see that h2 > hg2. Therefore, point 2 is in superheat region.

Then:

s2 := entropy_H2O_Ph(P2,h2) i.e. s2 = 6.803 kJ/kg.K

s3s := s2 ... for isentropic expn in second stage turbine

sg3 := SGSATP_H2O(P_cond) i.e. sg3 = 8.331 kJ/kg.K

We see that sg3 > s2. Therefore, point 3s is in two phase region.

x3s := quality_Ps_H2O(P_cond,s3s) i.e. x3s = 0.804 ..quality at 3s

Then:

h3s := enthalpy_2phase_Px_H2O(P_cond,x3s) i.e. $h3s = 2.094 \times 10^3$ kJ/kg

Therefore:

w_T2 := (h2 − h3s)·eta_T i.e. w_T2 = 645.057 kJ/kg .... work of second stage turbine

And:

h3 := h2 − w_T2 i.e. $h3 = 2.235 \times 10^3$ kJ/kg

Now, hg3 := HGSATP_H2O(P_cond) i.e. $hg3 = 2.566 \times 10^3$ kJ/kg

Since hg3 > h3, point 3 is in two phase region.

Further:

h4 := HFSATP_H2O(P_cond) i.e. h4 = 151.046 kJ/kg

vf4 := VFSATP_H2O(P_cond) i.e. $vf4 = 1.006 \times 10^{-3}$ m^3/kg

h5 := h4 + vf4·(P_boiler − P_cond) i.e. h5 = 163.117 kJ/kg

h7 := HFSATP_H2O(P2) i.e. h7 = 762.465 kJ/kg

To find h6:

$hf6 := HFSATT\_H2O(T6)$ i.e. $hf6 = 719.08$ kJ/kg

$vf6 := VFSATT\_H2O(T6)$ i.e. $vf6 = 1.114 \times 10^{-3}$ m^3/kg

$psat6 := PSAT\_H2O(T6)$ i.e. $psat6 = 792.19$ kPa

$h6 := hf6 + vf6 \cdot (P\_boiler - psat6)$ i.e. $h6 = 731.569$ kJ/kg

To find y, the fraction of steam extracted:

$y := \frac{h6 - h5}{h2 - h7}$ i.e. $y = 0.268$

Pump work:

$w\_P := (h5 - h4)$ i.e. $w\_P = 12.071$ kJ/kg

Total turbine work:

$w\_T := (h1 - h2) + (1 - y) \cdot (h2 - h3)$ i.e. $w\_T = 994.667$ kJ/kg

Net work:

$w\_net := w\_T - w\_P$ i.e. $w\_net = 982.596$ kJ/kg

Heat supplied:

$q\_in := h1 - h6$ i.e. $q\_in = 2.672 \times 10^{3}$ kJ/kg

Heat rejected:

$q\_out := (h3 - h4) \cdot (1 - y)$ i.e. $q\_out = 1.525 \times 10^{3}$ kJ/kg

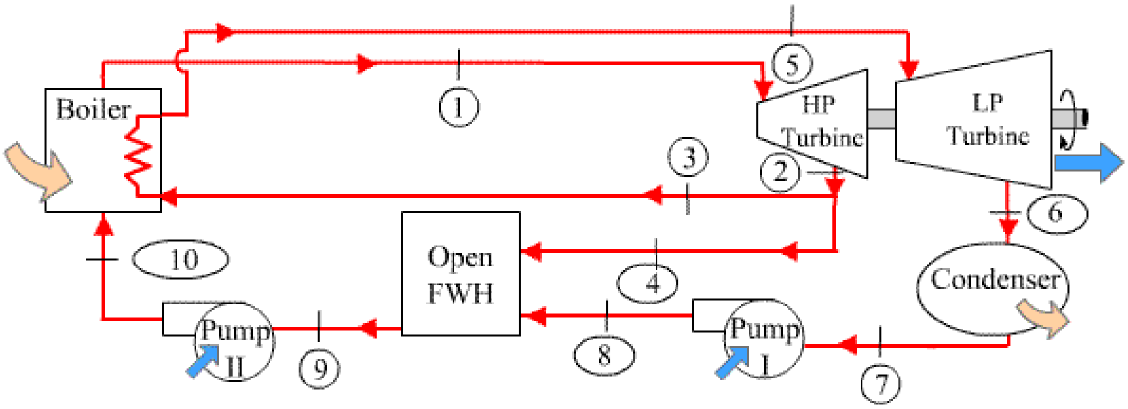
Thermal efficiency:

$eta := \frac{w\_net}{q\_in}$

i.e. $eta = 0.368$ **= 36.8%....Thermal efficiency .... Ans.**

==

Prob. 3.39 A power plant operates on an **Ideal reheat-regenerative Rankine cycle** and has a net power output (W·net) of 100 MW. Steam enters the high pressure turbine stage at 12 MPa, 550°C and leaves at 0.9 MPa. Some steam is extracted at 0.9 MPa to heat the feedwater in an open feedwater heater with the water leaving the FWH as saturated liquid. The rest of the steam is reheated to 500oC and is expanded in the low pressure turbine to the condenser at a pressure of 8 kPa. Determine (a) the thermal efficiency (ηth) of the cycle and (b) the mass flow rate (m·) of steam through the boiler. (c) plot the thermal effcy for boiler pressures of 3 to 12 MPa, and (d) what would the thermal efficiency be if the steam entered the turbine at 15 MPa? [8]



Data:

P_cond := 8 kPa   P_boiler := 12000 kPa   P2 := 900 kPa

T1 := 550 C   T5 := 500 C   TSAT_H2O(P2) = 175.352 C

Power_output := 100000 kW

Let us calculate the enthalpies at various state points, writing relevant quantities as functions of P_boiler, since we have to plot later:

h1(P_boiler) := enthalpy_H2O(P_boiler, T1)   i.e. $h1(P\_boiler) = 3.482 \times 10^{3}$ kJ/kg

s1(P_boiler) := entropy_H2O(P_boiler, T1)   s1(P_boiler) = 6.657 kJ/kg.K

s2(P_boiler) := s1(P_boiler)   ...for isentropic expn in HP turbine

sg2 := SGSATP_H2O(P2)   i.e. sg2 = 6.624 kJ/kg.K

We see that sg2 < s1. Therefore point 2 is in superheat region.

Then:

h2(P_boiler) := enthalpy_H2O_Ps(P2, s2(P_boiler))

i.e. $h2(P\_boiler) = 2.788 \times 10^{3}$ kJ/kg

And:

h3(P_boiler) := h2(P_boiler)

h4(P_boiler) := h2(P_boiler)

h5 := enthalpy_H2O(P2, T5) i.e. h5 = 3.48×10^{3} kJ/kg

s5 := entropy_H2O(P2, T5) i.e. s5 = 7.817 kJ/kg.K

s6 := s5 ..for isentropic expn in LP turbine

sg6 := SGSATP_H2O(P_cond) i.e. sg6 = 8.23 kJ/kg.K

We see that sg6 > s6. Therefore point 6 is in two phase region.

x6 := quality_Ps_H2O(P_cond, s6) i.e. x6 = 0.946 ..quality at 6

Then:

h6 := enthalpy_2phase_Px_H2O(P_cond, x6) i.e. h6 = 2.446×10^{3} kJ/kg

h7 := HFSATP_H2O(P_cond)

i.e. h7 = 173.347 kJ/kg

vf7 := VFSATP_H2O(P_cond) i.e. vf7 = 1.008×10^{-3} m^3/kg

h8 := h7 + vf7·(P2 − P_cond) i.e. h8 = 174.246 kJ/kg

h9 := HFSATP_H2O(P2) i.e. h9 = 741.588 kJ/kg

Now, we get by energy balance on the open FWH:

$$z(P\_boiler) := \frac{h9 - h8}{h4(P\_boiler) - h8}$$

i.e. z(P_boiler) = 0.217 ..fraction sent through the open FWH

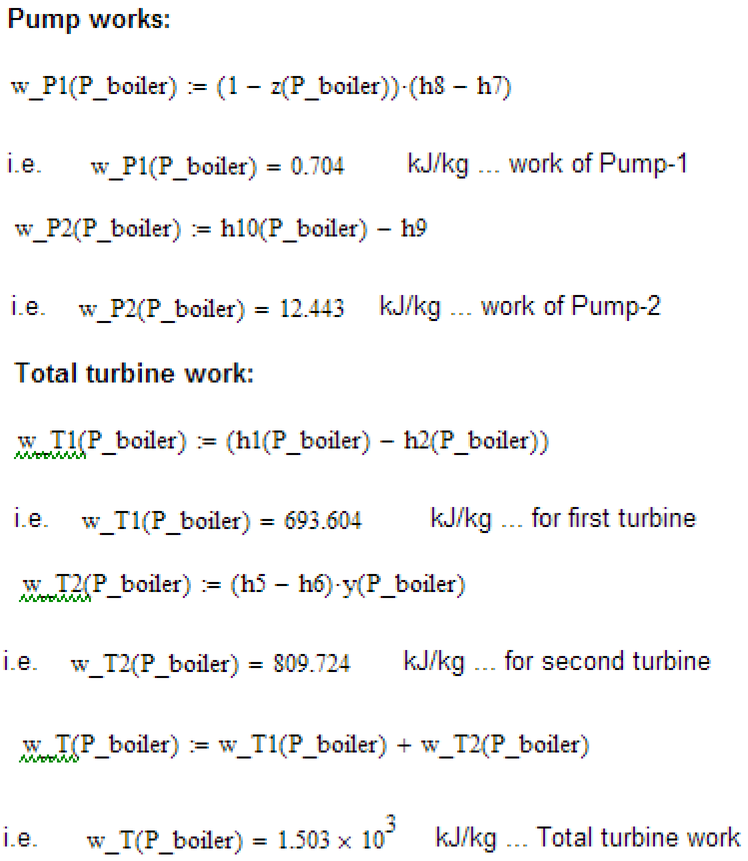
And,

y(P_boiler) := 1 − z(P_boiler)

i.e. y(P_boiler) = 0.783 ..fraction sent through the reheater

vf9 := VFSATP_H2O(P2) i.e. vf9 = 1.121×10^{-3} m^3/kg

h10(P_boiler) := h9 + vf9·(P_boiler − P2) i.e. h10(P_boiler) = 754.031 kJ/kg



Pump works:

$w\_P1(P\_boiler) := (1 - z(P\_boiler))\cdot(h8 - h7)$

i.e. $w\_P1(P\_boiler) = 0.704$ kJ/kg ... work of Pump-1

$w\_P2(P\_boiler) := h10(P\_boiler) - h9$

i.e. $w\_P2(P\_boiler) = 12.443$ kJ/kg ... work of Pump-2

Total turbine work:

$w\_T1(P\_boiler) := (h1(P\_boiler) - h2(P\_boiler))$

i.e. $w\_T1(P\_boiler) = 693.604$ kJ/kg ... for first turbine

$w\_T2(P\_boiler) := (h5 - h6)\cdot y(P\_boiler)$

i.e. $w\_T2(P\_boiler) = 809.724$ kJ/kg ... for second turbine

$w\_T(P\_boiler) := w\_T1(P\_boiler) + w\_T2(P\_boiler)$

i.e. $w\_T(P\_boiler) = 1.503 \times 10^{3}$ kJ/kg ... Total turbine work

Net work:

$$w\_net(P\_boiler) := w\_T(P\_boiler) - (w\_P1(P\_boiler) + w\_P2(P\_boiler))$$

i.e. $w\_net(P\_boiler) = 1.49 \times 10^{3}$ kJ/kg

Heat supplied:

$$q\_in(P\_boiler) := (h1(P\_boiler) - h10(P\_boiler)) + y(P\_boiler)\cdot(h5 - h3(P\_boiler))$$

i.e. $q\_in(P\_boiler) = 3.27 \times 10^{3}$ kJ/kg

Heat rejected:

$$q\_out(P\_boiler) := (h6 - h7)\cdot(1 - z(P\_boiler))$$

i.e. $q\_out(P\_boiler) = 1.779 \times 10^{3}$ kJ/kg

Thermal efficiency:

$$eta(P\_boiler) := \frac{w\_net(P\_boiler)}{q\_in(P\_boiler)}$$

i.e. $eta(P\_boiler) = 0.456$ **= 45.6% ..... Ans.**

Mass flow rate:

$$Mass\_Flow(P\_boiler) := \frac{Power\_output}{w\_net(P\_boiler)}$$

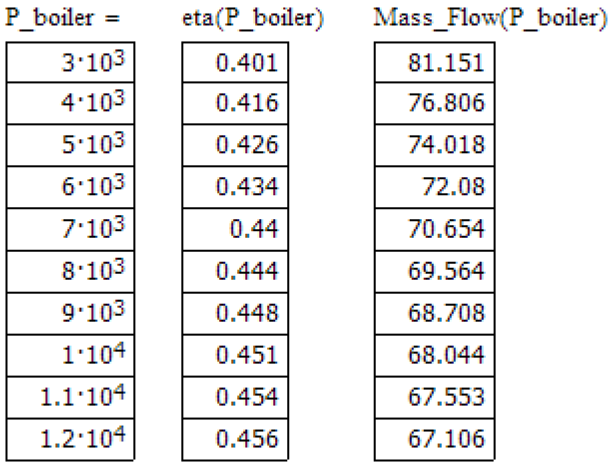
i.e. $Mass\_Flow(P\_boiler) = 67.106$ **kg/s = 2.416 x 10^{5} kg/h ... Ans.**

:===

Now, to plot efficiency for different values of P_boiler:

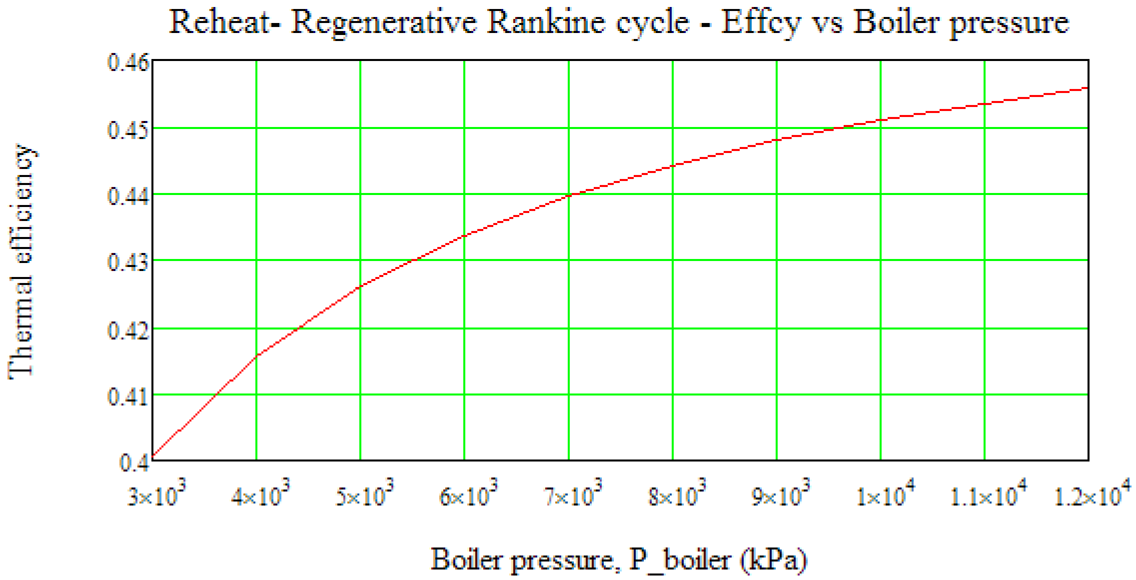
```
P_boiler := 3000,4000.. 12000     ...define a range variable
```

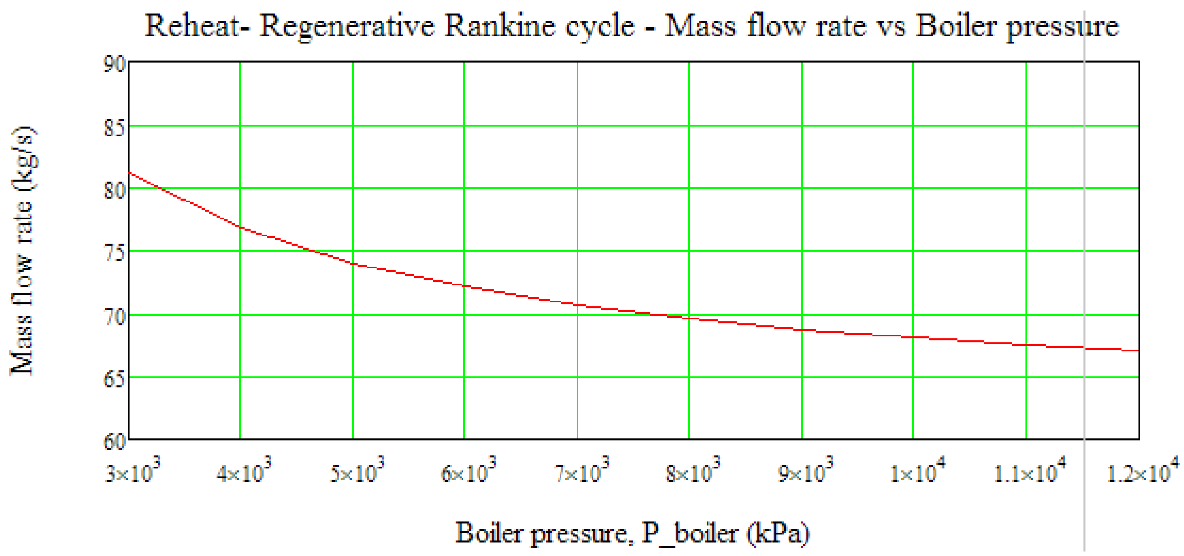
We get:



P_boiler =	eta(P_boiler)	Mass_Flow(P_boiler)
$3\cdot10^3$	0.401	81.151
$4\cdot10^3$	0.416	76.806
$5\cdot10^3$	0.426	74.018
$6\cdot10^3$	0.434	72.08
$7\cdot10^3$	0.44	70.654
$8\cdot10^3$	0.444	69.564
$9\cdot10^3$	0.448	68.708
$1\cdot10^4$	0.451	68.044
$1.1\cdot10^4$	0.454	67.553
$1.2\cdot10^4$	0.456	67.106

Plots:





When P_boiler is 15 MPa:

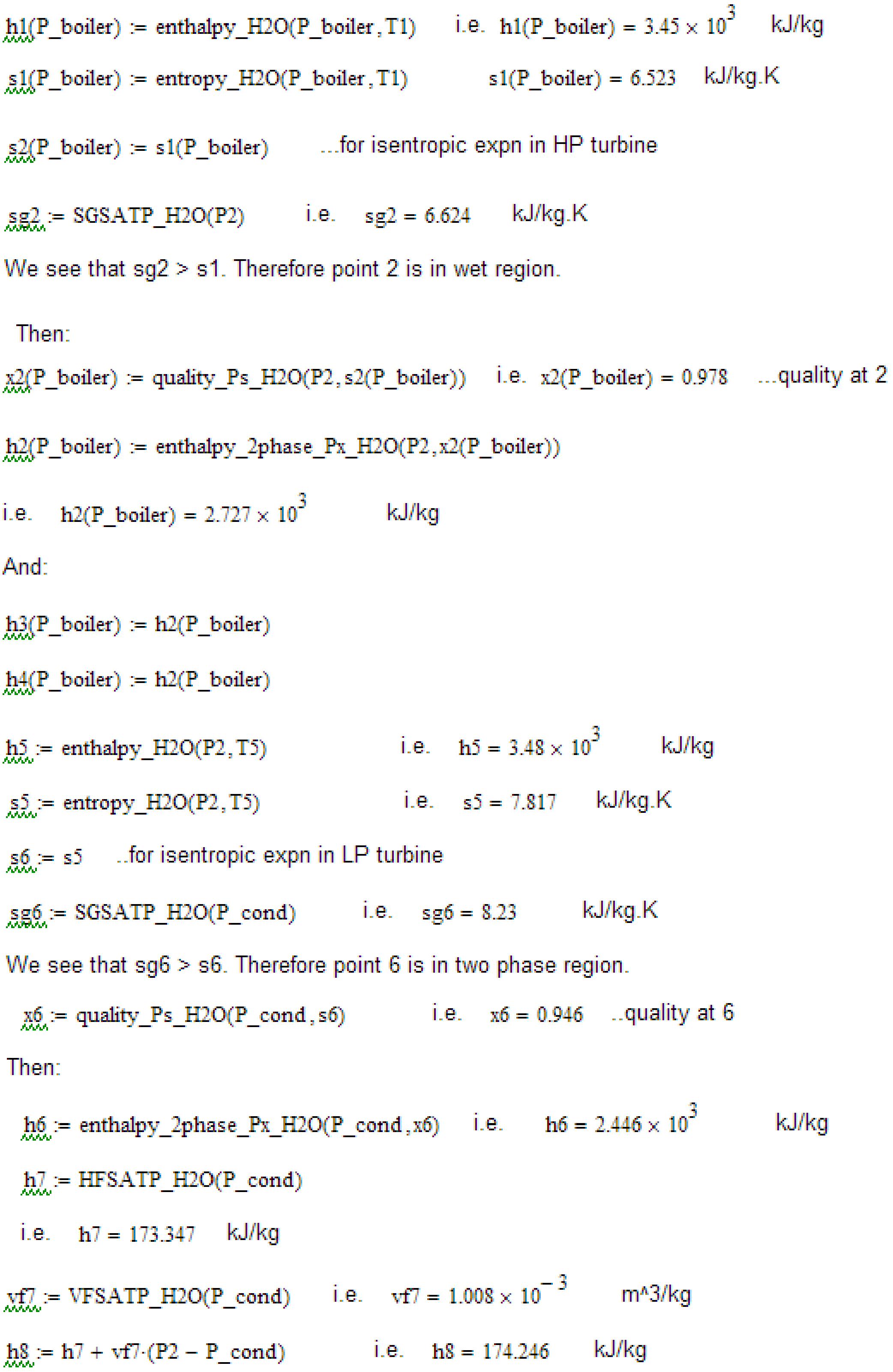
We have:

P_cond := 8 kPa   P_boiler := 15000 kPa   P2 := 900 kPa

T1 := 550 C   T5 := 500 C   TSAT_H2O(P2) = 175.352 C

Power_output := 100000 kW

Then, we get



h1(P_boiler) := enthalpy_H2O(P_boiler, T1) i.e. h1(P_boiler) = 3.45×10^{3} kJ/kg

s1(P_boiler) := entropy_H2O(P_boiler, T1) s1(P_boiler) = 6.523 kJ/kg.K

s2(P_boiler) := s1(P_boiler) ...for isentropic expn in HP turbine

sg2 := SGSATP_H2O(P2) i.e. sg2 = 6.624 kJ/kg.K

We see that sg2 > s1. Therefore point 2 is in wet region.

Then:

x2(P_boiler) := quality_Ps_H2O(P2, s2(P_boiler)) i.e. x2(P_boiler) = 0.978 ...quality at 2

h2(P_boiler) := enthalpy_2phase_Px_H2O(P2, x2(P_boiler))

i.e. h2(P_boiler) = 2.727×10^{3} kJ/kg

And:

h3(P_boiler) := h2(P_boiler)

h4(P_boiler) := h2(P_boiler)

h5 := enthalpy_H2O(P2, T5) i.e. h5 = 3.48×10^{3} kJ/kg

s5 := entropy_H2O(P2, T5) i.e. s5 = 7.817 kJ/kg.K

s6 := s5 ..for isentropic expn in LP turbine

sg6 := SGSATP_H2O(P_cond) i.e. sg6 = 8.23 kJ/kg.K

We see that sg6 > s6. Therefore point 6 is in two phase region.

x6 := quality_Ps_H2O(P_cond, s6) i.e. x6 = 0.946 ..quality at 6

Then:

h6 := enthalpy_2phase_Px_H2O(P_cond, x6) i.e. h6 = 2.446×10^{3} kJ/kg

h7 := HFSATP_H2O(P_cond)

i.e. h7 = 173.347 kJ/kg

vf7 := VFSATP_H2O(P_cond) i.e. vf7 = 1.008×10^{-3} m^3/kg

h8 := h7 + vf7·(P2 − P_cond) i.e. h8 = 174.246 kJ/kg

$h9 := HFSATP\_H2O(P2)$ i.e. $h9 = 741.588$ kJ/kg

Now, we get by energy balance on the open FWH:

$$z(P\_boiler) := \frac{h9 - h8}{h4(P\_boiler) - h8}$$

i.e. $z(P\_boiler) = 0.222$ ..fraction sent through the open FWH

And,

$y(P\_boiler) := 1 - z(P\_boiler)$

i.e. $y(P\_boiler) = 0.778$ ..fraction sent through the reheater

$vf9 := VFSATP\_H2O(P2)$ i.e. $vf9 = 1.121 \times 10^{-3}$ m^3/kg

$h10(P\_boiler) := h9 + vf9 \cdot (P\_boiler - P2)$ i.e. $h10(P\_boiler) = 757.394$ kJ/kg

Pump works:

$w\_P1(P\_boiler) := (1 - z(P\_boiler)) \cdot (h8 - h7)$

i.e. $w\_P1(P\_boiler) = 0.7$ kJ/kg ... work of Pump-1

$w\_P2(P\_boiler) := h10(P\_boiler) - h9$

i.e. $w\_P2(P\_boiler) = 15.806$ kJ/kg ... work of Pump-2

Total turbine work:

$w\_T1(P\_boiler) := (h1(P\_boiler) - h2(P\_boiler))$

i.e. $w\_T1(P\_boiler) = 722.854$ kJ/kg ... for first turbine

$w\_T2(P\_boiler) := (h5 - h6) \cdot y(P\_boiler)$

i.e. $w\_T2(P\_boiler) = 804.407$ kJ/kg ... for second turbine

$w\_T(P\_boiler) := w\_T1(P\_boiler) + w\_T2(P\_boiler)$

i.e. $w\_T(P\_boiler) = 1.527 \times 10^{3}$ kJ/kg ... Total turbine work

Net work:

$w\_net(P\_boiler) := w\_T(P\_boiler) - (w\_P1(P\_boiler) + w\_P2(P\_boiler))$

i.e. $w\_net(P\_boiler) = 1.511 \times 10^{3}$ kJ/kg

Heat supplied:

$q\_in(P\_boiler) := (h1(P\_boiler) - h10(P\_boiler)) + y(P\_boiler)\cdot(h5 - h3(P\_boiler))$

i.e. $q\_in(P\_boiler) = 3.278 \times 10^{3}$ kJ/kg

Heat rejected:

$q\_out(P\_boiler) := (h6 - h7)\cdot(1 - z(P\_boiler))$

i.e. $q\_out(P\_boiler) = 1.768 \times 10^{3}$ kJ/kg

Thermal efficiency:

$eta(P\_boiler) := \frac{w\_net(P\_boiler)}{q\_in(P\_boiler)}$

i.e. $eta(P\_boiler) = 0.461$ **= 46.1% ..... Ans.**

Mass flow rate:

$$\text{Mass\_Flow(P\_boiler)} := \frac{\text{Power\_output}}{\text{w\_net(P\_boiler)}}$$

i.e. Mass_Flow(P_boiler) = 66.192 **kg/s = 2.383 x 10^5 kg/h ... Ans.**

:==

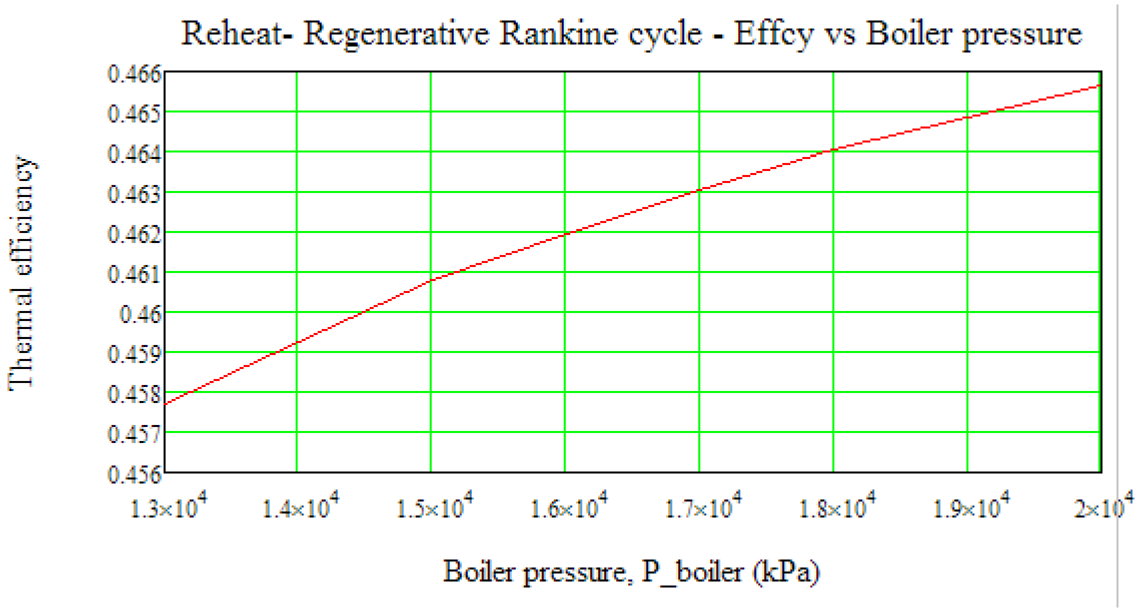
Now, to plot effcy. for different values of P_boiler:

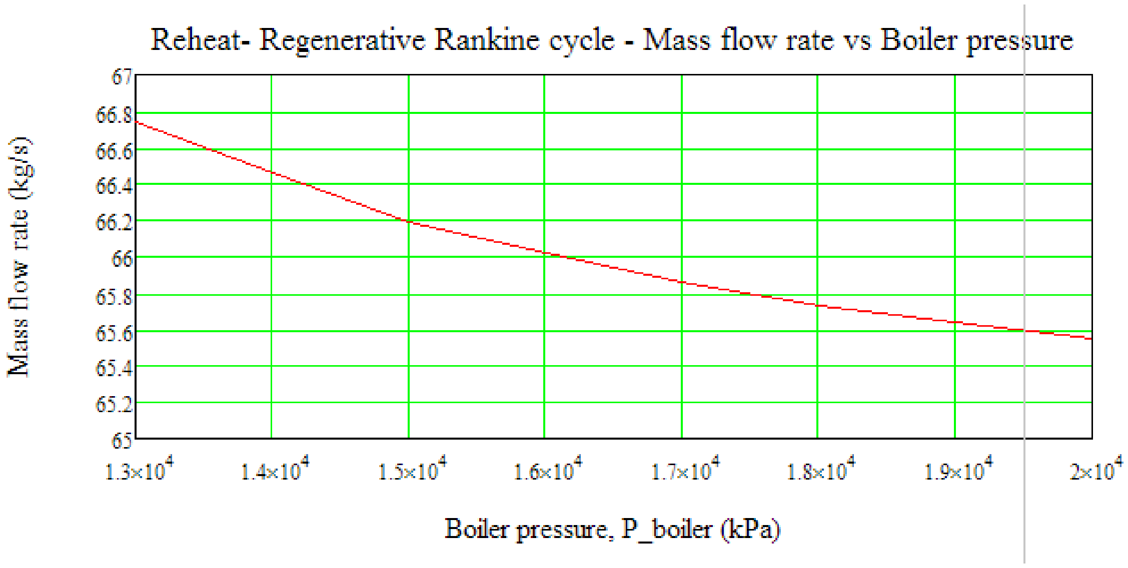
P_boiler := 13000, 14000.. 20000 ...define a range variable

We get:

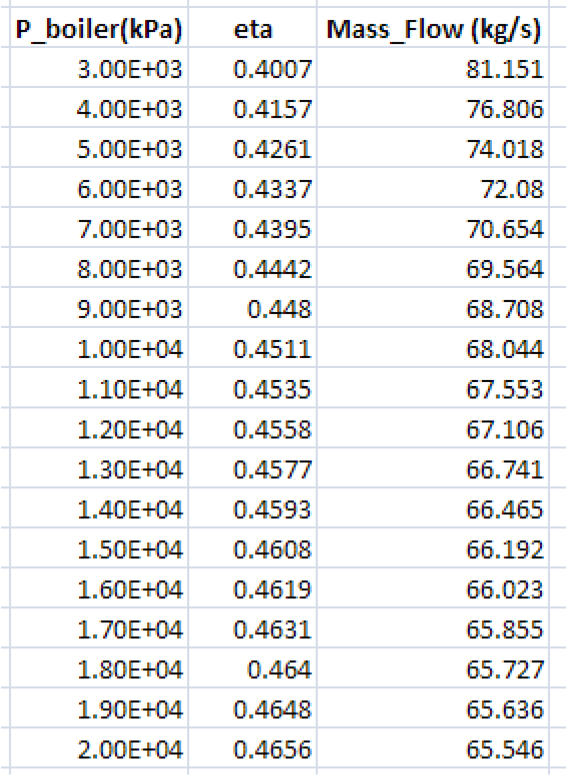
P_boiler =	eta(P_boiler)	Mass_Flow(P_boiler)
$1.3\cdot10^4$	0.4577	66.741
$1.4\cdot10^4$	0.4593	66.465
$1.5\cdot10^4$	0.4608	66.192
$1.6\cdot10^4$	0.4619	66.023
$1.7\cdot10^4$	0.4631	65.855
$1.8\cdot10^4$	0.464	65.727
$1.9\cdot10^4$	0.4648	65.636
$2\cdot10^4$	0.4656	65.546

Plots:



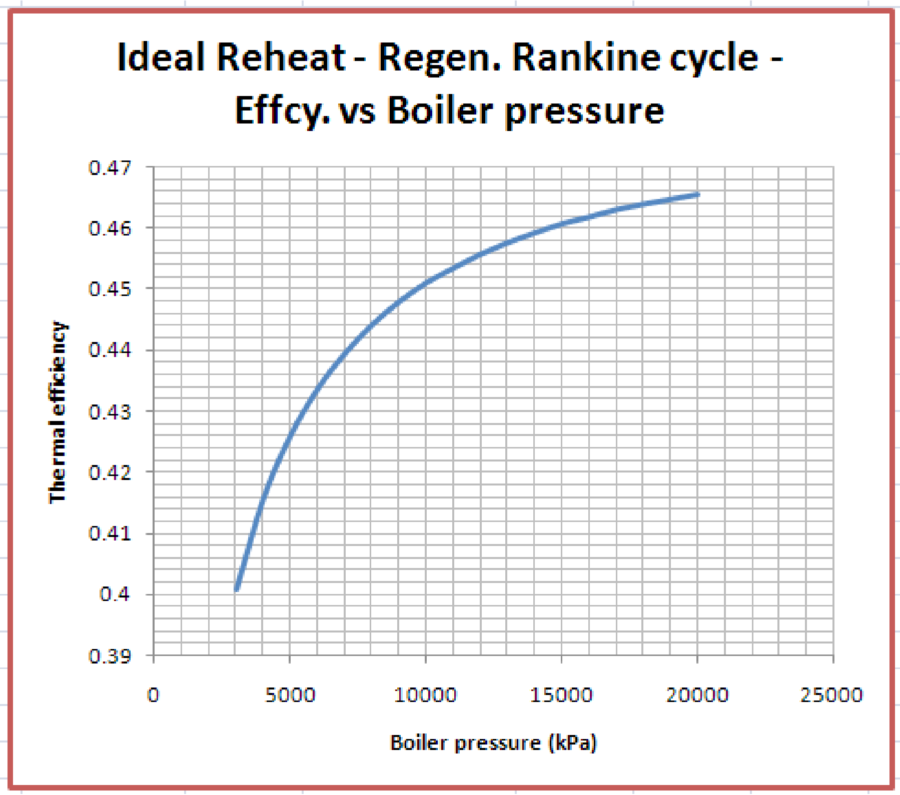


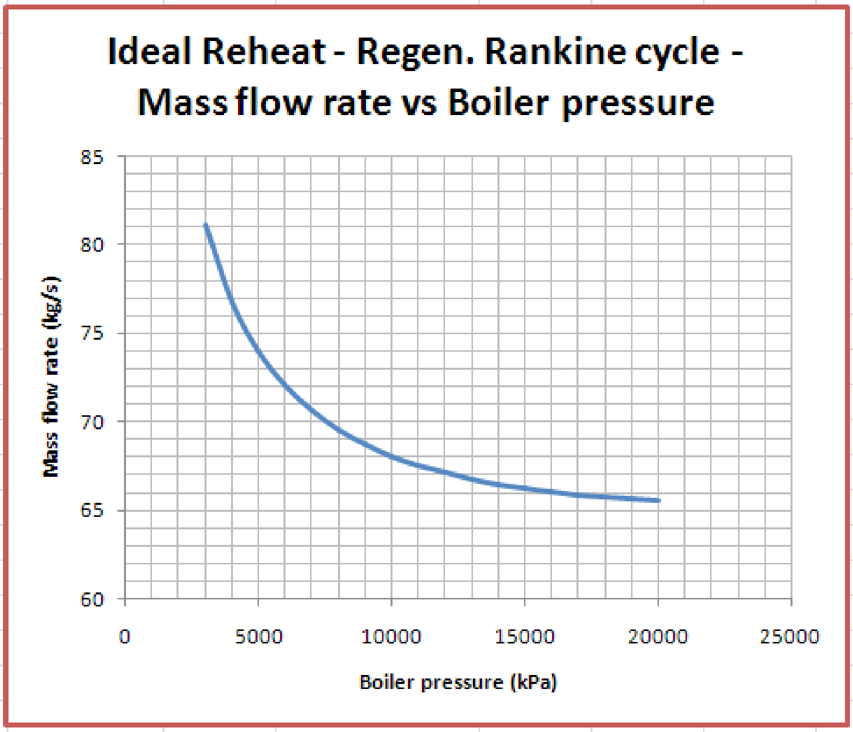
Combining both the solutions obtained above (i.e. one for boiler pressures below 12 bar, and the other, for boiler pressures above 12 bar), we get:



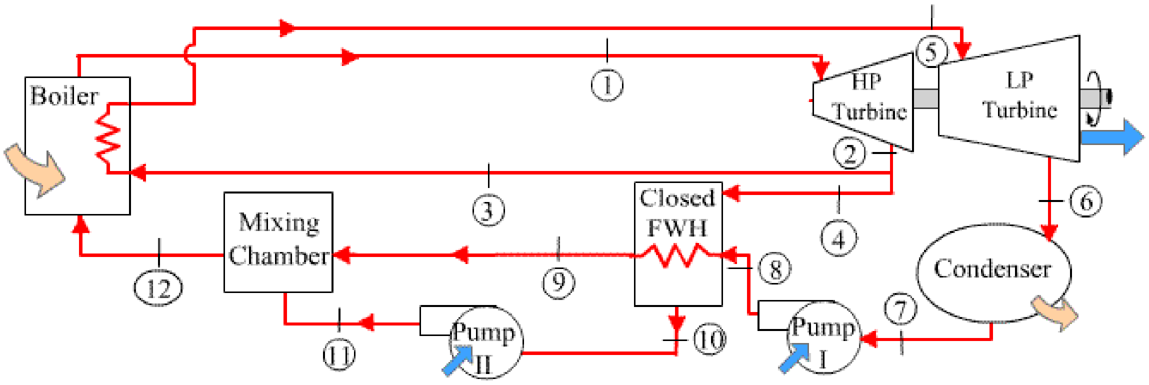
P_boiler(kPa)	eta	Mass_Flow (kg/s)
3.00E+03	0.4007	81.151
4.00E+03	0.4157	76.806
5.00E+03	0.4261	74.018
6.00E+03	0.4337	72.08
7.00E+03	0.4395	70.654
8.00E+03	0.4442	69.564
9.00E+03	0.448	68.708
1.00E+04	0.4511	68.044
1.10E+04	0.4535	67.553
1.20E+04	0.4558	67.106
1.30E+04	0.4577	66.741
1.40E+04	0.4593	66.465
1.50E+04	0.4608	66.192
1.60E+04	0.4619	66.023
1.70E+04	0.4631	65.855
1.80E+04	0.464	65.727
1.90E+04	0.4648	65.636
2.00E+04	0.4656	65.546

And, plots:


Ideal Reheat - Regen. Rankine cycle - Effcy. vs Boiler pressure
Thermal efficiency
0.47
0.46
0.45
0.44
0.43
0.42
0.41
0.4
0.39
0
5000
10000
15000
20000
25000
Boiler pressure (kPa)



Prob.3.40 Repeat problem 3.39, but replace the open FWH with a closed FWH. Assume that the feed water leaves the heater at the condensation temp of the extracted steam and that the extracted steam leaves the heater at state-10 as a saturated liquid before it is pumped to the line carrying the feed water. Determine: (a) thermal effcy. (b) mass flow rate of steam through the boiler. [8]



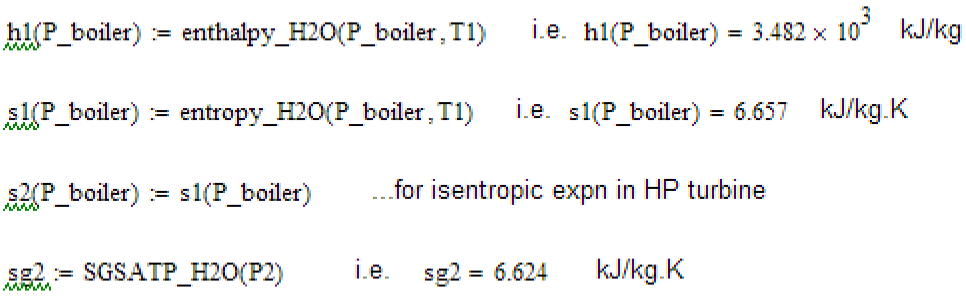
Data:

P_cond := 8 kPa P_boiler := 12000 kPa P2 := 900 kPa

T1 := 550 C T5 := 500 C TSAT_H2O(P2) = 175.352 C

Power_output := 100000 kW

Let us calculate the enthalpies at various state points, writing relevant quantities as functions of P_boiler, since we have to plot later:



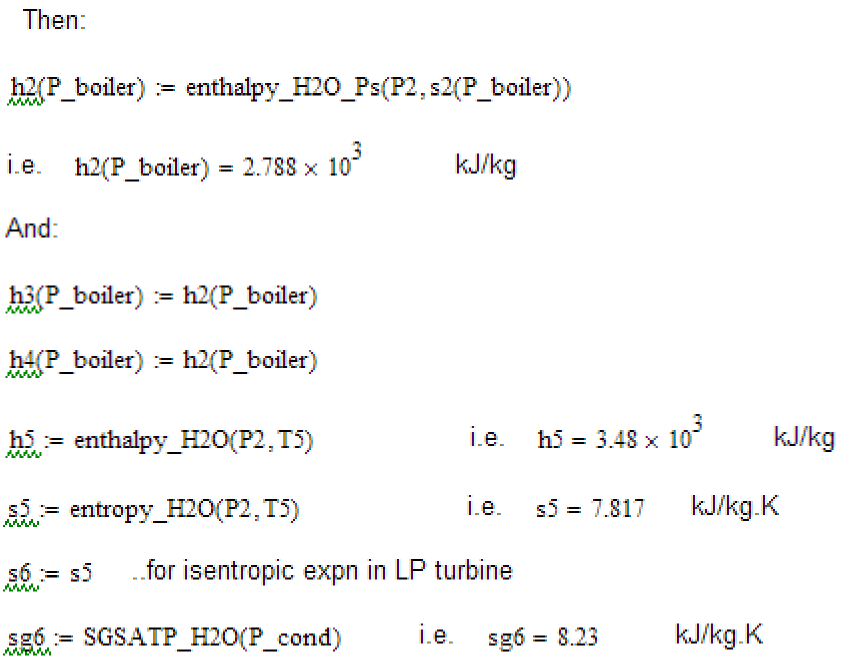
h1(P_boiler) := enthalpy_H2O(P_boiler, T1)   i.e. h1(P_boiler) = 3.482×10^3 kJ/kg

s1(P_boiler) := entropy_H2O(P_boiler, T1)   i.e. s1(P_boiler) = 6.657   kJ/kg.K

s2(P_boiler) := s1(P_boiler)   ...for isentropic expn in HP turbine

sg2 := SGSATP_H2O(P2)   i.e. sg2 = 6.624   kJ/kg.K

We see that sg2 < s1. Therefore point 2 is in superheat region.



Then:

h2(P_boiler) := enthalpy_H2O_Ps(P2, s2(P_boiler))

i.e. h2(P_boiler) = 2.788×10^3 kJ/kg

And:

h3(P_boiler) := h2(P_boiler)

h4(P_boiler) := h2(P_boiler)

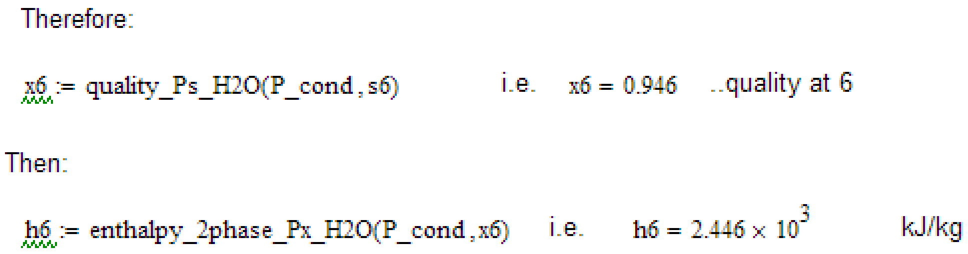
h5 := enthalpy_H2O(P2, T5)   i.e. h5 = 3.48×10^3 kJ/kg

s5 := entropy_H2O(P2, T5)   i.e. s5 = 7.817   kJ/kg.K

s6 := s5   ..for isentropic expn in LP turbine

sg6 := SGSATP_H2O(P_cond)   i.e. sg6 = 8.23   kJ/kg.K

We see that sg6 > s6. Therefore point 6 is in two phase region.



Therefore:

x6 := quality_Ps_H2O(P_cond, s6)   i.e. x6 = 0.946   ..quality at 6

Then:

h6 := enthalpy_2phase_Px_H2O(P_cond, x6)   i.e. h6 = 2.446×10^3 kJ/kg

Now:

$h7 := \text{HFSATP\_H2O}(P\_cond)$

i.e. $h7 = 173.347$ kJ/kg

$vf7 := \text{VFSATP\_H2O}(P\_cond)$ i.e. $vf7 = 1.008 \times 10^{-3}$ m^3/kg

$h8 := h7 + vf7 \cdot (P\_boiler - P\_cond)$ i.e. $h8 = 185.44$ kJ/kg

Also: $T9 := \text{TSAT\_H2O}(P2)$ i.e. $T9 = 175.352$ C ... temp at state 9

Therefore:

$h9 := \text{HFSATT\_H2O}(T9)$ i.e. $h9 = 742.612$ kJ/kg

And:

$h10 := \text{HFSATP\_H2O}(P2)$ i.e. $h10 = 741.588$ kJ/kg

Now, we get by energy balance on the *closed* FWH:

$$z(P\_boiler) := \frac{h9 - h8}{h4(P\_boiler) - h8 - h10 + h9}$$

i.e. $z(P\_boiler) = 0.214$ ..fraction sent through the closed FWH

And,

$y(P\_boiler) := 1 - z(P\_boiler)$

i.e. $y(P\_boiler) = 0.786$ ..fraction sent through the reheater

$vf9 := VFSATT\_H2O(T9)$ i.e. $vf9 = 1.121 \times 10^{-3}$ m^3/kg

Pump works:

$w\_P1(P\_boiler) := (1 - z(P\_boiler)) \cdot (h8 - h7)$

i.e. $w\_P1(P\_boiler) = 9.505$ kJ/kg ... work of Pump-1

$vf10 := VFSATP\_H2O(P2)$ i.e. $vf10 = 1.121 \times 10^{-3}$ m^3/kg

$h11(P\_boiler) := h10 + vf10 \cdot (P\_boiler - P2)$ i.e. $h11(P\_boiler) = 754.031$ kJ/kg

And $w\_P2(P\_boiler) := z(P\_boiler) \cdot (h11(P\_boiler) - h10)$ kJ/kg ... work of Pump-2

i.e. $w\_P2(P\_boiler) = 2.663$ kJ/kg ... work of Pump-2

Also:

$h12(P\_boiler) := (1 - z(P\_boiler)) \cdot h9 + z(P\_boiler) \cdot h11(P\_boiler)$

i.e. $h12(P\_boiler) = 745.056$ kJ/kg

Total turbine work:

$w\_T1(P\_boiler) := (h1(P\_boiler) - h2(P\_boiler))$

i.e. $w\_T1(P\_boiler) = 693.604$ kJ/kg ... for first turbine

$w\_T2(P\_boiler) := (h5 - h6) \cdot y(P\_boiler)$

i.e. $w\_T2(P\_boiler) = 812.887$ kJ/kg ... for second turbine

$w\_T(P\_boiler) := w\_T1(P\_boiler) + w\_T2(P\_boiler)$

i.e. $w\_T(P\_boiler) = 1.506 \times 10^{3}$ kJ/kg ... Total turbine work

Net work:

$w\_net(P\_boiler) := w\_T(P\_boiler) - (w\_P1(P\_boiler) + w\_P2(P\_boiler))$

i.e. $w\_net(P\_boiler) = 1.494 \times 10^{3}$ kJ/kg

Heat supplied:

$$q\_in(P\_boiler) := (h1(P\_boiler) - h12(P\_boiler)) + y(P\_boiler)\cdot(h5 - h3(P\_boiler))$$

i.e. $q\_in(P\_boiler) = 3.281 \times 10^{3}$ kJ/kg

Heat rejected:

$$q\_out(P\_boiler) := (h6 - h7)\cdot(1 - z(P\_boiler))$$

i.e. $q\_out(P\_boiler) = 1.786 \times 10^{3}$ kJ/kg

Thermal efficiency:

$$eta(P\_boiler) := \frac{w\_net(P\_boiler)}{q\_in(P\_boiler)}$$

i.e. $eta(P\_boiler) = 0.456$ **= 45.6% ..... Ans.**

Mass flow rate:

$$Mass\_Flow(P\_boiler) := \frac{Power\_output}{w\_net(P\_boiler)}$$

i.e. $Mass\_Flow(P\_boiler) = 66.92$ **kg/s = 2.409 x 10^5 kg/h ... Ans.**

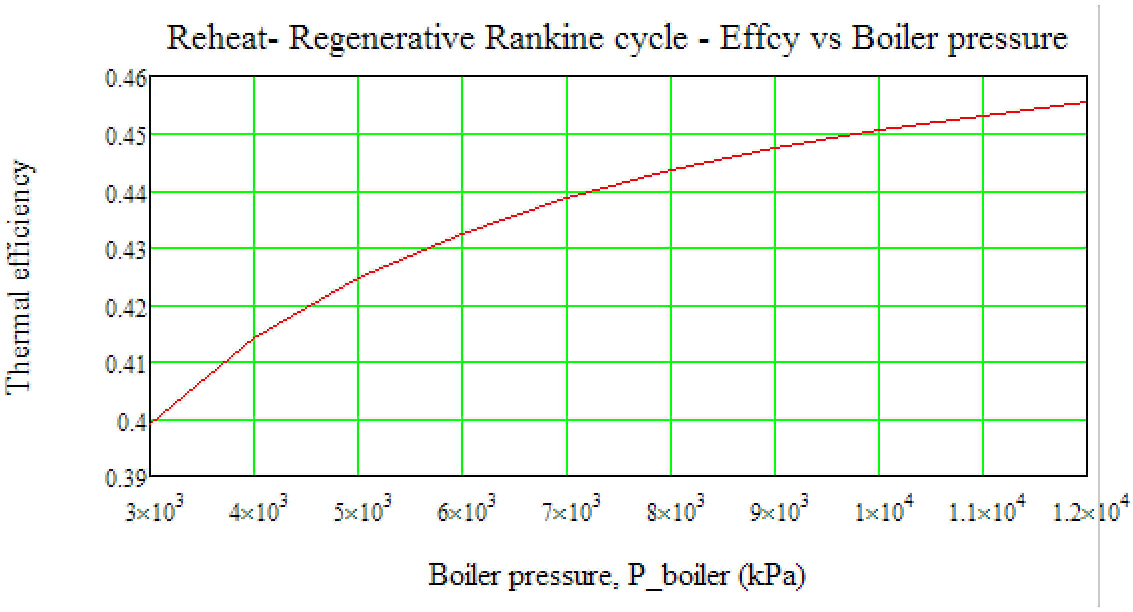
==

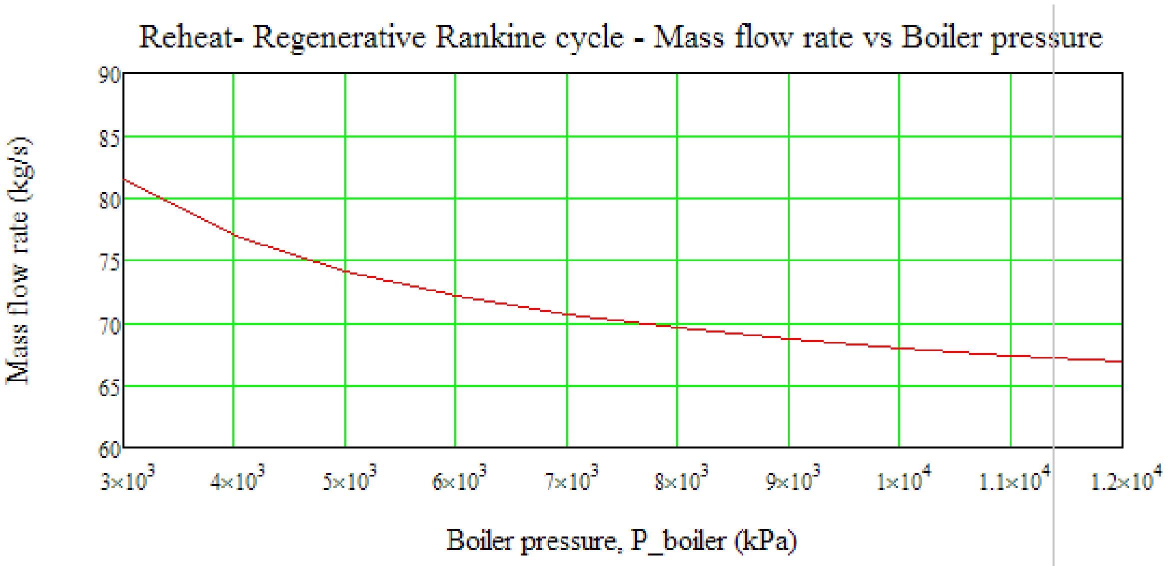
Now, to plot effcy. for different values of P_boiler:

$P\_boiler := 3000, 4000 .. 12000$ ...define a range variable

P_boiler =	eta(P_boiler) =	Mass_Flow(P_boiler)
$3\cdot10^{3}$	0.3991	81.438
$4\cdot10^{3}$	0.4142	77.003
$5\cdot10^{3}$	0.4248	74.146
$6\cdot10^{3}$	0.4325	72.152
$7\cdot10^{3}$	0.4386	70.675
$8\cdot10^{3}$	0.4434	69.54
$9\cdot10^{3}$	0.4473	68.641
$1\cdot10^{4}$	0.4506	67.936
$1.1\cdot10^{4}$	0.4531	67.406
$1.2\cdot10^{4}$	0.4555	66.92

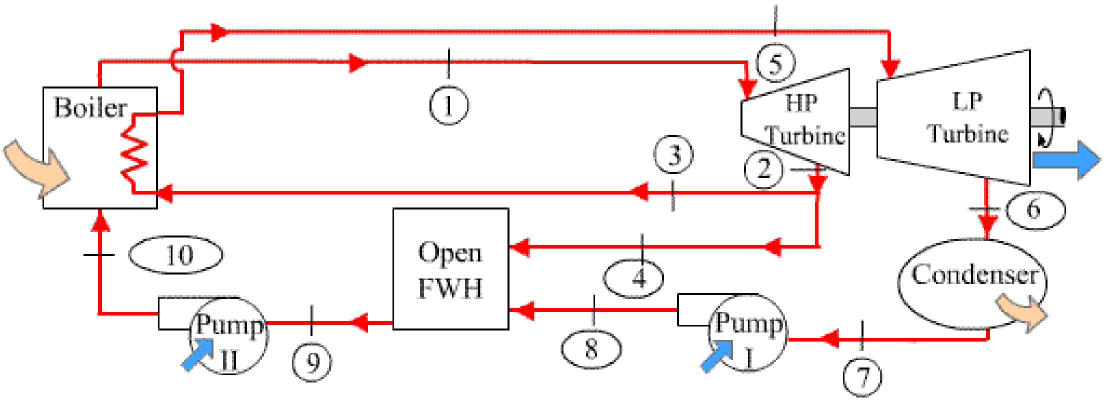
Plots:


Reheat- Regenerative Rankine cycle - Effcy vs Boiler pressure
Thermal efficiency
0.46
0.45
0.44
0.43
0.42
0.41
0.4
0.39
3×10³
4×10³
5×10³
6×10³
7×10³
8×10³
9×10³
1×10⁴
1.1×10⁴
1.2×10⁴
Boiler pressure, P_boiler (kPa)



==

Prob. 3.41 Net power output of an ideal reheat-regenerative Rankine cycle is 80 MW. Steam enters the high pressure turbine stage at 80 bar, 500°C and expands till it becomes saturated vapor. Some of the steam then goes to an open feedwater heater and the balance is reheated to 400°C after which it expands in the low pressure turbine to the condenser at a pressure of 0.07 bar. Determine (a) the reheat pressure, (b) the steam flow rate to the HP turbine, and (c) the thermal efficiency of the cycle. [VTU]



Data:

P_cond := 7 kPa P_boiler := 8000 kPa

T1 := 500 C T5 := 400 C

Power_output := 80000 kW

Let us calculate the enthalpies at various state points:

h1 := enthalpy_H2O(P_boiler, T1)   i.e. $h1 = 3.399 \times 10^{3}$ kJ/kg

s1 := entropy_H2O(P_boiler, T1)   i.e. $s1 = 6.726$ kJ/kg.K

To find reheat pressure, P2:

P2 is found out very easily using the "Solve block' of Mathcad.

s2 := s1   ...for isentropic expn in HP turbine

Use the 'Solve block' of Mathcad:

P2 := 5000   kPa .... trial value

Given

s2 = SGSATP_H2O(P2)

P2 := Find(P2)

i.e. $P2 = 665.495$ **kPa ..... reheat pressure .... Ans.**

Now:

h2 := HGSATP_H2O(P2)

i.e. $h2 = 2.76 \times 10^{3}$ kJ/kg

And:

h3 := h2

h4 := h2

h5 := enthalpy_H2O(P2, T5)   i.e. $h5 = 3.27 \times 10^{3}$ kJ/kg

s5 := entropy_H2O(P2, T5)   i.e. $s5 = 7.665$ kJ/kg.K

s6 := s5   ..for isentropic expn in LP turbine

sg6 := SGSATP_H2O(P_cond)   i.e. $sg6 = 8.277$ kJ/kg.K

We see that sg6 > s6. Therefore point 6 is in two phase region.

x6 := quality_Ps_H2O(P_cond, s6)   i.e. $x6 = 0.921$ ..quality at 6

Then:

$h6 := \text{enthalpy\_2phase\_Px\_H2O}(P\_cond, x6)$ i.e. $h6 = 2.381 \times 10^{3}$ kJ/kg

$h7 := \text{HFSATP\_H2O}(P\_cond)$

i.e. $h7 = 162.949$ kJ/kg

$vf7 := \text{VFSATP\_H2O}(P\_cond)$ i.e. $vf7 = 1.007 \times 10^{-3}$ m^3/kg

$h8 := h7 + vf7 \cdot (P2 - P\_cond)$ i.e. $h8 = 163.612$ kJ/kg

$h9 := \text{HFSATP\_H2O}(P2)$ i.e. $h9 = 687.319$ kJ/kg

Now, we get by energy balance on the open FWH:

$$z := \frac{h9 - h8}{h4 - h8}$$

i.e. $z = 0.202$ ..fraction of the stream sent through the open FWH

And,

$y := 1 - z$

i.e. $y = 0.798$ ..fraction of the stream sent through the reheater

$vf9 := VFSATP\_H2O(P2)$ i.e. $vf9 = 1.105 \times 10^{-3}$ m^3/kg

$h10 := h9 + vf9 \cdot (P\_boiler - P2)$ i.e. $h10 = 695.426$ kJ/kg

Pump works:

$w\_P1 := (1 - z) \cdot (h8 - h7)$

i.e. $w\_P1 = 0.53$ kJ/kg ... work of Pump-1

$w\_P2 := h10 - h9$

i.e. $w\_P2 = 8.107$ kJ/kg ... work of Pump-2

Total turbine work:

$w\_T1 := (h1 - h2)$

i.e. $w\_T1 = 639.197$ kJ/kg ... for HP turbine

$w\_T2 := (h5 - h6) \cdot y$

i.e. $w\_T2 = 709.805$ kJ/kg ... for LP turbine

$w\_T := w\_T1 + w\_T2$

i.e. $w\_T = 1.349 \times 10^{3}$ kJ/kg ... Total turbine work

Net work:

$w\_net := w\_T - (w\_P1 + w\_P2)$

i.e. $w\_net = 1.34 \times 10^{3}$ kJ/kg

Heat supplied:

$q\_in := (h1 - h10) + y \cdot (h5 - h3)$

i.e. $q\_in = 3.111 \times 10^{3}$ kJ/kg

Heat rejected:

$q\_out := (h6 - h7) \cdot (1 - z)$

i.e. $q\_out = 1.77 \times 10^{3}$ kJ/kg

Thermal efficiency:

$$eta := \frac{w\_net}{q\_in}$$

i.e. $eta = 0.431$ **= 43.1% ..... Ans.**

Mass flow rate:

$$Mass\_Flow := \frac{Power\_output}{w\_net}$$

i.e. $Mass\_Flow = 59.685$ **kg/s = 2.149 x 10^5 kg/h ... Ans.**

==

Problems on Second Law analysis [3]:

We have:

$$X_{dest} = T_0 \cdot S_{gen} = T_0 \cdot \left(S_{out} - S_{in}\right) = T_0 \cdot \left[\sum_{out} (mdot \cdot s) + \frac{Q_{out}}{Tb_{out}} - \sum_{in} (mdot \cdot s) - \frac{Q_{in}}{Tb_{in}}\right] \quad kW$$

On a ***unit mass basis***, for a one inlet, one exit, steady flow device, we have:

$$x_{dest} = T_0 \cdot s_{gen} = T_0 \cdot \left(s_e - s_i + \frac{q_{out}}{Tb_{out}} - \frac{q_{in}}{Tb_{in}}\right) \quad kJ/kg$$

where Tb_{in} and Tb_{out} are the temps at system boundary where heat is transferred in to and out of the system respectively.

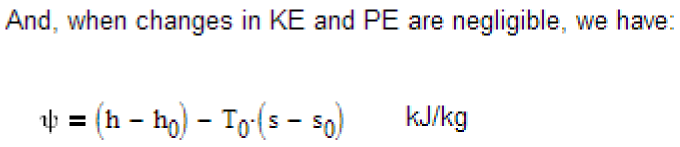
For a cycle with heat transfers at a source temp TH and sink temp TL, exergy destruction is:

$$x_{dest} = T_0 \cdot \left(\frac{q_{out}}{TL} - \frac{q_{in}}{TH}\right) \quad kJ/kg$$

And, exergy of a flow for a fluid stream at a state (P, T) is determined from:

$$\psi = \left(h - h_0\right) - T_0 \cdot \left(s - s_0\right) + \frac{V^2}{2 \cdot 1000} + \frac{g \cdot Z}{1000} \quad kJ/kg$$

where (h, s) are enthalpy and entropy at state (P,T), and (h0, s0) are enthalpy and entropy at ambient conditions of (P.0, T.0). Temp should be in Kelvin. V is the velocity in m/s and z is the elevation in m.

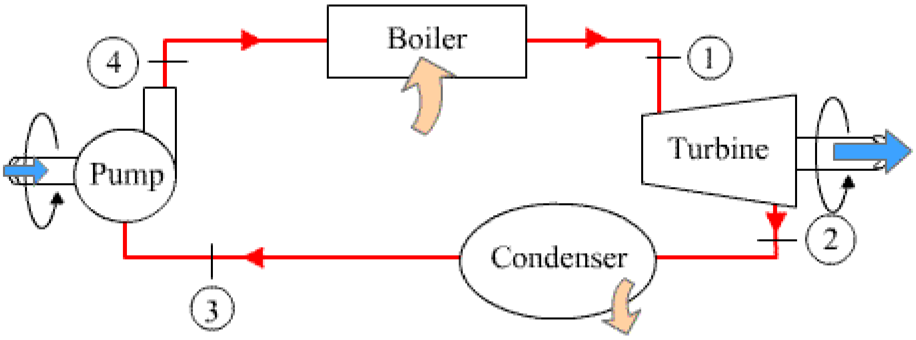


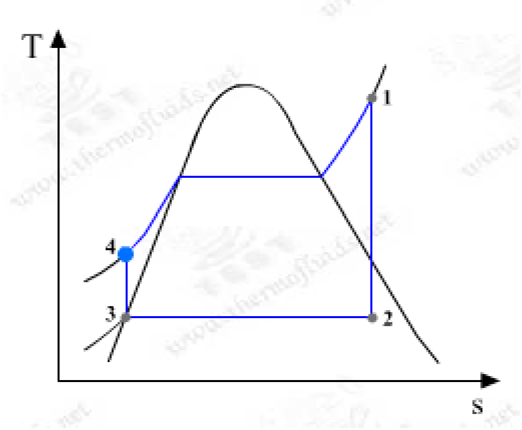
And, when changes in KE and PE are negligible, we have:

$$\psi = (h - h_0) - T_0 \cdot (s - s_0) \qquad \text{kJ/kg}$$

===

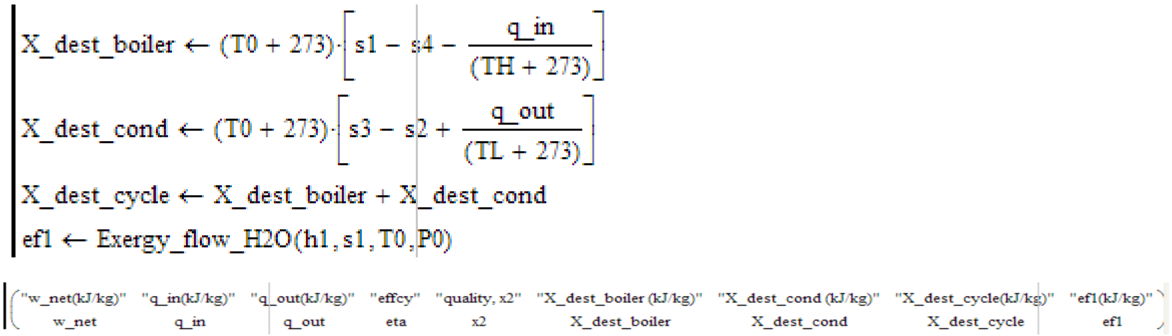
Prob. 3.42 Write a Mathcad program to find out the exergy destroyed in various processes for an **Ideal Rankine cycle** operating between a condenser pressure P_cond, Turbine inlet temp T1, and boiler pressure of P_boiler. Ambient conditions: P0 (kPa), T0 (C). Assume heat is transferred in boiler at a constant temp TH (deg.C), and heat is rejected to ambient at constant temp TL (deg.C).





Exergy_Ideal_Rankine(P_cond, P_boiler, T1, TH, TL, P0, T0) :=

```
T2 ← TSAT_H2O(P_cond)
h3 ← HFSATP_H2O(P_cond)
s3 ← SFSATP_H2O(P_cond)
vf3 ← VFSATP_H2O(P_cond)
w_P ← vf3·(P_boiler − P_cond)
h4 ← h3 + w_P
s4 ← s3
h1 ← enthalpy_H2O(P_boiler, T1)
q_in ← h1 − h4
s1 ← entropy_H2O(P_boiler, T1)
s2 ← s1
x2 ← quality_Ps_H2O(P_cond, s2)
h2 ← enthalpy_2phase_Tx_H2O(T2, x2)
w_T ← h1 − h2
w_net ← w_T − w_P
q_out ← h2 − h3
eta ← $\frac{w\_net}{q\_in}$
```



$$\text{X\_dest\_boiler} \leftarrow (\text{T0} + 273)\cdot\left[\text{s1} - \text{s4} - \frac{\text{q\_in}}{(\text{TH} + 273)}\right]$$

$$\text{X\_dest\_cond} \leftarrow (\text{T0} + 273)\cdot\left[\text{s3} - \text{s2} + \frac{\text{q\_out}}{(\text{TL} + 273)}\right]$$

$$\text{X\_dest\_cycle} \leftarrow \text{X\_dest\_boiler} + \text{X\_dest\_cond}$$

$$\text{ef1} \leftarrow \text{Exergy\_flow\_H2O}(\text{h1}, \text{s1}, \text{T0}, \text{P0})$$

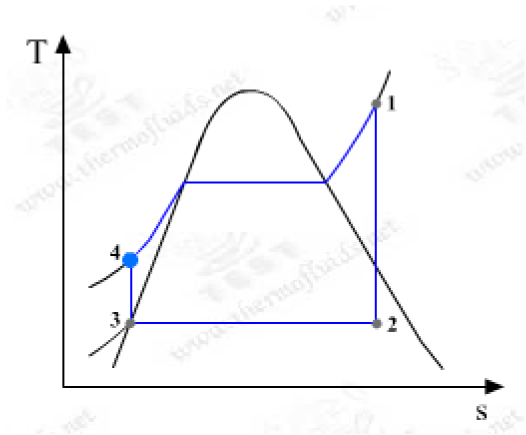
$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy"} & \text{"quality, x2"} & \text{"X\_dest\_boiler (kJ/kg)"} & \text{"X\_dest\_cond (kJ/kg)"} & \text{"X\_dest\_cycle(kJ/kg)"} & \text{"ef1(kJ/kg)"} \\ \text{w\_net} & \text{q\_in} & \text{q\_out} & \text{eta} & \text{x2} & \text{X\_dest\_boiler} & \text{X\_dest\_cond} & \text{X\_dest\_cycle} & \text{ef1} \end{pmatrix}$$

Explanation for the above Function:

This function gives exergy destroyed in various processes of an Ideal Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where pressures P_cond, P_boiler are in kPa. Turbine inlet temperature,T1, Source temp for heat supplied in boiler, TH, Sink temp for heat rejected in condenser, TL, are in deg.C and ambient conditions are (P0, T0). **Outputs** are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficieny (eta), quality of steam at turbine exit (x2), Exergy destroyed in boiler (X_dest_boiler), Exergy destroyed in condenser (X_dest_cond), Exergy destroyed in cycle (X_dest_cycle), and Exergy of flow of steam leaving the boiler (ef1). Units of each quantity are also given in output.

Prob.3.43 Consider a steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa. Determine (*a*) the quality of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, (*c*) exergy destroyed in boiler, condenser, and the cycle, and (d) exergy of flow at turbine exit. Take TH = 1500 K, and TL = 290 K. Ambient conditions: P0 = 101.3 kPa, T0 = 290 K. [2]



Data:

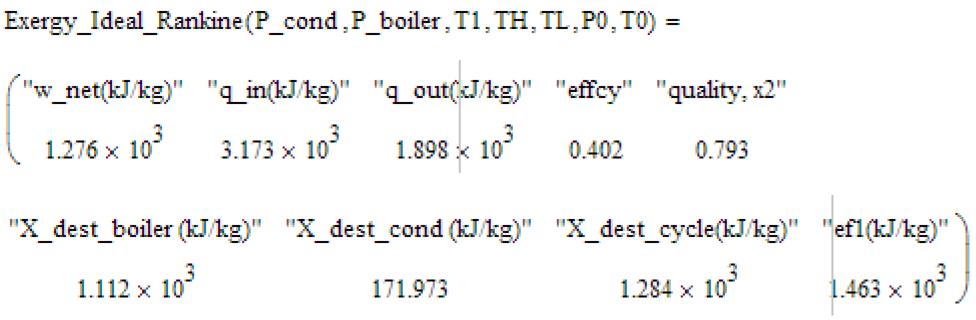
P_boiler := 10000 kPa   T1 := 500 C   TH := 1500 − 273 C   TL := 290 − 273 C

P_cond := 10 kPa   T0 := TL   P0 := 101.3 kPa

T_cond := TSAT_H2O(P_cond)   i.e. T_cond = 45.806 C

Note: In the above data, we have written TH and TL in deg.C, since for our Mathcad Functions, we have uniformly put the input pressures in kPa, and input temp in deg.C.

Now, apply the Mathcad Function for exergy losses in Ideal, simple, Rankine cycle, and get all parameters immediately:



```
Exergy_Ideal_Rankine(P_cond,P_boiler,T1,TH,TL,P0,T0) =

"w_net(kJ/kg)"   "q_in(kJ/kg)"   "q_out(kJ/kg)"   "effcy"   "quality, x2"
 1.276 × 10^3     3.173 × 10^3    1.898 × 10^3     0.402     0.793

"X_dest_boiler (kJ/kg)"   "X_dest_cond (kJ/kg)"   "X_dest_cycle(kJ/kg)"   "ef1(kJ/kg)"
     1.112 × 10^3                171.973                1.284 × 10^3        1.463 × 10^3
```

Thus:

Qualityof steam at turbine exit = x2 = 0.793…Ans.

Cycle effcy = 0.402 = 40.2%…Ans.

Exergy destroyed in boiler = 1112 kJ/kg…Ans.

Exergy destroyed in condenser = 171.973 kJ/kg…Ans.

Exergy destroyed in cycle = 1284 kJ/kg…Ans.

Exergy of flow at turbine exit = ef1 = 1463 kJ/kg…Ans.

Note:

1. Exergy of flow at turbine exit ef1, is obtained in the above Mathcad Function, by using the earlier Function written to find the Exergy of flow.
2. **Exergy destroyed in Turbine and pump are zero** since the processes in those components are isentropic.

Plot the exergy destroyed in boiler, condenser and the cycle as boiler pressure varies from 2 MPa to 12 MPa:

First, plot the relevant quantities as functions of boiler pressure:

X_dest_boiler(P_boiler) := Exergy_Ideal_Rankine(P_cond, P_boiler, T1, TH, TL, P0, T0)$_{1,5}$

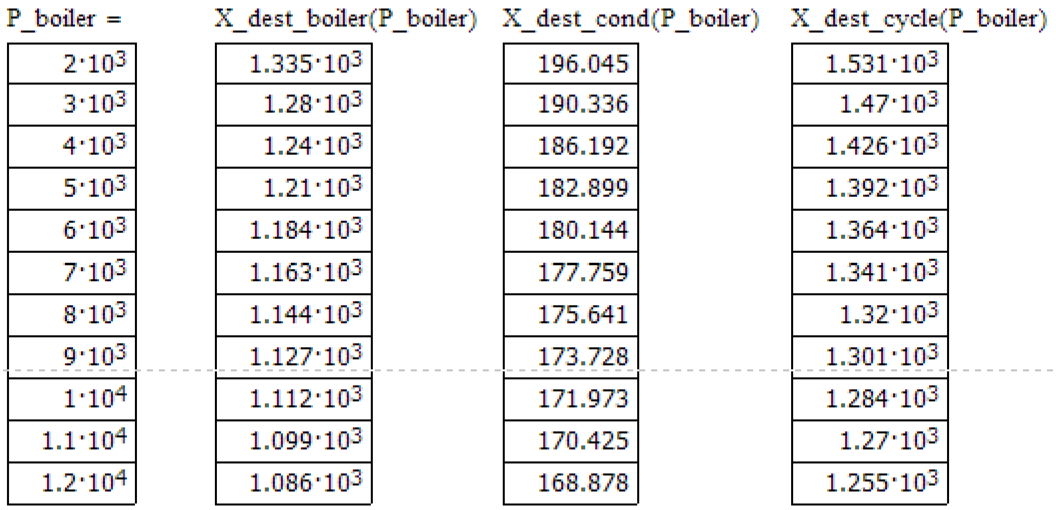
X_dest_cond(P_boiler) := Exergy_Ideal_Rankine(P_cond, P_boiler, T1, TH, TL, P0, T0)$_{1,6}$

X_dest_cycle(P_boiler) := Exergy_Ideal_Rankine(P_cond, P_boiler, T1, TH, TL, P0, T0)$_{1,7}$

Now:

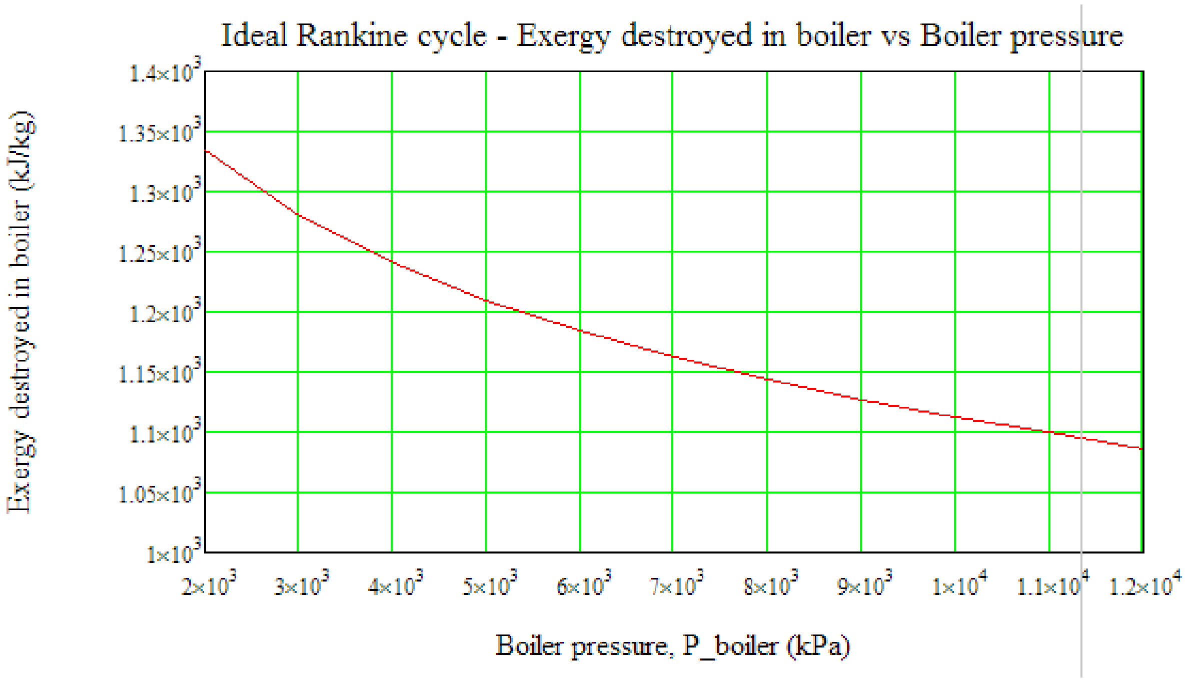
P_boiler := 2000, 3000.. 12000 ...define a range variable

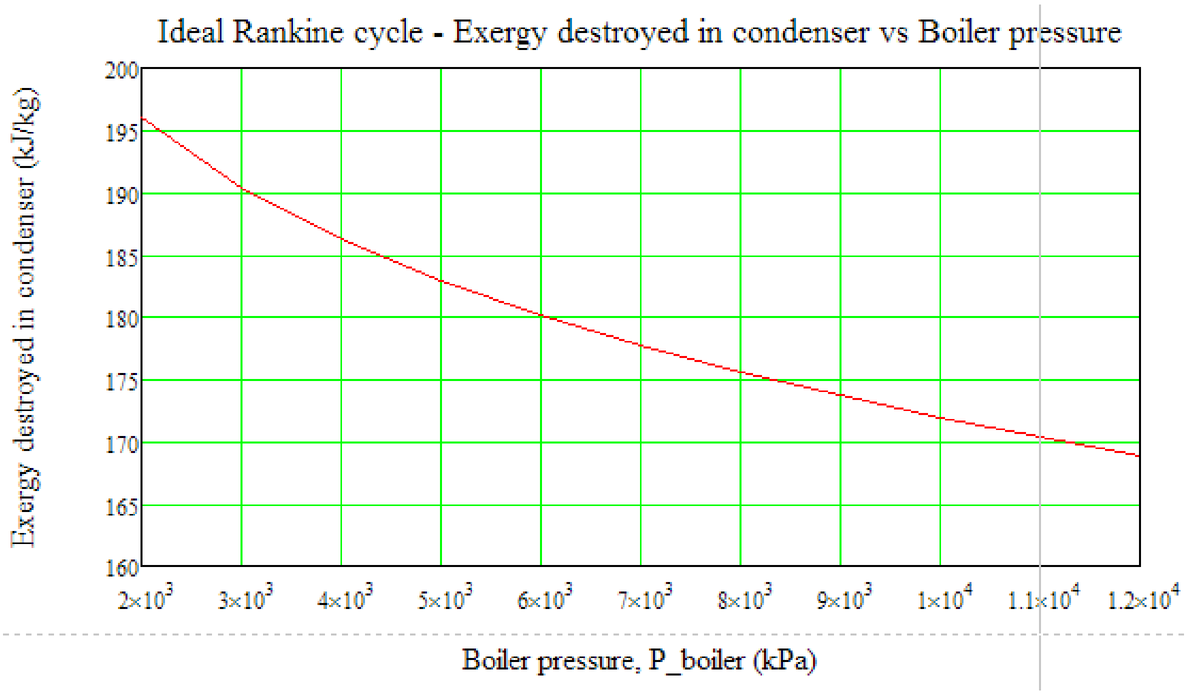
We get:

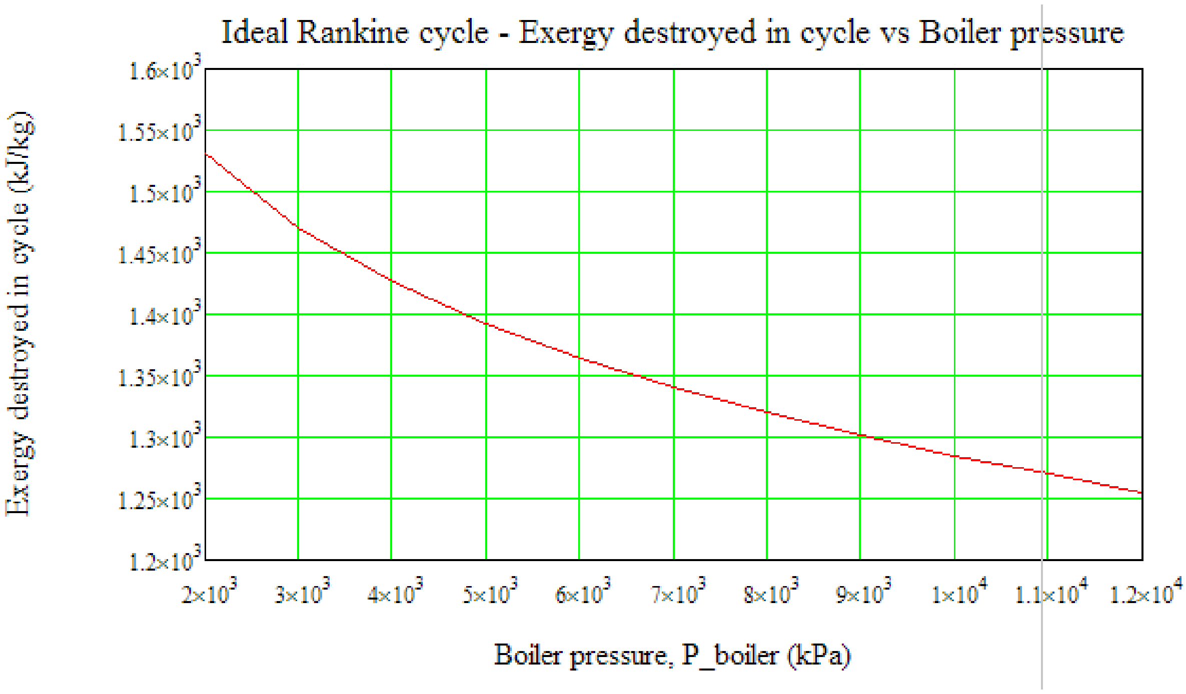


P_boiler =	X_dest_boiler(P_boiler)	X_dest_cond(P_boiler)	X_dest_cycle(P_boiler)
$2 \cdot 10^3$	$1.335 \cdot 10^3$	196.045	$1.531 \cdot 10^3$
$3 \cdot 10^3$	$1.28 \cdot 10^3$	190.336	$1.47 \cdot 10^3$
$4 \cdot 10^3$	$1.24 \cdot 10^3$	186.192	$1.426 \cdot 10^3$
$5 \cdot 10^3$	$1.21 \cdot 10^3$	182.899	$1.392 \cdot 10^3$
$6 \cdot 10^3$	$1.184 \cdot 10^3$	180.144	$1.364 \cdot 10^3$
$7 \cdot 10^3$	$1.163 \cdot 10^3$	177.759	$1.341 \cdot 10^3$
$8 \cdot 10^3$	$1.144 \cdot 10^3$	175.641	$1.32 \cdot 10^3$
$9 \cdot 10^3$	$1.127 \cdot 10^3$	173.728	$1.301 \cdot 10^3$
$1 \cdot 10^4$	$1.112 \cdot 10^3$	171.973	$1.284 \cdot 10^3$
$1.1 \cdot 10^4$	$1.099 \cdot 10^3$	170.425	$1.27 \cdot 10^3$
$1.2 \cdot 10^4$	$1.086 \cdot 10^3$	168.878	$1.255 \cdot 10^3$

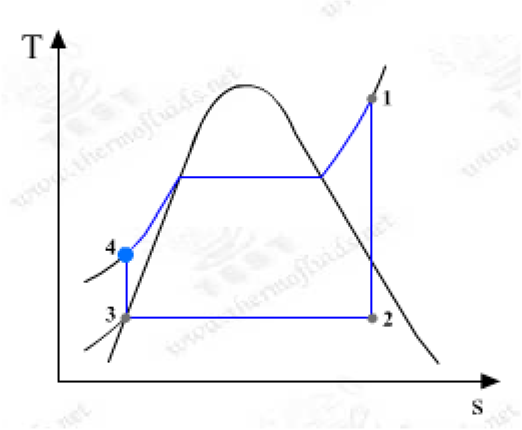
Now, plot the results:

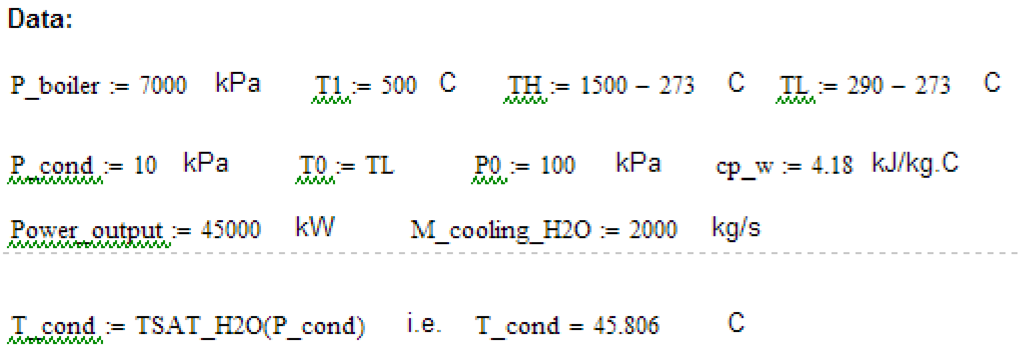



Ideal Rankine cycle - Exergy destroyed in condenser vs Boiler pressure
Exergy destroyed in condenser (kJ/kg)
200
195
190
185
180
175
170
165
160
2×10^3
3×10^3
4×10^3
5×10^3
6×10^3
7×10^3
8×10^3
9×10^3
1×10^4
1.1×10^4
1.2×10^4
Boiler pressure, P_boiler (kPa)


Ideal Rankine cycle - Exergy destroyed in cycle vs Boiler pressure
Exergy destroyed in cycle (kJ/kg)
1.6×10^3
1.55×10^3
1.5×10^3
1.45×10^3
1.4×10^3
1.35×10^3
1.3×10^3
1.25×10^3
1.2×10^3
2×10^3
3×10^3
4×10^3
5×10^3
6×10^3
7×10^3
8×10^3
9×10^3
1×10^4
1.1×10^4
1.2×10^4
Boiler pressure, P_boiler (kPa)

Prob.3.44 Consider a steam power plant that operates on a simple ideal Rankine cycle and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water (cp = 4.18 kJ/kg.C) from a lake through the tubes of the condenser at a rate of 2000 kg/s. Determine (*a*) the thermal efficiency of the cycle, (*b*) the mass flow rate of the steam, and (*c*) the temperature rise of the cooling water. Determine the exergy destruction associated with the heat rejection process. Assume a source temperature of 1500 K and a sink temperature of 290 K. Also, determine the exergy of the steam at the boiler exit. Take *P*0 = 100 kPa. [2]





Data:

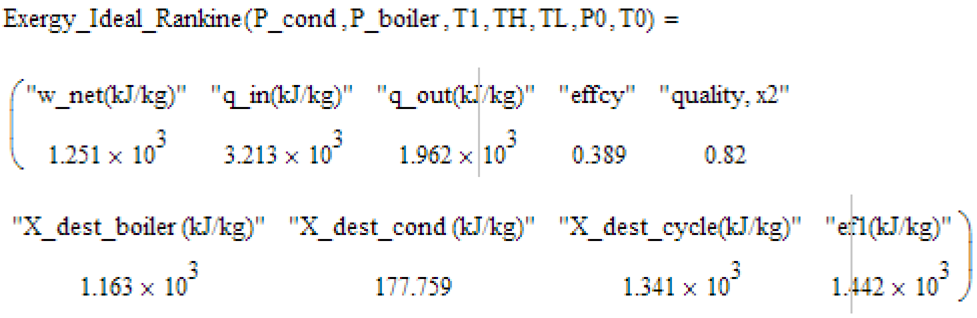
P_boiler := 7000 kPa   T1 := 500 C   TH := 1500 − 273 C   TL := 290 − 273 C

P_cond := 10 kPa   T0 := TL   P0 := 100 kPa   cp_w := 4.18 kJ/kg.C

Power_output := 45000 kW   M_cooling_H2O := 2000 kg/s

T_cond := TSAT_H2O(P_cond)   i.e.   T_cond = 45.806   C

Now, apply the Mathcad Function for exergy losses in Ideal, simple, Rankine cycle, and get all parameters immediately:



Exergy_Ideal_Rankine(P_cond, P_boiler, T1, TH, TL, P0, T0) =

"w_net(kJ/kg)"	"q_in(kJ/kg)"	"q_out(kJ/kg)"	"effcy"	"quality, x2"
1.251×10^3	3.213×10^3	1.962×10^3	0.389	0.82

"X_dest_boiler (kJ/kg)"	"X_dest_cond (kJ/kg)"	"X_dest_cycle(kJ/kg)"	"ef1(kJ/kg)"
1.163×10^3	177.759	1.341×10^3	1.442×10^3

Thus, we have:

Thermal effcy:

$\text{effcy} = 0.389$ = 38.9% .... Ans.

Mass flow rate of steam:

We have: $\text{w\_net} := 1251$ kJ/kg

Therefore: $\text{Mass\_flow} := \dfrac{\text{Power\_output}}{\text{w\_net}}$ kg/s

i.e. $\text{Mass\_flow} = 35.971$ **kg/s ..... Ans.**

Temp rise of cooling water:

We have, heat rejected in condenser:

$\text{q\_out} := 1962$ kJ/kg

Therefore, temp rise of cooling water:

$$\Delta T := \frac{q\_out \cdot Mass\_flow}{M\_cooling\_H2O \cdot cp\_w}$$

i.e. $\Delta T = 8.442$ C …… Ans.

Exergy of steam at exit of boiler:

$ef1 = 1442$ …kJ/kg …. Ans.

Further, we see from the output of the Function:

Exergy destroyed in condenser:

$X\_dest\_cond = 177.759$ kJ/kg …. Ans.

Plot exergy destroyed in condenser as a function of condenser pressure:

First, write exergy destroyed in condenser as a function of condenser pressure:

$X\_dest\_cond(P\_cond) := Exergy\_Ideal\_Rankine(P\_cond, P\_boiler, T1, TH, TL, P0, T0)_{1,6}$

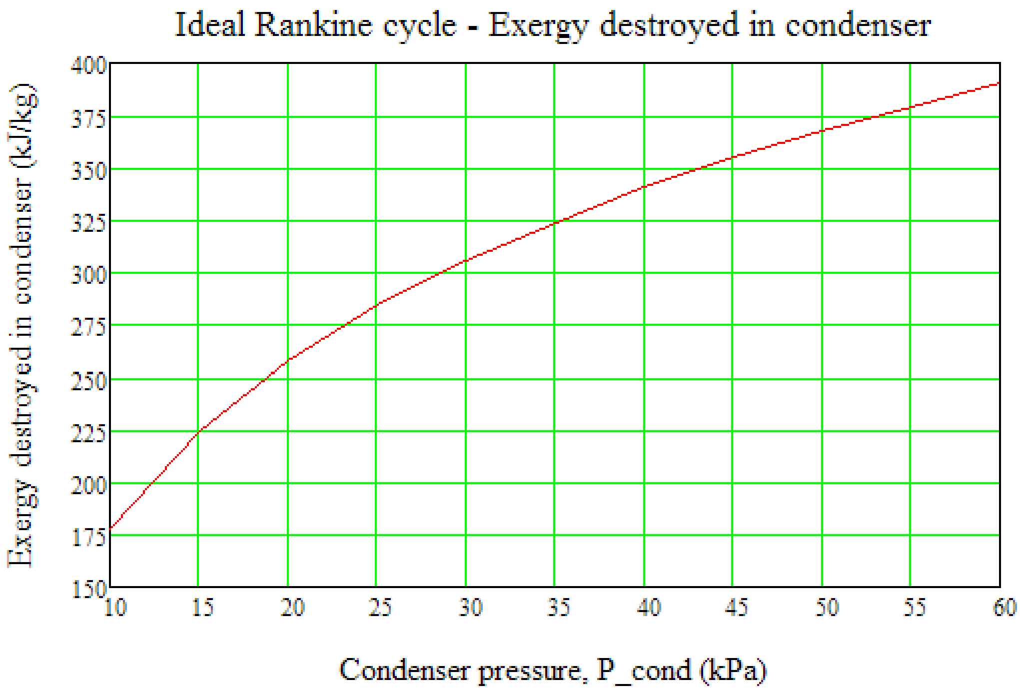
Then:

$P\_cond := 10, 15 .. 60$ ….define a range variable

We get:

P_cond =	X_dest_cond(P_cond)
10	177.759
15	223.994
20	257.814
25	284.151
30	305.616
35	324.006
40	340.431
45	354.698
50	367.653
55	379.417
60	390.306

Now, plot:



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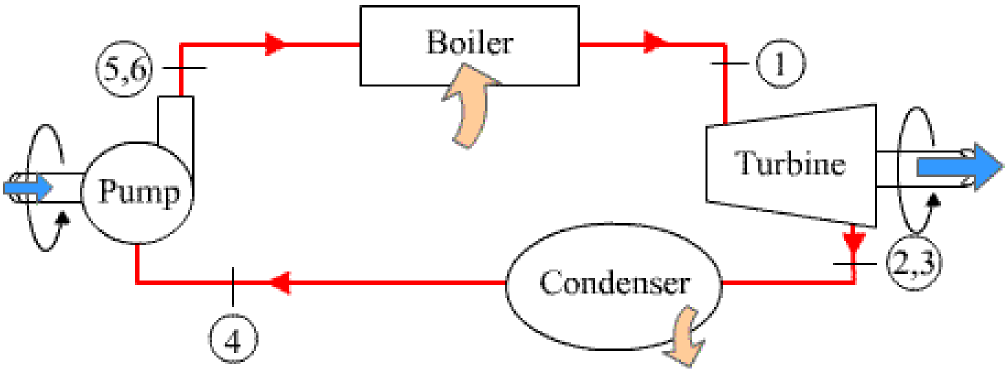
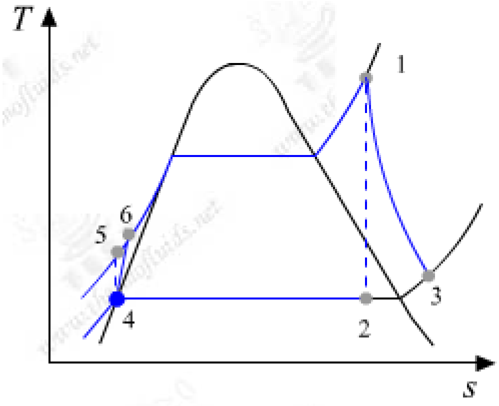
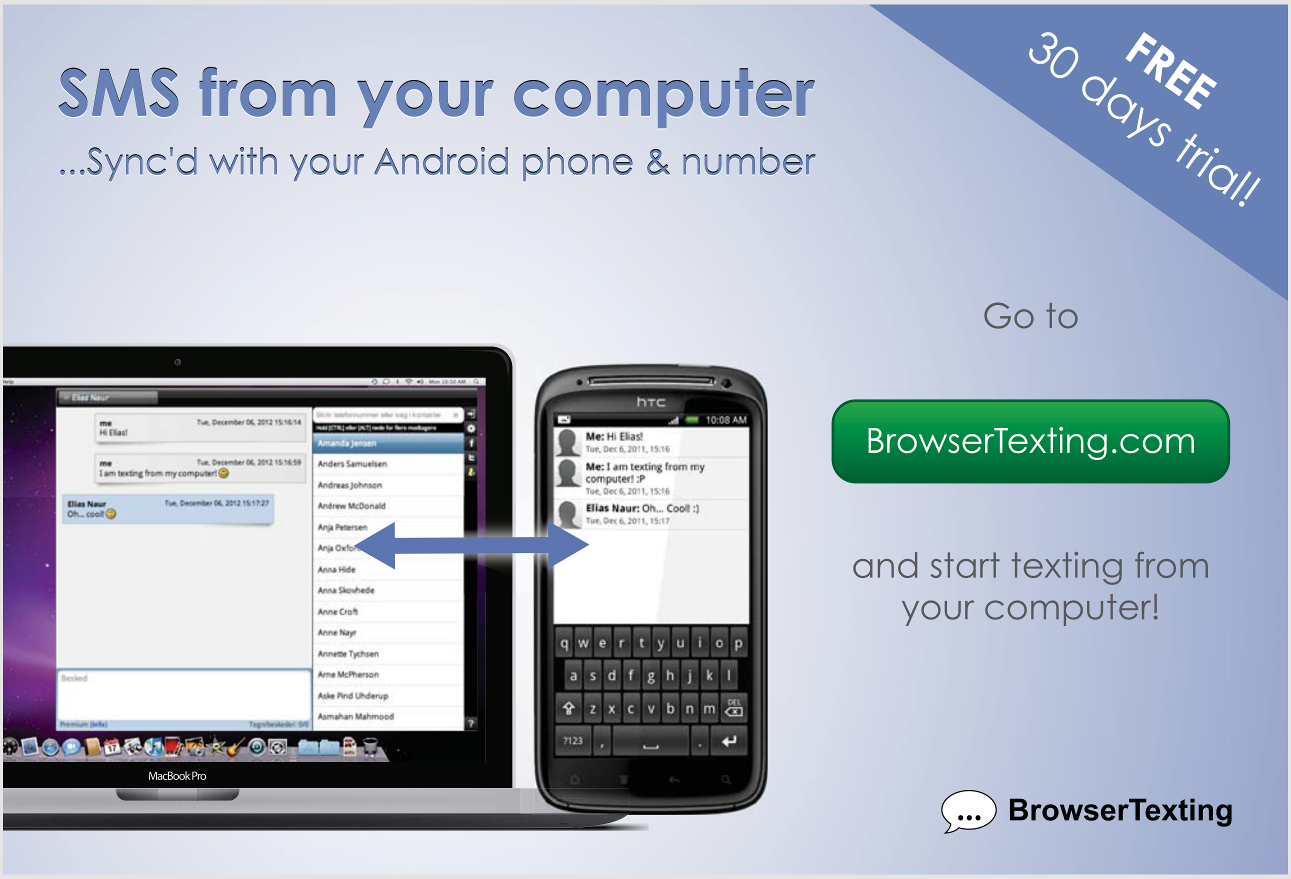
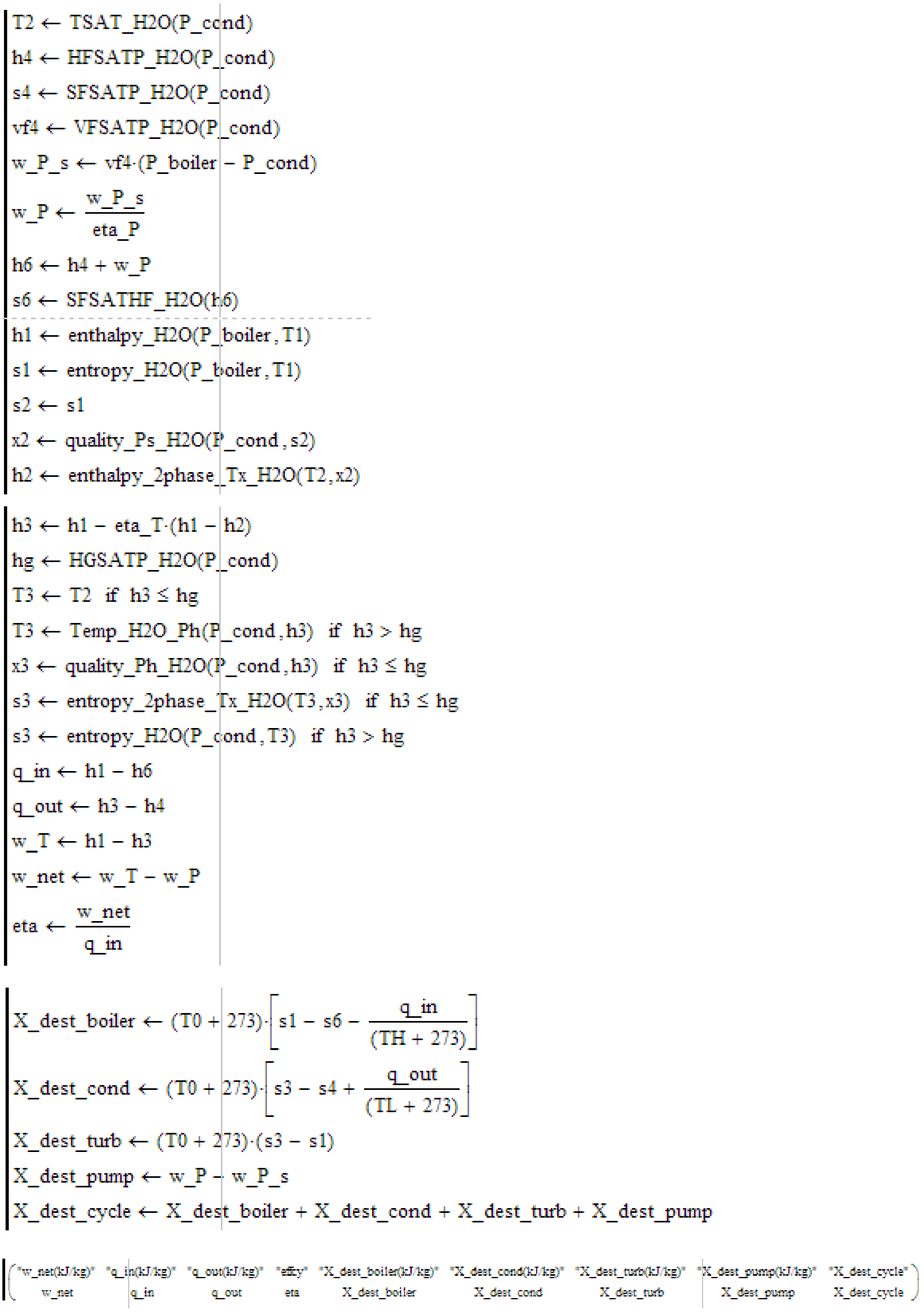
Prob. 3.45 Write a Mathcad program to find out the exergy destroyed in various processes for an **Actual Rankine cycle** operating between a condenser pressure P_cond, Turbine inlet temp T1, and boiler pressure of P_boiler. Isentropic effcy of Turbine and pump viz. eta_T and eta_P are given. Ambient conditions: P0 (kPa), T0 (C). Assume that heat is transferred in boiler at a const. temp TH (deg.C), and heat is rejected in condenser to ambient at const. temp TL (deg.C).





Exergy_Actual_Rankine(P_cond,P_boiler,T1,eta_T,eta_P,TH,TL,P0,T0) :=





```
T2 ← TSAT_H2O(P_cond)
h4 ← HFSATP_H2O(P_cond)
s4 ← SFSATP_H2O(P_cond)
vf4 ← VFSATP_H2O(P_cond)
w_P_s ← vf4·(P_boiler − P_cond)
w_P ← $\frac{w\_P\_s}{eta\_P}$
h6 ← h4 + w_P
s6 ← SFSATHF_H2O(h6)
h1 ← enthalpy_H2O(P_boiler, T1)
s1 ← entropy_H2O(P_boiler, T1)
s2 ← s1
x2 ← quality_Ps_H2O(P_cond, s2)
h2 ← enthalpy_2phase_Tx_H2O(T2, x2)
h3 ← h1 − eta_T·(h1 − h2)
hg ← HGSATP_H2O(P_cond)
T3 ← T2  if  h3 ≤ hg
T3 ← Temp_H2O_Ph(P_cond, h3)  if  h3 > hg
x3 ← quality_Ph_H2O(P_cond, h3)  if  h3 ≤ hg
s3 ← entropy_2phase_Tx_H2O(T3, x3)  if  h3 ≤ hg
s3 ← entropy_H2O(P_cond, T3)  if  h3 > hg
q_in ← h1 − h6
q_out ← h3 − h4
w_T ← h1 − h3
w_net ← w_T − w_P
eta ← $\frac{w\_net}{q\_in}$
X_dest_boiler ← (T0 + 273)·$\left[s1 - s6 - \frac{q\_in}{(TH + 273)}\right]$
X_dest_cond ← (T0 + 273)·$\left[s3 - s4 + \frac{q\_out}{(TL + 273)}\right]$
X_dest_turb ← (T0 + 273)·(s3 − s1)
X_dest_pump ← w_P − w_P_s
X_dest_cycle ← X_dest_boiler + X_dest_cond + X_dest_turb + X_dest_pump
```

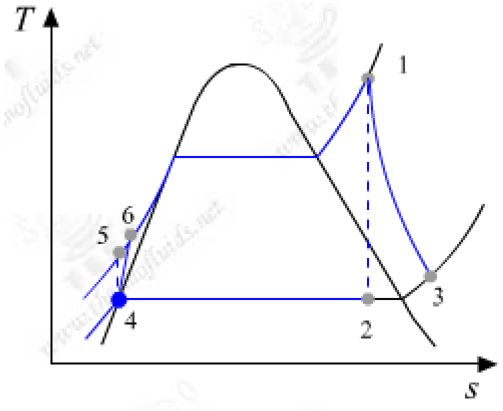
$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy"} & \text{"X\_dest\_boiler(kJ/kg)"} & \text{"X\_dest\_cond(kJ/kg)"} & \text{"X\_dest\_turb(kJ/kg)"} & \text{"X\_dest\_pump(kJ/kg)"} & \text{"X\_dest\_cycle"} \\ w\_net & q\_in & q\_out & eta & X\_dest\_boiler & X\_dest\_cond & X\_dest\_turb & X\_dest\_pump & X\_dest\_cycle \end{pmatrix}$$

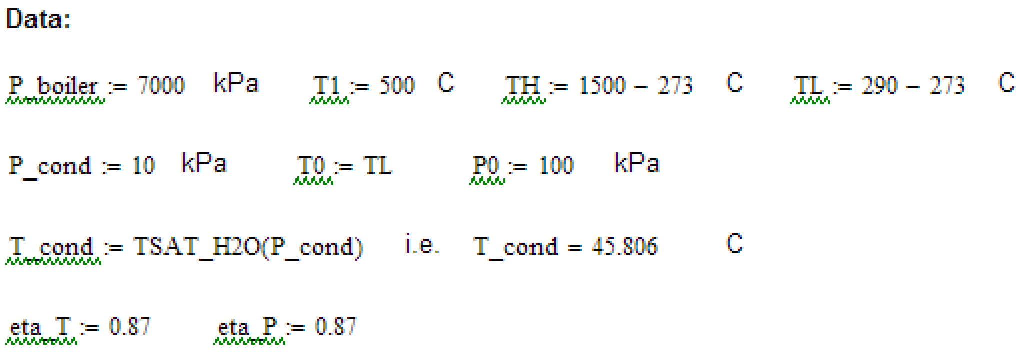
Explanation for the above Function:

This function gives exergy destroyed in various processes of an Actual Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where pressures P_cond, P_boiler are in kPa. Turbine inlet temperature,T1, Source temp for heat supplied in boiler, TH, Sink temp for heat rejected in condenser, TL, are in deg.C and ambient conditions are: (P0, T0). Also, eta_T and eta_P are the isentropic efficiencies of the Turbine and Pump respectively. **Outputs** are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficieny (eta), Exergy destroyed in boiler (X_dest_boiler), Exergy destroyed in condenser (X_dest_cond), Exergy destroyed in Turbine (X_dest_turb), Exergy destroyed in Pump (X_dest_pump), and Exergy destroyed in cycle (X_dest_cycle). Units of each quantity are also given in output.

Prob.3.46 Consider a steam power plant that operates on an actual, Rankine cycle. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa. Given: isentropic effcy of turbine and pump are 0.87 each. Determine (*a*) the thermal efficiency of the cycle, and (b) the exergy destruction associated with the various processes. Assume a source temperature of 1500 K and a sink temperature of 290 K. Also, determine the exergy destroyed for the whole cycle. Take P0 = 100 kPa.[2]





Data:

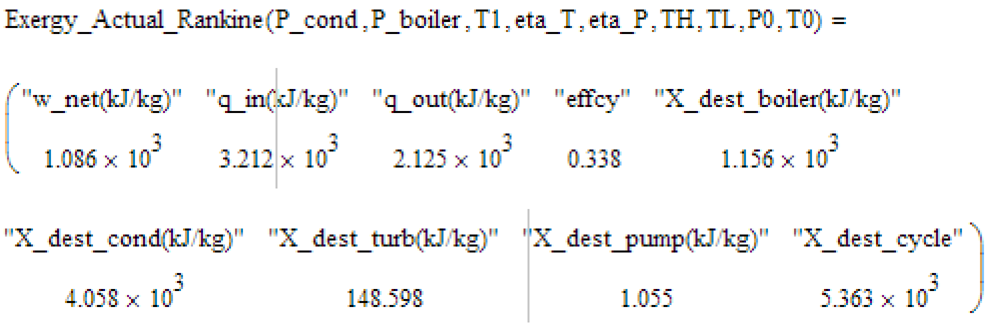
P_boiler := 7000 kPa   T1 := 500 C   TH := 1500 − 273 C   TL := 290 − 273 C

P_cond := 10 kPa   T0 := TL   P0 := 100 kPa

T_cond := TSAT_H2O(P_cond) i.e. T_cond = 45.806 C

eta_T := 0.87   eta_P := 0.87

Applying the Mathcad Function written above for an actual Rankine cycle, we get:



Exergy_Actual_Rankine(P_cond, P_boiler, T1, eta_T, eta_P, TH, TL, P0, T0) =

$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy"} & \text{"X\_dest\_boiler(kJ/kg)"} & \text{"X\_dest\_cond(kJ/kg)"} & \text{"X\_dest\_turb(kJ/kg)"} & \text{"X\_dest\_pump(kJ/kg)"} & \text{"X\_dest\_cycle"} \\ 1.086 \times 10^{3} & 3.212 \times 10^{3} & 2.125 \times 10^{3} & 0.338 & 1.156 \times 10^{3} & 4.058 \times 10^{3} & 148.598 & 1.055 & 5.363 \times 10^{3} \end{pmatrix}$$

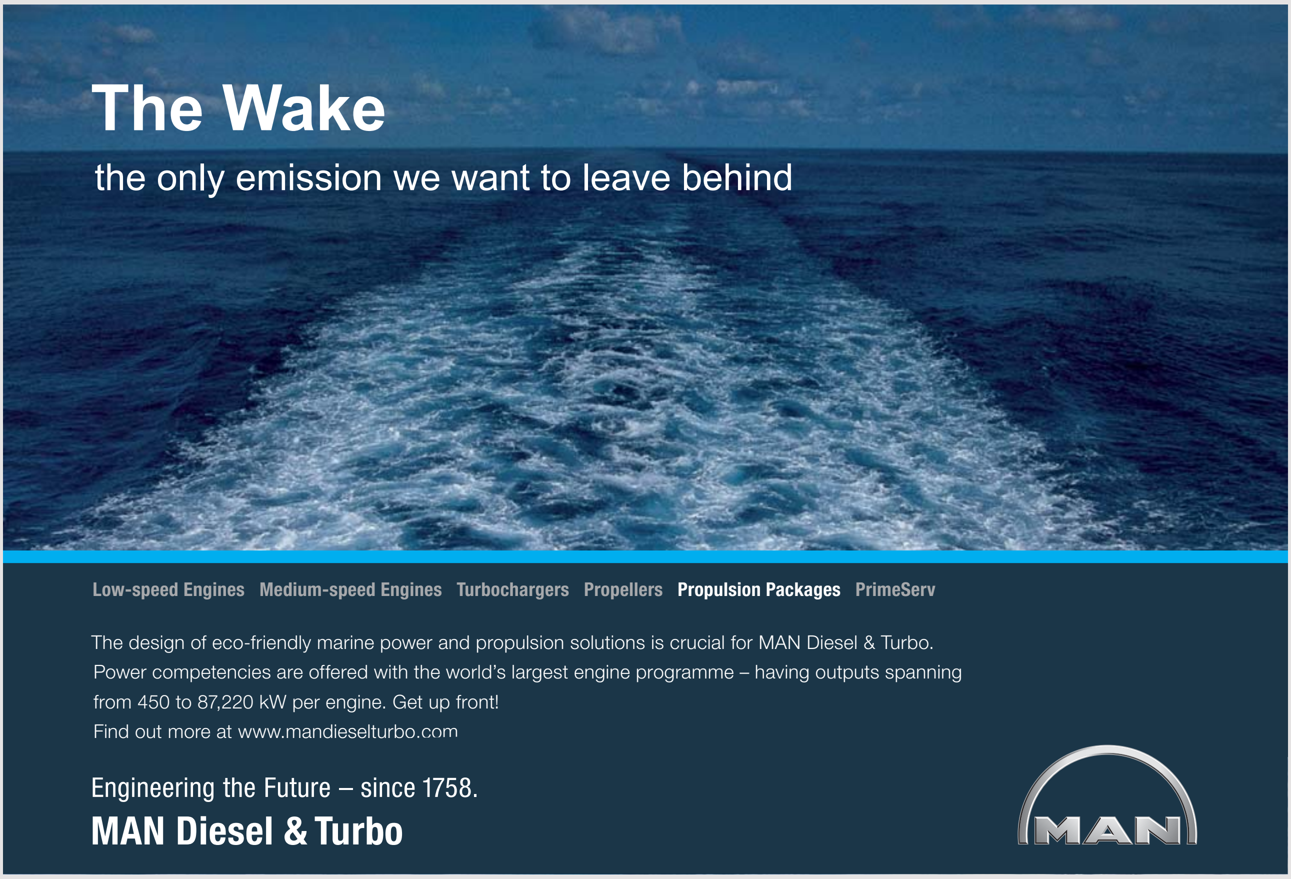
Thus, we have:

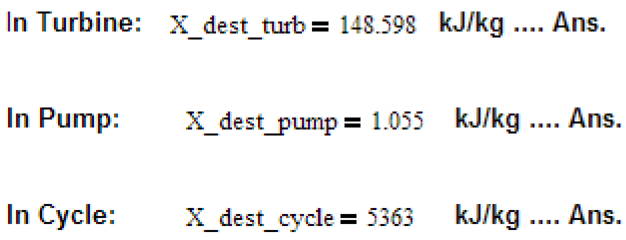
Efficiency: effcy = 0.338 = 33.8% ...Ans.

Exergy destroyed in various processes:

In boiler: X_dest_boiler = 1156 kJ/kg .... Ans.

In condenser: X_dest_cond = 4058 kJ/kg .... Ans.





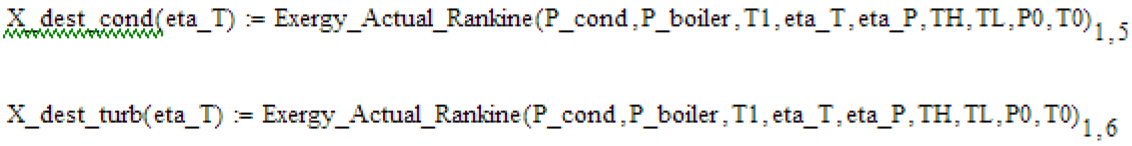
In Turbine: X_dest_turb = 148.598 **kJ/kg .... Ans.**

In Pump: X_dest_pump = 1.055 **kJ/kg .... Ans.**

In Cycle: X_dest_cycle = 5363 **kJ/kg .... Ans.**

Plot the exergy destroyed in the condenser and turbine as the turbine effcy. varies from 0.6 to 1, other conditions remaining the same:

First, write the relevant quantities as functions of eta_T:



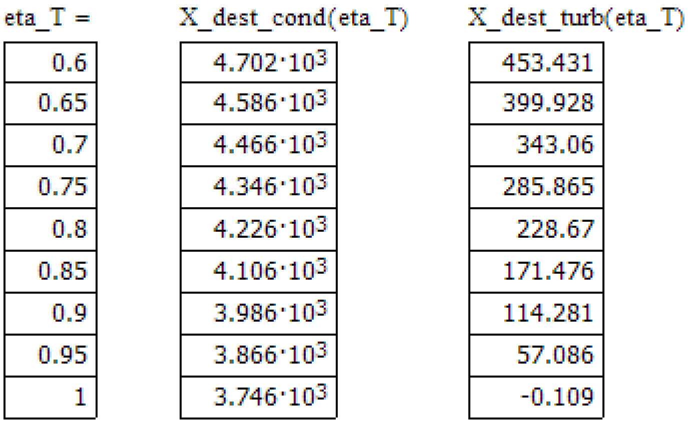
X_dest_cond(eta_T) := Exergy_Actual_Rankine(P_cond, P_boiler, T1, eta_T, eta_P, TH, TL, P0, T0)$_{1,5}$

X_dest_turb(eta_T) := Exergy_Actual_Rankine(P_cond, P_boiler, T1, eta_T, eta_P, TH, TL, P0, T0)$_{1,6}$

Now, to plot the results:

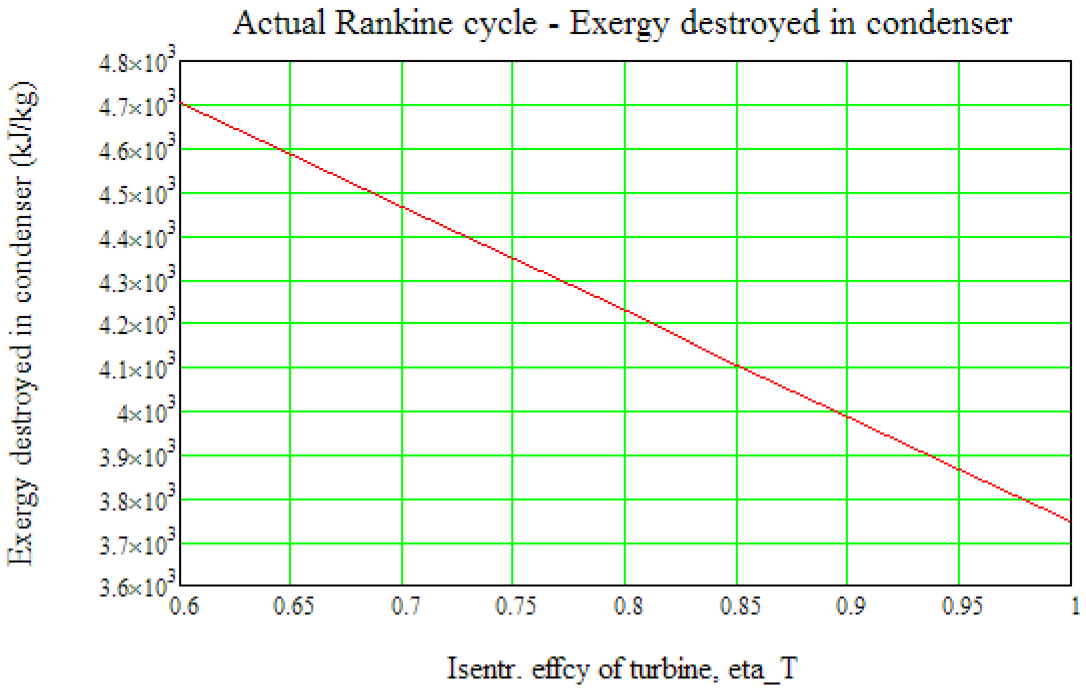
eta_T := 0.6, 0.65 .. 1 ...define a range variable

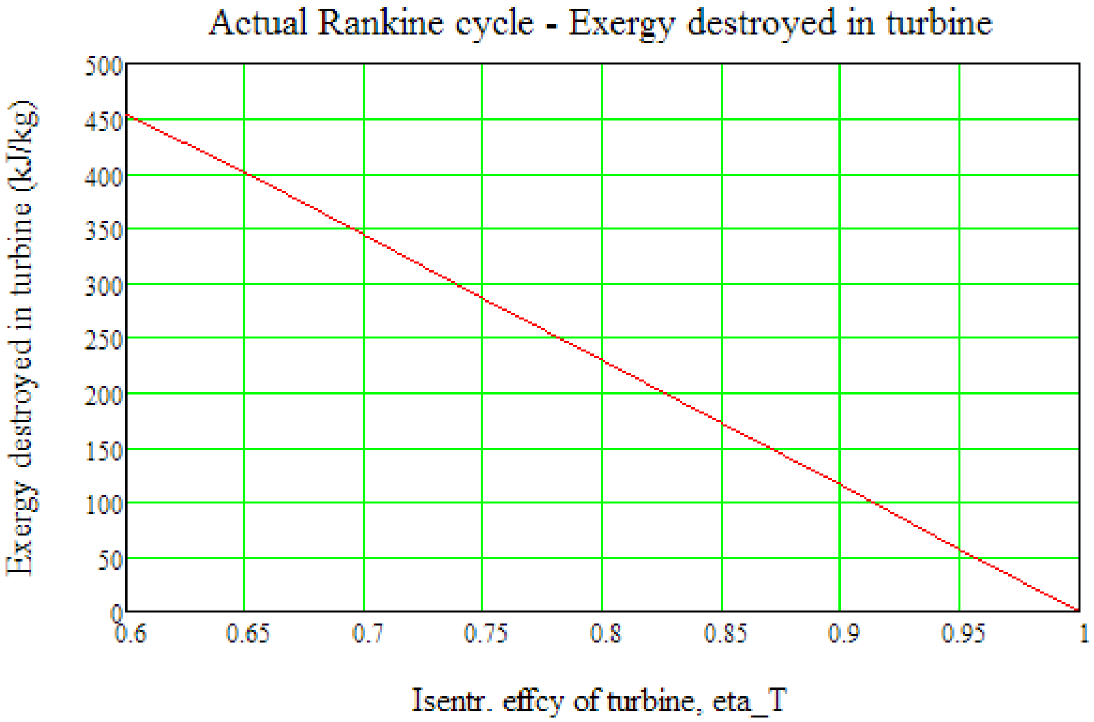
And, we get:



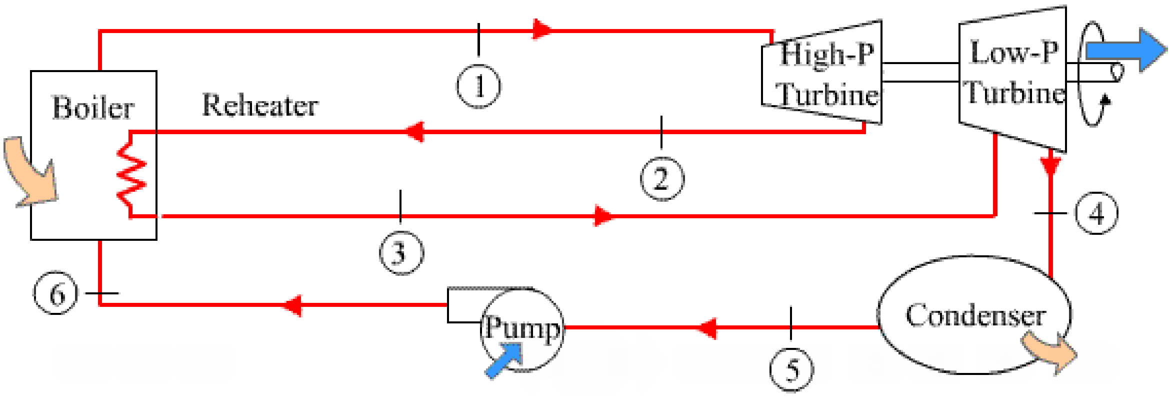
eta_T =	X_dest_cond(eta_T)	X_dest_turb(eta_T)
0.6	$4.702\cdot10^3$	453.431
0.65	$4.586\cdot10^3$	399.928
0.7	$4.466\cdot10^3$	343.06
0.75	$4.346\cdot10^3$	285.865
0.8	$4.226\cdot10^3$	228.67
0.85	$4.106\cdot10^3$	171.476
0.9	$3.986\cdot10^3$	114.281
0.95	$3.866\cdot10^3$	57.086
1	$3.746\cdot10^3$	-0.109

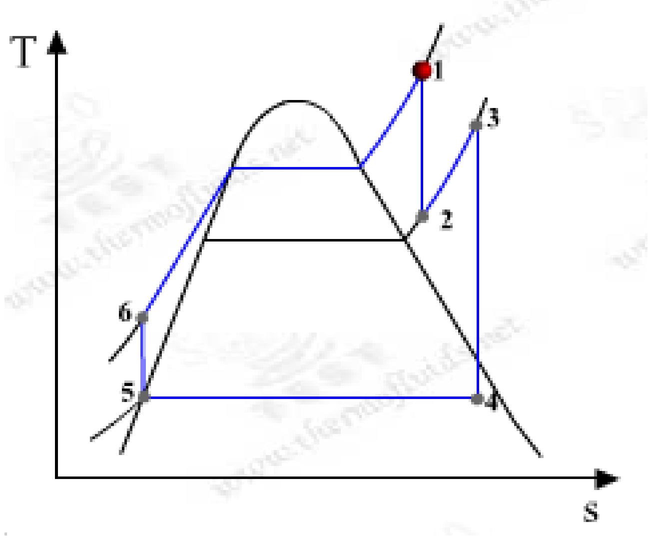
Plots:


Actual Rankine cycle - Exergy destroyed in condenser
Exergy destroyed in condenser (kJ/kg)
4.8×10^3
4.7×10^3
4.6×10^3
4.5×10^3
4.4×10^3
4.3×10^3
4.2×10^3
4.1×10^3
4×10^3
3.9×10^3
3.8×10^3
3.7×10^3
3.6×10^3
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Isentr. effcy of turbine, eta_T

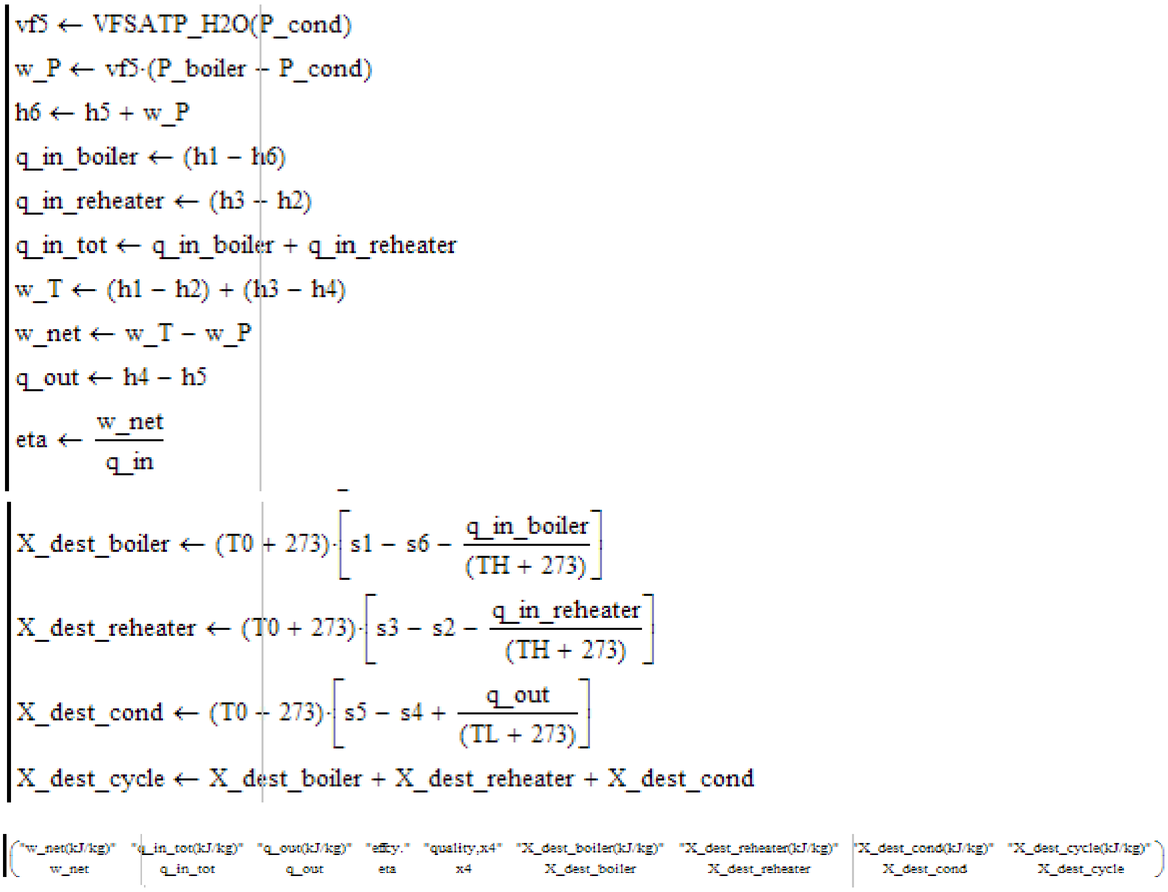

Actual Rankine cycle - Exergy destroyed in turbine
Exergy destroyed in turbine (kJ/kg)
500
450
400
350
300
250
200
150
100
50
0
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Isentr. effcy of turbine, eta_T

Prob.3.47 Write a Mathcad program to find out the exergy destroyed in various processes for an **Ideal Reheat Rankine cycle** operating between a condenser pressure P_cond, Turbine inlet temp T1(deg.C), and boiler pressure of P_boiler. Reheat pressure = P2 and reheat temp = T3. Ambient conditions: P0, T0 (C). Assume that heat is transferred in boiler at a const. temp TH (deg.C), and heat is rejected to ambient at const. temp TL (deg.C).





```
Exergy_Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3, TH, TL, P0, T0) :=

| h1 ← enthalpy_H2O(P_boiler, T1)
| s1 ← entropy_H2O(P_boiler, T1)
| s2 ← s1
| sg2 ← SGSATP_H2O(P2)
| x2 ← quality_Ps_H2O(P2, s2)  if  s1 ≤ sg2
| h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s1 ≤ sg2
| h2 ← enthalpy_H2O_Ps(P2, s2)  if  s1 > sg2
| h3 ← enthalpy_H2O(P2, T3)
| s3 ← entropy_H2O(P2, T3)
| s4 ← s3
| Tcond ← TSAT_H2O(P_cond)
| x4 ← quality_Ps_H2O(P_cond, s4)
| h4 ← enthalpy_2phase_Tx_H2O(Tcond, x4)
| h5 ← HFSATP_H2O(P_cond)
| s5 ← SFSATP_H2O(P_cond)
| s6 ← s5
```



```
vf5 ← VFSATP_H2O(P_cond)
w_P ← vf5·(P_boiler − P_cond)
h6 ← h5 + w_P
q_in_boiler ← (h1 − h6)
q_in_reheater ← (h3 − h2)
q_in_tot ← q_in_boiler + q_in_reheater
w_T ← (h1 − h2) + (h3 − h4)
w_net ← w_T − w_P
q_out ← h4 − h5
eta ← w_net / q_in

X_dest_boiler ← (T0 + 273)·[s1 − s6 − q_in_boiler / (TH + 273)]
X_dest_reheater ← (T0 + 273)·[s3 − s2 − q_in_reheater / (TH + 273)]
X_dest_cond ← (T0 + 273)·[s5 − s4 + q_out / (TL + 273)]
X_dest_cycle ← X_dest_boiler + X_dest_reheater + X_dest_cond

( "w_net(kJ/kg)"  "q_in_tot(kJ/kg)"  "q_out(kJ/kg)"  "effy."  "quality,x4"  "X_dest_boiler(kJ/kg)"  "X_dest_reheater(kJ/kg)"  "X_dest_cond(kJ/kg)"  "X_dest_cycle(kJ/kg)" )
(     w_net          q_in_tot           q_out         eta        x4          X_dest_boiler            X_dest_reheater            X_dest_cond           X_dest_cycle     )
```

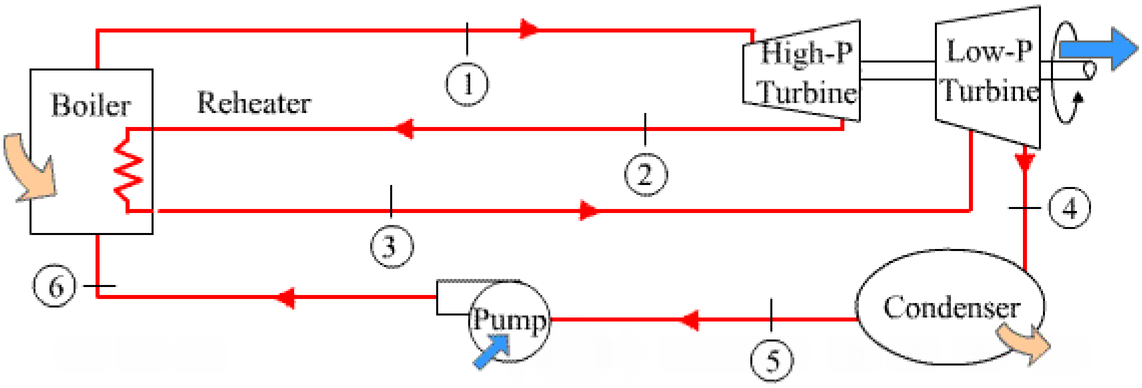
Explanation for the above Function:

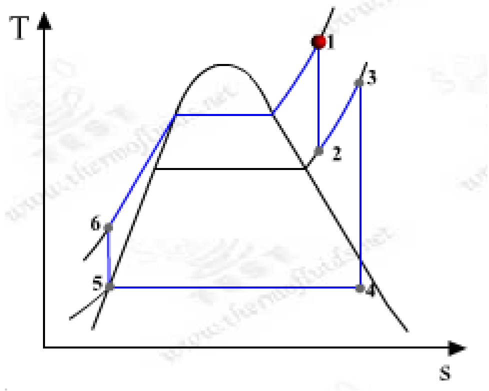
This function gives exergy destroyed in various processes of an Ideal Reheat Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where pressures P_cond, P_boiler and the reheat pressure P2 are in kPa. Turbine inlet temperature,T1, Reheat temp. T3, Source temp for heat supplied in boiler, TH, Sink temp for heat rejected in condenser, TL, are in deg.C and ambient conditions are (P0, T0). **Outputs** are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficieny (eta), quality of steam at turbine exit (x4), Exergy destroyed in boiler(X_dest_boiler), Exergy destroyed in reheater (X_dest_reheater), Exergy destroyed in condenser (X_dest_cond), and Exergy destroyed in cycle (X_dest_cycle). Units of each quantity are also given in output.

Prob.3.48 A steam power plant operates on the ideal reheat Rankine cycle. Steam enters the high pressure turbine at 8 MPa and 500°C and leaves at 3 MPa. Steam is then reheated at constant pressure to 500°C before it expands to 20 kPa in the low-pressure turbine. Determine the net work output, in kJ/kg, and the thermal efficiency of the cycle. [2]

Also, determine the exergy destroyed in various processes. Ambient conditions: P0 = 101.3 kPa, T0 = 300 K. Assume that heat is transferred in boiler at a const. temp TH = 1800 K, and heat is rejected to ambient at const. temp TL = 300 K. Plot the exergy losses in boiler and condenser as the reheat pressure varies from 1 MPa to 5 MPa.





Data:

P_boiler := 8000 kPa   T1 := 500 C   P2 := 3000 kPa   T3 := 500 C

P_cond := 20 kPa   TH := 1800 − 273 C   TL := 300 − 273 C

T0 := TL   P0 := 101.3 kPa

T_cond := TSAT_H2O(P_cond) i.e. T_cond = 60.058 C

Using the Mathcad Function for Exergy analysis of Ideal, Reheat Rankine cycle, written above:

Exergy_Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3, TH, TL, P0, T0) =

"w_net(kJ/kg)"	"q_in_tot(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"quality,x4"	"X_dest_boiler(kJ/kg)"	"X_dest_reheater(kJ/kg)"	"X_dest_cond(kJ/kg)"	"X_dest_cycle(kJ/kg)"
1.359×10^3	3.493×10^3	2.134×10^3	0.437	0.905	1.245×10^3	94.053	212.609	1.552×10^3

Thus, we have:

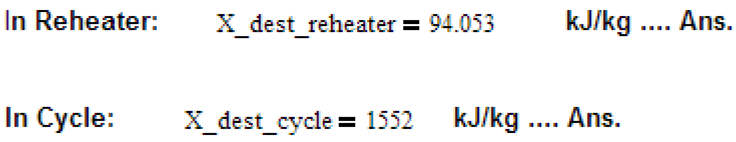
Net work output: w_net = 1359 **kJ/kg .... Ans.**

Thermal effcy: effcy = 0.437 **= 43.7% ... Ans.**

Exergy destroyed in various processes:

In boiler: X_dest_boiler = 1245 **kJ/kg .... Ans.**

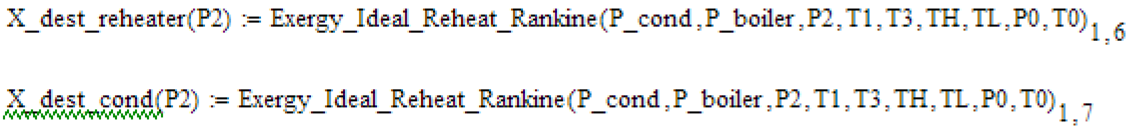
In condenser: X_dest_cond = 212.609 **kJ/kg .... Ans.**



In Reheater: X_dest_reheater = 94.053 kJ/kg .... Ans.

In Cycle: X_dest_cycle = 1552 kJ/kg .... Ans.

To plot the exergy destroyed in the condenser and reheater as the reheat pressure varies from 1 MPa to 5 MPa, other conditions remaining the same:



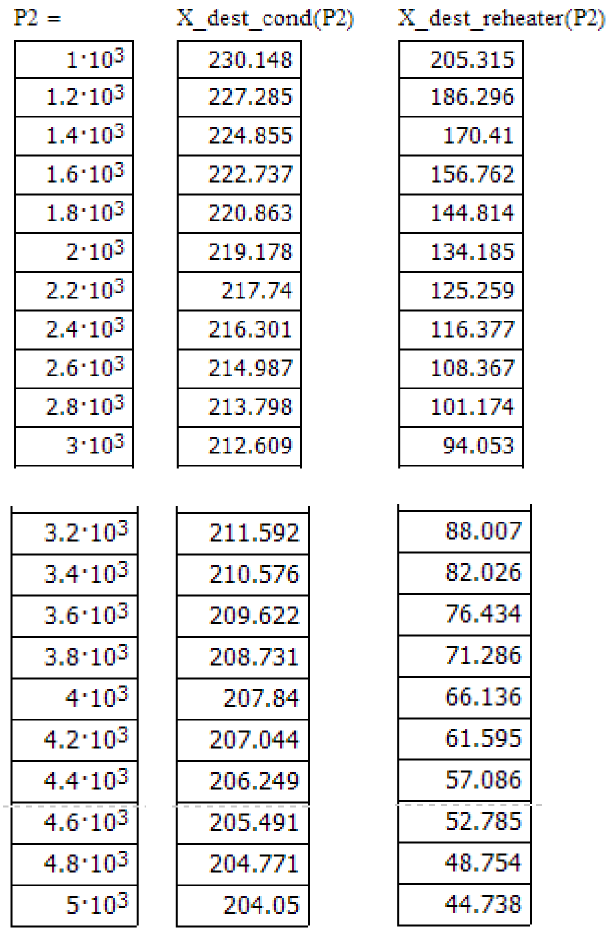
X_dest_reheater(P2) := Exergy_Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3, TH, TL, P0, T0)$_{1,6}$

X_dest_cond(P2) := Exergy_Ideal_Reheat_Rankine(P_cond, P_boiler, P2, T1, T3, TH, TL, P0, T0)$_{1,7}$

Now, to plot the results:

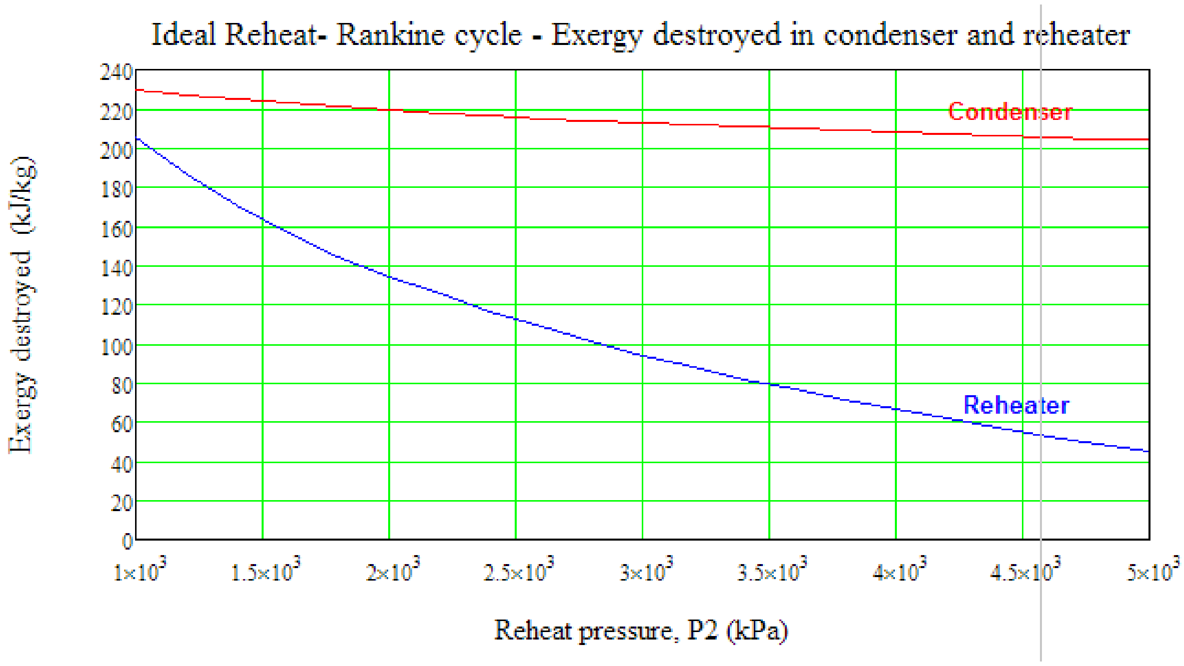
P2 := 1000, 1200.. 5000 ...define a range variable

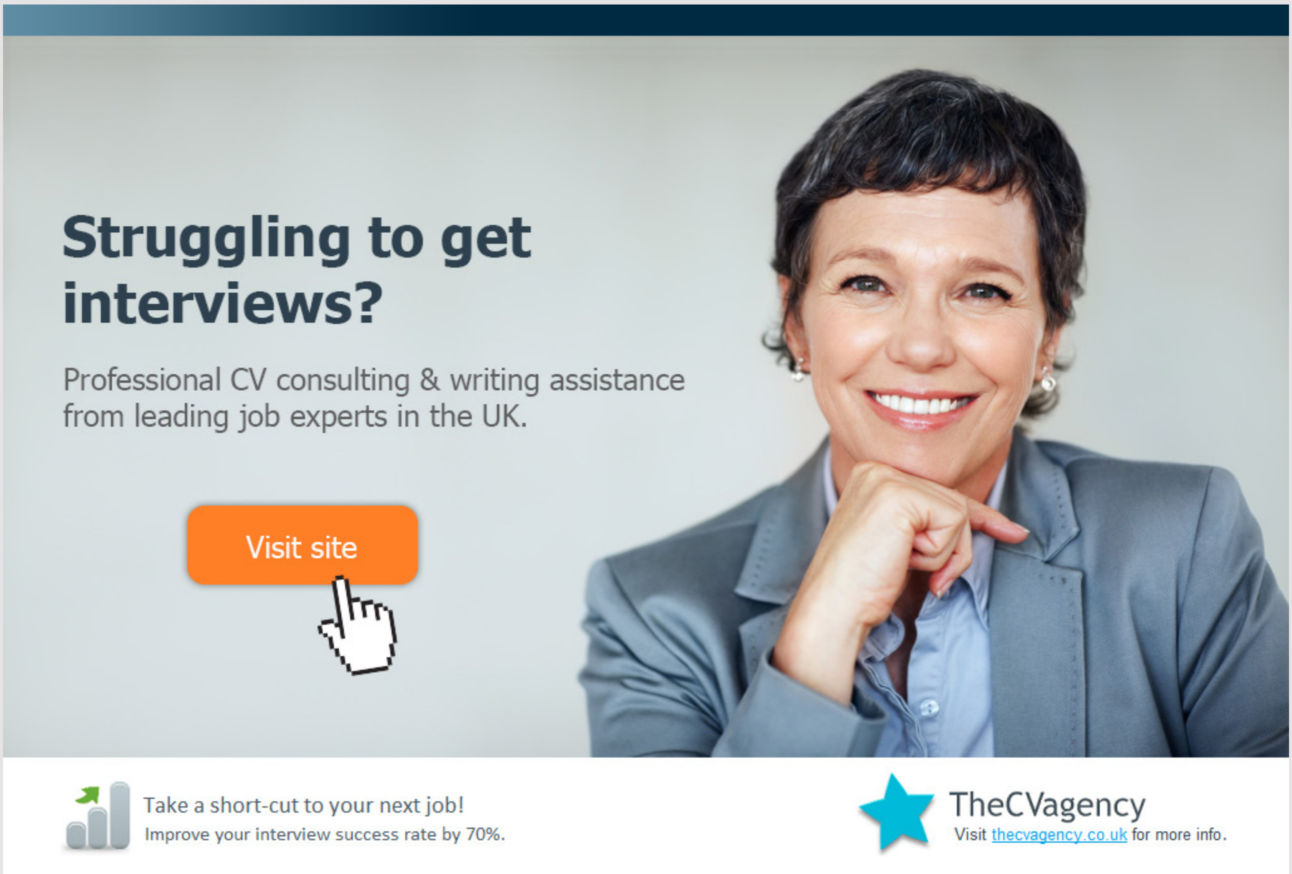
We get:



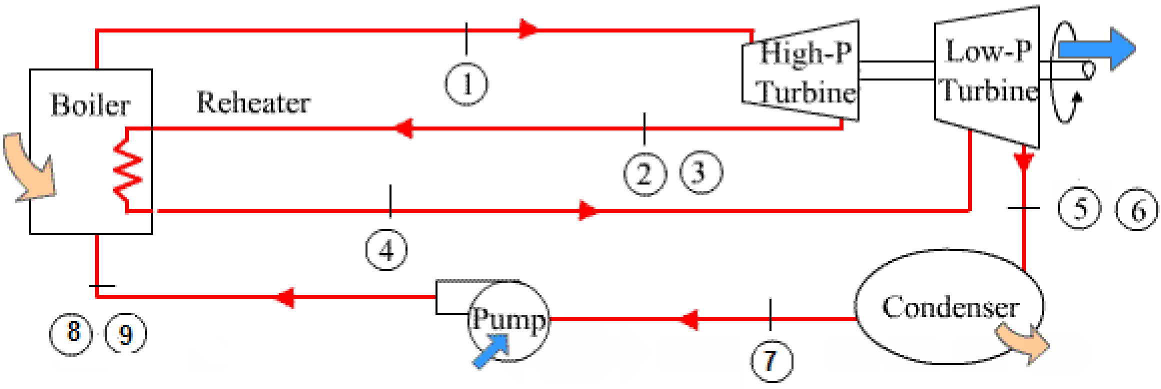
P2 =	X_dest_cond(P2)	X_dest_reheater(P2)
$1\cdot10^3$	230.148	205.315
$1.2\cdot10^3$	227.285	186.296
$1.4\cdot10^3$	224.855	170.41
$1.6\cdot10^3$	222.737	156.762
$1.8\cdot10^3$	220.863	144.814
$2\cdot10^3$	219.178	134.185
$2.2\cdot10^3$	217.74	125.259
$2.4\cdot10^3$	216.301	116.377
$2.6\cdot10^3$	214.987	108.367
$2.8\cdot10^3$	213.798	101.174
$3\cdot10^3$	212.609	94.053
$3.2\cdot10^3$	211.592	88.007
$3.4\cdot10^3$	210.576	82.026
$3.6\cdot10^3$	209.622	76.434
$3.8\cdot10^3$	208.731	71.286
$4\cdot10^3$	207.84	66.136
$4.2\cdot10^3$	207.044	61.595
$4.4\cdot10^3$	206.249	57.086
$4.6\cdot10^3$	205.491	52.785
$4.8\cdot10^3$	204.771	48.754
$5\cdot10^3$	204.05	44.738

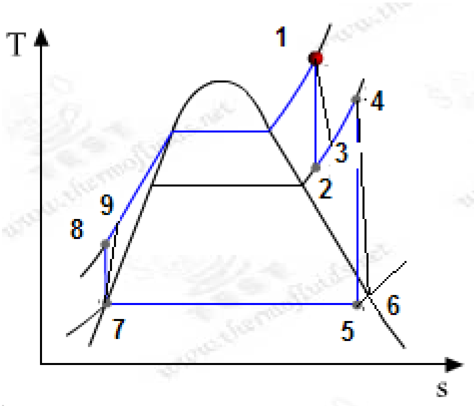
And, plot:

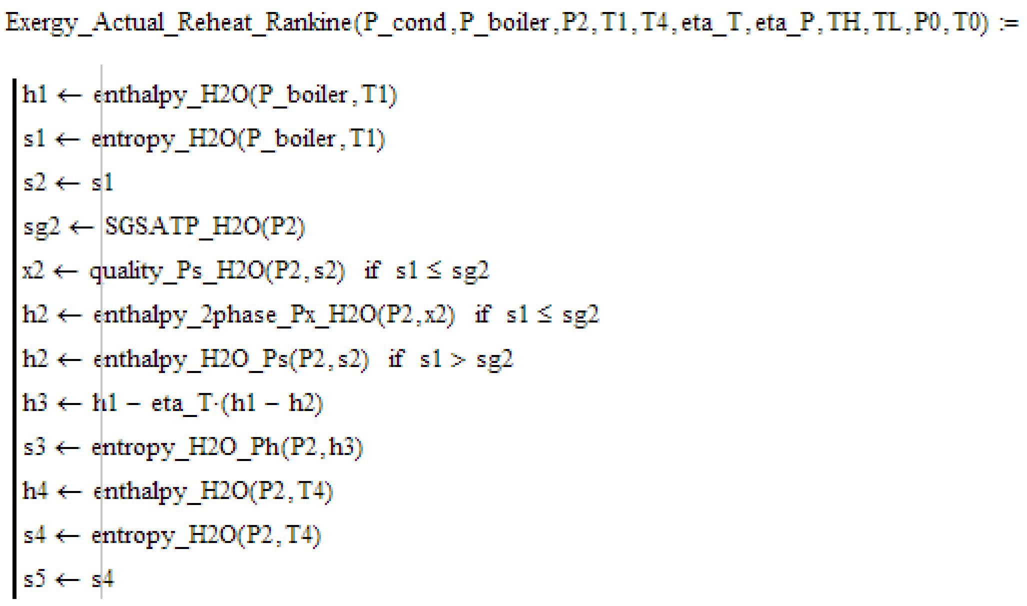

Ideal Reheat- Rankine cycle - Exergy destroyed in condenser and reheater
Exergy destroyed (kJ/kg)
240
220
200
180
160
140
120
100
80
60
40
20
0
Condenser
Reheater
1×10^3
1.5×10^3
2×10^3
2.5×10^3
3×10^3
3.5×10^3
4×10^3
4.5×10^3
5×10^3
Reheat pressure, P2 (kPa)



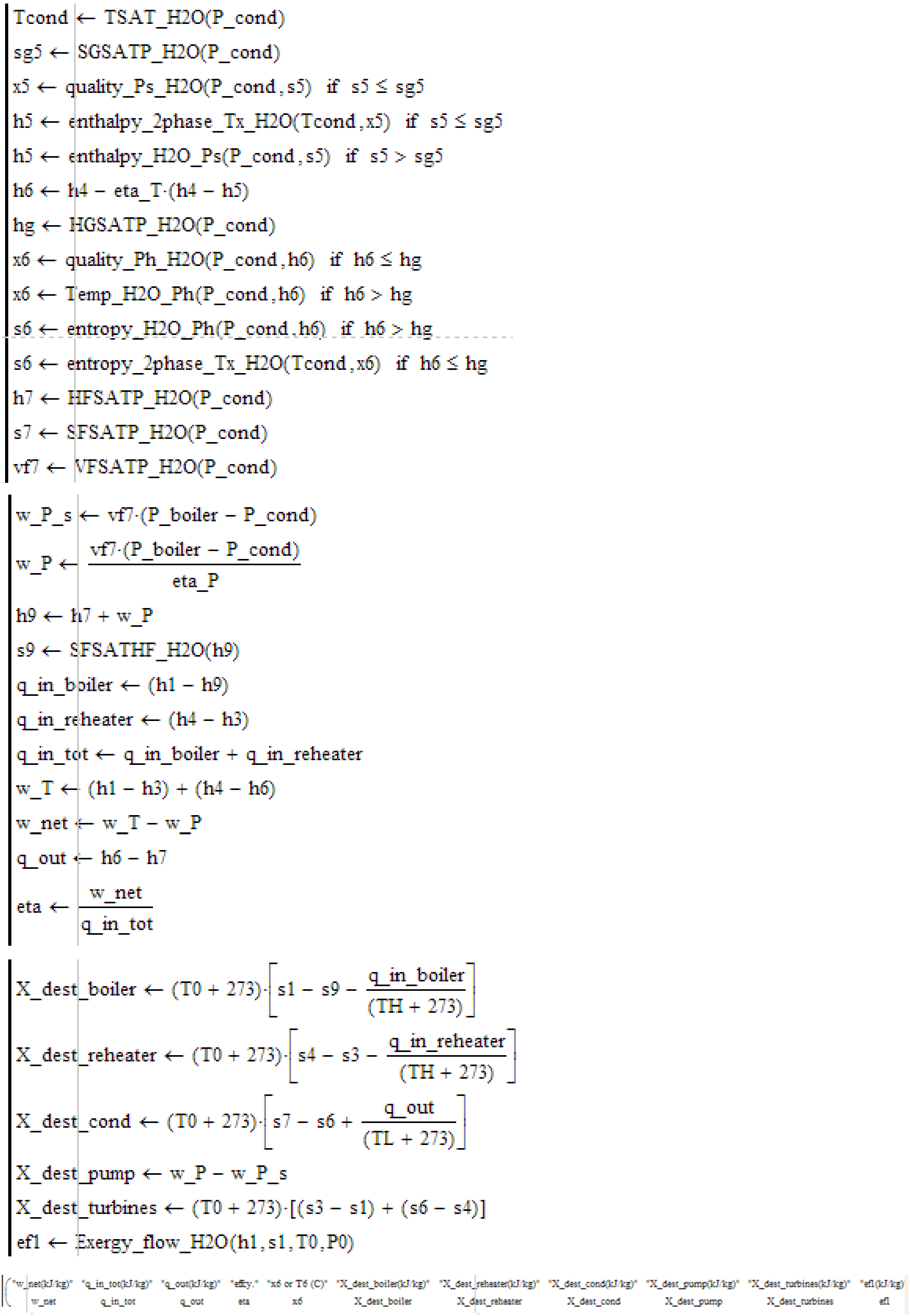
Prob.3.49 Write a Mathcad program to find out the exergy destroyed in various processes for an **Actual Reheat Rankine cycle** operating between a condenser pressure P_cond, Turbine inlet temp T1, and boiler pressure of P_boiler. Reheat pressure = P2 and reheat temp = T4. Isentropic effcy of Turbine and pump are: eta_T and eta_P, respectively. Ambient conditions: P0, T0 (C). Assume that heat is transferred in boiler at a const. temp TH (deg.C), and heat is rejected to ambient at const. temp TL (deg.C).







```
Exergy_Actual_Reheat_Rankine(P_cond,P_boiler,P2,T1,T4,eta_T,eta_P,TH,TL,P0,T0) :=

  h1 ← enthalpy_H2O(P_boiler,T1)
  s1 ← entropy_H2O(P_boiler,T1)
  s2 ← s1
  sg2 ← SGSATP_H2O(P2)
  x2 ← quality_Ps_H2O(P2,s2)  if  s1 ≤ sg2
  h2 ← enthalpy_2phase_Px_H2O(P2,x2)  if  s1 ≤ sg2
  h2 ← enthalpy_H2O_Ps(P2,s2)  if  s1 > sg2
  h3 ← h1 − eta_T·(h1 − h2)
  s3 ← entropy_H2O_Ph(P2,h3)
  h4 ← enthalpy_H2O(P2,T4)
  s4 ← entropy_H2O(P2,T4)
  s5 ← s4
```



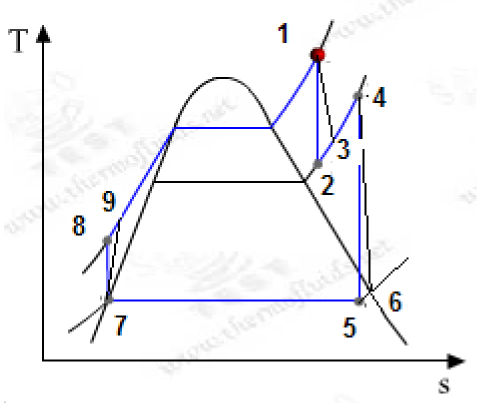
```
Tcond ← TSAT_H2O(P_cond)
sg5 ← SGSATP_H2O(P_cond)
x5 ← quality_Ps_H2O(P_cond, s5)  if  s5 ≤ sg5
h5 ← enthalpy_2phase_Tx_H2O(Tcond, x5)  if  s5 ≤ sg5
h5 ← enthalpy_H2O_Ps(P_cond, s5)  if  s5 > sg5
h6 ← h4 − eta_T·(h4 − h5)
hg ← HGSATP_H2O(P_cond)
x6 ← quality_Ph_H2O(P_cond, h6)  if  h6 ≤ hg
x6 ← Temp_H2O_Ph(P_cond, h6)  if  h6 > hg
s6 ← entropy_H2O_Ph(P_cond, h6)  if  h6 > hg
s6 ← entropy_2phase_Tx_H2O(Tcond, x6)  if  h6 ≤ hg
h7 ← HFSATP_H2O(P_cond)
s7 ← SFSATP_H2O(P_cond)
vf7 ← VFSATP_H2O(P_cond)

w_P_s ← vf7·(P_boiler − P_cond)
w_P ← $\frac{vf7\cdot(P\_boiler - P\_cond)}{eta\_P}$
h9 ← h7 + w_P
s9 ← SFSATHF_H2O(h9)
q_in_boiler ← (h1 − h9)
q_in_reheater ← (h4 − h3)
q_in_tot ← q_in_boiler + q_in_reheater
w_T ← (h1 − h3) + (h4 − h6)
w_net ← w_T − w_P
q_out ← h6 − h7
eta ← $\frac{w\_net}{q\_in\_tot}$

X_dest_boiler ← (T0 + 273)·$\left[s1 - s9 - \frac{q\_in\_boiler}{(TH + 273)}\right]$
X_dest_reheater ← (T0 + 273)·$\left[s4 - s3 - \frac{q\_in\_reheater}{(TH + 273)}\right]$
X_dest_cond ← (T0 + 273)·$\left[s7 - s6 + \frac{q\_out}{(TL + 273)}\right]$
X_dest_pump ← w_P − w_P_s
X_dest_turbines ← (T0 + 273)·[(s3 − s1) + (s6 − s4)]
ef1 ← Exergy_flow_H2O(h1, s1, T0, P0)

("w_net(kJ/kg)"  "q_in_tot(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "x6 or T6 (C)"  "X_dest_boiler(kJ/kg)"  "X_dest_reheater(kJ/kg)"  "X_dest_cond(kJ/kg)"  "X_dest_pump(kJ/kg)"  "X_dest_turbines(kJ/kg)"  "ef1(kJ/kg)"
  w_net  q_in_tot  q_out  eta  x6  X_dest_boiler  X_dest_reheater  X_dest_cond  X_dest_pump  X_dest_turbines  ef1
```

Explanation for the above Function:

This function gives exergy destroyed in various processes of an Actual Reheat Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where pressures P_cond, P_boiler are in kPa. Turbine inlet temperature, T1, Reheat temp. T4, Source temp for heat supplied in boiler, TH, Sink temp for heat rejected in condenser, TL, are in deg.C and ambient conditions are: (P0, T0). Also, eta_T and eta_P are the isentropic efficiencies of the Turbine and Pump respectively. **Outputs** are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficieny (eta), quality of steam at turbine exit (T6) if it is in two phase region, or its temp (T6) if it is in superheated region, Exergy destroyed in boiler (X_dest_boiler), Exergy destroyed in reheater (X_dest_reheater), Exergy destroyed in condenser (X_dest_cond), Exergy destroyed in pump (X_dest_pump), Exergy destroyed in Turbines (X_dest_turbines), and Exergy of flow of steam leaving the boiler, ef1. Units of each quantity are also given in output.

Prob.3.50 Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 500°C and the low-pressure turbine at 1 MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10 kPa. The isentropic efficiency of the turbine is 80 percent, and that of the pump is 95 percent. Determine (*a*) the quality (or temperature, if superheated) of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam. Determine the exergy destruction associated with the heat addition process and the expansion process. Assume a source temperature of 1600 K and a sink temperature of 285 K. Also, determine the exergy of steam at the boiler exit. Take P0 = 100 kPa. [2]



Data:

P_boiler := 10000 kPa   T1 := 500 C   P2 := 1000 kPa   T4 := 500 C

P_cond := 10 kPa   TH := 1600 − 273 C   TL := 285 − 273 C

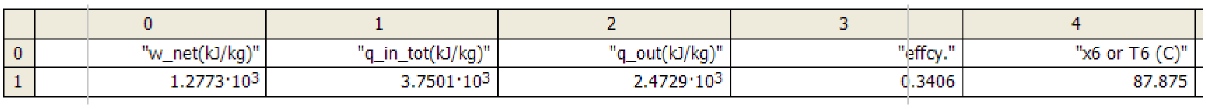
T0 := TL   P0 := 100 kPa   eta_T := 0.8   eta_P := 0.95

T_cond := TSAT_H2O(P_cond)   i.e.   T_cond = 45.806 C

Note: This problem is the same as Prob. 3.20, except for exergy aspects.

Applying the Mathcad Function for Actual, reheat Rankine cycle, we get:

Exergy_Actual_Reheat_Rankine(P_cond, P_boiler, P2, T1, T4, eta_T, eta_P, TH, TL, P0, T0) =



		0	1	2	3	4
0		"w_net(kJ/kg)"	"q_in_tot(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"x6 or T6 (C)"
1		$1.2773\cdot10^{3}$	$3.7501\cdot10^{3}$	$2.4729\cdot10^{3}$	0.3406	87.875

5	6	7	8
"X_dest_boiler(kJ/kg)"	"X_dest_reheater(kJ/kg)"	"X_dest_cond(kJ/kg)"	"X_dest_pump(kJ/kg)"
$1.1214 \cdot 10^3$	158.8021	267.6806	0.5312

9	10
"X_dest_turbines(kJ/kg)"	"ef1(kJ/kg)"
247.5332	$1.4953 \cdot 10^3$

Thus, we have:

Temp of steam at turbine exit (i.e. state 6):

$T6 = 87.875$ **deg.C .... Ans.**

Thermal effcy:

$effcy = 0.3406$ **= 34.06% ... Ans.**

Mass flow rate:

We have: $w\_net := 1277.3$ kJ/kg

$Power\_output := 80000$ kW

Therefore:

$$Mass\_Flow := \frac{Power\_output}{w\_net}$$

i.e. $Mass\_Flow = 62.632$ **kg/s ..... Ans.**

Exergy destroyed in various processes:

In boiler: $X\_dest\_boiler = 1245$ **kJ/kg .... Ans.**

In Reheater: $X\_dest\_reheater = 158.8$ **kJ/kg .... Ans.**

In condenser: $X\_dest\_cond = 267.68$ **kJ/kg .... Ans.**

In Pump: $X\_dest\_pump = 0.5312$ **kJ/kg .... Ans.**

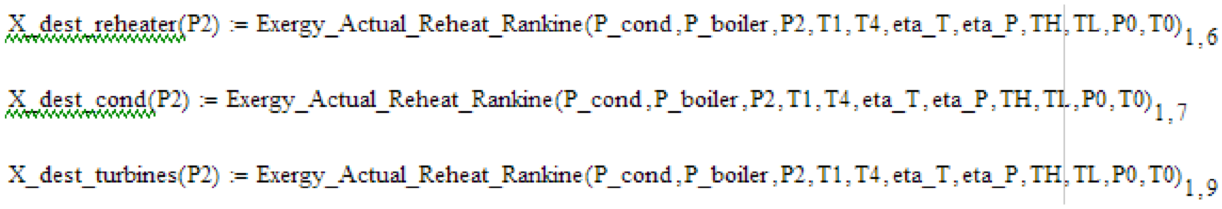
In Turbines (1 and 2): $X\_dest\_turbines = 247.533$ **kJ/kg .... Ans.**

Exergy of flow of steam leaving the boiler:

$ef1 = 1495.3$ **kJ/kg .... Ans.**

To plot the exergy losses in the reheater, condenser, and turbines as the reheat pressure varies from 1 MPa to 5 MPa:

First, write the relevant quantities as functions of Reheat pressure,P2:



$$\text{X\_dest\_reheater}(P2) := \text{Exergy\_Actual\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, P2, T1, T4, \text{eta\_T}, \text{eta\_P}, TH, TL, P0, T0)_{1,6}$$

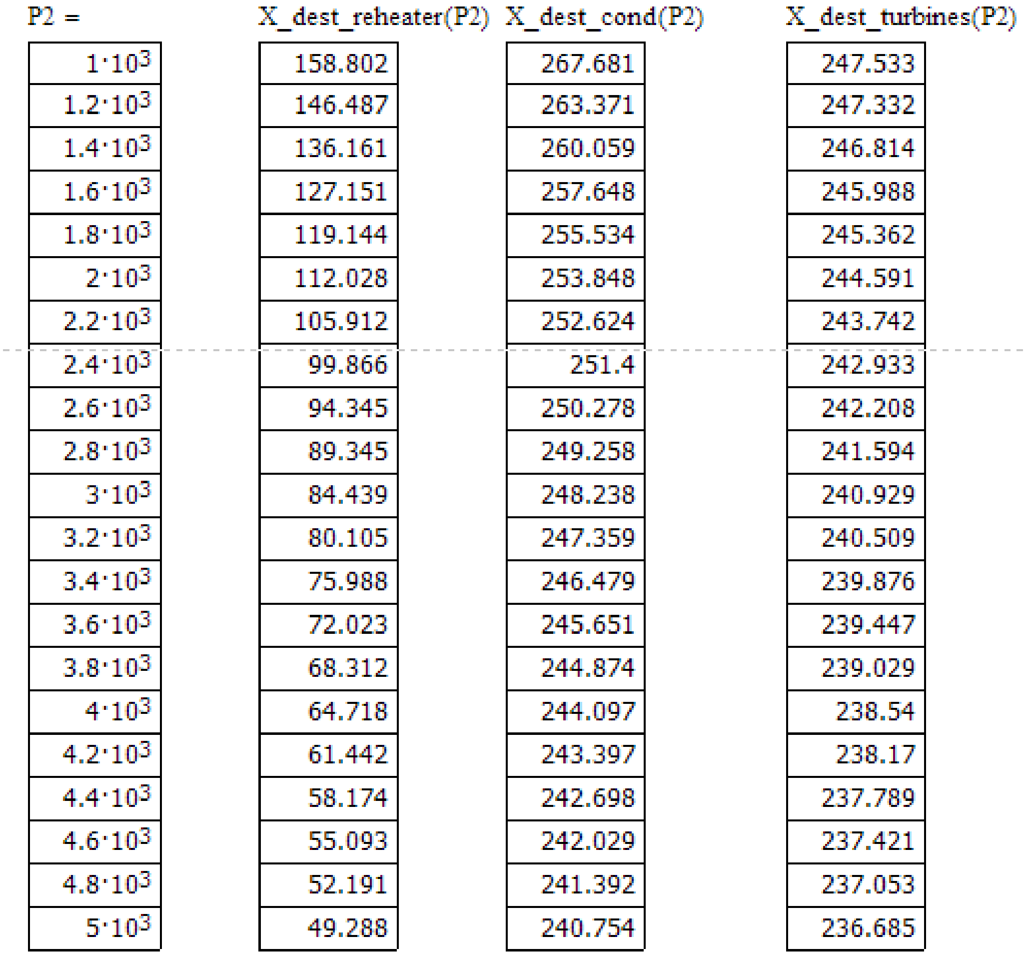
$$\text{X\_dest\_cond}(P2) := \text{Exergy\_Actual\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, P2, T1, T4, \text{eta\_T}, \text{eta\_P}, TH, TL, P0, T0)_{1,7}$$

$$\text{X\_dest\_turbines}(P2) := \text{Exergy\_Actual\_Reheat\_Rankine}(\text{P\_cond}, \text{P\_boiler}, P2, T1, T4, \text{eta\_T}, \text{eta\_P}, TH, TL, P0, T0)_{1,9}$$

Now, to plot the results:

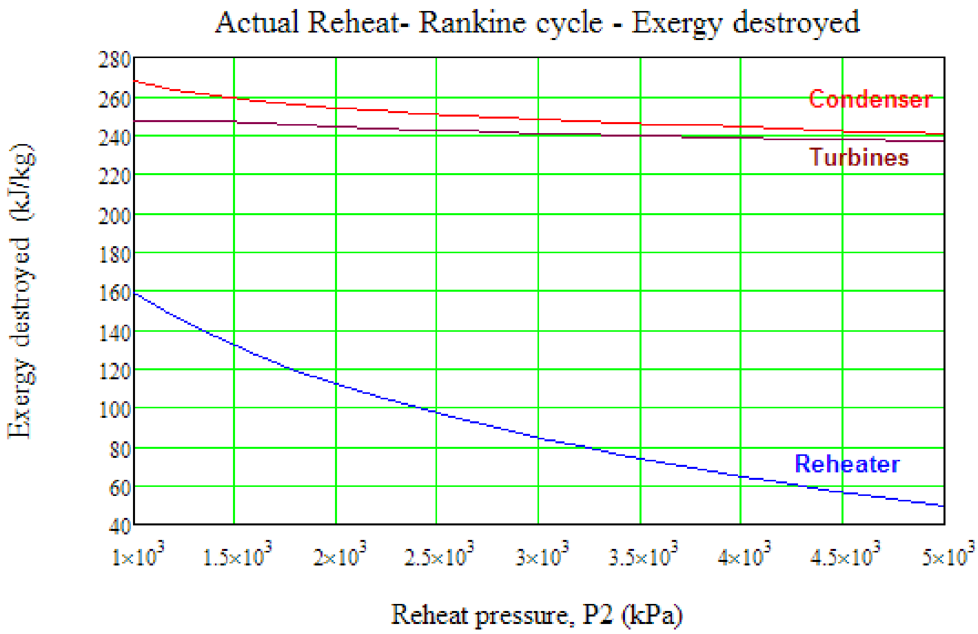
$P2 := 1000, 1200 .. 5000$ ...define a range variable

And, we get:



P2 =	X_dest_reheater(P2)	X_dest_cond(P2)	X_dest_turbines(P2)
$1\cdot10^3$	158.802	267.681	247.533
$1.2\cdot10^3$	146.487	263.371	247.332
$1.4\cdot10^3$	136.161	260.059	246.814
$1.6\cdot10^3$	127.151	257.648	245.988
$1.8\cdot10^3$	119.144	255.534	245.362
$2\cdot10^3$	112.028	253.848	244.591
$2.2\cdot10^3$	105.912	252.624	243.742
$2.4\cdot10^3$	99.866	251.4	242.933
$2.6\cdot10^3$	94.345	250.278	242.208
$2.8\cdot10^3$	89.345	249.258	241.594
$3\cdot10^3$	84.439	248.238	240.929
$3.2\cdot10^3$	80.105	247.359	240.509
$3.4\cdot10^3$	75.988	246.479	239.876
$3.6\cdot10^3$	72.023	245.651	239.447
$3.8\cdot10^3$	68.312	244.874	239.029
$4\cdot10^3$	64.718	244.097	238.54
$4.2\cdot10^3$	61.442	243.397	238.17
$4.4\cdot10^3$	58.174	242.698	237.789
$4.6\cdot10^3$	55.093	242.029	237.421
$4.8\cdot10^3$	52.191	241.392	237.053
$5\cdot10^3$	49.288	240.754	236.685

And, plot:



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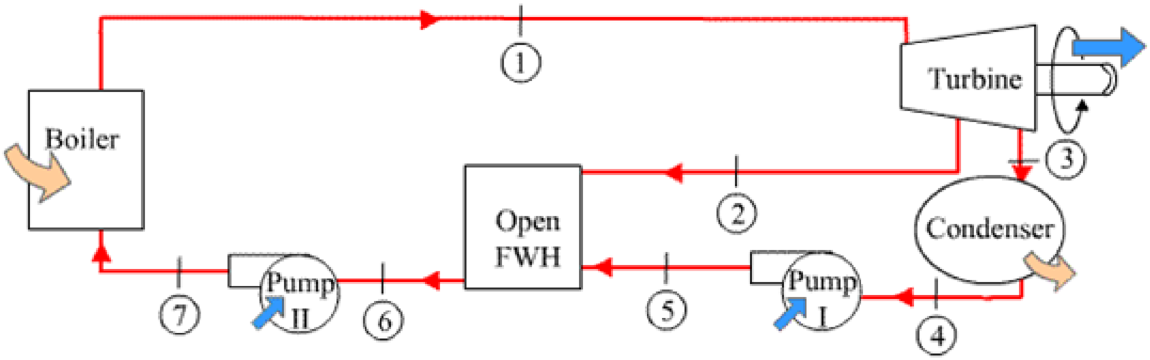
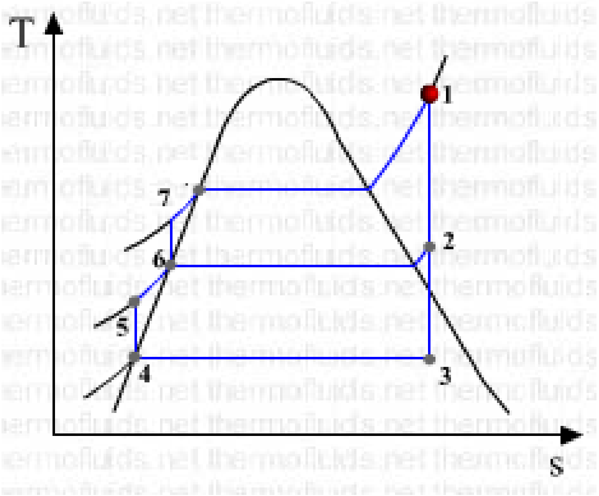
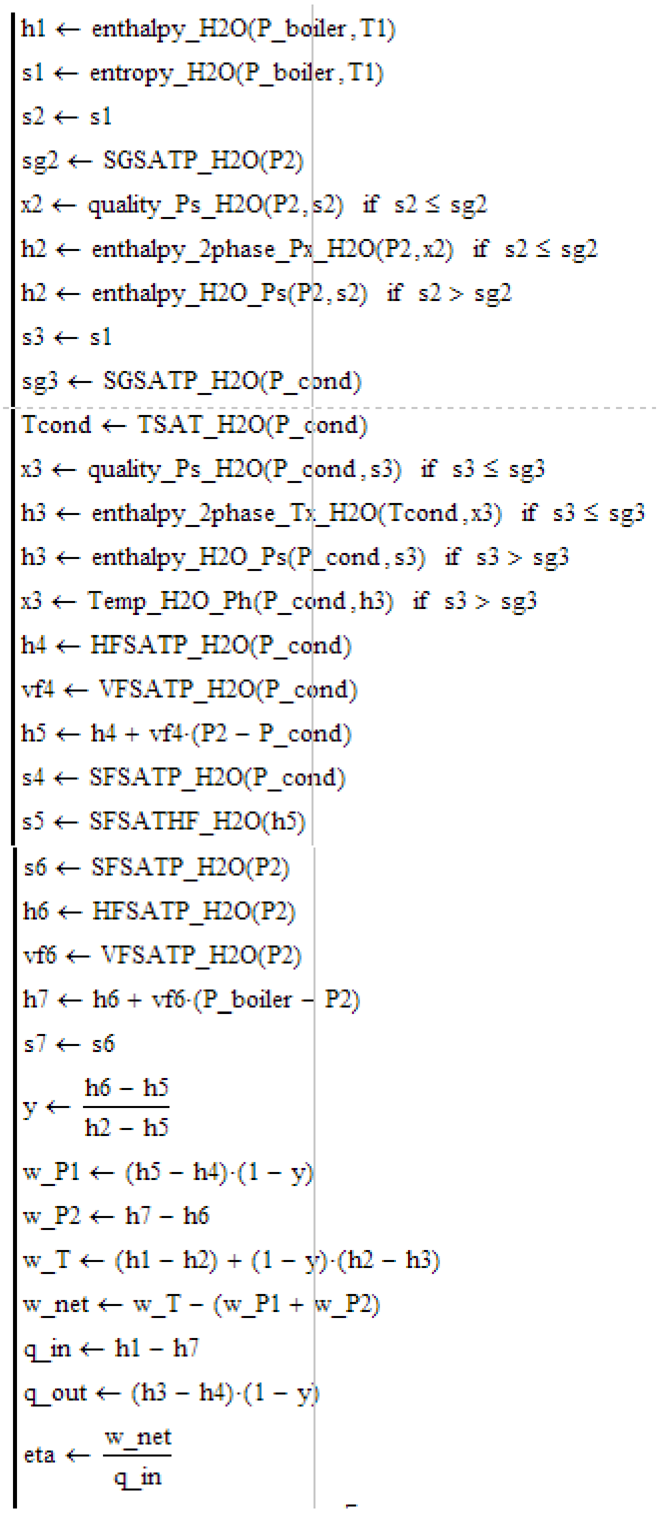
Prob.3.51 Write a Mathcad program to find out the exergy destroyed in various processes for an **Ideal, Regenerative Rankine cycle** with one open feed water heater (FWH), operating between a condenser pressure, P_cond, Turbine inlet temp, T1, and boiler pressure of P_boiler. Extraction pressure = P2. Ambient conditions: P0, T0 (C). Assume heat is transferred in boiler at a constant temp TH (deg.C), and heat is rejected to ambient at constant temp. TL (deg.C).

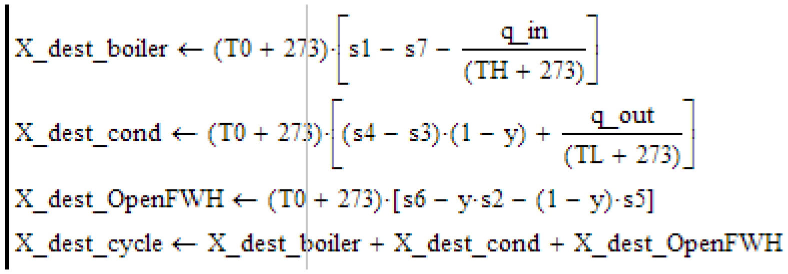




Exergy_Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1, TH, TL, P0, T0) :=



```
h1 ← enthalpy_H2O(P_boiler, T1)
s1 ← entropy_H2O(P_boiler, T1)
s2 ← s1
sg2 ← SGSATP_H2O(P2)
x2 ← quality_Ps_H2O(P2, s2)  if  s2 ≤ sg2
h2 ← enthalpy_2phase_Px_H2O(P2, x2)  if  s2 ≤ sg2
h2 ← enthalpy_H2O_Ps(P2, s2)  if  s2 > sg2
s3 ← s1
sg3 ← SGSATP_H2O(P_cond)
Tcond ← TSAT_H2O(P_cond)
x3 ← quality_Ps_H2O(P_cond, s3)  if  s3 ≤ sg3
h3 ← enthalpy_2phase_Tx_H2O(Tcond, x3)  if  s3 ≤ sg3
h3 ← enthalpy_H2O_Ps(P_cond, s3)  if  s3 > sg3
x3 ← Temp_H2O_Ph(P_cond, h3)  if  s3 > sg3
h4 ← HFSATP_H2O(P_cond)
vf4 ← VFSATP_H2O(P_cond)
h5 ← h4 + vf4·(P2 − P_cond)
s4 ← SFSATP_H2O(P_cond)
s5 ← SFSATHF_H2O(h5)
s6 ← SFSATP_H2O(P2)
h6 ← HFSATP_H2O(P2)
vf6 ← VFSATP_H2O(P2)
h7 ← h6 + vf6·(P_boiler − P2)
s7 ← s6
$y \leftarrow \frac{h6 - h5}{h2 - h5}$
w_P1 ← (h5 − h4)·(1 − y)
w_P2 ← h7 − h6
w_T ← (h1 − h2) + (1 − y)·(h2 − h3)
w_net ← w_T − (w_P1 + w_P2)
q_in ← h1 − h7
q_out ← (h3 − h4)·(1 − y)
$eta \leftarrow \frac{w\_net}{q\_in}$
```

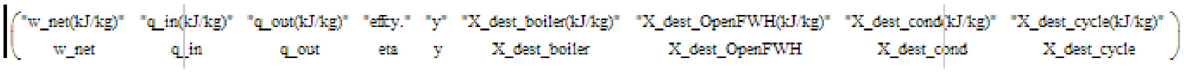


$$X\_dest\_boiler \leftarrow (T0 + 273)\cdot\left[s1 - s7 - \frac{q\_in}{(TH + 273)}\right]$$

$$X\_dest\_cond \leftarrow (T0 + 273)\cdot\left[(s4 - s3)\cdot(1 - y) + \frac{q\_out}{(TL + 273)}\right]$$

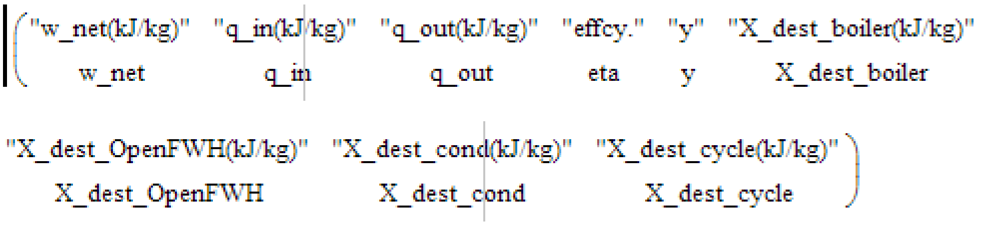
$$X\_dest\_OpenFWH \leftarrow (T0 + 273)\cdot[s6 - y\cdot s2 - (1 - y)\cdot s5]$$

$$X\_dest\_cycle \leftarrow X\_dest\_boiler + X\_dest\_cond + X\_dest\_OpenFWH$$



$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"y"} & \text{"X\_dest\_boiler(kJ/kg)"} & \text{"X\_dest\_OpenFWH(kJ/kg)"} & \text{"X\_dest\_cond(kJ/kg)"} & \text{"X\_dest\_cycle(kJ/kg)"} \\ w\_net & q\_in & q\_out & eta & y & X\_dest\_boiler & X\_dest\_OpenFWH & X\_dest\_cond & X\_dest\_cycle \end{pmatrix}$$

For clarity, the last line above, i.e. the output matrix is reproduced below:



$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"y"} & \text{"X\_dest\_boiler(kJ/kg)"} \\ w\_net & q\_in & q\_out & eta & y & X\_dest\_boiler \end{pmatrix}$$

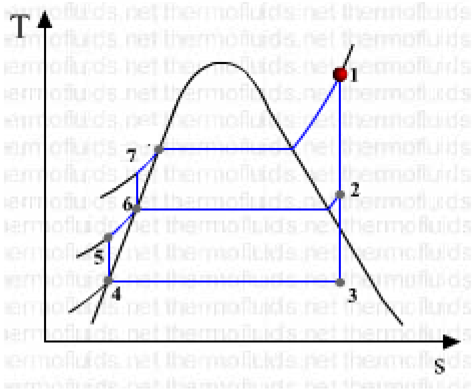
$$\begin{matrix} \text{"X\_dest\_OpenFWH(kJ/kg)"} & \text{"X\_dest\_cond(kJ/kg)"} & \text{"X\_dest\_cycle(kJ/kg)"} \\ X\_dest\_OpenFWH & X\_dest\_cond & X\_dest\_cycle \end{matrix}$$

Explanation for the above Function:

This function gives exergy destroyed in various processes of an Ideal Regenerative Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where pressures P_cond, P_boiler and the extraction pressure (or feedwater heater pressure), P2 are in kPa. Turbine inlet temperature,T1, Source temp for heat supplied in boiler, TH, Sink temp for heat rejected in condenser, TL, are in deg.C and ambient conditions are (P0, T0). **Outputs** are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Net work (w_net), Heat input in boiler (q_in), Heat rejected in condenser (q_out), Thermal efficieny (eta), fraction of steam extracted (y), Exergy destroyed in boiler(X_dest_boiler), Exergy destroyed in open FWH (X_dest_OpenFWH), Exergy destroyed in condenser (X_dest_cond), and Exergy destroyed in cycle (X_dest_cycle). Units of each quantity are also given in output.

Prob.3.52 A steam power plant operates on an ideal, regenerative Rankine cycle. Steam enters the turbine at 6 MPa and 450°C and is condensed in the condenser at 20 kPa. Steam is extracted from the turbine at 0.4 MPa to heat the feedwater in an open feedwater heater. Water leaves the feedwater heater as a saturated liquid. Determine (*a*) the net work output per kilogram of steam flowing through the boiler and (*b*) the thermal efficiency of the cycle. **Also:** determine the exergy destruction associated with this regenerative cycle. Assume a source temperature of 1500 K and a sink temperature of 290 K.[2]



Data:

P_boiler := 6000 kPa   T1 := 450 C   TH := 1500 − 273 C   TL := 290 − 273 C

P2 := 400 kPa   P_cond := 20 kPa   T0 := TL   P0 := 100 kPa

T_cond := TSAT_H2O(P_cond)   i.e.   T_cond = 60.058 C

Applying the Mathcad Function for exergy of Ideal, Regen. Rankine cycle, we get:

Exergy_Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1, TH, TL, P0, T0) =

$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"y"} & \text{"X\_dest\_boiler(kJ/kg)"} & \text{"X\_dest\_OpenFWH(kJ/kg)"} & \text{"X\_dest\_cond(kJ/kg)"} & \text{"X\_dest\_cycle(kJ/kg)"} \\ 1.017 \times 10^{3} & 2.693 \times 10^{3} & 1.676 \times 10^{3} & 0.378 & 0.146 & 914.307 & 23.699 & 217.344 & 1.155 \times 10^{3} \end{pmatrix}$$

Thus, we have:

Net work: w_net = 1017 **kJ/kg .... Ans.**

Thermal effcy of cycle:

effcy = 0.378 **= 37.8% .... Ans.**

Exergy destruction for the cycle:

X_dest_cycle = 1155 **kJ/kg .... Ans.**

To plot the exergy destroyed in the condenser and open FWH as the extraction pressure varies from 0.4 MPa to 3 MPa:

First, write the relevant quantities as functions of extraction pressure,P2:

$\text{X\_dest\_cond(P2)} := \text{Exergy\_Ideal\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, TH, TL, P0, T0)}_{1,7}$

$\text{X\_dest\_OpenFWH(P2)} := \text{Exergy\_Ideal\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, TH, TL, P0, T0)}_{1,6}$

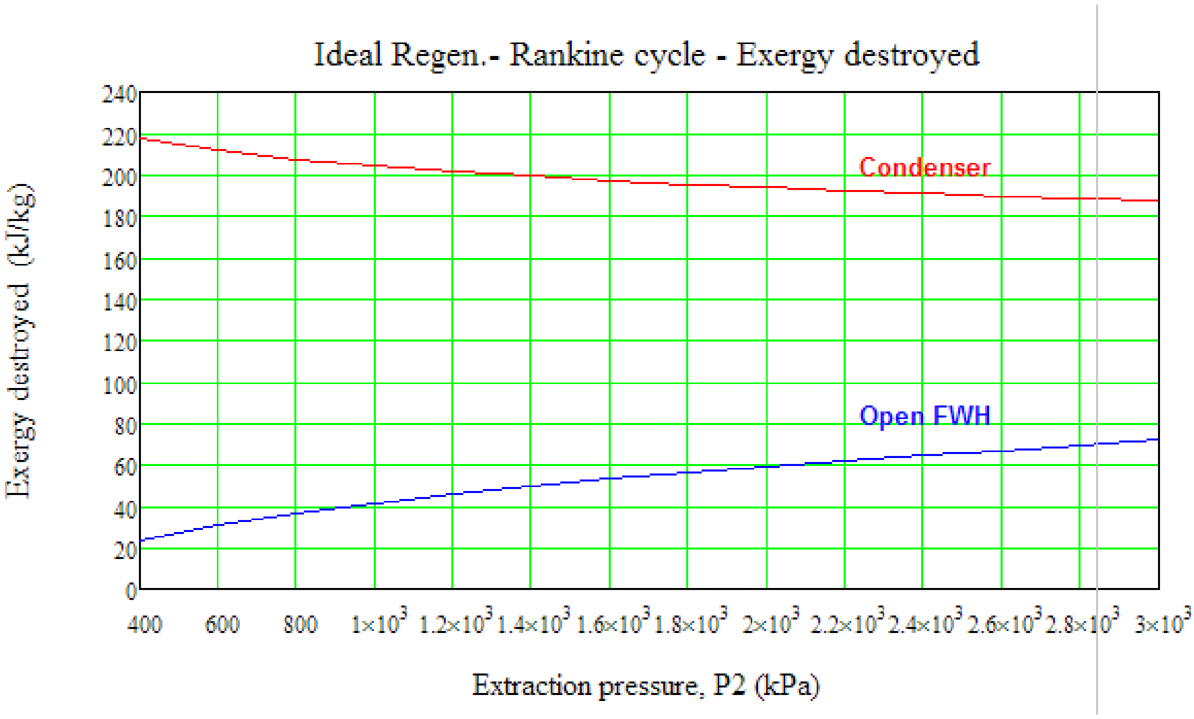
Now, to plot the results:

P2 := 400, 600.. 3000 ...define a range variable

And, we get:

P2 =	X_dest_cond(P2)	X_dest_OpenFWH(P2)
400	217.344	23.699
600	211.699	30.917
800	207.581	36.679
$1\cdot10^3$	204.314	41.466
$1.2\cdot10^3$	201.658	45.697
$1.4\cdot10^3$	199.352	49.512
$1.6\cdot10^3$	197.256	53.039
$1.8\cdot10^3$	195.447	56.223
$2\cdot10^3$	193.769	59.211
$2.2\cdot10^3$	192.217	61.796
$2.4\cdot10^3$	190.798	64.51
$2.6\cdot10^3$	189.519	67.028
$2.8\cdot10^3$	188.216	69.364
$3\cdot10^3$	187.143	71.739

Now, plot:

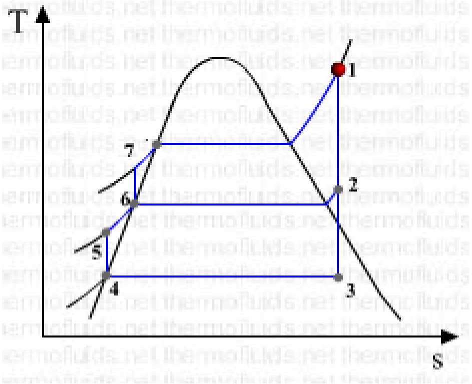


]

Prob.3.53 A power plant operates on a regenerative vapor power cycle with one open feedwater heater. Steam enters the first turbine stage at 12 MPa, 520 C and expands to 1 MPa, where some of the steam is extracted and diverted to the open feedwater heater operating at 1 MPa. The remaining steam expands through the second turbine stage to the condenser pressure of 6 kPa. Saturated liquid exits the open feedwater heater at 1 MPa. For isentropic processes in the turbines and pumps, determine for the cycle:

(a) the thermal efficiency and (b) the mass flow rate into the first turbine stage, in kg/h, for a net power output of 330 MW.

Plot the thermal efficiency and the rate of exergy destruction within the feedwater heater, in kW, versus the feedwater heater pressure ranging from 0.5 to 10 MPa. Let *T*0 = 293 K. [4]



Data:

P_boiler := 12000 kPa   T1 := 520 C   P2 := 1000 kPa

TH := 1500 − 273 C   TL := 293 − 273 C

P_cond := 6 kPa   T0 := TL   P0 := 100 kPa

T_cond := TSAT_H2O(P_cond)   i.e.   T_cond = 36.16 C

Applying the Mathcad Function for exergy of Ideal, Regen. Rankine cycle, we get:

Exergy_Ideal_Regen_Rankine(P_cond, P_boiler, P2, T1, TH, TL, P0, T0) =

$$\begin{pmatrix} \text{"w\_net(kJ/kg)"} & \text{"q\_in(kJ/kg)"} & \text{"q\_out(kJ/kg)"} & \text{"effcy."} & \text{"y"} & \text{"X\_dest\_boiler(kJ/kg)"} & \text{"X\_dest\_OpenFWH(kJ/kg)"} & \text{"X\_dest\_cond(kJ/kg)"} & \text{"X\_dest\_cycle(kJ/kg)"} \\ 1.197 \times 10^3 & 2.628 \times 10^3 & 1.432 \times 10^3 & 0.455 & 0.234 & 782.298 & 60.155 & 75.117 & 917.57 \end{pmatrix}$$

Thus, we have:

Thermal effcy of cycle: effcy = 0.455 **= 45.5% .... Ans.**

Net work: w_net := 1197 **kJ/kg .... Ans.**

Mass flow rate:

$$\text{Mass\_Flow} := \frac{\text{Power\_output}}{\text{w\_net}} \quad \text{kg/s}$$

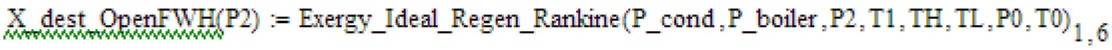
i.e. Mass_Flow = 275.689 **kg/s = 9.925×10^5 kg/h .... Ans.**

Exergy destruction for the cycle:

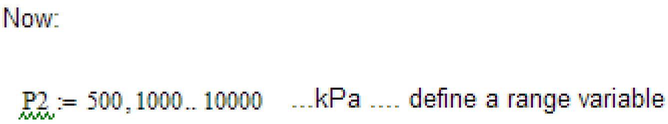
X_dest_cycle = 917.57 **kJ/kg .... Ans.**

To plot Exergy destroyed in open FWH against the Feedwater heater pressure, P2:

First, define the exergy destroyed in the FWH as a function of P2:



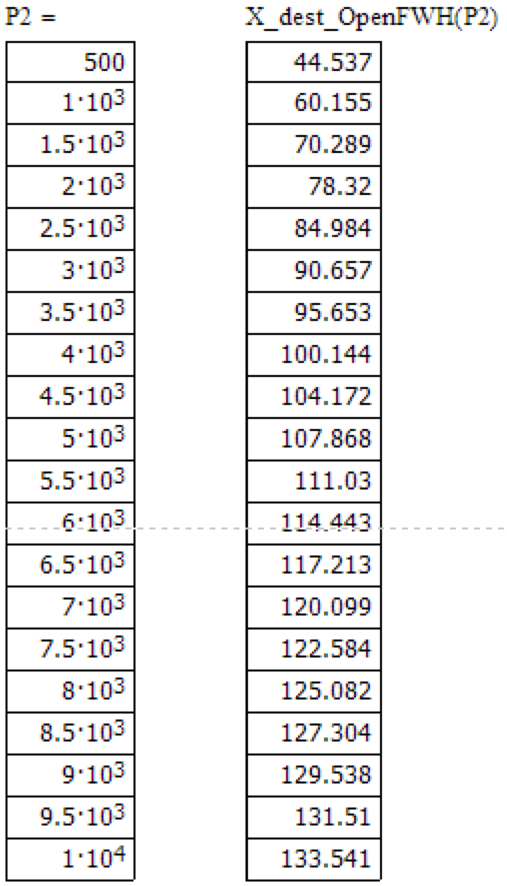
$X\_dest\_OpenFWH(P2) := Exergy\_Ideal\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, TH, TL, P0, T0)_{1,6}$



Now:

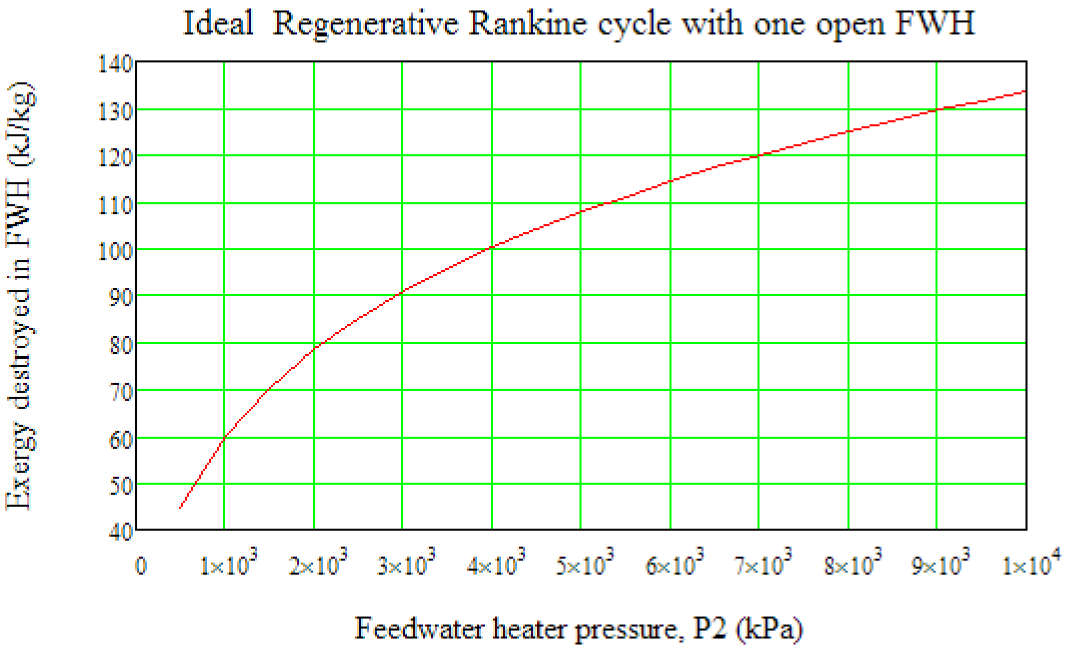
$P2 := 500, 1000 .. 10000$ ...kPa .... define a range variable

We get:



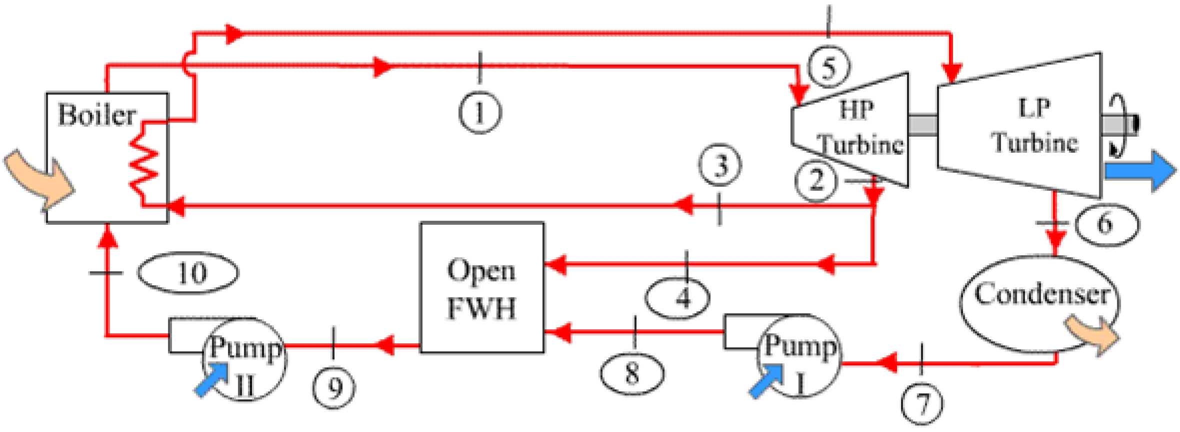
P2 =	X_dest_OpenFWH(P2)
500	44.537
$1\cdot10^3$	60.155
$1.5\cdot10^3$	70.289
$2\cdot10^3$	78.32
$2.5\cdot10^3$	84.984
$3\cdot10^3$	90.657
$3.5\cdot10^3$	95.653
$4\cdot10^3$	100.144
$4.5\cdot10^3$	104.172
$5\cdot10^3$	107.868
$5.5\cdot10^3$	111.03
$6\cdot10^3$	114.443
$6.5\cdot10^3$	117.213
$7\cdot10^3$	120.099
$7.5\cdot10^3$	122.584
$8\cdot10^3$	125.082
$8.5\cdot10^3$	127.304
$9\cdot10^3$	129.538
$9.5\cdot10^3$	131.51
$1\cdot10^4$	133.541

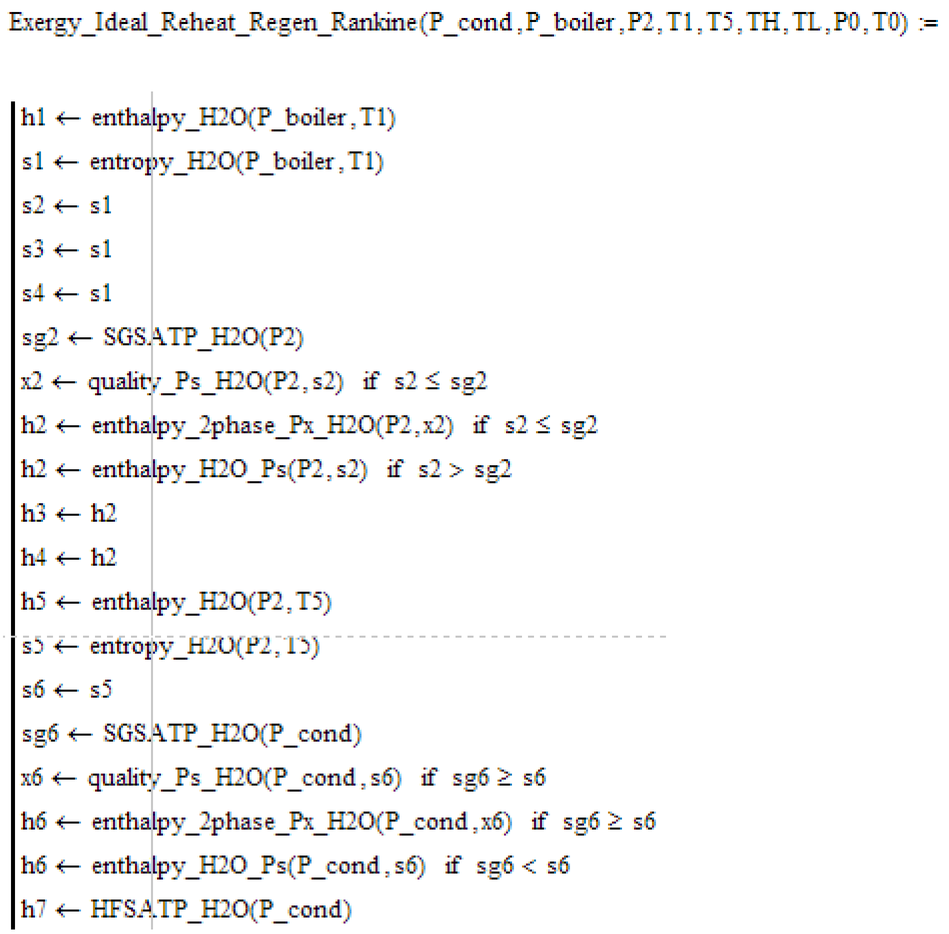
And, plot:


Ideal Regenerative Rankine cycle with one open FWH
Exergy destroyed in FWH (kJ/kg)
140
130
120
110
100
90
80
70
60
50
40
0
1×10^3
2×10^3
3×10^3
4×10^3
5×10^3
6×10^3
7×10^3
8×10^3
9×10^3
1×10^4
Feedwater heater pressure, P2 (kPa)

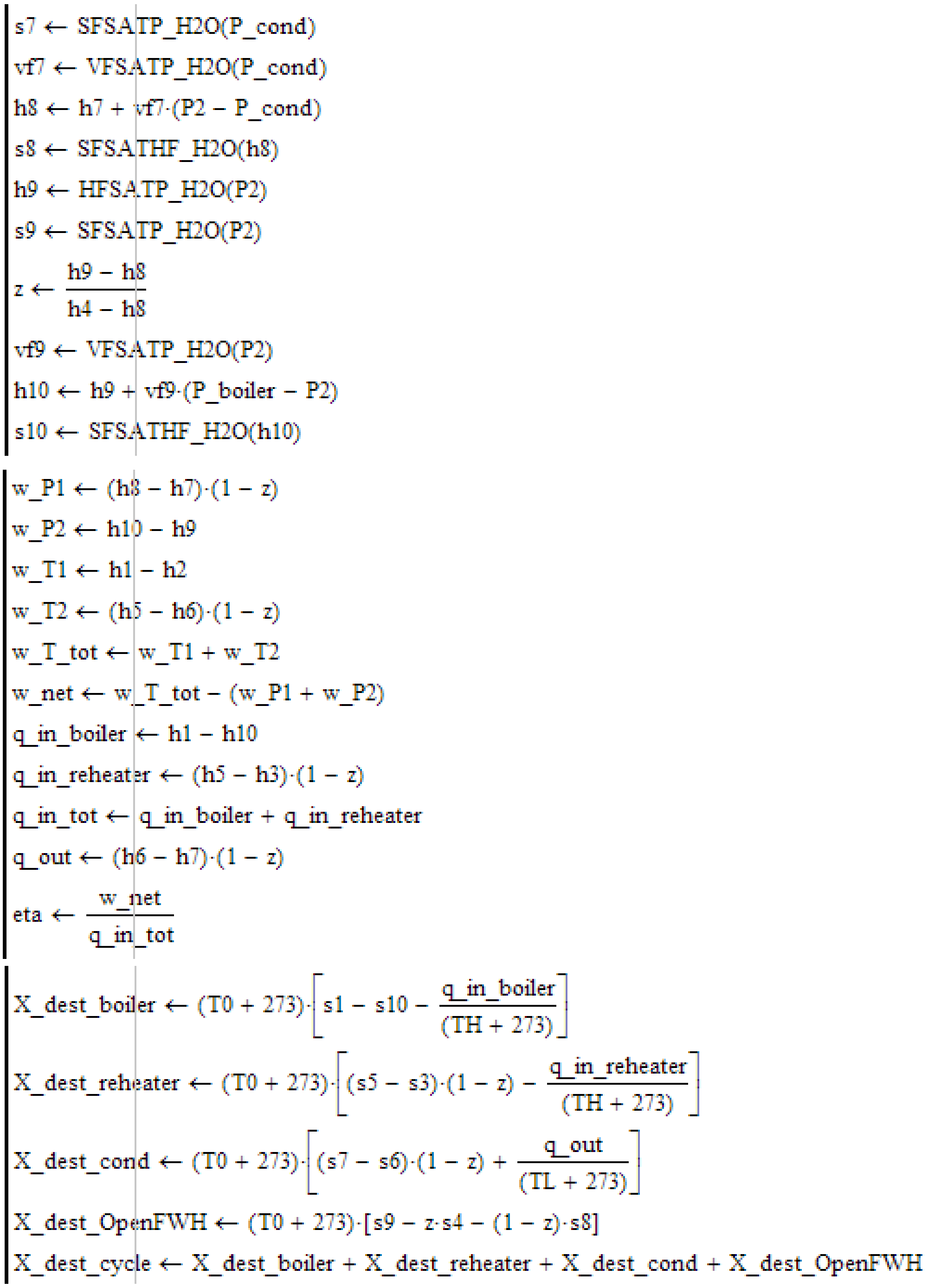
==

Prob.3.54 Write a Mathcad program to find out the exergy destroyed in various processes for an **Ideal Reheat Regenerative Rankine cycle** with one open feed water heater (FWH), operating between a condenser pressure P_cond, Turbine inlet temp T1, and boiler pressure of P_boiler. Extraction pressure = P2. Reheat temp. = T5. Ambient conditions: P0, T0 (C). Assume that heat is transferred in boiler at a constant temp TH (deg.C), and heat is rejected to ambient at constant temp TL (deg.C).

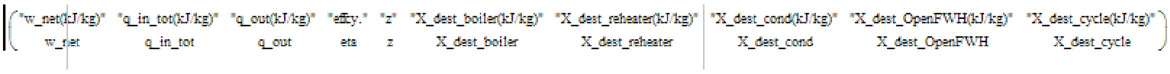




```
Exergy_Ideal_Reheat_Regen_Rankine(P_cond,P_boiler,P2,T1,T5,TH,TL,P0,T0) :=

    h1 ← enthalpy_H2O(P_boiler,T1)
    s1 ← entropy_H2O(P_boiler,T1)
    s2 ← s1
    s3 ← s1
    s4 ← s1
    sg2 ← SGSATP_H2O(P2)
    x2 ← quality_Ps_H2O(P2,s2)  if  s2 ≤ sg2
    h2 ← enthalpy_2phase_Px_H2O(P2,x2)  if  s2 ≤ sg2
    h2 ← enthalpy_H2O_Ps(P2,s2)  if  s2 > sg2
    h3 ← h2
    h4 ← h2
    h5 ← enthalpy_H2O(P2,T5)
    s5 ← entropy_H2O(P2,T5)
    s6 ← s5
    sg6 ← SGSATP_H2O(P_cond)
    x6 ← quality_Ps_H2O(P_cond,s6)  if  sg6 ≥ s6
    h6 ← enthalpy_2phase_Px_H2O(P_cond,x6)  if  sg6 ≥ s6
    h6 ← enthalpy_H2O_Ps(P_cond,s6)  if  sg6 < s6
    h7 ← HFSATP_H2O(P_cond)
```

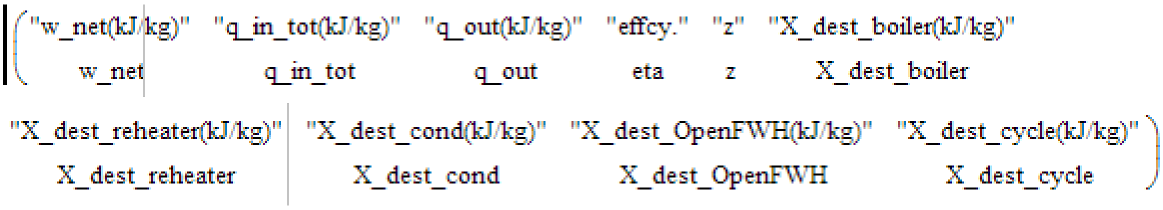


```
s7 ← SFSATP_H2O(P_cond)
vf7 ← VFSATP_H2O(P_cond)
h8 ← h7 + vf7·(P2 − P_cond)
s8 ← SFSATHF_H2O(h8)
h9 ← HFSATP_H2O(P2)
s9 ← SFSATP_H2O(P2)
       h9 − h8
z ← ─────────
       h4 − h8
vf9 ← VFSATP_H2O(P2)
h10 ← h9 + vf9·(P_boiler − P2)
s10 ← SFSATHF_H2O(h10)

w_P1 ← (h8 − h7)·(1 − z)
w_P2 ← h10 − h9
w_T1 ← h1 − h2
w_T2 ← (h5 − h6)·(1 − z)
w_T_tot ← w_T1 + w_T2
w_net ← w_T_tot − (w_P1 + w_P2)
q_in_boiler ← h1 − h10
q_in_reheater ← (h5 − h3)·(1 − z)
q_in_tot ← q_in_boiler + q_in_reheater
q_out ← (h6 − h7)·(1 − z)
          w_net
eta ← ──────────
        q_in_tot

                                      ┌               q_in_boiler ┐
X_dest_boiler ← (T0 + 273)·│ s1 − s10 − ─────────── │
                                      └                (TH + 273)  ┘
                                        ┌                                q_in_reheater ┐
X_dest_reheater ← (T0 + 273)·│ (s5 − s3)·(1 − z) − ───────────── │
                                        └                                 (TH + 273)   ┘
                                    ┌                             q_out    ┐
X_dest_cond ← (T0 + 273)·│ (s7 − s6)·(1 − z) + ────────── │
                                    └                           (TL + 273) ┘
X_dest_OpenFWH ← (T0 + 273)·[s9 − z·s4 − (1 − z)·s8]
X_dest_cycle ← X_dest_boiler + X_dest_reheater + X_dest_cond + X_dest_OpenFWH
```



```
⎛"w_net(kJ/kg)"  "q_in_tot(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "z"  "X_dest_boiler(kJ/kg)"  "X_dest_reheater(kJ/kg)"  "X_dest_cond(kJ/kg)"  "X_dest_OpenFWH(kJ/kg)"  "X_dest_cycle(kJ/kg)"⎞
⎝    w_net           q_in_tot          q_out         eta     z      X_dest_boiler           X_dest_reheater           X_dest_cond           X_dest_OpenFWH           X_dest_cycle    ⎠
```

For clarity, the last line above, i.e. the output matrix is reproduced below:



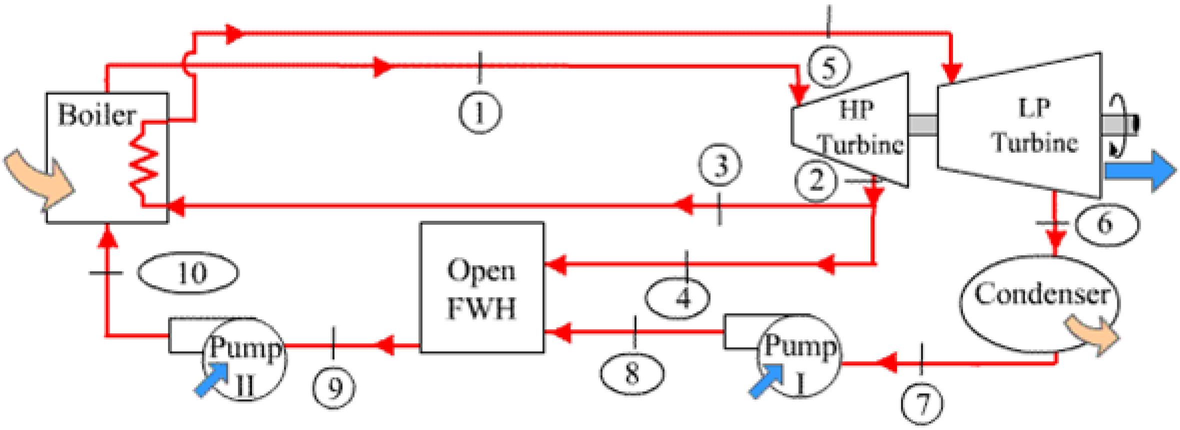
```
⎛"w_net(kJ/kg)"  "q_in_tot(kJ/kg)"  "q_out(kJ/kg)"  "effcy."  "z"  "X_dest_boiler(kJ/kg)"
⎝    w_net           q_in_tot           q_out          eta      z      X_dest_boiler

"X_dest_reheater(kJ/kg)"  "X_dest_cond(kJ/kg)"  "X_dest_OpenFWH(kJ/kg)"  "X_dest_cycle(kJ/kg)"⎞
     X_dest_reheater           X_dest_cond           X_dest_OpenFWH            X_dest_cycle   ⎠
```

Explanation for the above Function:

This function gives exergy destroyed in various processes of an Ideal Reheat Regenerative Rankine cycle.

First line is the LHS of the Function, and defines the Function. Quantities inside brackets are the **inputs**, where pressures P_cond, P_boiler and the Reheat pressure (or feedwater heater pressure), P2 are in kPa. Turbine inlet temperature,T1, Reheat temp. T5, Source temp for heat supplied in boiler, TH, Sink temp for heat rejected in condenser, TL, are in deg.C and ambient conditions are: (P0, T0). **Outputs** are presented compactly in a Matrix in the last step on the RHS. In the **output matrix**, we have: Net work (w_net), Total heat input in boiler (q_in_tot), Heat rejected in condenser (q_out), Thermal efficieny (eta), fraction of steam sent to open FWH (z), Exergy destroyed in boiler(X_dest_boiler), Exergy destroyed in open FWH (X_dest_OpenFWH), Exergy destroyed in condenser (X_dest_cond), and Exergy destroyed in cycle (X_dest_cycle). Units of each quantity are also given in output.

Prob.3.55 A steam power plant operates on an ideal reheat-regenerative Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 550°C and leaves at 0.8 MPa. Some steam is extracted at this pressure to heat the feedwater in an open feedwater heater. The rest of the steam is reheated to 500°C and is expanded in the low-pressure turbine to the condenser pressure of 10 kPa. Determine (*a*) the mass flow rate of steam through the boiler and (*b*) the thermal efficiency of the cycle. Determine the exergy destruction in the reheater and open FWH. Assume a source temperature of 1800 K and a sink temperature of 290 K. [2]



Data:

P_cond := 10 kPa   P_boiler := 10000 kPa   P2 := 800 kPa

TH := 1800 − 273 C   TL := 290 − 273 C   T1 := 550 C   T5 := 500 C

T0 := TL   P0 := 100 kPa   Power_output := 80000 kW

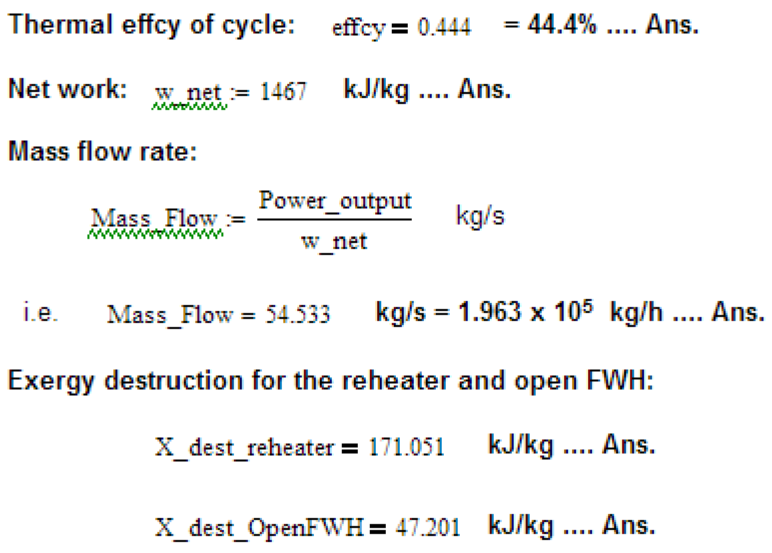
T_cond := TSAT_H2O(P_cond) i.e. T_cond = 45.806 C

Applying the Mathcad Function for exergy of Ideal, Reheat Regen. Rankine cycle, we get:

Exergy_Ideal_Reheat_Regen_Rankine(P_cond, P_boiler, P2, T1, T5, TH, TL, P0, T0) =

	0	1	2	3	4	5	6	7	8	9
0	"w_net(kJ/kg)"	"q_in_tot(kJ/kg)"	"q_out(kJ/kg)"	"effcy."	"z"	"X_dest_boiler(kJ/kg)"	"X_dest_reheater(kJ/kg)"	"X_dest_cond(kJ/kg)"	"X_dest_OpenFWH(kJ/kg)"	"X_dest_cycle(kJ/kg)"
1	$1.467 \cdot 10^3$	$3.305 \cdot 10^3$	$1.838 \cdot 10^3$	0.444	0.202	913.784	171.051	166.427	47.201	$1.298 \cdot 10^3$

Thus, we have:



Thermal effcy of cycle: effcy = 0.444 **= 44.4% .... Ans.**

Net work: w_net := 1467 **kJ/kg .... Ans.**

Mass flow rate:

$$\text{Mass\_Flow} := \frac{\text{Power\_output}}{\text{w\_net}} \quad \text{kg/s}$$

i.e. Mass_Flow = 54.533 **kg/s = 1.963 x 10^5 kg/h .... Ans.**

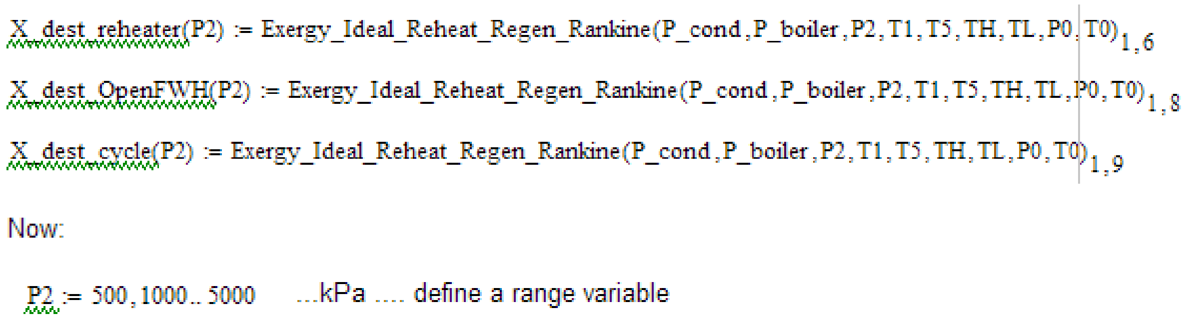
Exergy destruction for the reheater and open FWH:

X_dest_reheater = 171.051 **kJ/kg .... Ans.**

X_dest_OpenFWH = 47.201 **kJ/kg .... Ans.**

Plot exergy destroyed in the reheater, open FWH and the whole cycle as the feed water heater pressure varies from 500 kPa to 5 MPa:

First, define the exergy destroyed in the reheater, open FWH, and tin he Cycle as a function of P2:



$\text{X\_dest\_reheater(P2)} := \text{Exergy\_Ideal\_Reheat\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, T5, TH, TL, P0, T0)}_{1,6}$

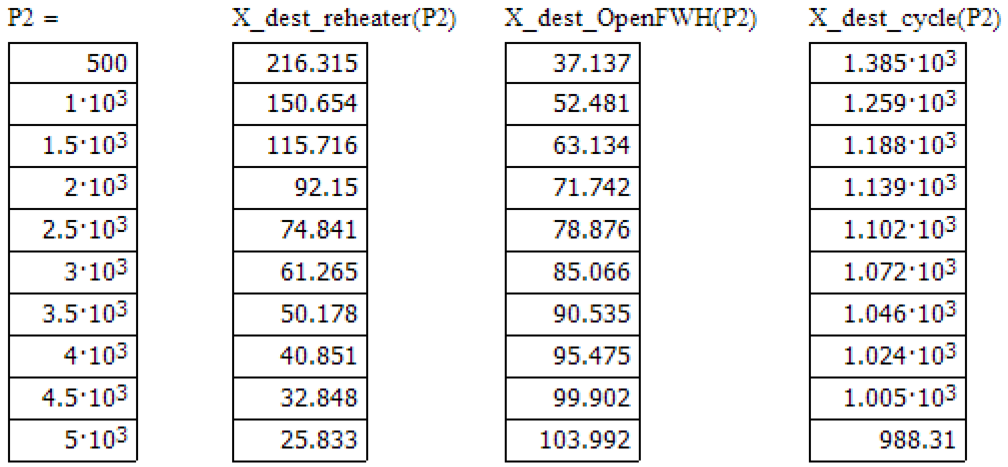
$\text{X\_dest\_OpenFWH(P2)} := \text{Exergy\_Ideal\_Reheat\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, T5, TH, TL, P0, T0)}_{1,8}$

$\text{X\_dest\_cycle(P2)} := \text{Exergy\_Ideal\_Reheat\_Regen\_Rankine(P\_cond, P\_boiler, P2, T1, T5, TH, TL, P0, T0)}_{1,9}$

Now:

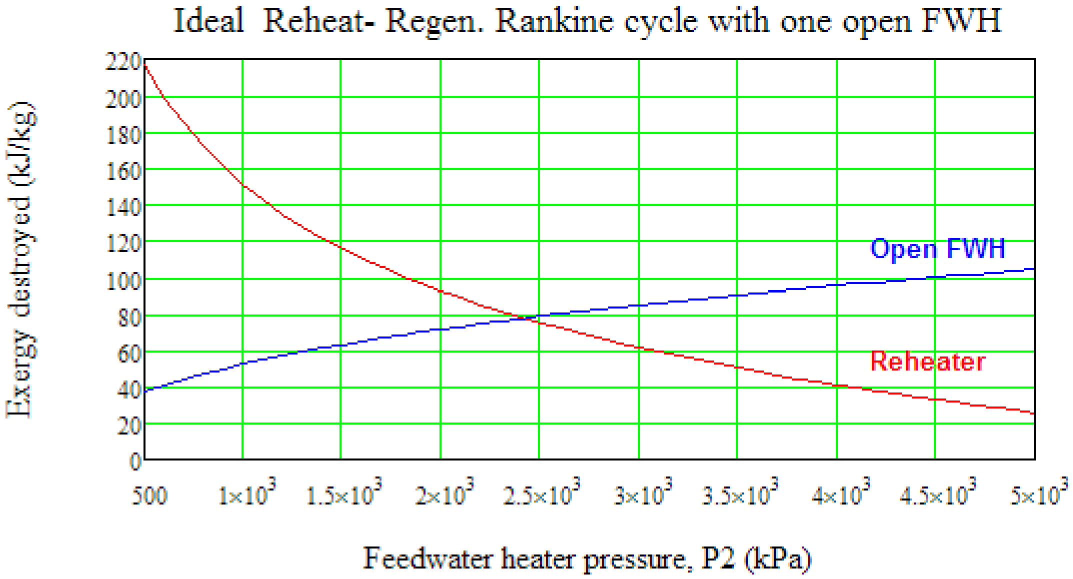
P2 := 500, 1000 .. 5000 ...kPa .... define a range variable

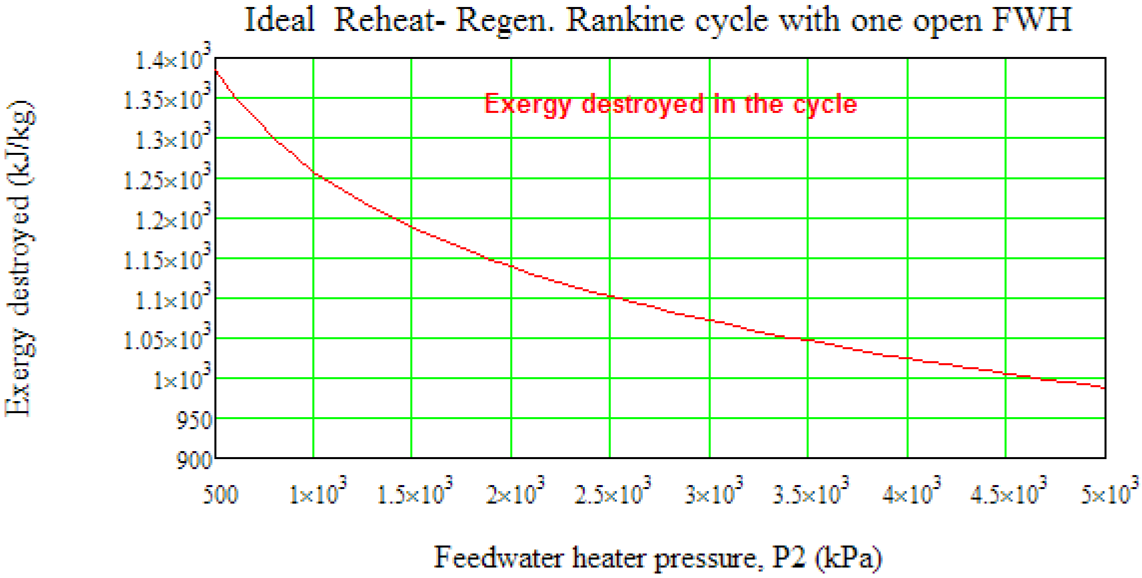
And, we get:



P2 =	X_dest_reheater(P2)	X_dest_OpenFWH(P2)	X_dest_cycle(P2)
500	216.315	37.137	$1.385\cdot10^3$
$1\cdot10^3$	150.654	52.481	$1.259\cdot10^3$
$1.5\cdot10^3$	115.716	63.134	$1.188\cdot10^3$
$2\cdot10^3$	92.15	71.742	$1.139\cdot10^3$
$2.5\cdot10^3$	74.841	78.876	$1.102\cdot10^3$
$3\cdot10^3$	61.265	85.066	$1.072\cdot10^3$
$3.5\cdot10^3$	50.178	90.535	$1.046\cdot10^3$
$4\cdot10^3$	40.851	95.475	$1.024\cdot10^3$
$4.5\cdot10^3$	32.848	99.902	$1.005\cdot10^3$
$5\cdot10^3$	25.833	103.992	988.31

Now, plot the results:





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