

Thermal fluid analysis of combined power and desalination concepts for a high temperature reactor

R. Nel

Student Number:21891907

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Supervisor: Prof. P.G. Rousseau
Co-Supervisor: Mr. J.P. van Ravenswaay

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ABSTRACT

South Africa is on a path of dramatically increasing its energy supplying capabilities. Eskom (the main utility supplying electricity to the national grid) recently announced that future power station technologies will focus on renewable energy and nuclear power. This is done in an effort to reduce South Africa's dependence on burning fossil-fuels and thereby decreasing CO₂ emissions and other harmful gases. This, together with the fact that there are a lot of fresh water scarce areas especially along the Eastern Cape coast of South Africa, is what inspired this study. This study investigates the use of a 200 MW_{th} High Temperature Reactor (HTR) for cogeneration purposes. Heat from the reactor is utilised for electricity generation (Rankine cycle) and process heat (desalination). Two desalination concepts were evaluated thermodynamically and economically, namely Multi-Effect Distillation (MED) and Reverse Osmosis (RO). Computer software, Engineering Equation Solver (EES), was used to simulate different cycle configurations, where the heat available in the condenser was increased successively.

The coupling of the two desalination technologies with a HTR was compared and it was found that a RO plant produces nearly twice as much water while sending the same amount of electricity to the grid (compared to coupling with MED). Coupling options were investigated and each simulation model was optimised to deliver maximum output (power and water).

The best configuration was found to be the coupling of a HTR with a RO plant producing 86.56 MW generator power. This is equal to 2077 MWh/day. Using 332 MWh/day for desalination through RO, delivers 73 833 m³/day fresh water and results in 1745 MWh/day sent to the grid. This scenario is the best option from a thermodynamic and economic point of view. From an investment point of view, it will produce an Internal Rate of Return (IRR) of 10.9 percent and the Net Present Value (NPV) is calculated to be R 2,486,958,689.

The results and analysis for the different cycle configurations are presented in such a way that an easy comparison can be made.

KEYWORDS

High Temperature Reactor (200 MW_{th})

Cogeneration

Desalination

Multi Effect distillation

Reverse Osmosis

Thermodynamically

Economically

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LIST OF ABBREVIATIONS

<i>Abbreviation</i>	<i>Description</i>
ED	Electrodialysis
EDR	Electrodialysis Reversal
EES	Engineering Equation Solver
ESKOM	Electricity Supplying Commission of South Africa
CSP	Concentration Solar Plant
HPP	High Pressure Pump
HPT	High Pressure Turbine
HTR	High Temperature Reactor
HTGR	High Temperature Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
IPP	Intermediate Pressure Pump
IPT	Intermediate Pressure Turbine
LOCA	Loss Of Coolant Accident
LPP	Low Pressure Pump
LPT	Low Pressure Turbine
MED	Multi-Effect Distillation
MED-TVC	Multi-Effect Distillation with Thermal Vapour Compression
MSF	Multi-Stage Flash
MW _e	Mega-Watt Electrical
MW _{th}	Mega-Watt Thermal
NF	Nanofiltration
PBMR	Pebble Bed Modular Reactor
PBR	Pebble Bed Reactor
ppm	Parts per million
RCS	Reactor Coolant System
RO	Reverse Osmosis
SA	South Africa
RPV	Reactor Pressure Vessel
TDS	Total Dissolved Solids
USD	United States Dollar
USA	United States of America

NOMENCLATURE

Symbol	Description
C	Constant for friction factor for pressure losses for laminar flow in a pipe
f_{IP}	Fraction of bled steam taken at intermediate pressure for feedwater heating
f_{LP}	Fraction of bled steam taken at low pressure for feedwater heating
f	Friction factor for pressure losses
g	Gravity = 9.81 m/s^2
h_x	Enthalpy of working fluid at node x
h_{xs}	Static enthalpy of working fluid at the exit of an isentropic process at node x
h_{0x}	Total enthalpy of working fluid at the exit of an isentropic process at node x
m_{dot}_R	Steam generator mass flow rate
m_{dot}_1	Mass flow rate of bled steam at intermediate pressure
m_{dot}_2	Mass flow rate of bled steam at low pressure
m_{dot}_e	Mass flow at end of increment
m_{dot}_i	Mass flow at start of increment
P_x	Pressure of working fluid at node x
P_{0x}	Total pressure of working fluid at node x
Q_C	Heat rejected by condenser
Q_G	Electricity delivered by the generator
Q_R	Reactor heat input
Q_{LPP}	Heat input by low pressure pump
Q_{IPP}	Heat input by intermediate pressure pump

NOMENCLATURE (Continued)

Symbol	Description
Q_{HPP}	Heat input by high pressure pump
Q_{LPT}	Work done by low pressure turbine
Q_{IPT}	Work done by intermediate pressure turbine
Q_{HPT}	Work done by high pressure turbine
Re	Reynolds number for working fluid
T_x	Static temperature of working fluid at node x
T_{0x}	Total pressure of working fluid at node x
V_x	Velocity of working fluid at node x
W_x	Work done on working fluid at node x
x_x	Quality of working fluid at node x
η_p	Pump efficiency
ρ_x	Density of the working fluid
η_{HPT}	Isentropic efficiency of high pressure turbine
η_{IPT}	Isentropic efficiency of intermediate pressure turbine
η_{LPT}	Isentropic efficiency of low pressure turbine
η	Cycle efficiency
s_x	Entropy of working fluid at node x
z_e	Height at end of increment
z_i	Height at start of increment
Δp_{0L}	Pressure loss due to friction and geometry
s_x	Entropy of working fluid at node x

1. INTRODUCTION

South Africa has a national grid that is mainly powered by large centralised power stations. This configuration (centralised) results in an unstable network when compared to a distributed-type network, made up of smaller, distributed power stations spread over the country. Out of the nine provinces in South Africa, five have base load power stations and peaking stations. This means that there are huge energy losses because of the distance between some of the base load power stations and the end-users.

Distributed generation is advantageous in the sense that distribution losses are reduced. Technologies which can be used in the implementation of such a distributed network include: Wind Farms, Solar Power Stations, Hydro Power or distributed stand-alone Nuclear Power Stations spread across the country. From the list above there are restrictions on some of these Power Plants operating in a country like South Africa. Wind Farms require many wind turbines and a lot of open space to be of significance. Hydro Stations are not feasible as base load stations in South Africa as we do not have sufficient water reserves. As for solar power, Eskom is planning to construct a Concentrating Solar Plant (CSP) in the Northern Cape. Countries like the USA and Spain are embarking on employing many such CSP's that can generate up to 50MW per solar plant.

A very plausible solution is the application of distributed nuclear reactors. The reactor should be inherently safe and relatively cost effective. Since the 1960's research has been done on the High Temperature Gas Cooled Pebble Bed Modular Reactor. In 1999 the Pebble Bed Modular Reactor Company Pty (Ltd) was established in South Africa. The founder investors in the project are Westinghouse Electric Company LCC, Eskom Holdings Limited and the Industrial Development Corporation of South Africa Limited (PBMR, 2006). The PBMR did extensive design and development on high temperature reactor technology. The high temperature which is produced within the High Temperature Gas-Cooled Reactor (HTGR) can be an excellent process heat source for the production of one of South Africa's biggest concerns – the supply of fresh water, especially in some of the coastal areas. The fresh water can be produced by desalination of seawater. This makes the application of distributed HTR's a feasible solution to two of South Africa's biggest challenges – the production of electricity and fresh water.

2. BACKGROUND

Desalination is the process of removing salts and impurities from seawater (and other water) and producing fresh water. According to Henthorne (2003) this product water can then be used for a variety of applications:

- It can be treated and used as drinking water in water scarce areas.
- Used as process water where high purities of water are necessary, such as demineralised water used in power stations.
- Zero discharge applications that require water for pharmaceutical, electronics, bio-medical, mining, power, petroleum, beverage, tourism and pulp-paper industries.
- The treatment of wastewater to be re-used.

Energy is needed in order to desalinate seawater. Energy can be obtained from electricity (membrane processes) or heat (distillation processes) or a combination of these. The following section investigates the different technologies used to desalinate water and the energy inputs of each.

2.1. Desalination processes used today

Membrane Processes

These processes make use of a semi-permeable membrane that separates salt feedwater into a high purity water stream and a high saline concentration water stream. These processes include (Henthorne, 2003):

- Reverse Osmosis (RO)
- Nanofiltration (NF)
- Electrodialysis (ED) and
- Electrodialysis Reversal (EDR)

RO and NF are processes that operate under high pressures. The feedwater is pumped at a sufficient pressure to overcome the osmotic pressure of the saline water, i.e. no natural osmosis can occur through the membrane. The high pressure saline stream is forced through the membrane and higher concentration saline water is left behind, while purified water exits the other end of the membrane. Figure 1 (Henthorne, 2003) shows an illustration of the configuration of the membranes used in RO and NF. Multiple membranes are placed in series in a membrane vessel.

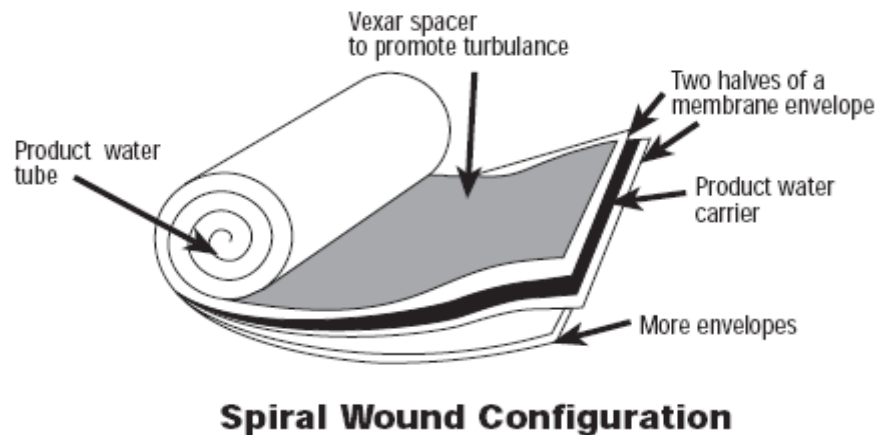


Figure 1: Spiral-wound configuration used in the high pressure desalination processes; RO and NF.

(Source: Henthorne, 2003)

ED and EDR produce low-salinity water by utilising electric potentials and attracting positive and negative ions from the feedwater. Figure 2 taken from AMTA (s.a.) shows a schematic of this technology. ED and EDR are usually used for brackish water. The salts dissolved in the feedwater are ionic (either positively or negatively charged) and this principle is used to attract positive or negative ions to electrodes with opposite electric charges (AMTA, s.a.). These membranes are configured in flat sheets.

Membrane methods in general are used in seawater, brackish water, ultra pure water, wastewater and many other processes (Henthorne, 2003). They require energy in the form of pump work because of the high pressure at which some of these processes operate.

ED / EDR Schematic

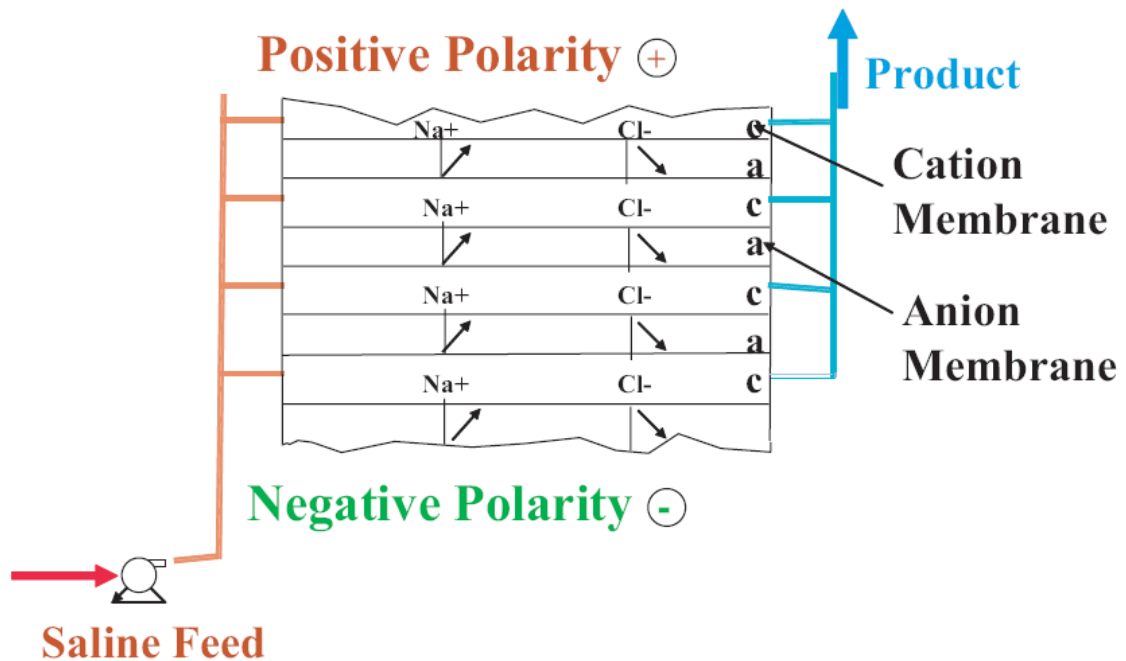


Figure 2: A schematic of the process followed with ED and EDR. (Source: AMTA, s.a.)

Thermal (Distillation) processes

The thermal desalination of seawater is done on exactly the same principle as rain is produced as fresh water. Seawater evaporates and clouds are formed which condenses and forms rain. Thermal processes utilise heat and distillates water at a low temperature and pressure to produce fresh water.

The thermal processes used today include (AMTA, s.a.):

- Multi-Stage Flash (MSF)
- Multi-Effect Distillation (MED) and
- Vapor Compression (VC)

MSF (shown in Figure 3 taken from Sidem (s.a.)) and MED (explained in section 3.2) require electric power and thermal energy to operate. Figure 3 shows the process followed with MSF. Seawater enters the system and passes through pipes through multiple stages. This cold seawater in the pipes acts as a surface against which the evaporated water (product) can condensate. The seawater is heated (112°C in this case) and passed through multiple stages. Each stage has a lower vapour pressure than the brine entering that stage. This causes the brine to evaporate in each stage. The vapour then condenses against the cold seawater pipes and is extracted as distillate.

With the use of higher temperature seawater the choice of materials used is a critical parameter. VC generally only utilises electrical energy, where the thermal energy is created from the compression process. Thermal processes typically produce product water at salinities of 5 to 50 parts per million (ppm) of Total Dissolved Solids (TDS) depending on the process used and the plant design (AMTA, s.a.).

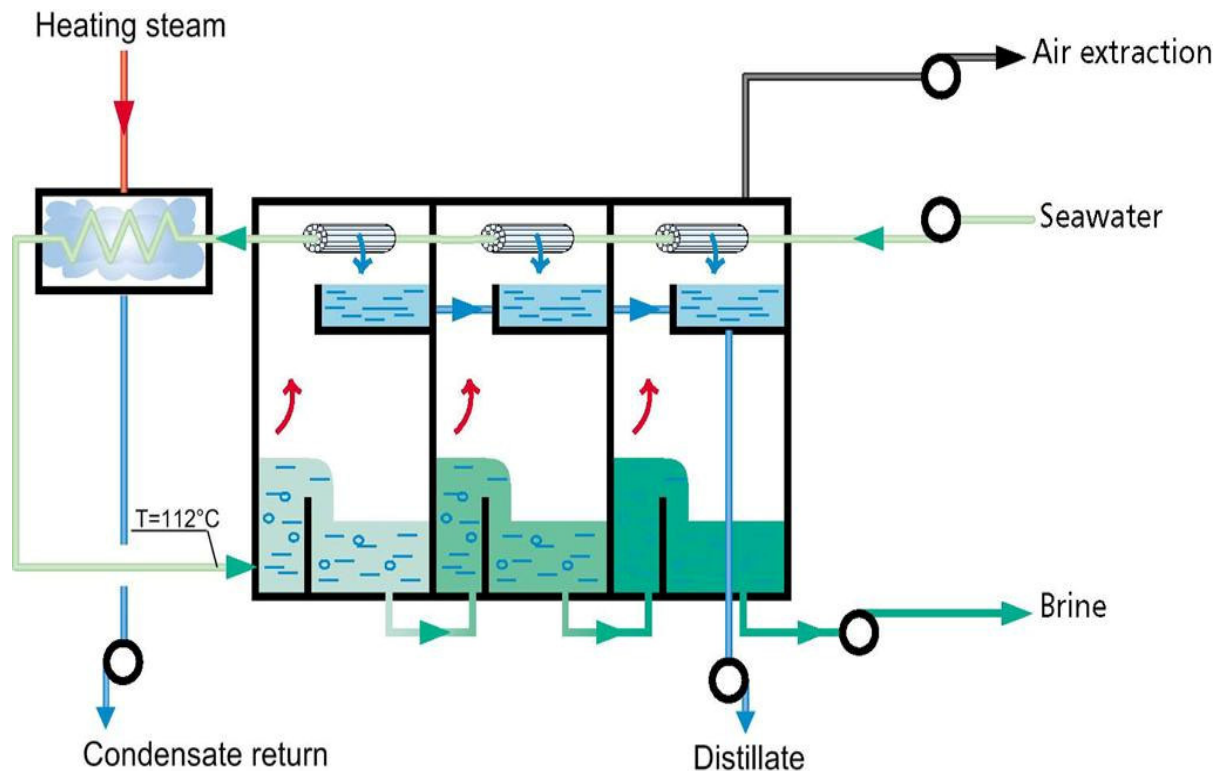


Figure 3: A schematic of the process followed with MSF. (Source: Sidem, s.a.)

2.2. General HTGR characteristics

According to Lamarsh and Baratta (2001:161), HTGR technology is summarised as follows:

- HTGR's are very useful for generating electricity or for producing process heat.
- Electricity can be produced by using an indirect Rankine cycle or a direct Brayton cycle because of the high temperature of the helium at the outlet of the core.
- Capable of producing process heat ranging from 50°C to 950°C.
- HTGR's are inherently safe as the maximum temperature that the fuel can reach is not high enough to damage the fuel.

- It is a graphite-moderated, helium-cooled, thermal reactor. Taking helium as the coolant has the advantage that it is far more inert than CO₂ for example.
- At startup conditions, HTGR's are fueled with either uranium or a mixture of thorium and highly enriched uranium. The production of ²³³U from thorium does replace some of the ²³⁵U, but as the HTGR is not a breeder reactor there must always be some ²³⁵U present in the core. Thus, the core at equilibrium conditions contains ²³⁵U, fertile ²³²Th and recycled ²³³U.
- The high temperature outlet of the helium – to a maximum of 950°C. This is ideal to be used directly in a gas turbine, eliminating an intermediate steam cycle. The reject steam after it has passed through the gas turbine can be used for other process heat applications.

2.3. Safety and economical aspects of nuclear desalination

Producing water through nuclear desalination is concerned with three technologies: The nuclear installation itself, the desalination method used and the coupling system. Some methods for providing safety for the coupling systems are discussed later. The major safety concern lies with the nuclear installation. Leakage of radioactivity to the product water should be avoided at all times, during normal operation and during a transient situation. Any variation in steam demand from the desalination plant should not cause a hazardous situation for the nuclear plant. Constant monitoring of radioactive material in the product water is to be done to provide constant feedback for safety protection. Quick decision making is crucial when operating nuclear desalination plants in case of an accident. To further mitigate the transport of radioactive materials to the product water an intermediate isolation loop is used.

Constant monitoring of radioactive materials, such as Tritium, needs to be done in the heating steam and product water. A list of international limits of tritium in drinking water is given in Table 1 (source: Anon, 2010:9). A near zero release of radioactive materials to the product water needs to be maintained. The risk of an accidental radioactivity carry-over also needs to be analysed. An agreement of all relevant parties on safety and quality standards and clear regulations are of utmost importance when desalination is done using nuclear heat (Anon, 2000: 84).

Table 1: Limits for Tritium in drinking water. (Source: Anon, 2010:9)

Country	Tritium limit (Bq/L)	Country	Tritium limit (Bq/L)
Australia	76 103	USA	740
Finland	30 000	WHO	10 000
Canada	7000	Kazakhstan	7700
EU*	100	Switzerland	10 000

At least two mechanical barriers and pressure reversal mechanisms, between the primary coolant and the brine must be incorporated (ANON, 2000). In the case of a pressurised water reactor being used as heating source, the steam generator is the first barrier and the condenser is the second barrier of a back pressure turbine configuration. The following economical criteria are important when using nuclear desalination according to an IAEA report of 2000 (ANON, 2000):

- Cost of product
- Percentage of local currency
- Investment
- Payback period and rate of return (Internal Rate of Return)
- Price of the product
- Value of the product to the customer (Net Present Value)
- Financing
- Economy of scale
- Techno-economical optimisation and scheduling are also important

The product water cost is most commonly evaluated by summing all principal cost components for desalinated water (ANON, 2000):

- The capital cost (30%-50%)
- The cost of energy (50%-30%)
- O&M Cost (15%-25%)

3. ENGINEERING PROBLEM STATEMENT

This project will assess potential coupling configurations where the energy from a High Temperature Reactor (200 MW_{th}) is used to generate process heat for desalination applications. The aim is to define medium temperature reactor (Reactor Outlet Temperature of 700°C-750°C) configurations producing combined process heat and power that supports desalination of water through Multi-Effect Distillation, Reverse Osmosis plants or a combination of these.

Various plant configurations will be investigated and potential coupling options will be evaluated. It will determine a technology growth path strategy that will best build on the process steam configuration taking aspects such as the thermal-fluid analyses and a cost evaluation of MED versus RO, into account.

The coupling of a 200MW_{th} HTR to a MED plant is shown in Figure 4. In this figure the various values of the different parameters are shown which would be applicable to the configuration. This scenario will be adjusted using different condenser operating parameters, and in this way adjusting the amount of water and power that will be produced.

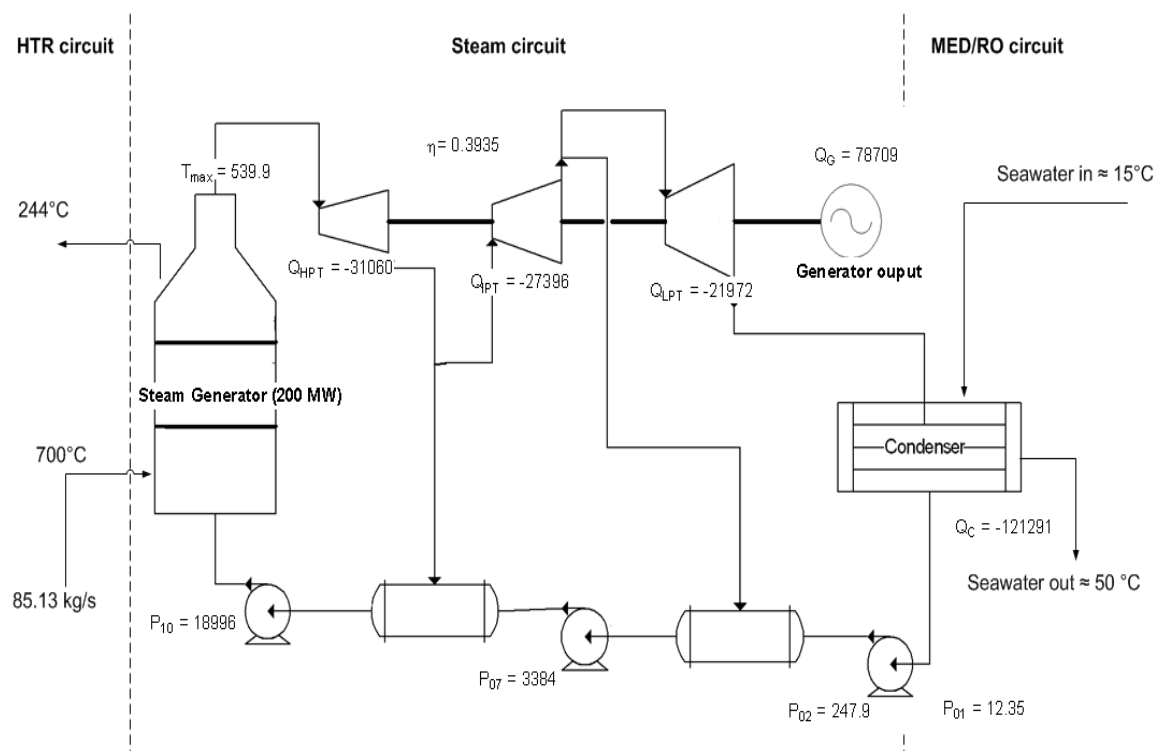


Figure 4: Schematic of coupling a 200MWth HTR to a MED plant.

One such an example where power is sacrificed for condenser heat is shown in Figure 4. In order to desalinate using MED technology, heat is needed. This heat is obtained from the condenser by putting a back-pressure on the low pressure turbine (LPT) and thereby condensing the steam at a higher temperature than normal.

The other alternative is to make use of RO to desalinate seawater. The condenser heat can be used to preheat the seawater and this will result in a 10-15 percent increase in fresh water produced by RO technology. (Cooley, et al. (2006))

This study will investigate the coupling of a HTR to MED and RO, respectively. The thermal efficiencies, water production rates and power produced will be compared and the optimal configuration will be determined.

4. PROJECT OBJECTIVES

The following objectives have to be achieved during the completion of the dissertation:

4.1. Literature Study

A detailed study has to be done on HTGR, particularly the PBR 200MW_{th} design. Detailed plant parameters have to be obtained and a thorough understanding of the operation of the plant is needed. In order to model the end-user process heat applications with Engineering Equation Solver (EES), plant parameters for a Multi-Effect Distillation plant and a Reverse Osmosis plant are needed. Previous configurations of nuclear heat being used for desalination will also be investigated.

4.2. Simulations

Cycle configuration simulations will be done using EES. Verification of results will be done with hand written calculations, without the help of computer software. Plant parameters will be identified when simulating a Rankine cycle with different condenser operating pressures. Increased condenser operating pressures results in higher condensing temperatures.

The increased heat that will be available in the condenser will be utilised in a MED plant for the purpose of desalinating seawater.

Only the PBR 200MW_{th} steam side will be modeled and used in the configurations. The steam generator will have as input helium at a certain temperature and pressure and this helium will then be used to heat up the secondary (steam) side. The most thermal efficient cogeneration configuration will be identified in which the plant is used to generate electricity and supply process heat to the application coupled to the reactor. An economic comparison will be done in which the internal rate of return (IRR) and net present value (NPV) will be calculated for each scenario. The most profitable configuration will be identified.

4.3. Analysis and Comparison

After each simulation is run, plant parameters will be tabulated for the chosen configuration. Water production will be determined using software in EES for MED. The results of each configuration simulation will be evaluated on a technical and high level economic basis.

5. LITERATURE STUDY

The growth path for a HTR has two possibilities. One growth path is for electricity generation from co-located 200MW_{th} reactors. The other is for cogeneration, generating electricity and process heat. This study focuses on determining a growth path strategy for the 200MW_{th} PBR reactor, in terms of electricity production versus process heat. To model the generation of electricity in this project the Rankine cycle will be used.

5.1. PBMR 200MW_{th}

The PBR design which is investigated is a 200MW_{th} design which delivers superheated steam through a steam generator. The steam produced from the cycle reaches a maximum temperature of 540°C . A HTGR typically uses silicon carbide-coated uranium particles encased by graphite to serve as moderator, for the fuel spheres. Helium is used as the coolant. These materials combined make a PBR inherently safe and free from risk of a meltdown.

PBMR is a HTR developed in South Africa by PBMR Pty (Ltd). Figure 5, taken from Adams (2009), shows a schematic for the PBMR cycle. It consists of the PBMR reactor core, blower, steam generator, pumps, turbines, condenser and generator. The working fluid used for cooling the core is helium.

The helium is forced through the PBMR core, passing through the fuel spheres and removing the heat created from fission from enriched uranium within the pebbles (fuel spheres). The heat in the helium is passed to water through a heat exchanger, called the Steam Generator. The water turns into steam and is used to generate electricity or for process heat applications like desalination. Fresh fuel is loaded at the top of the reactor and spent fuel is removed from the bottom of the vessel.

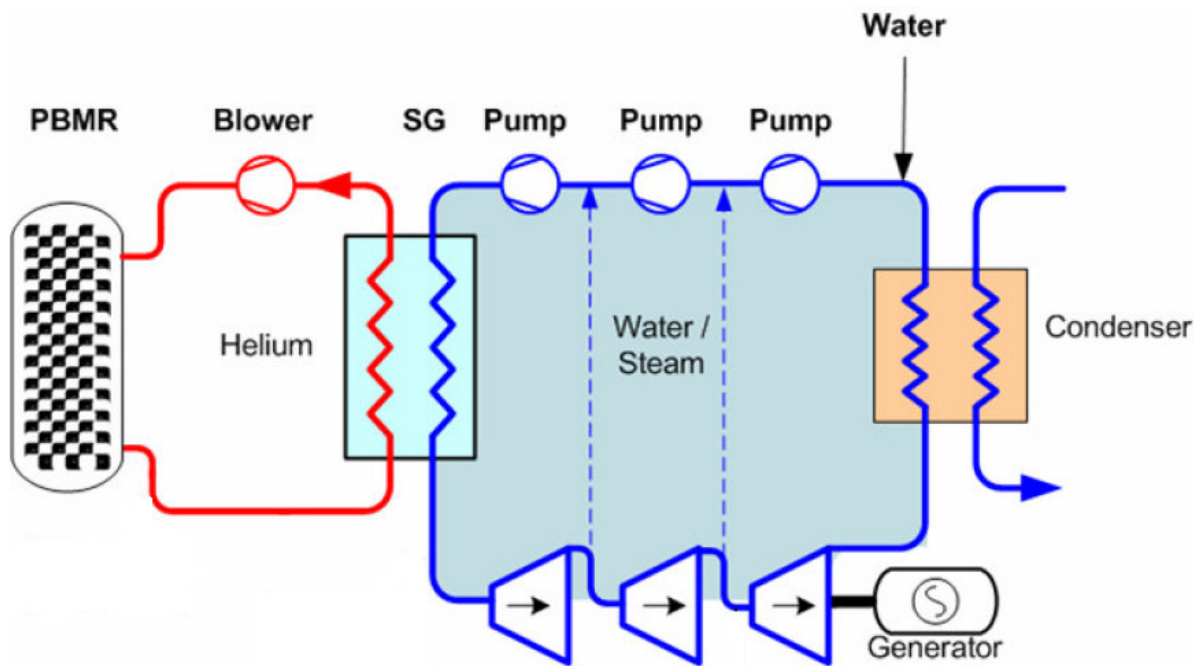


Figure 5: PBMR schematic. (Source: Adams, 2009)

When a sphere is removed from the bottom of the vessel it is measured for burn-up. If the sphere has reached its burn-up limit it is sent to the spent fuel storage and replaced with a fresh fuel sphere at the top of the reactor.

The PBMR has a vertical steel pressure vessel which contains and supports a metallic core barrel, which in turn supports the cylindrical fuel core. This cylindrical fuel core is surrounded on the side by an outer graphite reflector. The top and bottom of the core is surrounded by graphite structures which also serve as neutron reflectors. Vertical borings in the side reflector are provided for the reactivity control elements. Two diverse reactivity control systems are used to shut down the reactor in case of an emergency.

One of these systems consists of twenty four control rods in the outer reflector and the other system is small absorber spheres which are dropped in the eight borings in the central reflector. Figure 6 gives the layout of the pebble bed core and the path that the helium follows through the core, taken from Galperin and Shwageraus (s.a.).

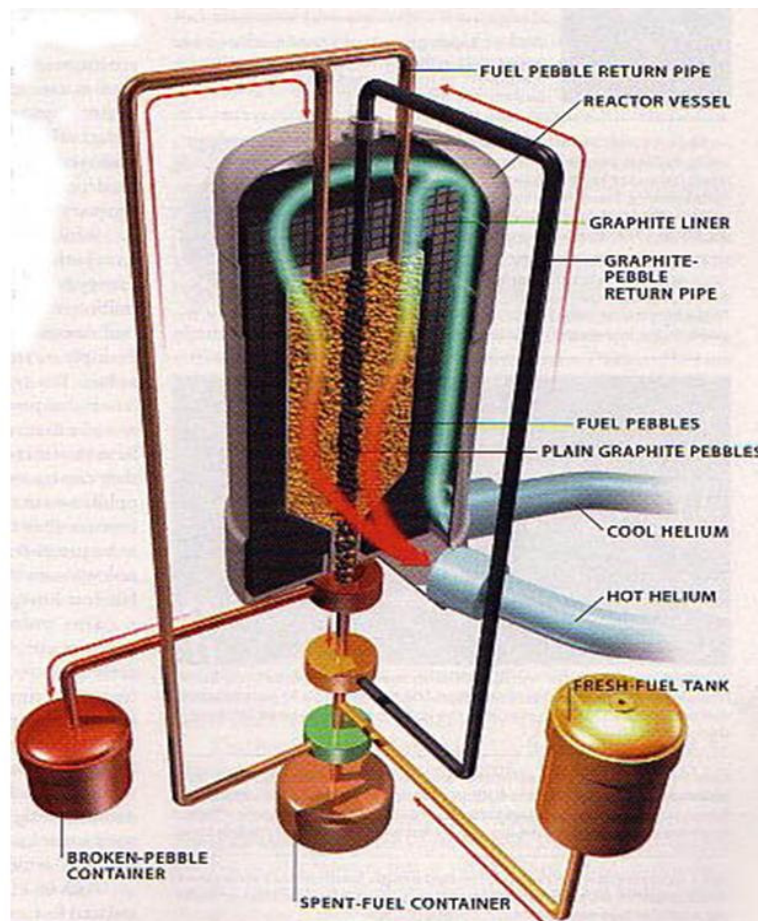


Figure 6: The pebble core. (Source: Galperin and Shwageraus, s.a.)

Fission occurs in particles of enriched uranium dioxide (UO_2), coated with silicon carbide and pyrolytic carbon. The particles are encased in graphite to form a fuel sphere or pebble about the size of a billiard ball. Figure 7 (Adams, 2009) shows a diagram of the pebbles. Each fuel sphere contains 7 g of uranium, of which $8 \pm 0.5\%$ is fissile ^{235}U and the remainder is ^{238}U . The core of the reactor contains about 360 000 of these fuel spheres. Each fuel sphere has a diameter of 60 mm and contains an internal graphite matrix filled with approximately 11 600 coated fuel particles (kernels).

Each of these kernels consists of a fuel core (UO_2) surrounded by several layers of carbon and one layer of Silicon Carbide. During normal operation the fuel spheres will reach a maximum temperature of about 850°C . This operating temperature is sufficiently low so that even during a loss of coolant accident (LOCA) the maximum temperature the fuel particles will reach is 1620°C . This upper limit on the temperature of the fuel particles makes the PBMR an inherent safe reactor. The average power density in the reactor is 3 MW/m^3 and the average outlet temperature from the reactor is 700°C .

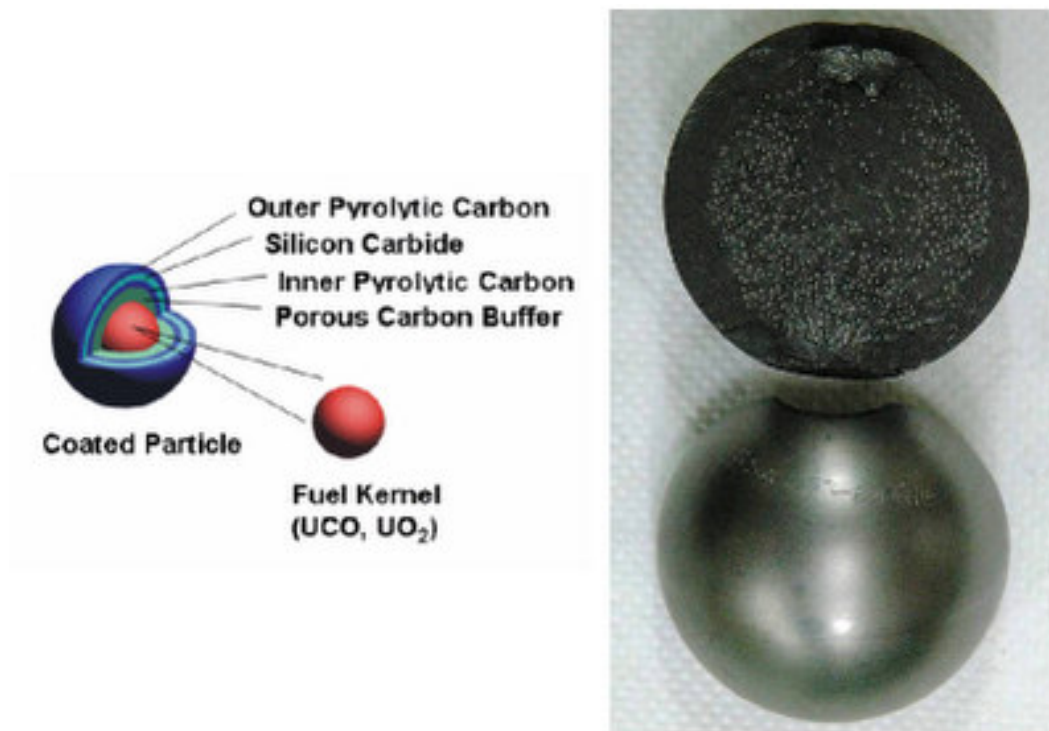


Figure 7: Schematic of a fuel pebble. (Source: Adams, 2009)

5.2. Multi-Effect Distillation (MED)

A multi-effect distillation (MED) plant is a desalination technology which operates using multiple cells or otherwise known as effects. Figure 8 (Flowserve, s.a.) gives a schematic of the layout of a MED plant. The number of cells varies depending on the amount of heat available for evaporation purposes. In Figure 8, the heat is supplied to the system in the form of steam. Seawater enters the system at the condenser (source pump), where some of the seawater is used to cool heated water entering the condenser (after passing through the different effects). The seawater is sent to the different cells for desalination (“Feedwater” in the diagram). In cell one the steam is used to heat and evaporate the seawater and to separate the distillate from the remaining seawater (brine). The brine is extracted and passed through successive cells using gravity and extracted after it passed through the condenser (“Brine Blowdown Pump”). The heated seawater is sent to the next cell, which operates at a lower temperature and pressure. In this way the heat in the seawater is used through successive cells to distillate the seawater until the condenser is reached and the remaining heat in the seawater is used to pre-heat the seawater entering the system.

Low pressure steam is generated in the first cell with a temperature and pressure of about 70°C and 0.35bar, respectively according to Hatzikioseyan and Vidali and Kousi (s.a.). The fresh water is extracted from the condenser using the distillate water pump.

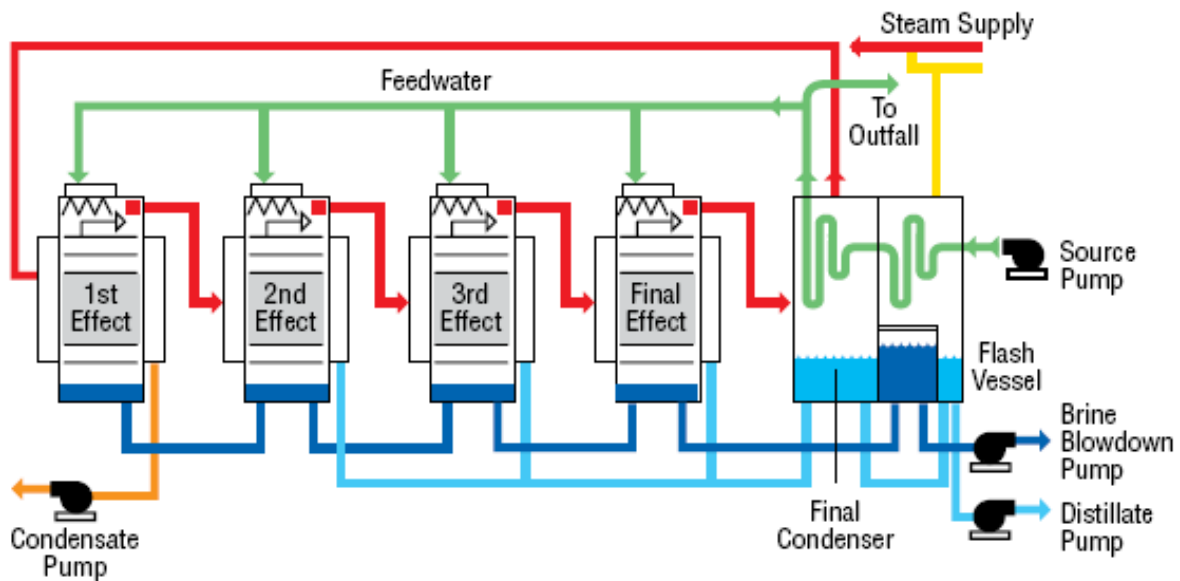


Figure 8: Schematic of a MED system. (Source: Flowserve, s.a.)

MED is a mature process and because of the scaling problems associated with the old design, MSF (Multi-Stage Flash) was introduced as an alternative in the 1960's. MSF plants in operation today operate with top brine temperatures between 90°C and 110°C. The top brine temperatures are limited by the solubility limits of calcium sulfate salts. MED plants are currently operating at about 65°C to prevent scale formation. The use of nanofiltration pretreatment with MED plants are promising higher temperatures in these plants without scaling. This will eventually lead to MED replacing MSF. MED has more efficient evaporation heat transfer than MSF. The product water is the same for MED and MSF, 5-25 TDS. MED uses 33 percent less electricity than MSF and can operate at lower feedwater temperatures of 65°C according to Van Ravenswaay et al (2007).

5.3. Reverse Osmosis (RO)

Reverse Osmosis (RO) is the most popular method for desalinating water. Osmosis is the term used for the phenomenon when two salt solutions of different concentrations are separated by a semi-permeable membrane and water then migrate from the weaker solution, through the membrane to the stronger solution until the salt concentrations of both solutions are in equilibrium.

Reverse Osmosis, as stated, is the reverse of this process by applying pressure on the stronger solution and then forcing the water to flow to the weaker solution. The membrane is porous, acting as a filter, and only allows water to flow through while blocking other salt molecules. The pores in the membrane are also restrictive to bacteria and other disease-causing pathogens. This makes RO an excellent solution to areas that do not have municipality treated water and that in general have water scarcity. Figure 9 (Flowserve, s.a.) shows a schematic of a typical RO plant.

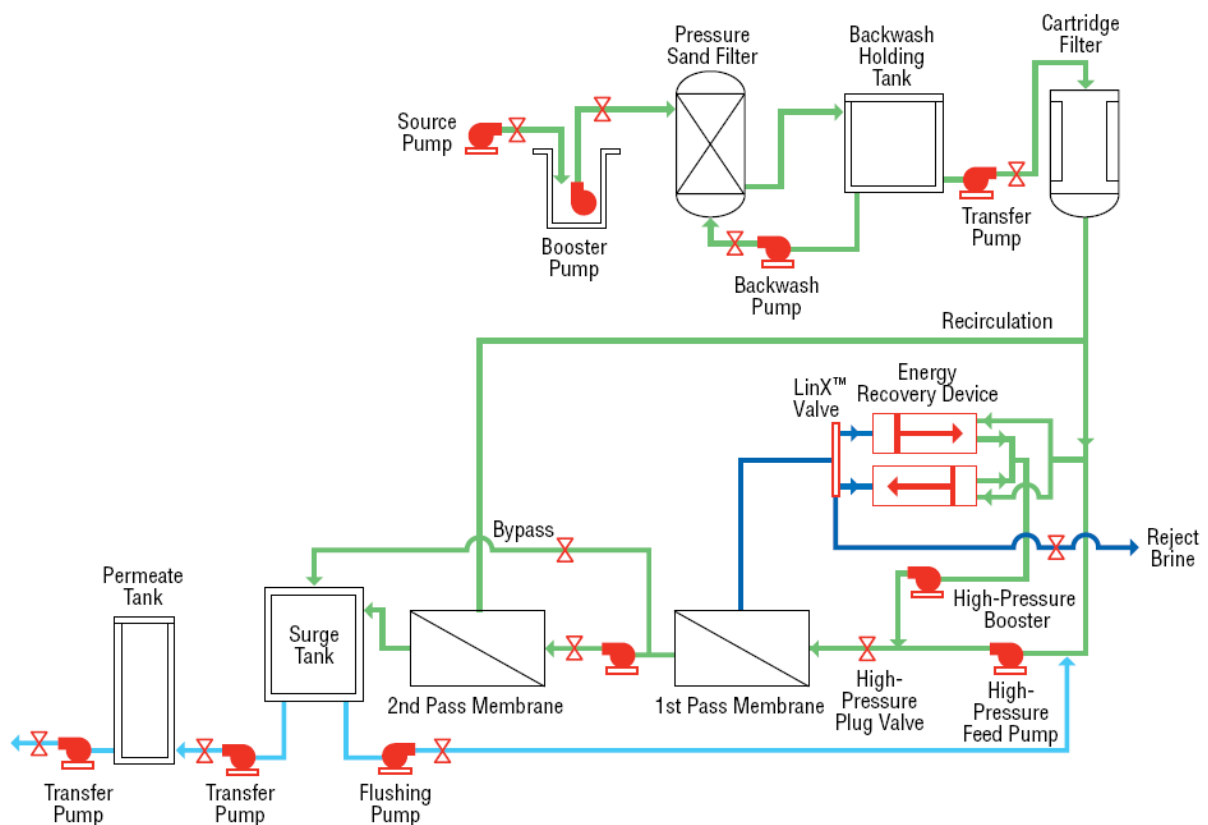


Figure 9: Schematic of a Reverse Osmosis system. (Source: Flowserve, s.a.)

The following two paragraphs are inspired by Anon (2010b). RO uses electricity rather than heat. Operating pressures required range between 70 and 80bar. This pressure is generated using pumps, which utilise electricity. This is one huge negative aspect of the application of RO in South Africa, seeing that South Africa is in an energy crisis. Stringent pretreatment of the feedwater is necessary to prevent premature failure of the membrane.

One disadvantage of the membrane is that the small pores block particles of large molecular structure like salt. More dangerous chemicals like pesticides, herbicides and chlorine which are molecularly smaller than water are allowed through. This is why a carbon filter must be placed in conjunction with the membrane to provide drinking water.

RO discharges a lot more brine when desalinating seawater than any of the thermal process. Compared to thermal processes, RO is a much slower technology. Pretreatment of the seawater used in the RO process leads to better efficiency. Using the waste heat from the condenser of the power station increases the temperature of the seawater and this leads to a higher membrane flux and producing approximately 10 percent more desalinated water for the same membrane area.

5.4. Rankine Cycle

The Rankine cycle is a thermodynamic cycle that is used all over the world for generating electricity. Energy from a heat source (Coal, Uranium, Solar, Gas, Oil, etc.) is used to convert water into steam. Steam is then used to do mechanical work and generate electricity. A schematic of the components in a basic Rankine cycle is shown in Figure 10 taken from Barber-Nichols (s.a.)

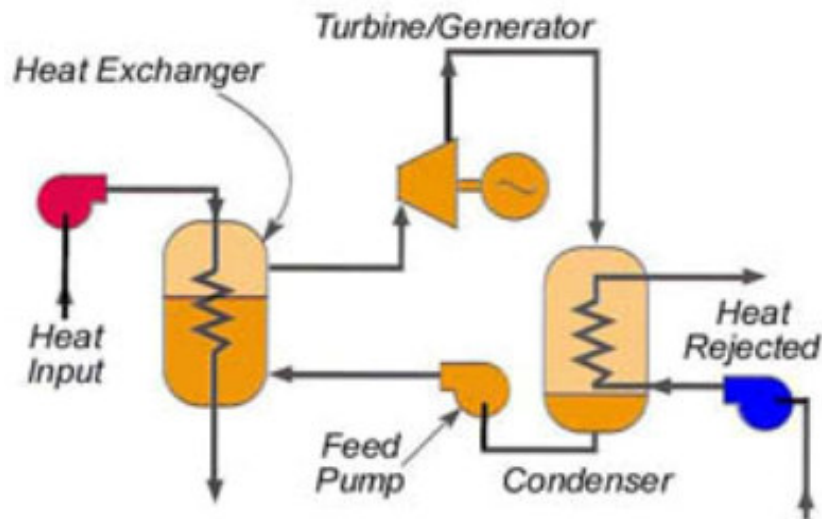


Figure 10: Schematic of the Rankine Cycle. (Source: Barber-Nichols, s.a.)

Figure 11 shows a numbered (1 to 4) T-s (Temperature-Entropy) diagram of the cycle. The manner in which the working fluid is circulated through the loop, passing through the different processes, is described as follows (Anon, s.a.):

- **Process 1-2:** The working fluid is pumped to a very high pressure [Liquid phase]
- **Process 2-3:** Heat is added at a constant pressure to the working fluid and the water is turned to steam. [Two phase]
- **Process 3-4:** The dry saturated vapor expands through the turbine delivering shaft work, which turns a generator and generates electricity.[Vapor phase]
- **Process 4-1:** The steam is condensed in a condenser where heat is removed to a heat sink at constant temperature and pressure. [Two phase]

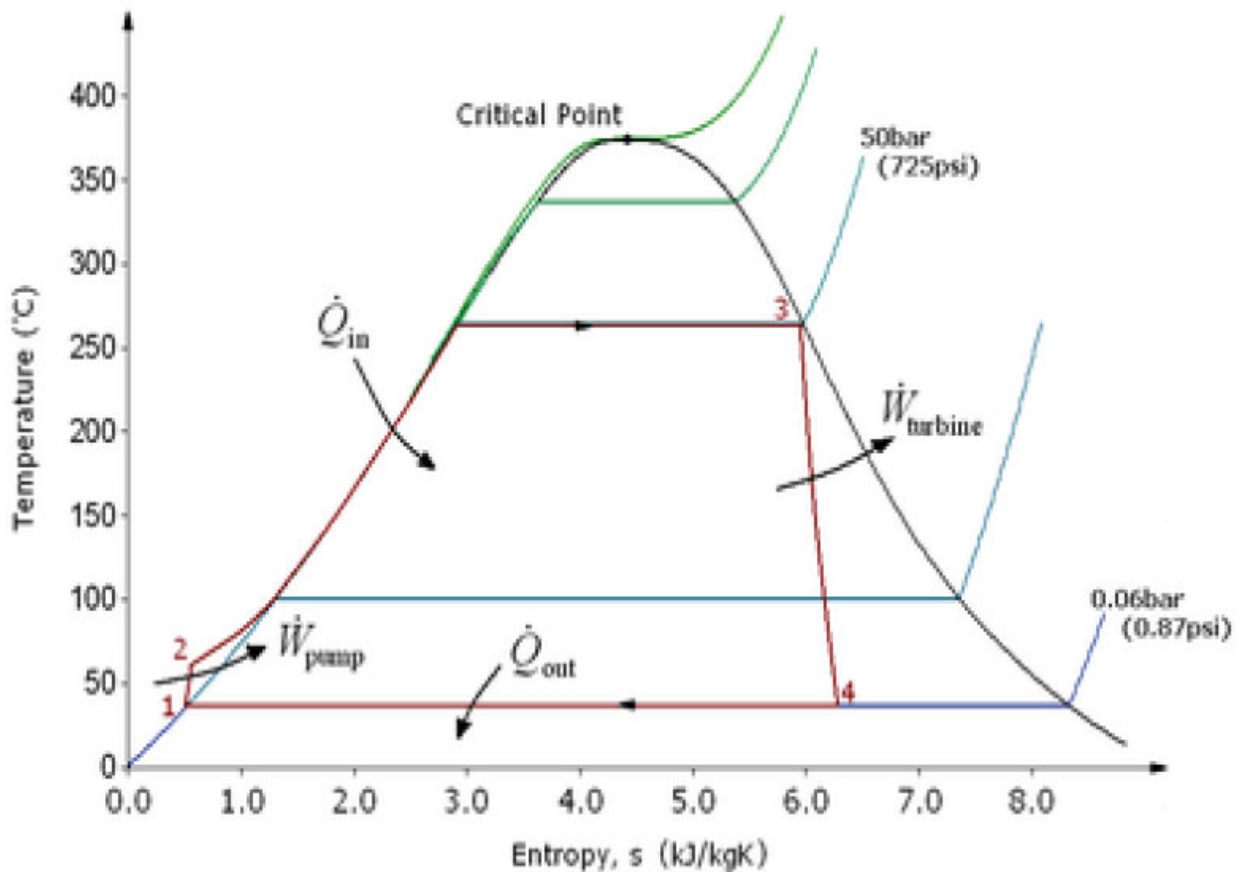


Figure 11: Temperature versus Entropy Graph showing the various stages of the Rankine cycle.
(Source: Anon, s.a.)

The Rankine cycle shown in Figure 11 is the basic Rankine cycle, showing what effect the different processes have on the working fluid. For a practical Rankine cycle there will be a need to superheat the steam in order to minimise droplets in the steam, which have an adverse effect on the turbine blades.

5.5. Coupling options

Coupling of a desalination plant to co-generation reactors is of major importance in terms of economic, technical and safety aspects. There are two options when coupling co-generation reactors to desalination plants according to Anon (2000):

1. Parallel co-generation
2. Series co-generation

In parallel co-generation, electricity is produced as a co-product with desalinated water. This is done by using some of the steam produced from the steam generator for driving power turbines. The remaining steam from the steam generator is used in parallel with the turbines in the desalination plant. This provides more flexible use of the energy.

In series co-generation, the steam is used to generate electricity by passing it through the turbine with an elevated back pressure and is then sent to the desalination process. Thermodynamically it makes more sense to extract as much work as possible from the steam. The elevated back pressure increases the heat available for the desalination process but decreases the amount of electricity that can be generated by the turbine because of the decrease in pressure drop over the turbine. In this study only the series configuration was investigated.

6. SIMULATIONS AND RESULTS

6.1. Simulation approach

6.1.1. Software

The computer software to be used for the simulations and producing the relevant results will mainly be Engineering Equation Solver (EES).

EES uses the Newton-Raphson numerical method for solving equations. It is able to solve up to 12 000 non-linear equations (for the professional version). EES will solve the equations on the condition that there is the same amount of equations as there are variables in the program. One advantage of EES is that it has built-in fluid properties. This makes it easy to lookup any fluid property for use in a calculation.

The simulation approach can be described as follows:

1. The Rankine cycle (Figure 12) will initially be simulated using a pressure in the condenser similar to that of a normal power station.
2. The heat available in the steam for the desalination plant after it has passed through all the turbines, will be the minimum when the Rankine cycle is simulated without any additional back-pressure on the LPT- as described in point one above.

This heat available will then be increased through successive simulations, by increasing the back pressure of the LPT. This will decrease the amount of work done by the LPT and will convey more heat to the condenser.

In Figure 12 the heat available to the condenser is indicated by Q_C . The condenser operating pressure will be changed in order to reach the required condenser operating temperatures of 50°C, 60°C and 70°C. The maximum temperature of 70°C is taken because it is the thermal boundary in the MED process, before scaling in the water starts to become a problem.

The pressures at the intermediate and low pressure sections will be optimised by performing parametric studies in each of the scenarios. For each condenser operating temperature the cycle configuration will be optimised and the calculated temperatures, pressures, mass flows and thermal efficiencies will be given. The simulation as done in EES will be verified using hand calculations and this is shown in Appendix B1.

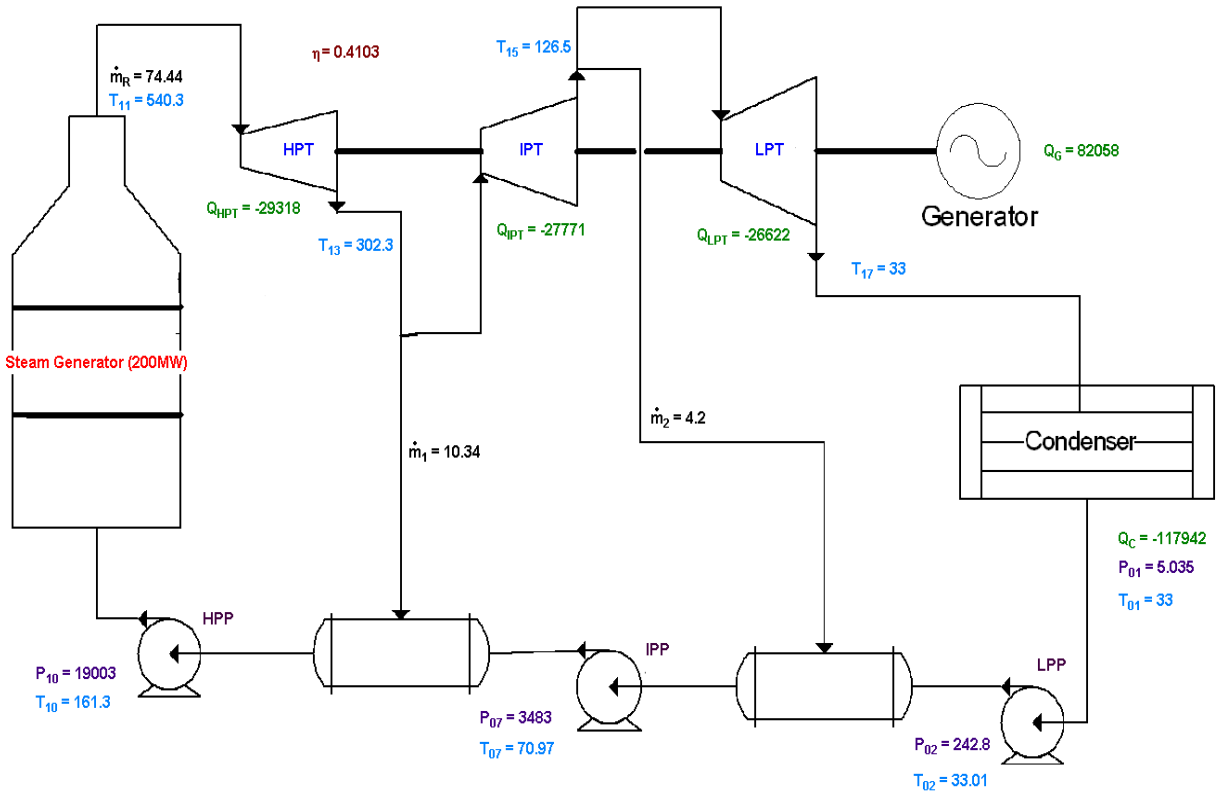


Figure 12: Rankine cycle simulation model.

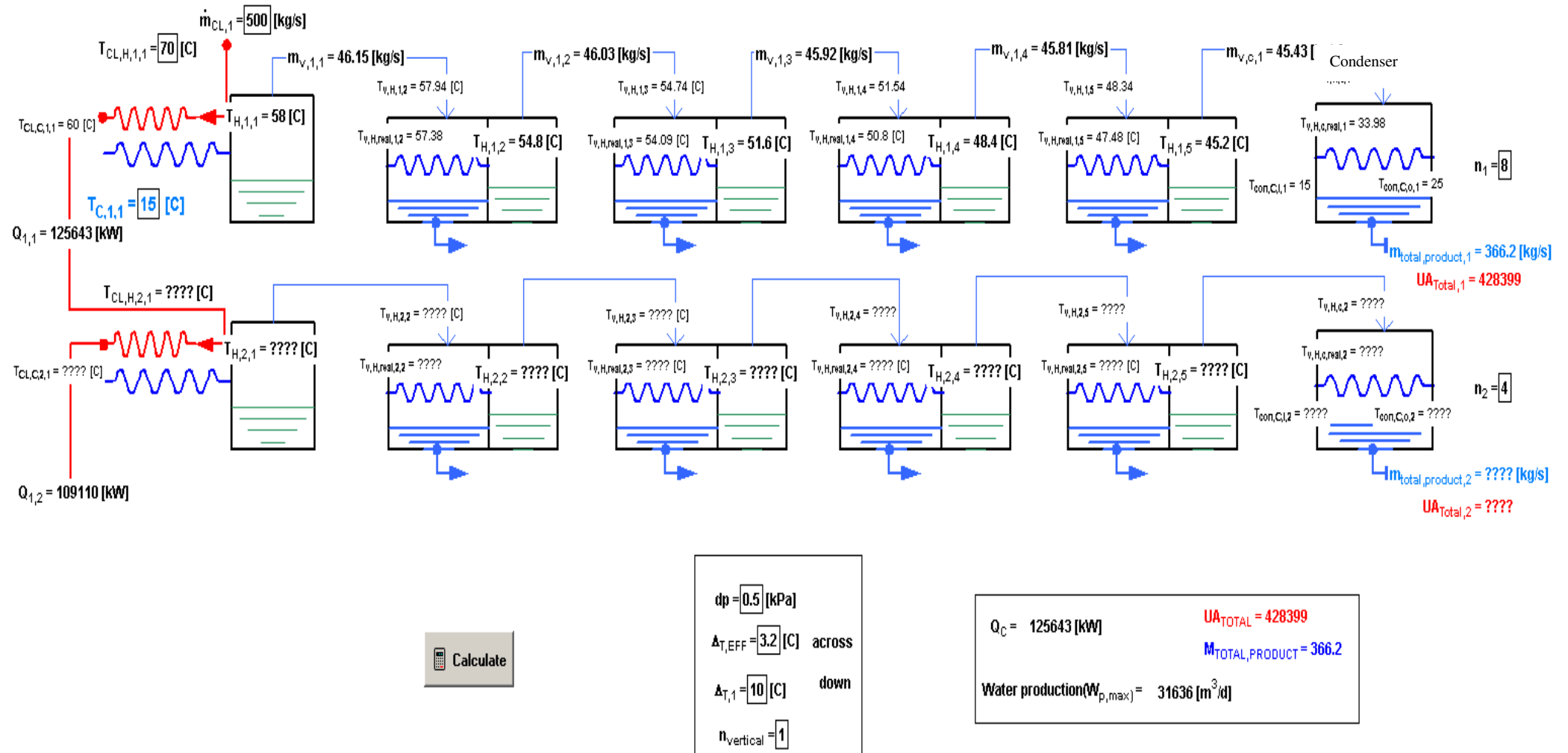
3. A customised version of software developed by De Bruyn (2010) is used to determine the amount of product water that will be produced using MED, at a given condenser heat input and temperature.

Figure 13 shows a diagram of the layout of the MED model as developed in EES. In this model each square represents one effect. The effects are arranged in two horizontal trains. The model takes as input the water temperature from the warm water used to evaporate the seawater in the first effect. It also requires the amount of waste heat available in the condenser. The pressure drop across each effect is taken as 0.5 kPa. The temperature loss across one effect is assumed to be 3.2°C.

In Figure 13, $Q_{1,1}$ - top left corner of diagram - represents the condenser waste heat available. $Q_{1,2}$ - bottom left corner of diagram - is the heat that is available after the heat required for MED is absorbed. This heat is dumped to atmosphere and has no further use. It is assumed that 10°C is lost in the heat transfer between the heated steam and the seawater. This can be seen in the top left corner of Figure 13, with the values of $T_{\text{CL,H},1,1}$ and $T_{\text{CL,C},1,1}$. As can be seen in the figure there is a temperature loss of 3.2°C across each effect. The mass flow passing to each successive cell decreases because of the brine that is separated from the distillate. This mass flow value is shown on the top of each effect. On the right hand side - $n_1 = 8$, indicate that there are eight effects in the first horizontal train. The result is the water produced ($W_{p_{\text{max}}}$) per day, as can be seen in the bottom right corner of the schematic.

This model will be used to determine the amount of water produced per day by MED for each cycle configuration. In order to compare the amount of water produced by RO, it will be determined using the total energy that is lost during the process of producing water through MED. Thus the amount of turbine work lost due to the increased back-pressure on the LPT and the electricity that is needed to produce that amount of water (4.5 kW/m^3). This topic will be thoroughly explained in Chapter 7.

Figure 13: Schematic of the MED software used to determine the water production



6.1.2. Theory used in simulations

The equations that the simulations will be based on can be summarised as follows:

The three conservation equations:

- **Conservation of mass:**

$$\dot{m}_e - \dot{m}_i = 0$$

- **Conservation of momentum(incompressible):**

$$(P_{0e} - P_{0i}) + \rho g(z_e - z_i) + \Delta p_{0L} = 0$$

- **Conservation of momentum(compressible):**

$$\frac{P}{P_0}(P_{0e} - P_{0i}) + \frac{1}{2}\rho V^2 \frac{1}{T_0}(T_{0e} - T_{0i}) + \rho g(z_e - z_i) = 0$$

- **Conservation of energy:**

$$\dot{Q} + \dot{W} = \dot{m}_e h_{0e} - \dot{m}_i h_{0i} + \dot{m}_e g z_e - \dot{m}_i g z_i$$

Component characteristics:

- **Pressure drop**

$$\Delta p_{0L} = f \frac{L}{D} \frac{1}{2} \rho V^2$$

For laminar flow:

$$f = \frac{C}{\text{Re}} \quad \text{with} \quad C = 64 \text{ for round ducts and pipes}$$

$$C = 57 \text{ for square ducts}$$

$$C = 96 \text{ for very flat rectangular-shaped ducts}$$

$$f = 0.25 \left(\log \left(0.27 \frac{\varepsilon}{D_H} + \frac{5.74}{\text{Re}^{0.9}} \right) \right)^{-2} \quad \text{For turbulent flow}$$

- **Heat transfer**

$$\dot{Q} = \varepsilon \dot{Q}_{\max} \quad \dot{Q}_{\max} = C_{\min} \Delta T_{\max}$$

$$C_{\min} = [\dot{m} c_p]_{\min}$$

$$\Delta T_{\max} = T_{pi} - T_{si}$$

- **Steam turbines:**

$$\dot{Q}_T = \eta_T \dot{m} (h_{0es} - h_{0i})$$

- **Pumps:**

$$\dot{Q}_P = \frac{\dot{m}}{\rho} \frac{1}{\eta_p} (P_{0e} - P_{0i})$$

- **Shaft energy balance:**

$$\eta_M \sum \dot{Q}_T + \sum \dot{Q}_P + \sum \dot{Q}_G = 0$$

Fluid properties:

- **Reynolds number:**

$$\text{Re} = \frac{\rho V L}{\mu}$$

- **Total temperature:**

$$T_0 = T + \frac{V^2}{2c}$$

- **Total pressure:**

$$P_0 = P + \frac{1}{2} \rho V^2$$

- **Enthalpy change over the components:**

$$h_{0e} - h_{0i} = \frac{\dot{Q}}{\dot{m}}$$

6.2. Assumptions and boundary values

In order to accurately simulate the different cycle configurations, assumptions made had to be consistent for all the models. Table 2 gives a summary of the assumptions and boundary values used for the simulations. The specific boundary values applicable to the different simulations are stated in section 6.3 through to 6.6. The following sections are set out as follows:

- 6.3:** Rankine cycle was simulated without any additional back-pressure on LPT (maximum electricity generation, no water, 33°C condenser operating temperature).
- 6.4:** Rankine cycle was simulated with 50°C condenser operating temperature (cogeneration).
- 6.5:** Rankine cycle was simulated with 60°C condenser operating temperature (cogeneration).
- 6.6:** Rankine cycle was simulated with 70°C condenser operating temperature (cogeneration).

The boundary values mentioned in each section were taken as the typical operating conditions of the PBMR HTR 200MW_{th} model developed in SA. It provides a realistic approach to the simulation.

No physical dimensions are specified. The simulation model for the Rankine cycle with a 33°C condenser operating temperature was verified using steam tables and hand calculations and can be seen in Appendix B1. The other simulations done in EES for the cases of 50°C, 60 °C and 70°C condenser operating temperatures are based on the fact that the base model for the Rankine cycle is verified and sufficiently showed that the equations and methodology followed was correct.

Table 2: Assumptions and boundary values

Parameter	Value/Description	Assumption
Type of reactor	High Temperature Reactor	Helium cooled
Thermal core power [MW]	$P_{th} = 200$	In order to investigate co-generation capabilities
Electricity generation cycle	Rankine cycle	Makes use of a steam generator which transfers heat from primary side (helium) to secondary side (steam).
Number of pump sets	3	In accordance with regular power station design
Number of turbine sets	3	In accordance with regular power station design
Low pressure boundary [kPa]	$P_{LPP} = 311 \text{ to } 477$	Vary between 311 kPa and 477 kPa for the different configurations. This is optimised using EES for each scenario.
Intermediate pressure boundary [kPa]	$P_{IPP} = 3056 \text{ to } 3633$	Vary between 3056 kPa and 3633 kPa for the different configurations. This is optimised using EES for each scenario.
High pressure boundary [kPa]	$P_{HPP} = 19000$	Nearly 19000 kPa for each scenario. Taken as the standard in HTR technology.
Condenser pressure [kPa]	$P_C = 5 \text{ to } 31.2$	Vary between 5 and 31.2 kPa according to required temperature for the MED desalination process.

Table 2: Assumptions and boundary values (Continued)

Parameter	Value/Description	Assumption
Quality after condenser	$x = 0$	The quality of the steam exiting the condenser is assumed to be 0, i.e. saturated liquid
Maximum cycle temperature [°C]	$T_{\max} = 540$	Taken from a typical Eskom power station as the maximum cycle temperature.
Fraction of bled steam at low pressure extraction point [%]	$f_{LP} = 12 \text{ to } 18.89$	Used to heat up the feedwater going to the SG (Regenerative feedwater heating). The steam is bled at the point after it passed through the HP turbine; before it enters the IP turbine.
Fraction of bled steam at intermediate pressure extraction point [%]	$f_{IP} = 12 \text{ to } 18.89$	Used to heat up the feedwater going to the SG (regenerative feedwater heating). The steam is bled after it passed through the IP turbine; before it enters the LP turbine
Efficiency of pumps [%]	$\eta_p = 75$	A realistic assumption for power station pumps
Efficiencies of turbines [%]	$\eta_{HPT} = 85$	The efficiencies of the LP, IP and HP turbines are taken as 85 percent, which is a good average assumption for a modern turbine.
	$\eta_{IPT} = 85$	
	$\eta_{LPT} = 85$	
Pressure loss fraction	$\alpha_{Pipe} = 0.005$ $\alpha_H = 0.02$	The pressure loss fractions for the piping and heat exchangers are taken as for modern designs in power stations. The physical size and material types were not specified.

6.3. Rankine cycle with 33°C condensing temperature

The Rankine cycle was simulated using a condenser pressure of a typical power station. This illustrates the amount of electricity that can be generated without a higher than normal back pressure on the LP turbine. The most electricity possible is generated using this configuration. The simulation model as done in EES is shown in section 6.3.2. The EES code for this model can be found in Appendix A1.

6.3.1. Boundary values for Rankine cycle model

Table 3 gives a summary of the boundary values that was specified for the Rankine cycle simulation with a 33°C condenser operating temperature.

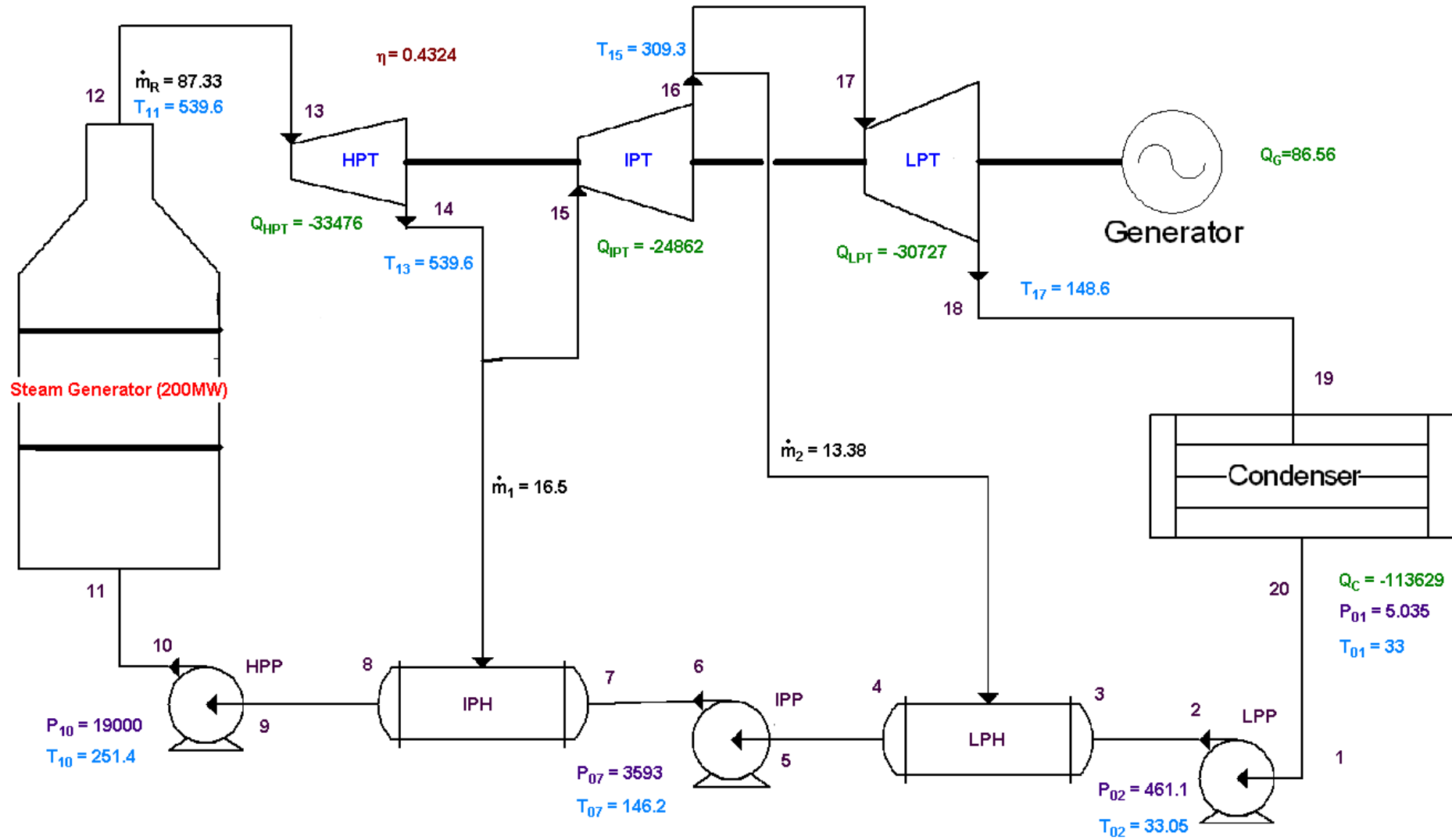
Table 3: Boundary values for Rankine cycle simulation

Parameter	Value
Condenser operating pressure [kPa]	5.035
Condenser operating temperature [°C]	33
Quality at condenser exit [%]	0
Maximum cycle temperature [°C]	540
Maximum cycle pressure [kPa]	19000

6.3.2. Simulation model for Rankine cycle

Figure 14 shows the layout of the Rankine cycle simulation model as done in EES. The model was developed based on the requirement to generate the maximum amount of electricity and no water. Figure 14 shows the layout of the model. The temperatures and pressures are given at the critical stages of the cycle. The bled steam is represented by the values of $\dot{m}_1$ and $\dot{m}_2$ [kg/s], at the intermediate and low pressure boundaries respectively.

Figure 14: Rankine cycle simulation model with 33°C condensing temperature as done in EES



The condenser operating pressure corresponds to a condenser operating temperature of 33°C. Using EES, the mass flow fraction of the bled steam for feedwater heating, bled at the intermediate and low pressure boundaries was found to be 18.89 percent. The optimisation method of this result is shown in section 6.3.4.

The results of the simulation are given in the next section. It is necessary to note that the maximum amount of electricity that can be generated from the given boundary values above is 86.56 MW. In this simulation the maximum work is extracted from the steam to generate electricity. The heat dumped in the condenser is the minimum amount of waste heat corresponding to maximum generator output.

6.3.3. Results for Rankine cycle with 33°C condensing temperature

The results can be summarised as given in Table 4. This configuration is for maximum electricity generation so it is worth taking note of the cycle thermal efficiency (43.24%), electricity delivered by generator (86.5MW) and the condenser heat available (113.58MW). As this model is only done for electricity generation, the condenser heat will not be utilised. However, during the simulations that follow, where the condenser operates at a higher temperature, the condenser heat will be utilised in the production of desalinated water through MED.

Table 4: Results of Rankine cycle simulation with 33°C condensing temperature

Parameter	Value
Cycle thermal efficiency [%]	43.24
Mass flow through SG [kg/s]	87.33
Quality after LPT [%]	81.58
Mass flow of bled steam at intermediate pressure [kg/s]	16.5
Mass flow of bled steam at low pressure [kg/s]	13.38
Low pressure boundary [kPa]	461.1

Intermediate pressure boundary [kPa]	3611
Condenser heat [MW]	113.58
Work done by LPP [W]	35.1
Work done by IPP [W]	324.1
Work done by HPP [W]	2227
Work done by LPT [MW]	30.47
Work done by IPT [MW]	24.757
Work done by HPT [MW]	33.88
Total electricity delivered by generator [MW]	86.561

6.3.4. Optimisation of pressures and bled steam fractions

The low and intermediate pressure boundaries were optimised. The optimisation can be seen in Figure 15. The optimum pressure was found to be 461.1 kPa for the low pressure (P_{02}) and 3611 kPa for the intermediate pressure (P_{06}). This gives a maximum cycle thermal efficiency of 43.24 percent.

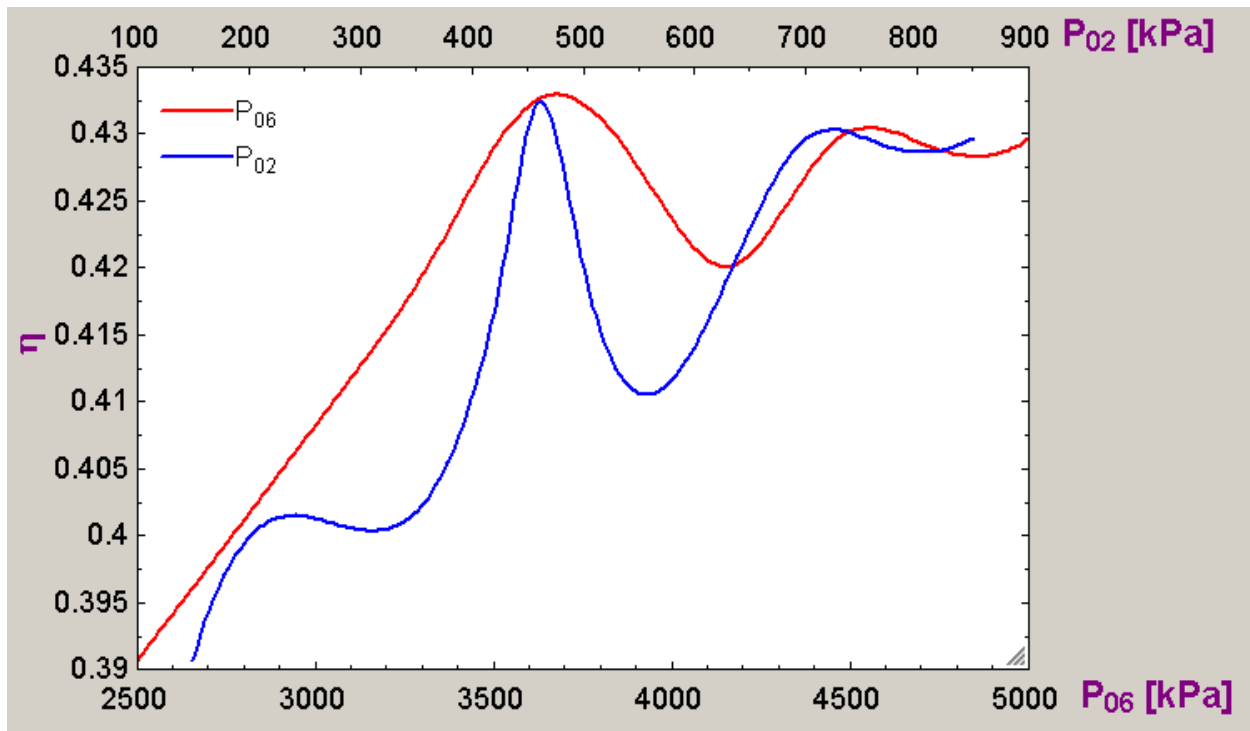


Figure 15: Optimisation curves for the low and intermediate pressure boundaries

The optimisation of the bled steam fractions at the low and intermediate pressure boundaries were done as can be seen in Figure 16. This figure shows what the effect of varying the bled steam fractions are on the efficiency of the cycle. The low pressure bled steam fraction (f_{LP}) as well as the intermediate pressure bled steam fraction (f_{IP}) was optimised to be 18.89 percent.

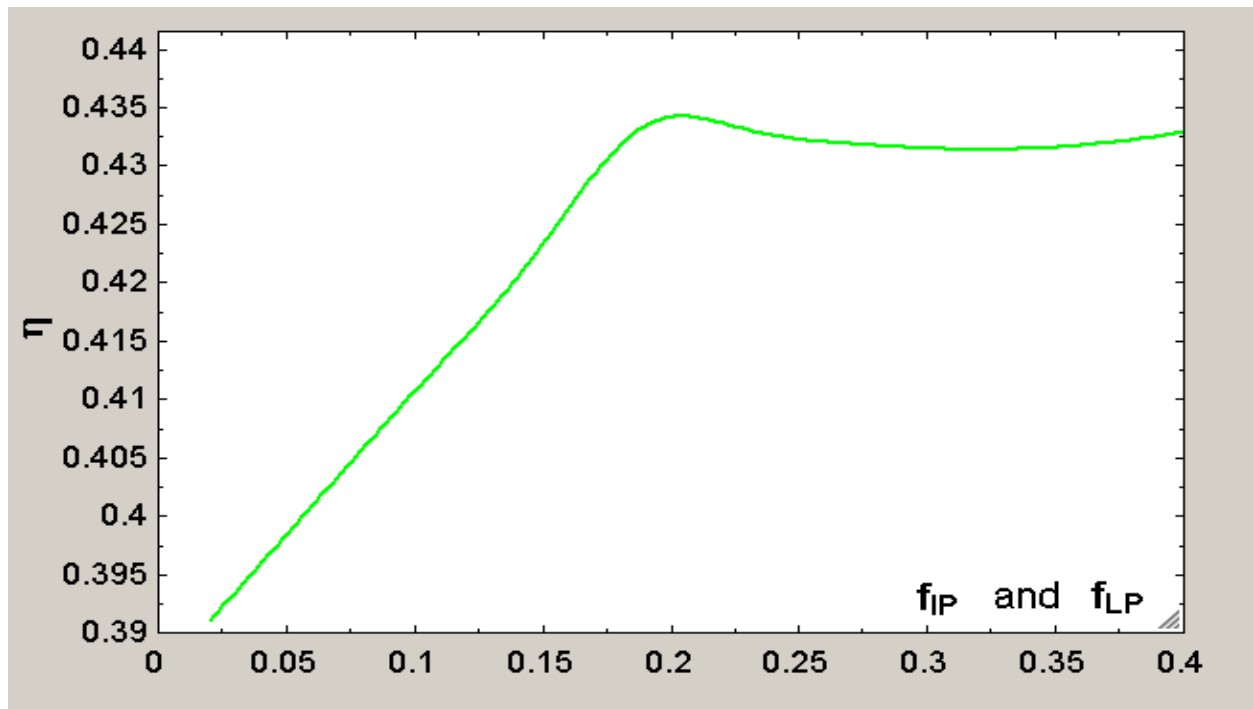


Figure 16: Optimisation curves for bled steam fractions at the low and intermediate pressures

6.4. Rankine cycle with 50°C condensing temperature

This simulation was done in order to simulate a cogeneration scenario. A back-pressure on the LPT causes a higher temperature in the condenser. The steam does not fully expand through the LPT and the heat remaining is then rejected through the condenser. The rejected heat is used to heat water which in turn is used in the desalination process of water through MED technology.

6.4.1. Boundary values for 50°C condenser operating temperature

Table 5 shows the boundary values specified for the simulation model with a condenser operating temperature of 50°C.

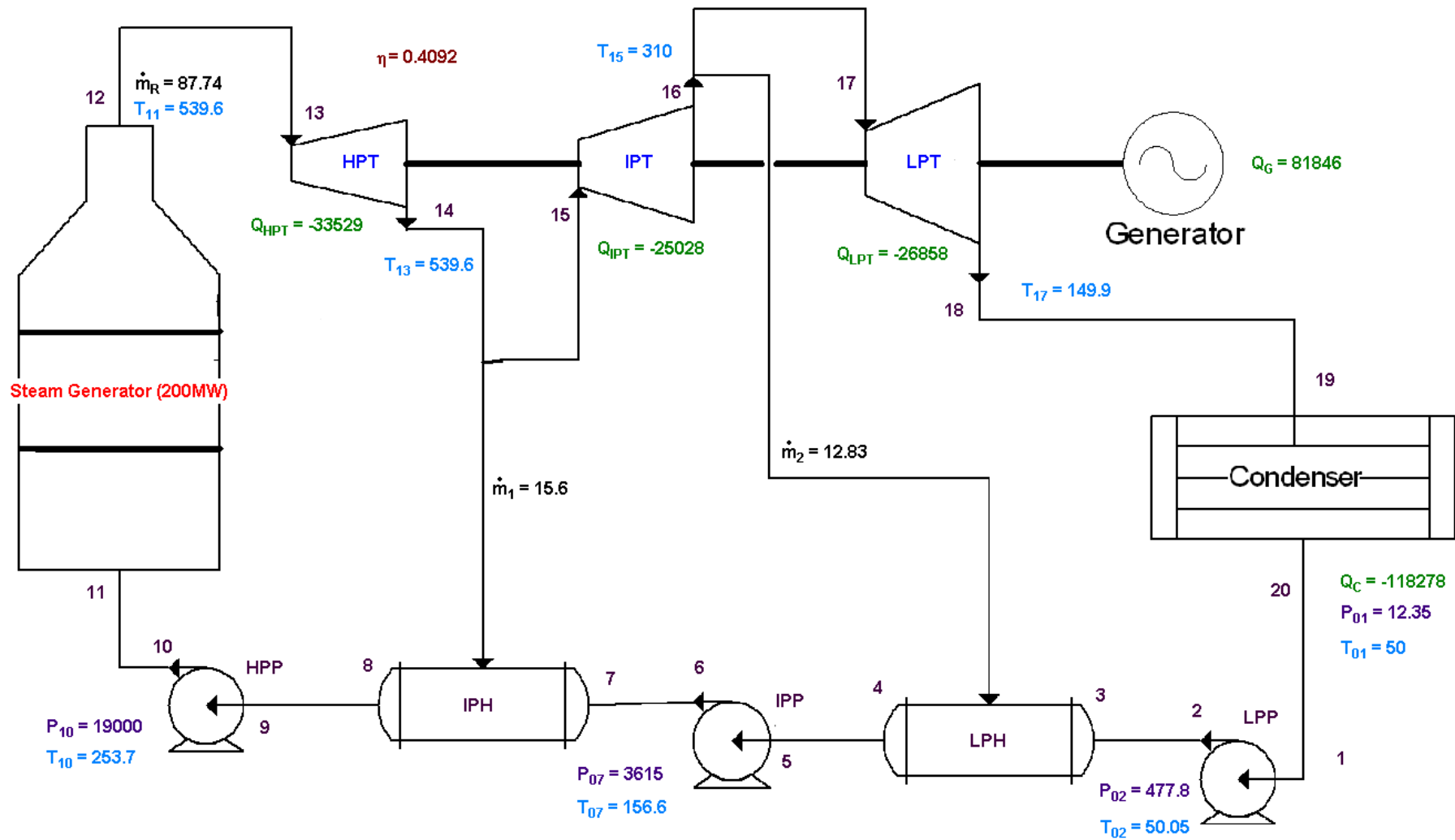
Table 5: Results of Rankine cycle simulation with 50°C condensing temperature

Parameter	Value
Condenser operating pressure [kPa]	12.35
Condenser operating temperature [°C]	50
Quality at condenser exit [%]	0
Maximum cycle temperature [°C]	540
Maximum cycle pressure [kPa]	19000

6.4.2. Simulation model for 50°C condenser operating temperature

The EES code for this simulation can be found in *Appendix A2: Rankine cycle EES model with 50°C condenser operating temperature*. This simulation was done in order to investigate how much water and electricity will be produced when increasing the back-pressure on the low pressure turbine, and thereby increasing the condenser operating temperature. The operating temperature increases from 33°C (normal Rankine cycle) to 50°C. The simulation model can be seen in Figure 17. When increasing the pressure after the LPT, the work done through the turbine by the steam is less than for the normal Rankine cycle and thus more heat is rejected through the condenser.

Figure 17: Rankine cycle simulation model with 50°C condensing temperature as done in EES



This heat is then used to heat up water, which in turn is used to desalinate seawater. In this scenario the condenser operating pressure is increased from 5.035 kPa to 12.35 kPa. The mass flow through the steam generator (SG) is calculated to be 87.74 kg/s. In this simulation the LPT generates less electricity than in the previous section when only power was generated by the model and no water.

It is important to note what the thermodynamic implications are when making more waste heat available in the condenser. Parameters which are influenced include: Cycle efficiency, power generated, condenser operating pressure and temperature and cycle operating pressures at the intermediate and low pressure stages. The results obtained from the model are given in the next section. In section 6.5, the condenser operating temperature is increased to 60°C.

6.4.3. Results for Rankine cycle with 50°C condensing temperature

The results from this simulation model are summarised and given in Table 6. This configuration is for cogeneration purposes (water and power) and it is worth taking note of the cycle thermal efficiency (40.92 %), electricity delivered by generator (81.85 MW) and the condenser heat available (118.3 MW). This heat available in the condenser is utilised in an MED plant. The MED model discussed in section 6.1 is used to determine the amount of water produced for a given amount of condenser heat available. The low and intermediate pressure boundaries and bled steam fractions were optimised and are given in section 6.4.5.

Table 6: Results of Rankine cycle simulation with 50°C condensing temperature

Parameter	Value
Cycle thermal efficiency [%]	40.92
Mass flow through SG [kg/s]	87.74
Quality after LPT [%]	83.63
Mass flow of bled steam at intermediate pressure [kg/s]	15.6
Mass flow of bled steam at low pressure [kg/s]	12.83

Low pressure boundary [kPa]	477.8
Intermediate pressure boundary [kPa]	3633
Condenser heat [MW]	118.3
Work done by LPP [W]	37.26
Work done by IPP [W]	1294
Work done by HPP [W]	2237
Work done by LPT [MW]	26.86
Work done by IPT [MW]	25.03
Work done by HPT [MW]	33.53
Total electricity delivered by generator [MW]	81.85

6.4.4. Water production from Rankine cycle with 50°C condensing temperature

As seen in Table 6, the condenser heat available is equal to 118.3 MW. With this heat and water at a temperature of 50°C, the amount of desalinated water that can be produced is equal to **15 670 m³/day**. This is calculated with the MED model as described in section 6.1.

6.4.5. Optimisation of pressures and bled steam fractions

The pressure boundaries at the intermediate and low pressure stages were optimised with a parametric study done in EES. The results of this optimisation are shown in Figure 18. The optimum pressure for the low pressure boundary (P_{02}) was calculated to be 477.8 kPa and 3633 kPa for the intermediate pressure boundary (P_{06}). This resulted in a cycle thermal efficiency of 40.92 percent.

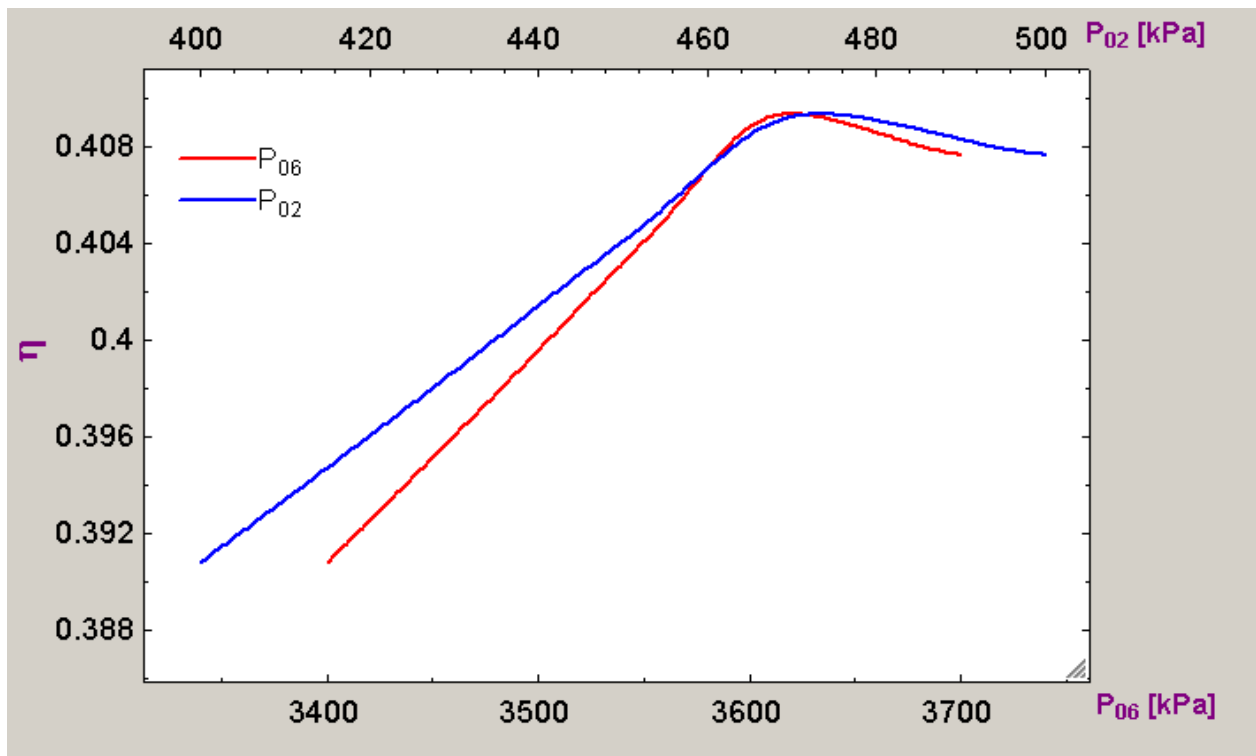


Figure 18: Optimisation curves for the low and intermediate pressure boundaries

Optimisation of the bled steam fractions at the low and intermediate pressure boundaries was done with a parametric study in EES. The result of the study is shown in Figure 19. The low and intermediate pressure bled steam fractions were optimised to be 17.78 percent.

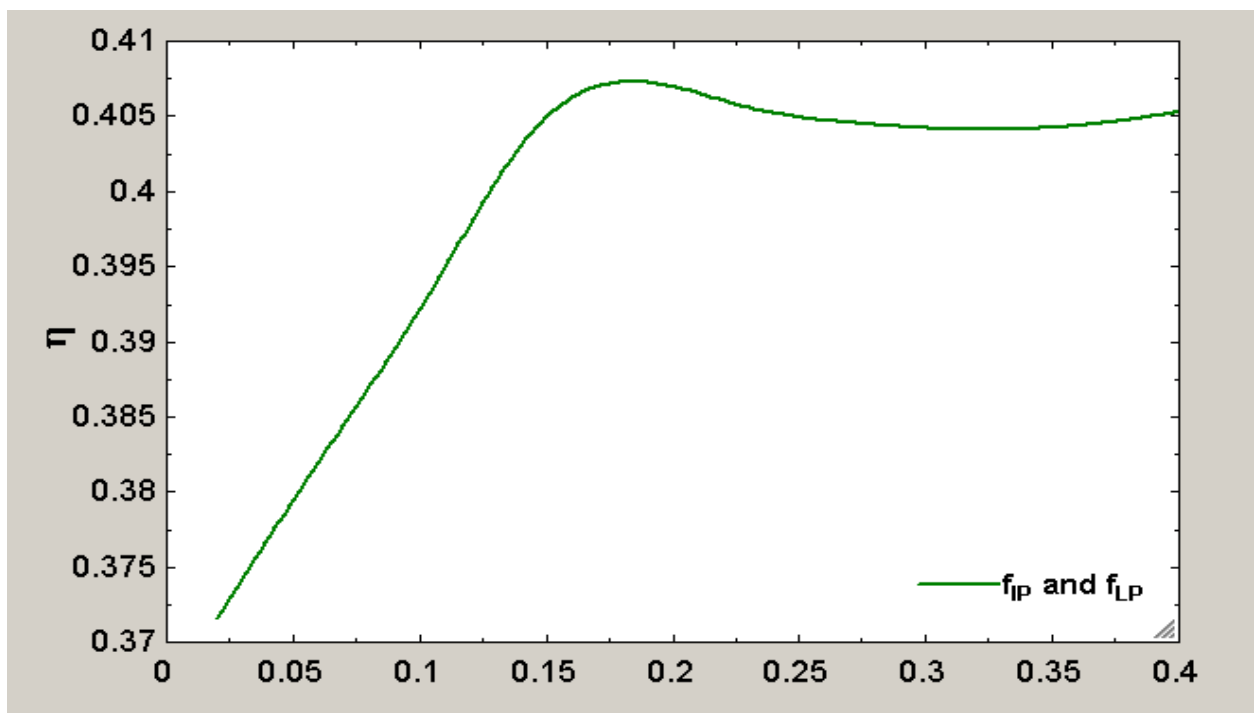


Figure 19: Optimisation curves for bled steam fractions at the low and intermediate pressures

6.5. Rankine cycle with 60°C condensing temperature

This simulation model, like the previous one, was done for a cogeneration scenario. An increased condenser operating pressure results in more heat being available in the condenser because of less work done by the LPT. This heat is again utilised in the desalination process of seawater through MED technology.

6.5.1. Boundary values for 60°C condenser operating temperature

Table 7 shows the boundary values for this simulation model. The results of this model are given in section 6.5.3.

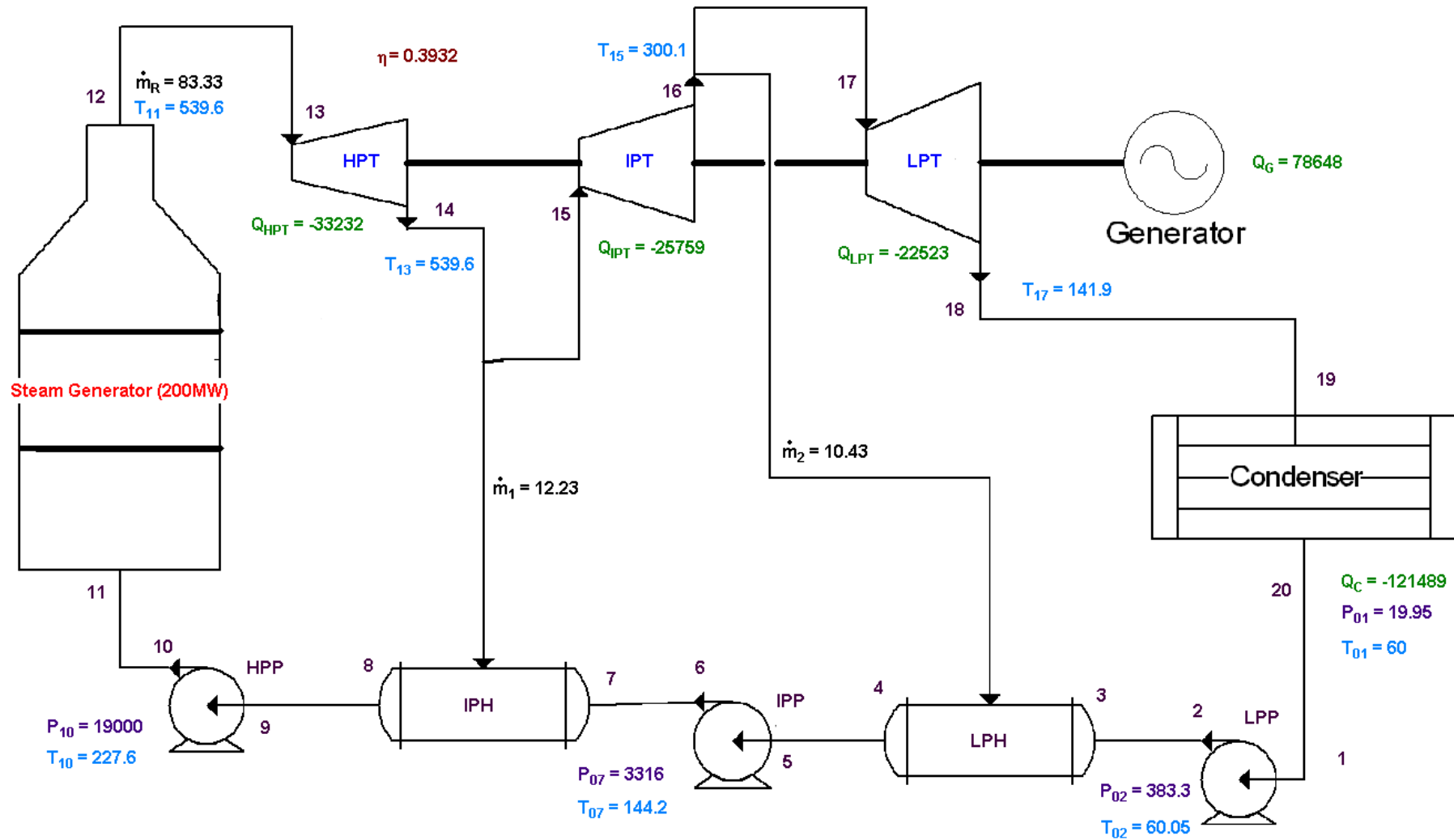
Table 7: Boundary values for cogeneration Rankine cycle with 60°C waste heat temperature

Parameter	Value
Condenser operating pressure [kPa]	19.95
Condenser operating temperature [°C]	60
Quality at condenser exit [%]	0
Maximum cycle temperature [°C]	540
Maximum cycle pressure [kPa]	19000

6.5.2. Simulation model for 60°C condenser operating temperature

The simulation model as done in EES is shown in Figure 20. The EES code for this simulation can be found in *Appendix A3: Rankine cycle EES model with 60°C condenser operating temperature*. In this model, the even higher condenser operating pressure resulted in an efficiency of 39.32 percent. This is much less than the 43.24 percent which was obtained by the Rankine cycle with a 33°C condenser operating temperature.

Figure 20: Rankine cycle simulation model with 60°C condensing temperature



6.5.3. Results for Rankine cycle with 60°C condensing temperature

The results from this simulation model are summarised and given in Table 8. This configuration is for cogeneration purposes (water and power) and it is worth taking note of the cycle thermal efficiency (39.32 %), electricity delivered by generator (78.65 MW) and the condenser heat available (121.5 MW). The MED model discussed in section 6.1 is used to determine the amount of water produced for a given amount of condenser heat available.

Table 8: Results of Rankine cycle simulation with 60°C condensing temperature

Parameter	Value
Cycle thermal efficiency [%]	39.32
Mass flow through SG [kg/s]	83.33
Quality after LPT [%]	84.83
Mass flow of bled steam at low pressure [kg/s]	10.43
Mass flow of bled steam at intermediate pressure [kg/s]	12.23
Low pressure boundary [kPa]	383.3
Intermediate pressure boundary [kPa]	3333
Condenser heat [MW]	121.5
Work done by LPP [W]	29.9
Work done by IPP [W]	689.7
Work done by HPP [W]	2146
Work done by LPT [MW]	22.5
Work done by IPT [MW]	25.76
Work done by HPT [MW]	33.23
Total electricity delivered by generator [MW]	78.65

6.5.4. Optimisation of pressures and bled steam fractions

The pressure boundaries at the intermediate and low pressure stages were optimised with a parametric study done in EES. The results of this optimisation are shown in Figure 21. The optimum pressure for the low pressure boundary (P_{02}) was calculated to be 383.3 kPa and 3333 kPa for the intermediate pressure boundary (P_{06}). This resulted in a cycle thermal efficiency of 39.32 percent.

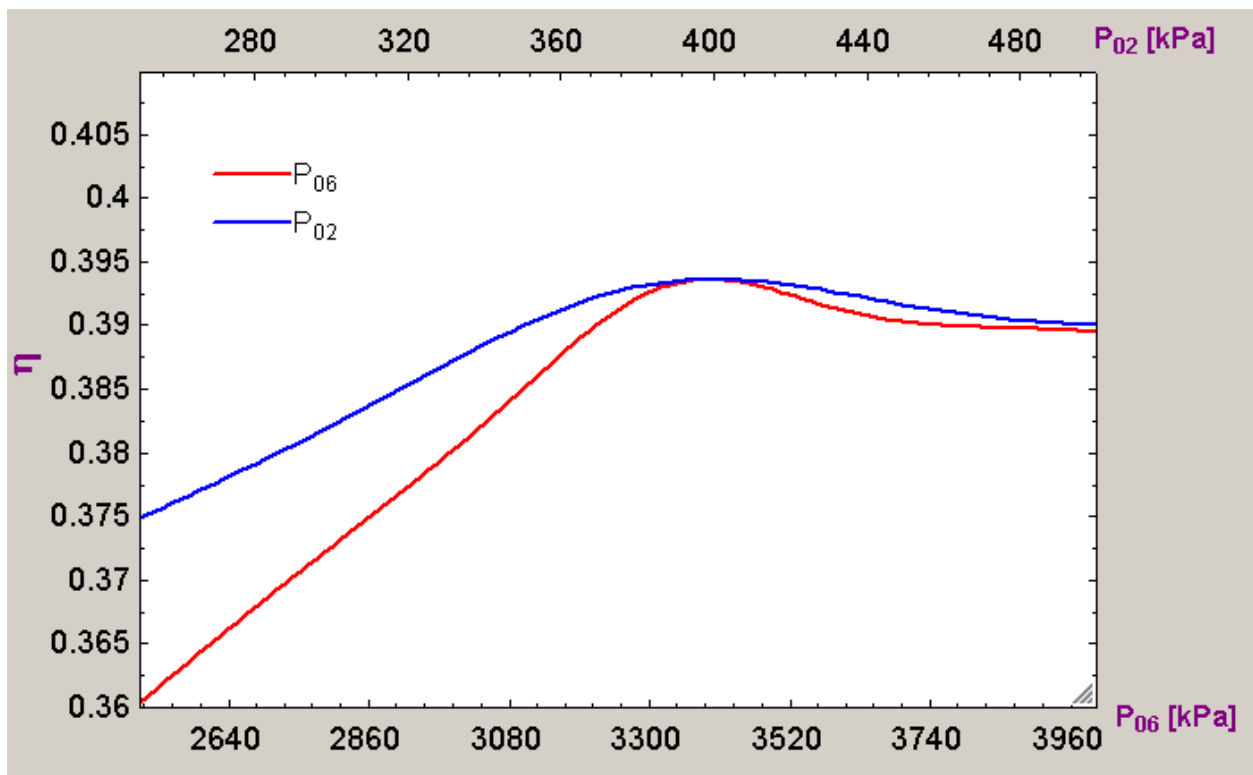


Figure 21: Optimisation curves for the low and intermediate pressure boundaries

Optimisation of the bled steam fractions at the low and intermediate pressure boundaries was done with EES. The result is shown in Figure 22. The low and intermediate pressure bled steam fractions were optimised to be 14.67 percent.

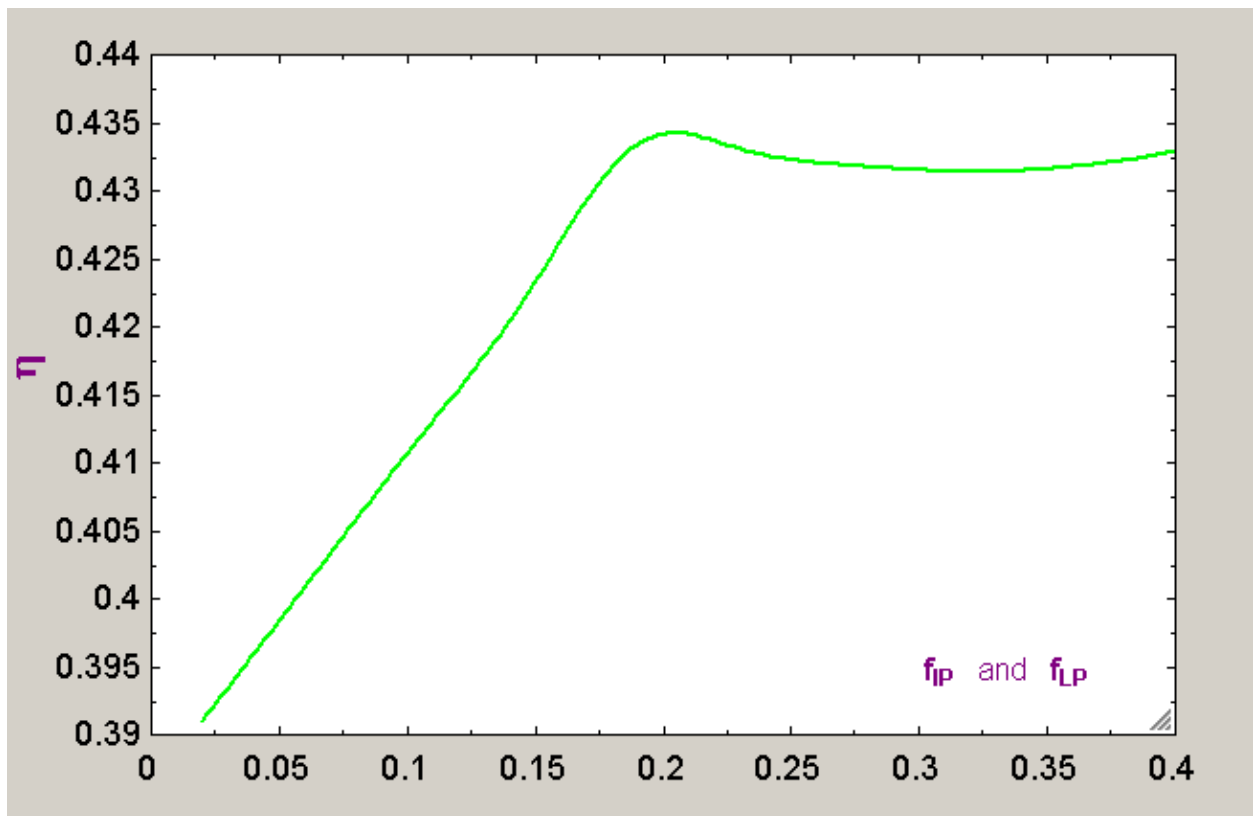


Figure 22: Optimisation curves for bled steam fractions at the low and intermediate pressures

6.5.5. Water production from Rankine cycle with 60°C condensing temperature

As seen in Table 8, the condenser heat available is equal to 121.5 MW. With this heat and water at a temperature of 60°C, the amount of desalinated water that can be produced is equal to **27 433 m³/day**.

6.6. Rankine cycle with 70 °C condensing temperature

This simulation was done by increasing the condenser operating temperature to 70°C. The higher condenser operating pressure results in more heat being available in the condenser and thus less electricity will be generated. This scenario will produce the most amount of water and least amount of electricity of all the models investigated in this study. There is an upper bound on the temperature with which MED can operate before scaling occurs. For this reason 70°C is the highest condenser operating temperature that will be investigated.

6.6.1. Boundary values for 70 °C condenser operating temperature

Table 9 shows the boundary values used in the simulation model with a condenser operating at 70°C. The layout of the model is shown in section 6.6.2 and the results are shown in section 6.6.3.

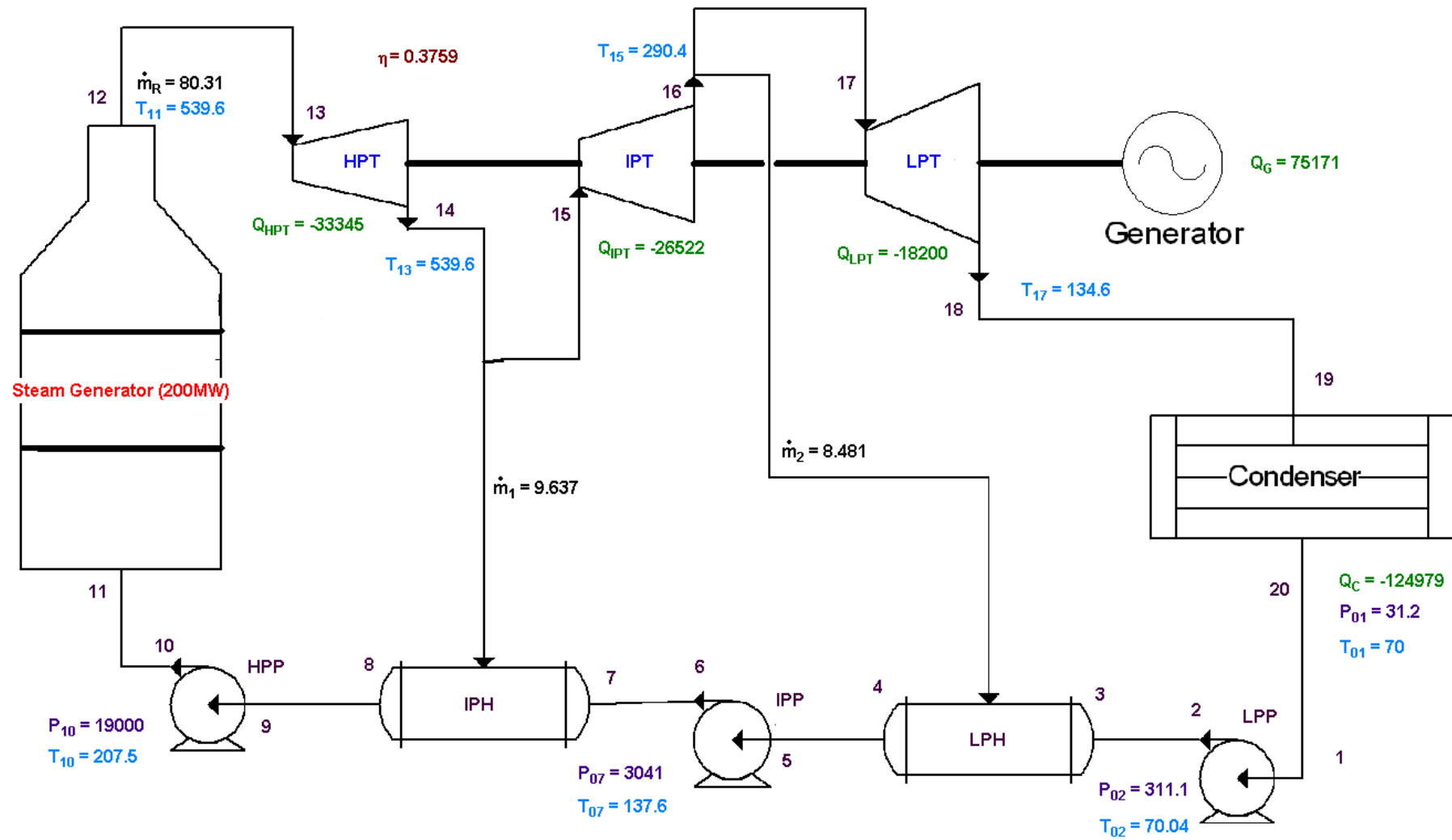
Table 9: Boundary values for cogeneration Rankine cycle with 70°C waste heat temperature

Parameter	Value
Condenser operating pressure [kPa]	19.95
Condenser operating temperature [°C]	70
Quality at condenser exit [%]	0
Maximum cycle temperature [°C]	540
Maximum cycle pressure [kPa]	19000

6.6.2. Simulation model for 70 °C condenser operating temperature

The EES code for this simulation can be found in *Appendix A4: Rankine cycle EES model with 70°C condenser operating temperature*.

Figure 23: Rankine cycle simulation model with 70°C condensing temperature



6.6.3. Results for Rankine cycle with 70°C condensing temperature

The results from this simulation model are summarised and given in Table 10. This configuration is for maximum electricity generation so it is worth taking note of the cycle thermal efficiency (37.59 %), electricity delivered by generator (75.17 MW) and the condenser heat available (124.98 MW).

Table 10: Results of Rankine cycle simulation with 60°C condensing temperature

Parameter	Value
Cycle thermal efficiency [%]	37.59
Mass flow through SG [kg/s]	80.31
Quality after LPT [%]	86.03
Mass flow of bled steam at low pressure [kg/s]	8.48
Mass flow of bled steam at intermediate pressure [kg/s]	9.64
Low pressure boundary [kPa]	311.1
Intermediate pressure boundary [kPa]	3056
Condenser heat [MW]	124.98
Work done by LPP [W]	23.74
Work done by IPP [W]	785.7
Work done by HPP [W]	2087
Work done by LPT [MW]	18.2
Work done by IPT [MW]	26.5
Work done by HPT [MW]	33.34
Total electricity delivered by generator [MW]	75.17

6.6.4. Water production from Rankine cycle with 70°C condensing temperature

As seen in Table 10, the condenser heat available is equal to 124.98 MW. With this heat and water at a temperature of 70°C, the amount of desalinated water that can be produced is equal to **39 261 m³/day**. This is calculated with the MED model as described in section 6.1.

6.6.5. Optimisation of pressures and bled steam fractions

The pressure boundaries at the intermediate and low pressure stages were optimised with a parametric study done in EES. The results of this optimisation are shown in Figure 24. The optimum pressure for the low pressure boundary (P_{02}) was calculated to be 311.1 kPa and 3056 kPa for the intermediate pressure boundary (P_{06}). This resulted in a cycle thermal efficiency of 37.59 percent.

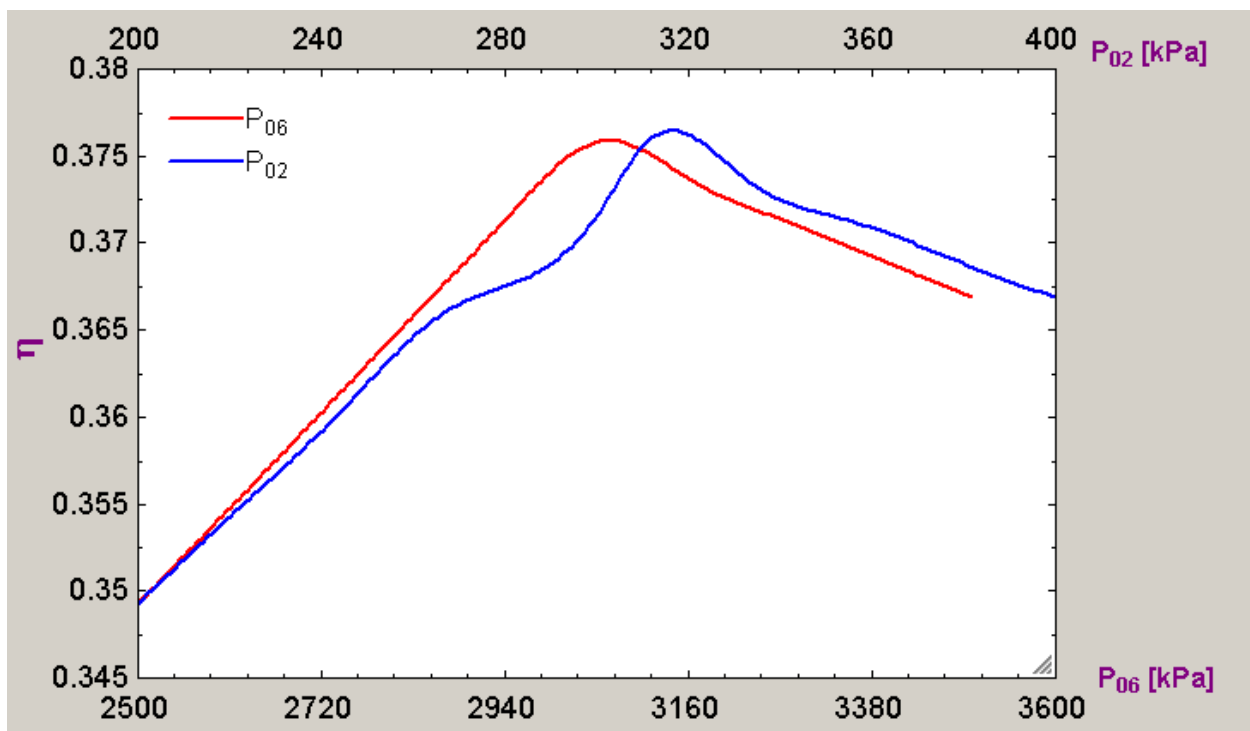


Figure 24: Optimisation curves for the low and intermediate pressure boundaries

Optimisation of the bled steam fractions at the low and intermediate pressure boundaries was done with a parametric study in EES. The result of the study is shown in Figure 25. The low and intermediate pressure bled steam fractions were optimised to be 12 percent.

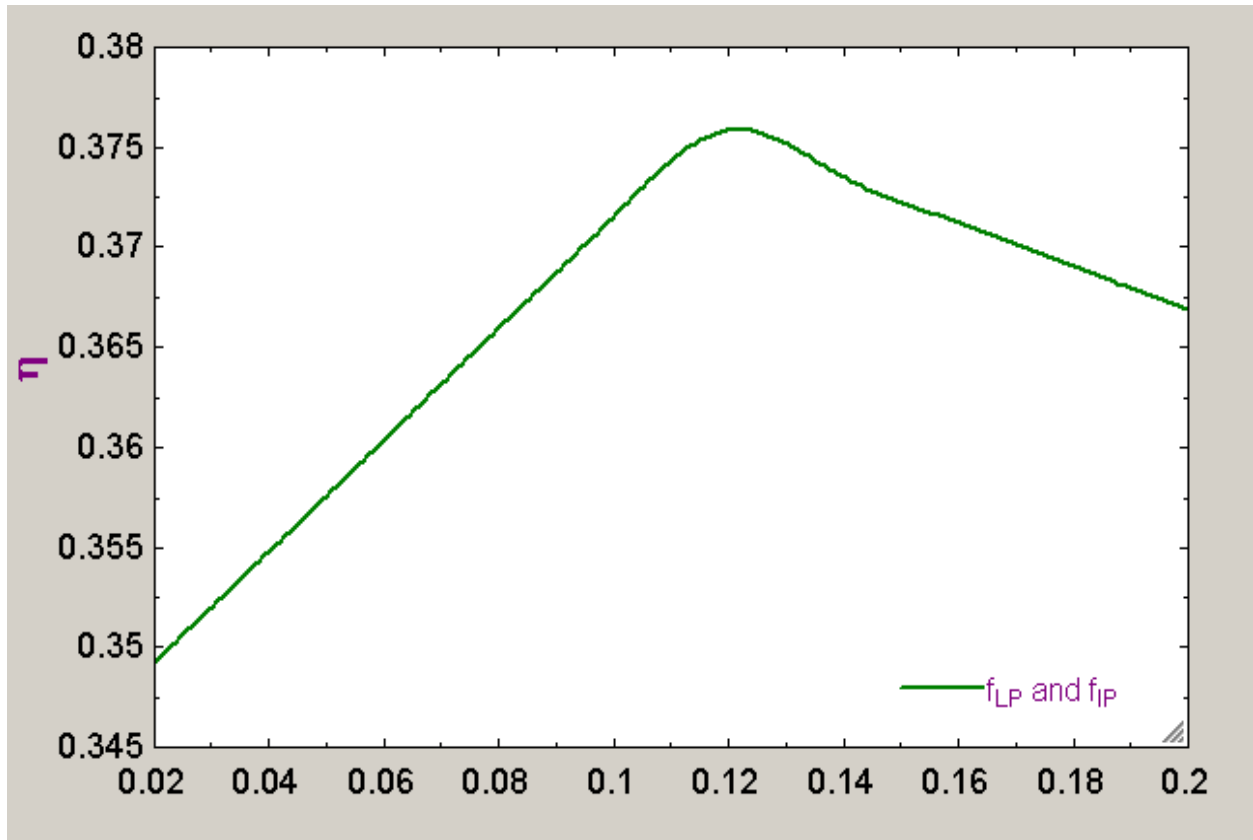


Figure 25: Optimisation curves for bled steam fractions at the low and intermediate pressures

6.7. Summary of results

The results of the different simulation models are summarised and given in Table 11. From the table it can be seen how the generator power decreases with rising condenser operating temperatures. The increase in condenser waste heat results in a decrease in generator power. The condenser waste heat is utilised in the production of desalinated water through MED. This leads to a cogeneration scenario where a trade-off can be made of electricity generated versus water production. In the next chapter an economic evaluation will be done, where the best configuration will be identified from a thermodynamic as well as an economic perspective.

Table 11: Summary of the results of the different simulation models with increasing condenser operating temperatures

Cycle configurations	Generator power (Q_G) [MW]	Cycle efficiency (η_{cycle}) [%]	Condenser waste heat (Q_C) [MW]	Low pressure boundary (P_{02}) [kPa]	Intermediate pressure boundary (P_{02}) [kPa]	Mass flow through SG [kg/s]	Mass fraction at low pressure boundary (f_{LP}) [kg/s]	Mass fraction at intermediate pressure boundary (f_{IP}) [kg/s]	Water produced via MED
Rankine cycle	86.56	43.24	113.58	461.1	3611	87.33	13.38	16.5	---
Rankine cycle with 50°C available for MED	81.85	40.92	118.3	477.8	3633	87.74	12.83	15.6	15 670
Rankine cycle with 60°C available for MED	78.65	39.32	121.5	383.3	3333	83.33	10.43	12.23	27 433
Rankine cycle with 70°C available for MED	75.17	37.59	124.98	311.1	3056	80.31	8.48	9.64	39 261

6.8. Water and Electricity Production of MED versus RO

In order to compare MED technology with RO technology, it is assumed that in the RO case the power plant will generate the same amount of electricity in all cases. In the MED case less electricity is generated and sent to the grid because of the reduction in turbine work. It is assumed that the same amount of electricity is sent to the grid for the two technologies. This means that different quantities of energy are available to the RO plant for each case resulting in the production of different quantities of water. I.e. the electricity lost due to the production of water through MED is taken as the electricity available to produce water through the RO technology.

Is it a reasonable assumption that the electricity consumption of the MED and RO technology are as follows:

- MED is 1.5 kWh / m³
- RO is 4.5 kWh / m³

To understand the analysis and comparison between MED and RO, it is crucial to understand Table 12. Table 12 shows how MED is comparable with RO for a given condenser operating temperature. The generator work decreases with each increase in condenser operating pressure and temperature. Taking the condenser operating temperature of 50°C as an example: Using the MED process, the generator will deliver **1964.4 MWh/day** (left column). This is less than the 2077.44 MWh/day which is the upper bound of the Rankine cycle without any additional back pressure on the LPT. As was seen in section 6.4.3, the condenser heat available is 118.3 MW for a Rankine cycle with a condenser operating at 50°C. With this heat, MED is able to produce **15 670 m³/day** of fresh water, calculated by the model presented in section 6.1. However, in order to produce 15 670 m³/day of water, the MED technology will require electricity to the amount of:

$$\text{Work consumption for water production} = \text{Water produced} * \text{electricity consumption rate}$$

$$\begin{aligned}\text{Work consumption for water production} &= (15\,670 \text{ m}^3/\text{day}) * (1.5 \text{ kWh} / \text{m}^3) \\ &= 23.5 \text{ MWh/day}\end{aligned}$$

The resultant amount of electricity that is send to the grid is equal to **1940.8 MWh/day**.
($1964.4 - 23.5 = 1940.9 \text{ MWh/day}$)

Comparing this calculation with that for RO it is as follows: The generator generates **2077.44 MWh/day** (maximum amount of electricity, no additional back-pressure on LPT). The amount of electricity available for desalination through RO = **the TOTAL amount of electricity used in the MED technology**.

For this particular case it is:

- Maximum generator work – electricity supplied to the grid (MED)
- $2077.44 - 1940.9 = \mathbf{136.55 \text{ MWh/day}}$

There is 136.55 MWh/day available for water production through RO technology.

Thus, the amount of water that can be produced through RO is

$$\text{Water produced} = \text{Work available for water production} / \text{electricity consumption rate}$$

$$\begin{aligned} \text{Water produced through RO} &= (136550 \text{ kWh/day}) / (4.5 \text{ kWh} / \text{m}^3) \\ &= \mathbf{30\ 343.33 \text{ m}^3/\text{day}} \end{aligned}$$

This methodology can be followed for the cases of 60°C and 70°C condenser operating temperatures. The results are shown in Table 12.

Table 12: Results of water production, MED versus RO from different condenser operating properties

Parameter	Condenser operating temperature		Condenser operating temperature		Condenser operating temperature	
	50 °C for MED	33 °C for RO	60 °C for MED	33 °C for RO	70 °C for MED	33 °C for RO
Generator work [MW]	81.85	86.56	78.65	86.56	75.17	86.56
Generator work [MWh/day]	1964.40	2077.44	1887.60	2077.44	1804.08	2077.44
Work consumption/ available for water production[MWh/day]	23.51	136.55	41.15	230.99	58.89	332.25
Electricity supplied to grid [MWh/day]	1940.90	1940.90	1846.45	1846.45	1745.19	1745.19
Water produced [m ³ /day]	15670.00	30343.33	27433.00	51331.00	39261.00	73833.67

Table 12 shows that RO clearly produces more water than what MED produces for the different cycle configurations. This done while the same amount of electricity is sent to the grid for each technology used. The following chapter will investigate the option of MED versus RO from an economic point of view.

7. ECONOMIC COMPARISON BETWEEN MED AND RO

Section 7.1 provides a look at the economic comparison between MED and RO technologies regarding electricity and capital costs. The Internal Rate of Return (IRR) and the Net Present Value (NPV) are evaluated in section 7.2. The model used in section 7.1 was taken from Cooley, et al. (2006).

7.1. Water production costs as a function of electricity and capital costs

Table 13 shows a summary of the parameters used for the economic assessment. The plant capacity is equal to the water produced from the cycle configurations (explained in Chapter 6.7). The maximum water production value seen in Table 13, 73 833 m³/day, is obtained by a RO plant with 332.25 MWh/day available for water production. The yearly interest rate and specific capital cost are as taken from Cooley, et al (2006).

Table 13: Important parameters relating to economic assessment

Parameter	Unit	Value
Plant capacity	m ³ /day	Between 15 670 to 73 833
Yearly electricity price increases	%	25% (2010); 25% (2011); 10% (2012); 10% (2013; 6% (2013)
Specific capital cost	USD/m ³	Between 1000 to 1500
Electricity cost	USD/kWh	0.05
Electrical consumption	kWh/m ³	1.5(MED) and 4.5(RO)
Specific electricity cost	USD/m ³	0.066(MED) and 0.198(RO)
Chemicals	USD/m ³	0.05(MED) and 0.071(RO)
Spare parts (1% of total capital investment)	USD/m ³	0.025(MED) and 0.043(RO)
Labour	USD/m ³	0.015
Average worker salary	R/year/worker	80000

The cost of spare parts in RO is nearly twice as much as those used in MED. Labour cost is taken as a standard for both technologies and the average worker salary is assumed to be 80 000 R/year/worker. The electricity cost of 35c/kWh is assumed as per Eskom's tariff. Electrical consumption is as assumed in the previous section, 1.5 kWh/ m³ for MED and 4.5 kWh/m³ for RO.

Using Table 13 and the assumptions listed above, a sensitivity graph of water production costs as a function of electricity costs were drawn up and is shown in Figure 26. The electricity costs are determined as from the assumptions above. The water production cost sensitivity to capital costs are taken as 1200 \$/m³ and 1500 \$/m³ for RO. For MED capital costs of 1000 \$/m³ and 1200 \$/m³ are shown in Figure 26.

From Figure 26, it is clear that the water production costs through RO technology is much more affected by higher electricity prices and capital costs than that for MED technology.

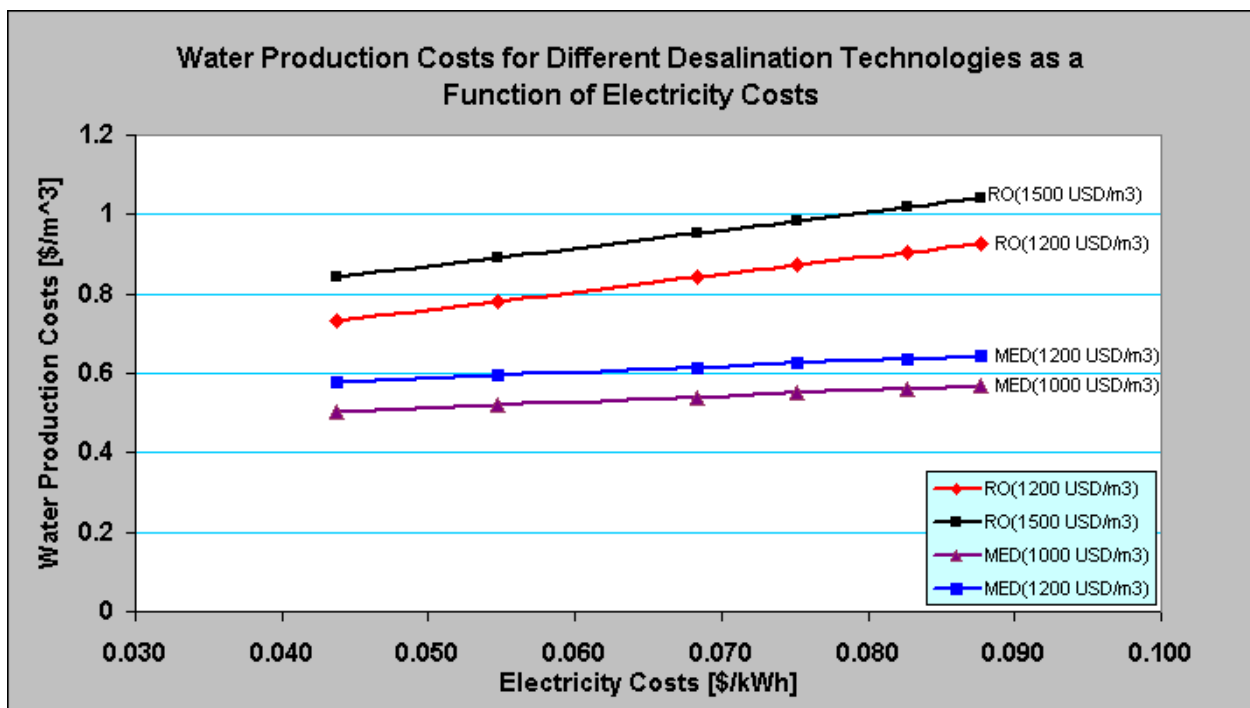


Figure 26: Water production cost versus electricity cost for MED and RO

7.2. Internal Rate of Return and Net Present Value Evaluation

The assumptions made for the Internal Rate of Return (IRR) and Net Present Value (NPV) model are as shown in Table 14. Inflation is assumed to be constant at 6 percent over the next 25 years. Company tax is currently (2011) at 28 percent. The profit made for the production of 1 kWh is 25 cents, assuming the current sales rate of 35c/kWh. From the previous section it is known that the water production cost of RO and MED are 5.88 R/m³ (0.84 \$/m³) and 4.06 R/m³ (0.58 \$/m³) respectively. A water selling price of 15 R/m³ is assumed to be reasonable. Capital investment are taken as 35 000 R/kWe (5000 \$/kWe) for the nuclear installation. The capital cost of MED and RO technologies are as from the previous section at 8400 R/m³ (1200 \$/m³) and 10 500 R/m³ (1500 \$/m³) respectively. In terms of the salvage cost of this project, it is assumed that 20 percent of the initial capital investment will be able to be salvaged and will serve as income at the end of the plant lifetime. The discount rate is the interest rate which could be earned elsewhere or at which money could be borrowed. It is assumed to be inline with inflation, which in this study, is assumed to be 6 percent as stated above.

Table 14: Assumptions made on IRR and NPV model

Parameter	Value
<i>Inflation over 25 years [%]</i>	6
<i>Company tax [%]</i>	28
<i>Profit from electricity sales [R / kWh]</i>	0.25
<i>Water production cost of RO [R / m³]</i>	5.88
<i>Water production cost of MED [R / m³]</i>	4.06
<i>Water selling price [R / m³]</i>	15
<i>Profit from water sales RO [R / m³]</i>	9.12
<i>Profit from water sales MED [R / m³]</i>	10.94
<i>Wear and tear</i>	Taken over 25 years
<i>Initial capital investment cost of power plant [R / kWe]</i>	35,000.00
<i>Initial capital cost of MED [R / m³]</i>	8,400.00
<i>Initial capital cost of RO [R / m³]</i>	10,500.00
<i>Salvage (percentage of initial capital investment) [%]</i>	20
<i>Exchange rate [R / \$]</i>	7
<i>Discount rate [%]</i>	6.00

Table 15 and Table 16 shows the results of the IRR and NPV calculations for the two configurations where a HTR is coupled to a MED and RO plant respectively. From Table 15, utilising an MED plant to desalinate seawater, it can be seen how the profit from electricity sales decrease as the condenser operating temperature increase. This is because more heat is available to the condenser and less work is done by the turbine. As more heat becomes available to the condenser, more water is produced through MED, and more profit is made from water. The IRR and NPV values are shown in the table. The IRR and NPV were calculated by assuming the cash flows will increase with inflation each year (6 percent).

Table 15: IRR and NPV calculations for the power station coupled to a MED plant

<i>Power plant with MED</i>			
Parameter	50°C condenser operating temperature	60°C condenser operating temperature	70°C condenser operating temperature
Generator power [MW]	81.85	78.65	75.17
Units sent to grid [MWh/day]	1940.9	1846.45	1745.19
Water production [m³/day]	15 670	27 433	39 261
Profit from electricity [R/year]	R 177,107,125.00	R 168,488,562.50	R 159,248,587.50
Profit from water [R/year]	R 62,571,877.00	R 109,542,712.30	R 156,773,099.10
Profit before tax and wear and tear	R 239,679,002.00	R 278,031,274.80	R 316,021,686.60
Wear and tear	R 101,159,296.00	R 101,159,296.00	R 101,159,296.00
Profit before tax	R 138,519,706.00	R 176,871,978.80	R 214,862,390.60
Tax @ 28 %	R 38,785,517.68	R 49,524,154.06	R 60,161,469.37
Total profit	R 99,734,188.32	R 127,347,824.74	R 154,700,921.23
Internal Rate of Return (IRR)	6.33%	7.51%	8.54%
Net Present Value (NPV)	R 133,946,198.31	R 659,474,775.17	R 1,178,715,270.91

As in Table 15, the best option for time value of money (best investment) seems to be when a HTR is coupled to a MED plant, with the condenser operating at 70°C. Nearly 40 000 m³/day of desalinated water is produced while the generator is able to produce 1745.19 MWh/day.

Table 16 shows the results of the IRR and NPV calculations of a power plant coupled with a RO plant. As more water is produced less electricity is sent to the grid. This configuration is the better option when comparing NPV and IRR values with that of an MED configuration.

Table 16: IRR and NPV calculations for the power station coupled to a RO plant

<i>Power plant with RO</i>			
Parameter	136.55 MWh/day available for RO	230.99 MWh/day available for RO	332.25 MWh/day available RO
Generator power [MW]	86.56	86.56	86.56
Units sent to the grid [MWh/day]	1940.9	1846.45	1745.19
Water production [m³/day]	30 343.33	51 331	73 833.67
Profit from electricity [R/year]	R 177,107,125.00	R 168,488,562.50	R 159,248,587.50
Profit from water [R/year]	R 101,006,876.90	R 170,870,632.80	R 245,777,520.70
Profit before tax and wear and tear	R 278,114,001.90	R 339,359,195.30	R 405,026,108.20
Wear and tear	R 104,321,190.40	R 104,321,190.40	R 104,321,190.40
Profit before tax	R 173,792,811.50	R 235,038,004.90	R 300,704,917.80
Tax @ 28 %	R 48,661,987.22	R 65,810,641.37	R 84,197,376.98
Total profit	R 125,130,824.28	R 169,227,363.53	R 216,507,540.81
Internal Rate of Return (IRR)	7.63%	9.29%	10.90%
Net Present Value (NPV)	R 704,968,522.80	R 1,546,683,286.57	R 2,486,958,689.64

Table 17 shows the IRR and NPV evaluation if a power plant is used without any desalination. The power station will operate on a condenser operating temperature of 33°C. This will generate the maximum amount of electricity of 2077.44 MWh/day. Choosing this configuration will result in less profit earned when comparing the possibility to invest money at an interest rate of 6 percent per year. The IRR will only be 5 percent, which is less than the 6 percent assumed for inflation.

Table 17: IRR and NPV calculation for a power plant

<i>Power plant</i>	
Parameter	33°C condenser operating temperature
Generator power [MW]	86.56
Units sent to the grid [MWh/day]	2077.44
Profit from electricity [R/year]	R 189,566,400.00
Profit before tax and wear and tear	R 189,566,400.00
Wear and tear	R 96,947,200.00
Profit before tax	R 92,619,200.00
Tax @ 28 %	R 25,933,376.00
Total profit	R 66,685,824.00
Internal Rate of Return (IRR)	5%
Net Present Value (NPV)	R -529,880,204.11

8. CONCLUSION AND SUMMARY

In Chapter 6 a thermodynamic assessment was done on what the effect will be on the cycle efficiency, generator output and condenser waste heat of a Rankine cycle when the condenser operating temperature was increased successively from 33°C to 50°C to 60 °C and finally to 70°C. In order to produce water through MED, the technology requires heat. RO requires only electricity in order to generate the pressure necessary for the RO process. The four simulations shown in Chapter 6, were done to determine how much water can be produced versus how much electricity can be generated with the Rankine cycle with a given inlet heat source of 200 MW_{th} and using the MED technology to produce the desalinated water.

Referring to Table 12, the production rates of desalinated water, through MED and RO, were compared against each other. For each condenser operating condition RO delivers between 87 and 93 percent more desalinated water than that of MED; with the same amount of electricity available to the grid.

When reviewing Figure 26, it can be seen that the water production costs for RO are much higher than for MED (as a function of electricity and capital costs). This will be of importance if electricity was bought from the grid in order to run the RO plant. In this study however, a 200 MW_{th} HTR is used for cogeneration purposes (power and water). A fair amount of water can be produced while the plant operates on its own electricity and supplies electricity to the national grid.

When looking at the most feasible desalination option to be used in conjunction with HTR technology, RO is the better option. Although RO in general has higher operating and capital investment costs, this is overshadowed by the reduction in the electricity generating efficiency of the Rankine cycle at higher condenser back pressures in order to provide heat for the MED process, making RO the more economic option.

Lastly, choosing a condenser operating temperature of 33°C and using RO technology for desalination, seems to be the best option. Nearly 74 000 m³/day of water is produced and 1745 MWh/day of electricity is available to the national grid (Table 12). The Internal Rate of Return (IRR) of this investment is calculated to be 10.9 percent and the Net Present Value (NPV) is calculated to be R 2,486, 958,689.

9. BIBLIOGRAPHY

ADAMS, R. 2009. PBMR sends pebbles for testing in Russia.

<http://atomicinsights.blogspot.com/2009/09/pbmr-sends-pebbles-for-testing-in.html>.

Date of access: 14 September 2010.

AMTA (American Membrane Technology Association). s.a. Water desalination processes.

http://www.amtaorg.com/amta_media/pdfs/8_WaterDesalinationProcesses.pdf.

Date of access: 15 September 2010.

ANON. s.a. Rankine cycle. <http://www.swtc.edu/assets/0/36/824/834/e12cd436-51e1-4e32-9e75-38288ed5e2d7.pdf>.

Date of access: 26 May 2010

ANON. 2000. Introduction of nuclear desalination: a guidebook international atomic energy agency, Vienna.

http://www.eskom.co.za/content/RW_0003ConsentrSolPowRev1.pdf.

Date of access: 23 September 2010.

ANON 2008. Engineering Equation Solver. 1p. <http://www.fchart.com/ees/ees.shtml>.

Date of access: 10 November 2010.

ANON. 2009. 1p. <http://www.Flownex>

SE.com/index.php?option=com_content&view=article&id=184&Itemid=39.

Date of access: 15 September 2010.

ANON. 2010a. Mitsubishi heavy signs MOU with PBMR Pty on development of small-size nuclear power generation plant.

<http://www.greencarcongress.com/2010/02/mhi-pbmr-20100207.html>.

Date of access: 28 May 2010.

ANON. 2010b Reverse Osmosis: pros and cons.

<http://www.historyofwaterfilters.com/reverse-osmosis-pc.html>.

Date of access: 20 September 2010.

ANON. 2010. Environmental impact assessment of nuclear desalination. International atomic energy agency, Vienna.

http://www-pub.iaea.org/MTCD/publications/PDF/te_1642_web.pdf.

Date of access: 9 November 2010.

ARS TECHNICA OPENFORM. 2001. High-Temperature-(nuclear)-Reactors: What they are and what they aren't

<http://arstechnica.com/civis/viewtopic.php?f=26&t=104024>.

Date of access: 28 May 2010.

BARBER – NICHOLS. s.a. Picture taken from: http://www.barber-nichols.com/images/rankine_cycle.jpg.

Date of access: 26 May 2010.

COOLEY, H. GLEICK, P.H. and WOLF, G. 2006. *Desalination with a Grain of Salt: A California Perspective*, Pacific Institute.

DE BRUYN, R. 2010. LT-MED Desalination Sizing. Software in EES used to determine water production rates. M Tech Industrial Potchefstroom.

DE BRUYN, R. & KUHR, R. & HANNINK, R. & VAN RAVENSWAAY, J.P. & ZERVOS, N. & BHAGAT, K. 2008. PBMR desalination options: an economic study. (Proceedings of the 4th International Topical Meeting on High Temperature Reactor Technology). HTR2008-58212.

FERREIRA, T. 2007. PBMR: Clean, Safe, And Affordable Energy.

http://www.schillerinstitute.org/conf-iclc/2007/landbridge_conf_ferreira.html.

Date of access: 28 May 2010.

FLOWSERVE. s.a. Brochure. Desalination reverse osmosis, multi-stage flash, multi-effect distillation.

<http://www.flowserve.com/files/Files/Literature/FPD/fpd-10-ea4.pdf>.

Date of access: 1 June 2010.

FRÖHLING, W. & UNGER, H.-M. & DONG, Y. s.a. Thermodynamic assessment of plant efficiencies for HTR power conversion systems. 5 p.

GALPERIN, A. & SHWAGERAUS E. s.a. Alternative fuel cycles and fuel management for PBMR's – Pebble bed modular gas cooled reactors

<http://web.bgu.ac.il/Eng/engn/nuclear/research/NucEnergy/GCR.htm>.

Date of access: 28 May 2010.

HATZIKIOSEYIAN, A. & VIDALI, R. & KOUSI, P. s.a Modeling and thermodynamic analysis of a multi-effect distillation (MED) plant for seawater desalination.

http://www.metal.ntua.gr/uploads/3024/179/Modelling_and_thermodynamic_analysis_of_a_MED_plant_for_seawater_desalination.pdf.

Date of access: 31 June 2010.

HENTHORNE, L. 2003. Desalination today.

http://www.swhydro.arizona.edu/archive/V2_N3/feature1.pdf.

Date of access: 15 September 2010.

LAMARSH, J.R. & BARATTA, A.J. 2001. Introduction to nuclear engineering. 3rd ed. New Jersey: Prentice hall, Inc. 783 p.

PBMR. 2006. Annual report.

<http://www.pbmr.co.za/contenthtml/Annual2007/index.html>.

Date of access: 27 May 2010.

ROUSSEAU, P.G. 2010. Thermal-fluid systems modeling 1 (MGII885).

Potchefstroom: North-West University. 155 p. (Study guide).

SIDEM, s.a. Picture taken from:

<http://www.sidem-esalination.com/sidem.en/repository/17192,MSF-OT.jpg>.

Date of access: 15 September 2010.

VAN RAVENSWAAY, J.P. & GREYVENSTEIN, R. & DU PLESSIS, G. 2007. Desalination using the PBMR DPP as heat source.

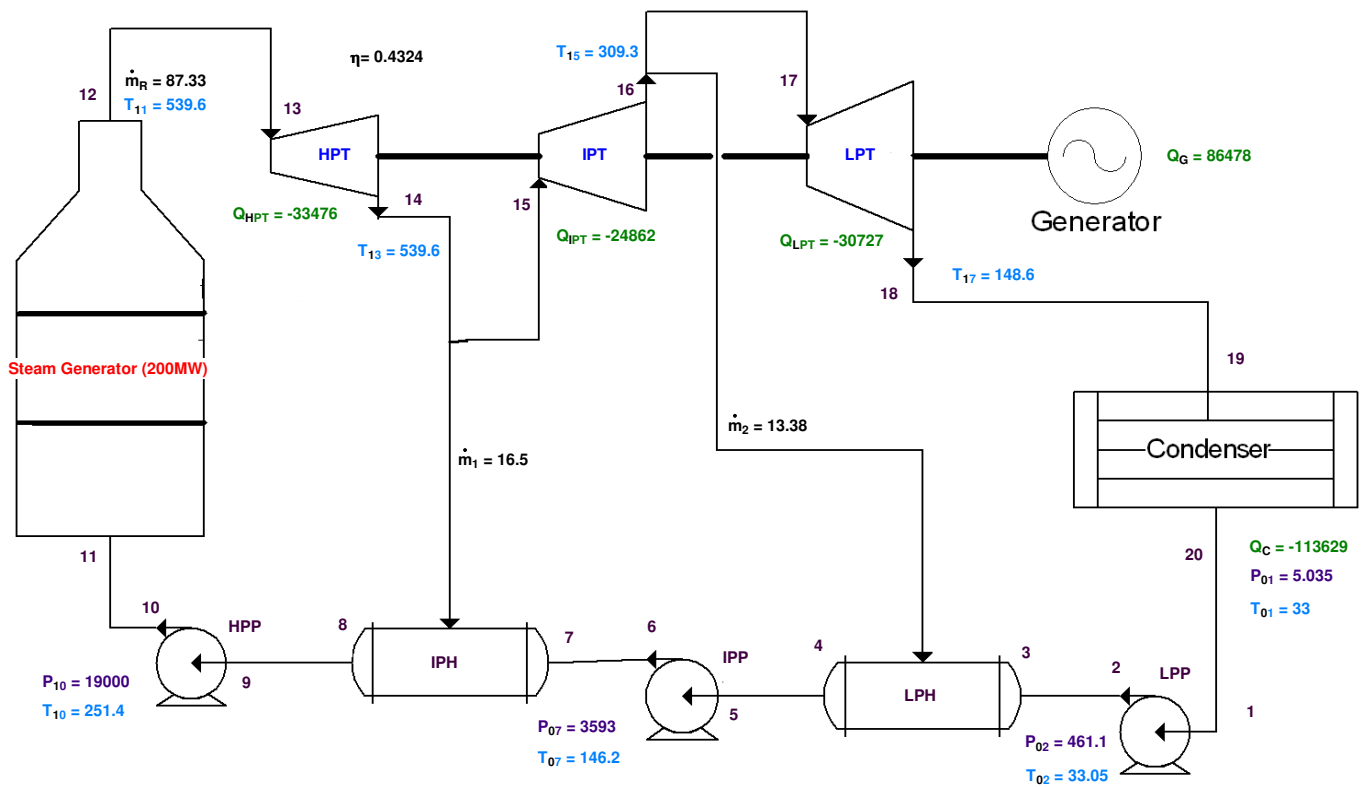
<http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2007/cn152/cn152p>.

Date of access: 1 June 2010.

Appendix A

Appendix A1

Rankine cycle EES model



"Rankine Cycle simulation"

"Node 1"

$T_{01} = 33$

$P_{01} = \text{Pressure}(\text{Steam_IAPWS}, x=x_1, T=T_{01})$

$x_1 = 0$

$h_{01} = \text{Enthalpy}(\text{Steam_IAPWS}, x=x_1, P=P_{01})$

$v_1 = 1/\text{Density}(\text{Water}, T=T_{01}, P=P_{01})$

"-----"

"LPP"

$f_{IP} = 0.1889$

$f_{LP} = 0.1889$

$P_{02} = 461.1$

$P_{06} = 3611$

$P_{10} = 19000$

$\alpha_{\text{pipe}} = 0.005$

$\alpha_H = 0.02$

$T_{\text{max}} = 540$

$Q_R = 200000$

$\{m_{\text{dot}}_R = 78.9\}$

$m_{\text{dot}}_1 = m_{\text{dot}}_R * f_{IP}$

$m_{\text{dot}}_2 = (m_{\text{dot}}_R - m_{\text{dot}}_1) * f_{LP}$

$\eta_p = 0.75$

$\rho_1 = \text{Density}(\text{Steam_IAPWS}, x=0, P=P_{01})$

$Q_{LPP} = ((m_{\text{dot}}_R - m_{\text{dot}}_1 - m_{\text{dot}}_2) / \rho_1) * (1/\eta_p) * (P_{02} - P_{01})$

$h_{02} - h_{01} = Q_{LPP} / (m_{\text{dot}}_R - m_{\text{dot}}_1 - m_{\text{dot}}_2)$

"Pipe pressure loss fraction"

T_02=Temperature(Steam_IAPWS,h=h_02,P=P_02)

"-----"

"Pipe between LPP and LPH"

DELTA_P_23 = alpha_pipe * 0.5 * (P_03 + P_02)

P_03 - P_02 = -DELTA_P_23

h_03-h_02 = 0

"No heat transfer"

T_03=Temperature(Steam_IAPWS,h=h_03,P=P_03)

"-----"

"Low pressure heater (LPH)"

DELTA_P_34 = alpha_H * 0.5 * (P_03 + P_04)

P_04 - P_03 = -DELTA_P_34

T_04=Temperature(Steam_IAPWS,h=h_04,P=P_04)

(m_dot_R - m_dot_1) * h_04 = (m_dot_R - m_dot_1 - m_dot_2) * h_03 + m_dot_2 * h_16

"-----"

"Pipe between LPH and IPP"

DELTA_P_45 = alpha_pipe * 0.5 * (P_04 + P_05)

P_05-P_04 = -DELTA_P_45

h_05-h_04 = 0

T_05=Temperature(Steam_IAPWS,h=h_05,P=P_05)

"-----"

"IPP"

v_5 = 1 / Density(Steam_IAPWS,h=h_05,P=P_05)

T_06=Temperature(Steam_IAPWS,h=h_06,P=P_06)

rho_5=Density(Steam_IAPWS,h=h_05,P=P_05)

Q_IPP = ((m_dot_R-m_dot_1)/rho_5)*(1/eta_p)*(p_06-p_05)

h_06-h_05 = Q_IPP/(m_dot_R-m_dot_1)

"-----"

"Pipe between IPP and IPH"

DELTA_P_67 = alpha_pipe * 0.5 * (P_06 + P_07)

P_07-P_06 = -DELTA_P_67

h_07-h_06 = 0

T_07=Temperature(Steam_IAPWS,h=h_07,P=P_07)

"-----"

"IPH"

DELTA_P_78 = alpha_H * 0.5 * (P_07 + P_08)

P_08 - P_07 = -DELTA_P_78

T_08=Temperature(Steam_IAPWS,h=h_08,P=P_08)

m_dot_R * h_08 = (m_dot_R - m_dot_1) * h_07 + (m_dot_1) * h_14

v_08 = 1 / Density(Steam_IAPWS,h=h_08,P=P_08)

"-----"

"Node between IPH and HPP"

```

DELTAP_89 = alpha_pipe * 0.5 * (P_08 + P_09)
P_09-P_08 = -DELTAP_89
h_09-h_08 = 0
T_09=Temperature(Steam_IAPWS,h=h_09,P=P_09)
v_09 = 1 / Density(Steam_IAPWS,x=0,P=P_09)

```

"-----"

"HPP"

```

T_10=Temperature(Steam_IAPWS,h=h_10,P=P_10)
rho_9=Density(Steam_IAPWS,x=0,P=P_09)
Q_HPP = (m_dot_R/rho_9)*(1/eta_p)*(P_10-P_09)
h_10-h_09 = Q_HPP/(m_dot_R)
v_10 = 1 / Density(Steam_IAPWS,h=h_10,P=P_10)

```

"-----"

"Pipe between HPP and Steam Generator(SG)"

```

DELTAP_1011 = alpha_pipe * 0.5 * (P_10 + P_11)
P_11-P_10 = -DELTAP_1011
h_11-h_10 = 0
T_11 = Temperature(Steam_IAPWS,h=h_13,P=P_13)

```

"-----"

"Steam Generator"

```

DELTAP_1112 = alpha_H * 0.5 * (P_11 + P_12)
P_12-P_11 = -DELTAP_1112
h_12 = Enthalpy(Steam_IAPWS,T=T_12,P=P_12)
h_12-h_11 = Q_R/m_dot_R
T_12 = T_max
s_12 = Entropy(Steam_IAPWS,h=h_12,P=P_12)

```

"-----"

"Pipe between SG and HPT"

```

DELTAP_1213 = alpha_pipe * 0.5 * (P_12 + P_13)
P_13-P_12 = -DELTAP_1213
h_13-h_12 = 0
T_13 = Temperature(Steam_IAPWS,h=h_13,P=P_13)
s_13 = s_12

```

"-----"

"HPT"

```

eta_HPT = 0.85
P_14 = P_06
h_14s=Enthalpy(Steam_IAPWS,P=P_14,s=s_13)
eta_HPT = (h_14-h_13)/(h_14s-h_13)
Q_HPT = (m_dot_R) * (h_14-h_13)
T_14=Temperature(Steam_IAPWS,h=h_14,P=P_14)
x_14s =Quality(Steam_IAPWS,P=P_14,h=h_14s)
x_14 =Quality(Steam_IAPWS,T=T_14,h=h_14)
s_14 =Entropy(Steam_IAPWS,h=h_14,P=P_14)

```

$\{Q_{HPT} = (87.27) * (2995-3383)\}$

"-----"

"Pipe between HPT and IPT"

DELTA_P_1415 = alpha_pipe * 0.5 * (P_14 + P_15)
P_15-P_14 = -DELTA_P_1415
h_15-h_14 = 0
T_15=Temperature(Steam_IAPWS,h=h_15,P=P_15)
s_15 =Entropy(Steam_IAPWS,h=h_15,P=P_15)
x_15 = Quality(Steam_IAPWS,T=T_15,h=h_15)

"-----"

"IPT"

P_16 = P_02
h_16s=Enthalpy(Steam_IAPWS,P=P_16, s=Entropy(Steam_IAPWS,h=h_15,P=P_15))
eta_IPT = 0.85
eta_IPT = (h_16-h_15)/(h_16s-h_15)
h_16-h_15 = Q_IPT/(m_dot_R-m_dot_1)
s_16f = Entropy(Steam_IAPWS,x=0,P=P_16)
T_16=Temperature(Steam_IAPWS,h=h_16,P=P_16)
x_16s = Quality(Steam_IAPWS,P=P_16,h=h_16s)
x_16 = Quality(Steam_IAPWS,P=P_16,h=h_16)
s_16 = Entropy(Steam_IAPWS,h=h_16,P=P_16)

"-----"

"Pipe between IPT and LPT"

DELTA_P_1617 = alpha_pipe * 0.5 * (P_16 + P_17)
P_17-P_16 = -DELTA_P_1617
h_17-h_16 = 0
T_17=Temperature(Steam_IAPWS,h=h_17,P=P_17)

"-----"

"LPT"

P_18 = P_01
h_18s=Enthalpy(Steam_IAPWS,P=P_18,s=Entropy(Steam_IAPWS,h=h_17,P=P_17))
eta_LPT = 0.85
eta_LPT = (h_18-h_17)/(h_18s-h_17)
h_18-h_17 = Q_LPT/(m_dot_R-m_dot_1-m_dot_2)
T_18=Temperature(Steam_IAPWS,h=h_18,P=P_18)
x_18s=Quality(Steam_IAPWS,P=P_18,h=h_18s)
x_18=Quality(Steam_IAPWS,P=P_18,h=h_18)

"-----"

"Pipe between LPT and Condenser"

DELTA_P_1819 = alpha_pipe * 0.5 * (P_18 + P_19)
P_19-P_18 = -DELTA_P_1819
h_19-h_18 = 0
T_19=Temperature(Steam_IAPWS,h=h_19,P=P_19)

"-----"

"Condenser"

```

x_20 = 0
DELTAP_1920 = alpha_H * 0.5 * (P_19 + P_20)
P_20-P_19 = -DELTAP_1920
h_20=Enthalpy(Steam_IAPWS,x=x_20,P=P_20)
T_20=Temperature(Steam_IAPWS,h=h_20,P=P_20)
h_20-h_19 = Q_C/(m_dot_R-m_dot_1-m_dot_2)

```

-----"

"Generator"

```

Q_G = -(Q_LPT + Q_IPT + Q_HPT) - (Q_LPP + Q_IPP + Q_HPP)
eta = Q_G/(Q_R)

```

-----"

"Array Tables"

-----"

```

h_[1] = h_01
h_[2] = h_02
h_[3] = h_03
h_[4] = h_04
h_[5] = h_05
h_[6] = h_06
h_[7] = h_07
h_[8] = h_08
h_[9] = h_09
h_[10] = h_10
h_[11] = h_11
h_[12] = h_12
h_[13] = h_13
h_[14] = h_14
h_[15] = h_15
h_[16] = h_16
h_[17] = h_17
h_[18] = h_18
h_[19] = h_19

```

```

p_[1] = p_01
p_[2] = p_02
p_[3] = p_03
p_[4] = p_04
p_[5] = p_05
p_[6] = p_06
p_[7] = p_07
p_[8] = p_08
p_[9] = p_09
p_[10] = p_10
p_[11] = p_11
p_[12] = p_12
p_[13] = p_13
p_[14] = p_14
p_[15] = p_15
p_[16] = p_16
p_[17] = p_17
p_[18] = p_18

```

$$p_{[19]} = p_{19}$$

$$T_{[1]} = T_{01}$$

$$T_{[2]} = T_{02}$$

$$T_{[3]} = T_{03}$$

$$T_{[4]} = T_{04}$$

$$T_{[5]} = T_{05}$$

$$T_{[6]} = T_{06}$$

$$T_{[7]} = T_{07}$$

$$T_{[8]} = T_{08}$$

$$T_{[9]} = T_{09}$$

$$T_{[10]} = T_{10}$$

$$T_{[11]} = T_{11}$$

$$T_{[12]} = T_{12}$$

$$T_{[13]} = T_{13}$$

$$T_{[14]} = T_{14}$$

$$T_{[15]} = T_{15}$$

$$T_{[16]} = T_{16}$$

$$T_{[17]} = T_{17}$$

$$T_{[18]} = T_{18}$$

$$T_{[19]} = T_{19}$$

$$n = 19$$

$$\text{Duplicate } i = 1, n$$

$$s_{[i]} = \text{Entropy}(\text{Steam_IAPWS}, h = h_{[i]}, P = P_{[i]})$$

END

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$$\alpha_H = 0.02$$

$$\Delta P_{1112} = 374.4$$

$$\Delta P_{1617} = 2.3$$

$$\Delta P_{23} = 2.3$$

$$\Delta P_{67} = 18.01$$

$$\eta = 0.4324$$

$$\eta_{LPT} = 0.85$$

$$f_{LP} = 0.1889$$

$$h_{03} = 138.9$$

$$h_{06} = 617.6$$

$$h_{09} = 1068$$

$$h_{12} = 3383$$

$$h_{14s} = 2932$$

$$h_{16s} = 2587$$

$$h_{18s} = 2020$$

$$\dot{m}_1 = 16.5$$

$$n = 19$$

$$P_{03} = 458.8$$

$$P_{06} = 3611$$

$$P_{09} = 3504$$

$$P_{12} = 18531$$

$$P_{15} = 3593$$

$$P_{18} = 5.035$$

$$Q_C = -113629$$

$$Q_{HPT} = -33476$$

$$Q_{LPP} = 35.12$$

$$\rho_1 = 994.7$$

$$s_{12} = 6.354$$

$$\alpha_{\text{pipe}} = 0.005$$

$$\Delta P_{1213} = 92.42$$

$$\Delta P_{1819} = 0.02511$$

$$\Delta P_{34} = 9.085$$

$$\Delta P_{78} = 71.15$$

$$\eta_{HPT} = 0.85$$

$$\eta_p = 0.75$$

$$h_{01} = 138.3$$

$$h_{04} = 613.1$$

$$h_{07} = 617.6$$

$$h_{10} = 1093$$

$$h_{13} = 3383$$

$$h_{15} = 3000$$

$$h_{17} = 2649$$

$$h_{19} = 2114$$

$$\dot{m}_2 = 13.38$$

$$P_{01} = 5.035$$

$$P_{04} = 449.7$$

$$P_{07} = 3593$$

$$P_{10} = 19000$$

$$P_{13} = 18438$$

$$P_{16} = 461.1$$

$$P_{19} = 5.01$$

$$Q_G = 86478$$

$$Q_{IPP} = 324.4$$

$$Q_{LPT} = -30727$$

$$\rho_5 = 921.1$$

$$s_{13} = 6.354$$

$$\Delta P_{1011} = 94.76$$

$$\Delta P_{1415} = 18.01$$

$$\Delta P_{1920} = 0.09921$$

$$\Delta P_{45} = 2.243$$

$$\Delta P_{89} = 17.57$$

$$\eta_{IPT} = 0.85$$

$$f_{IP} = 0.1889$$

$$h_{02} = 138.9$$

$$h_{05} = 613.1$$

$$h_{08} = 1068$$

$$h_{11} = 1093$$

$$h_{14} = 3000$$

$$h_{16} = 2649$$

$$h_{18} = 2114$$

$$h_{20} = 136.4$$

$$\dot{m}_R = 87.33$$

$$P_{02} = 461.1$$

$$P_{05} = 447.5$$

$$P_{08} = 3522$$

$$P_{11} = 18905$$

$$P_{14} = 3611$$

$$P_{17} = 458.8$$

$$P_{20} = 4.911$$

$$Q_{HPP} = 2228$$

$$Q_{IPT} = -24862$$

$$Q_R = 200000$$

$$\rho_9 = 809.7$$

$$s_{14} = 6.473$$

$s_{15} = 6.475$	$s_{16} = 6.622$	$s_{16f} = 1.83$
$T_{01} = 33$	$T_{02} = 33.05$	$T_{03} = 33.05$
$T_{04} = 145.6$	$T_{05} = 145.6$	$T_{06} = 146.2$
$T_{07} = 146.2$	$T_{08} = 242.9$	$T_{09} = 242.6$
$T_{10} = 251.4$	$T_{11} = 539.6$	$T_{12} = 540$
$T_{13} = 539.6$	$T_{14} = 309.5$	$T_{15} = 309.3$
$T_{16} = 148.8$	$T_{17} = 148.6$	$T_{18} = 33$
$T_{19} = 32.91$	$T_{20} = 32.56$	$T_{\max} = 540$
$v_{08} = 0.00175$	$v_{09} = 0.001235$	$v_1 = 0.001005$
$v_{10} = 0.00123$	$v_5 = 0.001086$	$x_1 = 0$
$x_{14} = 100$	$x_{14s} = 100$	$x_{15} = 100$
$x_{16} = 0.9549$	$x_{16s} = 0.9257$	$x_{18} = 0.8156$
$x_{18s} = 0.7766$	$x_{20} = 0$	

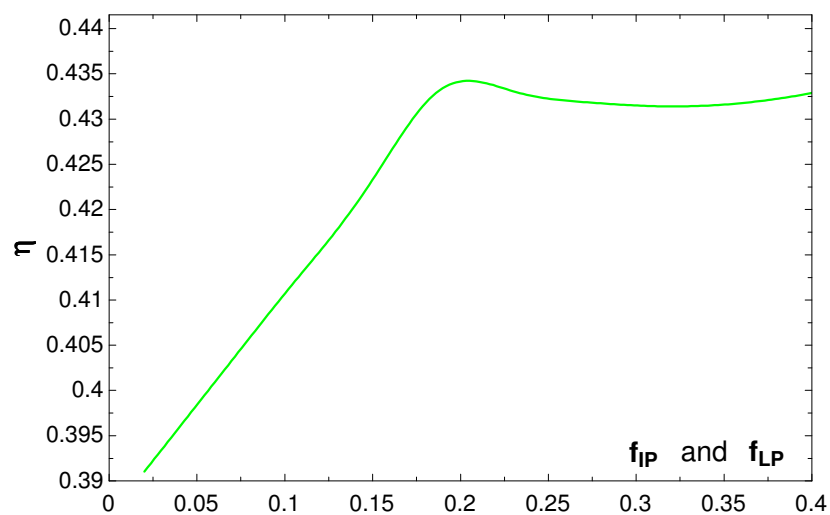
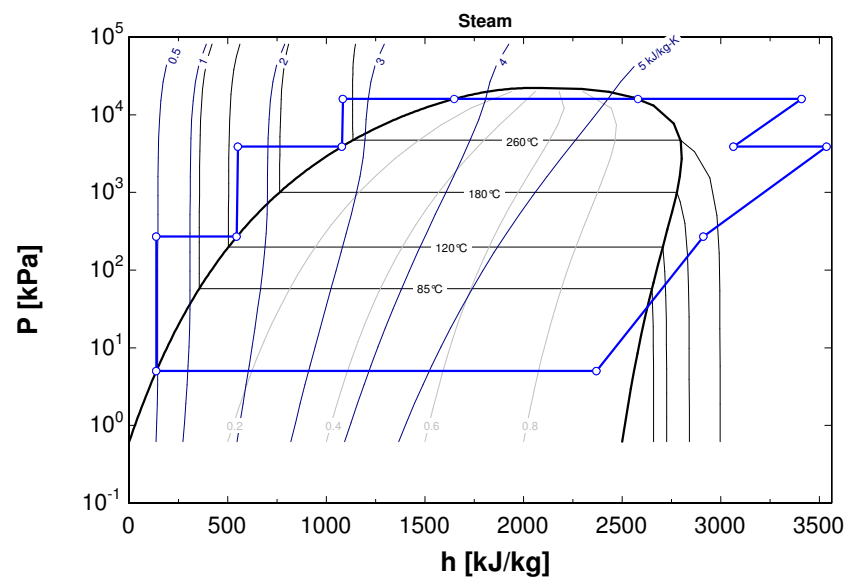
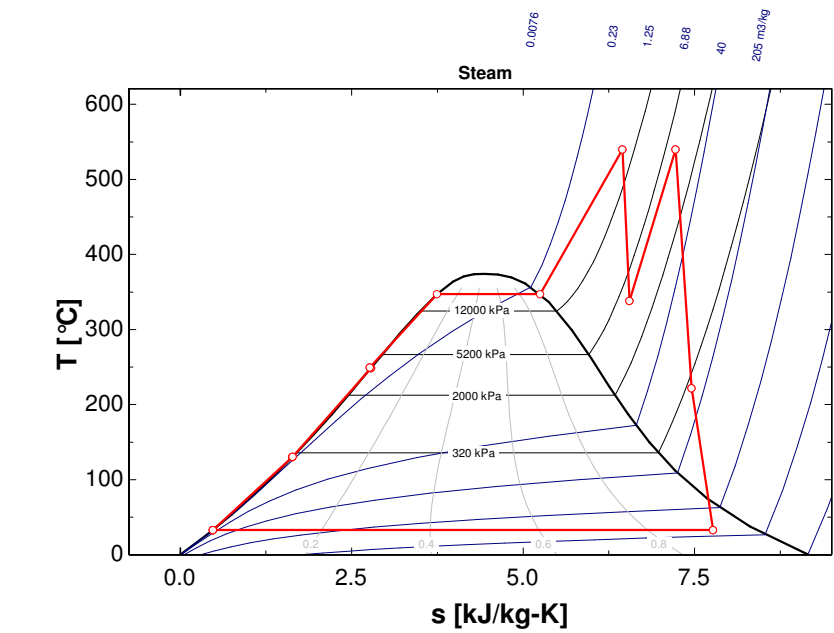
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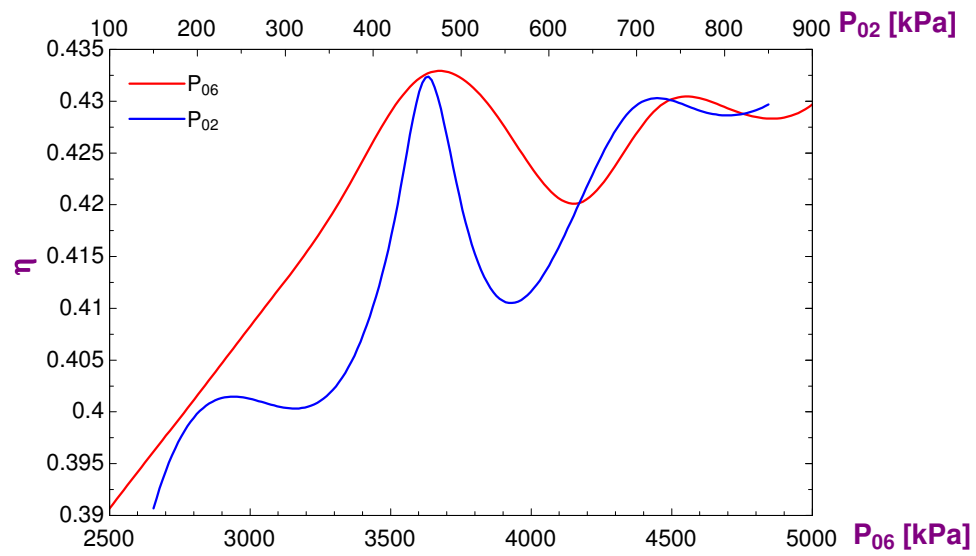
Arrays Table

	$\bar{h}_i$	$\bar{p}_i$	$\bar{s}_i$	$\bar{T}_i$
1	138.3	5.035	0.4779	33
2	138.9	461.1	0.4784	33.05
3	138.9	458.8	0.4784	33.05
4	613.1	449.7	1.796	145.6
5	613.1	447.5	1.796	145.6
6	617.6	3611	1.799	146.2
7	617.6	3593	1.799	146.2
8	1068	3522	2.76	242.9
9	1068	3504	2.76	242.6
10	1093	19000	2.772	251.4
11	1093	18905	2.772	539.6
12	3383	18531	6.354	540
13	3383	18438	6.356	539.6
14	3000	3611	6.473	309.5
15	3000	3593	6.475	309.3
16	2649	461.1	6.622	148.8
17	2649	458.8	6.624	148.6
18	2114	5.035	6.932	33
19	2114	5.01	6.934	32.91

Parametric Table: Table 5

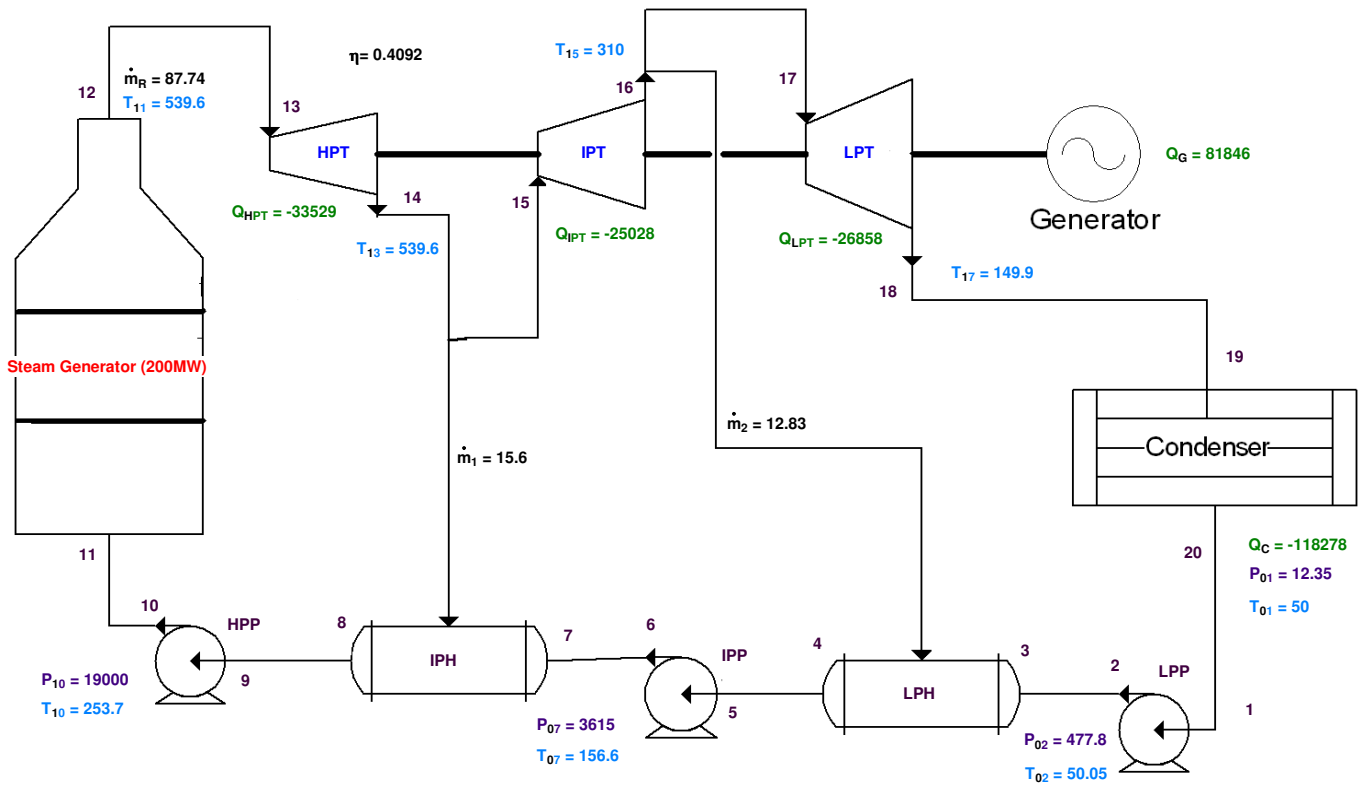
	η	f_{IP}	f_{LP}	P_{02}	P_{06}	Q_G
Run 1	0.3907	0.02	0.02	150	2500	78136
Run 2	0.4004	0.06222	0.06222	300	2778	80079
Run 3	0.4102	0.1044	0.1044	400	3056	82042
Run 4	0.421	0.1467	0.1467	430	3333	84201
Run 5	0.4324	0.1889	0.1889	461.1	3611	86477
Run 6	0.4282	0.2311	0.2311	480	3889	85636
Run 7	0.4201	0.2733	0.2733	500	4167	84027
Run 8	0.4292	0.3156	0.3156	694.4	4444	85845
Run 9	0.4291	0.3578	0.3578	772.2	4722	85815
Run 10	0.4297	0.4	0.4	850	5000	85937





Appendix A2

*Rankine cycle EES model with 50 °C
condenser operating temperature*



"Rankine Cycle simulation"

"Node 1"

$T_{01} = 50$

$P_{01} = \text{Pressure}(\text{Steam_IAPWS}, x=x_1, T=T_{01})$

$x_1 = 0$

$h_{01} = \text{Enthalpy}(\text{Steam_IAPWS}, x=x_1, P=P_{01})$

$v_1 = 1/\text{Density}(\text{Water}, T=T_{01}, P=P_{01})$

"-----"

"LPP"

$f_{IP} = 0.1778$

$f_{LP} = 0.1778$

$P_{02} = 477.8$

$P_{06} = 3633$

$P_{10} = 19000$

$\alpha_{\text{pipe}} = 0.005$

$\alpha_H = 0.02$

$T_{\text{max}} = 540$

$Q_R = 200000$

$\{m_{\text{dot}}_R = 78.9\}$

$m_{\text{dot}}_1 = m_{\text{dot}}_R \cdot f_{IP}$

$m_{\text{dot}}_2 = (m_{\text{dot}}_R - m_{\text{dot}}_1) \cdot f_{LP}$

$\eta_p = 0.75$

$\rho_1 = \text{Density}(\text{Steam_IAPWS}, x=0, P=P_{01})$

$Q_{LPP} = ((m_{\text{dot}}_R - m_{\text{dot}}_1 - m_{\text{dot}}_2) / \rho_1) \cdot (1/\eta_p) \cdot (P_{02} - P_{01})$

$h_{02} - h_{01} = Q_{LPP} / (m_{\text{dot}}_R - m_{\text{dot}}_1 - m_{\text{dot}}_2)$

"Pipe pressure loss fraction"

T_02=Temperature(Steam_IAPWS,h=h_02,P=P_02)

"-----"

"Pipe between LPP and LPH"

DELTA_P_23 = alpha_pipe * 0.5 * (P_03 + P_02)

P_03 - P_02 = -DELTA_P_23

h_03-h_02 = 0

"No heat transfer"

T_03=Temperature(Steam_IAPWS,h=h_03,P=P_03)

"-----"

"Low pressure heater (LPH)"

DELTA_P_34 = alpha_H * 0.5 * (P_03 + P_04)

P_04 - P_03 = -DELTA_P_34

T_04=Temperature(Steam_IAPWS,h=h_04,P=P_04)

(m_dot_R - m_dot_1) * h_04 = (m_dot_R - m_dot_1 - m_dot_2) * h_03 + m_dot_2 * h_16

"-----"

"Pipe between LPH and IPP"

DELTA_P_45 = alpha_pipe * 0.5 * (P_04 + P_05)

P_05-P_04 = -DELTA_P_45

h_05-h_04 = 0

T_05=Temperature(Steam_IAPWS,h=h_05,P=P_05)

"-----"

"IPP"

v_5 = 1 / Density(Steam_IAPWS,h=h_05,P=P_05)

T_06=Temperature(Steam_IAPWS,h=h_06,P=P_06)

rho_5=Density(Steam_IAPWS,h=h_05,P=P_05)

Q_IPP = ((m_dot_R-m_dot_1)/rho_5)*(1/eta_p)*(p_06-p_05)

h_06-h_05 = Q_IPP/(m_dot_R-m_dot_1)

"-----"

"Pipe between IPP and IPH"

DELTA_P_67 = alpha_pipe * 0.5 * (P_06 + P_07)

P_07-P_06 = -DELTA_P_67

h_07-h_06 = 0

T_07=Temperature(Steam_IAPWS,h=h_07,P=P_07)

"-----"

"IPH"

DELTA_P_78 = alpha_H * 0.5 * (P_07 + P_08)

P_08 - P_07 = -DELTA_P_78

T_08=Temperature(Steam_IAPWS,h=h_08,P=P_08)

m_dot_R * h_08 = (m_dot_R - m_dot_1) * h_07 + (m_dot_1) * h_14

"-----"

"Node between IPH and HPP"

```

DELTAP_89 = alpha_pipe * 0.5 * (P_08 + P_09)
P_09-P_08 = -DELTAP_89
h_09-h_08 = 0
T_09=Temperature(Steam_IAPWS,h=h_09,P=P_09)

```

"-----"

"HPP"

```

T_10=Temperature(Steam_IAPWS,h=h_10,P=P_10)
rho_9=Density(Steam_IAPWS,x=0,P=P_09)
Q_HPP = (m_dot_R/rho_9)*(1/eta_p)*(P_10-P_09)
h_10-h_09 = Q_HPP/(m_dot_R)
v_10 = 1 / Density(Steam_IAPWS,h=h_10,P=P_10)

```

"-----"

"Pipe between HPP and Steam Generator(SG)"

```

DELTAP_1011 = alpha_pipe * 0.5 * (P_10 + P_11)
P_11-P_10 = -DELTAP_1011
h_11-h_10 = 0
T_11 = Temperature(Steam_IAPWS,h=h_13,P=P_13)

```

"-----"

"Steam Generator"

```

DELTAP_1112 = alpha_H * 0.5 * (P_11 + P_12)
P_12-P_11 = -DELTAP_1112
h_12 = Enthalpy(Steam_IAPWS,T=T_12,P=P_12)
h_12-h_11 = Q_R/m_dot_R
T_12 = T_max
s_12 = Entropy(Steam_IAPWS,h=h_12,P=P_12)

```

"-----"

"Pipe between SG and HPT"

```

DELTAP_1213 = alpha_pipe * 0.5 * (P_12 + P_13)
P_13-P_12 = -DELTAP_1213
h_13-h_12 = 0
T_13 = Temperature(Steam_IAPWS,h=h_13,P=P_13)
s_13 = s_12

```

"-----"

"HPT"

```

eta_HPT = 0.85
P_14 = P_06
h_14s=Enthalpy(Steam_IAPWS,P=P_14,s=s_13)
eta_HPT = (h_14-h_13)/(h_14s-h_13)
Q_HPT = (m_dot_R) * (h_14-h_13)
T_14=Temperature(Steam_IAPWS,h=h_14,P=P_14)
x_14s =Quality(Steam_IAPWS,P=P_14,h=h_14s)
x_14 =Quality(Steam_IAPWS,T=T_14,h=h_14)
s_14 =Entropy(Steam_IAPWS,h=h_14,P=P_14)
{Q_HPT = (87.27) * (2995-3383)}

```

"-----"

"Pipe between HPT and IPT"

DELTA_P_1415 = alpha_pipe * 0.5 * (P_14 + P_15)
P_15-P_14 = -DELTA_P_1415
h_15-h_14 = 0
T_15=Temperature(Steam_IAPWS,h=h_15,P=P_15)
s_15 =Entropy(Steam_IAPWS,h=h_15,P=P_15)
x_15 = Quality(Steam_IAPWS,T=T_15,h=h_15)

"-----"

"IPT"

P_16 = P_02
h_16s=Enthalpy(Steam_IAPWS,P=P_16, s=Entropy(Steam_IAPWS,h=h_15,P=P_15))
eta_IPT = 0.85
eta_IPT = (h_16-h_15)/(h_16s-h_15)
h_16-h_15 = Q_IPT/(m_dot_R-m_dot_1)
s_16f = Entropy(Steam_IAPWS,x=0,P=P_16)
T_16=Temperature(Steam_IAPWS,h=h_16,P=P_16)
x_16s = Quality(Steam_IAPWS,P=P_16,h=h_16s)
x_16 = Quality(Steam_IAPWS,P=P_16,h=h_16)
s_16 = Entropy(Steam_IAPWS,h=h_16,P=P_16)

"-----"

"Pipe between IPT and LPT"

DELTA_P_1617 = alpha_pipe * 0.5 * (P_16 + P_17)
P_17-P_16 = -DELTA_P_1617
h_17-h_16 = 0
T_17=Temperature(Steam_IAPWS,h=h_17,P=P_17)

"-----"

"LPT"

P_18 = P_01
h_18s=Enthalpy(Steam_IAPWS,P=P_18,s=Entropy(Steam_IAPWS,h=h_17,P=P_17))
eta_LPT = 0.85
eta_LPT = (h_18-h_17)/(h_18s-h_17)
h_18-h_17 = Q_LPT/(m_dot_R-m_dot_1-m_dot_2)
T_18=Temperature(Steam_IAPWS,h=h_18,P=P_18)
x_18s=Quality(Steam_IAPWS,P=P_18,h=h_18s)
x_18=Quality(Steam_IAPWS,P=P_18,h=h_18)

"-----"

"Pipe between LPT and Condenser"

DELTA_P_1819 = alpha_pipe * 0.5 * (P_18 + P_19)
P_19-P_18 = -DELTA_P_1819
h_19-h_18 = 0
T_19=Temperature(Steam_IAPWS,h=h_19,P=P_19)

"-----"

"Condenser"

```

x_20 = 0
DELTAP_1920 = alpha_H * 0.5 * (P_19 + P_20)
P_20-P_19 = -DELTAP_1920
h_20=Enthalpy(Steam_IAPWS,x=x_20,P=P_20)
T_20=Temperature(Steam_IAPWS,h=h_20,P=P_20)
h_20-h_19 = Q_C/(m_dot_R-m_dot_1-m_dot_2)

```

"-----"

"Generator"

```

Q_G = -(Q_LPT + Q_IPT + Q_HPT) - (Q_LPP + Q_IPP + Q_HPP)
eta = Q_G/(Q_R)

```

"-----"

"Array Tables"

"-----"

```

h_[1] = h_01
h_[2] = h_02
h_[3] = h_03
h_[4] = h_04
h_[5] = h_05
h_[6] = h_06
h_[7] = h_07
h_[8] = h_08
h_[9] = h_09
h_[10] = h_10
h_[11] = h_11
h_[12] = h_12
h_[13] = h_13
h_[14] = h_14
h_[15] = h_15
h_[16] = h_16
h_[17] = h_17
h_[18] = h_18
h_[19] = h_19

```

```

p_[1] = p_01
p_[2] = p_02
p_[3] = p_03
p_[4] = p_04
p_[5] = p_05
p_[6] = p_06
p_[7] = p_07
p_[8] = p_08
p_[9] = p_09
p_[10] = p_10
p_[11] = p_11
p_[12] = p_12
p_[13] = p_13
p_[14] = p_14
p_[15] = p_15
p_[16] = p_16
p_[17] = p_17
p_[18] = p_18
p_[19] = p_19

```

$T_{[1]} = T_{01}$
 $T_{[2]} = T_{02}$
 $T_{[3]} = T_{03}$
 $T_{[4]} = T_{04}$
 $T_{[5]} = T_{05}$
 $T_{[6]} = T_{06}$
 $T_{[7]} = T_{07}$
 $T_{[8]} = T_{08}$
 $T_{[9]} = T_{09}$
 $T_{[10]} = T_{10}$
 $T_{[11]} = T_{11}$
 $T_{[12]} = T_{12}$
 $T_{[13]} = T_{13}$
 $T_{[14]} = T_{14}$
 $T_{[15]} = T_{15}$
 $T_{[16]} = T_{16}$
 $T_{[17]} = T_{17}$
 $T_{[18]} = T_{18}$
 $T_{[19]} = T_{19}$

$n=19$

Duplicate i=1,n

$s_{[i]} = \text{Entropy}(\text{Steam_IAPWS}, h=h_{[i]}, P=P_{[i]})$

END

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$\alpha_H = 0.02$	$\alpha_{\text{pipe}} = 0.005$	$\Delta P_{1011} = 94.76$
$\Delta P_{1112} = 374.4$	$\Delta P_{1213} = 92.42$	$\Delta P_{1415} = 18.12$
$\Delta P_{1617} = 2.383$	$\Delta P_{1819} = 0.06161$	$\Delta P_{1920} = 0.2434$
$\Delta P_{23} = 2.383$	$\Delta P_{34} = 9.414$	$\Delta P_{45} = 2.324$
$\Delta P_{67} = 18.12$	$\Delta P_{78} = 71.58$	$\Delta P_{89} = 17.67$
$\eta = 0.4092$	$\eta_{\text{HPT}} = 0.85$	$\eta_{\text{IPT}} = 0.85$
$\eta_{\text{LPT}} = 0.85$	$\eta_p = 0.75$	$f_{\text{IP}} = 0.1778$
$f_{\text{LP}} = 0.1778$	$h_{01} = 209.3$	$h_{02} = 210$
$h_{03} = 210$	$h_{04} = 644.6$	$h_{05} = 644.6$
$h_{06} = 662.5$	$h_{07} = 662.5$	$h_{08} = 1078$
$h_{09} = 1078$	$h_{10} = 1104$	$h_{11} = 1104$
$h_{12} = 3383$	$h_{13} = 3383$	$h_{14} = 3001$
$h_{14s} = 2934$	$h_{15} = 3001$	$h_{16} = 2654$
$h_{16s} = 2593$	$h_{17} = 2654$	$h_{18} = 2201$
$h_{18s} = 2122$	$h_{19} = 2201$	$h_{20} = 207.2$
$\dot{m}_1 = 15.6$	$\dot{m}_2 = 12.83$	$\dot{m}_R = 87.74$
$n = 19$	$P_{01} = 12.35$	$P_{02} = 477.8$
$P_{03} = 475.4$	$P_{04} = 466$	$P_{05} = 463.7$
$P_{06} = 3633$	$P_{07} = 3615$	$P_{08} = 3543$
$P_{09} = 3526$	$P_{10} = 19000$	$P_{11} = 18905$
$P_{12} = 18531$	$P_{13} = 18438$	$P_{14} = 3633$
$P_{15} = 3615$	$P_{16} = 477.8$	$P_{17} = 475.4$
$P_{18} = 12.35$	$P_{19} = 12.29$	$P_{20} = 12.05$
$Q_C = -118278$	$Q_G = 81846$	$Q_{\text{HPP}} = 2237$
$Q_{\text{HPT}} = -33529$	$Q_{\text{IPP}} = 1294$	$Q_{\text{IPT}} = -25028$
$Q_{\text{LPP}} = 37.26$	$Q_{\text{LPT}} = -26858$	$Q_R = 200000$
$\rho_1 = 988$	$\rho_5 = 235.5$	$\rho_9 = 809.2$
$s_{12} = 6.354$	$s_{13} = 6.354$	$s_{14} = 6.472$
$s_{15} = 6.474$	$s_{16} = 6.619$	$s_{16f} = 1.843$
$T_{01} = 50$	$T_{02} = 50.05$	$T_{03} = 50.06$

T ₀₄ = 149.2	T ₀₅ = 149	T ₀₆ = 156.6
T ₀₇ = 156.6	T ₀₈ = 243.3	T ₀₉ = 243
T ₁₀ = 253.7	T ₁₁ = 539.6	T ₁₂ = 540
T ₁₃ = 539.6	T ₁₄ = 310.2	T ₁₅ = 310
T ₁₆ = 150.1	T ₁₇ = 149.9	T ₁₈ = 50
T ₁₉ = 49.9	T ₂₀ = 49.5	T _{max} = 540
v ₁ = 0.001012	v ₁₀ = 0.001235	v ₅ = 0.004247
x ₁ = 0	x ₁₄ = 100	x _{14s} = 100
x ₁₅ = 100	x ₁₆ = 0.9566	x _{16s} = 0.9276
x ₁₈ = 0.8363	x _{18s} = 0.8028	x ₂₀ = 0

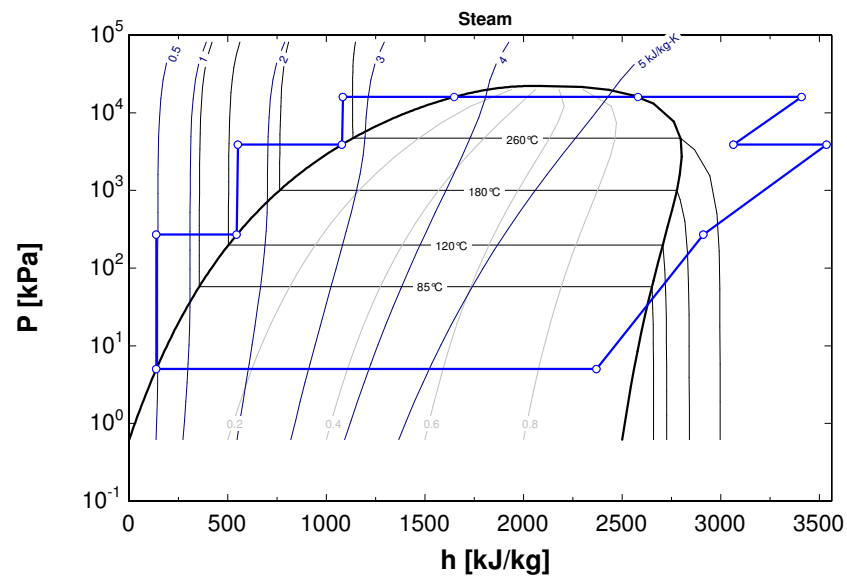
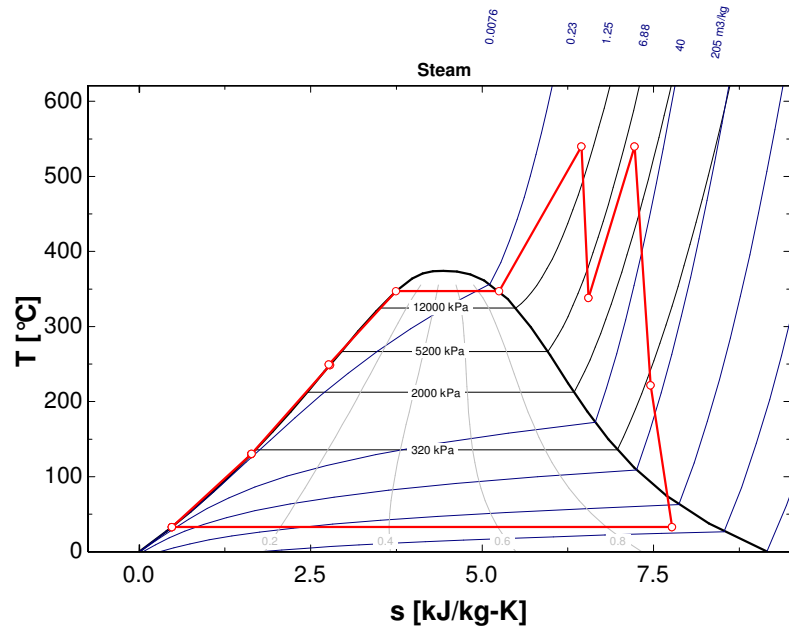
55 potential unit problems were detected.

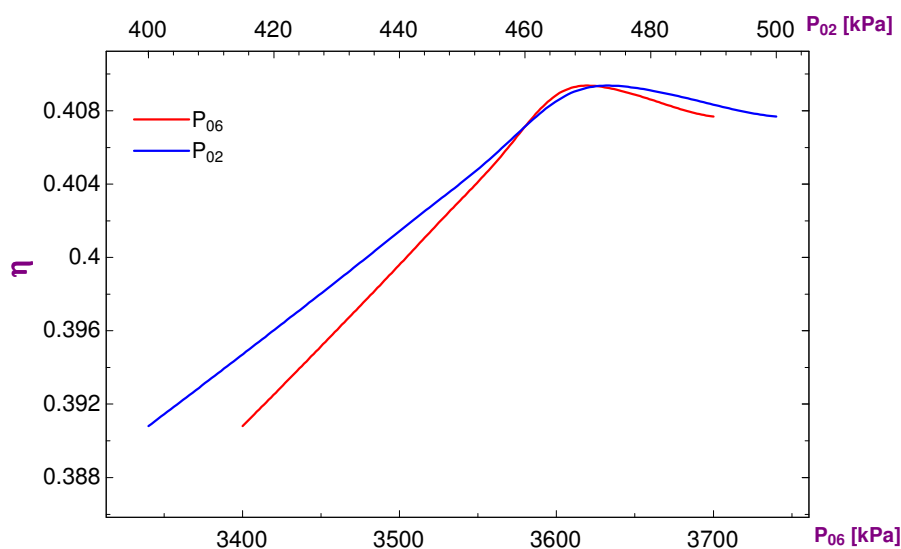
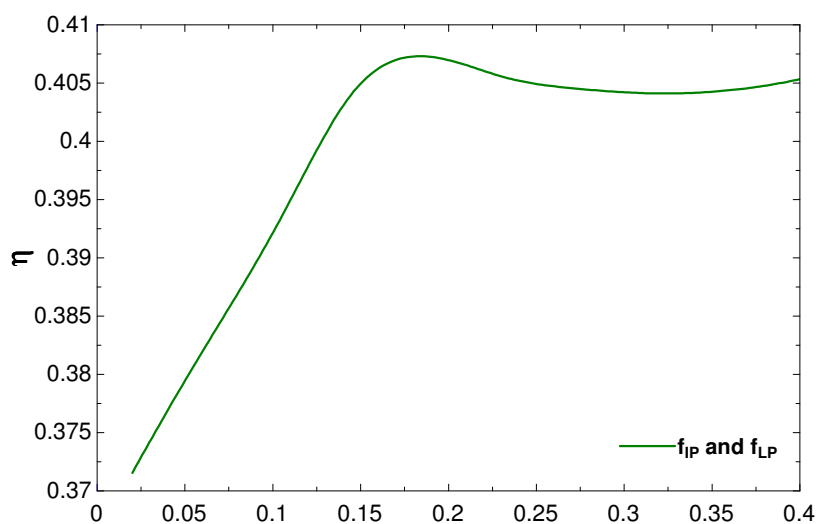
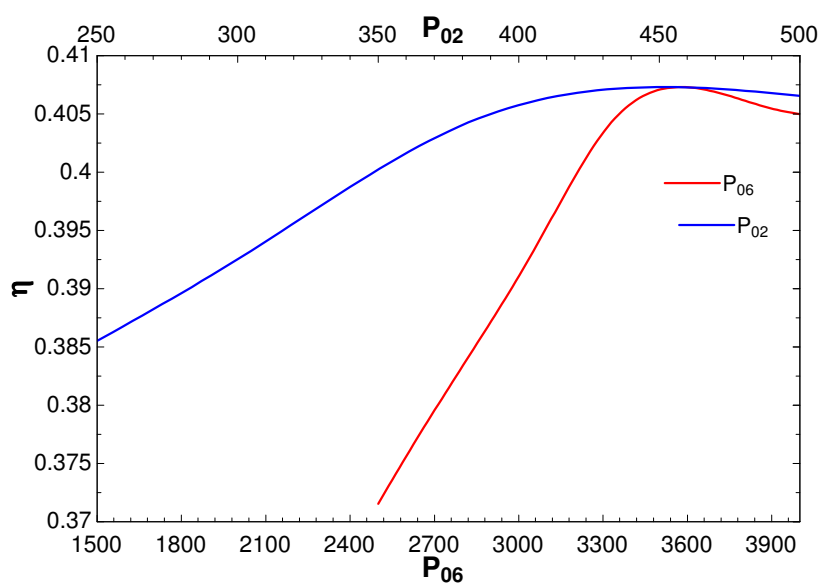
Arrays Table

	$\bar{h}_i$	$\bar{p}_i$	$\bar{s}_i$	$\bar{T}_i$
1	209.3	12.35	0.7038	50
2	210	477.8	0.7043	50.05
3	210	475.4	0.7043	50.06
4	644.6	466	1.871	149.2
5	644.6	463.7	1.871	149
6	662.5	3633	1.905	156.6
7	662.5	3615	1.905	156.6
8	1078	3543	2.781	243.3
9	1078	3526	2.781	243
10	1104	19000	2.792	253.7
11	1104	18905	2.793	539.6
12	3383	18531	6.354	540
13	3383	18438	6.356	539.6
14	3001	3633	6.472	310.2
15	3001	3615	6.474	310
16	2654	477.8	6.619	150.1
17	2654	475.4	6.621	149.9
18	2201	12.35	6.868	50
19	2201	12.29	6.87	49.9

Parametric Table: Table 5(copy)

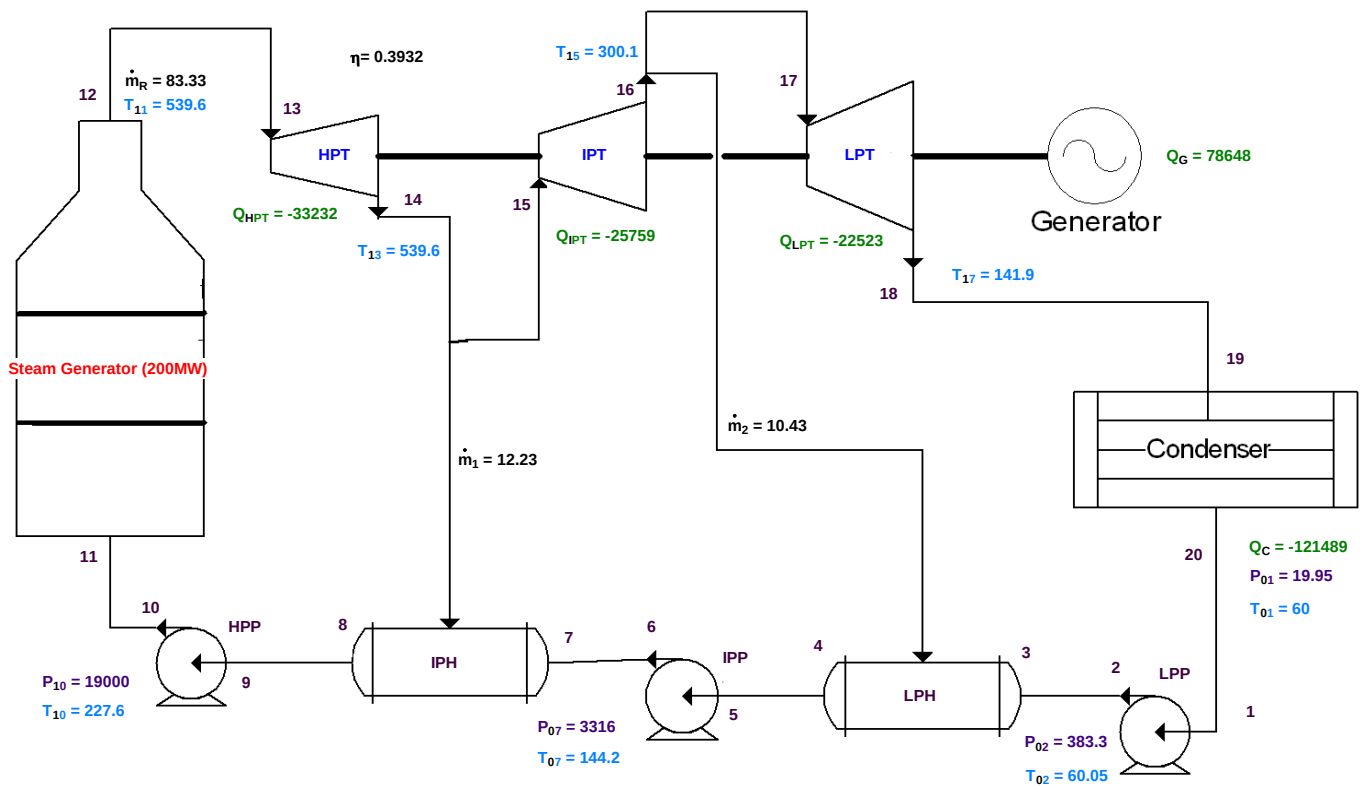
	η	f_{IP}	f_{LP}	P_{02}	P_{06}	Q_G
Run 1	0.3908	0.1	0.1	400	3400	78160
Run 2	0.3937	0.1111	0.1111	411.1	3433	78738
Run 3	0.3966	0.1222	0.1222	422.2	3467	79325
Run 4	0.3996	0.1333	0.1333	433.3	3500	79921
Run 5	0.4026	0.1444	0.1444	444.4	3533	80527
Run 6	0.4057	0.1556	0.1556	455.6	3567	81144
Run 7	0.4089	0.1667	0.1667	466.7	3600	81771
Run 8	0.4092	0.1778	0.1778	477.8	3633	81846
Run 9	0.4084	0.1889	0.1889	488.9	3667	81684
Run 10	0.4077	0.2	0.2	500	3700	81536





Appendix A3

*Rankine cycle EES model with 60 °C
condenser operating temperature*



"Rankine Cycle simulation"

"Node 1"

$T_{01} = 60$

$P_{01} = \text{Pressure}(\text{Steam_IAPWS}, x=x_1, T=T_{01})$

$x_1 = 0$

$h_{01} = \text{Enthalpy}(\text{Steam_IAPWS}, x=x_1, P=P_{01})$

$v_1 = 1/\text{Density}(\text{Water}, T=T_{01}, P=P_{01})$

"-----"

"LPP"

$f_{IP} = 0.1467$

$f_{LP} = 0.1467$

$P_{02} = 383.3$

$P_{06} = 3333$

$P_{10} = 19000$

$\alpha_{\text{pipe}} = 0.005$

$\alpha_H = 0.02$

$T_{\text{max}} = 540$

$Q_R = 200000$

$\{m_{\text{dot}_R} = 78.9\}$

$m_{\text{dot}_1} = m_{\text{dot}_R} * f_{IP}$

$m_{\text{dot}_2} = (m_{\text{dot}_R} - m_{\text{dot}_1}) * f_{LP}$

$\eta_p = 0.75$

$\rho_1 = \text{Density}(\text{Steam_IAPWS}, x=0, P=P_{01})$

$Q_{LPP} = ((m_{\text{dot}_R} - m_{\text{dot}_1} - m_{\text{dot}_2}) / \rho_1) * (1/\eta_p) * (P_{02} - P_{01})$

$h_{02} - h_{01} = Q_{LPP} / (m_{\text{dot}_R} - m_{\text{dot}_1} - m_{\text{dot}_2})$

"Pipe pressure loss fraction"

T_02=Temperature(Steam_IAPWS,h=h_02,P=P_02)

"-----"

"Pipe between LPP and LPH"

DELTAP_23 = alpha_pipe * 0.5 * (P_03 + P_02)

P_03 - P_02 = -DELTAP_23

h_03-h_02 = 0

"No heat transfer"

T_03=Temperature(Steam_IAPWS,h=h_03,P=P_03)

"-----"

"Low pressure heater (LPH)"

DELTAP_34 = alpha_H * 0.5 * (P_03 + P_04)

P_04 - P_03 = -DELTAP_34

T_04=Temperature(Steam_IAPWS,h=h_04,P=P_04)

(m_dot_R - m_dot_1) * h_04 = (m_dot_R - m_dot_1 - m_dot_2) * h_03 + m_dot_2 * h_16

"-----"

"Pipe between LPH and IPP"

DELTAP_45 = alpha_pipe * 0.5 * (P_04 + P_05)

P_05-P_04 = -DELTAP_45

h_05-h_04 = 0

T_05=Temperature(Steam_IAPWS,h=h_05,P=P_05)

"-----"

"IPP"

v_5 = 1 / Density(Steam_IAPWS,h=h_05,P=P_05)

T_06=Temperature(Steam_IAPWS,h=h_06,P=P_06)

rho_5=Density(Steam_IAPWS,h=h_05,P=P_05)

Q_IPP = ((m_dot_R-m_dot_1)/rho_5)*(1/eta_p)*(p_06-p_05)

h_06-h_05 = Q_IPP/(m_dot_R-m_dot_1)

"-----"

"Pipe between IPP and IPH"

DELTAP_67 = alpha_pipe * 0.5 * (P_06 + P_07)

P_07-P_06 = -DELTAP_67

h_07-h_06 = 0

T_07=Temperature(Steam_IAPWS,h=h_07,P=P_07)

"-----"

"IPH"

DELTAP_78 = alpha_H * 0.5 * (P_07 + P_08)

P_08 - P_07 = -DELTAP_78

T_08=Temperature(Steam_IAPWS,h=h_08,P=P_08)

m_dot_R * h_08 = (m_dot_R - m_dot_1) * h_07 + (m_dot_1) * h_14

"-----"

"Node between IPH and HPP"

```

DELTAP_89 = alpha_pipe * 0.5 * (P_08 + P_09)
P_09-P_08 = -DELTAP_89
h_09-h_08 = 0
T_09=Temperature(Steam_IAPWS,h=h_09,P=P_09)

```

"-----"

"HPP"

```

T_10=Temperature(Steam_IAPWS,h=h_10,P=P_10)
rho_9=Density(Steam_IAPWS,x=0,P=P_09)
Q_HPP = (m_dot_R/rho_9)*(1/eta_p)*(P_10-P_09)
h_10-h_09 = Q_HPP/(m_dot_R)
v_10 = 1 / Density(Steam_IAPWS,h=h_10,P=P_10)

```

"-----"

"Pipe between HPP and Steam Generator(SG)"

```

DELTAP_1011 = alpha_pipe * 0.5 * (P_10 + P_11)
P_11-P_10 = -DELTAP_1011
h_11-h_10 = 0
T_11 = Temperature(Steam_IAPWS,h=h_13,P=P_13)

```

"-----"

"Steam Generator"

```

DELTAP_1112 = alpha_H * 0.5 * (P_11 + P_12)
P_12-P_11 = -DELTAP_1112
h_12 = Enthalpy(Steam_IAPWS,T=T_12,P=P_12)
h_12-h_11 = Q_R/m_dot_R
T_12 = T_max
s_12 =Entropy(Steam_IAPWS,h=h_12,P=P_12)

```

"-----"

"Pipe between SG and HPT"

```

DELTAP_1213 = alpha_pipe * 0.5 * (P_12 + P_13)
P_13-P_12 = -DELTAP_1213
h_13-h_12 = 0
T_13 = Temperature(Steam_IAPWS,h=h_13,P=P_13)
s_13 = s_12

```

"-----"

"HPT"

```

eta_HPT = 0.85
P_14 = P_06
h_14s=Enthalpy(Steam_IAPWS,P=P_14,s=s_13)
eta_HPT = (h_14-h_13)/(h_14s-h_13)
Q_HPT = (m_dot_R) * (h_14-h_13)
T_14=Temperature(Steam_IAPWS,h=h_14,P=P_14)
x_14s =Quality(Steam_IAPWS,P=P_14,h=h_14s)
x_14 =Quality(Steam_IAPWS,T=T_14,h=h_14)
s_14 =Entropy(Steam_IAPWS,h=h_14,P=P_14)
{Q_HPT = (87.27) * (2995-3383)}

```

"-----"

"Pipe between HPT and IPT"

DELTA_P_1415 = $\alpha_{\text{pipe}} \cdot 0.5 \cdot (P_{14} + P_{15})$
 $P_{15} - P_{14} = -\text{DELTA}_{P_1415}$
 $h_{15} - h_{14} = 0$
 $T_{15} = \text{Temperature}(\text{Steam_IAPWS}, h=h_{15}, P=P_{15})$
 $s_{15} = \text{Entropy}(\text{Steam_IAPWS}, h=h_{15}, P=P_{15})$
 $x_{15} = \text{Quality}(\text{Steam_IAPWS}, T=T_{15}, h=h_{15})$

"-----"

"IPT"

$P_{16} = P_{02}$
 $h_{16s} = \text{Enthalpy}(\text{Steam_IAPWS}, P=P_{16}, s=\text{Entropy}(\text{Steam_IAPWS}, h=h_{15}, P=P_{15}))$
 $\eta_{\text{IPT}} = 0.85$
 $\eta_{\text{IPT}} = (h_{16} - h_{15}) / (h_{16s} - h_{15})$
 $h_{16} - h_{15} = Q_{\text{IPT}} / (m_{\text{dot_R}} - m_{\text{dot_1}})$
 $s_{16f} = \text{Entropy}(\text{Steam_IAPWS}, x=0, P=P_{16})$
 $T_{16} = \text{Temperature}(\text{Steam_IAPWS}, h=h_{16}, P=P_{16})$
 $x_{16s} = \text{Quality}(\text{Steam_IAPWS}, P=P_{16}, h=h_{16s})$
 $x_{16} = \text{Quality}(\text{Steam_IAPWS}, P=P_{16}, h=h_{16})$
 $s_{16} = \text{Entropy}(\text{Steam_IAPWS}, h=h_{16}, P=P_{16})$

"-----"

"Pipe between IPT and LPT"

DELTA_P_1617 = $\alpha_{\text{pipe}} \cdot 0.5 \cdot (P_{16} + P_{17})$
 $P_{17} - P_{16} = -\text{DELTA}_{P_1617}$
 $h_{17} - h_{16} = 0$
 $T_{17} = \text{Temperature}(\text{Steam_IAPWS}, h=h_{17}, P=P_{17})$

"-----"

"LPT"

$P_{18} = P_{01}$
 $h_{18s} = \text{Enthalpy}(\text{Steam_IAPWS}, P=P_{18}, s=\text{Entropy}(\text{Steam_IAPWS}, h=h_{17}, P=P_{17}))$
 $\eta_{\text{LPT}} = 0.85$
 $\eta_{\text{LPT}} = (h_{18} - h_{17}) / (h_{18s} - h_{17})$
 $h_{18} - h_{17} = Q_{\text{LPT}} / (m_{\text{dot_R}} - m_{\text{dot_1}} - m_{\text{dot_2}})$
 $T_{18} = \text{Temperature}(\text{Steam_IAPWS}, h=h_{18}, P=P_{18})$
 $x_{18s} = \text{Quality}(\text{Steam_IAPWS}, P=P_{18}, h=h_{18s})$
 $x_{18} = \text{Quality}(\text{Steam_IAPWS}, P=P_{18}, h=h_{18})$

"-----"

"Pipe between LPT and Condenser"

DELTA_P_1819 = $\alpha_{\text{pipe}} \cdot 0.5 \cdot (P_{18} + P_{19})$
 $P_{19} - P_{18} = -\text{DELTA}_{P_1819}$
 $h_{19} - h_{18} = 0$
 $T_{19} = \text{Temperature}(\text{Steam_IAPWS}, h=h_{19}, P=P_{19})$

"-----"

"Condenser"

```
x_20 = 0
DELTAP_1920 = alpha_H * 0.5 * (P_19 + P_20)
P_20-P_19 = -DELTAP_1920
h_20=Enthalpy(Steam_IAPWS,x=x_20,P=P_20)
T_20=Temperature(Steam_IAPWS,h=h_20,P=P_20)
h_20-h_19 = Q_C/(m_dot_R-m_dot_1-m_dot_2)
```

"-----"

"Generator"

```
Q_G = -(Q_LPT + Q_IPT + Q_HPT) - (Q_LPP + Q_IPP + Q_HPP)
eta = Q_G/(Q_R)
```

"-----"

"Array Tables"

"-----"

```
h_[1] = h_01
h_[2] = h_02
h_[3] = h_03
h_[4] = h_04
h_[5] = h_05
h_[6] = h_06
h_[7] = h_07
h_[8] = h_08
h_[9] = h_09
h_[10] = h_10
h_[11] = h_11
h_[12] = h_12
h_[13] = h_13
h_[14] = h_14
h_[15] = h_15
h_[16] = h_16
h_[17] = h_17
h_[18] = h_18
h_[19] = h_19
```

```
p_[1] = p_01
p_[2] = p_02
p_[3] = p_03
p_[4] = p_04
p_[5] = p_05
p_[6] = p_06
p_[7] = p_07
p_[8] = p_08
p_[9] = p_09
p_[10] = p_10
p_[11] = p_11
p_[12] = p_12
p_[13] = p_13
p_[14] = p_14
p_[15] = p_15
p_[16] = p_16
p_[17] = p_17
p_[18] = p_18
p_[19] = p_19
```

```

T_[1] = T_01
T_[2] = T_02
T_[3] = T_03
T_[4] = T_04
T_[5] = T_05
T_[6] = T_06
T_[7] = T_07
T_[8] = T_08
T_[9] = T_09
T_[10] = T_10
T_[11] = T_11
T_[12] = T_12
T_[13] = T_13
T_[14] = T_14
T_[15] = T_15
T_[16] = T_16
T_[17] = T_17
T_[18] = T_18
T_[19] = T_19

```

```

n=19
Duplicate i=1,n

```

```

s_[i]=Entropy(Steam_IAPWS,h=h_[i],P=P_[i])

```

```

END

```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$\alpha_H = 0.02$	$\alpha_{\text{pipe}} = 0.005$	$\Delta P_{1011} = 94.76$
$\Delta P_{1112} = 374.4$	$\Delta P_{1213} = 92.42$	$\Delta P_{1415} = 16.62$
$\Delta P_{1617} = 1.912$	$\Delta P_{1819} = 0.09949$	$\Delta P_{1920} = 0.393$
$\Delta P_{23} = 1.912$	$\Delta P_{34} = 7.552$	$\Delta P_{45} = 1.865$
$\Delta P_{67} = 16.62$	$\Delta P_{78} = 65.67$	$\Delta P_{89} = 16.21$
$\eta = 0.3932$	$\eta_{\text{HPT}} = 0.85$	$\eta_{\text{IPT}} = 0.85$
$\eta_{\text{LPT}} = 0.85$	$\eta_p = 0.75$	$f_{\text{IP}} = 0.1467$
$f_{\text{LP}} = 0.1467$	$h_{01} = 251.2$	$h_{02} = 251.7$
$h_{03} = 251.7$	$h_{04} = 599.5$	$h_{05} = 599.5$
$h_{06} = 609.2$	$h_{07} = 609.2$	$h_{08} = 957.6$
$h_{09} = 957.6$	$h_{10} = 983.4$	$h_{11} = 983.4$
$h_{12} = 3383$	$h_{13} = 3383$	$h_{14} = 2985$
$h_{14s} = 2914$	$h_{15} = 2985$	$h_{16} = 2622$
$h_{16s} = 2558$	$h_{17} = 2622$	$h_{18} = 2251$
$h_{18s} = 2186$	$h_{19} = 2251$	$h_{20} = 248.9$
$\dot{m}_1 = 12.23$	$\dot{m}_2 = 10.43$	$\dot{m}_R = 83.33$
$n = 19$	$P_{01} = 19.95$	$P_{02} = 383.3$
$P_{03} = 381.4$	$P_{04} = 373.8$	$P_{05} = 372$
$P_{06} = 3333$	$P_{07} = 3316$	$P_{08} = 3251$
$P_{09} = 3234$	$P_{10} = 19000$	$P_{11} = 18905$
$P_{12} = 18531$	$P_{13} = 18438$	$P_{14} = 3333$
$P_{15} = 3316$	$P_{16} = 383.3$	$P_{17} = 381.4$
$P_{18} = 19.95$	$P_{19} = 19.85$	$P_{20} = 19.45$
$Q_C = -121489$	$Q_G = 78648$	$Q_{\text{HPP}} = 2146$
$Q_{\text{HPT}} = -33232$	$Q_{\text{IPP}} = 689.7$	$Q_{\text{IPT}} = -25759$
$Q_{\text{LPP}} = 29.9$	$Q_{\text{LPT}} = -22523$	$Q_R = 200000$
$\rho_1 = 983.2$	$\rho_5 = 407$	$\rho_9 = 816.1$
$S_{12} = 6.354$	$S_{13} = 6.354$	$S_{14} = 6.48$
$S_{15} = 6.482$	$S_{16} = 6.636$	$S_{16f} = 1.761$
$T_{01} = 60$	$T_{02} = 60.05$	$T_{03} = 60.05$

T ₀₄ = 141.2	T ₀₅ = 141	T ₀₆ = 144.2
T ₀₇ = 144.2	T ₀₈ = 223	T ₀₉ = 223
T ₁₀ = 227.6	T ₁₁ = 539.6	T ₁₂ = 540
T ₁₃ = 539.6	T ₁₄ = 300.3	T ₁₅ = 300.1
T ₁₆ = 142.1	T ₁₇ = 141.9	T ₁₈ = 60
T ₁₉ = 59.89	T ₂₀ = 59.46	T _{max} = 540
v ₁ = 0.001017	v ₁₀ = 0.001184	v ₅ = 0.002457
x ₁ = 0	x ₁₄ = 100	x _{14s} = 100
x ₁₅ = 100	x ₁₆ = 0.9468	x _{16s} = 0.9169
x ₁₈ = 0.8483	x _{18s} = 0.8205	x ₂₀ = 0

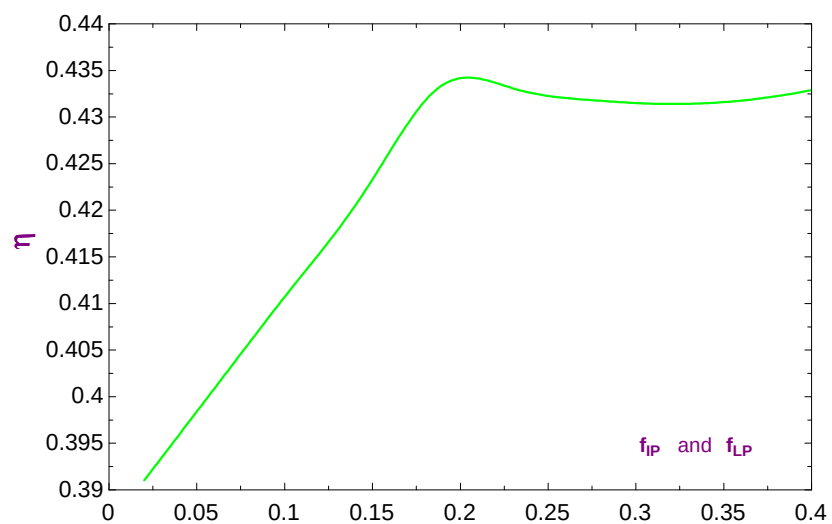
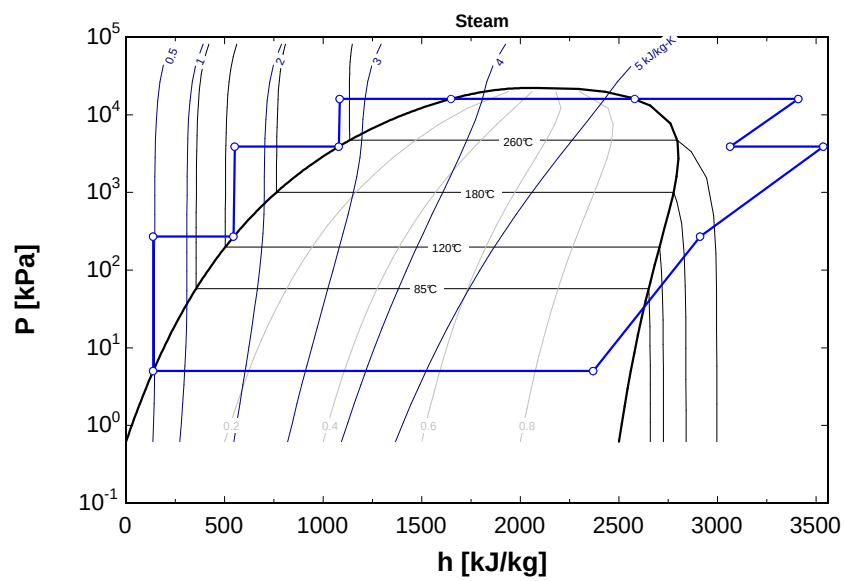
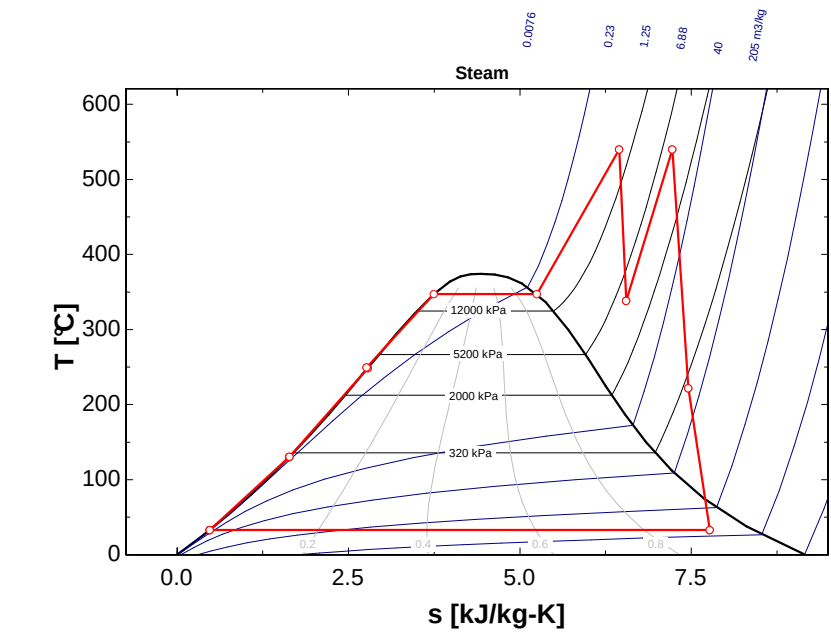
55 potential unit problems were detected.

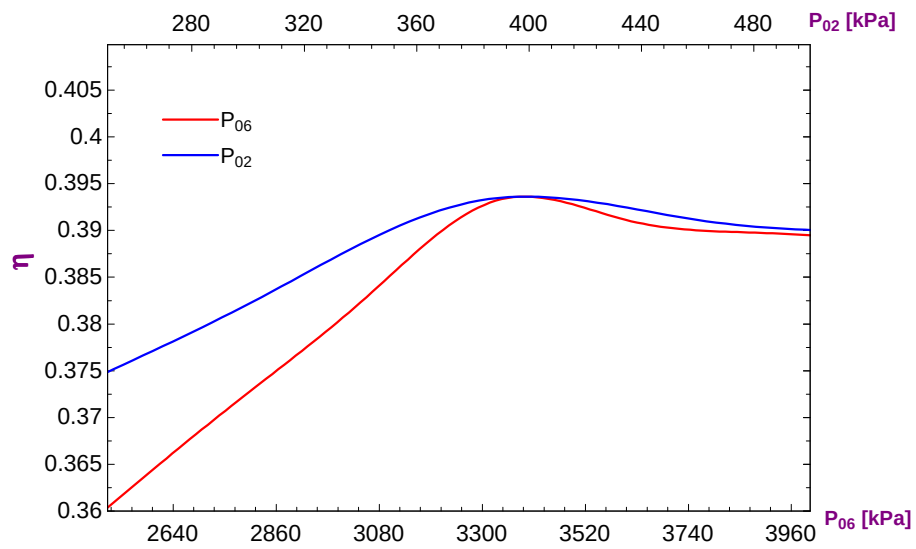
Arrays Table

	$\bar{h}_i$	$\bar{p}_i$	$\bar{s}_i$	$\bar{T}_i$
1	251.2	19.95	0.8313	60
2	251.7	383.3	0.8317	60.05
3	251.7	381.4	0.8317	60.05
4	599.5	373.8	1.764	141.2
5	599.5	372	1.764	141
6	609.2	3333	1.78	144.2
7	609.2	3316	1.78	144.2
8	957.6	3251	2.544	223
9	957.6	3234	2.544	223
10	983.4	19000	2.558	227.6
11	983.4	18905	2.558	539.6
12	3383	18531	6.354	540
13	3383	18438	6.356	539.6
14	2985	3333	6.48	300.3
15	2985	3316	6.482	300.1
16	2622	383.3	6.636	142.1
17	2622	381.4	6.638	141.9
18	2251	19.95	6.835	60
19	2251	19.85	6.836	59.89

Parametric Table: Table 5

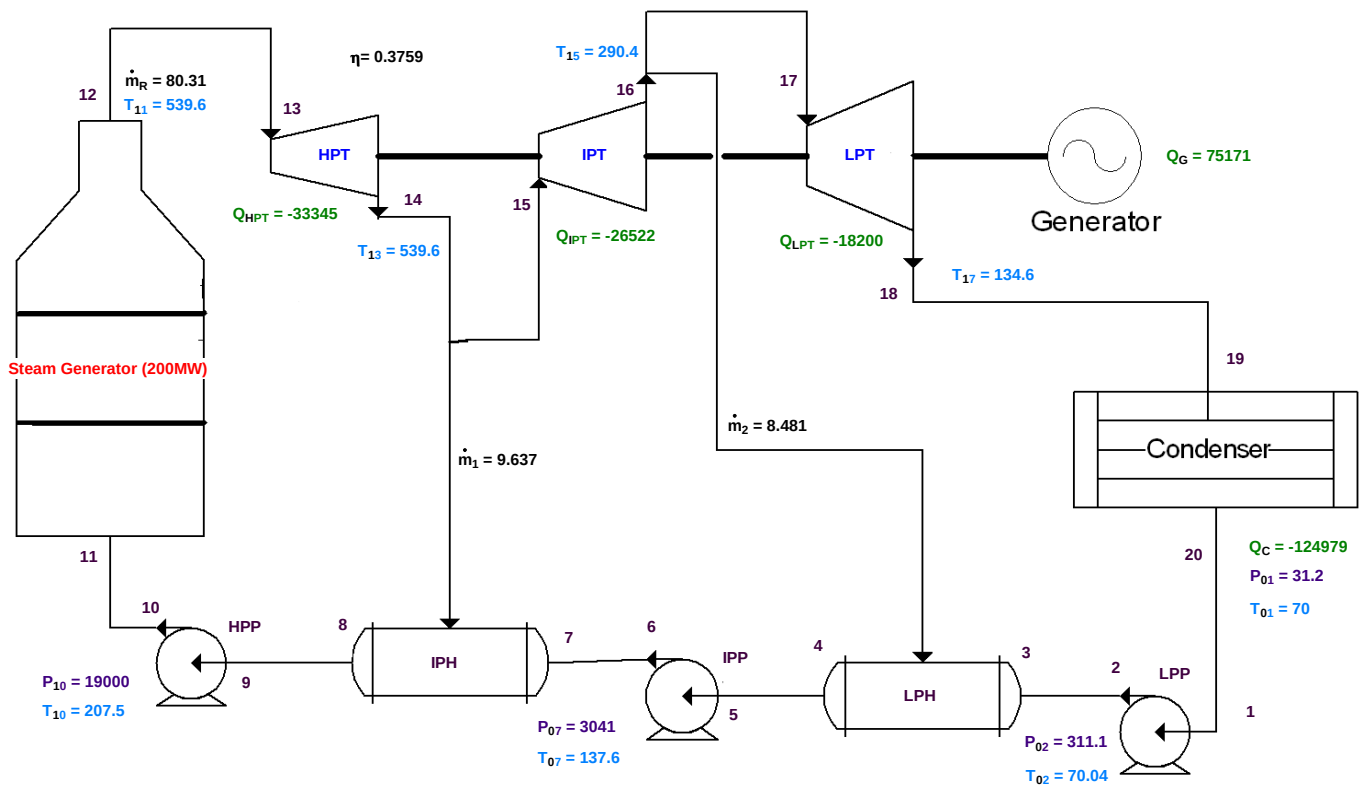
	η	f_{IP}	f_{LP}	P_{02}	P_{06}	Q_G
Run 1	0.3604	0.02	0.02	150	2500	72074
Run 2	0.3718	0.06222	0.06222	227.8	2778	74355
Run 3	0.383	0.1044	0.1044	305.6	3056	76600
Run 4	0.3932	0.1467	0.1467	383.3	3333	78649
Run 5	0.3911	0.1889	0.1889	461.1	3611	78213
Run 6	0.3898	0.2311	0.2311	538.9	3889	77950
Run 7	0.3891	0.2733	0.2733	616.7	4167	77814
Run 8	0.389	0.3156	0.3156	694.4	4444	77791
Run 9	0.3894	0.3578	0.3578	772.2	4722	77888
Run 10	0.3907	0.4	0.4	850	5000	78132





Appendix A4

*Rankine cycle EES model with 70 °C
condenser operating temperature*



"Rankine Cycle simulation"

"Node 1"

$T_{01} = 70$

$P_{01} = \text{Pressure}(\text{Steam_IAPWS}, x=x_1, T=T_{01})$

$x_1 = 0$

$h_{01} = \text{Enthalpy}(\text{Steam_IAPWS}, x=x_1, P=P_{01})$

$v_1 = 1/\text{Density}(\text{Water}, T=T_{01}, P=P_{01})$

"-----"

"LPP"

$f_{IP} = 0.12$

$f_{LP} = 0.12$

$P_{02} = 311.1$

$P_{06} = 3056$

$P_{10} = 19000$

$\alpha_{\text{pipe}} = 0.005$

$\alpha_H = 0.02$

$T_{\text{max}} = 540$

$Q_R = 200000$

$\{m_{\text{dot}_R} = 78.9\}$

$m_{\text{dot}_1} = m_{\text{dot}_R} * f_{IP}$

$m_{\text{dot}_2} = (m_{\text{dot}_R} - m_{\text{dot}_1}) * f_{LP}$

$\eta_p = 0.75$

$\rho_1 = \text{Density}(\text{Steam_IAPWS}, x=0, P=P_{01})$

$Q_{LPP} = ((m_{\text{dot}_R} - m_{\text{dot}_1} - m_{\text{dot}_2}) / \rho_1) * (1/\eta_p) * (P_{02} - P_{01})$

$h_{02} - h_{01} = Q_{LPP} / (m_{\text{dot}_R} - m_{\text{dot}_1} - m_{\text{dot}_2})$

"Pipe pressure loss fraction"

T_02=Temperature(Steam_IAPWS,h=h_02,P=P_02)

"-----"

"Pipe between LPP and LPH"

DELTA_P_23 = alpha_pipe * 0.5 * (P_03 + P_02)

P_03 - P_02 = -DELTA_P_23

h_03-h_02 = 0

"No heat transfer"

T_03=Temperature(Steam_IAPWS,h=h_03,P=P_03)

"-----"

"Low pressure heater (LPH)"

DELTA_P_34 = alpha_H * 0.5 * (P_03 + P_04)

P_04 - P_03 = -DELTA_P_34

T_04=Temperature(Steam_IAPWS,h=h_04,P=P_04)

(m_dot_R - m_dot_1) * h_04 = (m_dot_R - m_dot_1 - m_dot_2) * h_03 + m_dot_2 * h_16

"-----"

"Pipe between LPH and IPP"

DELTA_P_45 = alpha_pipe * 0.5 * (P_04 + P_05)

P_05-P_04 = -DELTA_P_45

h_05-h_04 = 0

T_05=Temperature(Steam_IAPWS,h=h_05,P=P_05)

"-----"

"IPP"

v_5 = 1 / Density(Steam_IAPWS,h=h_05,P=P_05)

T_06=Temperature(Steam_IAPWS,h=h_06,P=P_06)

rho_5=Density(Steam_IAPWS,h=h_05,P=P_05)

Q_IPP = ((m_dot_R-m_dot_1)/rho_5)*(1/eta_p)*(p_06-p_05)

h_06-h_05 = Q_IPP/(m_dot_R-m_dot_1)

"-----"

"Pipe between IPP and IPH"

DELTA_P_67 = alpha_pipe * 0.5 * (P_06 + P_07)

P_07-P_06 = -DELTA_P_67

h_07-h_06 = 0

T_07=Temperature(Steam_IAPWS,h=h_07,P=P_07)

"-----"

"IPH"

DELTA_P_78 = alpha_H * 0.5 * (P_07 + P_08)

P_08 - P_07 = -DELTA_P_78

T_08=Temperature(Steam_IAPWS,h=h_08,P=P_08)

m_dot_R * h_08 = (m_dot_R - m_dot_1) * h_07 + (m_dot_1) * h_14

"-----"

"Node between IPH and HPP"

```

DELTAP_89 = alpha_pipe * 0.5 * (P_08 + P_09)
P_09-P_08 = -DELTAP_89
h_09-h_08 = 0
T_09=Temperature(Steam_IAPWS,h=h_09,P=P_09)

```

"-----"

"HPP"

```

T_10=Temperature(Steam_IAPWS,h=h_10,P=P_10)
rho_9=Density(Steam_IAPWS,x=0,P=P_09)
Q_HPP = (m_dot_R/rho_9)*(1/eta_p)*(P_10-P_09)
h_10-h_09 = Q_HPP/(m_dot_R)
v_10 = 1 / Density(Steam_IAPWS,h=h_10,P=P_10)

```

"-----"

"Pipe between HPP and Steam Generator(SG)"

```

DELTAP_1011 = alpha_pipe * 0.5 * (P_10 + P_11)
P_11-P_10 = -DELTAP_1011
h_11-h_10 = 0
T_11 = Temperature(Steam_IAPWS,h=h_13,P=P_13)

```

"-----"

"Steam Generator"

```

DELTAP_1112 = alpha_H * 0.5 * (P_11 + P_12)
P_12-P_11 = -DELTAP_1112
h_12 = Enthalpy(Steam_IAPWS,T=T_12,P=P_12)
h_12-h_11 = Q_R/m_dot_R
T_12 = T_max
s_12 =Entropy(Steam_IAPWS,h=h_12,P=P_12)

```

"-----"

"Pipe between SG and HPT"

```

DELTAP_1213 = alpha_pipe * 0.5 * (P_12 + P_13)
P_13-P_12 = -DELTAP_1213
h_13-h_12 = 0
T_13 = Temperature(Steam_IAPWS,h=h_13,P=P_13)
s_13 = s_12

```

"-----"

"HPT"

```

eta_HPT = 0.85
P_14 = P_06
h_14s=Enthalpy(Steam_IAPWS,P=P_14,s=s_13)
eta_HPT = (h_14-h_13)/(h_14s-h_13)
Q_HPT = (m_dot_R) * (h_14-h_13)
T_14=Temperature(Steam_IAPWS,h=h_14,P=P_14)
x_14s =Quality(Steam_IAPWS,P=P_14,h=h_14s)
x_14 =Quality(Steam_IAPWS,T=T_14,h=h_14)
s_14 =Entropy(Steam_IAPWS,h=h_14,P=P_14)
{Q_HPT = (87.27) * (2995-3383)}

```

"-----"

"Pipe between HPT and IPT"

DELTA_P_1415 = alpha_pipe * 0.5 * (P_14 + P_15)
P_15-P_14 = -DELTA_P_1415
h_15-h_14 = 0
T_15=Temperature(Steam_IAPWS,h=h_15,P=P_15)
s_15 =Entropy(Steam_IAPWS,h=h_15,P=P_15)
x_15 = Quality(Steam_IAPWS,T=T_15,h=h_15)

"-----"

"IPT"

P_16 = P_02
h_16s=Enthalpy(Steam_IAPWS,P=P_16, s=Entropy(Steam_IAPWS,h=h_15,P=P_15))
eta_IPT = 0.85
eta_IPT = (h_16-h_15)/(h_16s-h_15)
h_16-h_15 = Q_IPT/(m_dot_R-m_dot_1)
s_16f = Entropy(Steam_IAPWS,x=0,P=P_16)
T_16=Temperature(Steam_IAPWS,h=h_16,P=P_16)
x_16s = Quality(Steam_IAPWS,P=P_16,h=h_16s)
x_16 = Quality(Steam_IAPWS,P=P_16,h=h_16)
s_16 = Entropy(Steam_IAPWS,h=h_16,P=P_16)

"-----"

"Pipe between IPT and LPT"

DELTA_P_1617 = alpha_pipe * 0.5 * (P_16 + P_17)
P_17-P_16 = -DELTA_P_1617
h_17-h_16 = 0
T_17=Temperature(Steam_IAPWS,h=h_17,P=P_17)

"-----"

"LPT"

P_18 = P_01
h_18s=Enthalpy(Steam_IAPWS,P=P_18,s=Entropy(Steam_IAPWS,h=h_17,P=P_17))
eta_LPT = 0.85
eta_LPT = (h_18-h_17)/(h_18s-h_17)
h_18-h_17 = Q_LPT/(m_dot_R-m_dot_1-m_dot_2)
T_18=Temperature(Steam_IAPWS,h=h_18,P=P_18)
x_18s=Quality(Steam_IAPWS,P=P_18,h=h_18s)
x_18=Quality(Steam_IAPWS,P=P_18,h=h_18)

"-----"

"Pipe between LPT and Condenser"

DELTA_P_1819 = alpha_pipe * 0.5 * (P_18 + P_19)
P_19-P_18 = -DELTA_P_1819
h_19-h_18 = 0
T_19=Temperature(Steam_IAPWS,h=h_19,P=P_19)

"-----"

"Condenser"

```

x_20 = 0
DELTAP_1920 = alpha_H * 0.5 * (P_19 + P_20)
P_20-P_19 = -DELTAP_1920
h_20=Enthalpy(Steam_IAPWS,x=x_20,P=P_20)
T_20=Temperature(Steam_IAPWS,h=h_20,P=P_20)
h_20-h_19 = Q_C/(m_dot_R-m_dot_1-m_dot_2)

```

-----"

"Generator"

```

Q_G = -(Q_LPT + Q_IPT + Q_HPT) - (Q_LPP + Q_IPP + Q_HPP)
eta = Q_G/(Q_R)

```

-----"

"Array Tables"

-----"

```

h_[1] = h_01
h_[2] = h_02
h_[3] = h_03
h_[4] = h_04
h_[5] = h_05
h_[6] = h_06
h_[7] = h_07
h_[8] = h_08
h_[9] = h_09
h_[10] = h_10
h_[11] = h_11
h_[12] = h_12
h_[13] = h_13
h_[14] = h_14
h_[15] = h_15
h_[16] = h_16
h_[17] = h_17
h_[18] = h_18
h_[19] = h_19

```

```

p_[1] = p_01
p_[2] = p_02
p_[3] = p_03
p_[4] = p_04
p_[5] = p_05
p_[6] = p_06
p_[7] = p_07
p_[8] = p_08
p_[9] = p_09
p_[10] = p_10
p_[11] = p_11
p_[12] = p_12
p_[13] = p_13
p_[14] = p_14
p_[15] = p_15
p_[16] = p_16
p_[17] = p_17
p_[18] = p_18
p_[19] = p_19

```

```

T_[1] = T_01
T_[2] = T_02
T_[3] = T_03
T_[4] = T_04
T_[5] = T_05
T_[6] = T_06
T_[7] = T_07
T_[8] = T_08
T_[9] = T_09
T_[10] = T_10
T_[11] = T_11
T_[12] = T_12
T_[13] = T_13
T_[14] = T_14
T_[15] = T_15
T_[16] = T_16
T_[17] = T_17
T_[18] = T_18
T_[19] = T_19

```

```

n=19
Duplicate i=1,n

```

```

s_[i]=Entropy(Steam_IAPWS,h=h_[i],P=P_[i])

```

```

END

```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$\alpha_H = 0.02$	$\alpha_{\text{pipe}} = 0.005$	$\Delta P_{1011} = 94.76$
$\Delta P_{1112} = 374.4$	$\Delta P_{1213} = 92.42$	$\Delta P_{1415} = 15.24$
$\Delta P_{1617} = 1.552$	$\Delta P_{1819} = 0.1556$	$\Delta P_{1920} = 0.6148$
$\Delta P_{23} = 1.552$	$\Delta P_{34} = 6.13$	$\Delta P_{45} = 1.513$
$\Delta P_{67} = 15.24$	$\Delta P_{78} = 60.21$	$\Delta P_{89} = 14.87$
$\eta = 0.3759$	$\eta_{\text{HPT}} = 0.85$	$\eta_{\text{IPT}} = 0.85$
$\eta_{\text{LPT}} = 0.85$	$\eta_p = 0.75$	$f_{\text{IP}} = 0.12$
$f_{\text{LP}} = 0.12$	$h_{01} = 293.1$	$h_{02} = 293.5$
$h_{03} = 293.5$	$h_{04} = 569.4$	$h_{05} = 569.4$
$h_{06} = 580.5$	$h_{07} = 580.5$	$h_{08} = 867$
$h_{09} = 867$	$h_{10} = 893$	$h_{11} = 893$
$h_{12} = 3383$	$h_{13} = 3383$	$h_{14} = 2968$
$h_{14s} = 2895$	$h_{15} = 2968$	$h_{16} = 2593$
$h_{16s} = 2527$	$h_{17} = 2593$	$h_{18} = 2300$
$h_{18s} = 2249$	$h_{19} = 2300$	$h_{20} = 290.7$
$\dot{m}_1 = 9.637$	$\dot{m}_2 = 8.481$	$\dot{m}_R = 80.31$
$n = 19$	$P_{01} = 31.2$	$P_{02} = 311.1$
$P_{03} = 309.5$	$P_{04} = 303.4$	$P_{05} = 301.9$
$P_{06} = 3056$	$P_{07} = 3041$	$P_{08} = 2981$
$P_{09} = 2966$	$P_{10} = 19000$	$P_{11} = 18905$
$P_{12} = 18531$	$P_{13} = 18438$	$P_{14} = 3056$
$P_{15} = 3041$	$P_{16} = 311.1$	$P_{17} = 309.5$
$P_{18} = 31.2$	$P_{19} = 31.05$	$P_{20} = 30.43$
$Q_C = -124979$	$Q_G = 75171$	$Q_{\text{HPP}} = 2087$
$Q_{\text{HPT}} = -33345$	$Q_{\text{IPP}} = 785.7$	$Q_{\text{IPT}} = -26522$
$Q_{\text{LPP}} = 23.74$	$Q_{\text{LPT}} = -18200$	$Q_R = 200000$
$\rho_1 = 977.7$	$\rho_5 = 330.3$	$\rho_9 = 822.8$
$S_{12} = 6.354$	$S_{13} = 6.354$	$S_{14} = 6.487$
$S_{15} = 6.489$	$S_{16} = 6.652$	$S_{16f} = 1.685$
$T_{01} = 70$	$T_{02} = 70.04$	$T_{03} = 70.04$

T ₀₄ = 133.9	T ₀₅ = 133.7	T ₀₆ = 137.6
T ₀₇ = 137.6	T ₀₈ = 203.2	T ₀₉ = 203.2
T ₁₀ = 207.5	T ₁₁ = 539.6	T ₁₂ = 540
T ₁₃ = 539.6	T ₁₄ = 290.6	T ₁₅ = 290.4
T ₁₆ = 134.8	T ₁₇ = 134.6	T ₁₈ = 70
T ₁₉ = 69.88	T ₂₀ = 69.42	T _{max} = 540
v ₁ = 0.001023	v ₁₀ = 0.001151	v ₅ = 0.003027
x ₁ = 0	x ₁₄ = 100	x _{14s} = 100
x ₁₅ = 100	x ₁₆ = 0.9381	x _{16s} = 0.9074
x ₁₈ = 0.8603	x _{18s} = 0.8382	x ₂₀ = 0

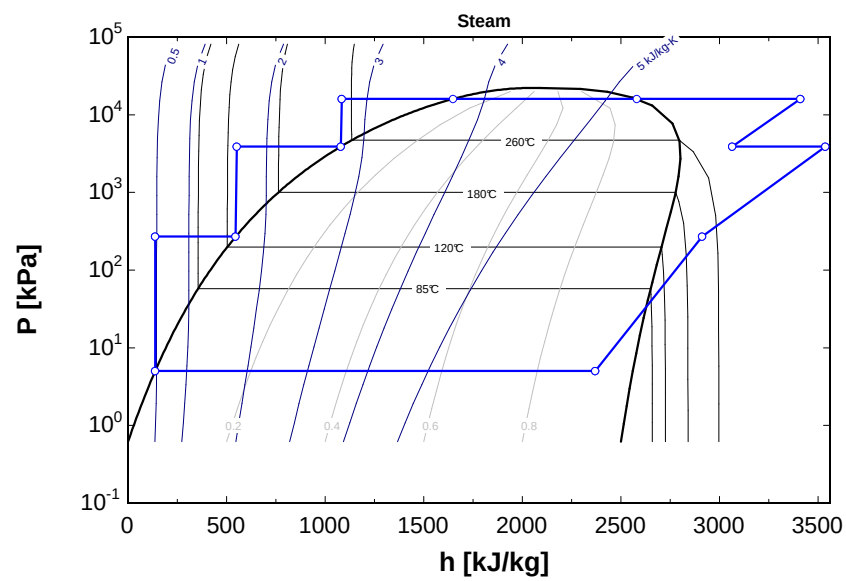
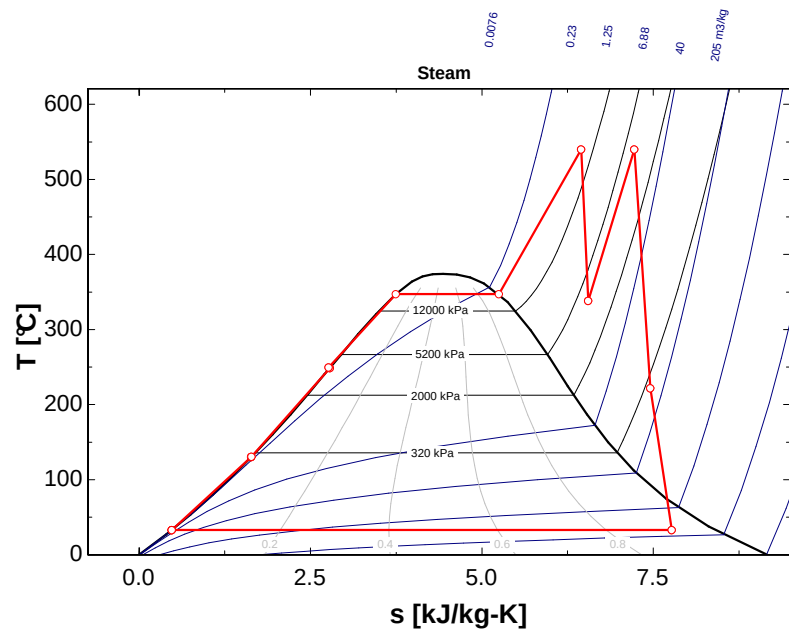
55 potential unit problems were detected.

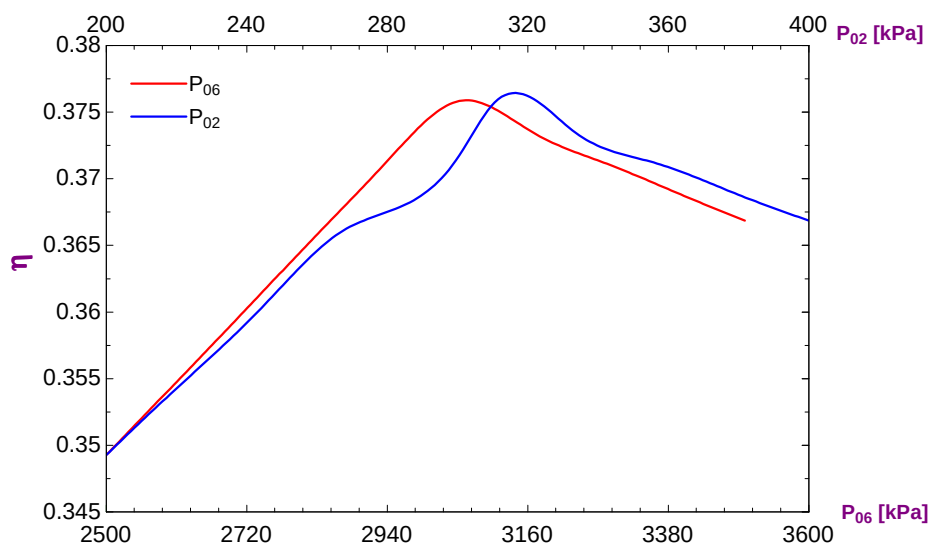
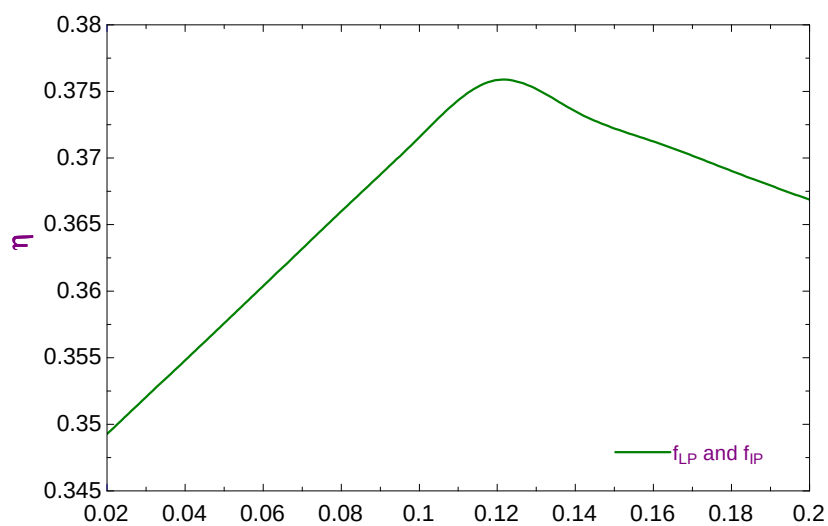
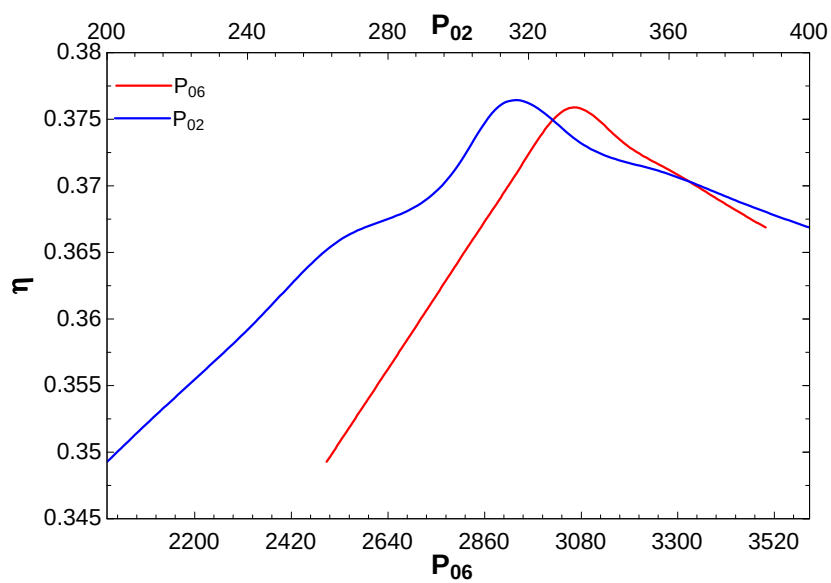
Arrays Table

	$\bar{h}_i$	$\bar{p}_i$	$\bar{s}_i$	$\bar{T}_i$
1	293.1	31.2	0.9551	70
2	293.5	311.1	0.9554	70.04
3	293.5	309.5	0.9554	70.04
4	569.4	303.4	1.691	133.9
5	569.4	301.9	1.691	133.7
6	580.5	3056	1.711	137.6
7	580.5	3041	1.711	137.6
8	867	2981	2.358	203.2
9	867	2966	2.358	203.2
10	893	19000	2.374	207.5
11	893	18905	2.374	539.6
12	3383	18531	6.354	540
13	3383	18438	6.356	539.6
14	2968	3056	6.487	290.6
15	2968	3041	6.489	290.4
16	2593	311.1	6.652	134.8
17	2593	309.5	6.654	134.6
18	2300	31.2	6.804	70
19	2300	31.05	6.806	69.88

Parametric Table: Table 5

	η	f_{IP}	f_{LP}	P_{02}	P_{06}	Q_G
Run 1	0.3493	0.02	0.02	200	2500	69854
Run 2	0.3548	0.04	0.04	222.2	2611	70962
Run 3	0.3604	0.06	0.06	244.4	2722	72075
Run 4	0.366	0.08	0.08	266.7	2833	73197
Run 5	0.3716	0.1	0.1	300	2944	74312
Run 6	0.3759	0.12	0.12	311.1	3056	75172
Run 7	0.3735	0.14	0.14	333.3	3167	74701
Run 8	0.3712	0.16	0.16	355.6	3278	74248
Run 9	0.369	0.18	0.18	377.8	3389	73807
Run 10	0.3669	0.2	0.2	400	3500	73374





Appendix B1

*Verification of Rankine cycle with 33 °C
condenser operating temperature*

The Rankine cycle with 33°C condenser operating temperature

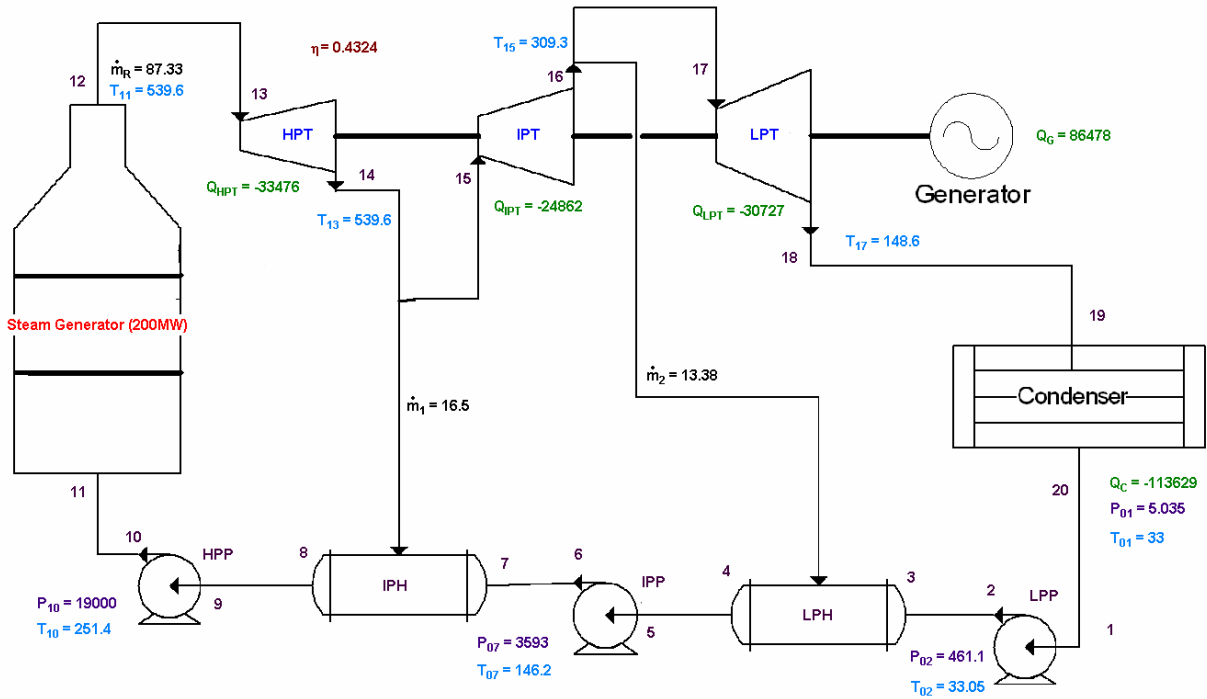


Figure 1: Rankine cycle with 33°C condenser operating temperature.

Node 1:

Condenser operating temperature:

$$T_1 = 33^\circ\text{C}$$

Condenser operating pressure:

Found via interpolation:

$$\frac{P_1 - 4.754}{5.318 - 4.754} = \frac{33 - 30}{35 - 30}$$

$$P_1 = 5.036 \text{ kPa}$$

Enthalpy at node 1:

$$h_1 = 138.25 \text{ kJ/kg}$$

LPP [1-2]: In order to calculate the enthalpy after the LPP, the pump work added to the fluid is used; this work increases the enthalpy of the working fluid as follows:

$$h_2 - h_1 = v_1(P_2 - P_1)$$

$$\frac{v_1 - 0.001005}{0.001006 - 0.001005} = \frac{1}{2}$$

$$v_1 = 0.0010055$$

$$P_2 = 461.1$$

$$\begin{aligned} h_2 &= h_1 + v_1(P_2 - P_1) \\ &= 138.25 + 0.0010055(461.1 - 5.036) \\ &= 138.7 \text{ kJ/kg} \end{aligned}$$

Pipe [2-3]: The pressure loss in the pipe 2-3, connecting the LPP to the LPH, is calculated as follows:

$$\begin{aligned} \Delta P_{23} &= \alpha_p \frac{1}{2}(P_2 + P_3) \\ &= 0.005(0.5)(461.1 + P_3) \end{aligned}$$

$$\begin{aligned} P_3 - P_2 &= -\Delta P_{23} \\ \Delta P_{23} &= P_2 - P_3 \end{aligned}$$

$$\begin{aligned} 461.1 - P_3 &= 0.005(0.5)(461.1 + P_3) \\ 461.1 - P_3 &= (2.5E-3)P_3 + 1.15725 \\ 1.0025P_3 &= 461.1 - 1.15725 \\ P_3 &= 458.8 \text{ kPa} \end{aligned}$$

$$\begin{aligned} P_3 - P_2 &= -\Delta P_{23} \\ \Delta P_{23} &= 2.3 \text{ kPa} \end{aligned}$$

LPH [3-4]: The pressure loss across the LPH is calculated as follows:

$$\begin{aligned} \Delta P_{34} &= \alpha_H \frac{1}{2}(P_3 + P_4) \\ &= 0.005(0.5)(458.8 + P_4) \end{aligned}$$

$$\begin{aligned} P_4 - P_3 &= -\Delta P_{34} \\ \Delta P_{34} &= P_3 - P_4 \end{aligned}$$

$$\begin{aligned} 458.8 - P_4 &= 0.02(0.5)(458.8 + P_4) \\ 458.8 - P_4 &= (0.01)P_4 + 1.147 \\ P_4 &= 449.714 \text{ kPa} \end{aligned}$$

$$\begin{aligned} P_4 - P_3 &= -\Delta P_{34} \\ \Delta P_{34} &= 9.085 \text{ kPa} \end{aligned}$$

The change in enthalpy across the LPH is calculated using the conservation of mass:

$$(1 - x_1)h_4 = (1 - x_1 - x_2)h_3 + x_2(h_{16}) \quad [1]$$

where

$$x_1 = 0.1889$$

$$x_2 = (1 - 0.1889)(0.1889) \\ = 0.153216$$

In order to calculate h_{16} , the properties of the working fluid are calculated from a point with known design conditions, i.e. after the working fluid is passed through the steam generator.

At this point the pressure is:

$$P_{12} = 18530.87 \text{ kPa}$$

and the temperature is given as 540°C .

Pipe 10-11: This is the piping which connects the HPP with the SG. The pressure of $P_{10} = 19000 \text{ kPa}$, is the operation design pressure of the steam generator. This pressure is delivered by the HPP. The pressure drop and pressure at point 11 in the cycle is calculated as follows:

$$\Delta P_{1011} = \alpha_p \frac{1}{2} (P_{10} + P_{11}) \\ = 0.005(0.5)(19000 + P_{11})$$

$$P_{10} - P_{11} = -\Delta P_{1011}$$

$$\Delta P_{1011} = P_{10} - P_{11}$$

$$19000 - P_{11} = 0.005(0.5)(19000 + P_{11})$$

$$19000 - P_{11} = (2.5E - 3)P_{11} + 47.5$$

$$1.0025P_{11} = 18952.5$$

$$P_{11} = 18905.23 \text{ kPa}$$

$$P_{11} - P_{10} = -\Delta P_{1011}$$

$$\Delta P_{1011} = 94.763 \text{ kPa}$$

Steam generator (SG) [11-12]: The pressure drop across the steam generator can be calculated as follows:

$$\Delta P_{1112} = \alpha_H \frac{1}{2} (P_{11} + P_{12}) \\ = 0.02(0.5)(18905.23 + P_{12})$$

$$P_{12} - P_{11} = -\Delta P_{1112}$$

$$\Delta P_{1011} = P_{11} - P_{12}$$

$$18905.23 - P_{12} = 0.02(0.5)(18905.23 + P_{12})$$

$$18905.23 - P_{12} = (0.01)P_{12} + 189.05$$

$$1.01P_{12} = 18716.177$$

$$P_{12} = 18530.87 \text{ kPa}$$

$$P_{12} - P_{11} = -\Delta P_{112}$$

$$\Delta P_{112} = 374.4 \text{ kPa}$$

Using these properties ($P_{12} = 18531 \text{ kPa}$ and 540°C) and interpolation, the enthalpy at 500°C and 550°C are calculated as follows:

The enthalpy of steam at 18531 kPa and 500°C is:

$$\frac{h_{500} - 3269}{3254 - 3269} = \frac{18531 - 18000}{19000 - 18000}$$

$$h_{500} = 3261.035 \text{ kJ/kg}$$

Using the pressure at point 12 and 540°C the value of the enthalpy is:

$$\frac{h_{550} - 3416}{3405 - 3416} = \frac{18531 - 18000}{19000 - 18000}$$

$$h_{550} = 3410.159 \text{ kJ/kg}$$

The enthalpy at the point 12 can then be calculated as:

$$\frac{h_{12} - 3261.035}{3410.159 - 3261.035} = \frac{540 - 500}{550 - 500}$$

$$h_{12} = 3380.33 \text{ kJ/kg}$$

Pipe 12-13. This pipe connects the SG to the HPT. The enthalpy at the point 12 and 13 will be equal, because there is no heat transfer across the pipe.

$$h_{12} = h_{13} = 3380.33 \text{ kJ/kg}$$

The pressure at point 13:

$$\Delta P_{1213} = \alpha_p \frac{1}{2} (P_{12} + P_{13})$$

$$= 0.005(0.5)(18530.87 + P_{13})$$

$$P_{13} - P_{12} = -\Delta P_{1213}$$

$$\Delta P_{1213} = P_{12} - P_{13}$$

$$18530.87 - P_{13} = 0.005(0.5)(18530.87 + P_{13})$$

$$18530.87 - P_{13} = (0.005)P_{13} + 46.32$$

$$1.0025P_{13} = 18484.55$$

$$P_{13} = 18438.45 \text{ kPa}$$

The pressure drop across the pipe:

$$P_{13} - P_{12} = -\Delta P_{1213}$$

$$\Delta P_{1213} = 92.42 \text{ kPa}$$

The entropy at point 12 can be calculated as follows:

$$\frac{s_{500} - 6.221}{6.182 - 6.221} = \frac{18531 - 18000}{19000 - 18000}$$

$$s_{500} = 6.2 \text{ kJ / kgK}$$

$$\frac{s_{550} - 6.406}{6.371 - 6.406} = \frac{18531 - 18000}{19000 - 18000}$$

$$s_{550} = 6.387 \text{ kJ / kgK}$$

$$\frac{s_{12} - 6.2}{6.387 - 6.2} = \frac{18531 - 18000}{19000 - 18000}$$

$$s_{12} = 6.35 \text{ kJ / kgK}$$

$$s_{12} = s_{13} = 6.35 \text{ kJ / kg}$$

This condition of entropy results in a superheated condition of the working fluid after it has passed through the HPT.

HPT [13-14]: The enthalpy at point 14 can be calculated as:
Temperature as 300°C and pressure as 3611 kPa ($P_{14} = P_6$)

$$s_{13} = s_{14s} = 6.35 \text{ kJ / kg}$$

The enthalpy at point 14 is calculated as if the expansion process of the steam in the turbine is of an isentropic nature, thus the ideal enthalpy is:

$$h_{14s} = 2933 \text{ kJ / kg}$$

The isentropic efficiency of the HPT is 85%. Using this efficiency, the real enthalpy is calculated to be:

$$\frac{h_{13} - h_{14}}{h_{13} - h_{14s}} = 0.85$$

$$\frac{3380.33 - h_{14}}{3380.33 - 2933} = 0.85$$

$$h_{14} = 3000 \text{ kJ / kg}$$

Pipe 14-15: The pipe connecting the HPT to the IPT.
There is no heat transfer across the pipe.

$$h_{14} = h_{15} = 3000 \text{ kJ / kg}$$

The pressure at the point 15 is:

$$\begin{aligned}
 \Delta P_{1415} &= \alpha_p \frac{1}{2} (P_{14} + P_{15}) \\
 &= 0.005(0.5)(3611 + P_{15}) \\
 P_{14} - P_{15} &= -\Delta P_{1415} \\
 \Delta P_{1415} &= P_{14} - P_{15} \\
 3611 - P_{15} &= 0.005(0.5)(3611 + P_{15}) \\
 3611 - P_{15} &= (2.5E - 3)P_{15} + 9.0275 \\
 1.0025P_{15} &= 3601.9725 \\
 P_{15} &= 3592.99 \text{ kPa}
 \end{aligned}$$

The pressure drop across the Pipe 14-15 is:

$$\begin{aligned}
 P_{15} - P_{14} &= -\Delta P_{1415} \\
 \Delta P_{1415} &= 18.1 \text{ kPa}
 \end{aligned}$$

IPT [15-16]: The enthalpy at point 16, after the IPT [461.1kPa], is calculated as follows:

For an isentropic process:

$$s_{15} = s_{16s} = 6.475 = s_{f16} + x_{16s} s_{fg16}$$

The ideal quality of the steam is calculated to be:

$$\begin{aligned}
 6.475 &= 1.829 + x_{16s} (5.021) \\
 x_{16s} &= 0.925
 \end{aligned}$$

This leads to the calculation of the ideal enthalpy as follows:

$$\begin{aligned}
 h_{16s} &= 626.7 + x_{16s} (2118) \\
 h_{16s} &= 626.7 + 0.925(2118) \\
 h_{16s} &= 2586 \text{ kJ / kg}
 \end{aligned}$$

The isentropic efficiency of the HPT is 85%. Using this efficiency, the real enthalpy is calculated to be:

$$\begin{aligned}
 \frac{h_{15} - h_{16}}{h_{15} - h_{16s}} &= 0.85 \\
 \frac{3000 - h_{16}}{3000 - 2586} &= 0.85 \\
 h_{16} &= 2648 \text{ kJ / kg}
 \end{aligned}$$

Using interpolation and the values of the steam @ 447.5kPa, the real quality of the steam can be calculated:

$$\frac{h_f - 604.73}{623.24 - 604.73} = \frac{447.43 - 400}{450 - 400}$$

$$h_f = 621.88 \text{ kJ / kg}$$

$$\frac{h_{fg} - 2133.8}{2120.7 - 2133.8} = \frac{47.5}{50}$$

$$h_{fg} = 2121.33 \text{ kJ / kg}$$

$$2644 = 621.88 + x_{16}(2121.33)$$

$$x_{16} = 0.95323$$

And with this, the real entropy can be calculated: (interpolation at 447.5kPa)

$$\frac{s_f - 1.7766}{1.8208 - 1.7766} = \frac{47.5}{50}$$

$$s_f = 1.8184 \text{ kJ / kgK}$$

$$\frac{s_{fg} - 5.1193}{5.039 - 5.1193} = \frac{47.5}{50}$$

$$s_{fg} = 5.04007 \text{ kJ / kgK}$$

$$s_{16} = 1.8184 + (0.9537)(5.04007)$$

$$s_{16} = 6.62512 \text{ kJ / kgK}$$

LPH [3-4] continued: Using equation [1] it is now possible to solve for the enthalpy at point 4:

$$\text{Eq. 1: } (1 - x_1)h_4 = (1 - x_1 - x_2)h_3 + x_2(h_{16})$$

$$(1 - 0.1889)h_4 = (1 - 0.1889 - ((1 - 0.1889) * 0.1889)) * (139.3) + (1 - 0.1889)(0.1889) * (2648.44)$$

$$h_4 = 613.2 \text{ kJ / kg}$$

Pipe 4-5: This pipe connects the LPH to the IPP. The pressure at point 5 can be calculated as follows:

$$\Delta P_{45} = \alpha_p \frac{1}{2} (P_4 + P_5)$$

$$= 0.005(0.5)(449.714 + P_5)$$

$$P_5 - P_4 = -\Delta P_{45}$$

$$\Delta P_{45} = P_4 - P_5$$

$$449.714 - P_5 = 0.005(0.5)(449.714 + P_5)$$

$$449.714 - P_5 = (2.5E - 3)P_5 + 1.1242$$

$$1.0025P_5 = 448.589$$

$$P_5 = 447.47kPa$$

The pressure loss across the pipe is:

$$P_5 - P_4 = -\Delta P_{45}$$

$$\Delta P_{45} = 2.24kPa$$

The enthalpy is the same as at point 4:

$$h_4 = h_5 = 613.2kJ / kg$$

IPP [5-6]: The enthalpy of the water at point 6 can be calculated using the work of the IPP. This is done as follows:

$$h_6 - h_5 = v_5(P_6 - P_5)$$

The pressure of the water as it exits the IPP is $P_6 = 3611kPa$. This gives:

$$h_6 = h_5 + v_5(3611 - 447.47)$$

Interpolating for v_5 at 447kPa gives:

$$\frac{v_5 - 0.001084}{0.001088 - 0.001084} = \frac{47.5}{50}$$

$$v_5 = 0.001087m^3 / kg$$

The enthalpy after the IPP is then:

$$h_6 = 613.2 + (0.001087)(3611 - 447.47)$$

$$h_6 = 616.6kJ / kg$$

Pipe 6-7: This pipe connects the IPP to the IPH. The pressure at point 7 can be calculated as follows:

$$\begin{aligned}\Delta P_{67} &= \alpha_p \frac{1}{2}(P_6 + P_7) \\ &= 0.005(0.5)(3611 + P_7)\end{aligned}$$

$$P_7 - P_6 = -\Delta P_{67}$$

$$\Delta P_{67} = P_6 - P_7$$

$$3611 - P_7 = 0.005(0.5)(3611 + P_7)$$

$$3611 - P_7 = (2.5E - 3)P_5 + 9.0275$$

$$1.0025P_7 = 3602$$

$$P_7 = 3593 \text{ kPa}$$

Pressure losses in Pipe 6-7:

$$P_7 - P_6 = -\Delta P_{67}$$

$$\Delta P_{67} = 18.01 \text{ kPa}$$

IPH [7-8]: The pressure as calculated at point 8:

$$\begin{aligned} \Delta P_{78} &= \alpha_H \frac{1}{2} (P_7 + P_8) \\ &= 0.02(0.5)(3593 + P_8) \end{aligned}$$

$$P_8 - P_7 = -\Delta P_{78}$$

$$\Delta P_{78} = P_7 - P_8$$

$$3593 - P_8 = 0.02(0.5)(3593 + P_8)$$

$$3593 - P_8 = (0.01)P_8 + 35.93$$

$$1.01P_8 = 3557.07$$

$$P_8 = 3522 \text{ kPa}$$

The pressure loss over the IPH can be calculated as follows:

$$P_8 - P_7 = -\Delta P_{78}$$

$$\Delta P_{78} = 71 \text{ kPa}$$

The enthalpy at the point 8, after the IPH, can be calculated using the energy balance:

$$h_8 = (1 - x_1)h_7 + x_1h_{14}$$

$$h_8 = (1 - 0.1889)616.6 + 0.1889h_{14}$$

$$h_8 = (0.8111)(616.6) + 0.1889(3003.15)$$

$$h_8 = 500.12 + 567.29$$

$$h_8 = 1067.45 \text{ kJ / kg}$$

Pipe 8-9: This pipe connects the IPH with the HPP. The pressure of the water at point 9 is calculated as:

$$\Delta P_{89} = \alpha_P \frac{1}{2} (P_8 + P_9)$$

$$= 0.005(0.5)(3522 + P_9)$$

$$P_9 - P_8 = -\Delta P_{89}$$

$$\Delta P_{89} = P_8 - P_9$$

$$3522 - P_9 = 0.005(0.5)(3522 + P_9)$$

$$3522 - P_9 = (2.5E - 3)P_9 + 8.805$$

The pressure loss across pipe 8-9 is:

$$P_9 = 3504.43kPa$$

$$P_9 - P_8 = -\Delta P_{89}$$

$$\Delta P_{89} = 17.56kPa$$

HPP [9-10]: The pressure of the water as it exits the HPP is given as $P_{10} = 19000kPa$, as from design criteria. The enthalpy of the water at point 10, after HPP, can be calculated by taking the HPP work into consideration:

$$h_8 = h_9 = 1067.45kJ / kg$$

$$h_{10} - h_9 = v_9(P_{10} - P_9)$$

$$P_{10} = 19000kPa$$

With interpolation the specific volume of the water at $P_9 = 3504.43kPa$ is:

$$v_9 = 0.00125m^3 / kg$$

$$h_{10} = h_9 + v_9(19000 - 3504.43)$$

$$h_{10} = 1088kJ / kg$$

Pipe 16-17: This pipe connects the IPT to the LPT. The pressure at point 17 can be calculated as:

$$\begin{aligned}\Delta P_{1617} &= \alpha_p \frac{1}{2}(P_{16} + P_{17}) \\ &= 0.005(0.5)(447.5 + P_{17})\end{aligned}$$

$$P_{17} - P_{16} = -\Delta P_{1617}$$

$$\Delta P_{1617} = P_{16} - P_{17}$$

$$447.5 - P_{17} = 0.005(0.5)(447.5 + P_{17})$$

$$447.5 - P_{17} = (2.5E - 3)P_{17} + 1.11875$$

$$1.0025P_{17} = 446.38$$

$$P_{17} = 445.27 \text{ kPa}$$

The pressure loss across pipe 16-17 is:

$$P_{17} - P_{16} = -\Delta P_{1617}$$

$$\Delta P_{1617} = 2.23 \text{ kPa}$$

LPT [17-18]: The enthalpy at point 18 in the cycle is calculated as:

$$s_{16} = s_{17} = s_{18s} = 6.625 \text{ kJ / kg}$$

$$s_{18s} = 6.625 = s_f + x_{18s} s_{fg}$$

$$6.625 = 0.4763 + x_{18s} (7.9187)$$

$$x_{18s} = 0.7764$$

$$\begin{aligned} h_{18s} &= h_f + x_{18s} h_{fg} \\ &= 138 + (0.7764)(2424) \\ &= 2020 \text{ kJ / kg} \end{aligned}$$

$$\frac{h_{17} - h_{18}}{h_{17} - h_{18s}} = 0.85$$

$$\frac{2648 - h_{18}}{2648 - 2020} = 0.85$$

$$h_{18} = 2114.2 \text{ kJ / kg}$$

Pipe 18-19: The pressure loss in Pipe 18-19 is calculated as:

$$\begin{aligned} \Delta P_{1819} &= \alpha_P \frac{1}{2} (P_{18} + P_{19}) \\ &= 0.005(0.5)(5.036 + P_{19}) \end{aligned}$$

$$P_{19} - P_{18} = -\Delta P_{1819}$$

$$\Delta P_{1819} = P_{18} - P_{19}$$

$$5.036 - P_{19} = 0.005(0.5)(5.036 + P_{19})$$

$$5.036 - P_{19} = (2.5E - 3)P_{19} + 0.01259$$

$$1.0025P_{19} = 5.02341$$

$$P_{19} = 5.01 \text{ kPa}$$

$$P_{19} - P_{18} = -\Delta P_{1819}$$

$$\Delta P_{1819} = 0.025 kPa$$

No heat transfer means that there is no change in enthalpy across the pipe:

$$h_{18} = h_{19}$$

Condenser [19-20]: The pressure loss across the condenser can be calculated as:

$$\Delta P_{1920} = \alpha_H \frac{1}{2} (P_{19} + P_{20})$$

$$= 0.02(0.5)(5.01 + P_{20})$$

$$P_{20} - P_{19} = -\Delta P_{1920}$$

$$\Delta P_{1920} = P_{19} - P_{20}$$

$$5.01 - P_{20} = 0.02(0.5)(5.01 + P_{20})$$

$$5.01 - P_{20} = (0.01)P_{20} + 0.0501$$

$$1.01P_{20} = 4.9599$$

$$P_{20} = 4.911 kPa$$

$$P_{20} - P_{19} = -\Delta P_{1920}$$

$$\Delta P_{1920} = 0.0992 kPa$$

$$h_{20} = 136.4 kJ / kg$$

Work done by the different components:

The mass flow through the SG is calculated to be:

$$\dot{m}_R = \frac{Q_R}{h_{12} - h_{11}}$$

$$h_{12} = 3380.33 kJ / kg$$

$$h_{10} = h_{11} = 1088 kJ / kg$$

$$\dot{m}_R = \frac{200000}{3380.33 - 1088}$$

$$\dot{m}_R = 87.25 kg / s$$

The mass flow of the bled steam at the intermediate pressure is:

$$\dot{m}_1 = \dot{m}_R (0.1889)$$

$$\dot{m}_1 = 16.5 kg / s$$

The mass flow of the bled steam at the low pressure is:

$$\dot{m}_2 = (\dot{m}_R - \dot{m}_1)(0.1889)$$

$$\dot{m}_2 = 13.36 \text{ kg / s}$$

This leads to the calculation of the work done by the following components:

Low pressure pump, intermediate pressure pump, high pressure pump, low pressure turbine, intermediate pressure turbine and high pressure turbine.

LPT:

$$Q_{LPT} = \eta_T (\dot{m}_R - \dot{m}_1 - \dot{m}_2)(h_{18s} - h_{17})$$

$$Q_{LPT} = 0.85(87.25 - 16.5 - 13.36)(2020 - 2648)$$

$$Q_{LPT} = -30667 \text{ kW}$$

IPT:

$$Q_{IPT} = \eta_T (\dot{m}_R - \dot{m}_1)(h_{16s} - h_{15})$$

$$Q_{IPT} = \eta_T (87.25 - 16.5)(2585.85 - 3000)$$

$$Q_{IPT} = -24957 \text{ kW}$$

HPT:

$$Q_{HPT} = \eta_T (\dot{m}_R)(h_{14s} - h_{13})$$

$$Q_{HPT} = \eta_T (87.25)(2933 - 3380.33)$$

$$Q_{HPT} = -33175 \text{ kW}$$

LPP:

The efficiencies of all the pumps are taken as 75%: $\eta_p = 0.75$

The density of the water at point 1 is: $\rho_1 = 994.7 \text{ kg / m}^3$

$$Q_{LPP} = \frac{\dot{m}_R - \dot{m}_1 - \dot{m}_2}{\rho_1} \left(\frac{1}{\eta_p} \right) (P_2 - P_1)$$

$$Q_{LPP} = \frac{87.25 - 16.5 - 13.3}{994.7} \left(\frac{1}{0.75} \right) (461.1 - 5.036)$$

$$Q_{LPP} = 35.1 \text{ kW}$$

IPP:

The density of the water at point 5 is: $\rho_5 = 921.3 \text{ kg / m}^3$

$$Q_{IPP} = \frac{\dot{m}_R - \dot{m}_1}{\rho_5} \left(\frac{1}{\eta_p} \right) (P_6 - P_5)$$

$$Q_{IPP} = \frac{87.21 - 16.5}{921.3} \left(\frac{1}{0.75} \right) (3611 - 447.47)$$

$$Q_{IPP} = 323.7 \text{ kW}$$

HPP:

The density of the water at point 9 is: $\rho_9 = 809.7 \text{ kg} / \text{m}^3$

$$Q_{HPP} = \frac{\dot{m}_R}{\rho_9} \left(\frac{1}{\eta_p} \right) (P_{10} - P_9)$$

$$Q_{HPP} = \frac{87.25}{809.7} \left(\frac{1}{0.75} \right) (19000 - 3504.4)$$

$$Q_{HPP} = 2231 \text{ kW}$$

The generator power is:

$$Q_G = -(Q_{LPT} + Q_{IPT} + Q_{HPT}) - (Q_{LPP} + Q_{IPP} + Q_{HPP})$$

$$Q_G = -(30667 + 24957 + 33175) - (35.05 + 323.6 + 2231)$$

$$Q_G = 86211 \text{ kW}$$

$$Q_G = 86.2 \text{ MW}$$

The cycle thermal efficiency is:

$$\eta_{th} = \frac{Q_G}{Q_R}$$

$$\dot{m}_1$$

$$\dot{m}_2$$

$$\eta_{th} = \frac{86211}{200000}$$

$$\eta_{th} = 0.4311$$

$$\eta_{th} = 43.11\%$$