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UOB-IEASMA-102: Energy Analyses for a Steam Power Plant Operating under the Rankine Cycle

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Abstract

We present a thermodynamic cycle design based on energy analyses for steam power plants (power station) when working according to the Rankine cycle. This thermodynamic cycle consists of a constant-entropy water pump, a constant-pressure water boiler, a constant-entropy steam turbine, and a constant-pressure-temperature steam condenser. We propose four states of water, representing the inlet of each of four devices in the Rankine cycle. Due to estimated losses, the net shaft (mechanical) power from the thermodynamic cycle should be 1.157 times the electric power output from the power plant. The thermodynamic cycle efficiency is 38.59%, but the power plant efficiency is 33.35%. The design is generic, and is not limited to a specific source of heat or power output. Thus, it can operate with clean energy sources (concentrated solar power or nuclear reactors), as well as with fossil fuels. The highest temperature in the cycle is 600 °C, the highest absolute pressure is 50 bar, the lowest temperature is 50.2 °C, and the lowest absolute pressure is 0.125 bar.

Keywords: Rankine Cycle, Power Plant, Electricity, Steam

Introduction

The scope of this work is a proposal of water states (phases, pressures, and temperatures) suitable for operating a power plant based on a simple Rankine cycle, which is a thermodynamic cycle for generating shaft power from heat energy. In this cycle, an external source of heat (like from burning a fuel) is taken as an input energy and converted into output mechanical work in the form of shaft rotation. The working

fluid used in the cycle for transferring energy is water. Water is used in a closed loop, which means it circulates through the components of the cycle again and again. Water takes four forms during the cycle, which are:

- Saturated liquid (or saturated water)
- Compressed liquid (or subcooled liquid, or sub-saturated water)
- Superheated vapor (or superheated steam)
- Liquid-vapor mixture (or saturated liquid-vapor mixture, or wet steam)

The problem statement of the work is as follows: Identify reasonable four states of water for utilization in a simple Rankine cycle in a steam power plant, and an estimated relation between the electric power generation and the mass flow rate of water.

The justification of the need for this work is related to the increase in electricity generation or consumption in the Sultanate of Oman particularly and in the world generally, as shown in Table 1 and Figures 1 and 2. As an example, an electric power of one thousand megawatts (1,000 MW) may be enough to meet the needs of 320,000 homes in the Sultanate of Oman (Arabian Business, 2019), with an estimate of about three kilowatts (3 kW) average power consumption per home.

Table 1: Annual electricity uses in the Sultanate of Oman over 2015-2019, by sector, in GWh (National Center for Statistics and Information - NCSI, 2020a)

Sector	Year				
	2015	2016	2017	2018	2019
Residential	13,757	13,995	14,892	15,326	15,059
Commercial	5,736	6,513	7,531	7,837	8,072
Industrial	4,723	5,153	5,021	5,169	5,092
Government	3,901	3,862	3,814	3,882	4,141
Others	795	836	1,092	1,335	1,431
Total	28,912	30,359	32,349 ^a	33,547 ^b	33,796 ^c

a) 32,350 if summing numbers for individual sectors (possible rounding effect)

b) 33,549 if summing numbers for individual sectors (possible rounding effect)

c) 33,795 if summing numbers for individual sectors (possible rounding effect)

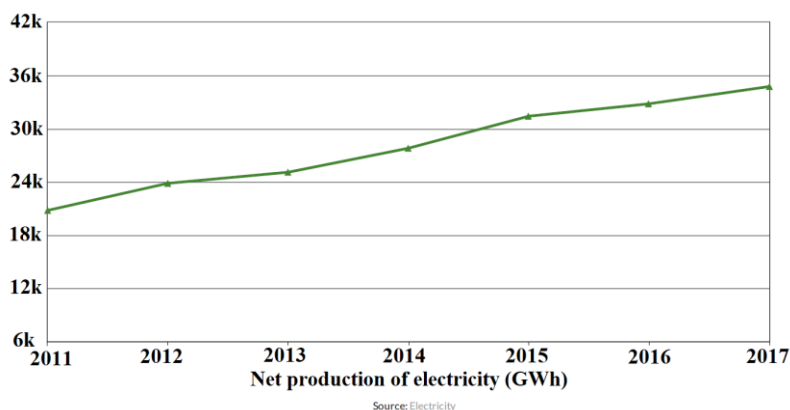


Fig 1. Annual records of the net production of electricity, in the Sultanate of Oman over 2011-2017, in GWh (National Center for Statistics and Information - NCSI, 2020b) – with some adjustments for better clarity without changing data points. GWh is gigawatt-hour. The vertical axis range is from 6,000 GWh to 42,000 GWh.

Electricity is probably the most flexible energy supply in the global economy and is therefore essential to social and economic development. The growth of electricity has surpassed all other energy forms, which led to a growing share in total final energy consumption (IEA, 2019). This pattern seems to continue over the next decades, as significant segments of the global population in developed countries (particularly rural ones) begin to ascend the energy ladder and become linked to power grids.

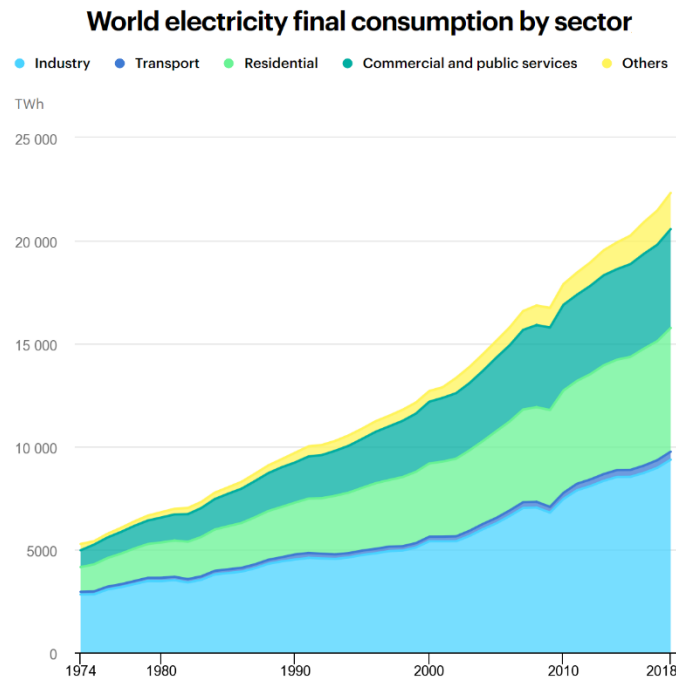


Fig 2. Annual records of world electricity final consumption by sector over 1974-2018, in TWh (IEA, 2020). TWh is terawatt-hour = 1,000 GWh
 Layers from top to bottom - Yellow (top layer): Others, Dark green: Commercial and public services, Light green: Residential, Dark blue: Transport, Light blue (bottom layer): Industry

To emphasize the growth in electricity generation, Figure 3 presents future predictions till 2100 for the electricity generation in the world under two scenarios, marked by the energy source (Lenzen, 2010; Nakicenovic and Swart, 2000). From the figure, one can see an expected reduction in using fossil fuels (coal, oil, and gas) as a source of electricity in the far future, with small changes in the contribution from nuclear energy. On the other hand, renewable energy sources are expected to become highly popular, with strong utilization of geothermal energy, concentrated solar power (CSP), and wind energy. Geothermal energy is a clean renewable energy source that benefits from the heat energy contained inside the earth at deep levels (like 10 km) below the surface (Unwin, 2019). The CSP technology collects and concentrates the heat from solar radiation by mirrors to be of a useful intensity and can then use this heat to generate electricity using steam turbines for example (Office of Energy Efficiency & Renewable Energy, 2020). However, the near future till 2050 may still show heavy dependence on fossil fuels combined with nuclear energy. Thus, the use of water Rankine cycle, with heat sources coming from burning fossil fuels or from a nuclear reactor is probably going to last for many years. Even with the transition to renewable energies, the water Rankine cycle can be used with CSP technology (Dunham and Iverson, 2014).

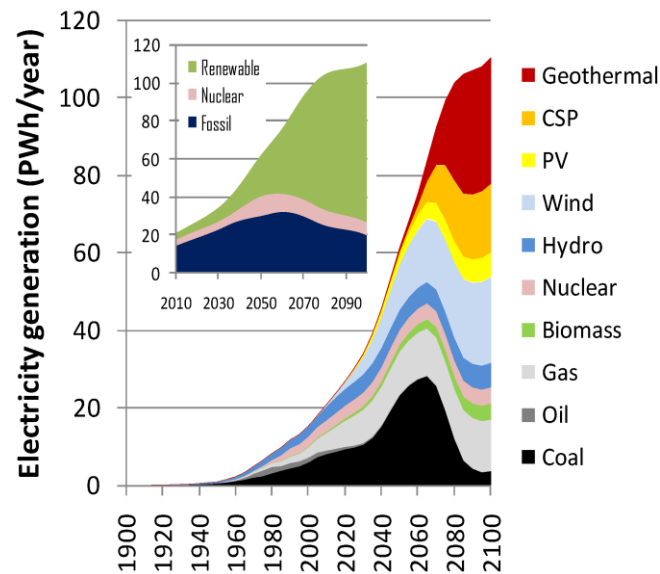


Fig 3. Future predictions of world electricity generation (Lenzen, 2010; Nakicenovic and Swart, 2000). PWh is petawatt-hour = 1,000 TWh

Rankine Cycle

Our work considers a simple Rankine cycle, where the working fluid is water, and irreversibility (like friction loss) and heat transfer are ignored during expansion and compression. This means that the pump (for compressing liquid water) operates in an isentropic process (so, the specific entropy at outlet is the same as at inlet). Similarly, the steam turbine (where steam expands) operates in an isentropic process, with a constant specific entropy. A constant entropy process is an ideal case that simplifies the analysis by having a condition relating the inlet and outlet states. Losses are taken into consideration by designing the cycle to produce 15.7% net shaft power more than the target electric power. This extra part of net output represents an overall penalty for all losses, not just those found in the thermodynamic part of the power plant, but also for an electric part represented by the electric generator that receives the shaft power from the steam turbine and converts it into electric power to be delivered to the electric grid. It is possible also to take losses into consideration at the level of individual components (for the pump alone, for the turbine alone, and for the generator alone) by assuming three individual efficiencies or loss fractions for them. For example, the isentropic efficiency of a steam turbine is about 90% (Froehling et al., 2002), and the large power plant electric generators can have a high efficiency of about 98% (Nowling, 2015). Andreasen et al. (2017) used an isentropic efficiency of 70% for a pump, but the pump consumption is relatively very small (can be less than 0.5%) compared to the power delivered by the steam turbine. Despite the possibility of assigning an efficiency to each component individually, making a single assumption about overall losses has the advantage of concentrated uncertainty in a single value rather than in three. In addition, this overall loss estimation absorbs in it other sources of losses outside these three devices (including heat loss in pipes transporting water between these devices). This extra loss percentage in net shaft power needed was estimated from the product of 90% (estimated turbine efficiency), 98% (estimated electric generator efficiency), and another 98% (estimated other losses, including the pump). The product gives 0.8644. Taking the reciprocal of this gives 1.157, which is 0.157 above 1, leading to the 15.7% estimated excess shaft power. The designer can control the design by moving this single figure estimating the overall losses up or down as felt suitable. Thus, for desired 1,000 MW electric power for example, one should multiply by a loss magnification factor (L_m) of 1.157 to get an estimated needed net shaft (mechanical) power output of 1,157 MW. The loss magnification factor is estimated according to Equation (1)

$$L_m = 1.157 = 1 / (0.90 \times 0.98 \times 0.98) = 1 / 0.8644 \quad (1)$$

The loss represented by the loss magnification factor (L_m) is different from the loss reflected in the thermodynamic cycle efficiency (η_{th}), whose cause is that even for the ideal thermodynamic cycle, not all input heat is converted into net output work, but a lot of this is lost as heat to the ambient atmosphere during the condensation process (where vapor water is converted into liquid water) and some is consumed to operate a pump. It should be mentioned that the power consumed by the water pump is negligible compared to that produced by the steam turbine. The main source of energy loss is those released uselessly during the condensation process.

Figure 4 shows the components of a power plant working by burning a fuel and uses a water Rankine cycle, which is related to our work. The fuel is not specified, and it can be for example natural gas, which is the major fuel used in power plants in the Sultanate of Oman (U.S. EIA, 2019).

Table 2 and Figure 5 provide a written and visual summary of the four devices in the Rankine cycle. Between each two consecutive devices, there is a water state and it is assigned a number from 1 to 4.

When a fossil fuel is used as a heat source, it is burned in a boiler and water is heated to form steam (subsystem B). Electricity is produced when the generator shaft turns in a magnetic field (subsystem C). Steam leaves the turbine at relatively a low pressure and low temperature, and possibly with little content of condensed liquid water droplet mixed with the gaseous part of the steam. Heat is removed from this steam using a condenser (which we consider as part of the Rankine cycle, subsystem A) and a related cooling device called cooling tower (subsystem D), and the resulting totally liquid water goes to the pump, which compresses this recovered liquid water before it moves to the boiler.

The current design work is aided by valuable guiding data on the Rankine cycle for the steam turbines after searching the literature. This helps taking reasonable operating conditions to help identify the design. Otherwise, infinite options would be uncomfortably available.

Specifically, we use the following operating conditions in this work as selected parameters:

- Boiler pressure (absolute, not gauge): 50 bar = 5 MPa = 5,000 kPa (Rao, 2012; SensorsONE, 2021)
- Turbine inlet temperature: 600 °C (Okita et al., 2017)
- Condenser pressure: 0.125 bar (absolute, not gauge) = 0.0125 MPa = 12.5 kPa (Zhang, 2020)

Table 2: Summary of processes and states in Rankine cycle (turbine exit is taken as wet steam, which is a liquid-vapor mixture)

Process	Device	Inlet state type and number	Exit state type and number	Process conditions
Compression	Pump	Saturated liquid (1)	Compressed liquid (2)	$s = \text{constant}$ (isentropic)
Heat addition	Boiler	Compressed liquid (2)	Superheated steam (3)	$P = \text{constant}$ (isobaric)
Expansion	Steam turbine	Superheated steam (3)	Liquid-vapor mixture (4)	$s = \text{constant}$ (isentropic)
Heat rejection	Condenser	Liquid-vapor mixture (4)	Saturated liquid (1)	$P = \text{constant}$ (isobaric) $T = \text{constant}$ (isothermal)

$$q_{\text{boiler}} \text{ (or } q_{\text{in}}) = h_3 - h_2 \quad (3)$$

Turbine (step 3-4): High temperature and pressure steam leaving the boiler is taken out to operate the turbine and is then released into the condenser at a much lower pressure. The work per unit mass extracted from steam is ideally the difference in specific enthalpy from the turbine inlet (state 2) and the turbine exit (state 3), where the specific enthalpy is a measure of both thermal energy content and pressure energy content of a unit mass (1 kg) of water. Thus, we have

$$w_{\text{turbine}} \text{ (or } w_{\text{out}}) = h_3 - h_4 \quad (4)$$

Condenser (step 4-1): The steam leaving the condenser is transformed into liquid water in the condenser by extracting suitable amount of heat from it. The energy balance for the condenser is

$$q_{\text{condenser}} \text{ (or } w_{\text{out}}) = h_4 - h_1 \quad (5)$$

Considering the overall cycle (all four components together), one can get the energy balance by enforcing zero net exchange of energy with the surroundings. This means that the received work and heat together must be equal in magnitude to the delivered work and heat together. In a mathematical form, this means

The net (or useful) work (per unit mass of water) leaving the cycle is modeled as

$$w_{\text{net}} = w_{\text{out}} - w_{\text{in}} = q_{\text{in}} - q_{\text{out}} \quad (6)$$

The thermal efficiency of the Rankine cycle is determined as

$$\eta_{\text{th}} = w_{\text{net}} / q_{\text{in}} = 1 - q_{\text{out}}/q_{\text{in}} \quad (7)$$

The mass flow rate of water (\dot{m}), net output shaft (mechanical) power (\dot{W}_{shaft}) and useful work per unit mass (w_{net}) for the Rankine steam cycle are related as

$$\dot{m} = \dot{W}_{\text{shaft}} / w_{\text{net}} \quad (8)$$

When adding the loss magnification factor (L_m), the mass flow rate of water (\dot{m}) can be linked to the needed electric output power (\dot{W}_{elec}) as

$$\dot{m} = L_m \dot{W}_{\text{elec}} / w_{\text{net}} \quad (9)$$

where the loss magnification factor (L_m) in this work is fixed at 1.157, according to Equation (1). Equation (9) is derived from Equation (8) with the use of the relation between the net shaft power output and the electric power output (\dot{W}_{elec}) as

$$\dot{W}_{\text{shaft}} = L_m \dot{W}_{\text{elec}} \quad (10)$$

The power plant efficiency (η_{pp}) is less than the thermodynamic cycle efficiency (η_{th}), because (η_{pp}) includes the loss of the ideal thermodynamic cycle and the loss because of non-ideal operations (which is expressed by the loss magnification factor, L_m). The two efficiencies are related by

$$\eta_{\text{pp}} = \eta_{\text{th}} / L_m \quad (11)$$

Figure 6 illustrates the 4 processes and 4 states of the Rankine cycle on the T-s diagram (temperature versus specific entropy). It shows the locations of the states 1, 2, 3, and 4 on a T-s thermodynamic diagram for water, which is a plot for the temperature (T) on the vertical axis and the specific entropy (s) on the horizontal axis. In the figure, there is a curve on the left called saturated liquid line and it separates the subcooled liquid region (compressed liquid water region) from the liquid-vapor mixture region (wet steam region). Similarly, another curve on the right called saturated vapor line separates the superheated steam region from the liquid-vapor mixture region. The two curves meet at a point

called the critical point, where the vapor and the liquid states of water merge. For water, the critical point is at 374 °C and 221 bar (Mallamace et al., 2020).

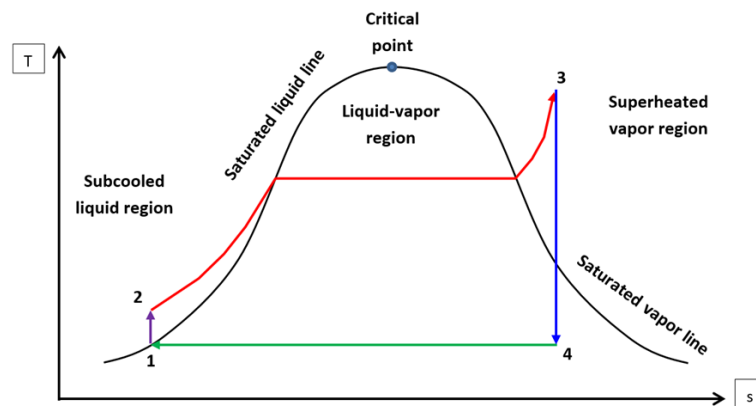


Fig 6. Illustration of the Rankine cycle on the T-s diagram (T: temperature, s: specific entropy)

Results Overview

In this part, we speak about the outcomes of the calculations of our propose thermodynamic cycle, by giving numerical values for related equations presented earlier. Again, our goal is to estimate the water (in any phase, either liquid, vapor, or a mixture of both) at the four states of a Rankine cycle and then estimate the needed mass flow rate of water to produce a specified target of electric power output. We also present the calculation of thermodynamic cycle efficiency.

In estimating the properties of water at each state, an online service (Spirax Sarco Limited, 2021) was used. It is a detailed digitized form of the steam tables, where two properties can be used to find other properties at the same state, such as temperature, pressure, specific volume (which is the reciprocal of the density), and the specific enthalpy. In order to use this free online tool, one needs first to be aware of the region or the line separating two regions in the T-s diagram. There are five options to choose from, which are

- 1) Sub saturated water region (or subcooled water or compressed water)
- 2) Saturated water line (it is the separation curve between the sub saturated water region and the wet steam region)
- 3) Wet steam region (or liquid-vapor mixture)
- 4) Dry saturated steam line (or saturated steam line, which is the separation curve between the wet steam region and the superheated steam region)
- 5) Superheated steam region

A snapshot of this online analysis tool showing the above 5 options is given in Figure 7.

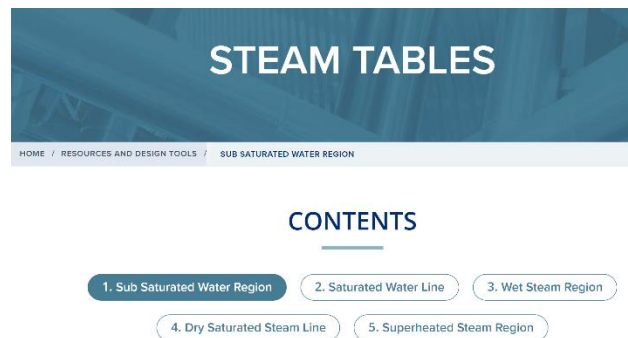


Fig 7. Online steam table calculator (Spirax Sarco Limited, 2021)

Outputs calculated

The specific enthalpies at the 4 states were found to be

- $h_1 = 209,835 \text{ J/kg}$
- $h_2 = 214,864 \text{ J/kg}$
- $h_3 = 3,666,330 \text{ J/kg}$
- $h_4 = 2,329,254 \text{ J/kg}$

Table 3 shows these values in addition to the temperature, pressure (absolute, not gauge) and specific entropy for each state.

Table 3: Summary of water states used in the design

State number	Phase	Temperature (°C)	Pressure (bar)	Specific enthalpy (J/kg)	Specific entropy (J/kg.K)
1	Saturated liquid	50.2	0.125	209,835	707.0
2	Compressed liquid	50.4	50	214,864	707.0
3	Superheated steam	600	50	3,666,330	7,260.6
4	Liquid-vapor mixture	50.2	0.125	2,329,254	7,260.6

Specific work (work per unit mass) to the pump

$$\begin{aligned}
 w_{\text{in}} &= h_2 - h_1 \\
 &= 214,864 \text{ J/kg} - 209,835 \text{ J/kg} \\
 &= 5,029 \text{ J/kg}
 \end{aligned}$$

Specific heat (heat per unit mass) to the boiler

$$\begin{aligned}
 q_{\text{in}} &= h_3 - h_2 \\
 &= 3,666,330 \text{ J/kg} - 214,864 \text{ J/kg} \\
 &= 3,451,466 \text{ J/kg}
 \end{aligned}$$

Specific work (work per unit mass) from the turbine

$$\begin{aligned}
 w_{\text{out}} &= h_3 - h_4 \\
 &= 3,666,330 \text{ J/kg} - 2,329,254 \text{ J/kg} \\
 &= 1,337,076 \text{ J/kg}
 \end{aligned}$$

Specific heat (heat per unit mass) from the condenser

$$\begin{aligned}
 q_{\text{out}} &= h_4 - h_1 \\
 &= 2,329,254 \text{ J/kg} - 209,835 \text{ J/kg}
 \end{aligned}$$

$$= 2,119,419 \text{ J/kg}$$

Net specific work from the cycle

$$\begin{aligned} \text{Net output work } (w_{\text{net}}) &= w_{\text{out}} - w_{\text{in}} \\ &= 1,337,076 \text{ J/kg} - 5,029 \text{ J/kg} \\ &= 1,332,047 \text{ J/kg} \end{aligned}$$

Cycle thermodynamic efficiency

$$\begin{aligned} \eta_{\text{th}} &= w_{\text{net}} / q_{\text{in}} \\ &= 1,332,047 \text{ J/kg} / 3,451,466 \text{ J/kg} \\ &= 0.3859 \text{ or } 38.59\% \end{aligned}$$

Power plant efficiency

$$\begin{aligned} \eta_{\text{pp}} &= \eta_{\text{th}} / L_m \\ &= 0.3859 / 1.157 \\ &= 0.3335 \text{ or } 33.35\% \end{aligned}$$

The mass flow of water to achieve a given electric power (\dot{W}_{elec}) is

$$\begin{aligned} \dot{m} &= 10^6 L_m \dot{W}_{\text{elec}} / w_{\text{net}} \\ &= (10^6) 1.157 \dot{W}_{\text{elec}} / 1,332,047 \text{ J/kg} \\ &= 0.8686 \dot{W}_{\text{elec}} \end{aligned}$$

where (\dot{W}_{elec}) is in MW, and the factor (10^6) appears because the electric power is expressed (more conveniently) in megawatts (MW) instead of watts (W), and (\dot{m}) is in kg/s. Thus,

$$\dot{m} \text{ (kg/s)} = 0.8686 \dot{W}_{\text{elec}} \text{ (MW)} \quad (12)$$

Remarks

As an example, when applying Equation (12) with 1,000 MW of electricity being needed, the proposed Rankine cycle is then expected to need a flow of water at the rate of 868.6 kg/s.

The pump energy consumption is only 0.376% of the turbine energy production. The pump contribution to the energy analysis of the cycle is not very important.

The specific enthalpies of the water in the saturated liquid condition, superheated steam condition, and saturated vapor condition are directly available from the online steam table calculator. These conditions correspond to states 1, 2, and 3, respectively. In these states, two properties of the water are known to sufficiently determine the specific enthalpy. However, some challenge happens in state 4 (liquid-vapor mixture), where the dryness (also called quality, which is fraction of the mass of vapor out of the total mass of the liquid-vapor mixture) is always needed by the online tool (in addition to a second property). However, the dryness is not known to us, and the online calculator cannot be used directly to find the properties of state 4 in the wet steam region (liquid-vapor mixture region). In our work, the specific entropy was used along with the known pressure, because the specific entropy should be equal to the already-known specific entropy of the superheated steam at the inlet of the turbine at state 3. The specific entropy of the saturated liquid (saturated water) at state 4 is $s_{f4} = 707.0 \text{ J/kg.K}$, and the specific entropy of evaporation s_{fg4} is $7,363.8 \text{ J/kg.K}$. These data are available from the (Dry Saturated Steam Line) option of the calculator at $P_4 = 0.125 \text{ bar}$. So, the dryness at state 4 is $x_4 = (s_4 - s_{f4}) / s_{fg4} = 89.0\%$. This is reasonably close to 100%, which means that the liquid-vapor mixture is mostly vapor, which is suitable for a steam turbine. After computing the dryness, one can go back to the (Dry

saturated steam line) option of the calculator, and get the specific enthalpy of saturated liquid (saturated water), $h_{f4} = 209,835$ J/kg, and the specific enthalpy of evaporation, $h_{fg4} = 2,381,370$ J/kg. With these data, the specific enthalpy at state 4 can be calculated as $h_4 = h_{f4} + x h_{fg4} = 2,329,254$ J/kg.

There is another remark related to the obtained steam quality (dryness) at the turbine outlet. The value was found to be 89.0%, meaning that 11.0% of the wet steam leaving the turbine is in the form of condensed water droplets. This is near the upper limit of 10% (Linder, 2007). Higher content of water droplets can damage the turbine blades.

With regard to power plant efficiency, the obtained value of 33.35% is close to actual values of coal-fired power plants (33%) but less than actual values of gas-fired steam power plants (42%) as of 2013 (The National Academy of Sciences NAS, 2021). Combining natural gas turbines with steam turbines (that utilize the waste heat from the gas turbines) can push the efficiency high to 60%, and this becomes a very attractive alternative at the expense of system complexity.

Conclusions

In this work, we conducted energy analyses for a proposed Rankine cycle (pump, boiler, steam turbine, and condenser) and a hypothetical steam power plant without specification of the exact source of input heat. The heat can come from burning a fuel, from solar heating, or from a nuclear reaction. The shaft rotation from the single steam turbine is to drive an electric generator to produce electricity. Four states of water (the transition points between devices in the thermodynamic cycle) were identified using online calculator of water properties plus principles of thermodynamics. The power plant efficiency is 33.35%, which is subject to improvement if the cycle is adapted, for example by using two steam turbines instead of one, although this also brings added complexity. For each MW of electricity generated from the power plant, the estimated mass flow rate of water in the cycle is 0.8686 kg/s.

References

- [1]. Andreasen, J.G., Meroni, A. and Haglind, F., 2017. A comparison of organic and steam Rankine cycle power systems for waste heat recovery on large ships, *Energies* 10, article number 547.
- [1]. Arabian Business. (2019). Oman's 50MW Dhofar wind farm starts generating electricity [Online]. Available at: <https://www.arabianbusiness.com/energy/425731-omans-50mw-dhofar-wind-farm-starts-generating-electricity> [Accessed 1 Nov. 2020].
- [2]. Donev, J.M.K.C. et al. (2018). Energy education - Rankine cycle [Online]. Available at: https://energyeducation.ca/encyclopedia/Rankine_cycle [Accessed 19 Dec. 2020].
- [3]. Dunham, M.T. and Iverson, B. (2014). High-efficiency thermodynamic power cycles for concentrated solar power systems, Brigham Young University BYU ScholarsArchive All Faculty Publications 1585.
- [4]. Electrical4U. (2020). Rankine cycle [Online]. Available at: <https://www.electrical4u.com/rankine-cycle> [Accessed 19 Dec. 2020].
- [5]. Froehling, W., Unger, H.-M. and Dong, Y., 2002, April. Thermodynamic assessment of plant efficiencies for HTR power conversion systems. In *Proceedings of Conference on High Temperature Reactors*.
- [6]. Lenzen, M., 2010. Current state of development of electricity-generating technologies: a literature review, *Energies* 3(3), pp. 462-591.

- [7]. Linder, R., 2007. Steam Generator Efficiency [Online]. Available at: <https://www.power-eng.com/coal/steam-generator-efficiency> [Accessed 10 Jan. 2021].
- [8]. Mallamace, F., Corsaro, C., Mallamace, D., Fazio, E., Chen, S.-H. and Cupane, A., 2020. Specific heat and transport functions of water, *International Journal of Molecular Sciences* 21, article number 622.
- [9]. Nakicenovic, N. and Swart, R., 2000. Special report on emissions scenarios, Intergovernmental Panel on Climate Change (IPCC).
- [10]. National Center for Statistics and Information (NCSI) of the Sultanate of Oman. (2020). Electricity visualizations [Online]. Available at: <https://data.gov.om/nmvkcc/electricity#> [Accessed 19 Dec. 2020].
- [11]. National Center for Statistics and Information (NCSI) of the Sultanate of Oman. (2020). Electricity visualizations [Online]. Available at: <https://data.gov.om/pqzsnr/energy> (the plot was expressed as a table and the numbers were taken) [Accessed 19 Dec. 2020].
- [12]. Nowling, U. (2015). Understanding Coal Power Plant Heat Rate and Efficiency [Online]. Available at: <https://www.powermag.com/understanding-coal-power-plant-heat-rate-and-efficiency> [Accessed 10 Jan. 2021].
- [13]. Office of Energy Efficiency & Renewable Energy, United States Department of Energy. (no date shown). Concentrating solar-thermal power [Online]. Available at: <https://www.energy.gov/eere/solar/concentrating-solar-thermal-power> [Accessed 19 Dec. 2020].
- [14]. Okita, N., Takahashi, T. and Nishimura, K. (2017). Steam turbines for solar thermal and other renewable energies. In: Tanuma, T., ed., *Advances in steam turbines for modern power plants.*, Elsevier, pp. 487-500.
- [15]. Rao, A. D. (Editor), 2012. Combined cycle systems for near-zero emission power generation - a volume in Woodhead publishing series in energy, Woodhead Publishing.
- [16]. SensorsONE - Measurement Instrumentation Products, 2021. (no date shown). Pressure Converter [Online]. Available at: <https://www.sensorone.com/pressure-converter> [Accessed 27 Feb. 2021].
- [17]. Spirax Sarco Limited. (2021). Steam Tables [Online]. Available at: <https://www.spiraxsarco.com/resources-and-design-tools/steam-tables> [Accessed 1 Nov. 2020, approximately].
- [18]. Struchtrup, H. (2014). *Thermodynamics and Energy Conversion*. Germany: Springer-Verlag, pp. 209-210.
- [19]. The National Academy of Sciences (NAS). (no date shown). Our Energy Sources, Natural Gas [Online]. Available at: <http://needtoknow.nas.edu/energy/energy-sources/fossil-fuels/natural-gas> [Accessed 10 Jan. 2021].
- [20]. United States Energy Information Administration (U.S. EIA). (2019). Background reference: Oman [Online]. Available at: <https://www.eia.gov/international/analysis/country/OMN/background> [Accessed 19 Dec. 2020].
- [21]. Unwin, J. (2019). What is geothermal energy? [Online]. Available at: <https://www.power-technology.com/features/what-is-geothermal-energy> [Accessed 19 Dec. 2020].
- [22]. Zhang, T., 2020. Methods of improving the efficiency of thermal power plants, *Journal of Physics: Conference Series* 149, article number 012001.