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Improvement of Steam Power Plants Performance Using a Heat Exchanger

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ABSTRACT

The present work focuses on the improvement of the ideal Rankine cycle performance used in steam power plants. Improving the steam power plant efficiency, or its components performance is desirable where the absence of renewable energy power conversion systems and the shortage of conventional fuels sources take place. The present work studies the possibility of using a counter flow heat exchanger along with the main components of the ideal Rankine cycle. The proposed counter flow heat exchanger will include the flow of compressed liquid exiting the pump and the flow of superheated steam exiting the steam turbine. The advantages of the proposed system which is investigated here include extracting heat through the heat exchanger which can be added to boiler for superheated steam production and thus reduce the amount fuel needed. In addition, since the proposed system assumes a superheated steam at the exit of the steam turbine, so no moisture is expected to form and thus increased effeciency of the steam turbine will be expected. The presents results show that the amount of heat extracted through the proposed heat exchanger for diffrent systematic four test cases of differet exits' temperatures of steam turbines and heat exchanger is systematically increasing when the those temperatures are decreasing suggesting the advantage of the proposed heat exchanger. In addition, however the proposed system eliminated the presence of moisture at the steam turbine which improve the performance of the steam turbine, a systematic reduction reduction in the delivered work by the steam turbine.

Keywords: *Ideal Rankine Cycle; Steam Power Plants; Heat Exchangers in Steam Power Plants; Steam Turbine Performance Improvement.*

1. Introduction

Producing electrical energy through steam power plants is considered to be one the reliable methods that are used to provide electrical energy to domestic, commercial, and industrial sectors however this method faces some obstacles through generation. These obstacles varies among plant and fuel initial cost, operating cost, and environmental effects. In addition, the availability of plant operating fuel forms another challenge to energy authorities due to several reasons such as cost, transportation, and sometimes-regional political condition (Badr et al., 1990, Wu et al., 2015, Desai and Bandyopadhyay, 2016). Therefore, solar steam power plant became a promising solution to overcome above obstacles (Aboelwafa et al., 2018) . Moreover, steam power plants requires maintenance to their components not only to reduce the replacement costs but also to maintain constant operating with high efficiency (Wu et al., 2015). Steam power plant are mostly operated through ideal Rankine cycles. It is well-known that the overall effeciency of Rankine cycle can be increased through the readjustment of pressure and temperature of the working fluid i.e. increasing the boiler pressure, increasing the superheated steam temperature, or lowering the condenser pressure. In addition, the introduction of some devices such as reheater or regenerator can further increase the overall thermal effeciency of the plant resulting in ideal reheat Rankine cycle and ideal regenerative Rankine cycle, respectively (Çengel and Boles 2008, Moran et al., 2010).

Increasing the overall thermal effeciency of steam power plant is always a subject of interest due to the reasons mentioned at the begining of this introduction and thus many researchers are always looking to further increase its effeciency and improve its various components performance (Çengel and Boles 2008).

The over thermal effeciency of steam power plant is the ratio of the difference between the work delivered by the turbine and consumed by the pump to the heat added in the boiler, thus higher thermal effeciencies are suspected mainly in the presence of larger amounts of mechanical energy output or smaller amounts of thermal energy input having in mind that the work consumed is relatively smaller amount in comparison to work delivered by steam turbine. Therefore, several systems have been proposed theoretically and others are used in practice such as ones that use multiple steam turbines, reheater, or regenratos, which attain larger overall thermal effeciencies. But if we look to this issue in an other way, we see that increasing the overall thermal effeciency we need to have larger heat to be added to boiler i.e., larger qin , which conradicts with the definition of the thermal effeciency. İn fact, at a specified boiler pressure, highest temperature at the boiler exit (steam turbine inlet) indicates higher enthalpy which we would like to convert to work through the steam turbine, and thus theortically increasing that enthalpy may result in a larger work out put hence steam turbibe effeciency and overall thermal effeciency of the plant.

Another practice problem that reduces the efficiency of the steam turbine and thus the overall efficiency of the steam power plant is represented by the excessive presence of moisture at the steam turbine exit. The excessive presence of moisture at the steam turbine exit erodes the turbine blades and thus reducing the steam turbine and over all thermal efficiencies. Therefore, several methods have been introduced to reduce the amount of moisture at the steam turbine exit; these methods include superheating the steam to high temperatures, or expand the steam in turbine in two stages and use reheaters (Çengel and Boles 2008). Therefore, in order to improve the overall thermal effeciency of steam power plant we still may think to:

i) For a specified cycle, find any possible ways to compensate any reduction from the amount of the heat added in the boiler.

ii) Find means to increase the work delivered by the steam turbibe.

The present work look further to increase the overall thermal effeciency of the ideal Rankine cycle i.e., decrease heat added in the boiler and/or increase work delivered by steam turbine and in addition, improve the performance of steam turbine i.e., eliminate the excessive presence of moisture at the steam turbine exit. The present system in addition to main components of ideal Rankine cycle (i.e., pump, boiler, steam turbine, and condenser) includes a counter flow heat exchanger. The introduced heat exchanger will be located in a location where it includes the flow of the superheated steam that leaves the steam turbine, and the flow of compressed liquid that leaves the pump. The steam will leave the steam turbine as superheated despite ideal Rankine cycle where it leaves as saturated mixture i.e. presence of moisture. The heat will be removed from the superheated steam exiting the steam turbine and added to the leaving compressed liquuid from the pump throough the proposed heat exchanger. The present system will ensure a better performance of the steam turbine due to the absence of any moisture at the steam turbine exit thus increase its effeciency, in addition the heat removed from the superheated steam existing the steam turbine will be added reducing the required heat in the boiler which is supposed to be produce the superheated heated at a specified temperature and pressure. The present system is investigated to highlight any advantages that can be associated with presence of the heat exchanger e.g. reducing amount of fuel needed in the boiler hence reduce fuel cost, increase the steady state efficiency of the boiler.

It is may be of interest to note that the present system can accompany any of the modified ideal Rankine cycles e.g. reheat or regenrative (not studied yet) hence higher efficiency with better components performance may be maintained. The expected improvement of ideal Rankine performance using this system will be demonstrated and explored through the evalulation of heat that can be extracted in the heat exchanger, work delivered by steam turbine and over all thermal effeciency systematically for four test cases that have different temperatures at the exits of both steam turbine and heat exchanger.

2. Investigation methodology

In the present investigation the a counter heat exchanger is added to the simple Rankine cycle main components i.e., pump, boiler, steam turbine, and condenser as shown in Fig. 1.

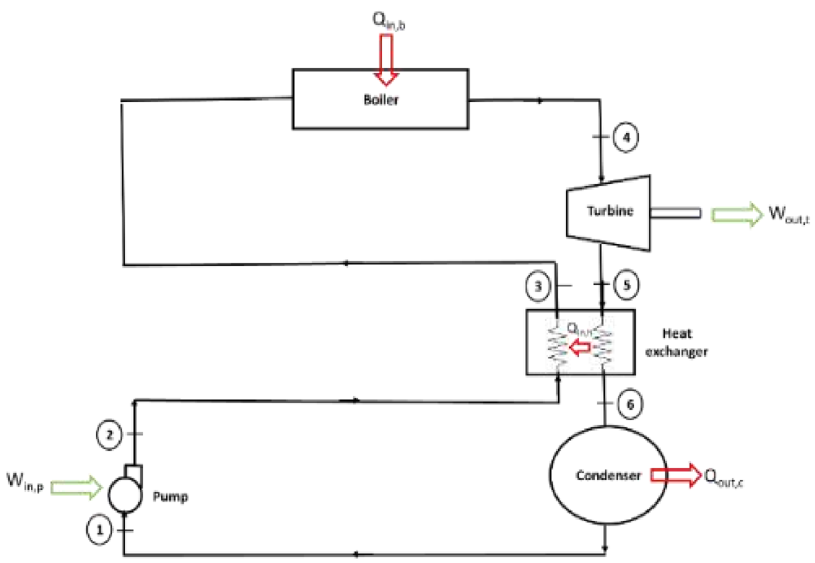

Figure 1: The ideal RC components with a heat exchanger

The introduced heat exchanger will include the flow of the working fluid (water) that exits the steam turbine in superheating state and the subcooled water that leaves the pump and that exits from the pump in compressed liquid state in such a way that the heat exchanger will grantee the extraction of heat from the superheated steam that leaves the steam turbine and added it to the compressed water from the pump. As consequences of that compressed water from the pump will be heated in the same amount of the heat extracted from the superheated steam and thus the amount of heat in put to the boiler will reduced of that amount extracted. It should be mentioned that the heat extraction process in heat exchanger will be undertaken in a pressure between the exit steam turbine pressure and the condensation pressure. In other hand, the state of the working fluid that leaves the turbine will be superheated and thus ensure that no moisture is present at the steam turbine exit where its presence can erodes the steam turbine blades and thus reduce the steam turbine efficiency.

The modified simple Rankine cycle with the heat exchanger investigated in this paper is shown represented on T-s diagram as shown in Fig. 2.

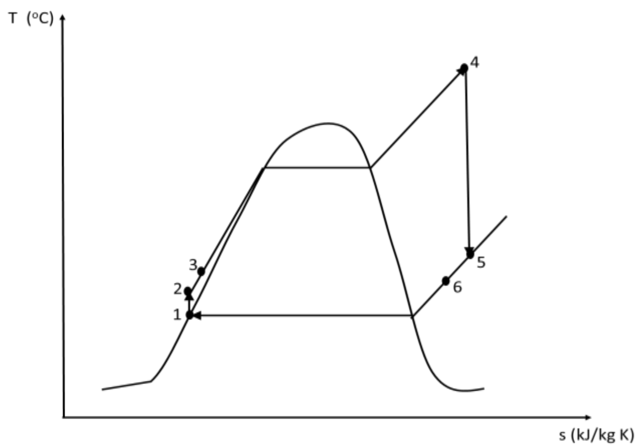

Figure 2: The modified ideal RC with a heat exchanger on T-s diagram

For clarity purpose and more insight to the present proposed system, the characterstics of all states shown in Fig. 2 are included in table 1 describing the their locations and phases.

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Table 1: The inlet and exit characteristics of proposed system's components

State	Location and device	Water Condition (or phase)
1	Pump inlet, Condenser exit	Saturated liquid
2	Pump exit, Heat exchanger inlet	Compressed liquid
3	Heat exchanger exit	Compressed liquid
4	Steam turbine inlet	Superheated steam
5	Steam turbine exit, Heat exchanger inlet	Superheated steam
6	Heat exchanger exit, Condenser inlet	Superheated steam

Going back to Fig.2, we should note that the state 6 (i.e., heat exchanger exit) must be higher and (thus its temperature) than the state 2 (i.e., pump exit) and thus its temperature. In fact, if we consider opposite condition, the heat exchanger will subtract heat from the compressed water adding it to the superheated steam that exit the steam turbine and that's why T_6 must be higher than T_2. In addition, state 5 (i.e., turbine exit) must be higher (thus its temperature) than the state 3 (i.e., heat exchanger exit) and thus its temperature to ensure that the heat exchanger is working effectively i.e., that's extracting the maximum possible heat from expanded superheated steam i.e., $T_3 < T_5$. It should be noted that the other states 1, 2, and 4 are similar to ones found in simple ideal Rankine cycle.

3. Mathematical relations and computations

The investigation is carried out by supposing that an ideal Rankine cycle is operating between condensation pressure of 100 kPa and boiler pressure of 2.5 MPa and the temperature of superheated steam that enters the steam turbine is 400 ^{o}C. The mathematical relations can be found in reference 3.

The mathematical computations which performed here are first made baed on simple ideal Rankine cycle (i.e., no heat exchanger) as presented on T-s diagram shown in Fig. 3 and thus the mathematical computations have led to the following results:

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State 1

P_1=100 kPa (saturated liquid)

$h_1=h_{f\ @100kPa}$= 417.51 kJ/kg

$v_1=v_{f@100kPa}$ =0.001043 m^3/kg

$s_1=s_{f@100kPa}$ =1.3028 kJ/kg.K

T_1= 99.97°C

State 2

P_1=100 kPa

P_1=2.5 MPa

$v_1=v_f$ =0.001043 m^3/kg

$s_2=s_{1@100kPa}$ = 1.3028 kJ/kg.K

wpump= v1($P_2 - P_1$)

= 0.001043 (2.5 x10^3 – 100)

=2.5032 kJ/kg

Wpump = $h_2 - h_1$

h_2 = wpump + h_1

= 2.5032 kJ/kg + 417.51

= 420.01 kJ/kg

T_2= 100°C

State 3

P_3=2.5 MPa (superheated steam)

T_3= 400°C

h_3=3240.1kJ/kg

s_3=7.0170 kJ/kg.K

T_{3sat}= 223.95°C

Cycle characteristics

$q_{boiler,in} = h_3 - h_2$ = 2820.09 kJ/kg

$q_{condenser,out} = h_4 - h_1 = 2128.82$ kJ/kg

$w_{turbine} = h3 - h4 = 693.77$ kJ/kg

$w_{net} = w_{turbine} - w_{pump} = 691.26$ kJ/kg

$\eta_{th,\ ideal} = w_{net} / q_{boiler} = 24$ %

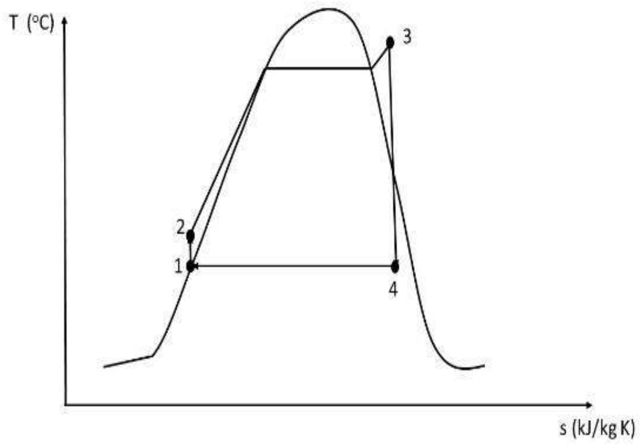

Figure 3: The ideal Rankine cycle on T-s diagram

The previous calculations for states points 1, 2 and 3 in simple Rankine cycle will remain the same while evaluating the use of the proposed heat exchanger holding notations 1, 2, and 4, respectively. Based on this suituations, missing properties are that on points 3, 5, and 6 which are computed accoriding to the following relations and assumptions.

State 6

P_6=100 kPa (saturared liquid), and $T_3 = 100$ °C

$T_{6a} = (T_3 + n_a)$ where $n_a = 50$ °C [assumption]

$= 100 + 50 = 150$ °C

$h_6a = 2776.6$ kJ/kg (superheated steam)

$T_{6b} = (T_3 + n_b)$ where $n_b = 100$°C [assumption]

$= 100 + 100 = 200$ °C

$h_{6b} = 2875.5$ kJ/kg (superheated steam)

$T_{6c} = (T_3 + n_c)$ where $n_c = 150$ °C [assumption]

$= 100 + 150 = 250$ °C

$h_{6c} = 2974.5$ kJ/kg (superheated steam)

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T_{6d}= (T_3 + n_d) where n_d = 200 ^oC [assumption]

= 100 +200 = 300 ^oC

h_{6d} = 3074.5 kJ/kg (superheated steam)

State 5

s_5=7.0170 kJ/Kg.K &

T_5 = (T_6+n), where n=50 ^oC [assumption]

T_{5a}= (T_{6a} + n)

= 150 +50 = 200 ^oC

h_{5a} = 2855.8 kJ/kg (superheated steam)

T_{5b}= (T_{6b} + n)

= 200 +50 = 250 ^oC

h_{5b} = 2950.4 kJ/kg (superheated steam)

T_{5c}= (T_{6c} + n)

= 250 +50 = 300 ^oC

h_{5c} = 3046.3 kJ/kg (superheated steam)

T_{5d}= (T_{6d} + n)

= 300 +50 = 350 ^oC

h_{5d} = 3141.9 kJ/kg (superheated steam)

State 3

Thermodynamic balance in the heat exchanger is undertaken to find h_3,Mathematically, we have $h_5 + h_2 = h_3 + h_6$, then: $h_3 =(h_5+h_2) - h_6$

h_{3a}= (h_{5a}+h_2) - h_{6a} = 499.21 kJ/kg

h_{3b}= (h_{5b}+h_2) - h_{6b} = 494.91 kJ/kg

h_{3c}= (h_{5c}+h_2) - h_{6c} = 491.81 kJ/kg

h_{3d}= (h_{5d}+h_2) - h_{6d} = 487.41 kJ/kg

The heat extracted through the heat exchanger from the suprheated steam that exits the steam turbine is equal to the heat added to the compressed liquid that leaves the pump i.e., $q_{heat\ exchanger} = h_3-h_2 = h_5 – h_6$. The amount of heat that extracted from superheated steam for various cases are given below:

$q_{heat\ exchanger,a} = h_{3a} - h_2 = 79.2$ kJ/kg

$q_{heat\ exchanger,b} = h_{3b} - h_2 = 74.9$ kJ/kg

$q_{heat\ exchanger,c} = h_{3c} - h_2 = 71.8$ kJ/kg

$q_{heat\ exchanger,d} = h_{3d} - h_2 = 67.4$ kJ/kg

Then the amount of heat added to the bioler based on the presence of the heat exhchanger will be the difference between the enthalpies of boiler exit and heat exchanger exit i.e., $q_{boiler\ in,\ new}$ = h4 – h3. The heat added for different cases investigated here are given below:

$q_{boiler\ in,\ new,a} = h_4 - h_{3a} = 2740.89$ kJ/kg

$q_{boiler\ in,\ new,b} = h_4 - h_{3b} = 2745.19$ kJ/kg

$q_{boiler\ in,\ new,c} = h_4 - h_{3c} = 2748.29$ kJ/kg

$q_{boiler\ in,\ new,d} = h_4 - h_{3d} = 2752.69$ kJ/kg

The workdone per kg by the steam turbine based on the various condition studied will be difference between the heats at the inlet and exit of the turbine i.e., $w_{turbine,new} = h_5 - h_6$.

$w_{turbine,new,a} = h_4 - h_{5a} = 384.3$ kJ/kg

$w_{turbine,new,b} = h_4 - h_{5b} = 289.7$ kJ/kg

$w_{turbine,new,c} = h_4 - h_{5c} = 193.8$ kJ/kg

$w_{turbine,new,d} = h_4 - h_{5d} = 98.2$ kJ/kg

Therefore, the over all thermal effeciency of the proposed system at different investigated cases are:

$\eta_{th,new,a} = (w_{turbine,new,a} - w_{pump}) / q_{boiler\ in,\ new,a} = 13.9$ %

$\eta_{th,new,,b} = (w_{turbine,new,b} - w_{pump}) / q_{boiler\ in,\ new,b} = 10.4$ %

$\eta_{th,new,c} = (w_{turbine,new,c} - w_{pump}) / q_{boiler\ in,\ new,c} = 6.9$ %

$\eta_{th,new,d} = (w_{turbine,new,d} - w_{pump}) / q_{boiler\ in,\ new,d} = 3.5$ %

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4. Results and discussion

Figure 4 shows the amount of heat extracted by the heat exchanger from the superheating steam that exits the steam turbine. As we can see the highest heat extracted is associated with lower exit temperatures at the steam turbine and heat exchanger; the amount of heat extracted through the heat exchanger is 79.2, 74.9, 71.8 and 67.4 kJ/kg, which represent a reduction of 2.8, 2.6, 2.5, and 2.4 % of the total heat added to the boiler of the ideal Rankine cycle (i.e., 2820.09 kJ/kg) corresponding to steam turbine exit temperatures and pressures of 200, 250, 300, and 350 ^oC, and 0.5, 0.8, 1.2, and 1.8 MPa and heat exchanger exit temperatures of 150, 200, 250, and 300 ^oC, respectively.

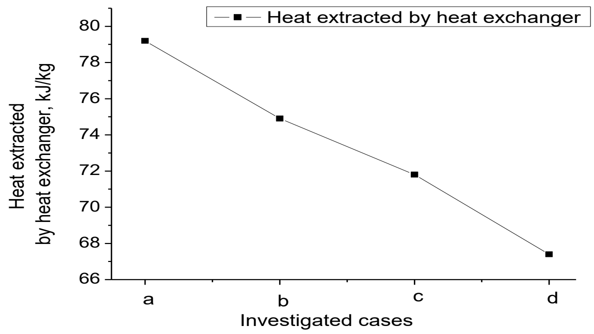

Figure 4: Heat extracted by the heat exchanger for various test cases

It is may be noted that the highest heat extracted through the heat exchanger is obtained at the lowest temperatures at the exits assumed temperatures at steam turbine and heat exchanger. To find reasons of such trends first let see table 2 which shows the pressures at the steam turbines exit with its saturation temperatures and the heat exchanger exit pressure which constant.

Table 2: The various cases investigated with their characteristics

Case	Amount of heat extracted (%)	Steam turbine exit pressure (MPa)	Saturation temperature at steam turbine exit pressure (^oC)	Heat exchanger exit pressure (MPa)
A	2.8	0.5	151	0.1
B	2.6	0.8	170	0.1

C	2.5	1.2	188	0.1
D	2.4	1.8	206	0.1

In fact examining table 2 doesn’t give acceptable reasons for such trends since the status of steam is superheated at both steam turbine and heat exchanger exits and thus having lowest saturation temperature for case "a" doesn’t explain why have the highest heat extracted there because the steam will leave both steam turbine and heat exchanger as superheated where no flashing is to occur at that lowest saturation temperature. The only possible which may be used to explain such increase in heat extracted i.e., case a at the heat exchanger is lowest exit temperature at the heat exchanger exit which is associated with case "a" i.e., 150 ^{o}C in comparison to other cases of higher temperature which suggest that at the lowest temperature a larger of thermal energy is extracted when the exit heat exchanger temperature is maintained.

Based on the present results as shown Fig. 4, the amount of heat extracted by the heat exchanger can reduce the the amount of heat supplied to the boiler. Figure Fig. 5 higlighs show the amount of heat that needed to be added in the boiler for ideal case with no heat exchanger and at various cases with heat exchanger where an obvious effect of the presence of the heat exchanger which can reduce the amount of heat added in the boiler more significantly at lower exit steam turbine Based on the present results as shown Fig. 4, the amount of heat extracted by the heat exchanger can reduce the the amount of heat supplied to the boiler.

Fig. 5 higlighs show the amount of heat that needed to be added in the boiler for ideal case with no heat exchanger and at various cases with heat exchanger where an obvious effect of the presence of the heat exchanger which can reduce the amount of heat added in the boiler more significantly at lower exit steam turbine and heat exchanger exits temperatures as was discussed early.

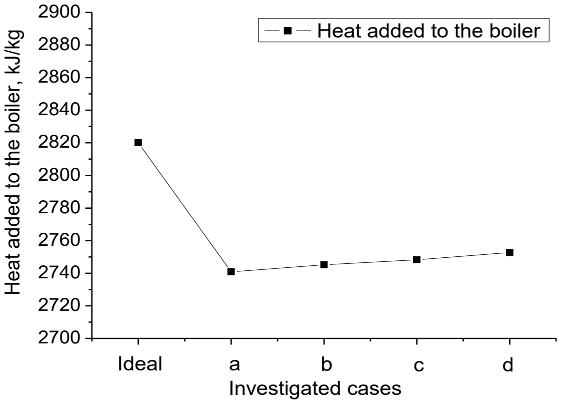

Figure 5: Heat input to the boiler for the ideal case compared to various test cases with heat exchanger

It is may be of intest to note that since the condition of the steam at the steam turbine is superheated steam at all cases hence no moisture is suspected there and thus better performances of such systems are expected having in mind the amount of work delivered by the steam turbine that are associated with such system which can affect the over all thermal effeciency as it will be investigated in the following figure and sections.

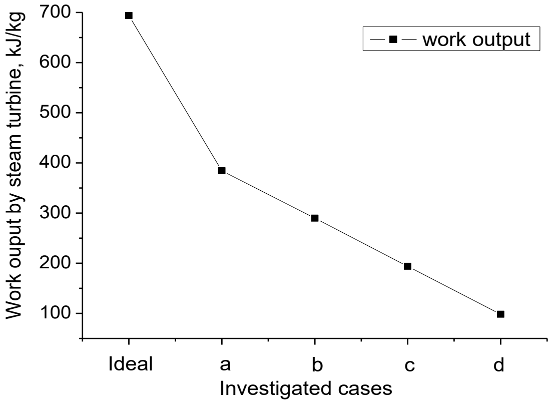

Figure 6: work output by the steam turbine for the ideal case compared to various test cases with heat exchanger

Work delivered by the steam trubine for the ideal case and for cases with heat exchanger are graphically represented in Fig. 6. As we can see the steam turbine for the ideal case gives the highest work output followed by cases a, b, c, and finally d. This is may be expected because in the ideal cycle with no heat exchanger, the steam exits the steam turbine as saturated mixture and in this suituation larger range of thermal energy can be converted to mechanical energy.

But on contrary when the heat exchanger is used, the working fluid exits the steam turbine as superheated steam where larger thermal energy can be missed and thus converted to work energy as compared to ideal one. Again the increased amount of work delivered by steam turbibe in case "a" can be attributed to increased of amount of heat extracted at the heat exchanger in comparison to other cases as was discussed early (see Fig. 4)

Figure 7 shows the over all thermal effeciencies for the ideal Rankine cycle compared to the other cases with heat exchanger. As expected the highest is found in the ideal case as it has the highest work out put followed by cases a, b, c, and d. Improved overall thermal effeciency in the ideal case can be attributed to higher work delivered by the steam turbine which is decreasing in other cases investigated with heat exchanger.

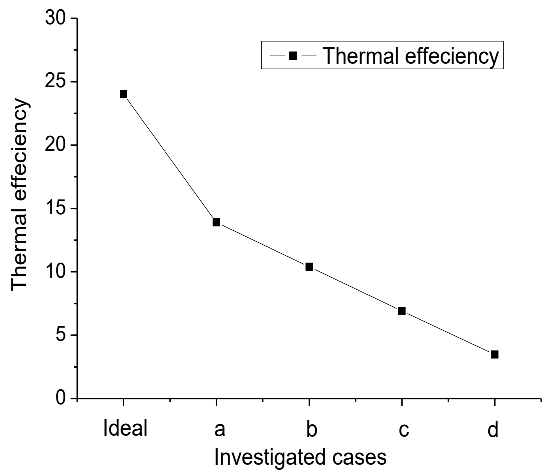

Figure 7: Thermal effeciency for the ideal case compared to various test cases with heat exchanger

5. Conclusions

The present study investigated the possibility of using a counter flow heat exchanger along the ideal Rankine cycle main components (i.e., pump, boiler, steam turbine and condenser). Four cases were investigated at different exit steam turbine and heat exchanger temperatures. The present thermal analysis revealed that the presence of heat exchanger heat can be extracted and added in the boiler as was observed by the four cases investigated cases, however, significant amount of heat can be extracted at lower exit steam turbine and heat exchanger exit temperature. But on the contrary however the moisture at the exit of steam turbine at all cases was eliminated as steam will be superheat at the steam turbine exit, the amount of work delivered by steam turbines in the presence of the heat exchanger reduced significantly when the steam turbine and heat exchanger exit temperatures. Consequently, the overall thermal effeciency of the proposed system with heat exchanger is less than the ideal case however, reducing the exit temperatures at the exit steam turbine and heat exchanger can increase it.

References

1. Aboelwafa O., Fateen S., Soliman A., and Ismail I. M., *A review on solar Rankine cycles: Working fluids, applications, and cycle modifications,* Renewable and Sustainable Energy Reviews, Vol. 82 (1), pp. 868-885, 2018.
2. Badr O., Probert S. D., and O'Callaghan P., *Rankine Cycles for Steam Power-plants*, Applied Energy 36, pp. 191-231, 1990.
3. Çengel Y., and Boles M., Thermodynamics: An Engineering Approach 5th Edition, Mcgraw-Hill College, 2008.
4. Desai N. B., Bandyopadhyay S., *Thermo-economic comparisons between solar steam Rankine and organic Rankine cycles*, Applied Thermal Engineering, Volume 105 (25), pp. 862-875, 2016.
5. Moran M. J. , Shapiro H. N., Boettner D. D., Fundamentals of Engineering Thermodynamics, 7th Edition, Wiley, 2010.
6. Wu X., Shen J., Li Y., and Lee K. Y., *Steam power plant configuration, design, and control, WIREs Energy Environ* 2015. doi: 10.1002/wene.161.