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Integration of Steam Cycle to Enhance the Efficiency of Power Plants

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Abstract

The continuous and simultaneous increases in energy price and energy consumption have motivated researchers for further operation improvement. The steam power stations as a part of power plant require a sophisticated study and development. This work is aiming to improve the steam power stations systems to be more efficient The main idea of this study is combining the reheat and regenerative cycles of steam to have a new cycle (reheat-regenerative cycle). The combination of such cycles has been conducted in three different ways. The data for analysis the proposed combined cycles was taken from Garri Thermal Power Station. The produced shaft work from the turbine is calculated using Willian's Line Equation Consequently, the efficiency has been calculated for each pattern of combined cycles and compared to choose the best one. From three combined cycles, it is found that the highest efficiency could be obtained when combining the normal reheat cycle with the normal regenerative cycles. It is found to be more than 90% compared to 80% and 85% of reheat and regenerative respectively. Moreover, the effect of changing the steam flow rate has positively effected on the cycle efficiency. Further work should be carried out on the economic study of the systems. Also the effect of fuel switching could be studied for the suggested combination on steam cycles.

Keywords: *Steam Cycles, Efficiency of Power Plants, Regenerative Cycles, Reheat Cycle (Reheat-Regenerative Cycle).*

1. Introduction

Cheap and abundant supply of electric power is the major factor in the development and progress of countries. Despite the rapid progress of internal combustion engines and the intensive development of water power, steam power plant still lead the field in power generation and expected to continue over [1]. The function of steam power plant is to convert the row energy of fossil fuels into mechanical and then electric power [2].

This can be done by expansion of steam in suitable steam turbine and drivers for auxiliary equipments such as pumps, stockers, fans, etc. the working fluid which mainly high pressure steam is generated in boilers by burning fossil fuel in furnaces.

A power plant could be used for the production of steam, electricity or a combination of them [3]. Nowadays steam is considered to be critical energy resource in industrial countries. Moreover, it is essential for the production of papers, preparation of food, cooling and heating of large buildings, driving equipment such as pumps and compressors [2]. However, steam is commonly known as the primary source of power and energy production [3].

Steam has the advantage that, it can be raised from water which is available in abundance it does not react much with the materials of the equipment of power plant and is stable at the temperature required in the plant. Steam is used to drive steam engines, steam turbines etc. Steam power station is most suitable where coal is available in abundance.

Therefore, interactions exist between the process and the utility system via steam usage and generation. Simply, there is a heat recovery interaction between the processes on site using the steam as intermediate for the heat transfer [4].

The progressive industrial and social development all over the word requires a parallel development in energy and electrical supply. Moreover, the price of fossil fuel is increasing in a fluctuating trend where it is very difficult to predict the energy price in the future. Therefore, it is very crucial to seek for a low hanging fruit solution to enhance the efficiency of power plant stations instead of building new ones. Increasing the efficiency will ether reduce the fuel consumption or increase the power output.

2. Objectives

1. To study and analyze the classical steam cycles.

2. To improve the steam power systems using different alternatives.

3. To study the effect of changing the steam flow rate on the efficiency of the steam cycles.

3. Material and Methods

This chapter is mainly presenting the suggested methods for how to enhance the efficiency of thermodynamics steam cycles. The analysis of existing cycle has been made based on a data taken from Garri Thermal Power Station in Sudan.

Actual Cycle

The cycles encountered in actual devices are difficult to analyze because of the presence of complicating effects, such as friction and the absence of sufficient time for establishment of the equilibrium conditions during the cycle[5].

Ideal Cycle

When the actual cycle is stripped of all the internal irreversibility's and complexities, we end up with a cycle that resembles the actual cycle closely but is made up totally of internally reversible processes. Such cycle is called an Ideal cycle.

Steam cycle components

Steam boiler

Steam Turbine
- Steam condenser
- Pumps

Materials of the work

The data (temperature, pressure) for analyzing the proposed combined cycles was taken from Garri Thermal power station. The produced shaft work from the turbine is calculated using Willian's Line equation [13] consequently, the efficiency has been calculated for each pattern of classical or suggested combined cycles and compared to choose the best one.

Hypothesis

- The cycle does not involve any friction.
- Isotropic expansion and compression in all the turbines and pumps, respectively.
- The pipe connecting the various component of a system is well insulated and heat transfer and pressure drop through them are negligible.
- The turbine before the condenser is condensing turbine and the other one is Back pressure turbine.
- All the pumps are negligible except the condensing pump.

3.1 The Standard Carnot Cycle

Steam power plant could be analyzed ideally using carnot cycle as shown in the schematic representation shown in fig(3.1)

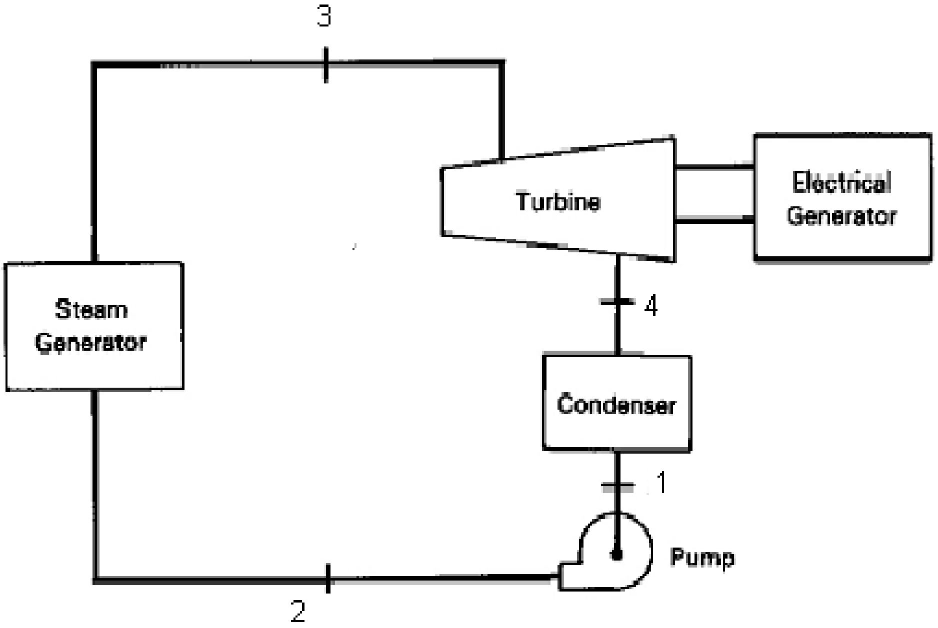

Fig (3.1): Standard Carnot Cycle

Steam power plant could also be analyzed using Rankin cycle which is a bit closer to actual steam plant as shown in fig (3.2)

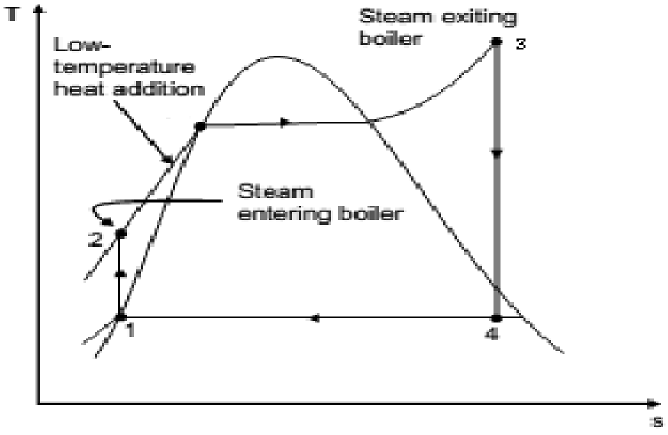

Fig (3.2): T-S diagram for standard Rankin cycle

3.2 The standard steam cycle processes

The cycle consists of the following four processes:

1-2: Isentropic compression in pump (compressors)
2-3: Constant pressure heat addition in boiler
3-4: Isentropic expansion in turbine
4-1: Constant pressure heat rejection in a condenser

Mathematics for calculating the efficiency of standard cycle

- Using Willian's line equation to calculate the shaft work W.
- b_0, b_1, b_2, b_3 are regression parameters values for the steam turbine model from table (3.1).
- The steam properties are obtained from steam tables.
- Calculate the network for the cycle.
- Then calculate the efficiency (η).

Table 3.1: Regression parameters values for the steam turbine model

Coefficients	**Back-pressure Turbine**		**Condensing Turbine**	
	W_{max}<2 MW	**W_{max}>2 MW**	**W_{max}<2 MW**	**W_{max}>2 MW**
b_0	**0**	**0**	**0**	**-0.463**
b_1	**0.000108**	**0.00423**	**0.000662**	**0.00353**
b_2	**1.097**	**1.155**	**1.191**	**1.220**
b_3	**0.00172**	**0.000538**	**0.000759**	**0.000148**

$$W = n \times m - W_{\text{int}} \tag{3.1}$$

$$W_{\text{int}} = \frac{L}{B}(\Delta H_{is} \times m_{\max} - A) \tag{3.2}$$

$$n = \frac{L+1}{B}(\Delta H_{is} - \frac{A}{m_{\max}}) \tag{3.3}$$

$$A = b_0 + b_1 \times \Delta T_{sat} \tag{3.4}$$

$$B = b_2 + b_3 \times \Delta T_{sat} \tag{3.5}$$

$$\Delta T_{sat} = T_{in} - T_{out} \tag{3.6}$$

$$\Delta H_{is} = H_{in} - H_{out} \tag{3.7}$$

$$W_{net} = |W| - W_p \tag{3.8}$$

$$\eta = \frac{|W_{net}|}{Q_c} \times 100 \tag{3.9}$$

M_{max}=20.8 kg/s

ΔH_{is}=756.9 kJ/kg

A=0.35 kw

B=1.25

L=0.1

W_{int}=1259.4 kw

n=666 kw/kg

W=4841.16 kw

W_{net}=-1158.9 kw

Qc=3342.2

3.3 The Reheat Cycle

The standard reheat cycle could be improved further by introducing the reheat cycle as shown in fig (3.3) [12].

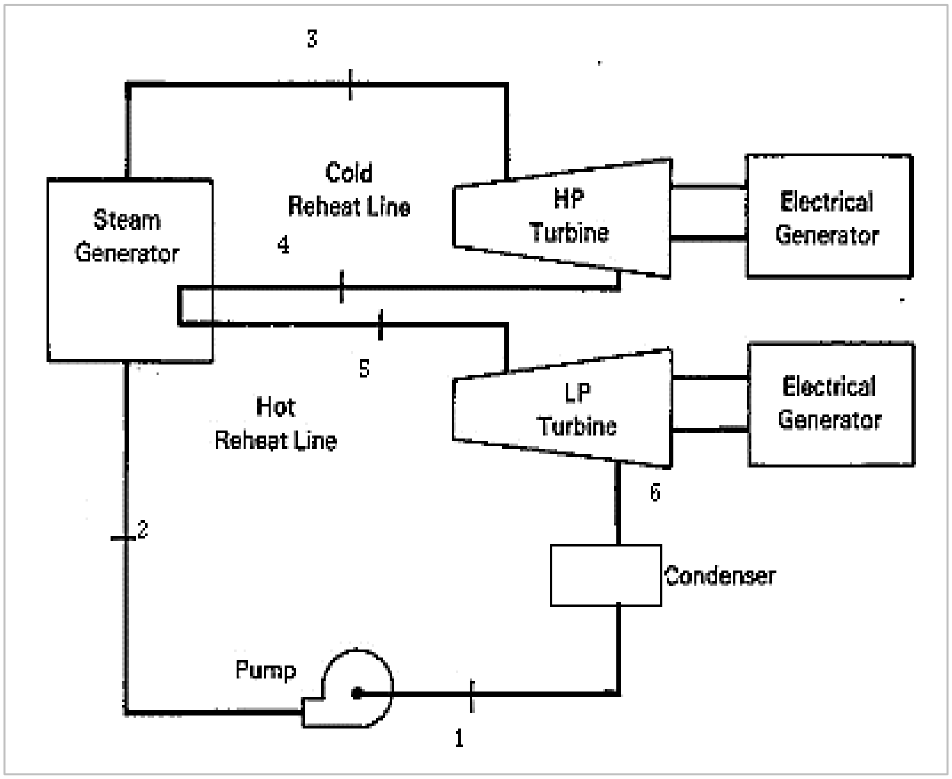

Fig (3.3): Reheat cycle

Mathematics for calculating the efficiency of reheat cycle

- Using Willians line equation to calculate the W_1 and W_2.
- b_0, b_1, b_2, b_3 are regression parameters values for the steam turbine model from table(3.1).
- The steam properties are obtained from steam tables.
- Calculate the network for the cycle.
- Then calculate the efficiency (η).

W_1 and W_2 could be obtained using equation (3.1),(3.2),(3.3),(3.4),(3.5),(3.6),(3.7). And the net work could be calculated using equation (3.10). And finally the efficiency could be obtained using equation (3.9).

A=0.135kw
B=1.31
W_{int}=879.6 kw
n=465.9 kw/kg
W_1=3388 kw
ΔH_{is}=838.3kJ/kg
A=0.07 kw
B=1.27
n=726.08 kw/kg
W_{int}=1372.9 kw
W_2=5277.9 kw
W_{net}=2665.9 kw

$$W_{NET} = |W_1 + W_2| - W_P \tag{3.10}$$

3.4 Regenerative Cycle

Another way to improve the standard stream cycle is by introducing the regenerative cycle as shown in fig (3.4) [14].

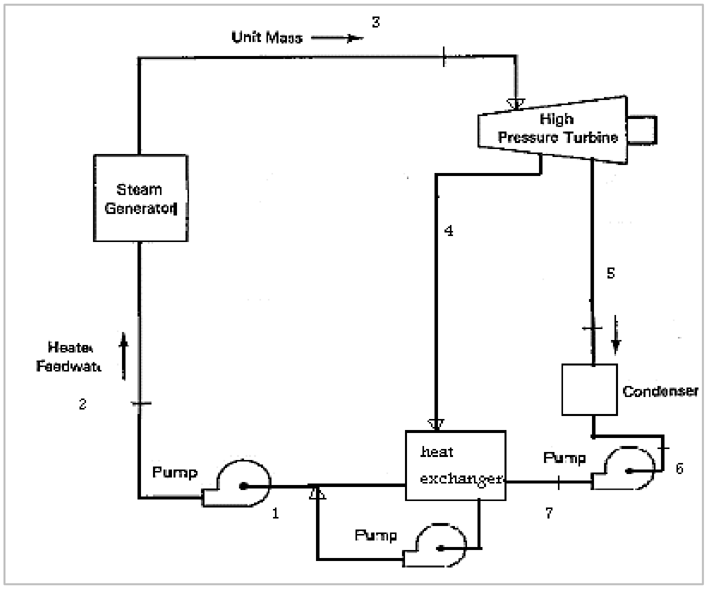

Fig (3.4): Regenerative Cycle

Mathematics for calculating the efficiency of regenerative cycle

- Using willian's line equation to calculate the shaft work W.
- b_0, b_1, b_2, b_3 are regression parameters values for the steam turbine model from table(3.1)
- The steam properties are obtained from steam tables.
- Calculate the network for the cycle.
- Then calculate the efficiency (η).

W could be obtained using equation (3.1), (3.2), (3.3), (3.4), (3.5), (3.6), (3.7) and the net work could be obtained using equation (3.8).Also isentropic enthalpy deference (ΔH_{is}) could be calculated using equation (3.11). And finally the efficiency could be obtained using equation (3.9).

$$\Delta H_{is} = H_3 - (H_4 + H_5) \tag{3.11}$$

ΔH_{is}=-1383.1 kJ/kg

A=0.059 kw

B=1.26

W_{int}=-2283.2 kw

n=-1207.46 kw/kg

W_T=-8785.18 kw

W_{net}=2785.18 kw

3.5 Model process for enhancing the efficiency of steam power plant

It is proposed to enhance the efficiency of steam power station for two purposes. It could be achieved for ether increasing the power output if needed or decreasing the fuel consumption in boiler house in case of high fuel price. The idea could be introduced logically and mathematically using the following parameters:

- The amount of absorbed heat in the boiler Q_{in} is x.
- The value of cycle efficiency η is y.
- The value of shat work output w is z.

And suppose that the efficiency is increasing by the amount, the model could be formulated as follows:

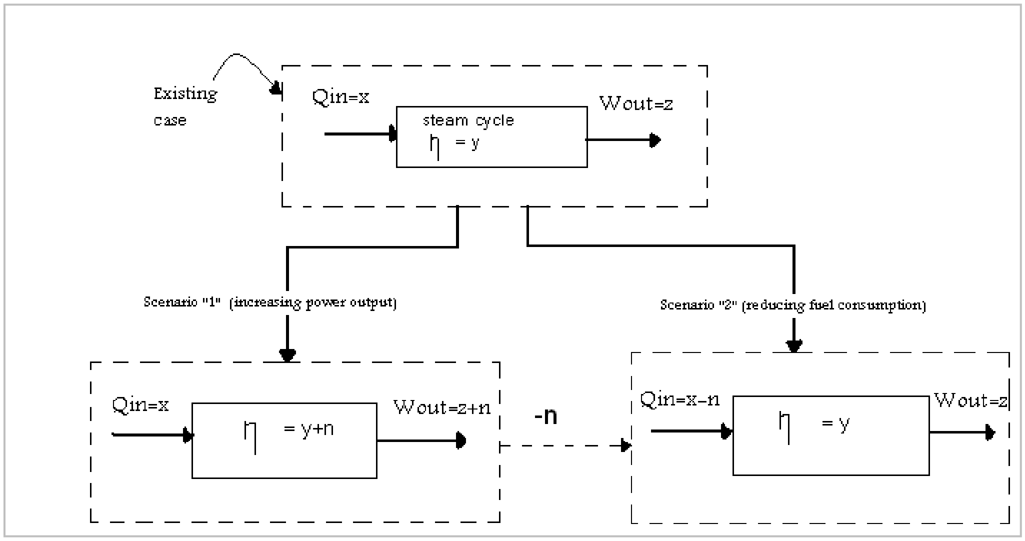

Fig (3.5): Model process for enhancing the efficiency of steam power plant

3.6 Efficiency enhancement procedure

There are three different suggested options in this study to enhance the steam cycle efficiency as explained in the following section.

3.7 The first suggested reheat-regenerative cycle (1)

It is proposed to combine he classical reheat and regenerative cycle in one steam cycle called “reheat-regenerative” as explained in fig (3.6) bellow:

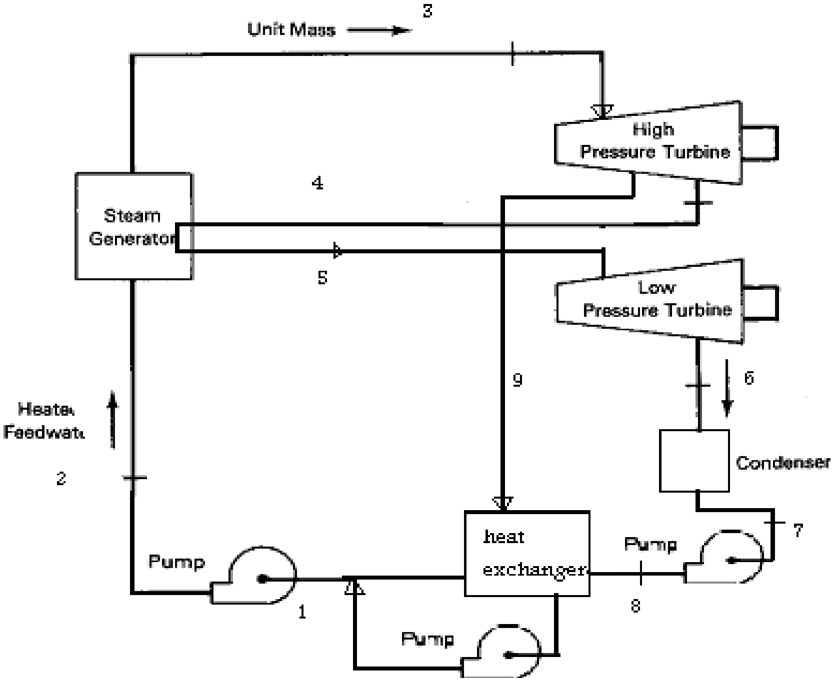

Fig (3.6): Reheat -regenerative cycle (1)

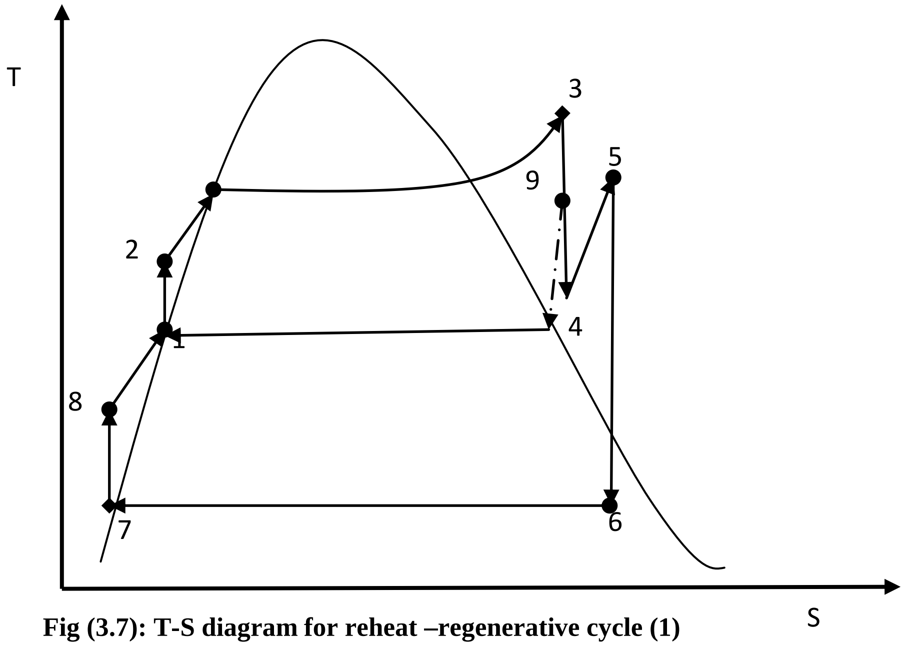

Fig (3.7): T-S diagram for reheat –regenerative cycle (1)

Mathematics for calculating the efficiency of reheat-regenerative cycle (1)

- Using Willians line equation to calculate the W_1 and $W_{2.}$
- $b_{0,}b_{1,}b_{2,}b_3$ are regression parameters values for the steam turbine model from table(3.1).
- The steam properties are obtained from steam tables.
- Calculate the network for the cycle.
- Then calculate the efficiency (η).

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3), (3.4), (3.5), (3.6), (3.7). And the net work could be calculated using equation (3.10). Also isentropic enthalpy deference (ΔH_{is}) could be calculated using equation (3.12).And finally the efficiency could be obtained using equation (3.9).

$$\Delta H_{IS} = H_3 - (H_4 + H_9) \qquad (3.12)$$

ΔH_{is}=-2167 kJ/s

A=0.016 kw

B=1.21

W_{int}=-3725.1 kw

n=-1969.9 kw/kg

W_1=-14319.2 kw

W_2=5277.9 kw

W_{net}=3041.3 kw

3.8 The second suggested reheat-regenerative cycle (2)

It is case the regenerative process could be done by extracting supper heated steam at low pressure before interring the second low pressure turbine as shown by schematic diagram in fig (3.9).

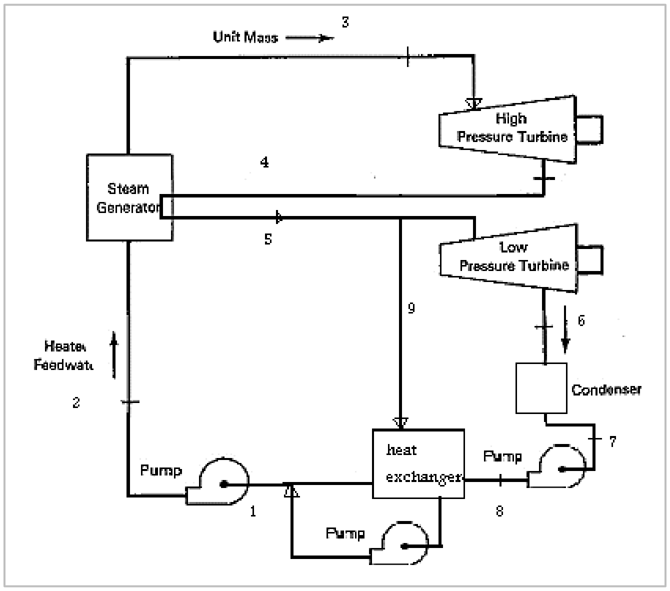

Fig (3.8): Reheat-regenerative cycle (2)

This new combine cycle could be presented in a T-s diagram as in fig (3.9) below:

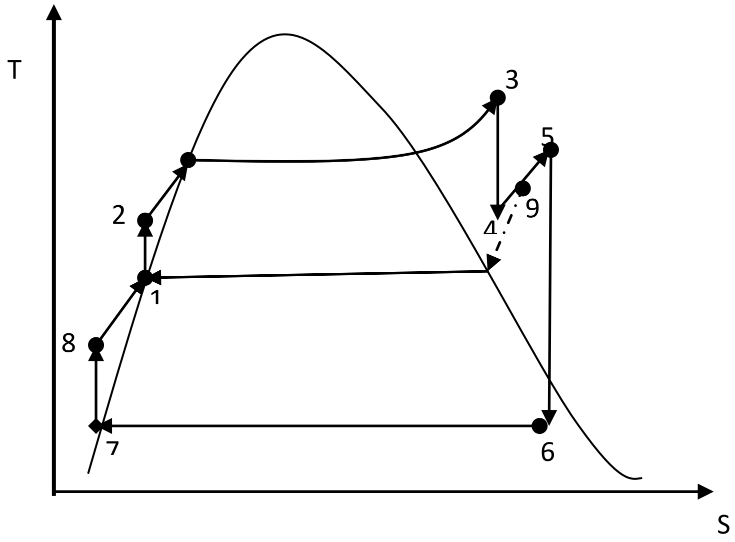

Fig (3.9): T-S diagram for reheat-regenerative cycle (2)

Mathematics for calculating the efficiency of reheat-regenerative cycle (2)

- Using Willians line equation to calculate the W_1 and W_2.
- b_0, b_1, b_2, b_3 are regression parameters values for the steam turbine model from table(3.1).
- The steam properties are obtained from steam tables.
- Calculate the network for the cycle.
- Then calculate the efficiency (η).

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3), (3.4), (3.5), (3.6), (3.7). And the net work could be calculated using equation (3.10). Also isentropic enthalpy deference (ΔH_{is}) for the second turbine could be calculated by assuming that extracted steam which entering the heat exchanger has 30% steam content and 70% steam content entering the second turbine. For example if 30% of supper heated steam has extracted for the preheating purpose as in the following fig (3.11). And finally the efficiency could be obtained using equation (3.9).

ΔH_{is}=-34.4 kJ/kg

A=0.07 kw

B=1.27

n=-29.8 kw/kg

W_{int}=-56.3 kw

W_2=-216.6 kw

W_1=3388 kw

W_{net}=-2828.6 kw

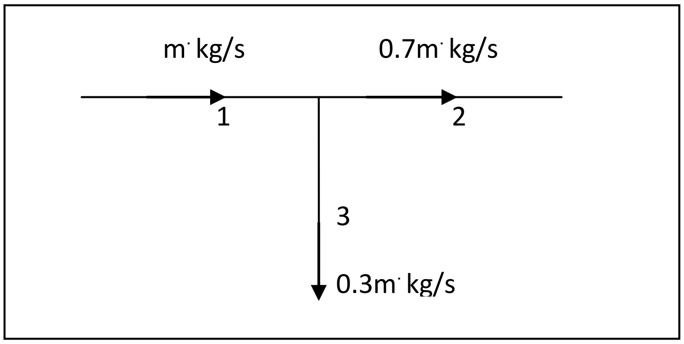

Fig (3.10): material balance for extracted steam

In this case the energy balance could be calculated using equation (3.13) below:

$$H_1 = 0.7H_2 + 0.3H_3 \tag{3.13}$$

3.9 The third suggested reheat-regenerative cycle (3)

Combined by extract a stream from the supper heated steam interring the first turbine

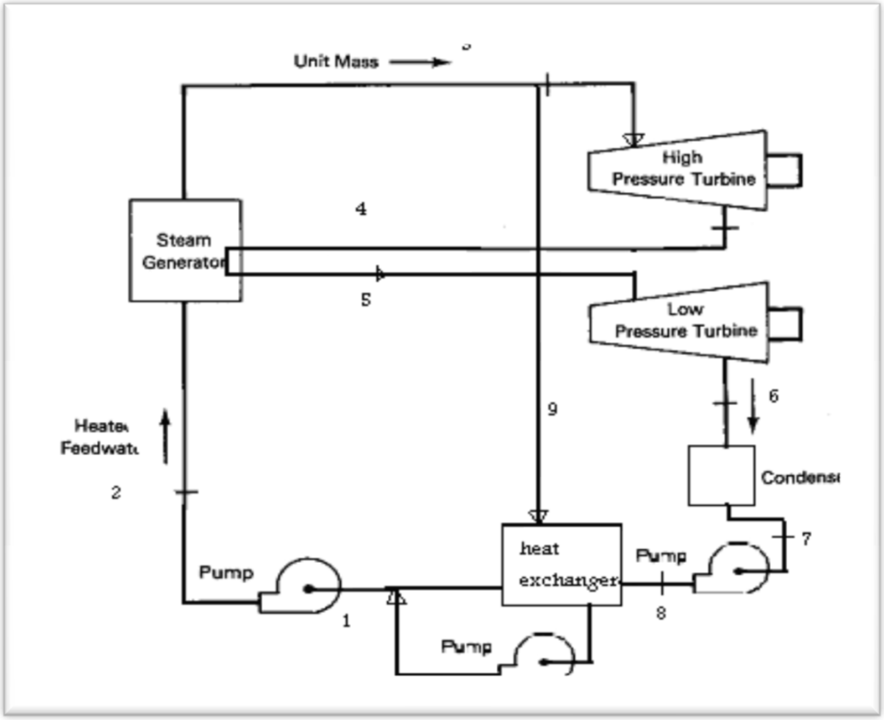

Fig (3.11): Reheat-regenerative cycle (3)

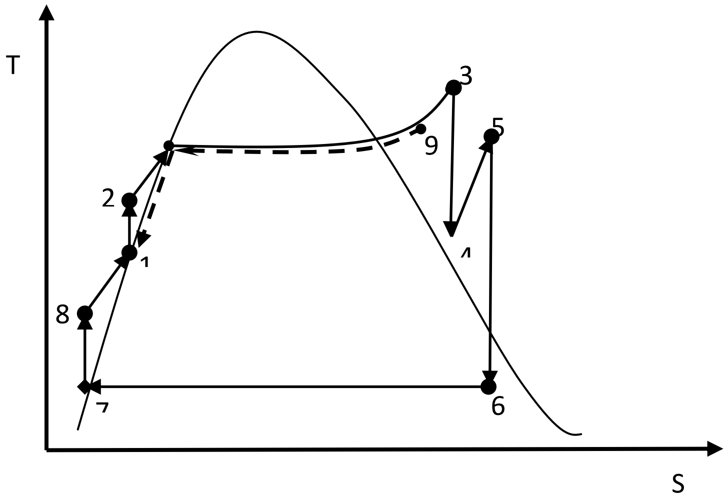

Fig (3.12): T-s diagram for reheat-regenerative cycle (3)

Mathematics for calculating the efficiency of reheat-regenerative cycle (3)

- Using Willians line equation to calculate the W_1 and $W_{2.}$
- $b_{0,}b_{1,}b_{2,}b_3$ are regression parameters values for the steam turbine model from table(3.1).
- The steam properties are obtained from steam tables.
- Calculate the network for the cycle.
- Then calculate the efficiency (η).

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3), (3.4), (3.5), (3.6), (3.7). And the net work could be calculated using equation (3.10). Also isentropic enthalpy deference (ΔH_{is}) for the first turbine could be calculated by the same assuming of material balance that shown in figure above and the energy balance obtained using equation (3.13). And finally the efficiency could be obtained using equation (3.9).

ΔH_{is}=-508 kJ/kg

n=-426.6 kw/kg

W_{int}=-806.6 kw

W_1=-3101 kw

W_2=5277.9 kw

W_{net}=2378.9 kw

4. Results and Discussion

In this section the results of the efficiency and the relationship between the floe rate and efficiency for reheat cycle and regenerative cycle and reheat with regenerative cycles (1), (2) and (3) are presented.

4.1 Standard Steam Cycle

It must be mentioned that the steam properties required to calculate the steam cycle efficiency are obtained from the steam table.Using Wiillian's line equation from (3.1) to (3.9) presented in chapter (3), the cycle efficiency I found to be:

η=34.6%.

It is also found that the cycle efficiency has altered negatively while increasing the steam flow rate as shown in table (4.1) below:

Table (4.1): The efficiency of standard steam cycle at different steam flow rats

Flow rate	Efficiency
7 kg/s	77.7%
7.5 kg/s	67.7%
8 kg/s	57.7%
8.5 kg/s	47%
9 kg/s	37,8%
9.16 kg/s	34.6%

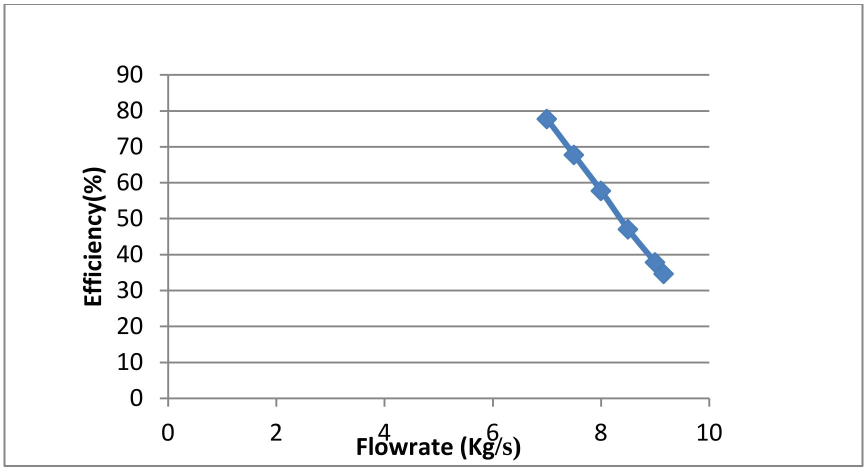

Fig (4.1): Efficiency profile for different steam flow in standard cycle

The highest value of efficiency is at 7 kg/s. the profile of standard steam cycle efficiency for variable steam flow could be presented as in fig (4.1)

4.2 Reheat steam cycle

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3),(3.4),(3.5),(3.6),(3.7) presented in chapter three. And the net work could be calculated using equation (3.10). And finally the efficiency could be obtained using equation (3.9).The efficiency for the reheat steam cycle is found to be: η=79%.

Compared to the standard steam cycle, Garri power station could simply increase the cycle efficiency from 43% to 79% by introducing the reheating processes. In contrast to the standard steam cycle, the profile of the reheat cycle has positively affected (increased) when increasing the steam flow. Table (4.2) and fig (4.2) illustrate the profile of such efficiency while increasing the steam flow. The highest value of efficiency is at 9.5 kg/s

Table (4.2): The efficiency of reheat steam cycle at different steam flow rats

Flow rate	Efficiency
7.5 kg/s	20.8%
8 kg/s	38%
8.5 kg/s	56%
9 kg/s	74%
9.16 kg/s	79%
9.5 kg/s	91%

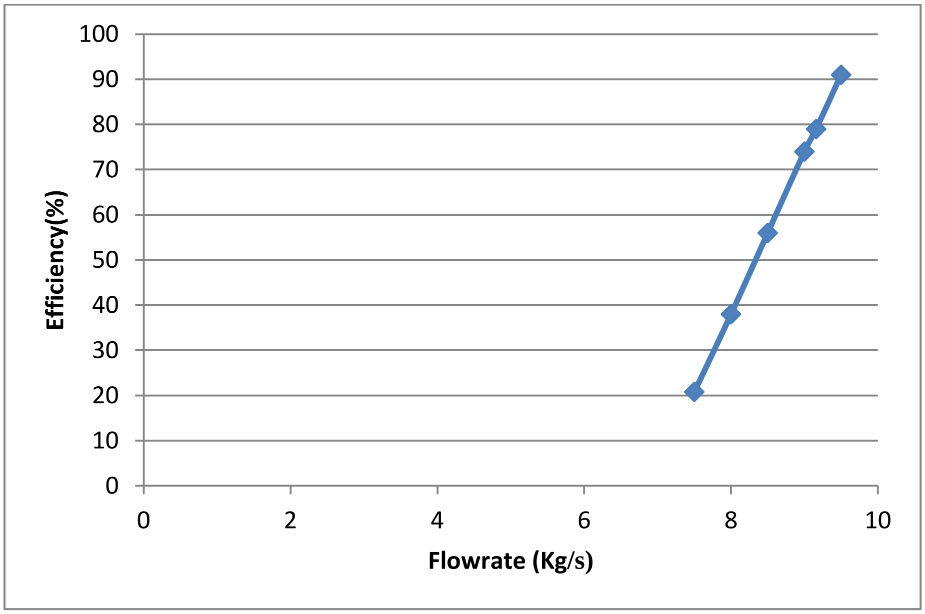

Fig (4.2): Efficiency profiles for different steam flow in reheat cycle

4.3 Regenerative Steam Cycle

W_T could be obtained using equation (3.1), (3.2),(3.3),(3.4),(3.5),(3.6),(3.7)presented in chapter three. And the net work could be obtained using equation (3.8).Also isentropic enthalpy deference (ΔH_{is}) could be calculated using equation (3.11). And finally the efficiency could be obtained using equation (3.9). The efficiency for the reheat steam cycle is found to be: η=83%.

Compared to the standard ad reheat steam cycles, Garri power station could increase the cycle efficiency from 43% to 83% by introducing the regenerative cycle. The profile of the reheat cycle has positively affected (increased) when increasing the steam flow. Table (4.3) and fig

(4.3) illustrate the profile of such efficiency while increasing the steam flow. The highest value of efficiency is at 9.5 kg/s.

Table (4.3): The efficiency of regenerative steam cycle at different steam flow rats

Flow rate	Efficiency
7.5 kg/s	23%
8 kg/s	41%
8.5 kg/s	59%
9 kg/s	77.3%
9.16 kg/s	83%
9.5 kg/s	95%

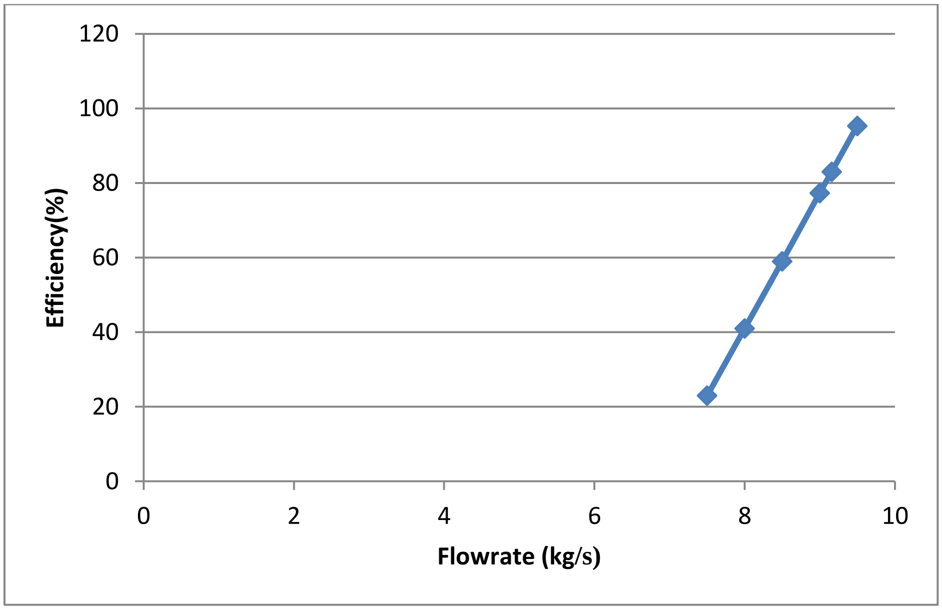

Fig (4.3): Efficiency profiles for different steam flow in regenerative cycle

4.4 Reheat- regenerative steam cycle (1)

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3),(3.4),(3.5),(3.6),(3.7) presented in chapter three. And the net work could be calculated using equation (3.10). Also isentropic enthalpy deference (ΔH_{is}) could be calculated using equation (3.12).And finally the efficiency could be obtained using equation (3.9). The efficiency for reheat-regenerative (1) is found to be: η=90%.

It must be mentioned that the proposed combination of reheat and regenerative cycles in one cycle have tremendously increased the steam cycle efficiency. The profile of the reheat cycle has positively affected (increased) when increasing the steam flow. Table (4.4) and fig (4.4) illustrate the profile of such efficiency while increasing the steam flow. The highest value of efficiency is at 9.16 kg/s.

Table (4.4): The efficiency of reheat-regenerative(1) steam cycle at different steam flow rates

Flow rate	**Efficiency**
7.5 kg/s	**6.8%**
8 kg/s	**22.6%**
8.5 kg/s	**52%**
9 kg/s	**85%**
9.16 kg/s	**90%**

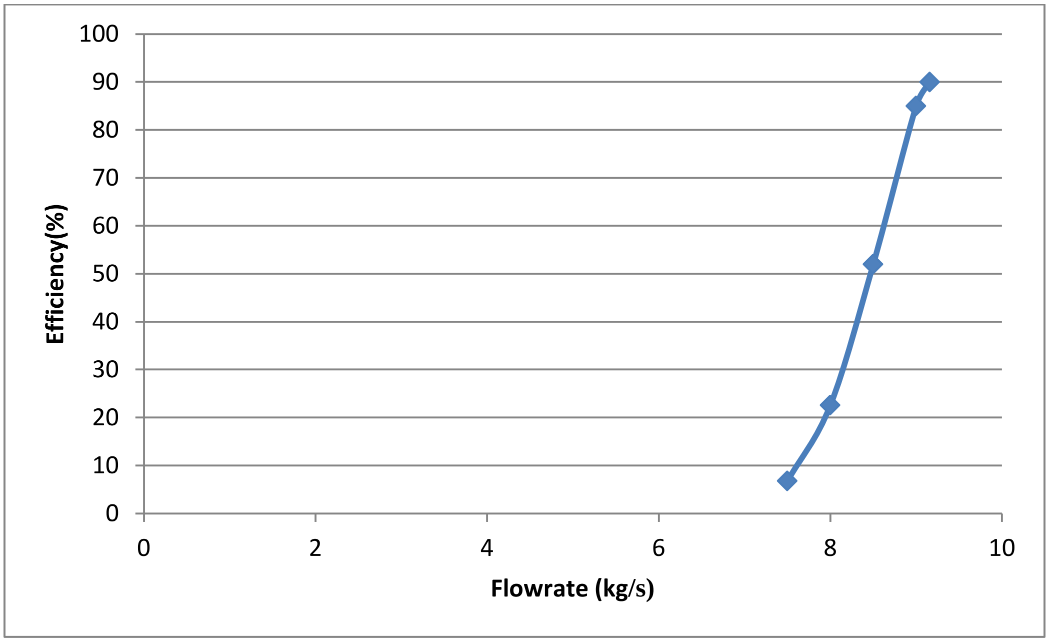

Fig (4.4): Efficiency profiles for different steam flow in reheat-regenerative (1) cycle

4.5 Reheat – regeneration steam cycle (2)

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3), (3.4), (3.5), (3.6), (3.7) presented in chapter three. And the net work could be calculated using equation (3.10).Also isentropic enthalpy deference (ΔH_{is}) for the second turbine could be calculated by the assuming of material balance that shown in fig (3.13).And finally the efficiency could be obtained using equation (3.9).The efficiency for reheat-regenerative (2) is found to be: η=84%.

It is also found that the cycle efficiency has altered negatively while increasing the steam flow rate as shown in table (4.5) and fig (4.5) illustrated the profile of such efficiency while increasing the steam flow. The highest value of efficiency is at 8 kg/s.

Table (4.5): The efficiency of reheat-regenerative (2) steam cycle at different steam flow rates

Flow rate	**Efficiency**
8 kg/s	**99.5%**
8.5 kg/s	**93.2%**
9 kg/s	**86.7%**
9.16 kg/s	**84%**
10 kg/s	**73.6%**

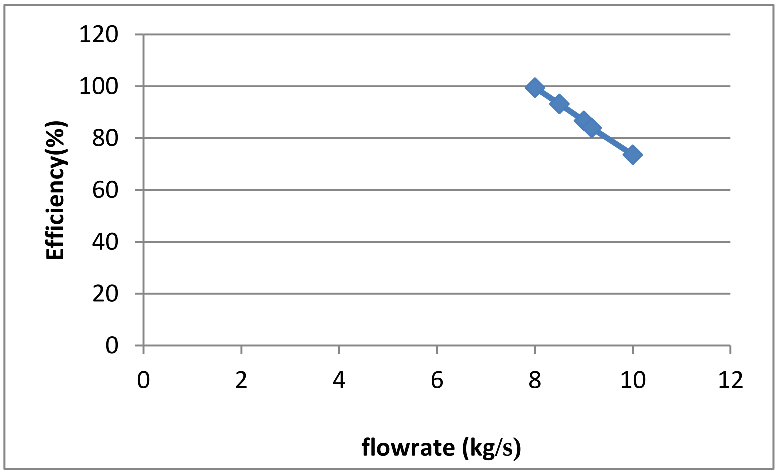

Fig (4.5): Efficiency profiles for different steam flow in reheat-regenerative (2) cycle

4.6 Reheat- regenerative steam cycle (3)

W_1 and W_2 could be obtained using equation (3.1), (3.2), (3.3), (3.4), (3.5), (3.6), (3.7) presented in chapter three. And the net work could be calculated using equation (3.10). Also isentropic enthalpy deference (ΔH_{is}) for the first turbine could be calculated by the same assuming in reheat-regenerative (2) of material balance that shown in fig (3.13), and the energy balance obtained using equation (3.13). And finally the efficiency could be obtained using equation (3.9).The efficiency for reheat-regenerative (3) is found to be: η=71%.

The profile of the reheat cycle has positively affected (increased) when increasing the steam flow. Table (4.6) and fig (4.6) illustrate the profile of such efficiency while increasing the steam flow. The highest value of efficiency is at 10 kg/s.

Table (4.6): The efficiency of reheat-regenerative (3) steam cycle at different steam flow rates

Flow rate	Efficiency
7.5 kg/s	13.5%
8 kg/s	31.1%
8.5 kg/s	48.4%
9 kg/s	65.6%
9.5 kg/s	82.9%
10 kg/s	100%

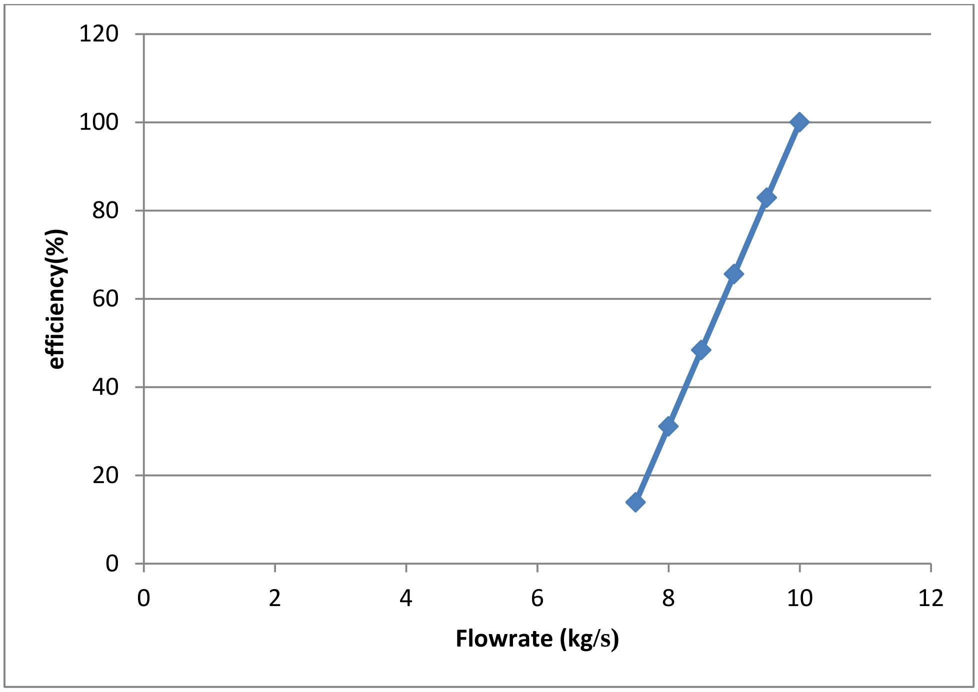

Fig (4.6): Efficiency profiles for different steam flow in reheat-regenerative (3) cycle

4.7 Comparison between the proposed steam cycles

For the purpose of decision making, it is important to have all the existing and suggested scenarios in one unite picture. Fig (4.7) illustrates the thermal efficiency for all the steam cycles.

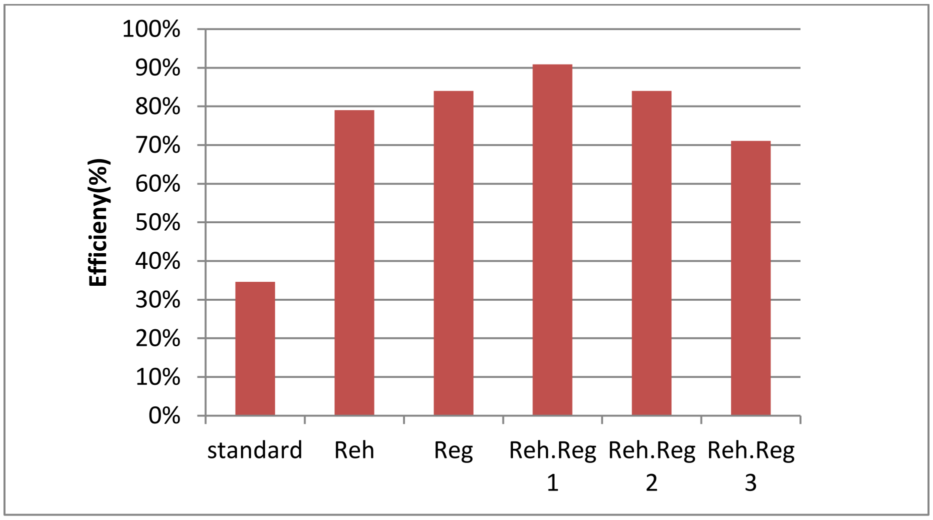

Fig (4.7): Efficiency for all the cycles

From the figure, it is very clear that the first suggestion of reheat-regenerative cycle without steam extraction is the most useful (η=90%). The next one could be the cycle in which the steam extraction was made after the reheating process for the purpose of regenerative (η=83%).

5. Conclusion

The research brings a great result that helps us in producing more energy which is very important in every process and technology, and also reducing the energy consumption by increasing the efficiency of the steam power cycle.

The produced shaft work from the turbine is calculated using Willian's Line equation consequently, the efficiency has been calculated for each pattern of combined cycles and compared to choose the best one. From the three combined cycles, it is found that the highest efficiency could be obtained when combining the normal reheat with the normal regenerative cycle. It is found to be 90% compared to 80% and85% of reheat and regenerative respectively. Moreover, the effect of changing the steam flow rate has positively affected the cycle efficiency.

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