Chapter One

Steam Power Cycles

Introduction

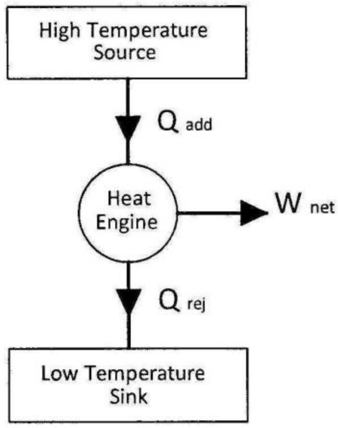
Thermodynamic cycle is a succession of processes undergone by a working fluid to perform a task in condition that the working fluid returns back to its initial state.

Concept of the heat engine

Heat engine is the living presentation of the Kelvin-Blank statement of the second law of thermodynamics.

The cycles considered here have two characteristics in common:

1. The working fluid is a condensable vapour
2. The cycle consists of a succession of steady-flow processes



Criteria of performance

Thermal efficiency

$$\eta_{th} = \frac{W_{net}}{Q_{add}} = 1 - \frac{Q_{rej}}{Q_{add}}$$

Work ratio

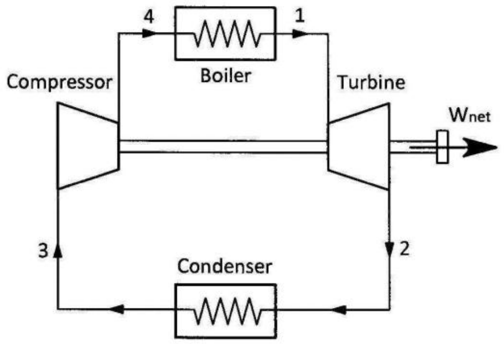
$$WR = \frac{W_{net}}{W_{gross}}$$

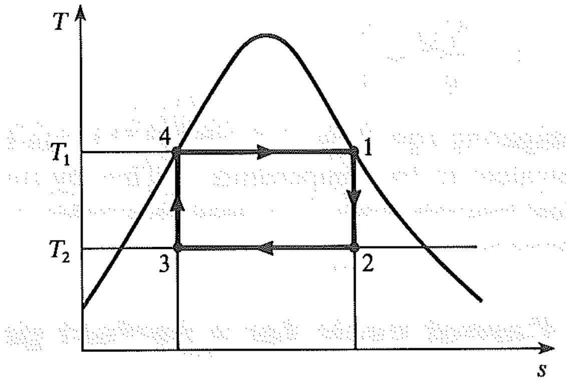
Specific consumption

$$s.c. = \frac{3600}{w_{net}}$$

Carnot cycle

Carnot cycle can be adopted as the fundamental reference cycle for power plants since it considered as the most efficient cycle working between two specified temperatures.



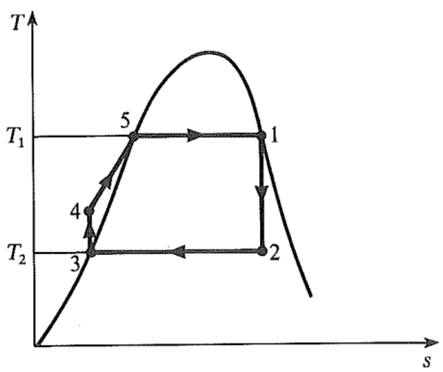


$$\eta_C = 1 - \frac{T_2\left(s_1 - s_4\right)}{T_1\left(s_1 - s_4\right)} = 1 - \frac{T_2}{T_1}$$

$$\boxed{\eta_C = 1 - \frac{T_{min}}{T_{max}}}$$

Rankine cycle

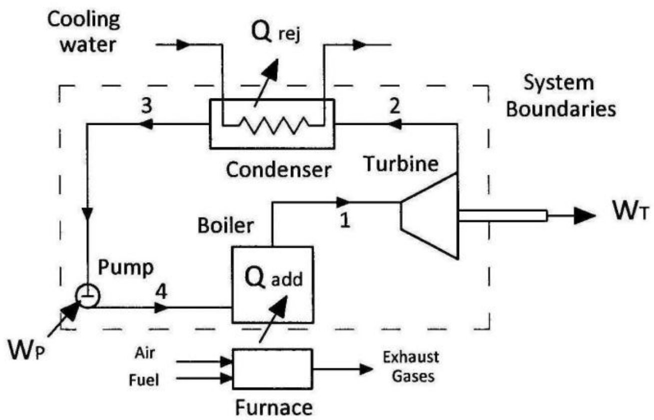
There are several practical difficulties associated with the application of Carnot cycle to any vapour power cycle in spite of its higher efficiency. The new cycle arrangement is known as "***Rankine Cycle***".



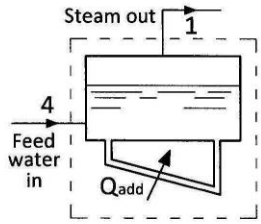
Energy analysis in Rankine cycle

The steady-flow energy equation will have the following form in analysis and each process is to be considered in turn;

$$h_{in} + q = h_{out} + w$$



<u>Boiler</u>

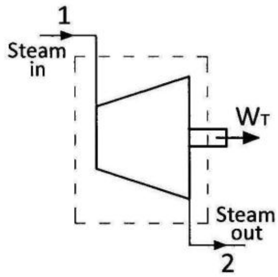


$$h_4 + q_{add} = h_1$$

or;

$$\boxed{q_{add} = h_1 - h_4}$$

<u>Turbine</u>

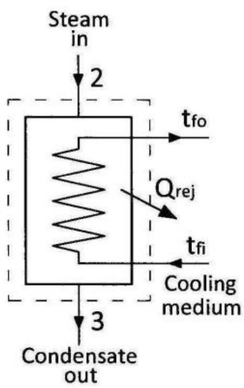


$$h_1 = h_2 + w_T$$

or;

$$\boxed{w_T = h_1 - h_2}$$

<u>Condenser</u>

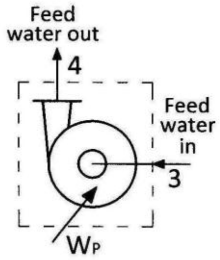


$$h_2 + q_{rej} = h_3$$

or;

$$\boxed{q_{rej} = h_3 - h_2}$$

Pump



$h_3 = h_4 + w_P$

or;

$$w_P = h_3 - h_4$$

Net work done in the cycle;

$w_{net} = w_T + w_P$

then the cycle thermal efficiency will be;

$$\eta_R = \frac{w_{net}}{q_{add}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

If the feed pump term, ***$h_4 - h_3$***, is neglected, then it becomes;

$$\eta_R = \frac{(h_1 - h_2)}{(h_1 - h_3)}$$

Deviation of the actual steam cycle

Isentropic efficiency

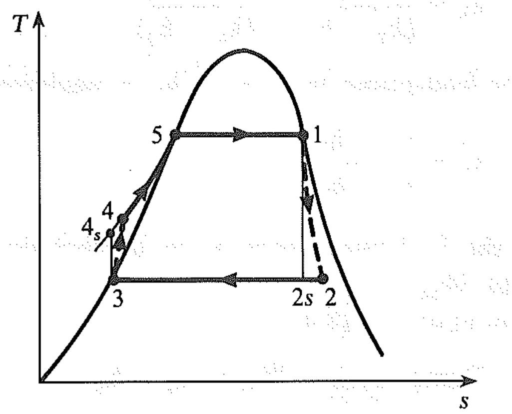
For turbine it is defined as;

$$\eta_T = \frac{W_{act}}{W_{isent}} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

but for the pump it is to be defined differently as;

$$\eta_P = \frac{W_{isent}}{W_{act}} = \frac{h_{4s} - h_3}{h_4 - h_3}$$

For both definitions, the value is less than unity.



Indicated thermal efficiency

$$\eta_{I,th} = \frac{W_{act}}{Q_{add}} = \frac{h_1 - h_2}{h_1 - h_4}$$

Efficiency ratio

$$\eta_{rel} = \frac{\eta_{act}}{\eta_R} = \frac{\eta_{I,th}}{\eta_R}$$

Brake thermal efficiency

$$\eta_{B,th} = \frac{W_{bu}}{\dot{m}\left(h_1 - h_4\right)}$$

Mechanical efficiency

$$\eta_m = \frac{W_{bu}}{\dot{m}\left(h_1 - h_2\right)} = \frac{\eta_{B,th}}{\eta_{I,th}}$$

Generator efficiency

$$\eta_{gen} = \frac{W_E}{W_{bu}}$$

Boiler efficiency

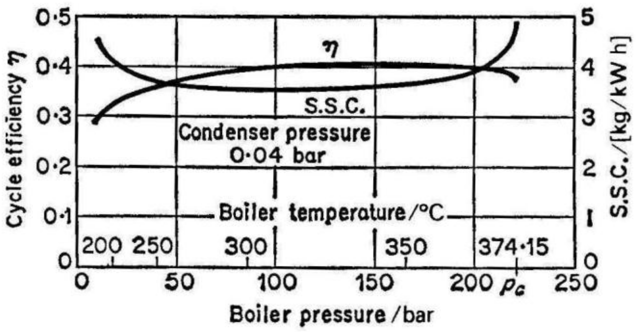
$$\eta_B = \frac{\dot{m}\left(h_1 - h_4\right)}{\dot{m}_F \; HV_F}$$

Overall cycle efficiency

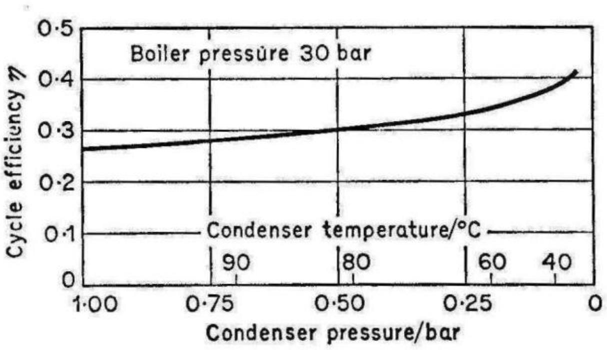
$$\eta_{ov} = \frac{W_E}{\dot{m}_F \; HV_F}$$

Improving cycle efficiency

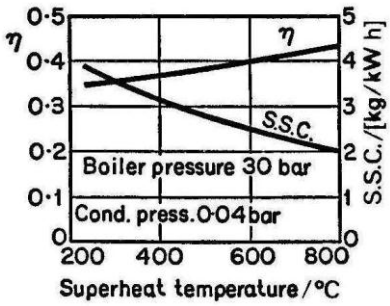
influence of boiler pressure



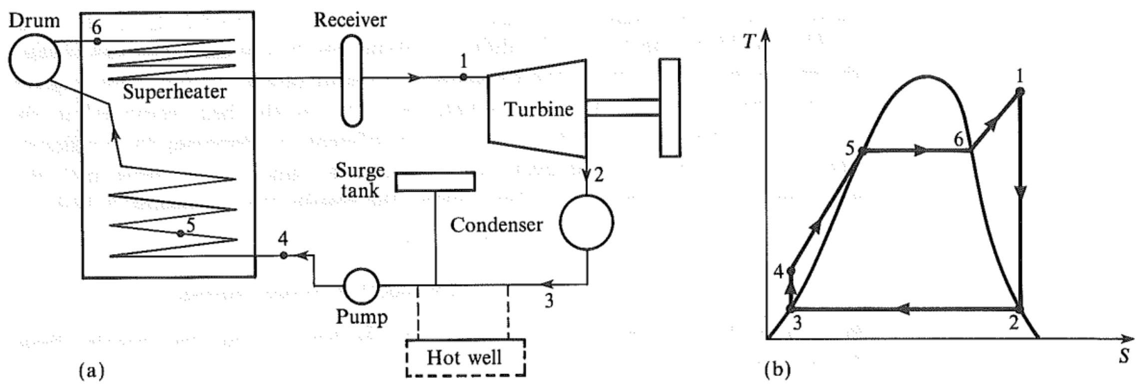
<u>influence of condenser pressure</u>



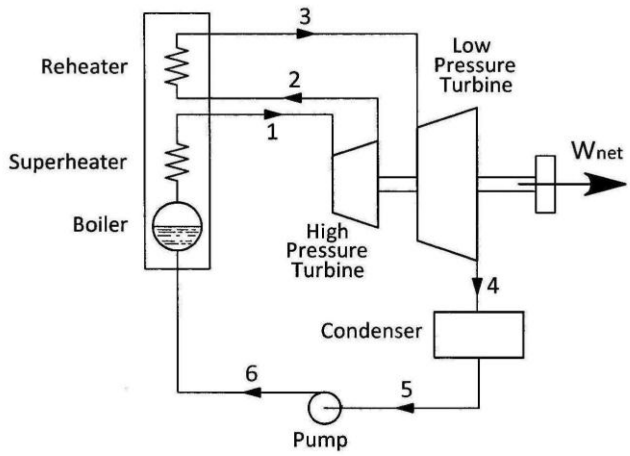
<u>influence of turbine inlet temperature</u>

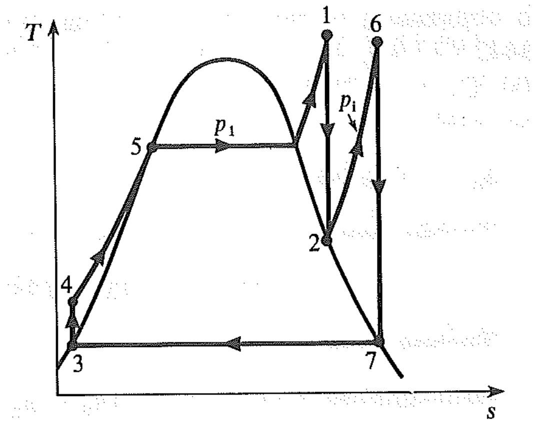


Rankine cycle with superheat



Rankine cycle with reheat



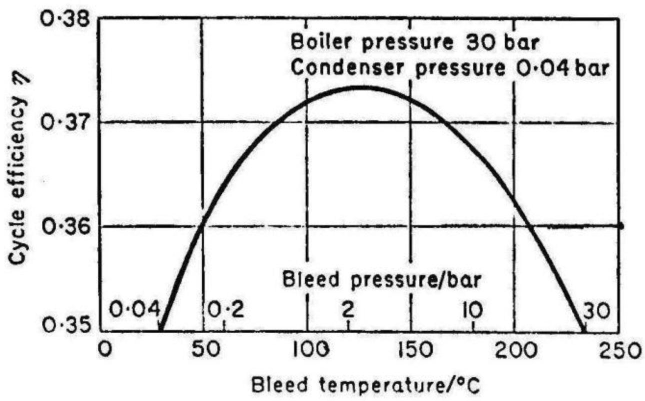


Then, the cycle thermal efficiency will be given by;

$$\eta_{th} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_5) + (h_3 - h_2)}$$

Regenerative steam cycle

If the part of external heating at varying temperature being added internally from another part of the cycle then this kind of cycles is known as "***Regenerative cycle***".



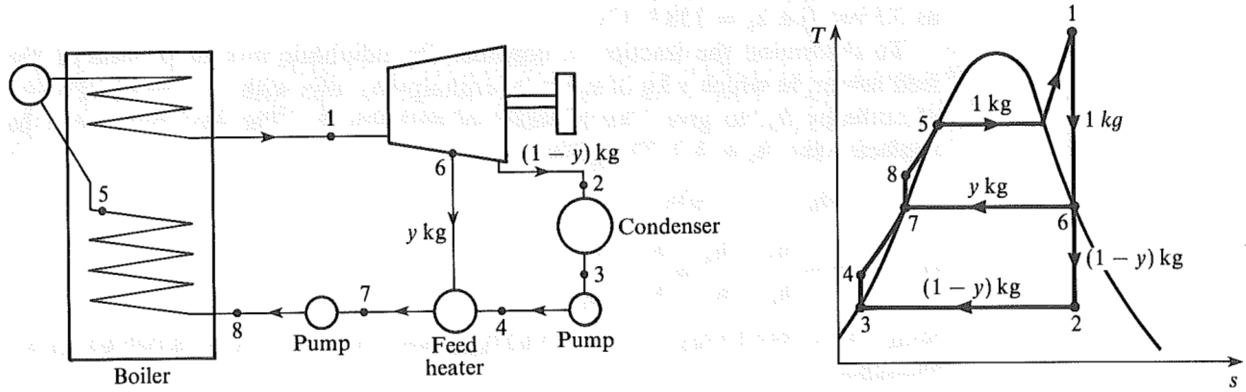
$$\Delta T_{opt} = \frac{t_S(p_B) - t_S(p_C)}{k+1}$$

$$p_{Bleed} \cong p_{sat}\left(t_{j+1}\right)$$

Types of feed water heaters

The feed water heater is basically a heat exchanger where heat is exchanged between hot bled steam and the cold feed water.

Open type feed heater



(a) (b)

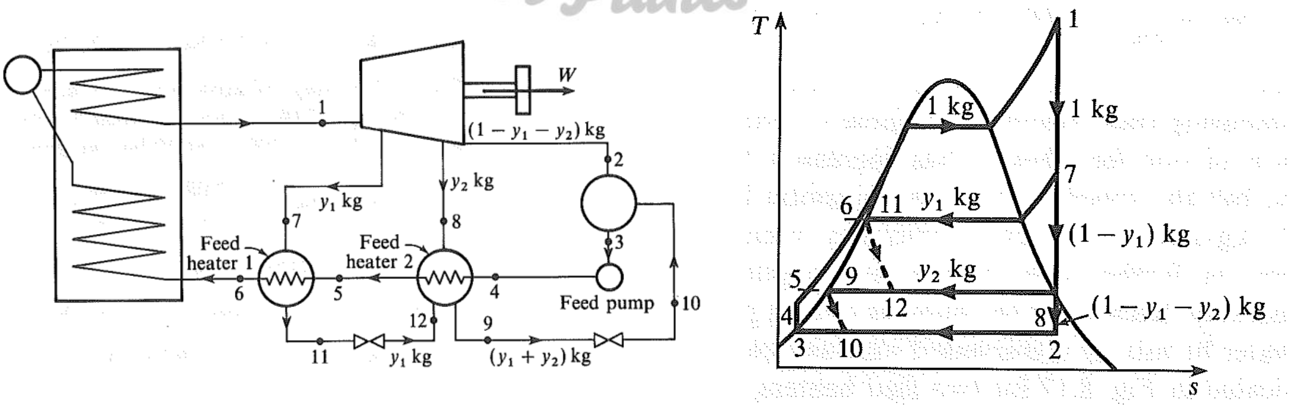
the amount of extracted steam can be determined by energy balance around the heater;

$$\sum E_{IN} = \sum E_{OUT}$$

$$y\,h_6 + (1 - y)h_4 = 1 \times h_7$$

$$y = \frac{h_7 - h_4}{h_6 - h_4}$$

Closed type feed heater



$$\sum E_{IN} = \sum E_{OUT}$$

$$y_1\,h_7 + h_5 = y_1\,h_{11} + h_6$$

$$y_1 = \frac{h_6 - h_5}{h_7 - h_{11}}$$

Chapter Two

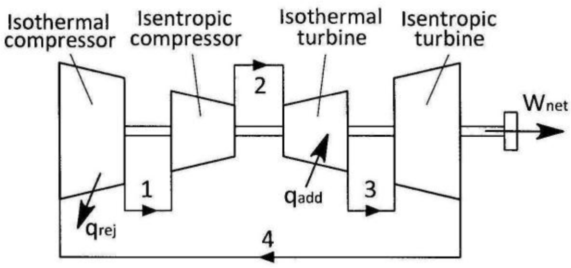
Gas Power Cycles

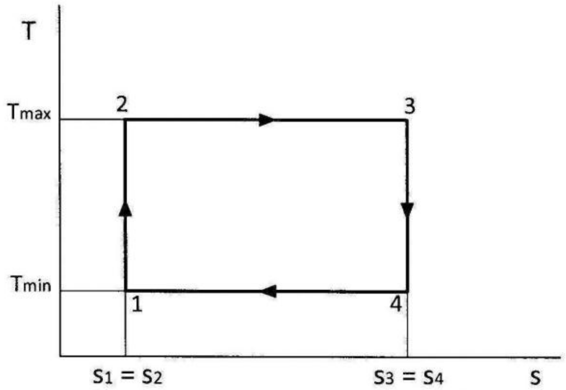
Introduction

Cycles with the working fluid is a single-phase substance, i.e. a gas normally air or combustion products of fuel and air are refer to as " ***Gas power cycles*** ".

Carnot cycle for a gas

Carnot cycle can be executed in a closed system or a steady-flow system. Hence, the processes that compose the cycle for a gas are as follows;



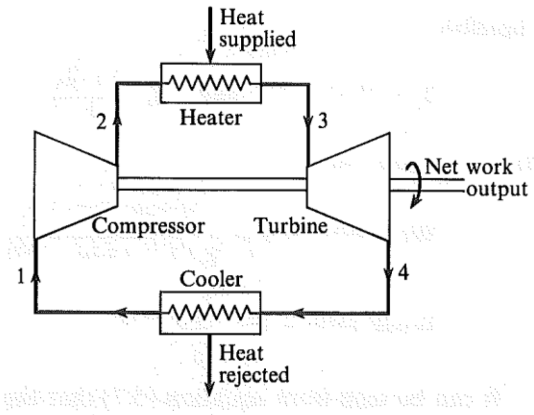


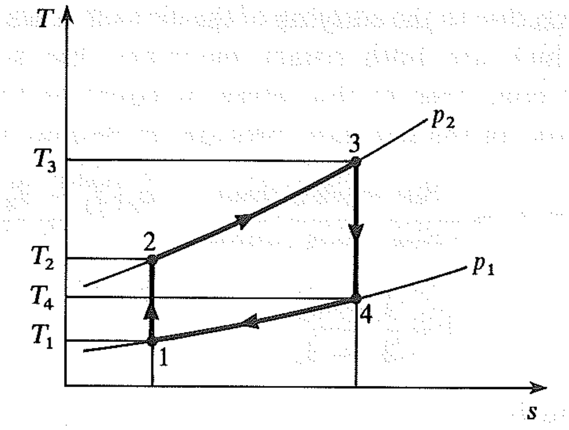
The cycle efficiency is defined generally as;

$$\eta_{th} = 1 - \frac{q_{rej}}{q_{add}}$$

$$\boxed{\eta_C = 1 - \frac{T_{min}}{T_{max}}}$$

Brayton cycle



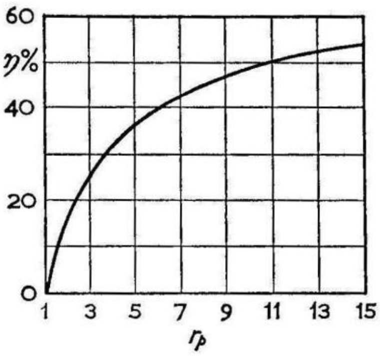


The steady-flow energy equation will have the following form in analysis and each process is to be considered in turn;

$$h_{in} + q = h_{out} + w$$

$$w_C = h_2 - h_1 = C_p\left(T_2 - T_1\right)$$

$$w_T = h_3 - h_4 = C_p\left(T_3 - T_4\right)$$



on the other hand:

$$q_{sup} = h_3 - h_2 = C_p\left(T_3 - T_2\right)$$

$$q_{rej} = h_4 - h_1 = C_p\left(T_4 - T_1\right)$$

from which the Brayton cycle efficiency can be expressed as;

$$\eta\left(Brayton\right) = 1 - \left(\frac{1}{r_p^{\gamma-1/\gamma}}\right)$$

There are one more criteria to judge the gas turbine engine performance dealing with cycle irreversibility, which is the work ratio and it is given by:

$$WR = 1 - \left(\frac{T_1}{T_3}\right) r_p^{\gamma-1/\gamma}$$

Optimum pressure ratio

There will be some intermediate pressure ratio at which the net work is at its maximum. This ratio can be taken as:

$$r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$$

Thus, for maximum work output, the optimum pressure ratio is given by;

$$r_p(opt) = \sqrt{r_p(max)}$$

Deviation of actual gas turbine cycle

for compressor;

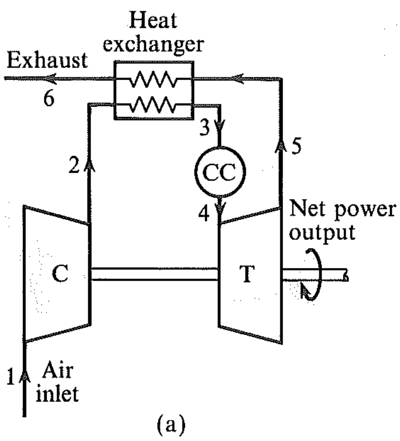
$$\eta_C = \frac{w_{isent}}{w_{act}} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

and for turbine;

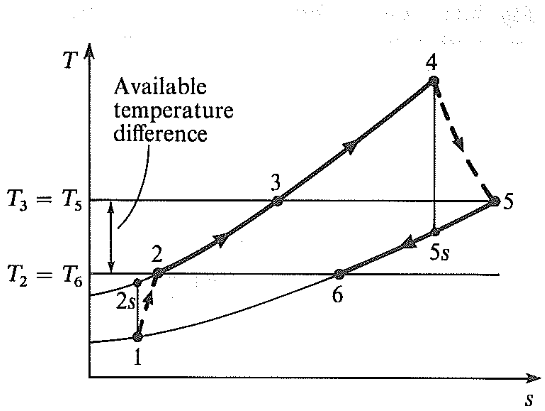
$$\eta_T = \frac{w_{act}}{w_{isent}} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

Modification to the Brayton cycle

Brayton cycle with regeneration



(a)



(b)

The energy balance over the regenerator can be done as;

$$q_{reg,a} = h_5 - h_2 = C_p\left(T_5 - T_2\right)$$

and the maximum, possible heat exchanged to be;

$$q_{reg,max} = h_4 - h_2 = C_p\left(T_4 - T_2\right)$$

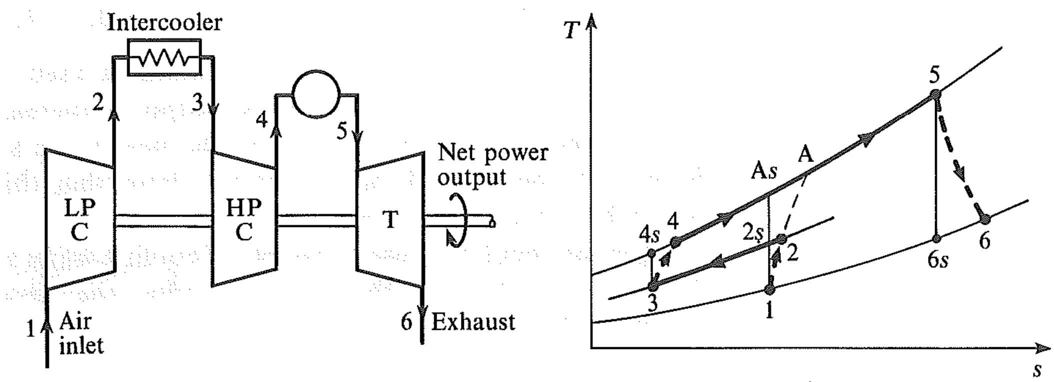
The " ***Effectiveness*** " is a parameter that measure the performance of the regenerator

$$\varepsilon = \frac{q_{reg,a}}{q_{reg,max}} = \frac{h_5 - h_2}{h_4 - h_2} = \frac{T_5 - T_2}{T_4 - T_2}$$

The air-standard cycle efficiency is now can be shown to be;

$$\eta_{reg} = 1 - \left(\frac{T_1}{T_3}\right) r_p^{\frac{\gamma-1}{\gamma}}$$

Brayton cycle with intercooling



(a) (b)

The save in work depends upon the choice of the intermediate pressure $\boldsymbol{p_{im}}$ which can be found as;

$$\frac{p_{im}}{p_1} = \frac{p_2}{p_{im}}$$

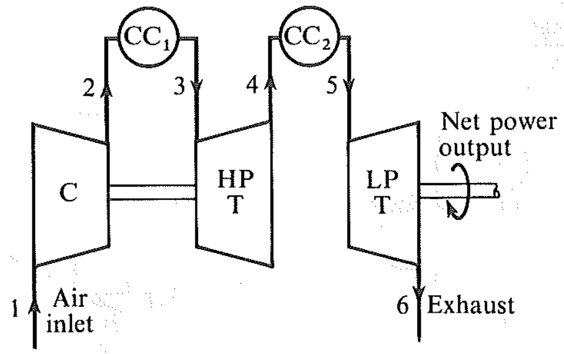
Therefore, *the condition of minimum work is that the pressure ratio for all stages should be the same*. Then, in terms of the overall pressure ratio $\boldsymbol{p_2/p_1}$ where;

$$w_C(min) = 2 \times C_p\, T_1\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{2\gamma}} - 1\right]$$

Brayton cycle with reheating

The optimum pressure ratio makes the work output a maximum can be approved such that;

$$\frac{p_{im}}{p_3} = \frac{p_6}{p_{im}}$$



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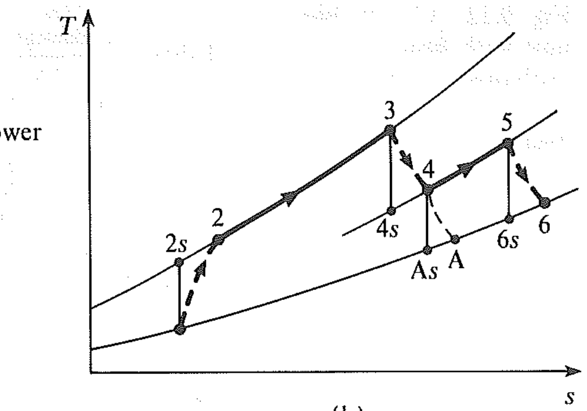

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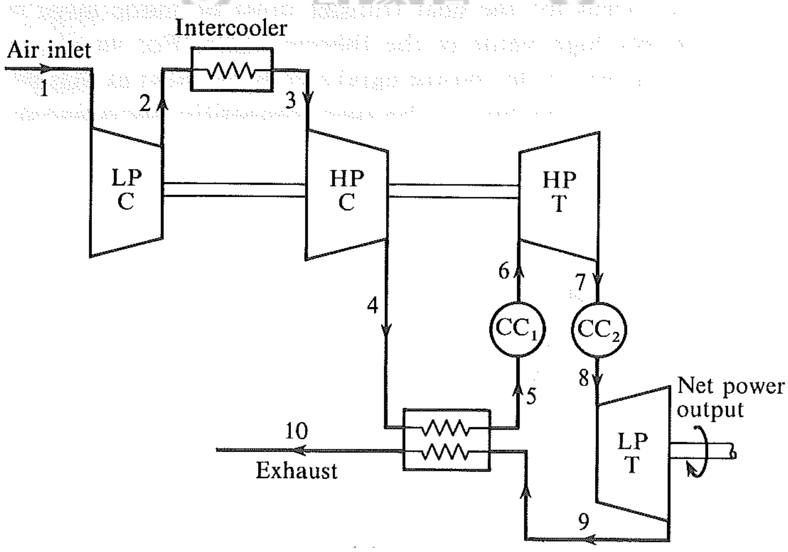


Chapter Three

Diesel Power Plants

Introduction

Diesel engine – driven generating plants are available in certain established sizes

Engine classification

1 According to number of cylinders

2 According to strokes per cycle

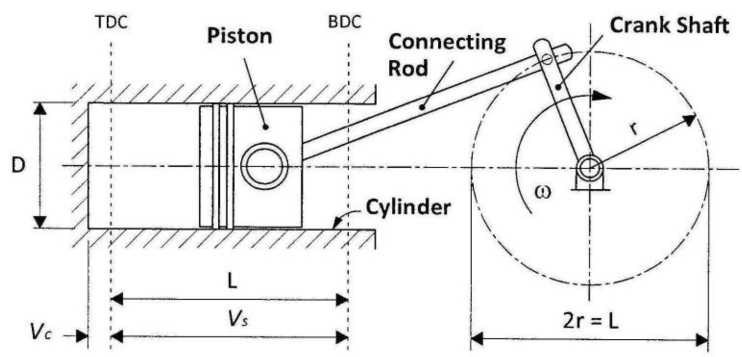
3 According to fuel type

4 According to pistons layout

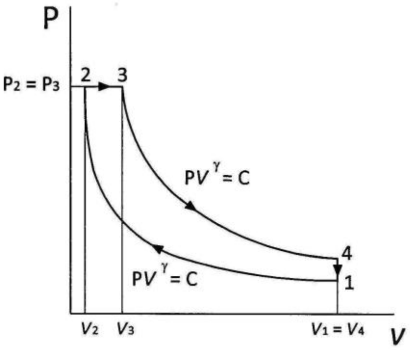
5 According to cooling system

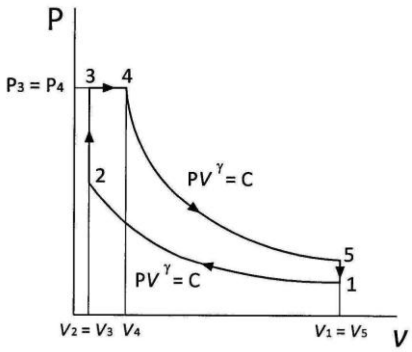
6 According to engine speed

7 According to charge induction



Thermodynamic cycles for diesel engines





The thermal efficiency of the Diesel cycle is given by;

$$\eta_{Diesel} = 1 - \left\{ \left(\frac{1}{r_V^{\gamma-1}} \right) \left[\frac{r_C^{\gamma} - 1}{\gamma \left(r_C - 1 \right)} \right] \right\}$$

while for the dual-pressure cycle, the thermal efficiency is given by;

$$\eta_{dual} = 1 - \left\{ \left(\frac{1}{r_V^{\gamma-1}} \right) \left[\frac{r_p \, r_C^{\gamma} - 1}{\left(r_p - 1 \right) + \gamma \, r_p \left(r_C - 1 \right)} \right] \right\}$$

Theoretical fuel-air diesel cycle

The working fluid involved is actually a mixture of air and fuel rather than air only, and the cycle is known as "***Fuel-Air cycle***".

limited pressure fuel-air cycle

The maximum cycle pressure is limited to a value that commonly reached in real diesel engine by proper injection timing and characteristics. This arrangement is best to be expressed as "***dual-combustion fuel-air cycle***".

Approximate procedure of cycle calculation

For the dual combustion cycle, the amount of heat added during each part of the heating process is proportional to the amount of fuel injected and burn such that;

$$\frac{Q_i}{Q_{Tot}} \cong \frac{m_{Fi}}{m_{F-Tot}}$$

It is a common practice to assume that the specific heat varies with temperature only, and give that variation a linear function such that;

$$C_V = a + \beta T$$

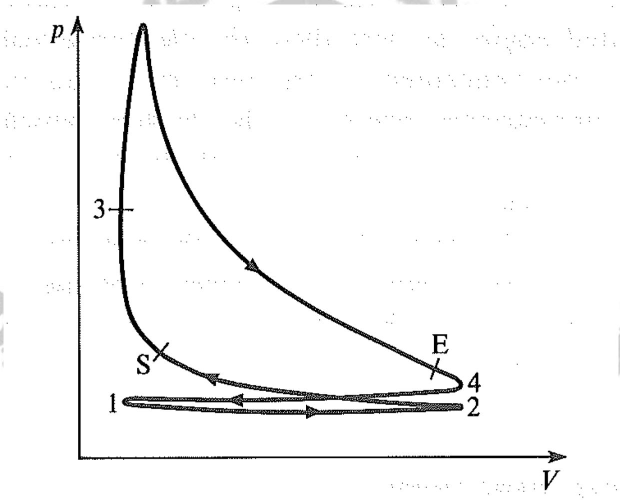
where α and β are constant. For a mixture of gases composing the cylinder contents, the average specific heat can be determined as;

$$\overline{C}_V^* = \sum x_i C_{Vi}^* = \sum x_i \left(a_i + \beta_i T \right)$$

This can be expressed in average form as;

$$\overline{C}_V^* = \overline{a} + \overline{\beta} T$$

Four-stroke diesel cycle



Evaluation of performance for diesel plant

Engine capacity

$$V_E = A \times L \times n_C$$

Indicated power

$$I.P. = \frac{p_{mi} A L N n_C}{2}$$

Brake power

$$B.P. = 2\pi\tau N$$

Mechanical efficiency

$$\eta_m = \frac{B.P.}{I.P.}$$

Mean effective pressure

$$p_m = \frac{W}{V_S}$$ kN/m^2

Brake thermal efficiency

$$\eta_{bth} = \frac{B.P.}{\dot{m}_F\, HV_F}$$

Brake specific fuel consumption

$$bsfc = \frac{\dot{m}_F}{B.P.}$$

Volumetric efficiency

$$\eta_V = \frac{V}{V_S}$$

Chapter Four

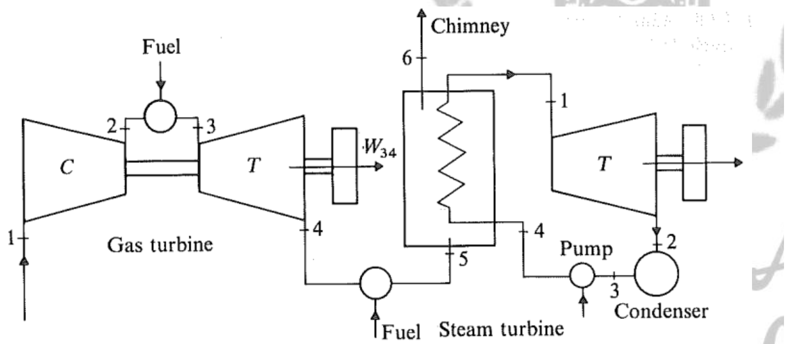
Total Energy Exploitation

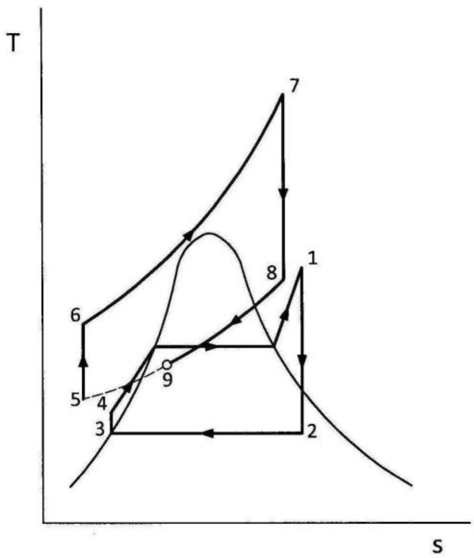
Introduction

The complete use of the energy available to a system is called the "***Total energy exploitation***" approach. In that manner, the energy wasted to the ambient is to be a minimum. This continued quest for higher thermal efficiency led to innovative modifications to conventional power plants.

Combined cycle

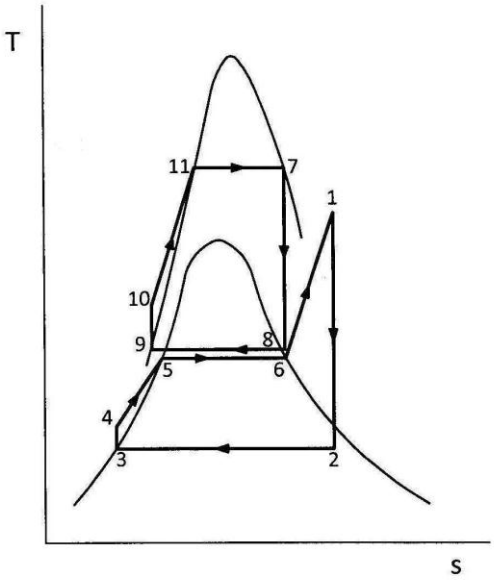
A most popular modification involves a gas turbine cycle topping a steam power cycle, which is called "***The combined cycle***".





Binary vapour cycle

In such a cycle, the condenser of the topping cycle serves as the boiler of the bottoming cycle. Mercury is preferable as most suitable for the topping cycle.



Cogeneration cycle

A cogeneration system is the simultaneous generation of multiple forms of useful energy in a single integrated system known as " ***Combined heat and power generation, CHP*** " system.

Steam turbine cogeneration system

Steam turbines are widely used for CHP applications. In reaching the compromise between power and process demands a number of possibilities are available. These layouts are listed hereunder.

Back pressure turbine

Pass-out or Extraction turbine

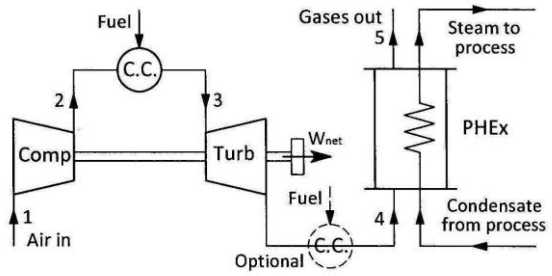
Mixed pressure turbine

Exhaust turbine

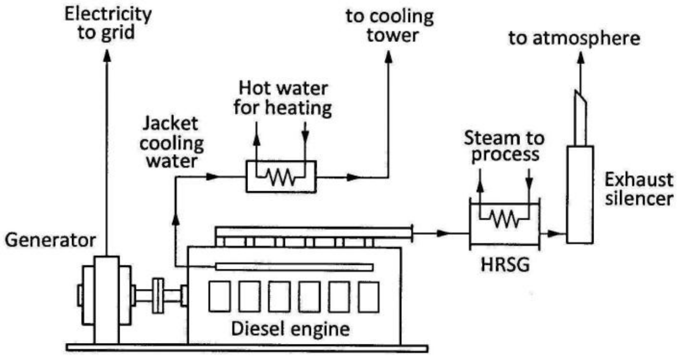
Vacuum turbine

Gas turbine cogeneration system

The energy released at high temperature in the exhaust gases can be recovered for various heating and cooling applications.



Diesel engine cogeneration system



Other classification of cogeneration systems

Topping cycle cogeneration system

In a topping cycle, the fuel burned is firstly utilised in power production, and then thermal energy used for process heating or

Bottoming cycle cogeneration system

In a bottoming cycle, the fuel burned is firstly utilised in thermal energy production, and the heat rejected by the process heat exchanger is used in power generation through a recovery steam generator and a turbine.

Performance evaluation of Cogeneration system

Specific heat rate

$$SHR = \frac{\dot{Q}_S}{\dot{W}} = \frac{\dot{m}_S\left(h_S - h_{fw}\right)}{\dot{W}_{Tot}} \quad \text{kJ/kWh}$$

Specific fuel rate

$$SFR = \frac{\dot{m}_F}{\dot{W}_{Tot}} \quad \text{kg/kWh}$$

Utilization factor

$$\zeta_u = \frac{\dot{W}_{Tot} + \dot{Q}_P}{\dot{Q}_{IN}}$$

Chapter Five

Nuclear Power Cycles

Introduction

Nuclear power plants are alternatives or supplement to power generated by fossil fuels. The nuclear power plant reduces the production of carbon dioxide and other pollutants.

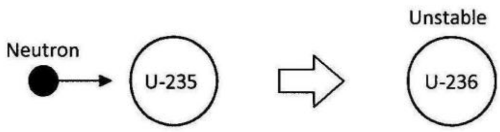
Nuclear reactions

Nuclear fusion

The fusion process occurs in nature in the stars, like our sun. Fusion occurs when light atoms interact to form a heavier atom.

Nuclear fission

Nuclear fission is a process of breaking massive atoms into two large atoms accompanied by mass loss and release of energy. This nuclear fission results from the collision of the atom with a neutron.



Materials of nuclear reactor

- Fissionable materials or fuels.
- Fertile materials.
- Coolant.
- Moderator.
- Structural materials.

Types of nuclear reactor

- Light water reactors.
- Gas cooled reactors.
- Liquid metals cooled reactors.