Faculty of Engineering
Naval Architecture and Marine Engineering Department

MR352 – Marine Power Plants

Third Year

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Course Contents

References

1. Introduction to marine engineering 2nd ed., Taylor, 1996
2. Design of propulsion and electric power generation systems, IMarEST, 2002
3. The jet engine, Rolls-Royce, 1996
4. Steam turbines theory and design, P. Shlyakhin
5. Mechanical Engineers data handbook, James Carvill, 1993
6. Marine auxiliary machinery 7th ed., H D McGeorge, 1995

Marine power plants

Requirements for marine power plants

1. To be approved by classification societies
2. Have as minimum as possible volume and weight
3. Have low fuel consumption
4. Easy maintenance and repair
5. Have to work at heavy duty levels for long periods

Selection of marine power plants

1. Good reliability
2. Good maintainability
3. Weight and volume
4. Type of fuel and fuel consumption
5. Cost
6. Vibration and noise
7. Level of experience for personnel

Types of marine power plants

1. Diesel engine driven
2. Gas turbine driven
3. Steam turbine driven
4. Combined power plants (ex. COGAS)

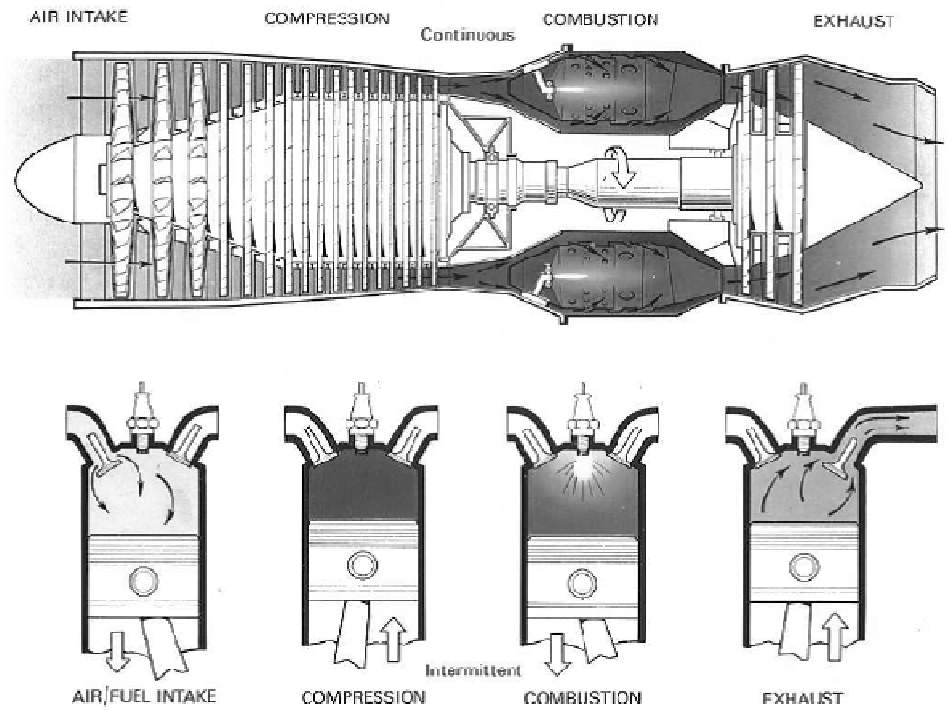
Gas turbines

Introduction

The gas turbine engine is essentially a heat engine using air as a working fluid to provide power. To achieve this, the air passing through the engine has to be accelerated; this means that the velocity or kinetic energy of the air is increased. To obtain this increase, the pressure energy is first of all increased, followed by the addition of heat energy, before final conversion back to kinetic Energy in the form of a rotating shaft.

Working cycle

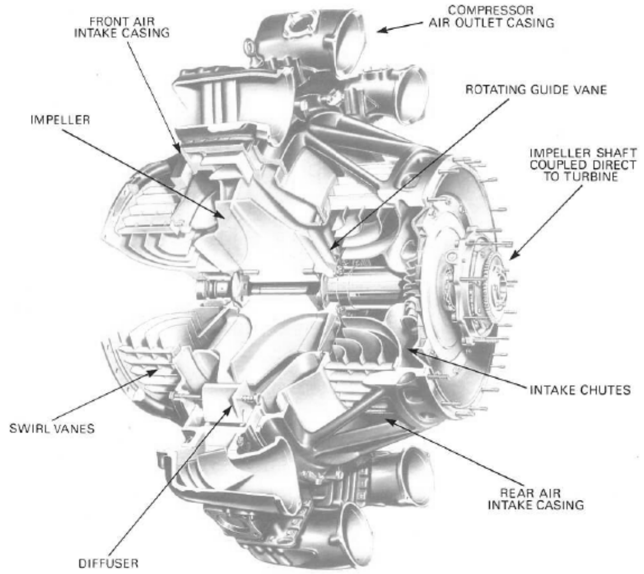
The working cycle of the gas turbine engine is similar to that of the four-stroke piston engine. However, in the gas turbine engine, combustion occurs at a constant pressure, whereas in the piston engine it occurs at a constant volume.



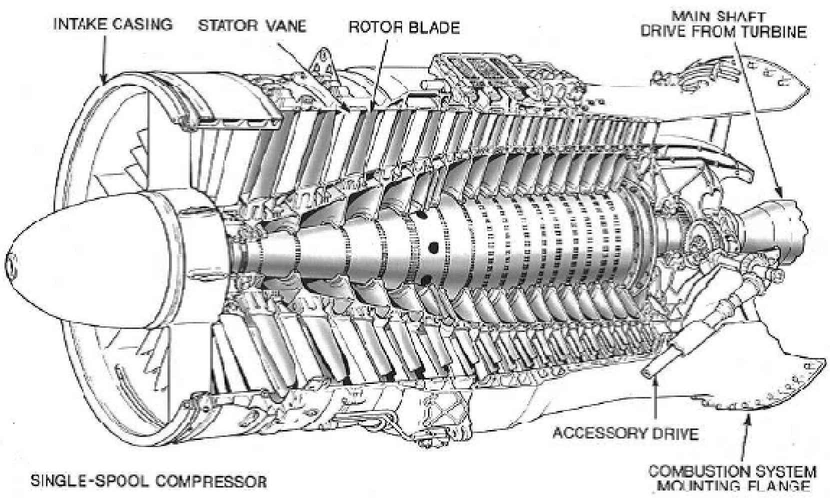
Gas turbine components

1- Compressor

In gas turbines, the compression of air is effected by one of two basic types of compressor; centrifugal or axial. Both types are driven by the turbine and are direct coupled to the turbine shaft.



Centrifugal compressor



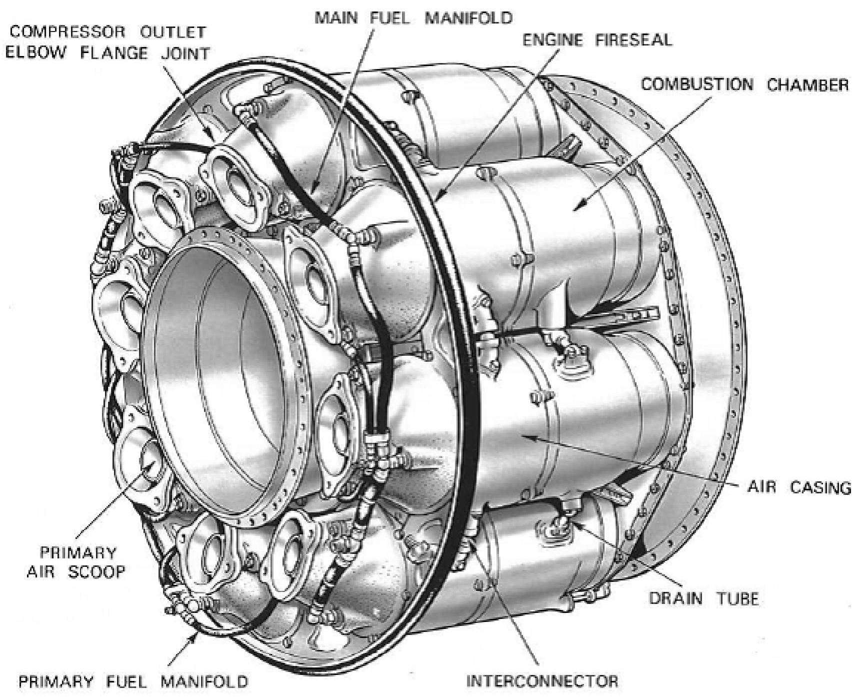
Axial compressor

2- Combustion chamber

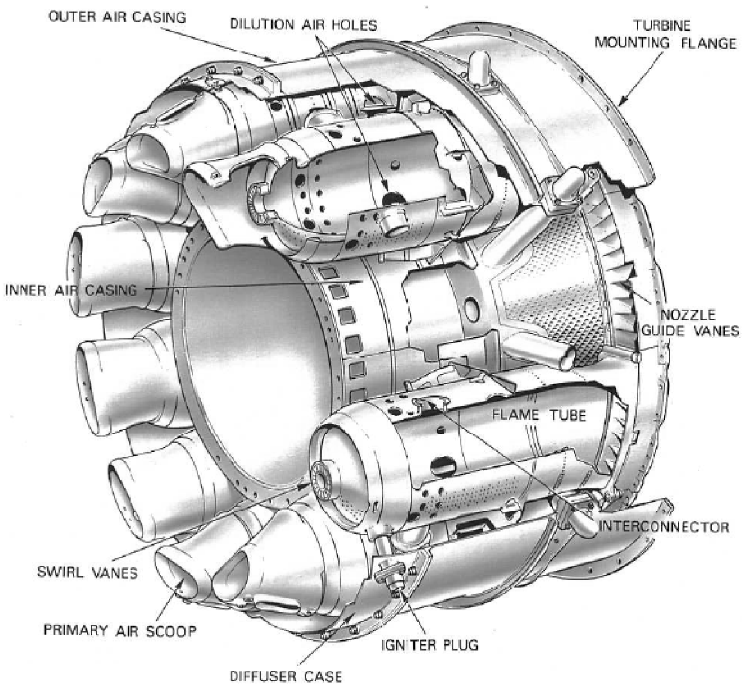
The combustion chamber has the difficult task of burning large quantities of fuel, supplied through the fuel spray nozzles, and releasing the heat in such a manner that the air is expanded and accelerated to give a smooth stream of uniformly heated gas at all conditions required by the turbine. The amount of fuel added to the air will depend upon the temperature rise required. However, the maximum temperature is limited to within the range of 850 to 1700 °C by the materials from which the turbine blades and nozzles are made.

Three types of combustion chamber exist:

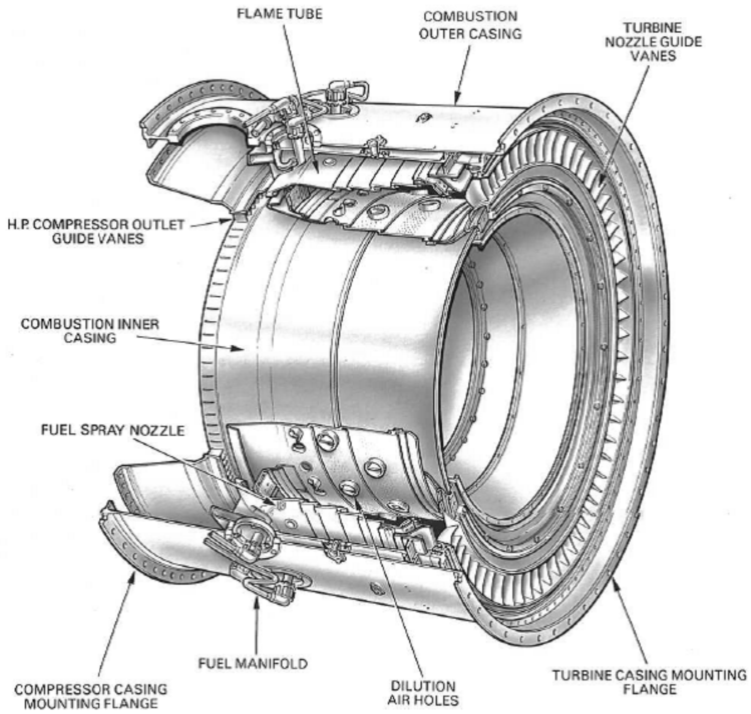
Multiple tube combustion chamber



Tubo-annular combustion chamber

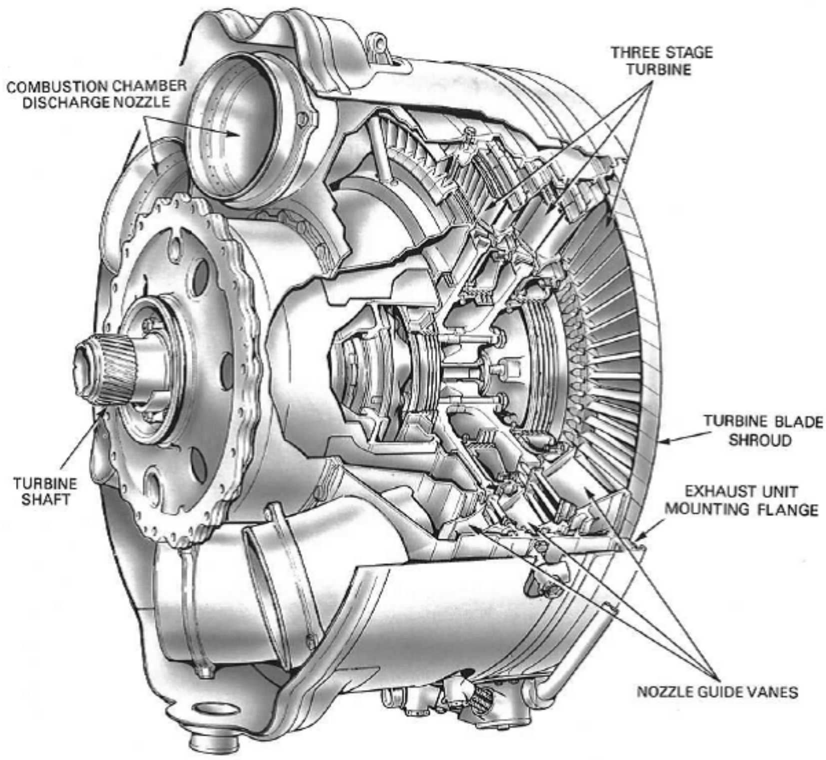


Annular combustion chamber

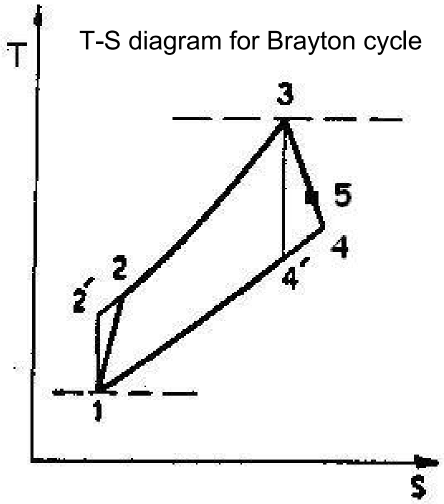


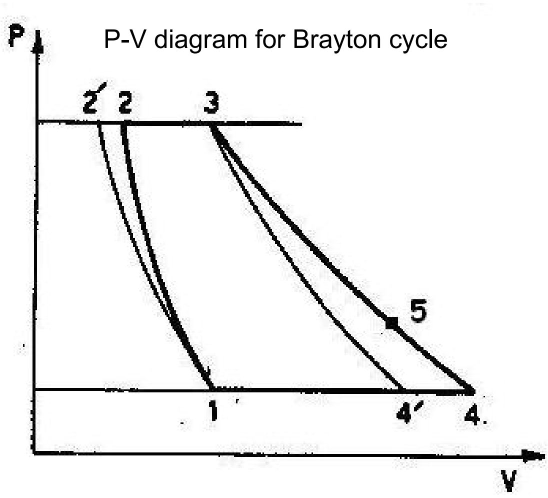
3- Turbine

The turbine has the task of providing the power to drive the compressor, accessories and shaft power for a propeller or rotor. It does this by extracting energy from the hot gases released from the combustion system and expanding them to a lower pressure and temperature.



Performance and heat balance calculations





1-2 Compression (in the compressor)

$$\frac{T_{2'}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\eta_C = \frac{T_{2'} - T_1}{T_2 - T_1}$$

$$\dot{W}_C = \dot{m}_a \times C_{p\ air} \times (T_2 - T_1)$$

2-3 Heat addition (in the combustion chamber)

$$\dot{Q}_{add} = \dot{m}_f \times CV$$
$$\dot{Q}_{add} = (\dot{m}_a + \dot{m}_f) \times C_{P\ gas} \times (T_3 - T_2)$$

3-5 Expansion (in the compressor turbine)
5-4 Expansion (in the power turbine)

$$\frac{T_3}{T_{4'}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma_g-1}{\gamma_g}}$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4'}}$$

$$\dot{W}_T = \left(\dot{m}_{air} + \dot{m}_f\right) \times C_{p\,gas} \times (T_3 - T_4)$$

$\dot{W}_T = \dot{W}_{CT} + \dot{W}_{PT}$ (compressor turbine + power turbine)

$$\dot{W}_{CT} = \dot{W}_C$$

$$Output\ Power = Power\ turbine\ power$$

$$\dot{W}_{CT} = \left(\dot{m}_{air} + \dot{m}_f\right) \times C_{P\,gas} \times (T_3 - T_5)$$

$$\eta_{cycle} = \frac{\dot{W}_{PT}}{\dot{Q}_{add}}$$

$$\pi_r = \frac{P_2}{P_1} \quad (compression\ ratio)$$

$$Work\ ratio = \frac{\dot{W}_{PT}}{\dot{W}_T}$$

Example

A gas turbine unit has a pressure ratio of 10:1 and a maximum temperature of 700°C. The isentropic efficiencies of the compressor and turbine are 0.82 and 0.85 respectively. Calculate the power output of an electric generator geared to the turbine when the air enters the compressor at 15°C at the rate of 15 kg/sec. Take Cp=1.005 kJ/kg.K and γ = 1.4 for the compression process, and take Cp=1.11 kJ/kg.K and γ = 1.333 for the expansion process. Neglect the fuel mass.

Solution

$$\frac{T_{2'}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad T_{2'} = (15 + 273) \times \left(\frac{10}{1}\right)^{\frac{0.4}{1.4}} = 556\ K$$

$$\eta_C = \frac{T_{2'} - T_1}{T_2 - T_1} \qquad 0.82 = \frac{556 - 288}{T_2 - 288} \qquad T_2 = 614.8\ K$$

$$\frac{T_3}{T_{4'}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma g-1}{\gamma g}} \qquad \frac{700+273}{T_{4'}} = \left(\frac{10}{1}\right)^{\frac{0.33}{1.33}} \qquad T_{4'} = 547.16\ K$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4'}} \qquad 0.85 = \frac{T_4 - 973}{547.16 - 973} \qquad T_4 = 611\ K$$

$$\dot{W}_T - \dot{W}_C = \dot{m}_a\left[\left(C_{P\ gas}(T_3 - T_4)\right) - \left(C_{P\ air}(T_2 - T_1)\right)\right]$$

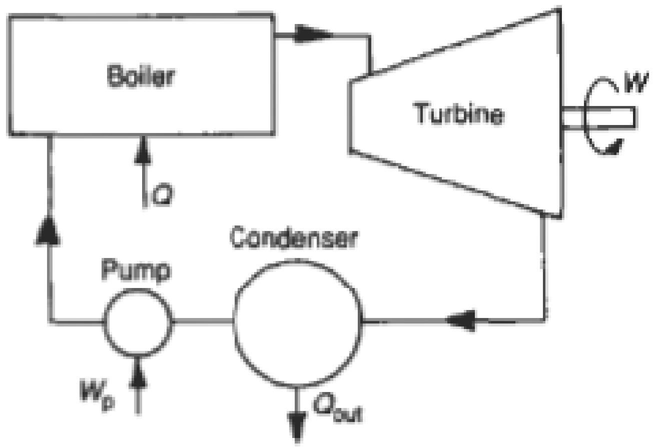
$$\dot{W}_{net} = 15\left[\left(1.11(973 - 611)\right) - \left(1.005(614.8 - 288)\right)\right]$$

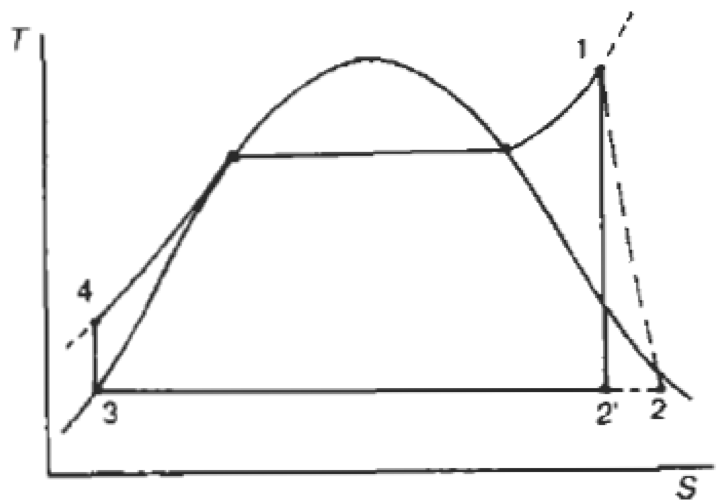
$$\dot{W}_{\text{net}} = 1100\ \text{kW}$$

Steam cycles

The steam cycle used is the simplest steam cycle of practical value; the Rankine cycle with dry saturated steam supplied by a boiler to one or more turbine, which exhausts to a condenser where the condensed steam is pumped back into the boiler.

Simple Rankine cycle





$\dot{Q}_B = \dot{m}_s(h_1 - h_4)$ $\quad$ $h_4 = h_3$ *when neglecting the pump work*

$\dot{W}_T = \dot{m}_s(h_1 - h_2)$

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2'}}$$

$$\dot{Q}_C = \dot{m}_s(h_2 - h_3)$$

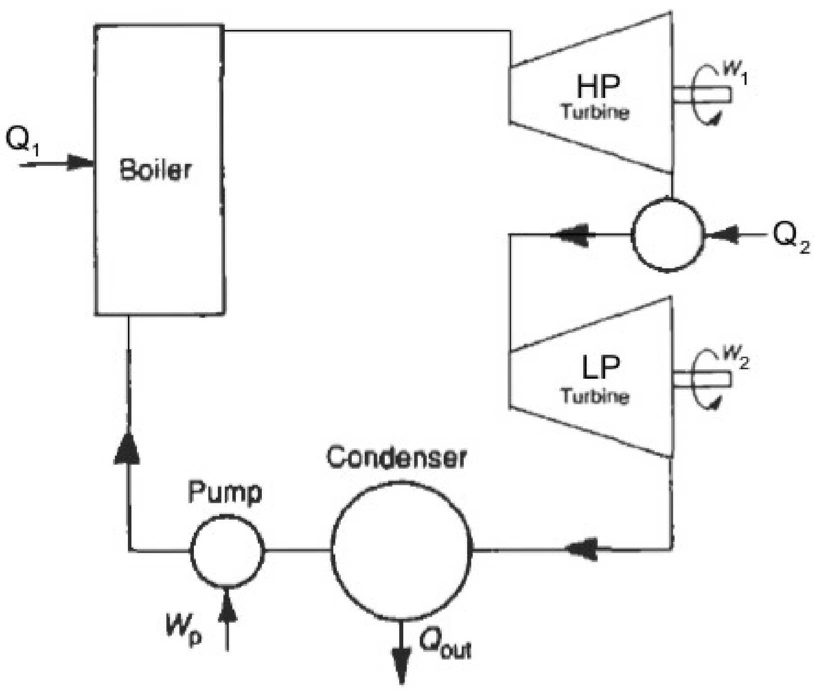
$$\dot{W}_P = \dot{m}_s(h_4 - h_3)$$

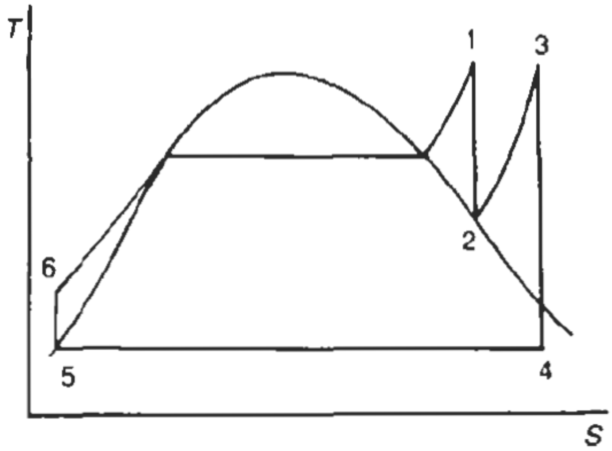
$$\eta_{cycle} = \frac{\dot{W}_{net}}{\dot{Q}_B} = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}_B}$$

$$specific\ steam\ consumption\ \ SSC = \frac{3600\ \dot{m}_s}{\dot{W}_T}\ [kg/kWh]$$

$$specific\ heat\ consumption\ SHC = \frac{3600\ \dot{Q}_B}{\dot{W}_T}\ [kJ/kWh]$$

Reheat Rankine cycle





$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2 = \dot{m}_s[(h_1 - h_6) + (h_3 - h_2)]$$

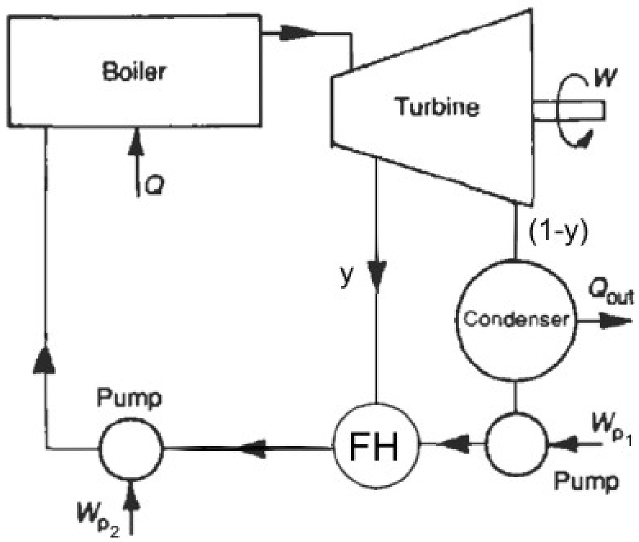
$$\dot{W}_T = \dot{W}_{HP} + \dot{W}_{LP} = \dot{m}_s[(h_1 - h_2) + (h_3 - h_4)]$$

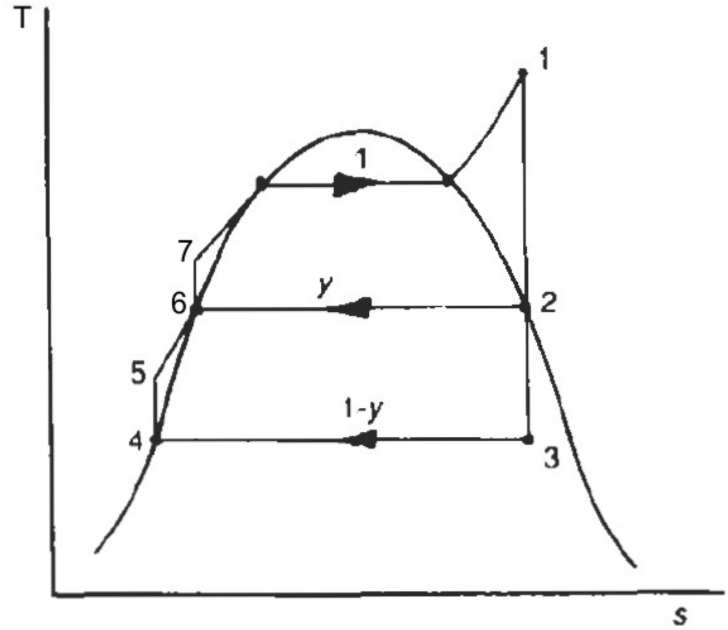
$$\dot{Q}_C = \dot{m}_s(h_4 - h_5)$$

$$\dot{W}_P = \dot{m}_s(h_6 - h_5)$$

$$\eta_{cycle} = \frac{\dot{W}_{net}}{\dot{Q}} = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}}$$

Regenerative Rankine cycle





$\dot{Q}_B = \dot{m}_s(h_1 - h_7)$

$\dot{W}_T = \dot{m}_s[(h_1 - h_2) + (1 - y)(h_2 - h_3)]$

$\dot{Q}_C = \dot{m}_s(1 - y)(h_3 - h_4)$

$\dot{W}_P = \dot{m}_s[(1 - y)(h_5 - h_4) + (h_7 - h_6)]$

$$\eta_{cycle} = \frac{\dot{W}_{net}}{\dot{Q}_B} = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}_B}$$

Feed heater heat balance

$y h_2 + (1 - y) h_5 = h_6$

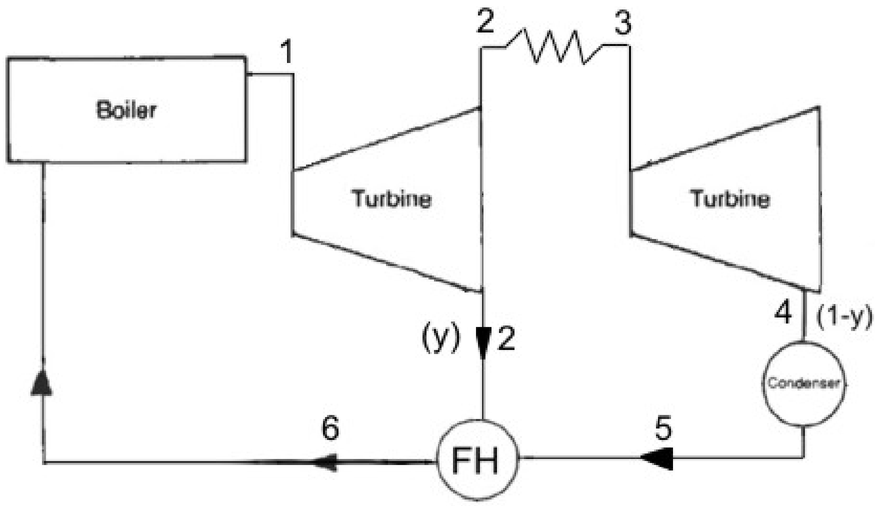
➔ You are required to draw the TS diagram and cycle schematic diagram for reheat-regenerative Rankine cycle.

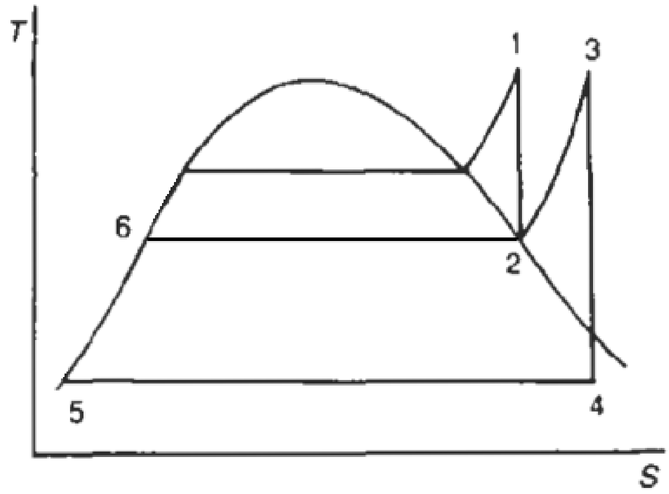
Example

In a reheat regenerative steam plant, the net power is 80 MW. Steam enters the HP turbine at 80 bar and 550°C, after expansion to 6 bar, some of the steam goes to a feed water heater and the rest is reheated to 350°C after which it expands to 0.07 bar.
Calculate:

- Rate of steam flow to high pressure turbine
- Fraction of steam extracted to the feed heater
- SHC
- SSC
- Cycle efficiency
- Rate of fuel consumption if the boiler efficiency is 95% and fuel calorific value is 40000 kJ/kg (neglect pump work)

Solution





From steam tables or chart:

	1	2	3	4	5	6
h	3521	2809	3165	2344	163.4	670.6

$yh_2 + (1-y)h_5 = h_6 \qquad y = 0.1917$

$Power = \dot{m}_s[(h_1 - h_2) + (1-y)(h_3 - h_4)] \qquad \dot{m}_s = 58.15\ kg/s$

$$SSC = \frac{3600\dot{m}_s}{Power} = 2.617\ kg/kWh$$

$$SHC = \frac{3600\dot{m}_s(h_1 - h_6)}{Power} = 7459\ kJ/kWh$$

$$\eta_{cycle} = \frac{Power}{\dot{Q}_B} = 48.26\%$$

$\dot{m}_f.CV.\eta_b = \dot{m}_s(h_1 - h_6) \qquad \dot{m}_f = 4.362\ kg/s$

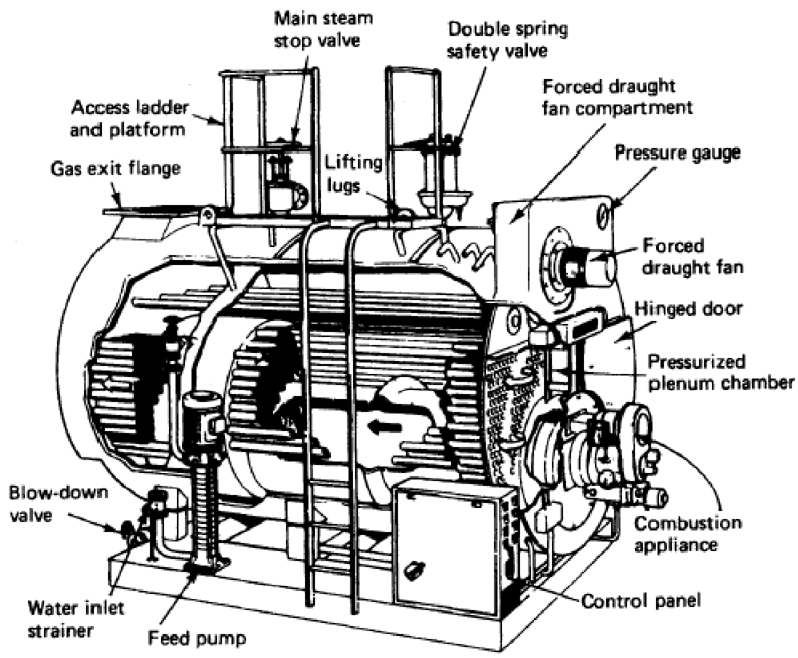
Steam cycle components

1- Boiler

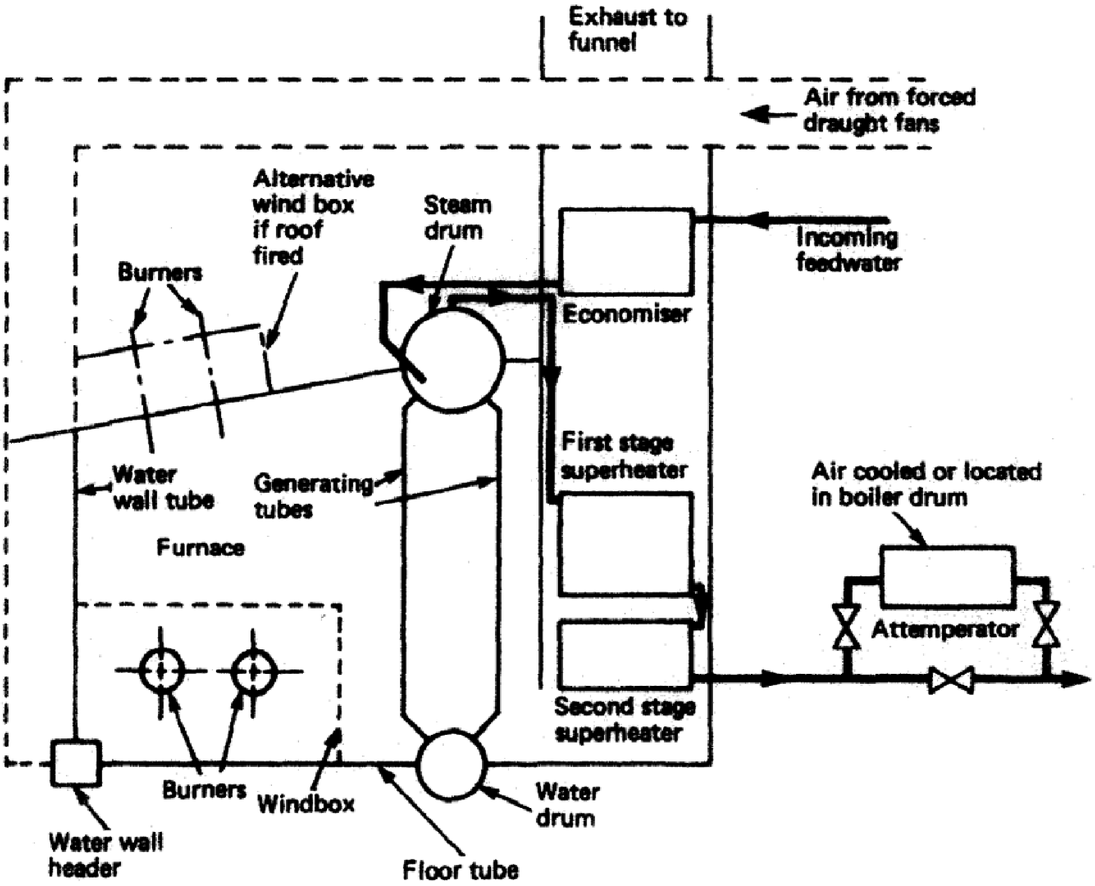
A boiler is used to heat feed water in order to produce steam. The energy released by the burning fuel in the boiler furnace is stored in the steam produced. All boilers have a furnace or combustion chamber where fuel is burnt to release its energy. Air is supplied to the boiler furnace to enable combustion of the fuel to take place.

Where the main machinery is steam powered, one or more large watertube boilers will be fitted to produce steam at very high temperatures and pressures. On a diesel main machinery vessel, a smaller (usually firetube type) boiler will be fitted to provide steam for the various ship services. Even within the two basic design types, watertube and firetube, a variety of designs and variations exist.

Two basically different types of boiler exist, namely the watertube and the firetube. In the watertube the feed water is passed through the tubes and the hot gases pass over them. In the firetube boiler the hot gases pass through the tubes and the feed water surrounds them.



Fire tube boiler



Water tube boiler

Boiler definitions

- $Actual\ evaporation\ W_A = \frac{\dot{m}_{st}}{\dot{m}_f} = \frac{total\ evaporation\ per\ hour}{fuel\ used\ per\ hour}$

- $Equivalent\ evaporation\ W_E = \frac{W_A\ (H-h)}{L}$
  H = steam enthalpy
  h = water enthalpy
  L = 583.9 kcal/kg at 100°C (latent heat)

- $Factor\ of\ equivalent\ evaporation\ FEE = \frac{H-h}{L}$

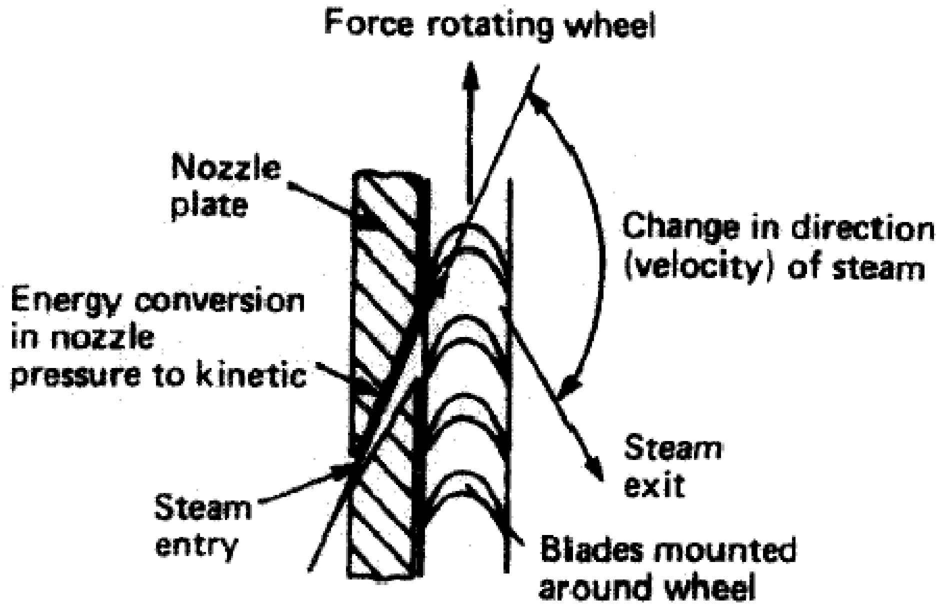
- $Boiler\ HP = \frac{\dot{m}_{st}(H-h)}{15.63\ L}$

- $Evaporation\ per\ m^2\ surface\ area = \frac{\dot{m}_{st}}{A}$

- $Boiler\ thermal\ efficiency\ \eta_B = \frac{W_A(H-h)}{CV}$
  CV = fuel calorific value

2- Steam turbines

The steam turbine is a device for obtaining mechanical work from the energy stored in steam. Steam enters the turbine with high energy content and leaves after giving up most of it. The high-pressure steam from the boiler is expanded in nozzles to create a high-velocity jet of steam. The nozzle acts to convert heat energy in the steam into kinetic energy. This jet is directed into blades mounted on the periphery of a wheel or disc. The shaping of the blades causes a change in direction and hence velocity of the steam jet.

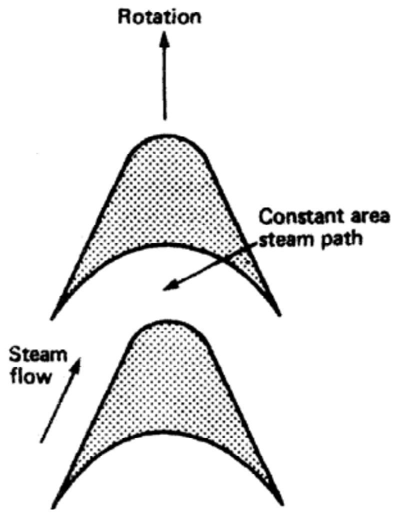


The steam from the first set of blades then passes to another set of nozzles and then blades and so on along the rotor shaft until it is finally exhausted. Each set comprising nozzle and blades is called a stage.

There are two main types of turbine, the 'impulse' and the 'reaction'. The names refer to the type of force which acts on the blades to turn the turbine wheel.

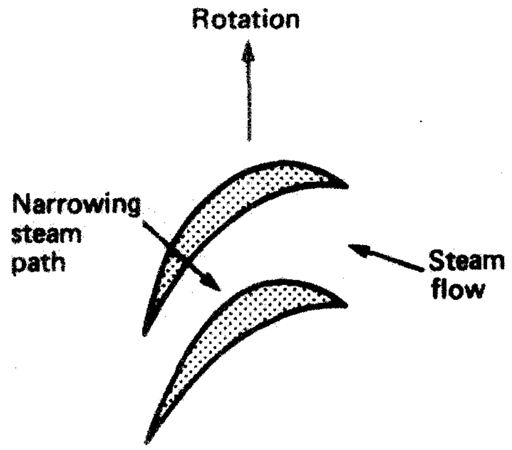
Impulse turbine

The impulse arrangement is made up of a ring of nozzles followed by a ring of blades. The high-pressure, high-energy steam is expanded in the nozzle to a lower-pressure, high-velocity jet of steam. This jet of steam is directed into the impulse blades and leaves in a different direction. The changing direction and therefore velocity produces an impulsive force which mainly acts in the direction of rotation of the turbine blades. There is only a very small end thrust on the turbine shaft.



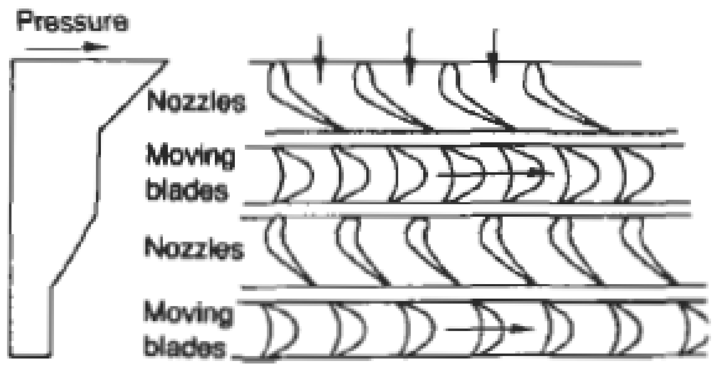
Reaction turbine

The reaction arrangement is made up of a ring of fixed blades attached to the casing, and a row of similar blades mounted on the rotor, i.e. moving blades. The blades are mounted and shaped to produce a narrowing passage which, like a nozzle, increases the steam velocity. This increase in velocity over the blade produces a reaction force which has components in the direction of blade rotation and also along the turbine axis. There is also a change in velocity of the steam as a result of a change in direction and an impulsive force is also produced with this type of blading. The more correct term for this blade arrangement is 'impulse-reaction'.

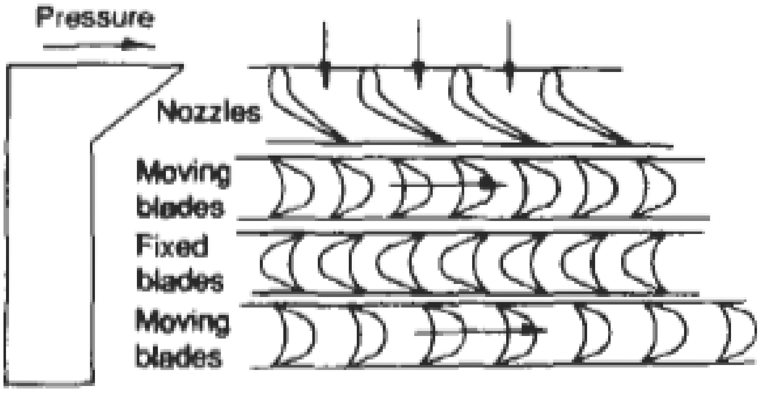


Compounding

Compounding is the splitting up, into two or more stages, of the steam pressure or velocity change through a turbine.
Pressure compounding of an impulse turbine is the use of a number of stages of nozzle and blade to reduce progressively the steam pressure. This results in lower or more acceptable steam flow speeds and better turbine efficiency.



Velocity compounding of an impulse turbine is the use of a single nozzle with an arrangement of several moving blades on a single disc. Between the moving blades are fitted guide blades which are connected to the turbine casing. This arrangement produces a short lightweight turbine with a poorer efficiency which would be acceptable in, for example, an astern turbine.



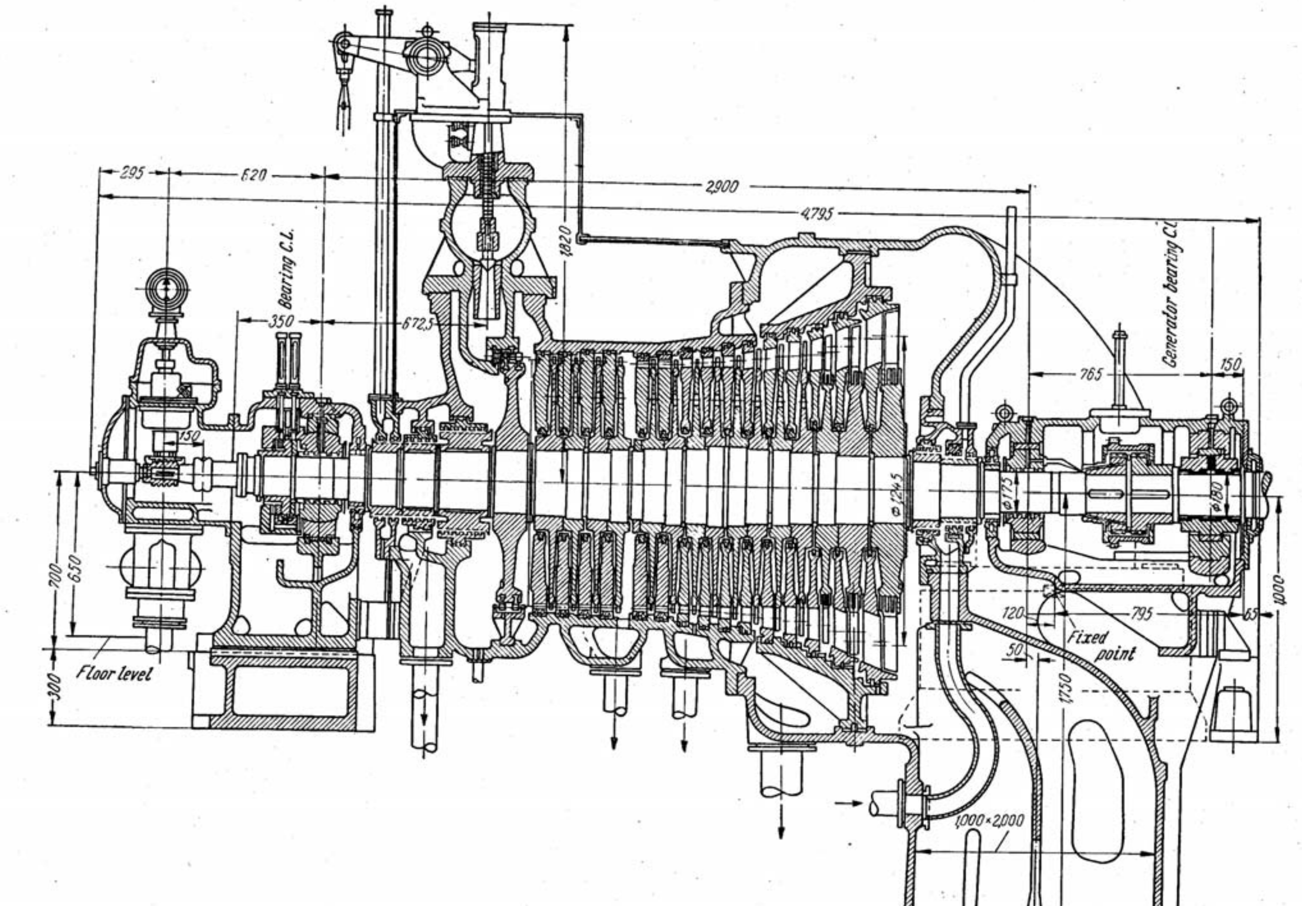
Named turbine types
A number of famous names are associated with certain turbine types.

Parsons. A reaction turbine where steam expansion takes place in the fixed and moving blades. A stage is made up of one of each blade type. Half of the stage heat drop occurs in each blade type, therefore providing 50% reaction per stage.

Curtis. An impulse turbine with more than one row of blades to each row of nozzles, i.e. velocity compounded.

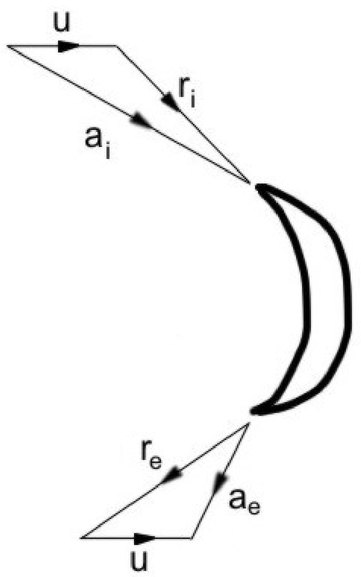
De Laval, A high-speed impulse turbine which has only one row of nozzles and one row of blades.

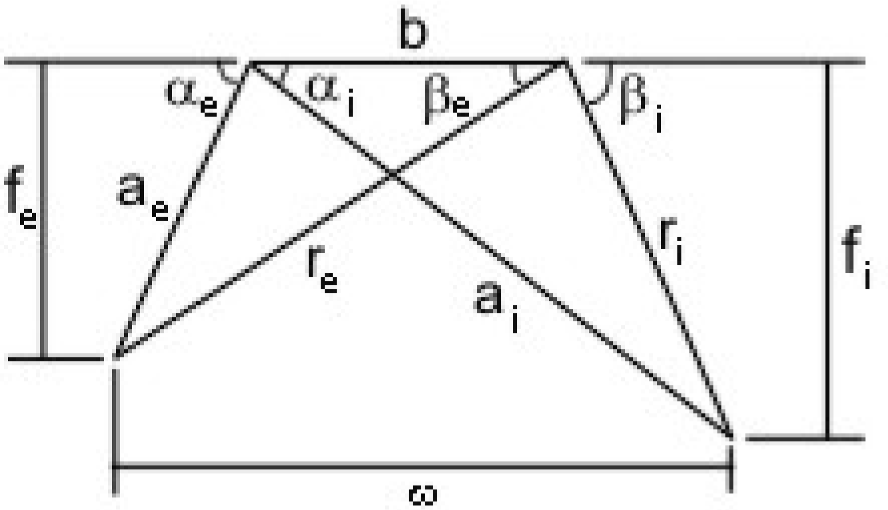
Rateau. An impulse turbine with several stages, each stage being a row of nozzles and a row of blades, i.e. pressure compounded.



Turbine K-6-35 (AK-6) of Lenin Nevsky Works

Turbine blade calculations





b = blade velocity = u
a_i = absolute inlet velocity
a_e = absolute exit velocity
r_i = relative inlet velocity
r_e = relative exit velocity
β_i = inlet angle
β_e = exit angle

$r_e = K\, r_i$ (K = blade velocity coefficient $K \leq 1$)

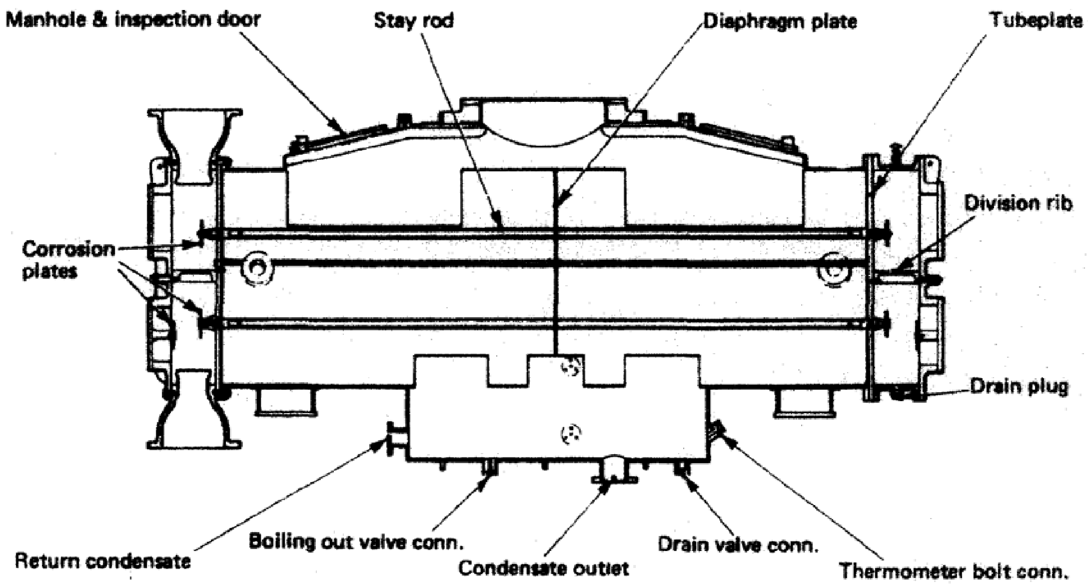
f = driving force on wheel = $f_i - f_e$

power output = mωb

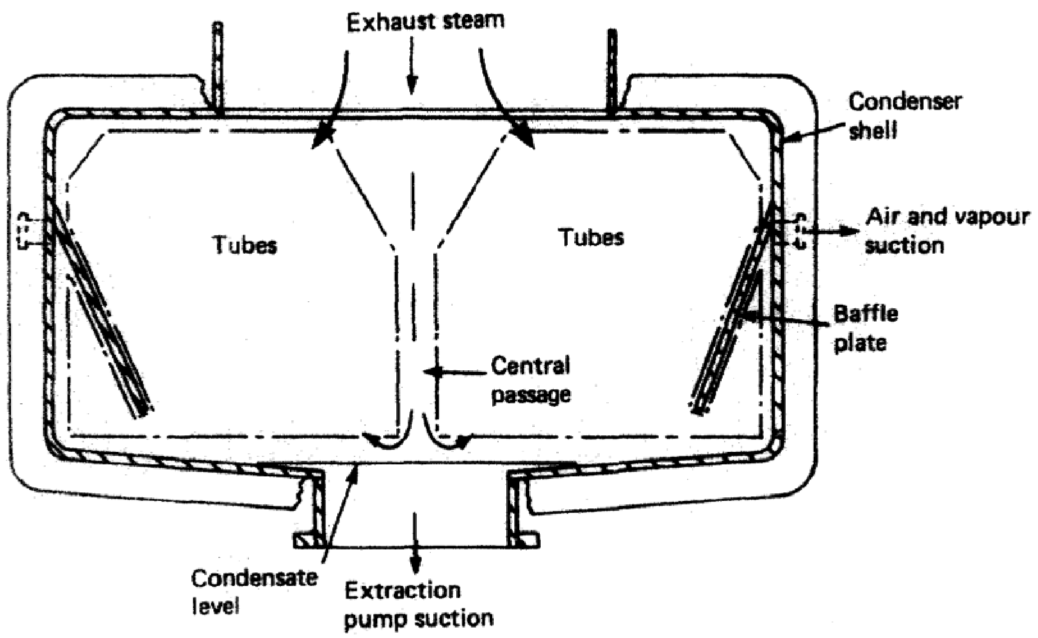
3- Condenser

The condenser is a heat exchanger which removes the latent heat from exhaust steam so that it condenses and can be pumped back into the boiler. This condensing should be achieved with the minimum of under-cooling, i.e. reduction of condensate temperature below the steam temperature. A condenser is also arranged so that gases and vapors from the condensing steam are removed.

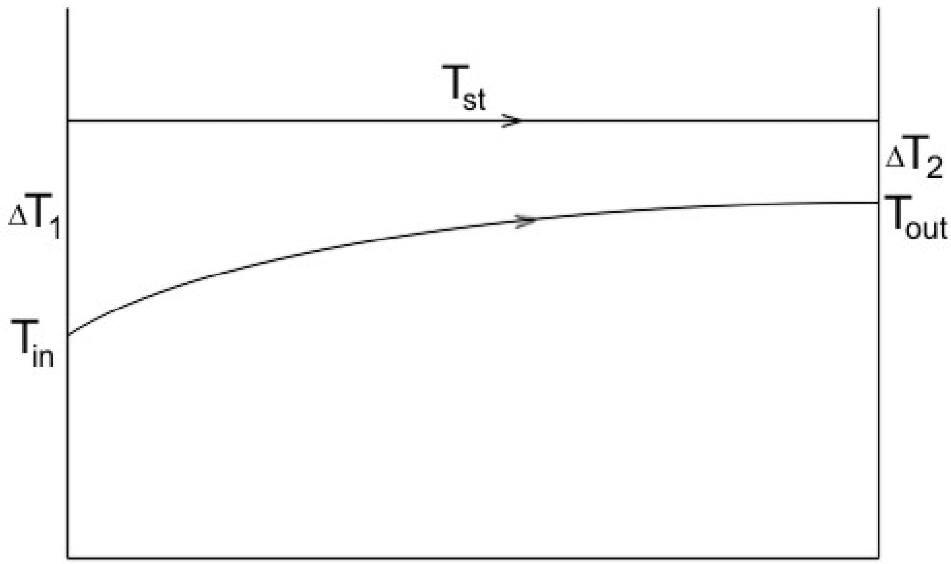
An auxiliary condenser is shown in next figure. The circular cross-section shell is provided with end covers which are arranged for a two-pass flow of sea water. Sacrificial corrosion plates are provided in the water boxes. The steam enters centrally at the top and divides into two paths passing through ports in the casing below the steam inlet hood. Sea water passing through the banks of tubes provides the cooling surface for condensing the steam. The central diaphragm plate supports the tubes and a number of stay rods in turn support the diaphragm plate. The condensate is collected in a sump tank below the tube banks. Air suction is provided on the condenser shell for the withdrawal of gases and vapors released by the condensing steam.



Main condensers associated with steam turbine propulsion machinery are of the regenerative type. In this arrangement some of the steam bypasses the tubes and enters the condensate sump as steam. The condensate is thus reheated to the same temperature as the steam, which increases the efficiency of the condenser.



Condenser calculations



$$\dot{Q}_c = \dot{m}_{st}(h_2 - h_3) = \dot{m}_w C_w (T_{out} - T_{in}) = AU\Delta T_{mean}$$

h_2 = enthalpy of steam before condenser
h_3 = enthalpy of saturated water after condenser
$\dot{m}_w = \frac{\pi}{4} d^2 \rho V Z$ (V = water speed inside the tubes = 2 ~ 3 m/s)
Z = number of tubes
d = tube diameter
T_{out} = water temperature after condenser
T_{in} = water temperature before condenser (20°C)
$T_{out} - T_{in}$ = 10 ~ 15°C
A = lateral area of tubes = $\pi d l Z$
l = tube length
U = heat transfer coefficient = 3000 W/m^2K
ΔT_{mean} = logarithmic mean temperature difference

$$\Delta T_{mean} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

Combined Gas and Steam plant
COGAS

Example

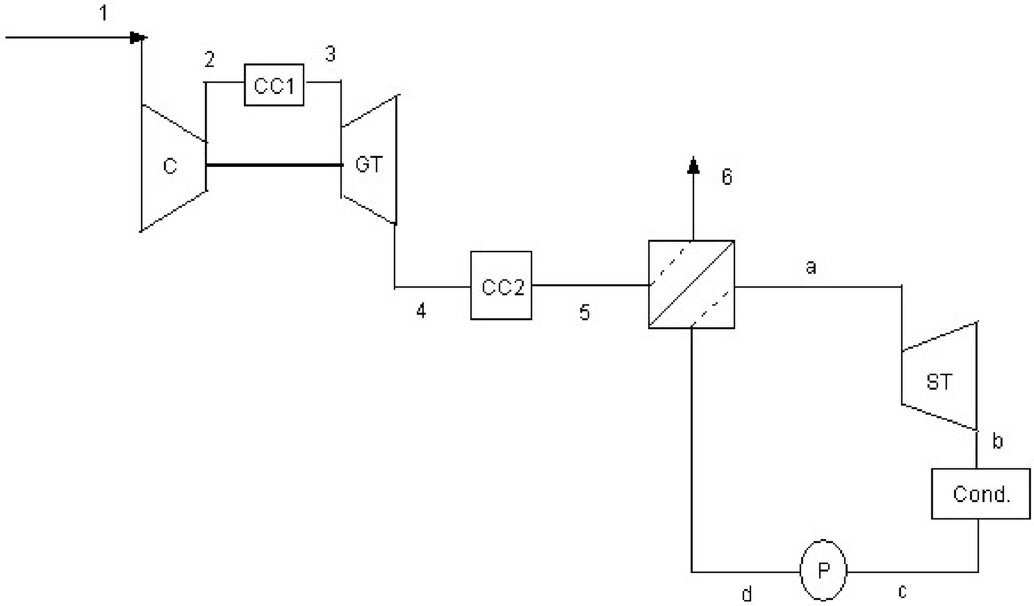
In a combined cycle power plant the air is supplied at a rate of 2000 ton/hr and at temperature of 20°C. The pressure ratio is 7:1. The temperature of gases before the gas turbine is 1000°C. Efficiency for compressor is 80% and for turbine 85%. The calorific value of oil used is 45 MJ/kg.

The temperature of gas used for steam generation is increased to 1200°C by burning the fuel in the exhaust coming out from the gas turbine. The condition of steam generated in the boiler is 50 bar and 500°C. The condenser pressure is 0.1 bar. The temperature of gas going to stack is 200°C. Find the following:

1. Total power generated from the plant
2. Overall efficiency of the plant
3. Mass of fuel used per hour
4. Specific fuel consumption

Take Cp_{air}=1 kJ/kg.K , Cp_{gas}=1.1 kJ/kg.K, γ_{air}=1.4, γ_{gas}=1.33

Solution



Compressor

$$\frac{T_{2'}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad \frac{T_{2'}}{20+273} = \left(\frac{7}{1}\right)^{\frac{0.4}{1.4}}$$

$$T_{2'} = 237.9°C$$

$$\eta_C = \frac{T_{2'} \_ T_1}{T_2 - T_1} \qquad 0.8 = \frac{237.9-20}{T_2 - 20}$$

$$T_2 = 292.4°C$$

$$\dot{W}_c = \dot{m}_a \times C_{p_a} \times (T_2 - T_1)$$

$$\dot{W}_c = 151310\ kW$$

Turbine

$$\frac{T_3}{T_{4'}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma_g-1}{\gamma_g}} \qquad \frac{1273}{T_4'} = \left(\frac{7}{1}\right)^{\frac{0.33}{1.33}}$$

$$T_4' = 512.5°C$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4'}} \qquad 0.85 = \frac{1000 - T_4}{1000 - 512.5}$$

$$T_4 = 585.6°C$$

$$\dot{W}_T = \left(\dot{m}_a + \dot{m}_{f1}\right) \times C_{p_{gas}} \times (T_3 - T_4)$$

$$\dot{W}_T = 257690\ kW$$

$$P_{GT} = \dot{W}_T - \dot{W}_c = 257690 - 151310 = 106380\ kW$$

Combustion chamber 1

$$\dot{m}_{f1} \times CV = \left(\dot{m}_a + \dot{m}_{f1}\right) \times C_{P\ gas} \times (T_3 - T_2)$$

$$45000 \times \dot{m}_{f1} = \left(555.6 + \dot{m}_{f1}\right) \times 1.1 \times (100 - 292.4)$$

$\dot{m}_{f1} = 9.779\ kg/s$

Combustion chamber 2

$$\dot{m}_{f2} \times CV = (\dot{m}_a + \dot{m}_{f1} + \dot{m}_{f2}) \times C_{p_{gas}} \times (T_5 - T_4)$$

$$45000 \times \dot{m}_{f2} = (555.6 + 9.779 + \dot{m}_{f2}) \times 1.1 \times (1200 - 585.6)$$

$$\dot{m}_{f2} = 8.62\ kg/s$$

$$\dot{m}_f = 9.779 + 8.62 = 18.4\ kg/s = 66.24\ ton/h$$

	a	**b**	**c**	**d**
h	3434	2210	191.7	196.7

Exhaust gas boiler

$$\dot{m}_s(h_a - h_d) = (\dot{m}_a + \dot{m}_f) \times C_{p_{gas}} \times (T_5 - T_6)$$

$$\dot{m}_s(3434 - 196.7) = (555.6 + 18.4) \times 1.1 \times (1200 - 200)$$

$$\dot{m}_s = 195\ kg/s$$

Steam turbine

$$P_s = \dot{m}_s[(h_a - h_b) - (h_d - h_c)]$$

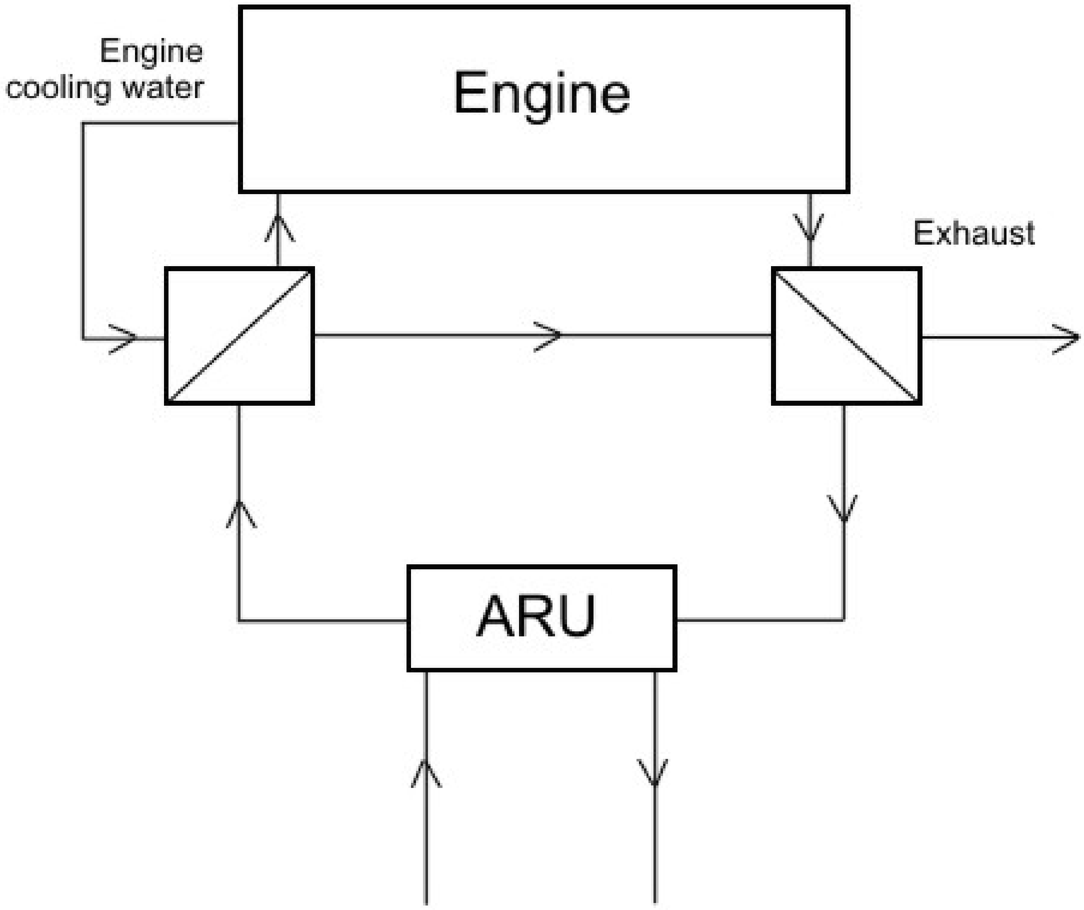
$$P_s = 237787\ kW$$

$$P = P_s + P_{GT} = 237787 + 106380 = 344167\ kW$$

$$\eta = \frac{P}{\dot{m}_f \times CV} = \frac{344167}{18.4 \times 45000} = 0.4157$$

$$sfc = \frac{\dot{m}_f}{P} = \frac{18.4 \times 3600}{344167} = 0.192\ kg/kWh$$

Waste heat recovery systems
Ex. Absorption refrigeration systems



The absorption refrigeration unit is used for cooling water for refrigeration or air conditioning, it takes the heat contained in the cooling water of the engine and in the exhaust. There is a closed circuit of water which takes the heat from the engine (cooling water and exhaust) and delivers it to the absorption unit. Then another circuit is connected to the unit for the cold water.

The heat gained from the cooling water (Q_{CW})
$Q_{CW} = \dot{m}_{cw} \times C_w \times \Delta T_{cw}$

The heat gained from the exhaust (Q_{exARU})

$$Q_{exARU} = \dot{m}_{ex} \times C_{p_{ex}} \times (T_{at} - T_{stack})$$

The total heat gained (Q_h)

$$Q_h = Q_{CW} + Q_{exARU}$$

The temperature of closed circuit water entering the refrigeration unit is called the supply temperature (T_s)

The coefficient of performance of the unit (COP)

$$COP = \frac{Q_c}{Q_h}$$

Where Q_c is the cooling load required from the unit.

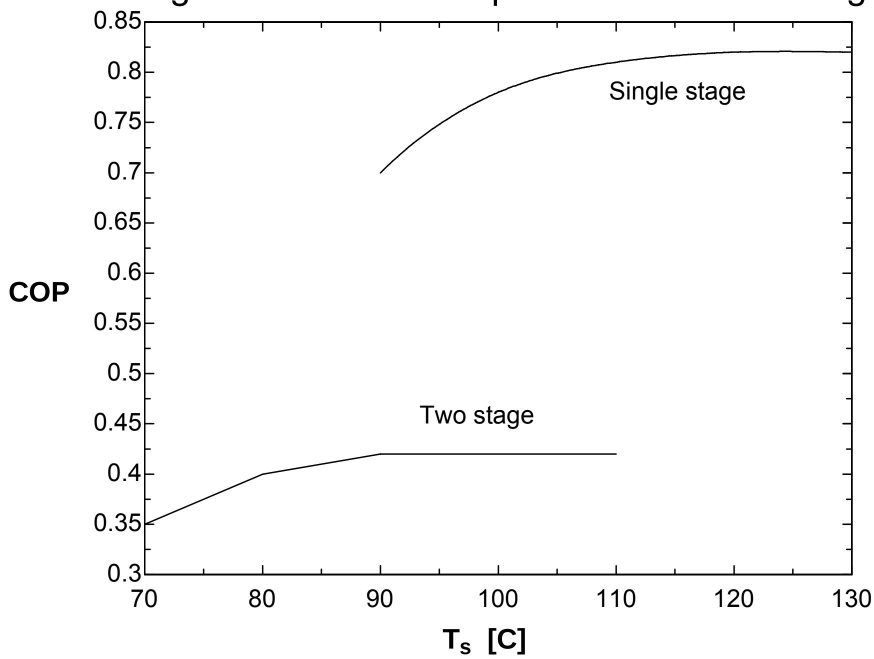
Example

A waste heat recovery system of a diesel engine uses a LiBr-water absorption refrigeration unit of 100 kW cooling load.

Determine:

- The heat gained of the ARU at 85°C supply temperature and 30°C ambient temperature
- The engine brake power if η_{bth}=40%

Assume that heat gained to the unit equal heat lost of the engine



Solution

By interpolation at 85°C the COP=0.4131

$$COP = \frac{Q_c}{Q_h}$$

$$0.4131 = \frac{100}{Q_h}$$

Q_h=242 kW

$$Q_h = Q_{CW} + Q_{ex}$$

For the diesel engine

$$Q_a = BP + Q_{ex} + Q_{CW} + Q_{rad} = BP + Q_h + 0.02Q_h$$

$$0.98 = \eta_{bth} + \frac{Q_h}{Q_a}$$

$$0.98 = 0.4 + \frac{242}{Q_a}$$

Q_a=417.24 kW

BP=167 kW

Ship piping systems

The piping systems onboard the ship are grouped into two main categories; machinery piping systems (reviewed in the ship propulsion systems course) and hull piping systems.

The machinery piping systems include:

- Fuel oil system
- Lubrication oil system
- Cooling water system
- Starting air system

The hull piping systems include:

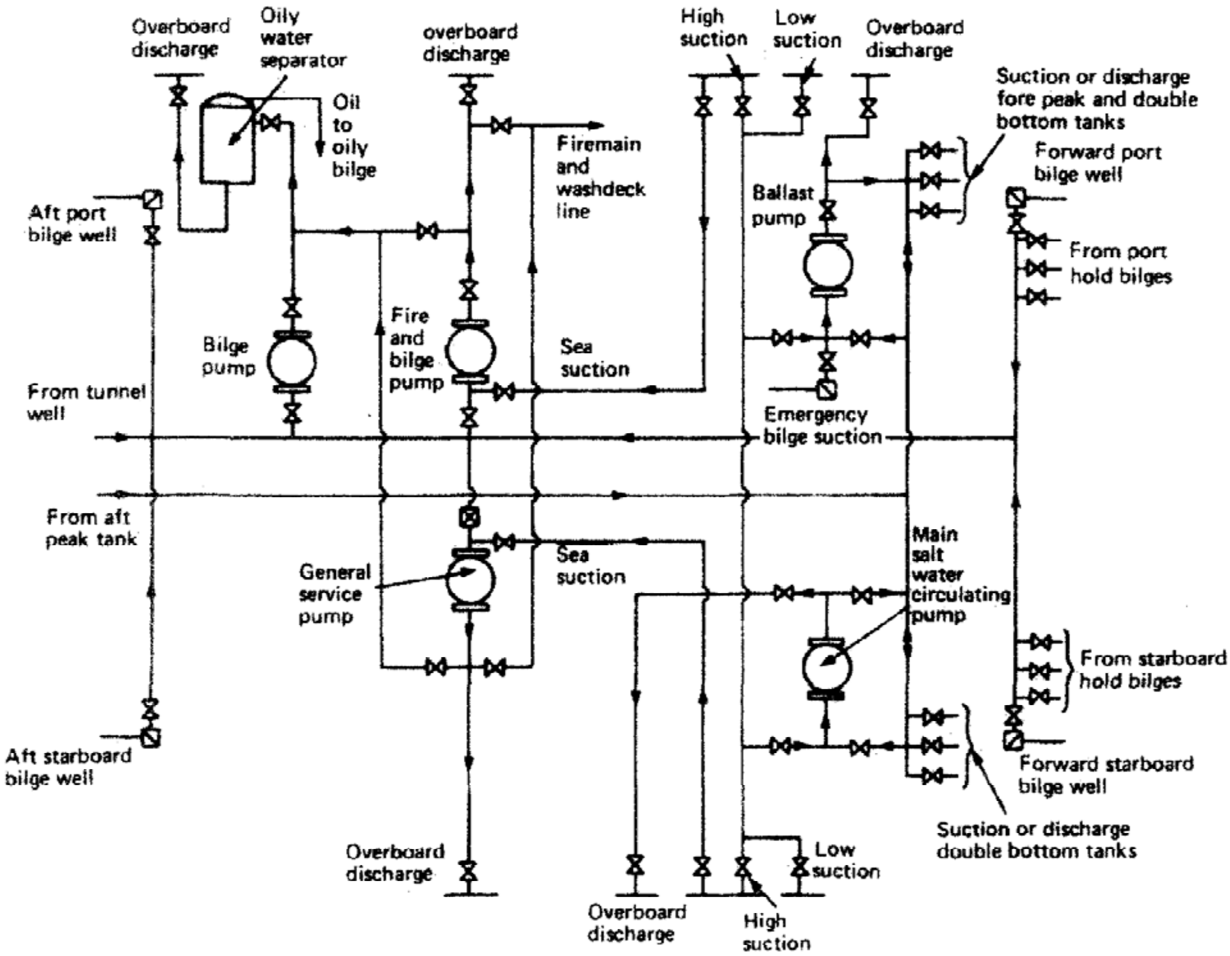
- Bilge system
- Ballast system
- Fire fighting system
- Sewage system
- Domestic water system

Bilge system

The essential purpose of a bilge system is to clear water from the ship's dry compartments, in emergency. The major uses of the system are for clearing water and oil which accumulates in machinery space bilges as the result of leakage or draining, and when washing down dry cargo holds. The number of pumps and their capacity depend upon the size, type and service of the ship.

Ballast system

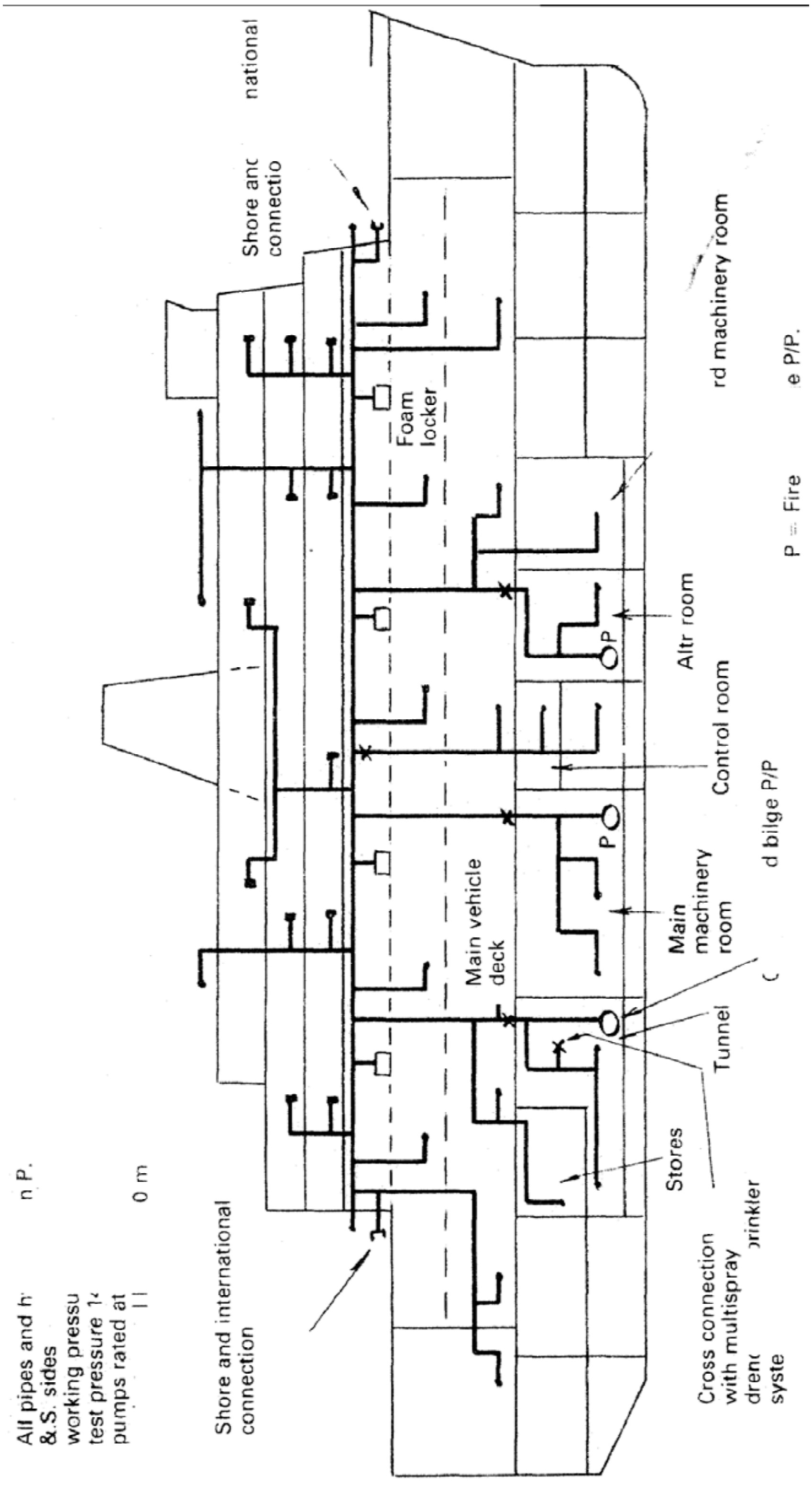
The bilge system and the ballast system each have particular functions to perform, but are in many ways interconnected, especially that both works with the general service pump of the ship. The ballast system is arranged to ensure that water can be drawn from any tank or the sea and discharged to any other tank or the sea as required to trim the vessel. Combined or separate mains for suction and discharge may be provided.



Oil/water separators are necessary aboard vessels to prevent the discharge of oil overboard mainly when pumping out bilges. They also find service when deballasting or when cleaning oil tanks. The requirement to fit such devices is the result of international legislation.

Fire fighting system

Water is the chief fire fighting medium on a ship and the fire main is the basic installation for fighting fires. The fire main extends to the full length of the ship and from the machinery spaces to the highest levels. Hydrants served by the main, are situated so that with suitable hoses any area on the ship can be reached. For accommodation spaces, sprinklers are fitted in the ceiling. Foam, CO_2 and other materials are used instead of water according to the space protected in the ship.

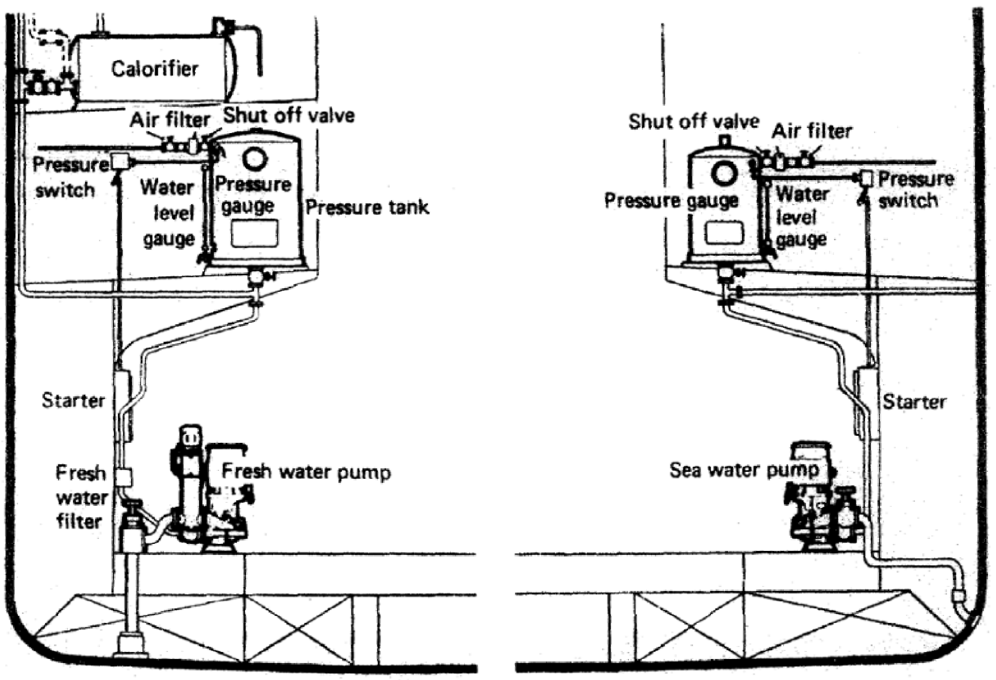


Sewage system

This system is used for draining sewage from baths, laundries, showers, etc., to the sanitary tanks or to treatment units. The exact amount of sewage and waste water flow generated on board ship is difficult to quantify. European designers tend to work on the basis of 70 litres/person/day of toilet waste (including flushing water) and about 130-150 litres/person/day of washing water (including baths, laundries, etc.). US authorities suggest that the flow from toilet discharges is as high as 114 litres/person/day with twice this amount of washing water.

Domestic water system

Domestic water systems usually comprise a fresh water system for washing and drinking and a salt water system for sanitary purposes. Both use a basically similar arrangement of an automatic pump supplying the liquid to a tank which is pressurized by compressed air. The compressed air provides the head or pressure to supply the water when required. The pump is started automatically by a pressure switch which operates as the water level falls to a predetermined level. The fresh water system has, in addition, a calorifier or heater which is heated, usually with steam.



Electric generation

A ship at sea cannot use an external source of energy; consequently its electric power plant generates, distributes and converts electric power. Electricity is used for the motor drive of many auxiliaries and also for deck machinery, lighting, ventilation and air conditioning equipment.

A distinction can be made between three phase alternating current and direct current supply systems. Most commonly used are the three phase alternating current systems with a frequency of 60 Hz and voltages between 440-450 V or 50 Hz and 380-400 V. if very large electric consumers, such as bow thrusters or propulsion motors, have to be supplied, the main electric power system may use a higher voltage of 3.3 – 6 – 6.6 – 11 or 15 kV. In this case the smaller users are fed through transformers or from secondary electric power supply systems, usually single phase alternating current with frequency of 50 Hz / 230 V or 60 Hz / 115 V. direct current system, usually 24 V, is used to supply the control and monitoring systems.

Beside the main and secondary supply systems, the plant has an emergency system. A separate genset: emergency/harbor generator. The emergency genset with the associated transforming equipment and emergency switchboard should be located above the uppermost continuous deck. This system should supply the vital electric consumers in the ship for at least 18 hours for cargo ships and 36 hours for passenger ships.

The diesel engines

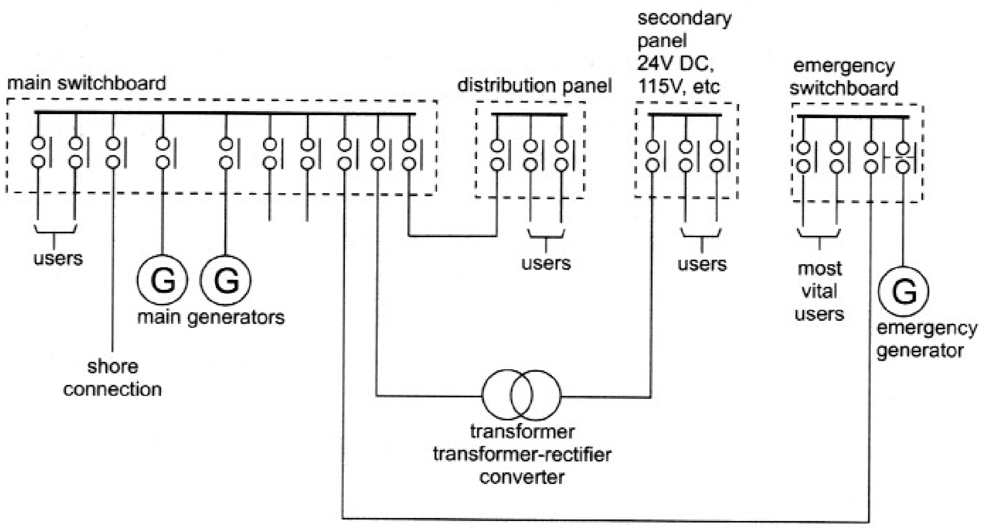
Main electric power systems of 50 Hz require an engine with a speed of 750, 1000 or 1500 rpm, 60 Hz systems require 900, 1200 or 1800 rpm.

Gas turbines may be used but it is not preferred due to its low fuel economy.

Electric power distribution

Switchboards receive, control and distribute electric energy from generators to loads. Every ship has at least one main switchboard and one emergency board. Main switchboards receive electric energy directly from the main generators. The switchboard may receive electricity from shore when in port or in dock.

The main switchboard distributes electricity to near electrical systems and to distribution boards which group electrical systems that are located further. Between the main switchboard and the secondary electric supplies, the electric energy needs to be converted from main to secondary. The type of converter is either a transformer (voltage), a rectifier (AC to DC) or frequency converters.



Electric load

In order to determine the electric power pant capacity and configuration, the electric load of the ship must be analyzed under various operational conditions. For many ship types the studied operational conditions are:

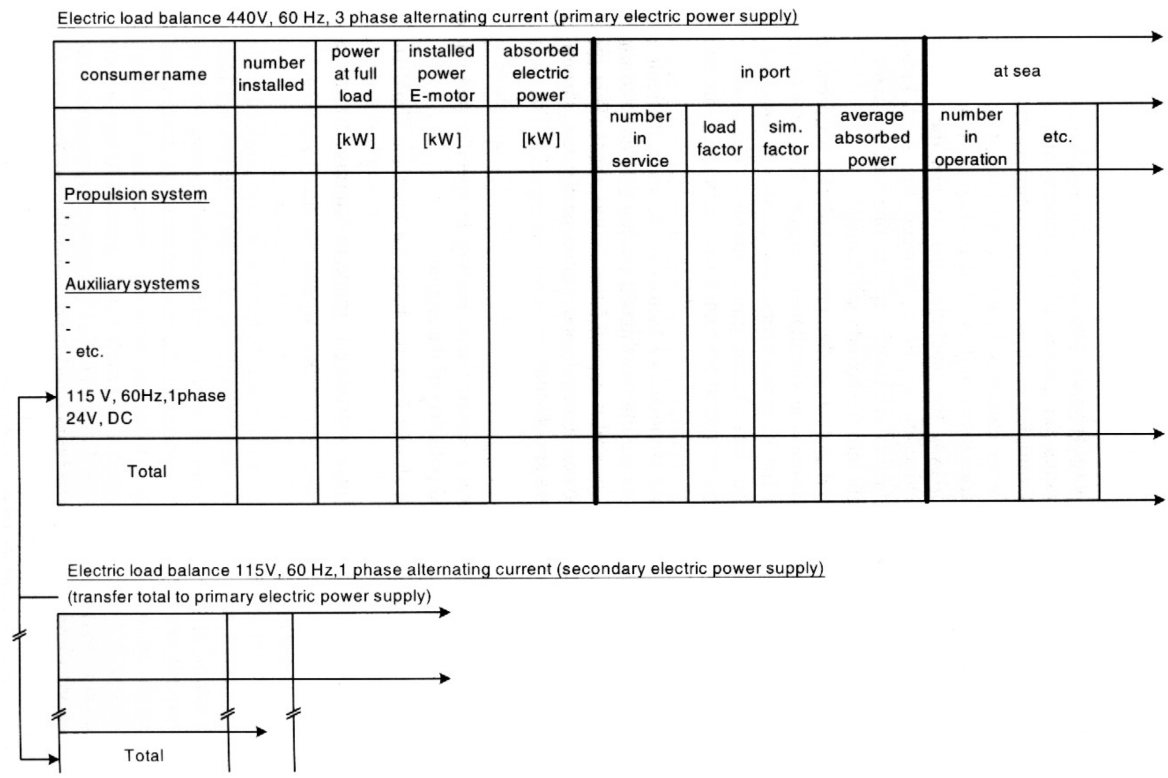
- At sea
- Manoeuvring
- In port: loading and discharging
- In port without loading or discharging
- At anchor

Ships with special missions (OSVs, naval vessels …) have special operational conditions.

Three ways are used to determine the electric power demand for the ship: empirical formulae, electric load analysis and simulation.

Empirical formulae can be used successfully to obtain a first estimate of the electric power demand in the pre-design stage. The example given here is a formula that uses installed propulsion power to determine the electric demand at sea for conventional cargo ship. As a rule the electric load when manoeuvring is 130% of the electric load at sea and the load in port without loading or discharging is 30 to 40%. $P_{EL} = 100 + 0.55(MCR)^{0.7}$

The most used method is the electric load analysis or electric load balance. The next figure gives an example of a balance sheet.



The balance sheet lists all electric consumers vertically, the next columns tabulate nominal properties of the electric consumers.

The second part of the sheet describes the various operational conditions to determine the actual load for each condition.

- Power at full load is the power that has to be supplied to the flange of the machinery. For direct electric users, such as lighting and computers, this power equals the power absorbed from the electric net. For electric users driven by motors, the power absorbed from the net is the power demanded by the user divided by the electric motor efficiency.

- Number in service is the number of pieces of the machinery that are operated in same time. Some machinery will only be in service in certain operational conditions.

- The load factor indicated the relative load of the machinery and thus specifies how much electric power is absorbed in an actual situation. The load factor varies between 0 and 1.

- The simultaneity factor accounts for pieces of machinery that are not operated continuously but intermittently. (Air compressors, fuel pumps, ballast pumps …). The simultaneity factor indicates the relative mean operational time of the machinery. Te simultaneity factor varies between 0 and 1.

- The average absorbed power is the product of the absorbed power, the number in service, the load factor and the simultaneity factor.

Example

For a container feeder ship an electric load analysis has to be made. Three operating conditions need to be investigated:

- Sea service: the ship is sailing at service speed and a number of containers need to be cooled
- In port- loading and unloading: no propulsion

For this exercise only a limited number of electric consumers are considered. Where applicable, electric motors have to be selected from a standard range of electric motors with nameplate (nominal) power of: 0.25, 0.5, 1, 2, 4, 7, 10, 20, 30, 40 and 50 kW.

Determine the load analysis for the following consumers:

(A) Propulsion system:

- High temperature (HT) cooling water pumps:

  Two centrifugal pumps will be installed, one of which will be in operation and one stand-by. The pump capacity is 85 m^3/h at pressure head of 2 bar. The pump efficiency is 0.75.

- Fuel oil service pump:

  One to be in operation and one stand-by. The pump capacity is 4 m^3/h at a pressure head of 5 bar. The pump efficiency is 0.65.

- Lubricating oil pump:

  Two screw-type pumps, one of which is in operation and one stand-by. The pump capacity is 100 m^3/h at a pressure of 6 bar. The pump efficiency is 0.8.

(B) Auxiliary systems:

- Fuel oil separators:

  Two separators are installed. They run continuously during sea service. The excess capacity is re-circulated from the clean fuel oil daily tank, back to the fuel oil settling tank. Each separator has a 4 kW electric motor. The motors are not fully loaded. The separators require 3 kW of mechanical power input.

- Fuel oil heater for separators:

  Two electric heaters are installed. The heaters are in operation during operation of the fuel separators. The maximum capacity of one heater is 40 kW. This capacity is based on heating of the full fuel flow (corresponding with the maximum separator capacity) from 5^{o}C to 90^{o}C. During normal operation approximately 50% of the separator output is re-circulated and the fuel supplied from the settling tank will have an average temperature of 55^{o}C.

- Fuel oil transfer pumps:

  Two screw-type pumps are provided, to pump fuel from storage tanks to settling tank and to transfer fuel between storage tanks (for stability and trim operations of the ship). The pump capacity is 40 m^3/h at a pressure head of 4 bar. The pump efficiency is 0.70.

(C) Hotel systems:

- Hydrophore system:

  To provide fresh water throughout the ship, a hydrophore system is provided. A hydrophore tank is kept under a pressure of 4 to 6 bar. Therefore, two hydrophore pumps are provided. Their pump capacity is 3 m^3/h at a pressure head of 6 bar. The pump efficiency is 0.60.

- Hot water heater:

  For use of hot water in the galley and for showering. Two hot water heaters are provided. Each heater has a maximum capacity of 120 l/h and can heat fresh water from 10^oC to 80^oC. The electrical power used by one boiler is maximum 10 kW.

- Hot water circulation pump:

  Two centrifugal pumps circulate hot water through the ship, such that at every wash basin, shower and galley tap, hot water is immediately available. The pump capacity is 0.4 m^3/h at a pressure head of 2 bar. The pump efficiency is 0.50.

(D) Hull machinery:

- Steering gear:

  The ship is provided with an electric-hydraulic steering machine. The steering machine contains two hydraulic pumps of the controllable axial piston type. Each pump requires 24 kW at full output.

- Capstans/winches:

  The ship has two winches on the fore-deck and two on the aft-deck. The installed power per winch is 30 kW. Two winches are only in operation during maneuvering.

- Bow thruster:

  The ship has one electrically-driven bow thruster to aid maneuvering in port. The bow thruster has a FP propeller and runs at a fixed speed. The propeller requires 280 kW and the installed motor power is 300 kW.

(E) Cargo systems:

- Reefer containers:

  The ship can carry 100 reefer containers. A reefer container is provided with its individual cooling system. The maximum compressor power per reefer container is 12 kW. The installed motor power is 15 kW.

The following relations may be useful:

1. $P_{pump} = \dfrac{\dot{V}.\Delta P}{\eta_{pump}}$
2. $P_{absorbed} = \dfrac{P_{pump}}{\eta_{em}}$
3. η_{em} = electric motor efficiency, it ranges from 0.85 for 1 kW motor power to 0.90 for 20-50 kW motor power and to 0.92 for 300 kW motor power.

You are required to make an electric load balance sheet.

Solution

(A) Propulsion system:

- High temperature (HT) cooling water pumps:
  $\dot{V} = 85\ m^3/hr$, $\Delta P = 2\ bar$, $\eta_p = 0.75$, $\eta_{em} = 0.86$
  $P_{pump} = \frac{\left(\frac{85}{3600}\right)*(2*100)}{0.75} = 6.3\ kW$ the motor will be 7 kW
  The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{6.3}{0.86} = 7.3kW$

- Fuel oil service pump:
  $\dot{V} = 4\ m^3/hr$, $\Delta P = 5\ bar$, $\eta_p = 0.65$, $\eta_{em} = 0.84$
  $P_{pump} = \frac{\left(\frac{4}{3600}\right)*(5*100)}{0.65} = 0.9\ kW$ the motor will be 1 kW
  The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{0.9}{0.84} = 1\ kW$

- Lubricating oil pump:
  $\dot{V} = 100\ m^3/hr$, $\Delta P = 6\ bar$, $\eta_p = 0.8$, $\eta_{em} = 0.89$
  $P_{pump} = \frac{\left(\frac{100}{3600}\right)*(6*100)}{0.8} = 20.8\ kW$ the motor will be 30 kW
  The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{20.8}{0.89} = 23.4\ kW$

(B) Auxiliary systems:

- Fuel oil separator:
  $P_{separator} = 3\ kW$, $\eta_{em} = 0.86$
  The absorbed power = $\frac{P_{separator}}{\eta_{em}} = \frac{3}{0.86} = 3.5\ kW$

- Fuel oil heaters:
  Absorbed power = 40 kW

- Fuel oil transfer pumps:
  $\dot{V} = 40\ m^3/hr$, $\Delta P = 4\ bar$, $\eta_p = 0.7$, $\eta_{em} = 0.86$
  $P_{pump} = \frac{\left(\frac{40}{3600}\right)*(4*100)}{0.86} = 6.4\ kW$ the motor will be 7 kW

The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{6.4}{0.86} = 7.4\ kW$

(C) Hotel systems:

- Hydrophore system:
  $\dot{V} = 3\ m^3/hr$, $\Delta P = 6\ bar$, $\eta_p = 0.6$, $\eta_{em} = 0.84$
  $P_{pump} = \frac{\left(\frac{3}{3600}\right)*(6*100)}{0.6} = 0.85\ kW$ the motor will be 1 kW
  The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{0.85}{0.84} = 1\ kW$

- Hot water heaters:
  Absorbed power = 10 kW

- Hot water circulation pumps:
  $\dot{V} = 0.4\ m^3/hr$, $\Delta P = 2\ bar$, $\eta_p = 0.5$, $\eta_{em} = 0.8$
  $P_{pump} = \frac{\left(\frac{0.4}{3600}\right)*(2*100)}{0.5} = 0.05\ kW$ the motor will be 0.25 kW
  The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{0.05}{0.8} = 0.1\ kW$

(D) Hull machinery:

- Steering gear:
  $P_{pump} = 24\ kW$ the motor will be 30 kW
  The absorbed power = $\frac{P_{pump}}{\eta_{em}} = \frac{24}{0.89} = 27\ kW$

- Winches:
  $P_{winch} = 30\ kW$, $\eta_{em} = 0.89$
  The absorbed power = $\frac{P_{winch}}{\eta_{em}} = \frac{30}{0.89} = 33.7\ kW$

- Bow thruster:
  $P_{thruster} = 280\ kW$, $\eta_{em} = 0.92$
  The absorbed power = $\frac{P_{thruster}}{\eta_{em}} = \frac{280}{0.92} = 304\ kW$

(E) Cargo systems:

- Reefer containers:

  $P_{reefer} = 12\ kW,\ \eta_{em} = 0.88$

  The absorbed power $= \frac{P_{reefer}}{\eta_{em}} = \frac{12}{0.88} = 13.6\ kW$

					Sea service				Port: loading/unloading			
	No. installed	Power at full load	Installed motor power	Absorbed electric power	no. in service	Load factor	Sim. factor	Average abs. power	no. in service	Load factor	Sim. factor	Average abs. power
Systems												
Propulsion												
CW pumps	2	6.3	7	7.2	1	1.00	1.00	7.2	0	-	-	-
FO service	2	0.9	1	1	1	0.80	1.00	0.7	0	-	-	-
FO pumps	2	20.8	30	23.4	1	0.83	1.00	19.4	0	-	-	-
Auxiliary systems												
FO sep.	2	3	4	3.5	2	0.90	1.00	6.3	0	-	-	-
FO heater	2	40	-	40	2	0.53	1.00	42.4	0	-	-	-
FO trans.	2	6.4	7	7.4	1	0.75	0.25	1.4	0	-	-	-
Hotel systems												
Hydrophore	2	0.85	1	1	1	0.83	0.03	0.1	1	0.83	0.03	0.1
HW heater	2	10	-	10	2	0.09	1.00	0.1	2	0.09	1.00	1.8
HW pump	2	0.05	0.25	0.1	1	1.00	1.00	0.1	1	1.00	1.00	0.1
Hull machinery												
Steering	2	24	30	27	1	0.10	1.00	2.7	0	-	-	-
Winches	4	30	30	33.7	0	-	-	-	0	-	-	-
Bow thrust.	1	280	300	304	0	-	-	-	0	-	-	-
Cargo systems												
Reefer	100	12	15	13.6	100	0.55	0.9	675	100	0.55	0.4	300

The total power at sea = 755.4 kW

The total power at port (loading/unloading) = 302.9 kW

Renewable energy

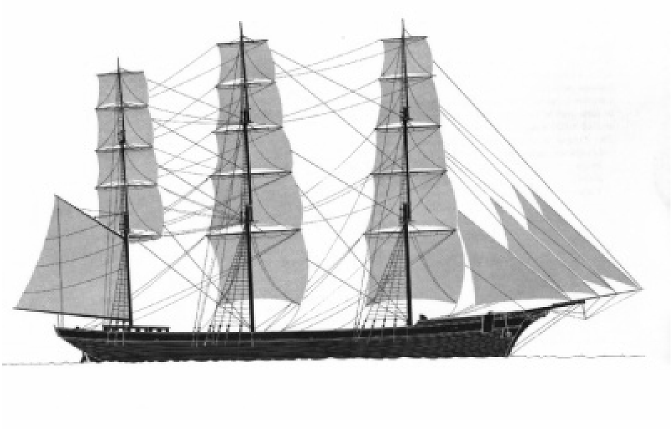
Renewable energies include every energy source which is not harmful to the environment and is not depleted. This includes solar, wind and wave energies. Some types of fuels like biomass and hydrogen are not depleted but have very small effect on the environment.

The marine field cannot use all the renewable energy sources as some of them requires land based facilities or stationary plants, wave energy for example cannot be easily used in moving ships. Actually, an increased concern allover the world is focusing on new and clean types of energies for ship propulsion to reduce the harmful effects on the environment resulting from the burning of fossil fuels.

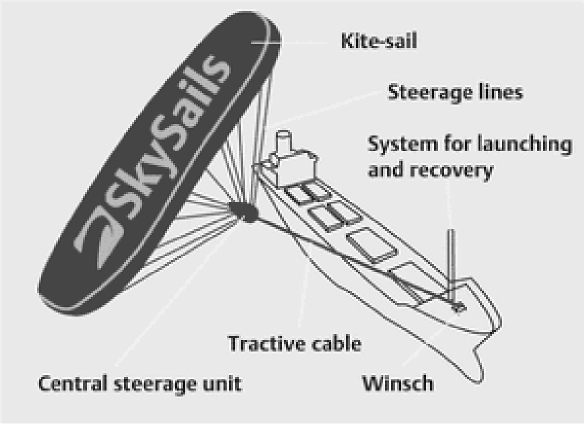
The scientific research in this field can be grouped into two categories; the first trying to reduce the emissions from the thermal power plants already installed either by using cleaner fuels, e.g. natural gas, biomass and hydrogen, or by improving the engines' design, the second group trying to adopt renewable energy technologies in the marine field.

Wind

Till the beginning of the industrial revolution in the 19th century, ships were propelled by wind driven sails.



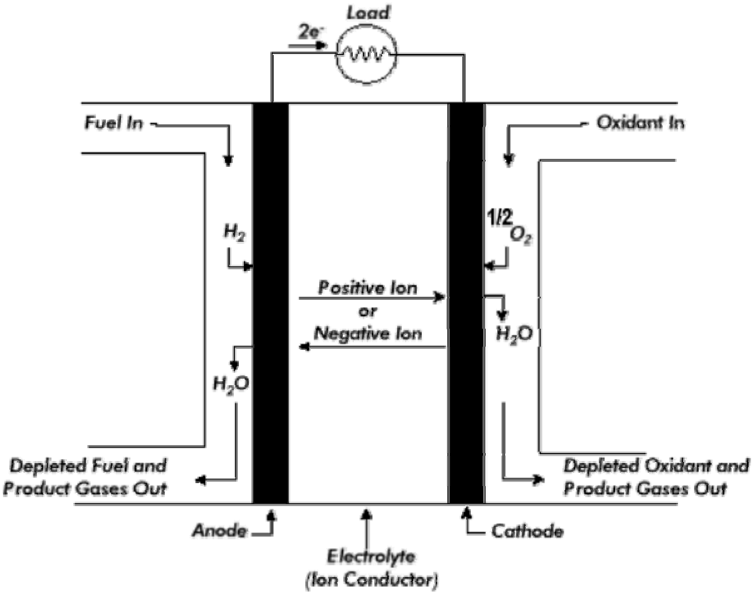
More and more researches are published every day and more prototypes are made to reuse sails as a marine propulsion method.



Skysails is one of many companies manufacturing new types of sails for ships propulsion, these systems are used as auxiliary power source in order to reduce the fuel consumption and thus the emissions. Companies claim that fuel savings of up to 50% are possible using these new technologies.

Fuel cells

The fuel cell converts the chemical energy of a fuel directly to electrical energy without combustion.



Fuel cells may be used in the marine field mainly as auxiliary power unit feeding the ship's electric network.
There are five main fuel cell types in markets:

- Polymer electrolyte FC (PEFC)
- Alkaline FC (AFC)
- Phosphoric acid FC (PAFC)
- Molten carbonate FC (MCFC)
- Solid oxide FC (SOFC)

The difference between all the types is in the type of electrolyte between the anode and the cathode of the cell.

Type	**Low temperature cells (0-250°C)**			**High temperature cells (600-1000°C)**	
FC type	**PEFC**	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Ion exchange membranes	Potassium hydroxide	Phosphoric acid	Molten carbonate	ceramic
Temperature	80°C	65-220°C	205°C	650°C	600-1000°C
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites
Water management	Evaporative	Evaporative	Evaporative	Gaseous	Gaseous
Heat management	Process gas	Process gas	Process gas	Internal reforming	Internal reforming
Power range	300 kW	20 kW	50-200 kW	300-3000 kW	100-1000 kW
Efficiency	40-50%	45-55%	40-50%	50-60%	45-65%

Advantages of fuel cells include high efficiency, low emissions and quiet operation.

Solar energy

The solar radiations may be exploited in one of two ways. The first is directly converting the sunlight into electricity and the other is by heating a medium for heating purposes or to use it for electric generation in a later process.

Photovoltaic panels (PV) are used for directly converting sunlight into electric current. They are used in the marine field as auxiliary source of power generally for DC users, since the output of these panels is limited to few hundreds of watts; they are used only in leisure crafts industry. Few companies, e.g. Solar Sailor, are producing PV panels which can be used in the same time as sails for the ships to further reduce the fuel consumption.

Solar collectors are used for collecting heat from sunlight to produce hot water for heating or air conditioning purposes. Also these units are used in leisure crafts industry. The major problem for any type of solar energy is the orientation as the panels have to be continuously oriented towards the sun to do the job, so these systems are useful only in crafts working in daylight and with long stops.

Three types of solar collectors are widely used; simple flat collectors, coated collectors and evacuated (vacuum) collectors. Each type is used for a specific range of temperatures and applications. The simple flat collector is the cheapest while the evacuated is the most expensive.

Beside the cost and the temperature range provided by each type, efficiency is a factor that has to be taken into consideration. The collector efficiency is the ratio between the useful amount of heat transported to the heating medium and the amount of heat received by the collector.

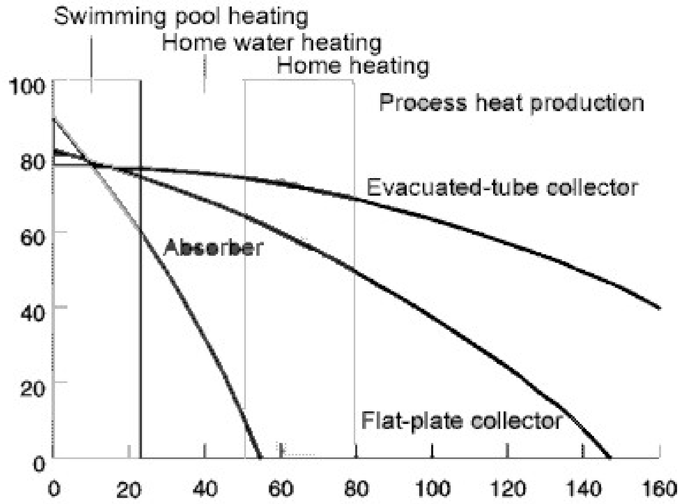
$$\eta = \frac{\dot{m}.C.\Delta T}{I.A}$$

$\dot{m}$ is the flow rate of the heating medium

C is the specific heat

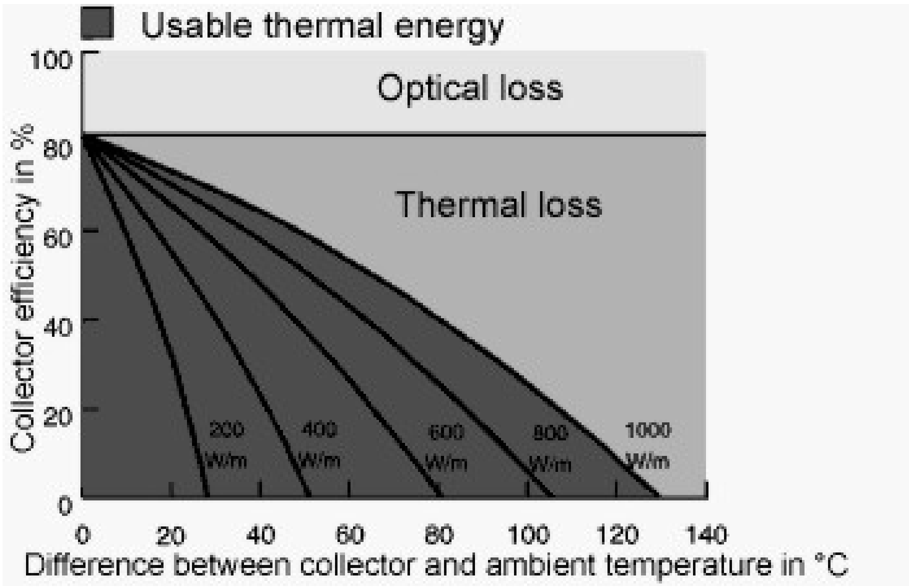
I is the solar radiation in W/m^2

A is the collector's area



The x-axis is the difference between the average temperature across the collector and the ambient temperature.

Note that the efficiency never reaches 100% due to optical losses



Example

A Nile floating hotel has a free roof area of 20 m^2, a solar collector is to be fitted in this area for water heating.

The solar radiation in this area is 1000 W/m^2 and the ambient temperature is 35°C. The temperature of water across the collector is 40/120°C.

The performance curves of different collectors at previous conditions are:

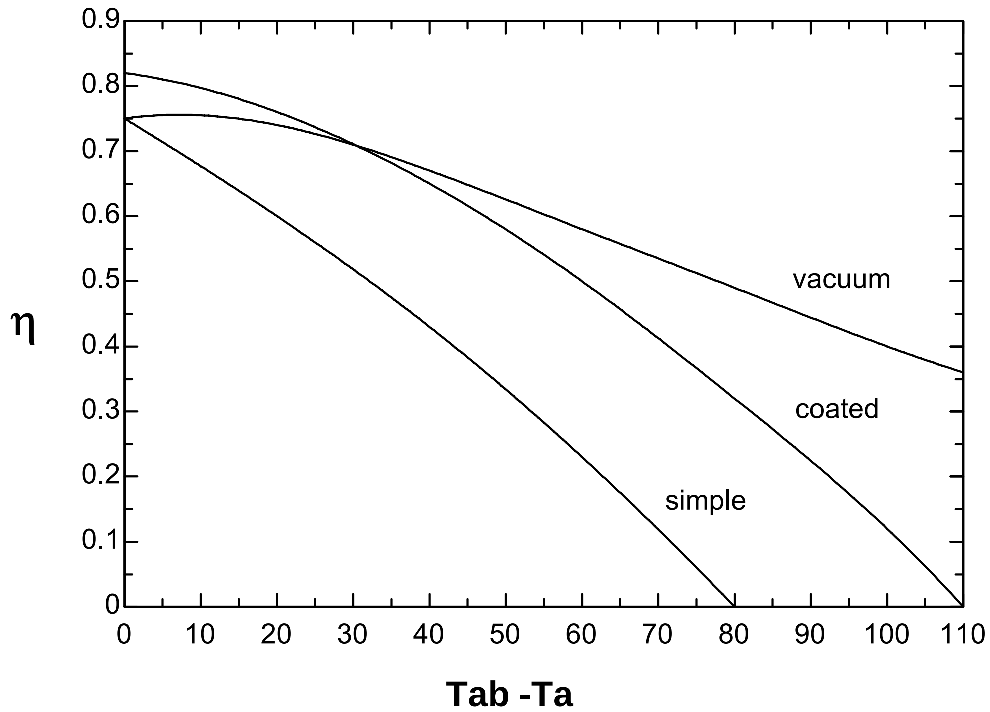
(T_{ab}-T_a) °C	0	20	40	60	80	100	110
Simple collector(η_c)	0.75	0.60	0.43	0.23	0.0	-	-
Coated collector(η_c)	0.82	0.76	0.65	0.50	0.32	0.12	0.0
Evacuated Collector(η_c)	0.75	0.74	0.67	0.58	0.49	0.40	0.36

Given:

The cost of one m^2 is 1000, 2000 and 3000 LE respectively.

- Estimate the mass flow rate of the water pump used with the most economic collector.
- Estimate the new area for the most efficient collector for the same flow rate.

Solution



$$T_{ab} - T_a = \frac{120 + 40}{2} - 35 = 45°C$$

At 45°C η_{simple} = 0.38

$$0.38 = \frac{\dot{m} \times 4.18 \times (120 - 40)}{1 \times 20}$$

$$\dot{m} = 0.0227\ kg/s$$

At 45°C $\eta_{evacuated}$ = 0.65

$$0.65 = \frac{0.0227 \times 4.18 \times (120 - 40)}{1 \times A}$$

A = 11.69 m^2