Energy Auditing: Assessment and Enhancement of Energy Efficiency in Power Plants including Captive Power Plants

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Keynote Presentation: *Seminar organised by*

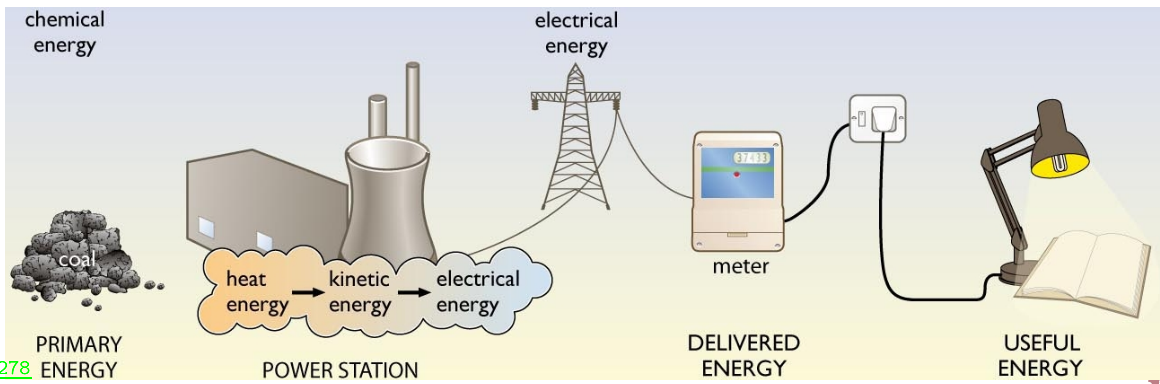
Overview

Self Introduction

1995 - 1998	Ph.D., The University of Leeds, Leeds, UK.
2004 - to date	Professor, Dept. of Mechanical Engineering, BUET.
2024 - to date	Dean, Faculty of Mechanical Engineering, BUET.
2014 - 2016	Head/Chairman, Dept. of Mechanical Engineering, BUET.
2012 - 2014	Director, Centre for Energy Studies, BUET.
2013 - 2015	Member, WG on Energy & Carbon-Footprint, ISO.
2008 - 2009	Member, Board of Directors, Rupantarita Prakitik Gas Co. Ltd.
2007 - 2015	Member, Project Management Board, Haripur GT Power Station.

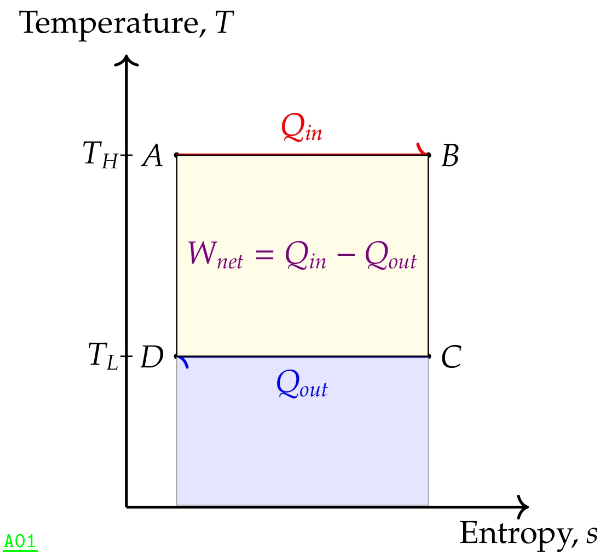
Significance of Effective Use of Energy Resources

Efficiency in energy conversion, as well as an increase in the effective use of renewable energy and waste heat, are critical for ensuring energy security, enhancing industrial productivity, mitigating the effects of global warming, and fulfilling UN's SDG 7.

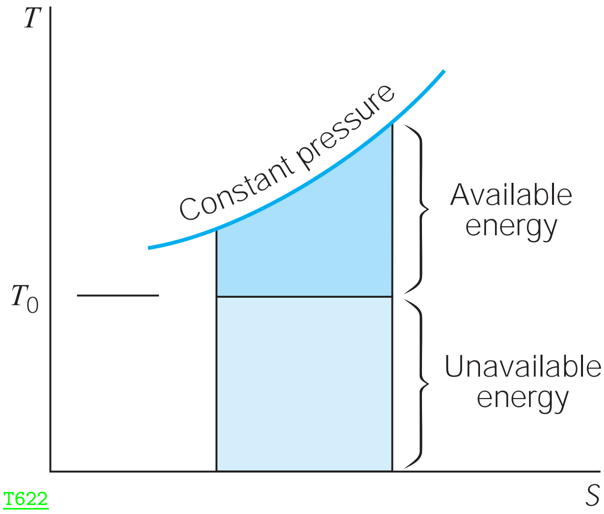


T1278

Effects of Source/Sink Temperatures on Efficiency

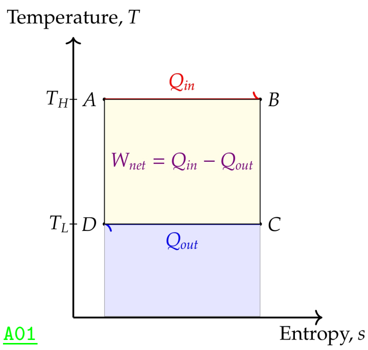


A01

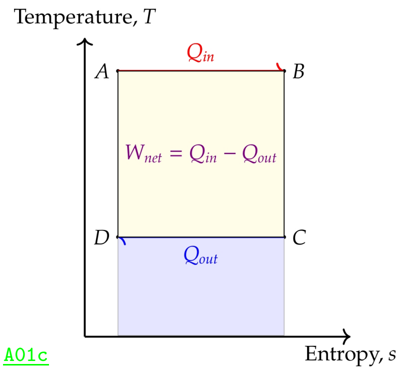


T622

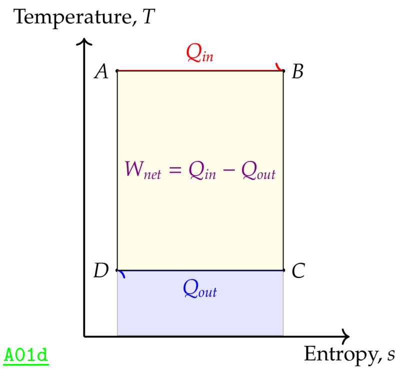
$$\eta_{th} \equiv \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \sim 1 - \frac{T_{L,av}}{T_{H,av}}$$



A01



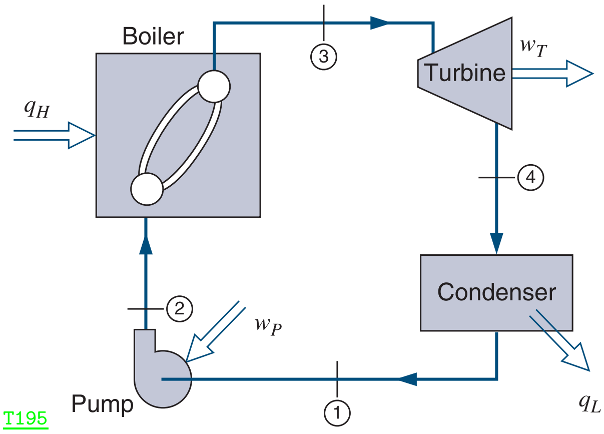
A01c



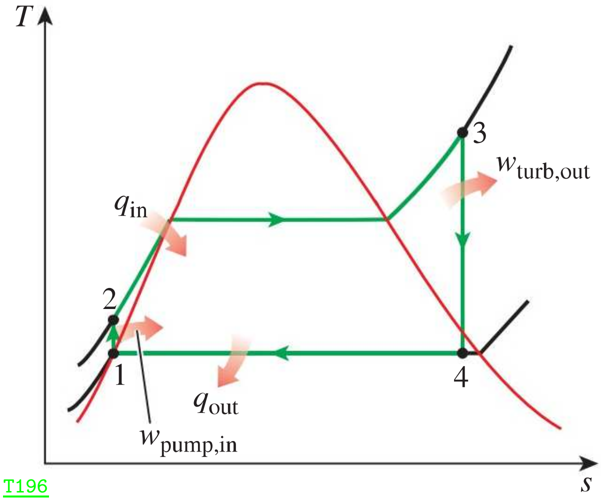
A01d

$$\eta_{th} \equiv \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \sim 1 - \frac{T_{L,av}}{T_{H,av}}$$

Basic Rankine Cycle for Steam Power Plants



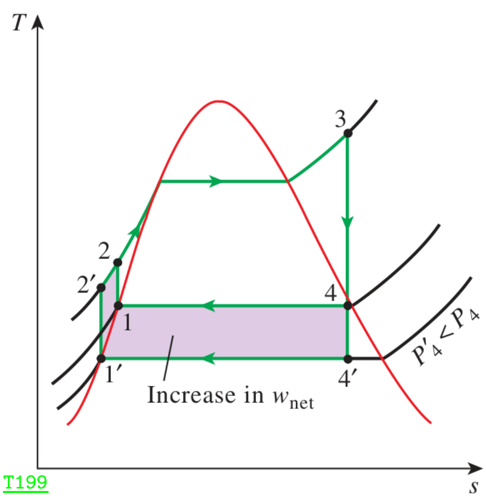
T195



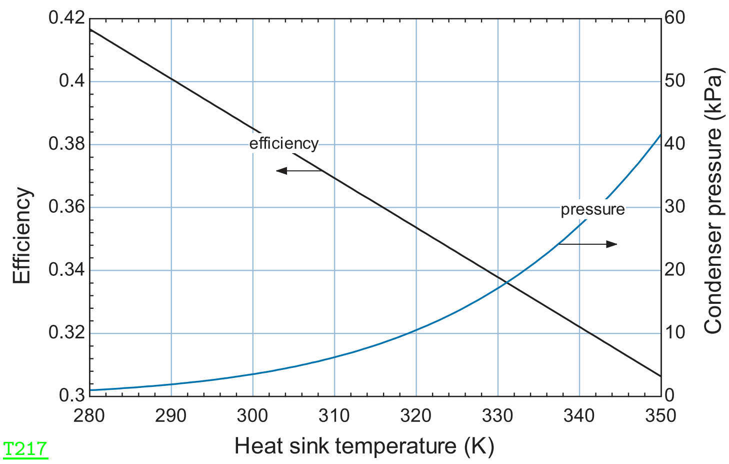
T196

- $1 \longrightarrow 2$: Isentropic compression in a pump
- $2 \longrightarrow 3$: Isobaric heat addition in a boiler
- $3 \longrightarrow 4$: Isentropic expansion in a turbine
- $4 \longrightarrow 1$: Isobaric heat rejection in a condenser

Steam Power Plants: Effect of Condenser Pressure



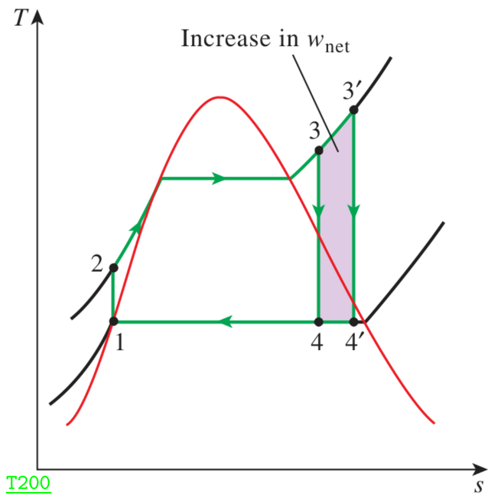
T199



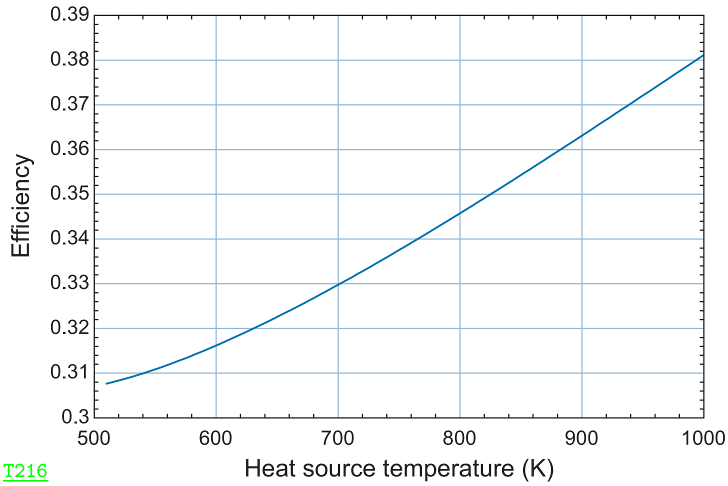
T217

- $P_{cond} = P_{sat}(T_{cond})$: $T_{cond} - T_{atm} \simeq 10 - 15^{o}$C.
- $P_{cond} \downarrow \Longrightarrow w_{net} \uparrow$, $\eta_{th} \uparrow$ & $x_4 \downarrow$. Higher moisture decreases turbine efficiency and erodes its blades. In general, $x_4 \geq 0.9$ is maintained. Lower P_{cond} promotes leakage.

Steam Power Plants: Effect of Steam Superheating



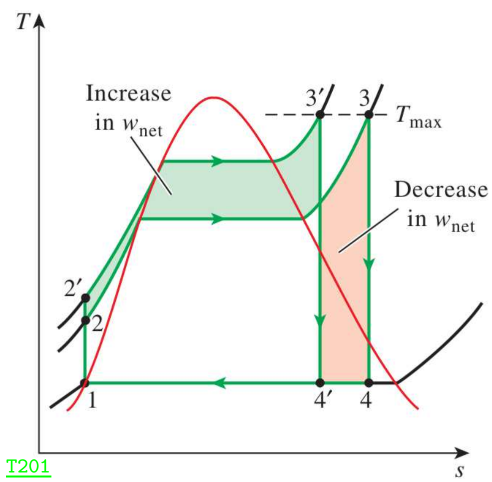
T200



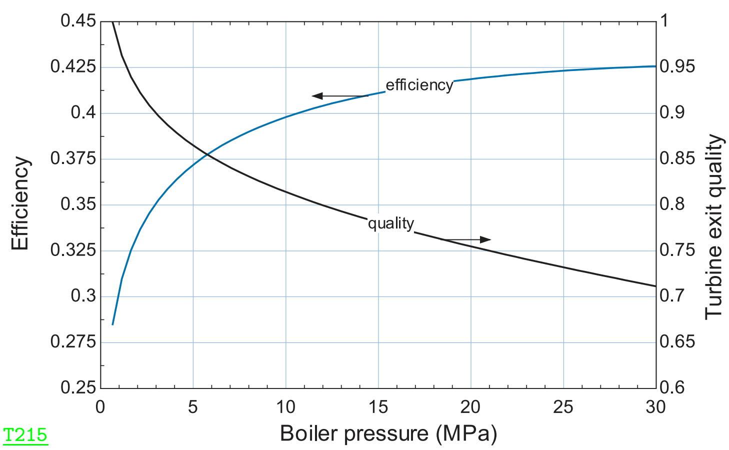
T216

- $T_{max} \uparrow :\Longrightarrow w_{net} \uparrow$, $\eta_{th} \uparrow$ & $x_4 \uparrow$.
- Higher average temperature of heat addition increases η_{th}. T_{max} is limited by metallurgical considerations. In general, $T_{max} = 620^oC$.

Steam Power Plants: Effect of Boiler Pressure



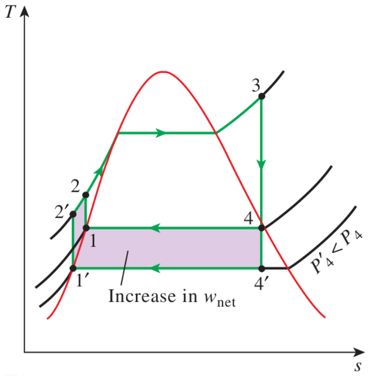
T201



T215

- For fixed T_{max} : $P_B \uparrow :\Longrightarrow \eta_{th} \uparrow$ & $x_4 \downarrow$. Higher η_{th} is achieved because of higher average temperature of heat addition.

Effects of T & P on Rankine Cycle



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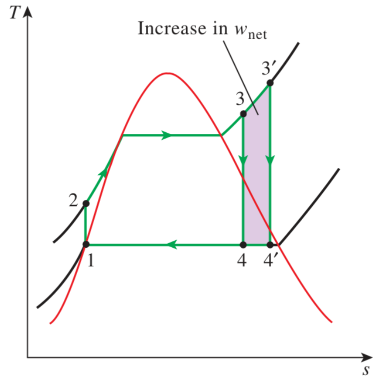

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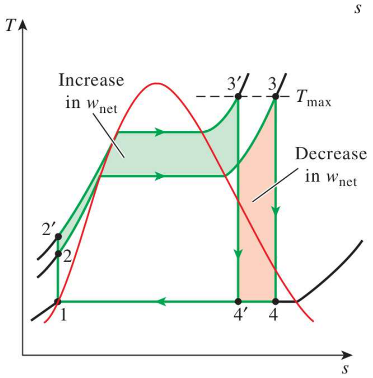


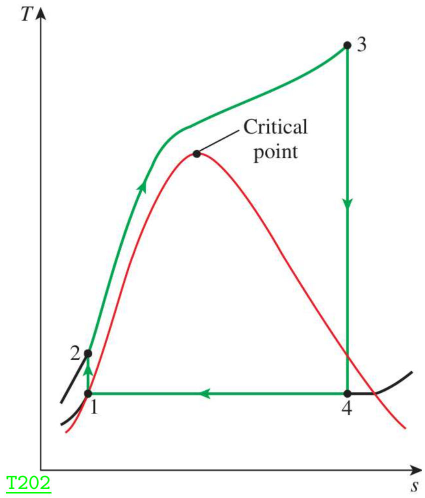
T201

- $P_{cond} \downarrow \rightarrowtail T_{L,av} \downarrow \rightarrowtail \eta_{th} \uparrow$
- $T_{boiler} \uparrow \rightarrowtail T_{H,av} \uparrow \rightarrowtail \eta_{th} \uparrow$
- $P_{boiler} \uparrow \rightarrowtail T_{H,av} \uparrow \rightarrowtail \eta_{th} \uparrow$

Effects of Operating Parameters on Ideal Rankine Cycle Efficiency

Boiler Pressure	[MPa]	3.0	3.0	3.0	15.0
Max. Temperature	[^{o}C]	350	350	600	600
Cond. Pressure	[kPa]	75	10	10	10
Heat added	[kJ/kg]	2727	2920	3487	3375
Turbine work	[kJ/kg]	713	979	1302	1467
Pump work	[kJ/kg]	3.03	3.02	3.02	15.1
Thermal efficiency	[%]	26.0	33.4	37.3	43.0
x_4	[-]	0.886	0.812	0.914	0.804

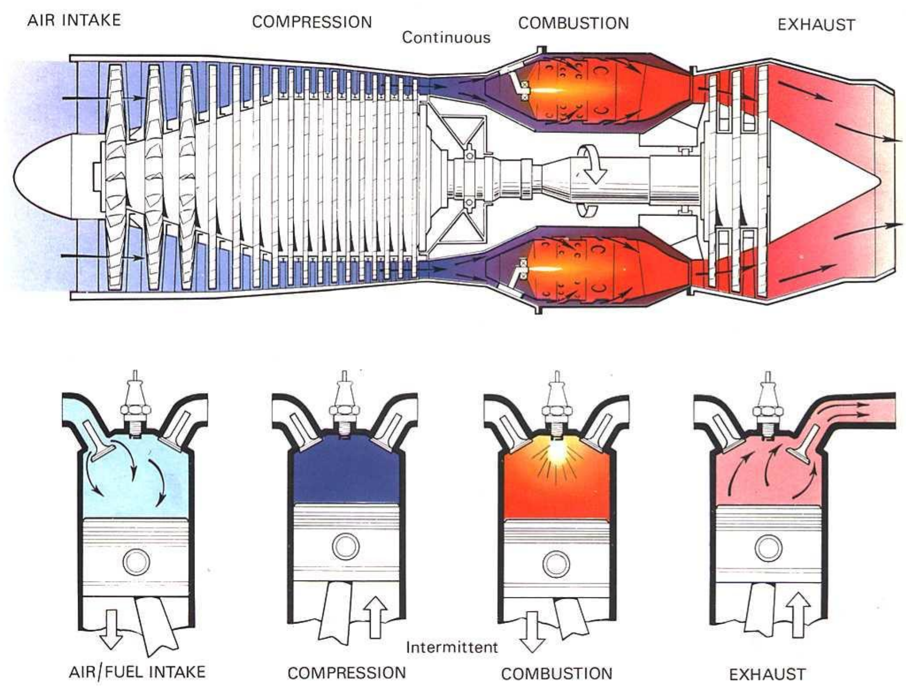
Super-critical Rankine cycle



T202

- Some modern power plants operate at $P \approx 30$ MPa $> P_C = 22.06$ MPa and have
  - $\eta_{th} \sim 40\%$ for fossil-fuel plants,
  - $\eta_{th} \sim 34\%$ for nuclear power plants.
- Lower η_{th} of nuclear power plants are due to lower maximum temperatures used due to safety reasons.

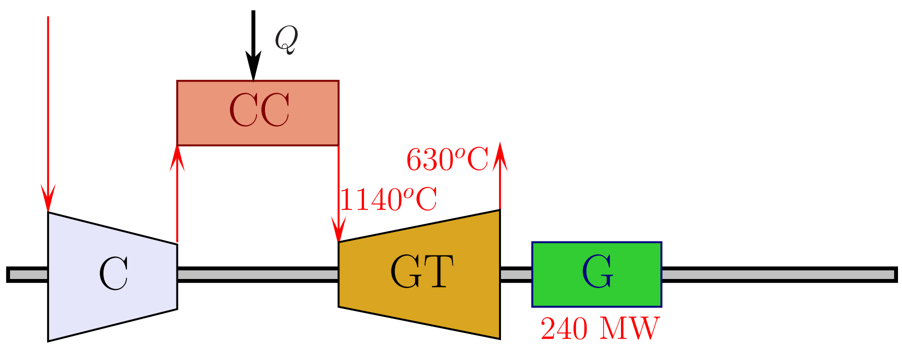
Gas Turbines



T371

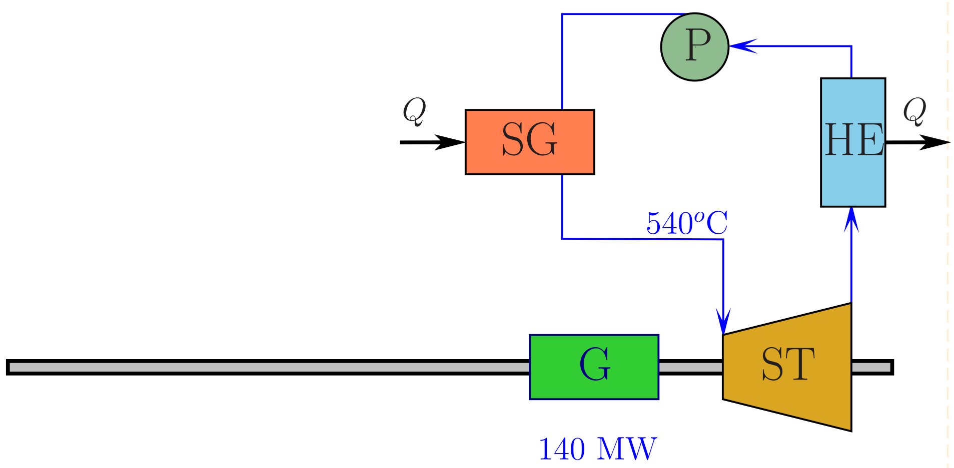
A comparison between Gas turbine and a piston engine cycle

Gas Turbine



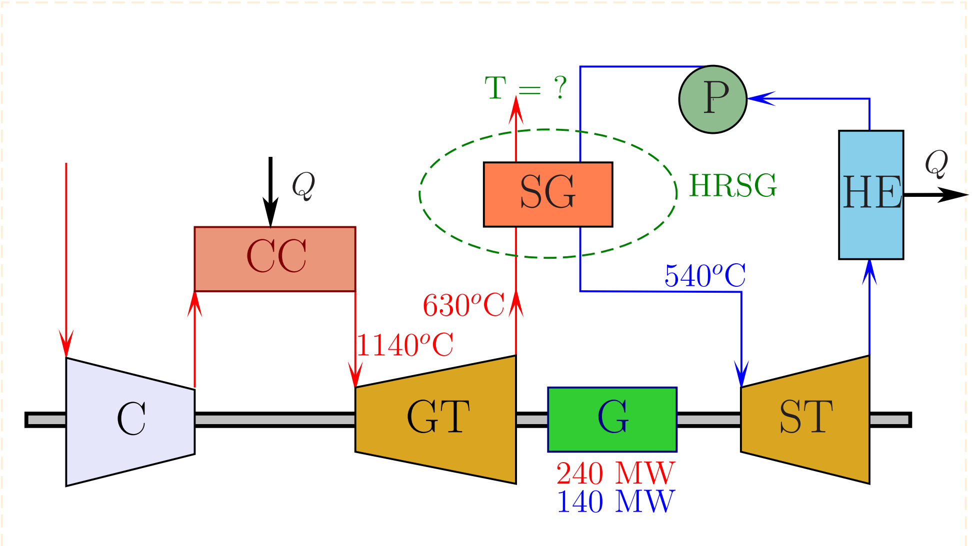
T1340

Steam Turbine



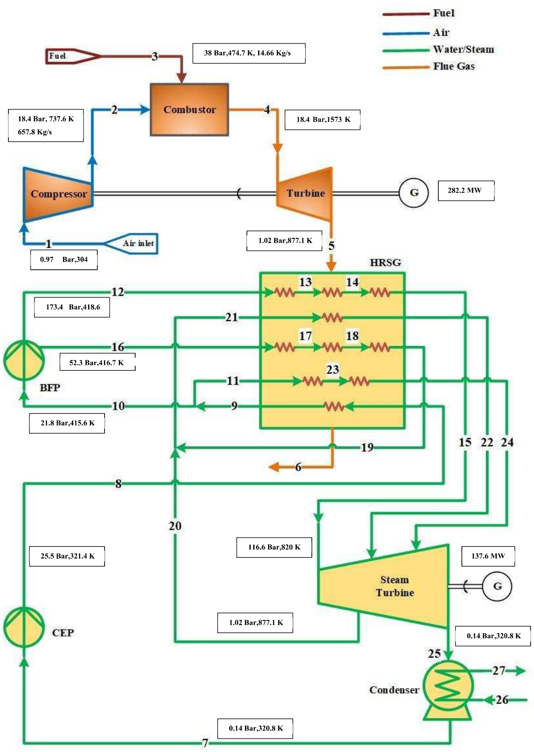
T1341

Combined Cycle

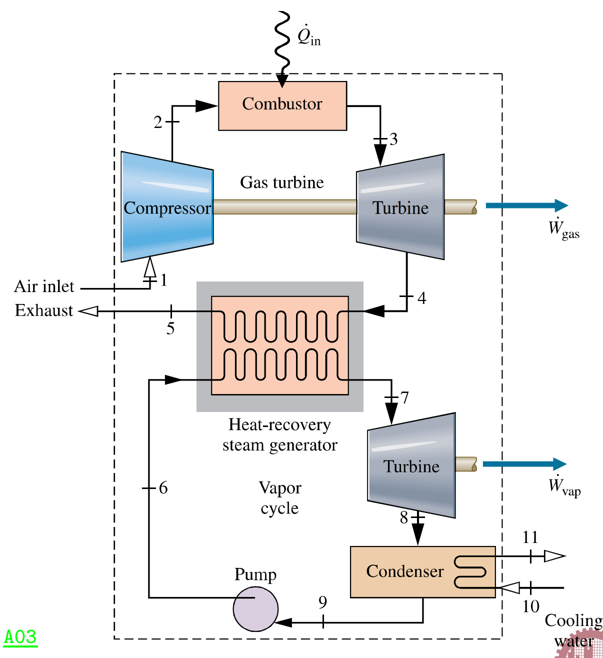


T1342

Case Study: Combined Cycle Power Plant

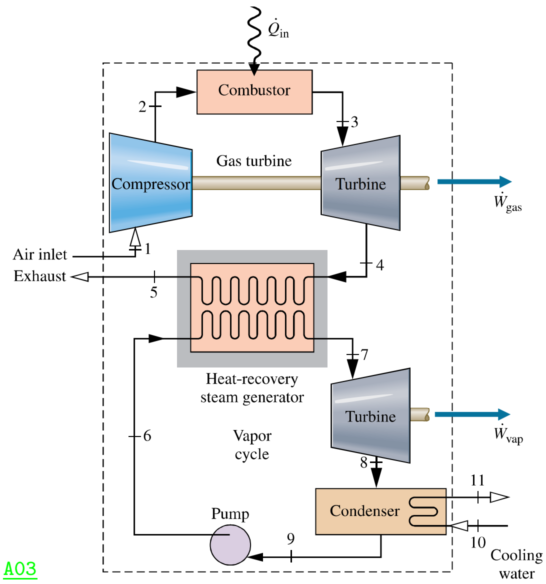


A02

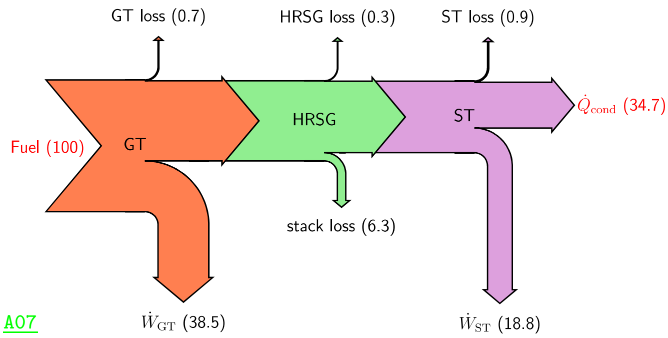


A03

- $\dot{m}_a = 657.8$ kg/s, $\dot{m}_f = 14.66$ kg/s
- $\dot{m}_{w,max} = 105.8$ kg/s, $\dot{m}_{cw} = 10350$ kg/s
- $T_{03} = 1300°C$, $T_{04} = 604°C$, $T_{05} = 94°C$, $T_{07} = 547°C$, $T_{09} = 47.8°C$



A03

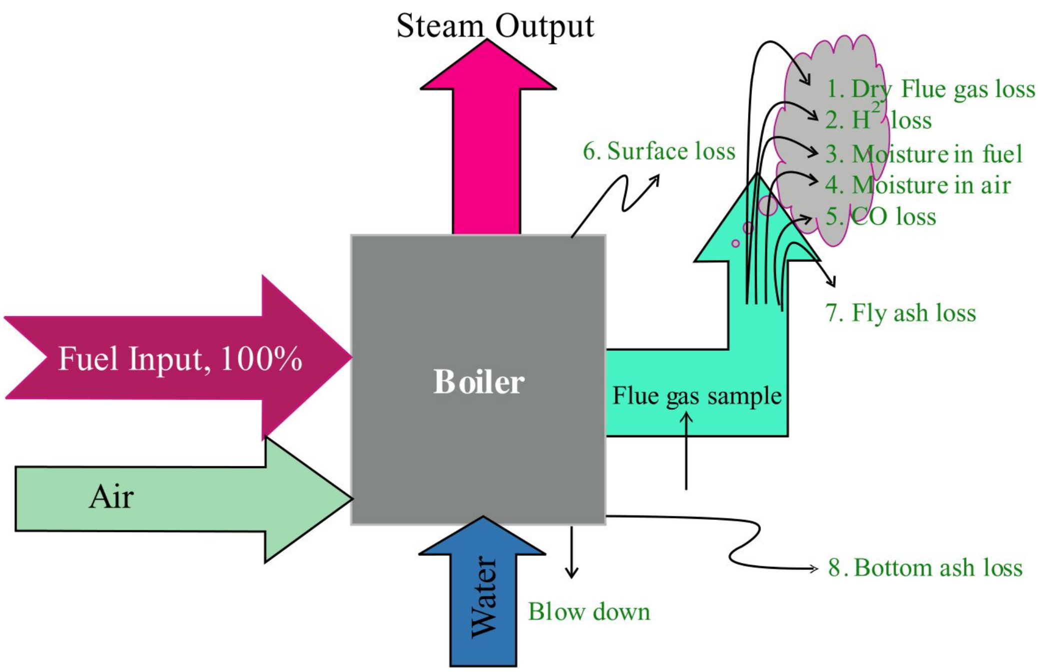


A07

OEM	Model	GT Efficiency(%)	CC Efficiency(%)
MHPS	M701F4	39.9	60.10
MHPS	M701F5	40.0	61.10
GE	9F-5	38.7	60.65
GE	9F-7	41.1	61.25
GE	9HA.01	42.4	62.65
GE	9HA.02	42.7	62.75
Siemens	SGT5-4000F	40.0	58.70
Siemens	SGT5-8000H	40.0	60.50

A04

Boiler Audit: Sources of Losses



T1757

$$Boiler\ efficiency = 100 - \sum L_i$$

The following losses are applicable to liquid, gas and solid fired boiler

- L_1 - Loss due to dry flue gas (sensible heat)
- L_2 - Loss due to hydrogen in fuel (H_2)
- L_3 - Loss due to moisture in fuel (H_2O)
- L_4 - Loss due to moisture in air (H_2O)
- L_5 - Loss due to carbon monoxide (CO)
- L_6 - Loss due to surface radiation, convection & other losses
- L_7 - Unburnt losses in fly ash (carbon)
- L_8 - Unburnt losses in bottom ash (carbon)

L_1 - Loss due to dry flue gas (sensible heat)

$$L_1 = \frac{m_{dg} C_{p,g} (T_f - T_a)}{GCV} \times 100$$

- m_{dg} = Mass of dry flue gas in kg/kg of fuel
- $C_{p,g}$ = Specific heat of flue gas kCal/kg°C
- T_f = Flue gas temperature in °C
- T_a = Ambient temperature in °C
- GCV = Gross calorific value of fuel in kCal/kg

$$m_{dg} = \left(\frac{A}{F}\right)_{A,G,D} + 1 - R - M - 9H_2$$

- R = Ash or residue content of fuel
- M = moisture content of fuel
- H_2 = H_2 content of fuel

L_2 - Loss due to hydrogen in fuel (H_2)

$$L_2 = 9H_2 \left[\frac{585 + C_{p,s}(T_f - T_a)}{GCV}\right] \times 100$$

L_3 - Loss due to moisture in fuel (H_2O))

$$L_3 = M \left[\frac{585 + C_{p,s}(T_f - T_a)}{GCV}\right] \times 100$$

L_4 - Loss due to moisture in air (H_2O))

$$L_4 = \omega \left(\frac{A}{F}\right)_{A,G,D} \left[\frac{C_{p,s}(T_f - T_a)}{GCV}\right] \times 100$$

- $C_{p,s}$ = Specific heat of steam kCal/kg°C
- ω = Humidity ratio of air kg-water/kg-dry-air

L_5 - Loss due to partial conversion of C to CO

$$L_5 = \frac{\%CO \times C}{\%CO + \%CO_2} \left[\frac{5654}{GCV}\right] \times 100$$

L_6 - Loss due to surface radiation, convection and other unaccounted losses

$$L_{loss} = 0.548 \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] + 1.957(T_s - T_a)^{1.25} \left[\frac{196.85\,V_m + 68.9}{68.9}\right]^{0.5} \text{W/m}^2$$

$$L_s = \frac{L_{loss} \times A}{m_f \times GCV}$$

L_7 - Unburnt losses in fly ash (carbon)

$$L_7 = \frac{m_{fly\ ash} \times GCV_{fly\ ash}}{GCV} \times 100$$

L_8 - Unburnt losses in bottom ash (carbon)

$$L_8 = \frac{m_{bottom\ ash} \times GCV_{bottom\ ash}}{GCV} \times 100$$

Boiler Efficiency Calculation

Fuel Analysis (in %)

Ash	=	48
Moisture	=	4.4
Carbon	=	36
Hydrogen	=	2.6
Nitrogen	=	1.1
Oxygen	=	7.3
Sulphur	=	0.6
GCV	=	3501 kcal/kg

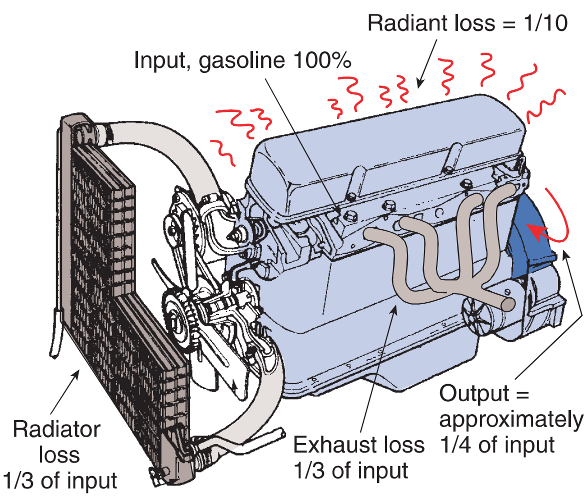
T1780

Fuel firing rate	=	5600 kg/hr
Steam generation rate	=	21940 kg/hr
Steam pressure	=	43 kg/cm^2 (g)
Steam temperature	=	377 °C
Feed water temperature	=	96 °C
%CO_2 in Flue gas	=	14
%CO in flue gas	=	0.55
Average flue gas temperature	=	190 °C
Ambient temperature	=	31 °C
Humidity in ambient air	=	0.0204 kg / kg dry air
Surface temperature of boiler	=	70 °C
Wind velocity around the boiler	=	3.5 m/s
Total surface area of boiler	=	90 m^2
GCV of Bottom ash	=	800 kcal/kg
GCV of fly ash	=	450 kcal/kg
Ratio of bottom ash to fly ash	=	90:10

T1779

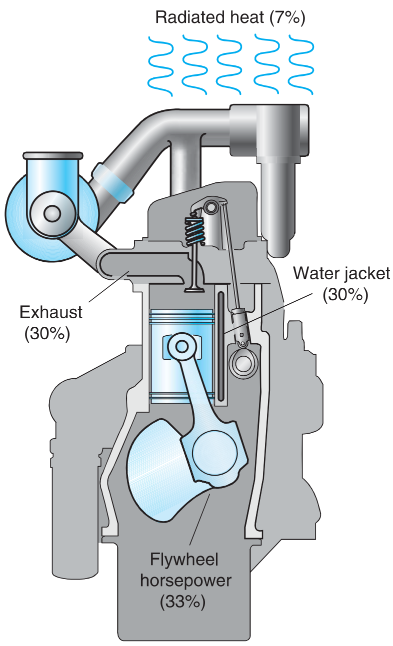
[η = 100 - (7.1+4.37+0.82+0.25+2.2+0.37+0.62+9.98) = 74.4%]

Engine Energy Balance



T918

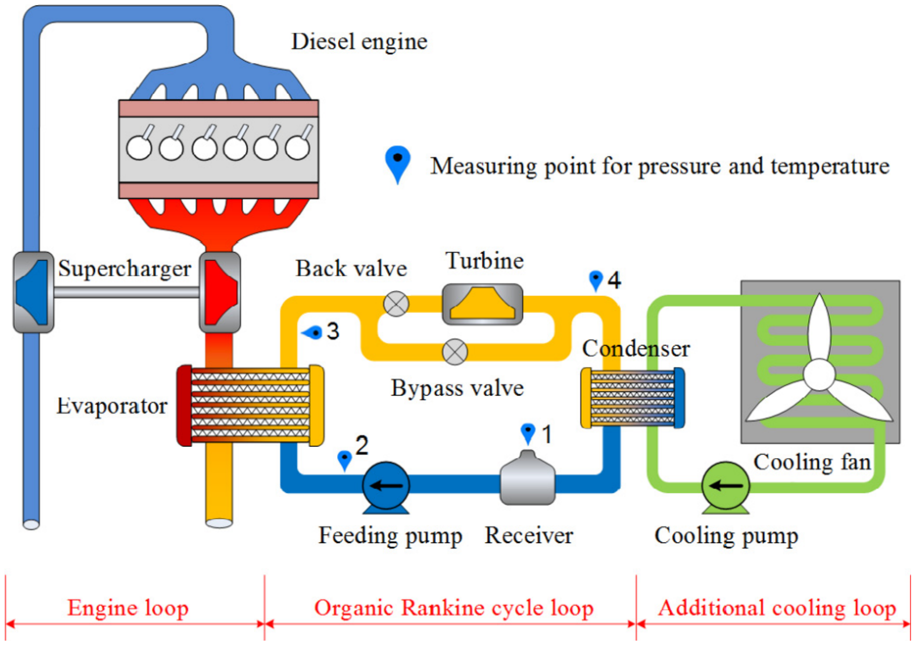
SI Engine



T919

CI Engine

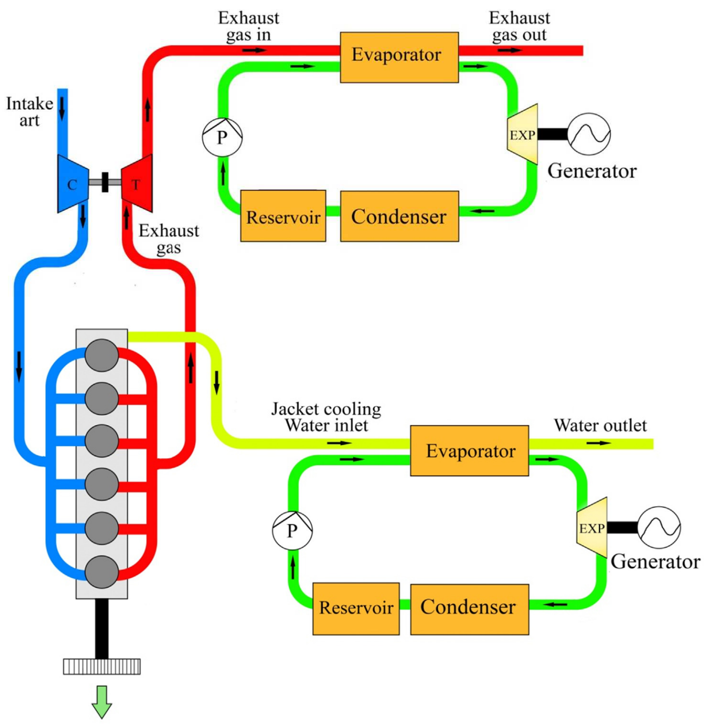
Engine WHR using ORC



A05

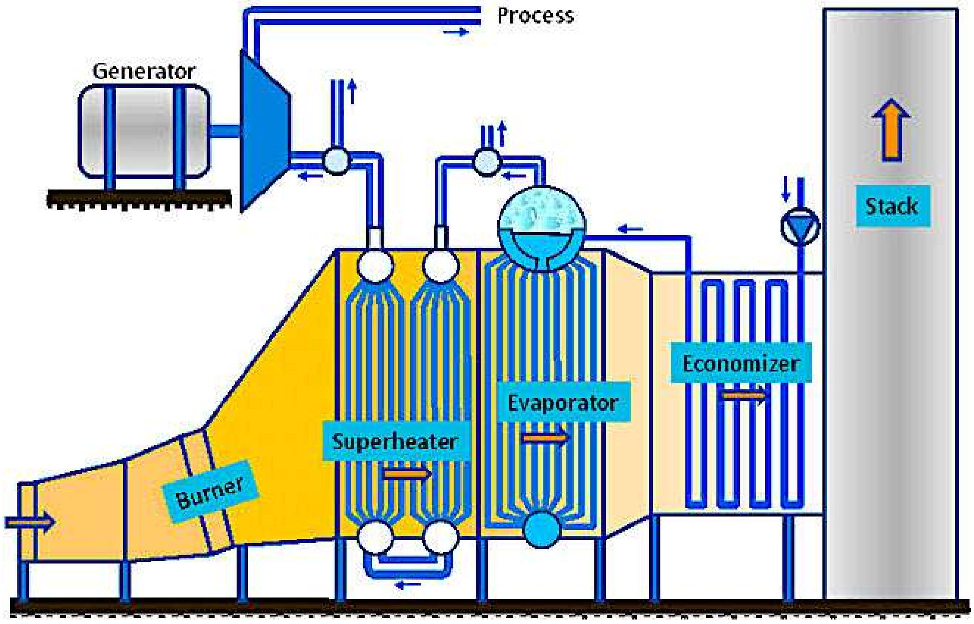
Engine Waste Heat Recovery (WHR)

Engine WHR using ORC



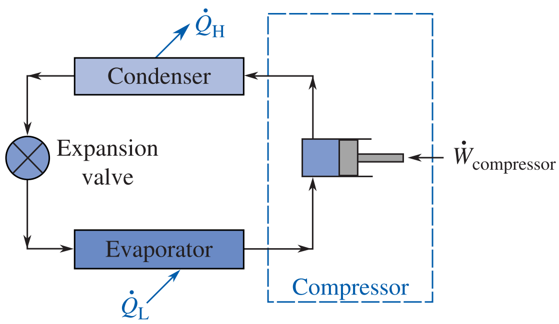
T1745

Waste Heat Recovery Boilers

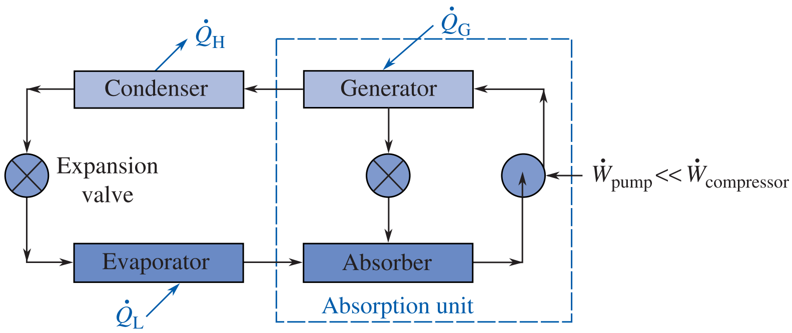


A06

Absorption Chillers using WH



(a) Standard vapor-compression refrigeration.



T272

(b) Absorption vapor-compression refrigeration.

Thanks a Lot!