Thermodynamics of Power Generation: Rationale for Exergy

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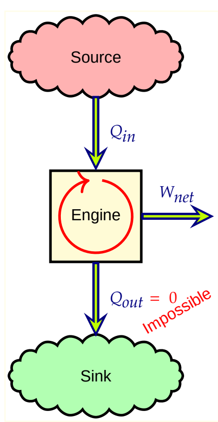
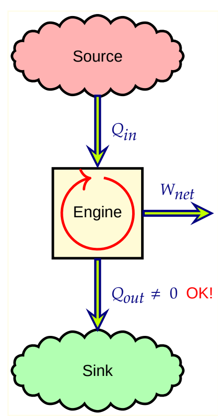
Overview

> *Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, so it doesn't bother you any more.*
>
> **Arnold Sommerfeld**

2^{nd} Law of Thermodynamics



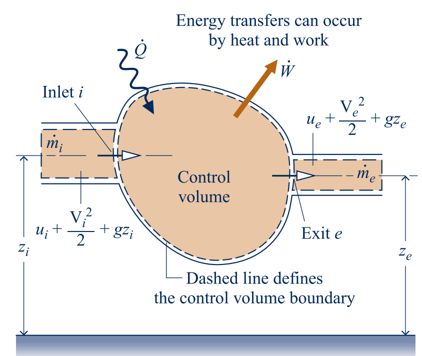
F001



F002

$$\text{Thermal efficiency, } \eta_{th} \equiv \frac{W_{net}}{Q_{in}} < 1.0$$

Conservation of Energy: 1^{st} Law of Thermodynamics

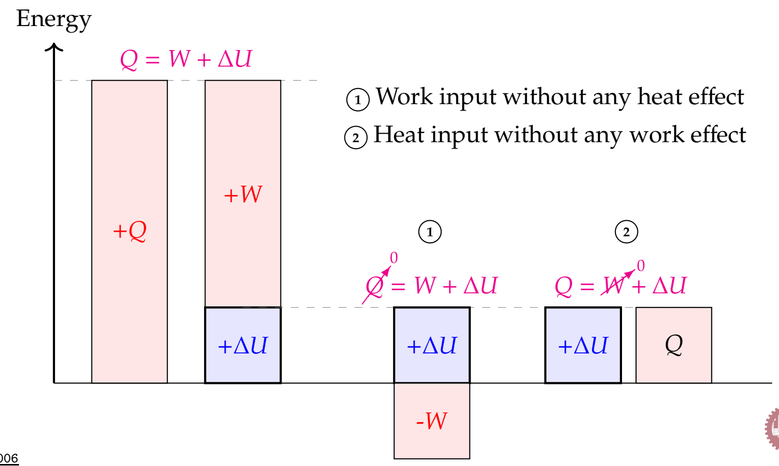


T099

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \dot{m}_i\left(u_i + \frac{\mathbb{V}_i^2}{2} + gz_i\right) - \dot{m}_e\left(u_e + \frac{\mathbb{V}_e^2}{2} + gz_e\right)$$
$$= \dot{Q} - \dot{W}_{cv} + \dot{m}_i\left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e\right)$$

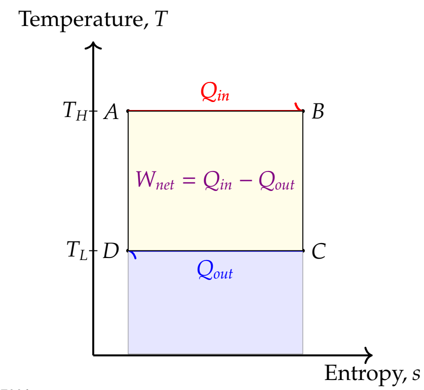
A. Cyclic process: $\oint \delta W = \oint \delta Q \Longrightarrow W_{net} = Q_{net}$

B. Non-flow process: $Q = W + \Delta U$

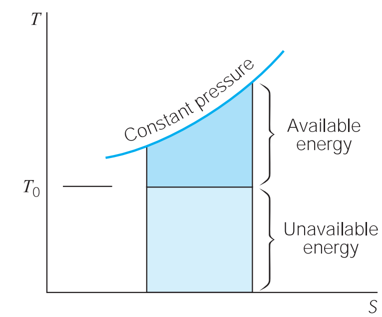


F006

Effects of Reservoir Temperatures on Efficiency

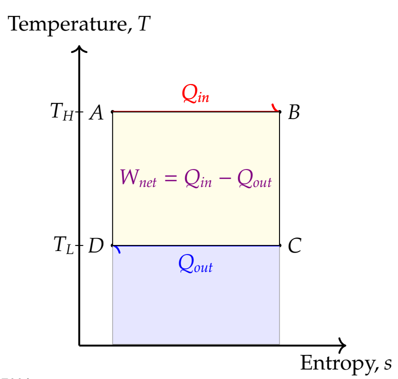


F004

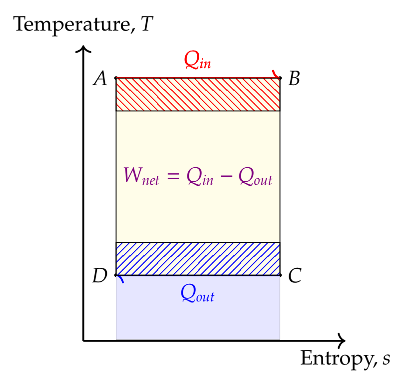


T622

$$\eta_{th} \equiv \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$



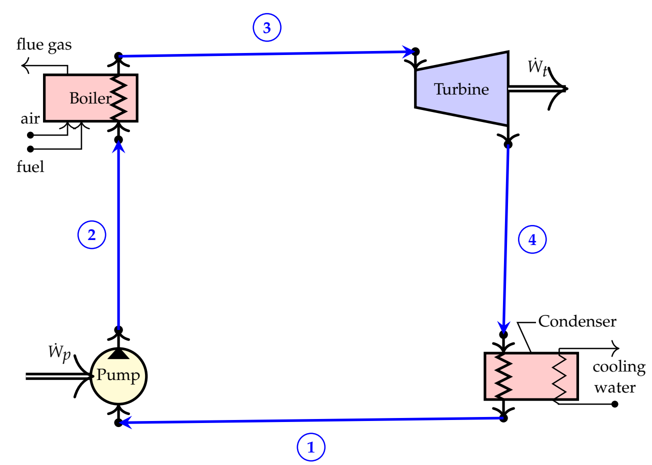
F004



F005

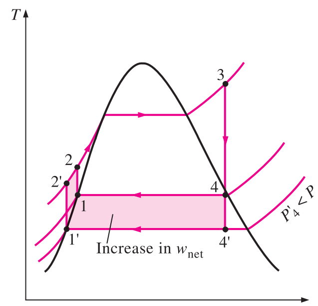
- $T_H \uparrow \ \mapsto \eta_{th} \uparrow$
- $T_L \downarrow \ \mapsto \eta_{th} \uparrow$

Components of a Simple Vapour Power Plant

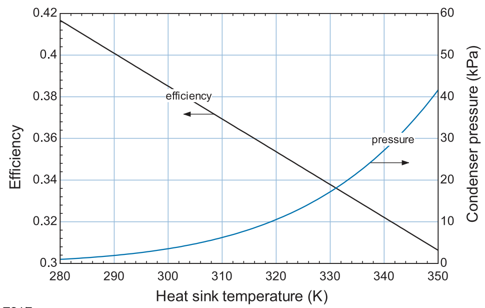


F003

Thermal Power Plants: Effect of Condenser Pressure



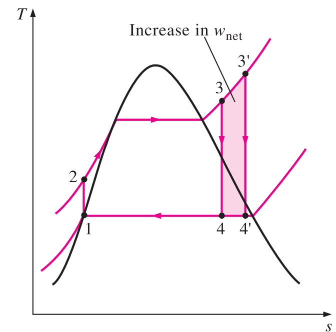
T199



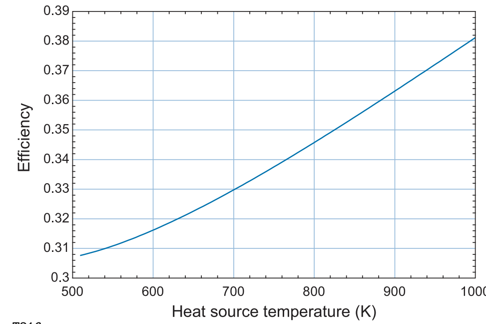
T217

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

Thermal Power Plants: Effect of Steam Superheating



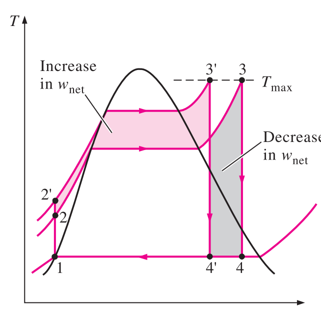
T200



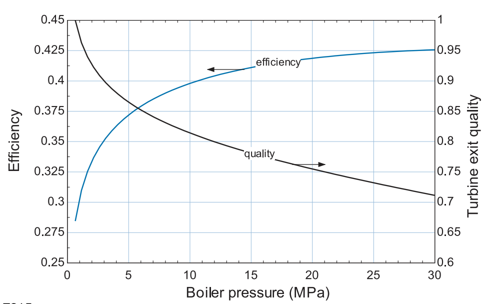
T216

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

Thermal 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 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

Energy: Quantity & Quality

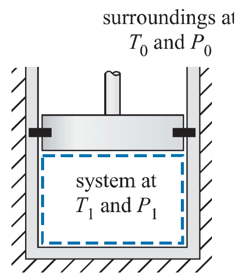
- *Quality of energy* is its potential to produce useful work.
- **First Law of Thermodynamics:**
  energy is conserved in all (non-nuclear) processes.
- **Second Law of Thermodynamics:**
  the quality of energy is reduced in all real processes.

⇒ During transformation and transfer, energy is both conserved and degraded.

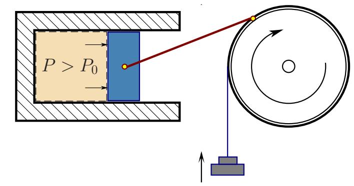
⇒ Exergy provides a direct relationship between the thermodynamic state of a system and its capability to do useful work.

⇒ **Exergy** is defined a the maximum work potential of a system at a given state as it proceeds towards a state of equilibrium with the environment while exchanging heat solely with environment.

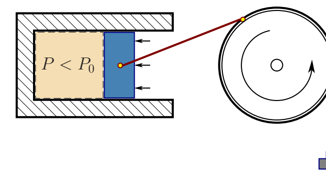
Exergy Concept



T621

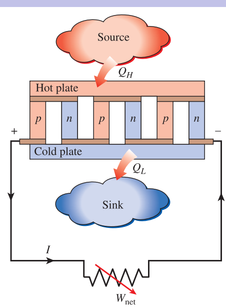


F008



F009

When the pressure, temperature, composition, velocity, or elevation of a system is different from the environment, there is an opportunity to develop work.



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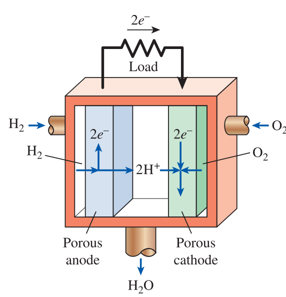
F014

Standard atmosphere

- $P_0 = 100$ kPa, $T_0 = 300$ K
- relative humidity, $\phi = 100\%$

Species	Mole fraction	Mass fraction
N_2	0.78084	0.75520
O_2	0.20947	0.23143
Ar	0.00934	0.01288
CO_2	0.00031	0.00048



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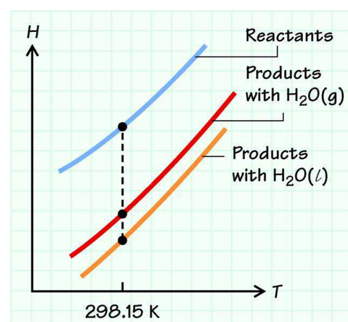
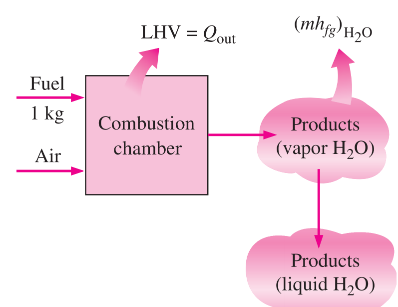
Heat Release Parameters

$$\dot{Q}_{in} = \dot{m} \times HV$$



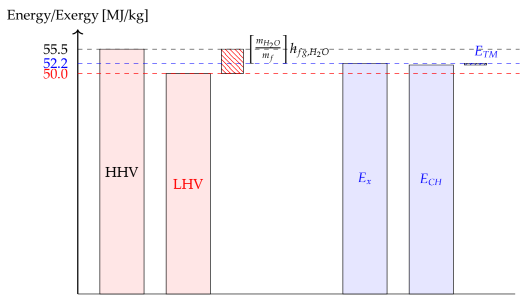
T299



T304

$$Q_{HHV,P} = Q_{LHV,P} + \left[\frac{m_{H_2O}}{m_f}\right] h_{fg,H_2O}$$

Methane: Energy Availability



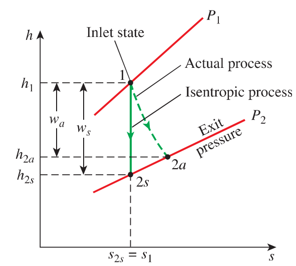
F011

$$E_{x,TM} = (h - h_0) - T_0(s - s_0)$$
$$E_{x,CH} = \sum X_k E_{x,CH,k} + RT_0 \sum X_k \ln X_k \quad \text{Env. species}$$
$$= -\Delta G + \sum_P \nu_k E_{x,CH,k} - \sum_R \nu_k E_{x,CH,k} \quad \text{Non-Env. species}$$
$$E_x = E_{x,CH} + E_{x,TM}$$

Revisiting Energy Efficiency

- Thermal Efficiency, $\eta_{th} = \frac{W_{net}}{Q_{in}}$
- Isentropic Efficiency or First Law Efficiency, η_I

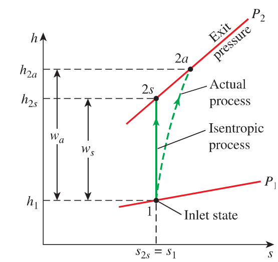
Turbine



T623

$$\eta_I = \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$

Compressor

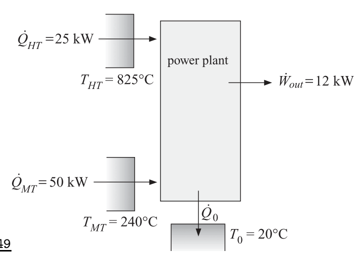


T624

$$\eta_I = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

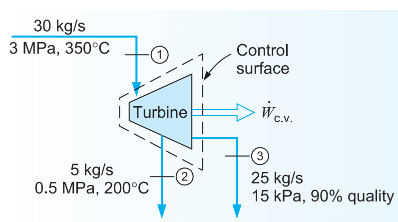
- A performance parameter based on the exergy concept is know as Second Law Efficiency (η_{II}) or as Second Law Effectiveness (ϵ).

$$\eta_{II} \equiv \epsilon \equiv \frac{\text{useful exergy out}}{\text{exergy in}} = 1 - \frac{\text{exergy destruction}}{\text{exergy in}}$$



T349

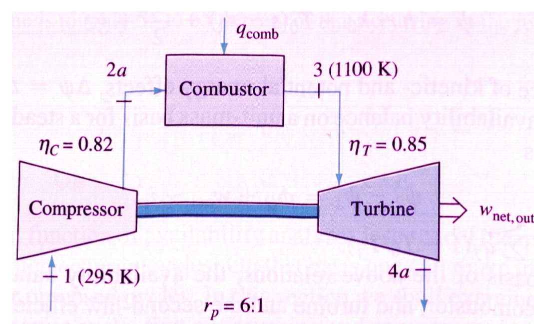
- $\eta_I = \frac{W_{out}}{Q_{HT}+Q_{MT}} = \frac{12}{25+50} = 16\%$
- $\Phi_{Q,HT} = 25\left(1 - \frac{293}{1098}\right) = 18.33$
- $\phi_{Q,MT} = 50\left(1 - \frac{293}{513}\right) = 21.44$
- $\eta_{II} = \frac{W_{out}}{E_{x,Q,HT}+E_{x,Q,MT}} = 30.2\%$



T351

- $\eta_I = 79.9\%$
- $\eta_{II} = 81.9\%$

Example: Gas Turbine Cycle Analysis

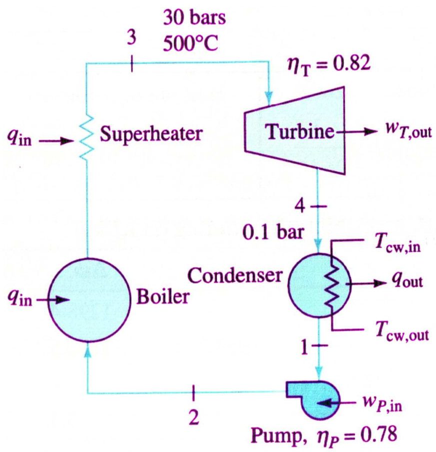


T493

$\Longrightarrow \eta = \frac{w_{net,out}}{q_{comb}} = \frac{144.1}{655} = 21.9\%$ ◀

$\Longrightarrow \epsilon = \frac{w_{net,out}}{E_{x,Q}} = \frac{144.1}{399.9} = 36.0\%$ ◀

Example: Simple Steam Power Cycle Analysis

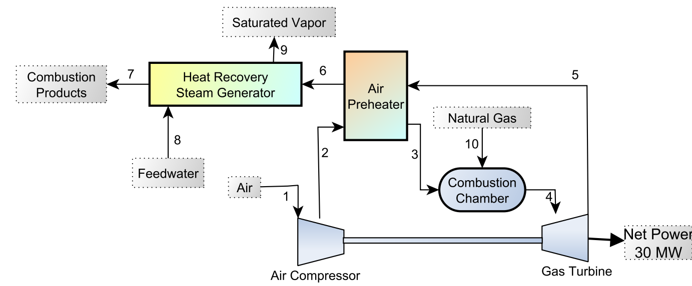


T494

$\Longrightarrow \eta = \frac{w_{net,out}}{q_{comb}} = 29.1\%$ ◀

$\Longrightarrow \epsilon = \frac{w_{net,out}}{\Phi_Q} = 73.1\%$ ◀

Example: Cogeneration



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state	fluid	$\dot{m}$ [kg/s]	P [bar]	T[K]	E_n [MW]	E_x [MW]
1	air	91.27	1.01	298	0.0	0.0
2	air	91.27	10.13	604	29.73	27.63
3	air	91.27	9.53	850	53.71	41.34
4	combut. prod.	92.92	9.05	1520	134.36	101.77
5	combut. prod.	92.92	1.01	1010	72.56	39.04
6	combut. prod.	92.92	1.01	794	50.65	22.77
7	combut. prod.	92.92	1.01	429	11.93	3.53
8	water	14.0	20	298	0	0.03
9	water	14.0	20	485	11.25	12.83
10	methane	1.64	12	298	79.12	82.73

Thanks a Lot