Technische Universität Berlin
Institute for Energy Engineering

Exergy Analysis

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Energy-Based Thermodynamic Analysis

- **Identifies only energy transfers to the environment as thermodynamic inefficiencies**
- **Fails to identify any inefficiencies in an adiabatic process (e.g., throttling valve)**
- **Misleads the engineer by considering as an inefficiency the heat rejection to the environment dictated by the second-law of thermodynamics (e.g., Carnot process)**

There is a need for an additional concept.

EXERGY - Definition

Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable from a thermal system as it is brought into thermodynamic equilibrium with the environment while interacting with the environment only.

Exergy is a measure of the quality of energy and also of the departure of the state of the system from the state of the environment.

Exergy represents the useful part of energy for processes operating above the ambient temperature.

ENVIRONMENT - Definition

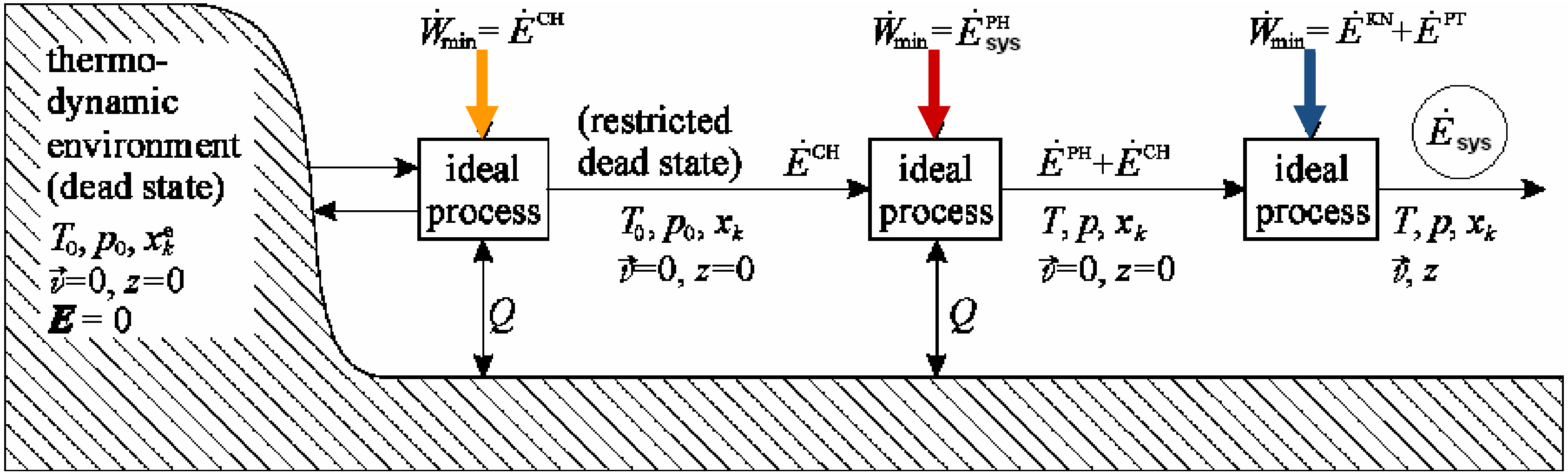
Large equilibrium system in which the state variables (T_0 , p_0) and the chemical potential of the chemical components (μ_0) contained in it remain constant, when, in a thermodynamic process, heat and materials are exchanged between another system and the environment.

No chemical reactions can take place between the environmental chemical components.

The environment is free of irreversibilities.

The exergy of the environment is equal to zero.

Exergy Components



Total exergy of a system

$$E_{sys} = E^{CH} + E^{PH}_{sys} + E^{KN} + E^{PT} + \left[E^{N} + E^{MG} + E^{EL} + E^{ST}\right]$$

Total specific exergy on a mass basis

$$e_{sys} = e^{CH} + e^{PH}_{sys} + e^{KN} + e^{PT}$$

Exergy Components: E^{KN} and E^{PT}

Kinetic exergy

$$E^{KN} = \frac{1}{2} m \vec{v}^2$$

Potential exergy

$$E^{PT} = mgz$$

where

m – mass; g – gravitational acceleration;

$\vec{v}$ – velocity; z - elevation

Exergy Components: E^{PH}

Physical exergy **is the maximum theoretical useful work obtainable as the system passes from its initial state (T, p, μ) to the restricted dead state (T_0, p_0, μ)**

Physical exergy associated with a system

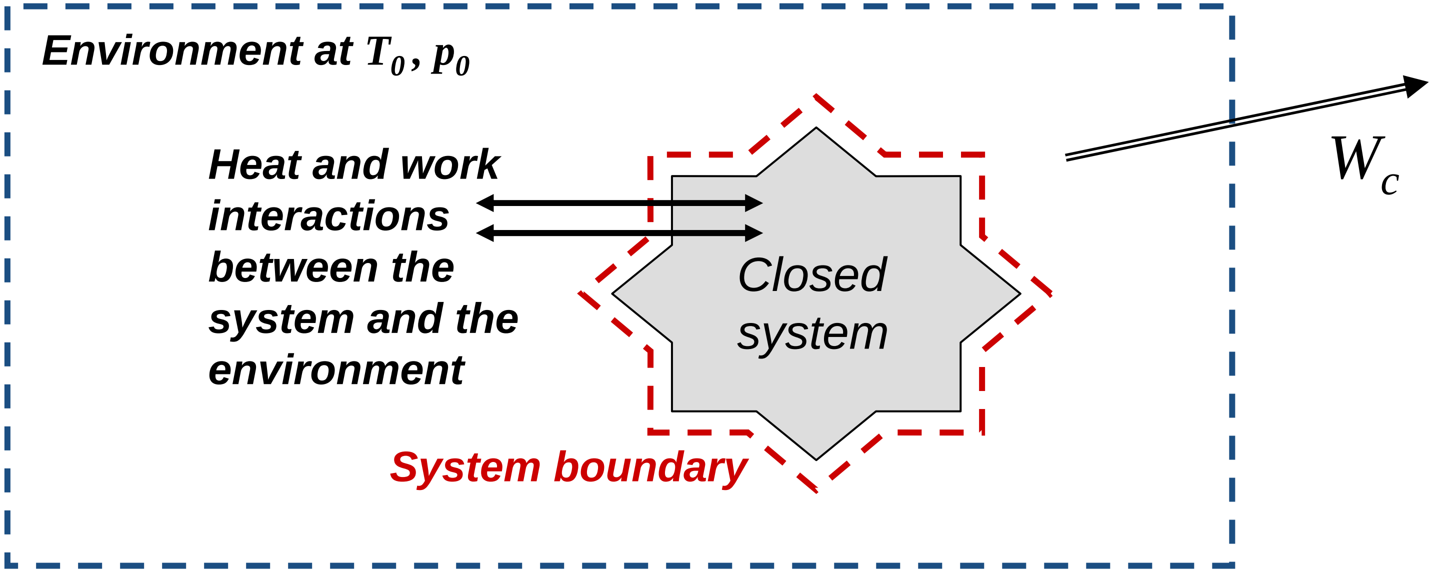
$$E_{sys}^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0)$$

Physical exergy associated with a material stream

$$\dot{E}_{ms}^{PH} = (\dot{H} - \dot{H}_0) - T_0(\dot{S} - \dot{S}_0)$$

Exergy Components: E^{PH}

Boundary of the combined system. Only work interactions are allowed. Total volume is constant.

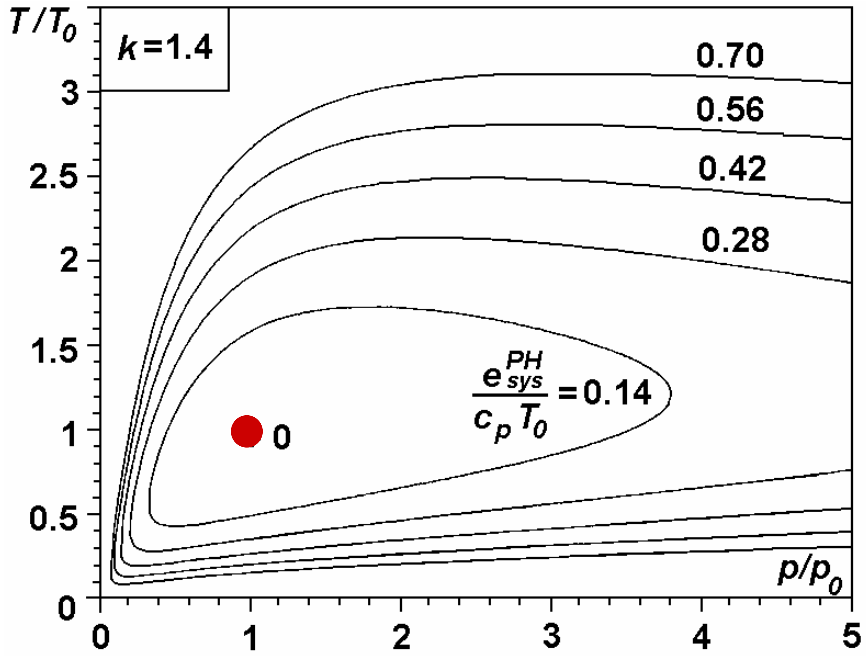


$$W_c = \underbrace{(U - U_0) + p_0(V - V_0) - T_0(S - S_0)} - T_0 S_{gen}$$

Exergy Components: E^{PH}

Physical exergy of a system **consisting of an ideal gas with constant specific heat ratio** $k = c_p / c_v$

$$\frac{e_{sys}^{PH}}{c_p T_0} = \frac{T}{T_0} - 1 - \ln\frac{T}{T_0} + \frac{k-1}{k}\left[\ln\frac{p}{p_0} + \frac{T}{T_0}\left(\frac{p}{p_0} - 1\right)\right]$$

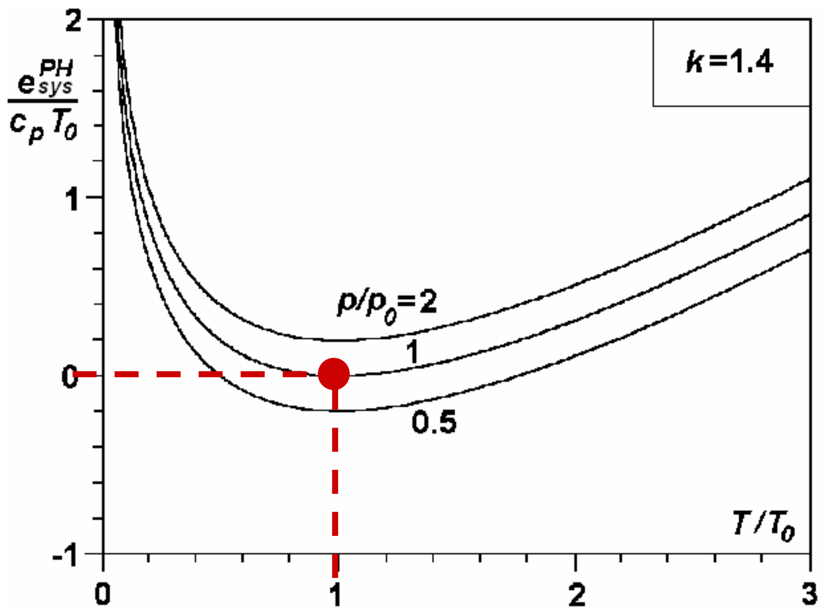


Exergy Components: E^{PH}

Physical exergy associated with a material stream

$$e_{ms}^{PH} = (h - h_0) - T_0 (s - s_0)$$

Physical exergy of a material stream **consisting of an ideal gas with constant specific heat ratio** $k = c_p / c_v$



$$\frac{e_{ms}^{PH}}{c_p T_0} = \underbrace{\left[\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right]}_{\text{Thermal exergy}} + \underbrace{\ln \left(\frac{p}{p_0} - 1 \right)^{\frac{k-1}{k}}}_{\text{Mechanical exergy}}$$

Exergy Components: $E^{PH} = E^{T} + E^{M}$

Physical exergy **associated with material streams on a mass basis**

$$e_{ms}^{PH} = h - h_0 - T_0 (s - s_0)$$

$$e_{ms}^{PH} = e_{ms}^{T} + e_{ms}^{M}$$

$$T \neq T_0$$

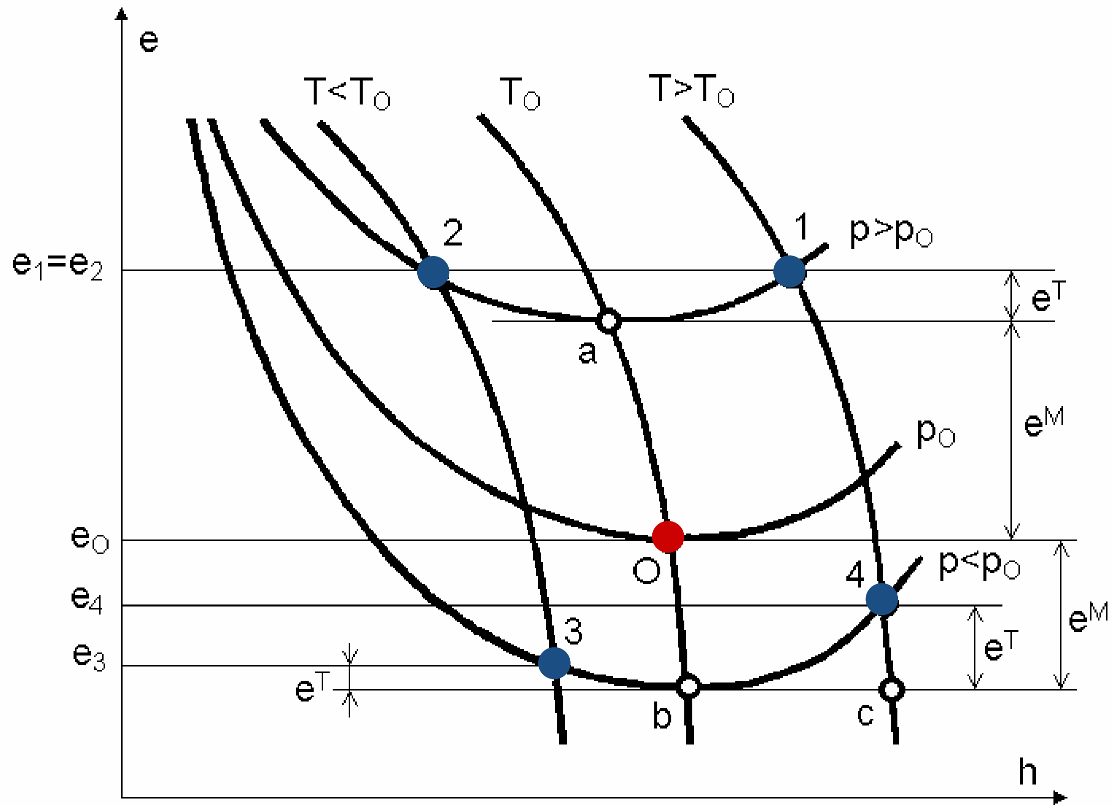
Thermal component
of physical exergy

$$p \neq p_O$$

Mechanical component
of physical exergy

Exergy Components: $E^{PH} = E^{T} + E^{M}$

Thermal and mechanical components of physical exergy



Point 1 - $T_1 > T_0;\ p_1 > p_0;$
$e_1^T = e_1 - e_a;\ e_1^M = e_a - e_0;$
$e_1^T + e_1^M = e_1 - e_0$

Point 2 - $T_2 < T_0;\ p_2 > p_0;$
$e_2^T = e_2 - e_a;\ e_2^M = e_a - e_0$

Point 3 - $T_3 < T_0;\ p_3 < p_0;$
$e_3^T = e_3 - e_b;\ e_3^M = e_b - e_0;$
$e_3^T + e_3^M = e_3;\ e_3^M < 0;\ e_3^T > 0$

Point 4 - $T_4 > T_0;\ p_4 < p_0;$
$e_4^T = e_4 - e_c;\ e_4^M = e_c - e_0$

Exergy Components: $E^{PH} = E^{T} + E^{M}$

Splitting the physical exergy into its thermal and mechanical components for engineering calculations, for any position of point being considered (p, T, h, s)

$$e_{ms}^{PH} = \underbrace{(h - h^*) - T_O (s - s^*)}_{e^T} + \underbrace{T_O (s_O - s^*) - (h_O - h^*)_{T_O = const}}_{e^M}$$

- **thermodynamic parameters in the *point being considered* (p, T, h, s),**
- **thermodynamic parameters in the point *0* (p_0, T_0, h_0, s_0),**
- **values of enthalpy (h^*) and entropy (s^*) in point ∗ where $p^* = p$ and $T^* = T_0$**

Exergy Components: E^{CH}

Chemical exergy **is the maximum useful work as the system at temperature T_0 and pressure p_0 is brought into chemical equilibrium with the environment.**

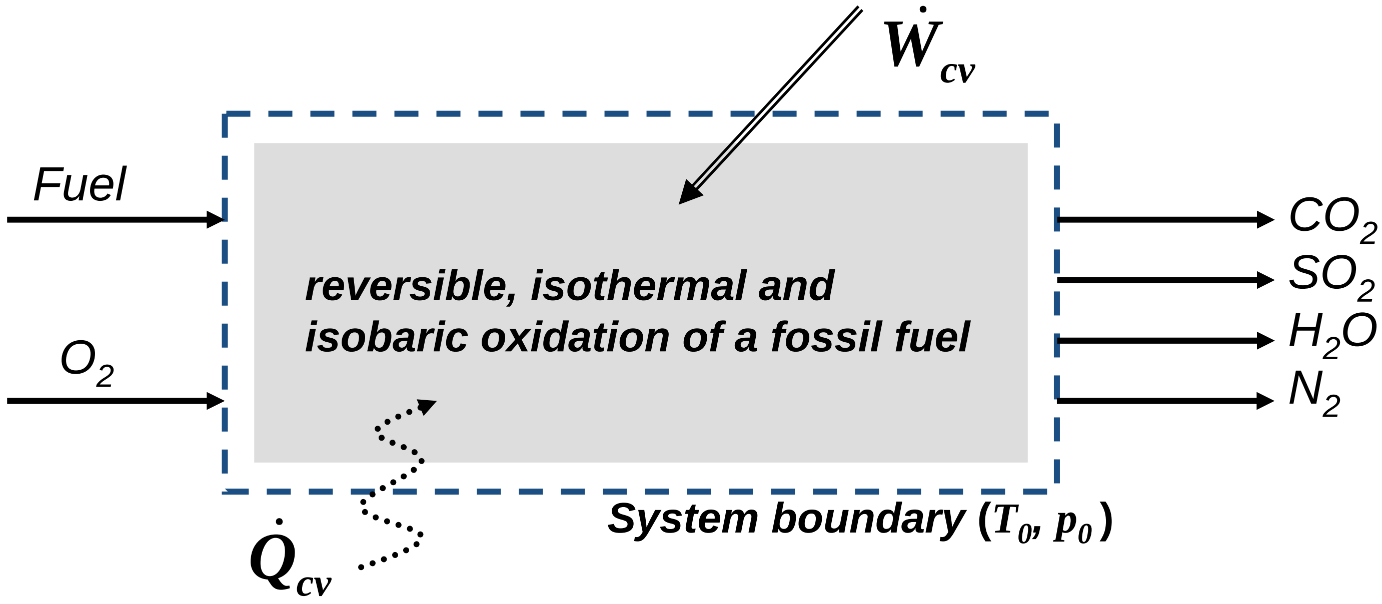
Standard chemical exergies **for substances contained in the environment at standard conditions (T_{ref} = 298.15 K and p_{ref}) are tabulated.**

Exergy Components: E^{CH}

Standard molar chemical exergies

Substance	Formula[a]	$\bar{e}^{CH}$ [$kJkmol^{-1}$]		
		Model I[b]	Model II[c]	Model III[d]
Ammonia	$NH_3(g)$	336684	337900	335951
Carbon dioxide	$CO_2(g)$	14176	19870	16137
Carbon monoxide	$CO(g)$	269412	275100	270875
Ethane	$C_2H_6(g)$	1482033	1495840	1482300
Hydrogen	$H_2(g)$	235249	236100	234690
Hydrogen sulfide	$H_2S(g)$	799890	812000	732886
Methane	$CH_4(g)$	824348	831650	824164
Methanol (l)	$CH_3OH(l)$	710747	718000	710437
Nitrogen	$N_2(g)$	639	720	799
Nitrogen monoxide	$NO(g)$	88851	88900	89442
Nitrogen dioxide	$NO_2(g)$	55565	55600	55634
Oxygen	$O_2(g)$	3951	3970	4973
Sulphur dioxide	$SO_2(g)$	301939	313400	236417
Sulphur trioxide (g)	$SO_3(g)$	233041	249100	167909
Sulphur trioxide (l)	$SO_3(l)$	235743	-	165329
Sulphuric acid (l)	$H_2SO_4(l)$	151233	163400	86240
Water (g)	$H_2O(g)$	8636	9500	8567
Water (l)	H_2O (l)	45	900	36

Exergy Components: E^{CH}



$$\bar{e}_f^{CH} = -\left(\Delta\bar{h}_R - T_0 \Delta\bar{s}_R\right) + \Delta\bar{e}^{CH} = -\Delta\bar{g}_R + \Delta\bar{e}^{CH}$$

Exergy Components: E^{CH}

$$\Delta\bar{h}_R = \sum_i \nu_i \bar{h}_i = -\bar{h}_f + \sum_k \nu_k \bar{h}_k = -\overline{HHV}$$

$$\Delta\bar{s}_R = \sum_i \nu_i \bar{s}_i = -\bar{s}_f + \sum_k \nu_k \bar{s}_k$$

$$\Delta\bar{g}_R = \Delta\bar{h}_R - T_0 \Delta\bar{s}_R$$

$$\Delta\bar{e}^{CH} = \sum_k \nu_k \bar{e}_k^{CH}$$

where

$$i = f, O_2, CO_2, H_2O, SO_2, N_2$$

$$k = O_2, CO_2, H_2O, SO_2, N_2$$

$$\nu_i \text{ and } \nu_k \geq 0 : CO_2, H_2O, SO_2, N_2$$

$$\nu_i \text{ and } \nu_k < 0 : f, O_2$$

Exergy Components: E^{CH}

Chemical exergy of an ideal mixture of N ideal gases

$$\bar{e}^{CH}_{M,ig} = \sum_{k=1}^{N} x_k \bar{e}^{CH}_k + \bar{R} T_0 \sum_{k=1}^{N} x_k \ln(x_k)$$

Chemical exergy of solution of liquids

$$\bar{e}^{CH}_{m,l} = \sum_{k=1}^{N} x_k \bar{e}^{CH}_k + \bar{R} T_0 \sum_{k=1}^{N} x_k \ln(\gamma_k x_k)$$

Where γ_k is activity coefficient

Exergy Components: E^{CH}

The standard molar chemical exergy of any substance **not present in the environment can be determined using the change in the specific Gibbs function for the reaction of this substance with substances present in the environment**

$$\bar{e}_s^{CH} = -\Delta\bar{g} + \Delta\bar{e}^{CH} = -\sum_i \nu_i \bar{g}_i + \sum_{i \neq s} \nu_i \bar{e}_i^{CH}$$

where $\bar{g}_i, \nu_i$ and $\bar{e}_i^{CH}$ denote, for the *i*-th substance, the Gibbs function at T_0 and p_0, the stoichiometric coefficient in the reaction, and the chemical exergy, respectively.

Exergy Components: E^{CH}

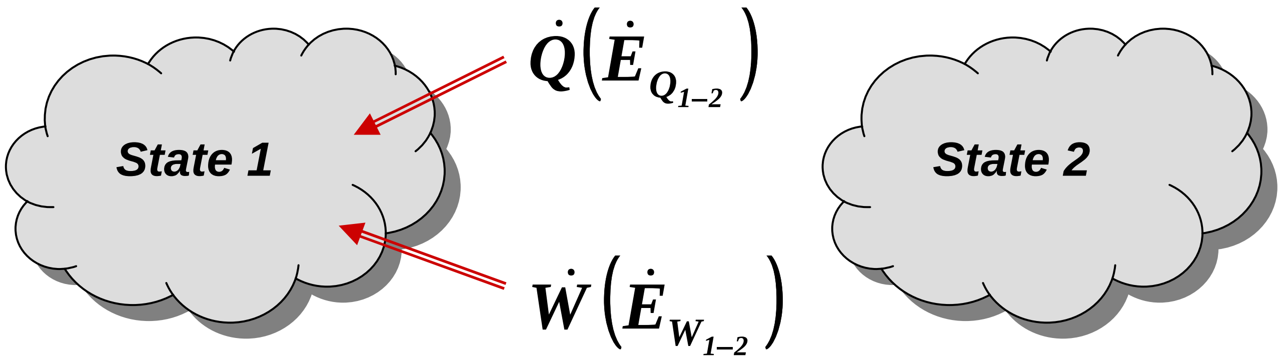
Chemical exergy of a fuel

The higher heating value (HHV) is the main contributor to the chemical exergy of a fossil fuel. For back-of-the envelope calculations, the molar chemical exergy of a fossil fuel may be estimated with the aid of its molar higher heating value

$$\frac{\bar{e}_f^{CH}}{\overline{HHV}} \approx \begin{cases} 0.95-0.985 & \textit{for gaseous fuels} \\ 0.98-1.00 & \textit{for liquid fuels} \\ 1.00-1.04 & \textit{for solid fuels} \end{cases}$$

For hydrogen and methane, this ratio is 0.83 and 0.94, respectively, when the model of Ahrends is used.

Closed System Exergy Balance



Change in total exergy of a closed system caused through transfers of energy by work and heat between the system and its surroundings

$$\dot{E}_2 - \dot{E}_1 = \dot{E}_{Q_{1-2}} + \dot{E}_{W_{1-2}} - \dot{E}_D$$

Closed System Exergy Balance

$$E_2 - E_1 = E_{Q_{1-2}} + E_{W_{1-2}} - E_D$$

Exergy transfer associated with heat transfer

$$E_{Q_{1-2}} = \int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q$$

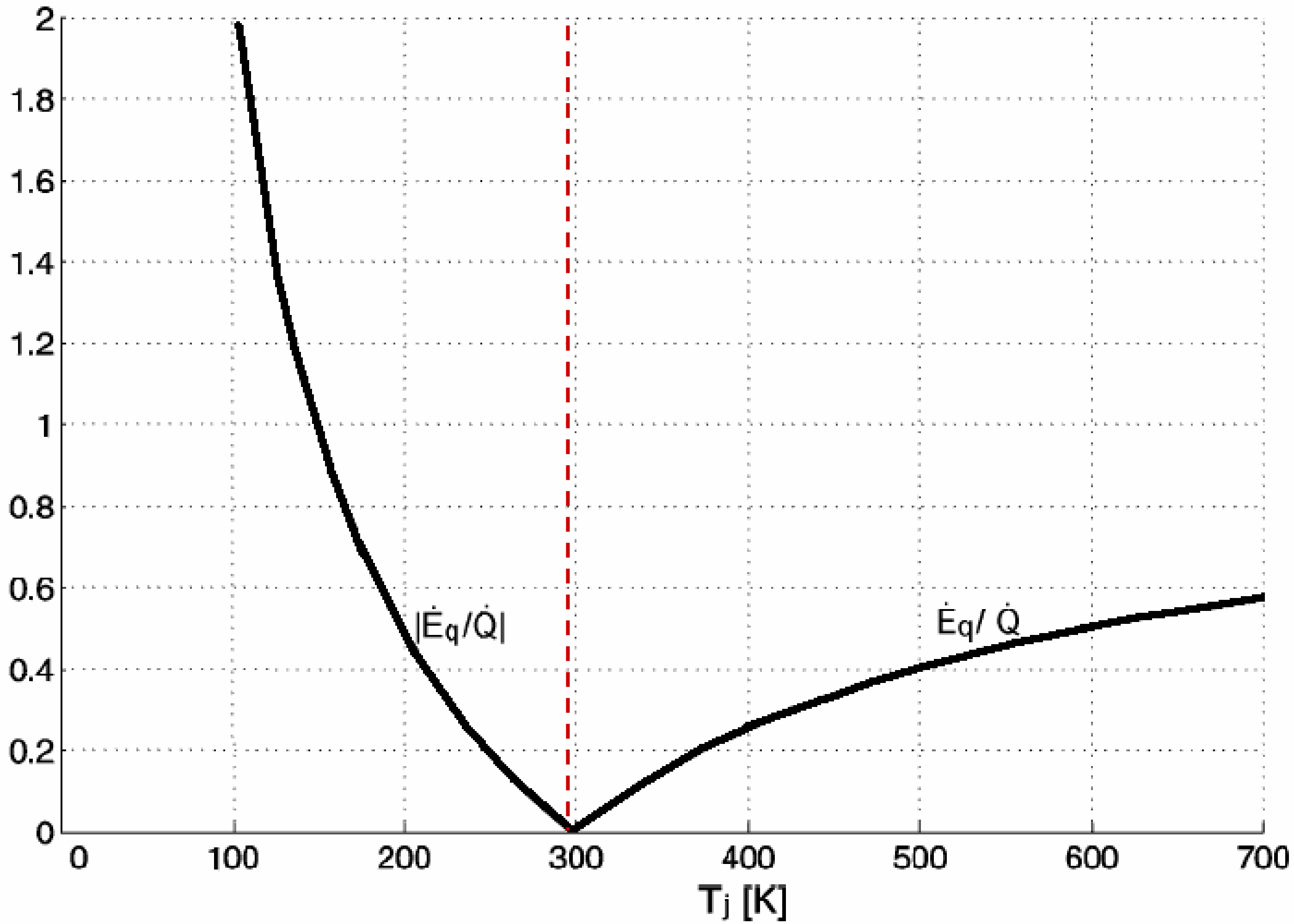
Exergy transfer associated with the transfer of energy by work

$$E_{W_{1-2}} = W + p_0 \left(V_2 - V_1\right)$$

Exergy destruction

$$E_D = T_0 S_{gen} \geq 0$$

Exergy Transfer Associated with Heat Transfer



Control Volume Exergy Balance

$$\frac{dE_{cv}}{dt} = \underbrace{\sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j}_{\dot{E}_{Q,j}} + \underbrace{\left(\dot{W}_{cv} + p_0 \frac{dV_{cv}}{dt}\right)}_{\dot{E}_W} + \sum_i \dot{E}_i - \sum_e \dot{E}_e - \dot{E}_D$$

Rate of exergy change — **Rate of exergy transfer** — **Rate of exergy destruction**

Control Volume Exergy Balance

$$\frac{dE_{cv}}{dt} = \underbrace{\sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j}_{\dot{E}_{Q,j}} + \underbrace{\left(\dot{W}_{cv} + p_0 \frac{dV_{cv}}{dt}\right)}_{\dot{E}_W} + \sum_i \dot{E}_i - \sum_e \dot{E}_e - \dot{E}_D$$

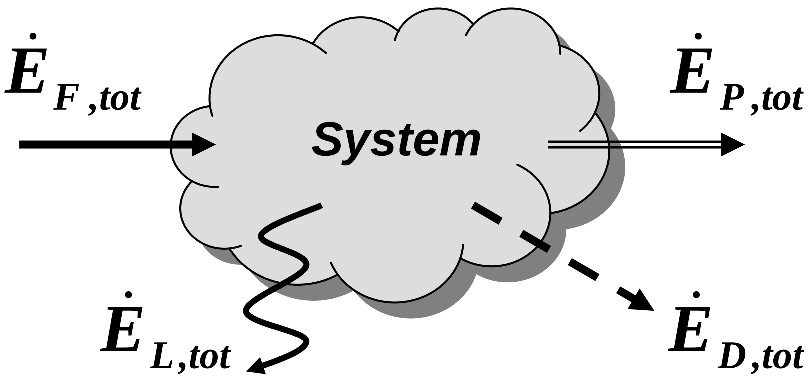
Exergy transfer associated with the time rate of heat transfer

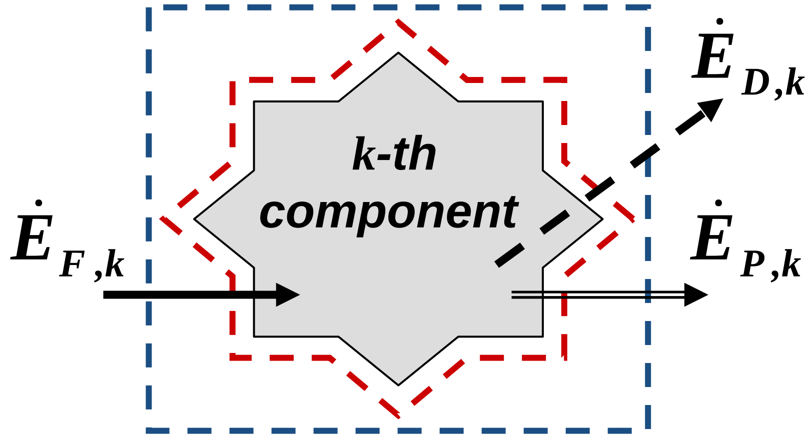
Exergy transfer associated with the time rate of energy transfer by work

Exergy balance under steady-state conditions

$$0 = \sum_j \dot{E}_{Q,j} + \dot{W}_{cv} + \sum_i \dot{E}_i - \sum_e \dot{E}_e - \dot{E}_D$$

Exergy Balances





$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot}$$

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k}$$

Exergy of fuel

Exergy of product

Exergy destruction

Exergy loss

Exergetic Variables: E_P

Exergy of product

The desired result, expressed in exergy terms, achieved by the system (the *k*-th component) being considered

The product is defined to be equal to:

- all the exergy values to be considered at the outlet (including the exergy of energy streams generated in the *k*-th component)

plus

- all the exergy increases between inlet and outlet (i.e., the exergy additions to the respective material streams) that are in accord with the purpose of the *k*-th component.

Exergetic Variables: E_F

Exergy of fuel

The exergetic resources expended to generate the exergy of the product

The fuel is defined to be equal to:

- all the exergy values to be considered at the inlet (including the exergy of energy streams supplied to the component)

plus

- all the exergy decreases between inlet and outlet (i.e., the exergy removals from the respective material streams)

minus

- all the exergy increases (between inlet and outlet) that are not in accord with the purpose of the component.

Exergetic Variables: E_D, E_L and ε

Exergy destruction: $\dot{E}_D$

Exergy destroyed due to irreversibilities within a system (the k-th component)

Exergy loss: $\dot{E}_L$

Exergy transfer to the system surroundings. This exergy transfer is not further used in the installation being considered or another one

Exergetic efficiency: ε

The ratio between exergy of product and exergy of fuel

$$\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = 1 - \frac{\dot{E}_{D,tot} + \dot{E}_{L,tot}}{\dot{E}_{F,tot}} \qquad \varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}$$

Exergetic Variables: $y_{D,k}$

Exergy destruction ratio for the *k*-th component

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$

Exergetic efficiency of the overall system

$$\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = 1 - \sum_{k} y_{D,k} - \frac{\dot{E}_{L,tot}}{\dot{E}_{F,tot}}$$

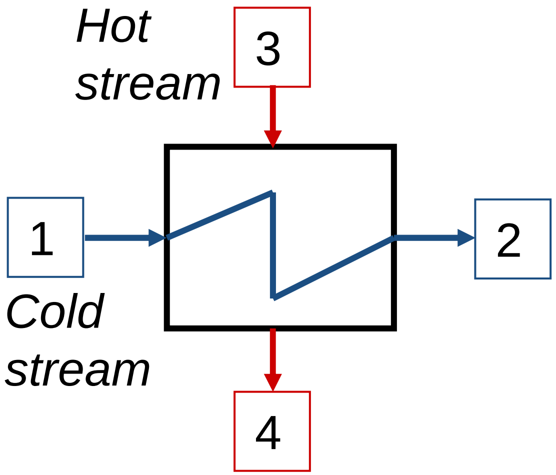
Real Processes

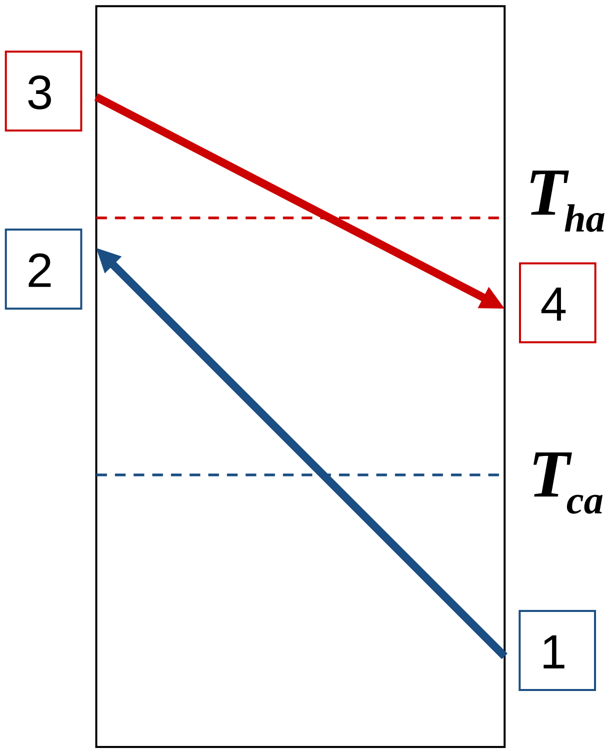
All real processes are *irreversible* due to effects such as:

- **heat transfer through a finite temperature difference,**
- **mixing of matter at different compositions or states,**
- **unrestrained expansion,**
- **friction, and**
- **chemical reaction.**

Heat Transfer - 1

Temperature profiles and thermodynamic average temperatures for two streams passing through an adiabatic heat exchanger at constant pressure.

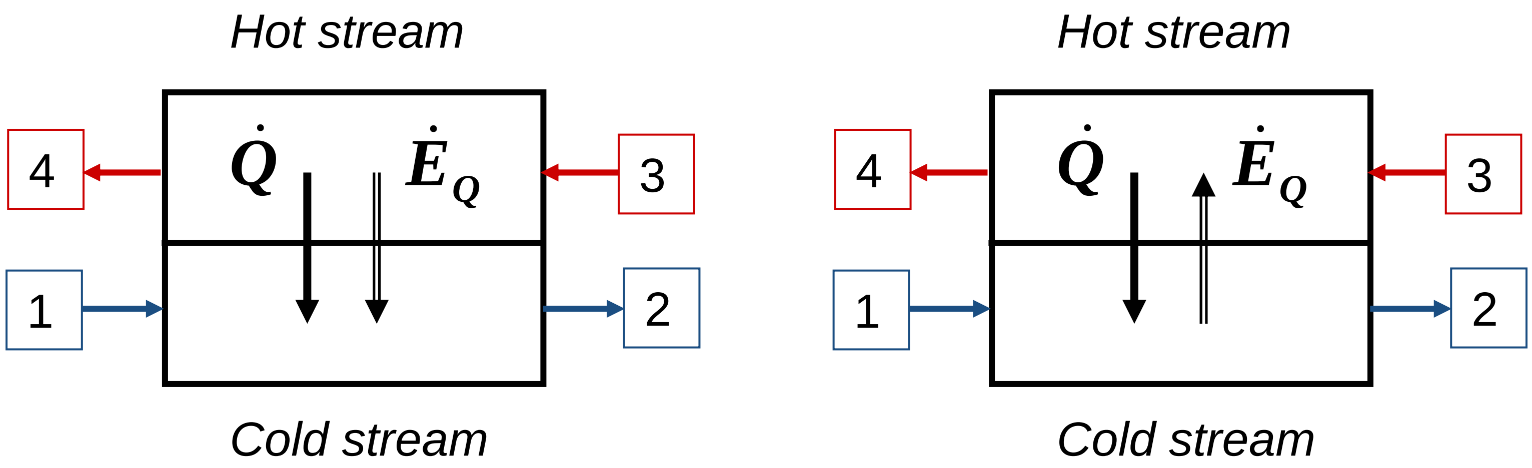




$$T_{ha} = \frac{\dot{H}_3 - \dot{H}_4}{\dot{S}_3 - \dot{S}_4}$$

$$T_{ca} = \frac{\dot{H}_2 - \dot{H}_1}{\dot{S}_2 - \dot{S}_1}$$

Heat Transfer - 2



$$T_1 \geq T_0$$

$$\dot{E}_3 > \dot{E}_4,\ \dot{E}_1 < \dot{E}_2$$

$$T_3 \leq T_0$$

$$\dot{E}_3 < \dot{E}_4,\ \dot{E}_1 > \dot{E}_2$$

Heat Transfer - 3

Exergy destruction due to heat transfer from the hot stream 3 to the cold stream 1

$$\dot{E}_{D,Q} = T_0 \dot{S}_{gen,Q} = T_0 \dot{Q} \frac{T_{ha} - T_{ca}}{T_{ha} T_{ca}}$$

with the thermodynamic average temperature

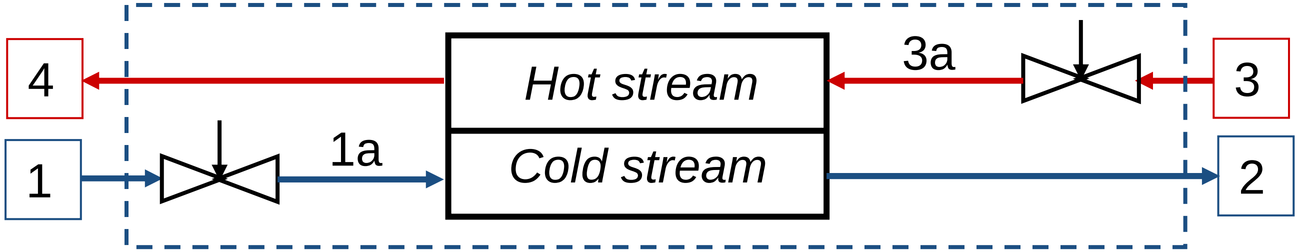
$$T_a = \frac{\int_i^e T ds}{s_e - s_i} = \frac{h_e - h_i - \int_i^e v dp}{s_e - s_i}$$

For constant pressure $$T_a = \frac{h_e - h_i}{s_e - s_i}$$

Friction - 1

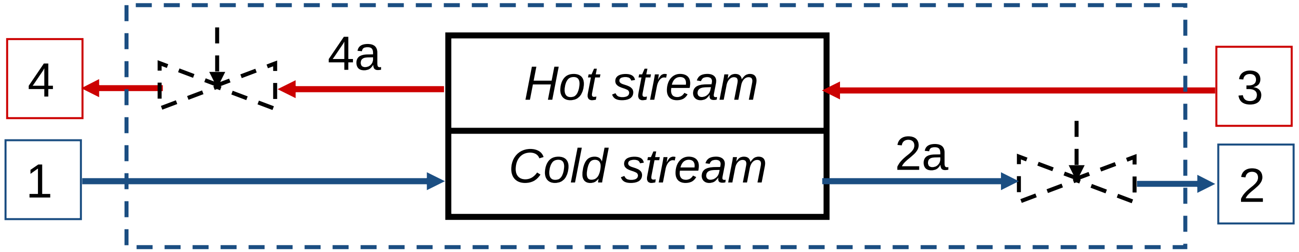
Heat Exchanger with Pressure Drop

$$h_{3a} = h_3\ ;\ p_{3a} = p_4$$



$$h_{1a} = h_1\ ;\ p_{1a} = p_2$$

$$h_{4a} = h_4\ ;\ p_3 = p_{4a}$$



$$h_{2a} = h_2\ ;\ p_1 = p_{2a}$$

Friction - 2

Rate of exergy destruction associated with friction

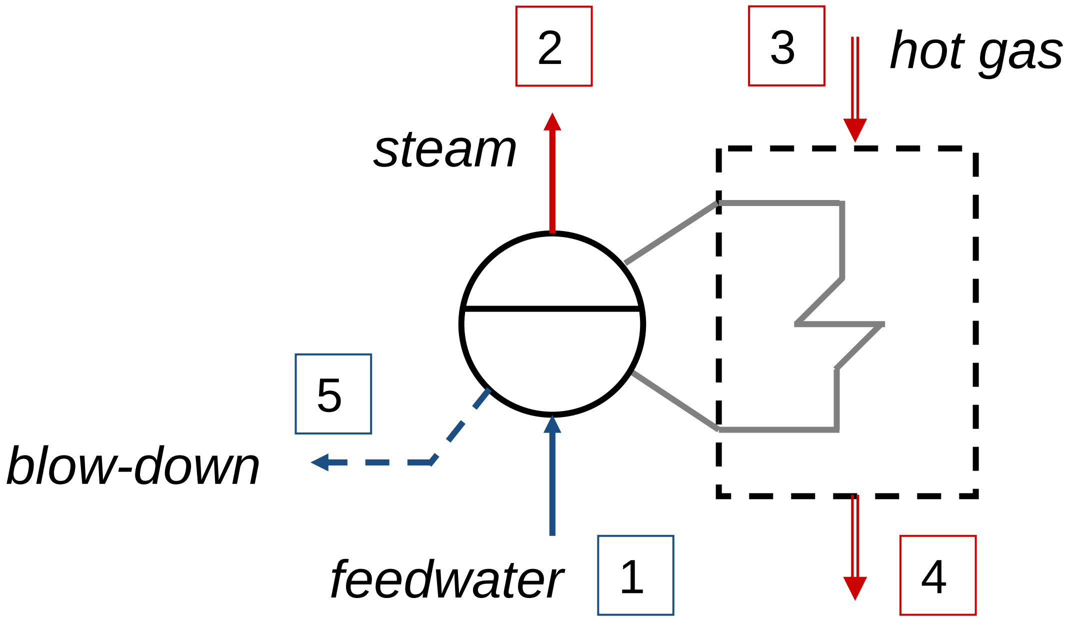
$$\dot{E}_{D,fr} = -\frac{T_0}{T_a}\dot{m}\int_i^e v\,dp$$

Where Ta is the thermodynamic average temperature of the working fluid, and $\int_i^e v\,dp$ **is the head loss.**

The effect of friction is more significant at higher mass flow rates and lower temperature levels.

Exergetic Efficiency: Heat Transfer

Evaporator including steam drum

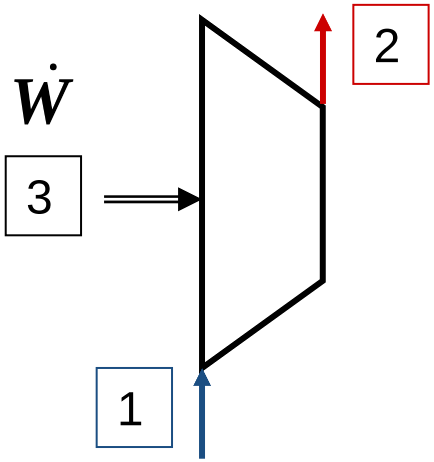


$$\dot{E}_P = \dot{E}_2 + \dot{E}_5 - \dot{E}_1$$

$$\dot{E}_F = \dot{E}_3 - \dot{E}_4$$

Exergetic Efficiency: Compressor, Pump, or Fan

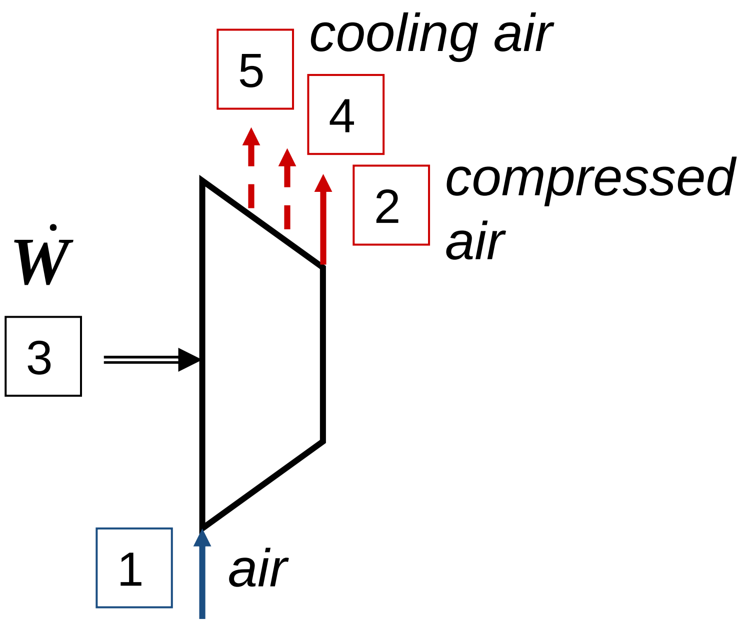
General Case



$$\dot{E}_P = \dot{E}_2 - \dot{E}_1$$

$$\dot{E}_F = \dot{E}_3 = \dot{W}$$

Compressor with cooling air extractions

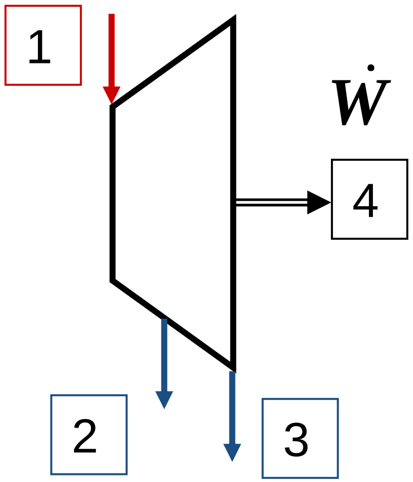


$$\dot{E}_P = \dot{E}_2 + \dot{E}_4 + \dot{E}_5 - \dot{E}_1$$

$$\dot{E}_F = \dot{E}_3 = \dot{W}$$

Exergetic Efficiency: Turbine or Expander

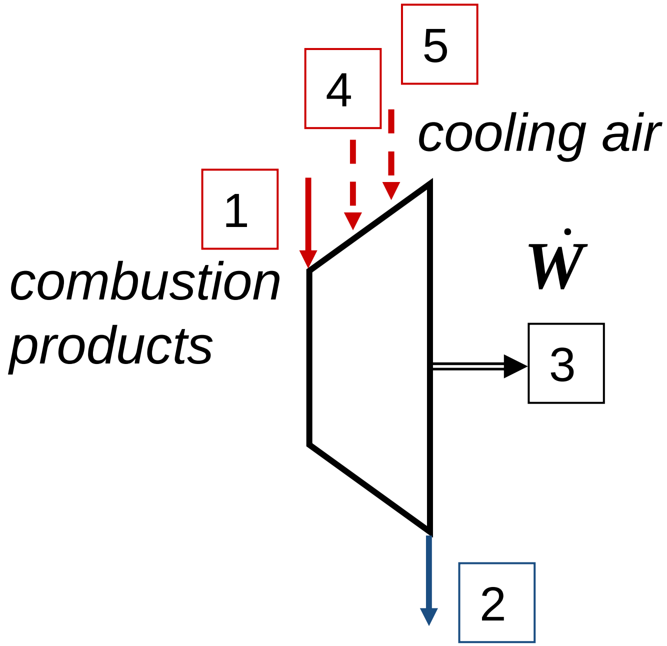
General Case



$$\dot{E}_P = \dot{E}_4 = \dot{W}$$

$$\dot{E}_F = \dot{E}_1 - \dot{E}_2 - \dot{E}_3$$

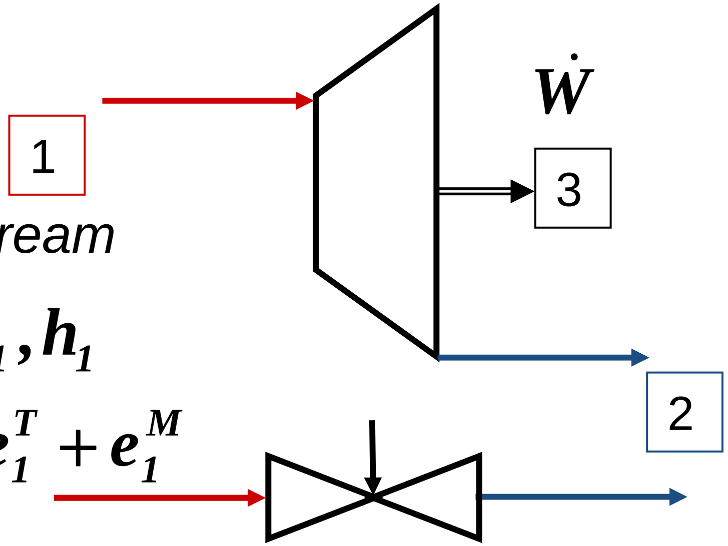
Expander with cooling air supply



$$\dot{E}_P = \dot{E}_3 = \dot{W}$$

$$\dot{E}_F = \dot{E}_1 + \dot{E}_4 + \dot{E}_5 - \dot{E}_2$$

Exergetic Efficiency: Expansion in Refrigeration



hot stream

$$p_1, T_1, h_1$$

$$e_1 = e_1^T + e_1^M$$

$$p_2 < p_1, T_1 < T_o$$

$$e_2 = e_2^T + e_2^M$$

$$e_2^T > e_1^T \, , \, e_2^M < e_2^M$$

cold stream

Throttling valve

$$h_2 = h_1$$

$$\dot{E}_P = \dot{E}_2^T - \dot{E}_1^T$$

$$\dot{E}_F = \dot{E}_1^M - \dot{E}_2^M$$

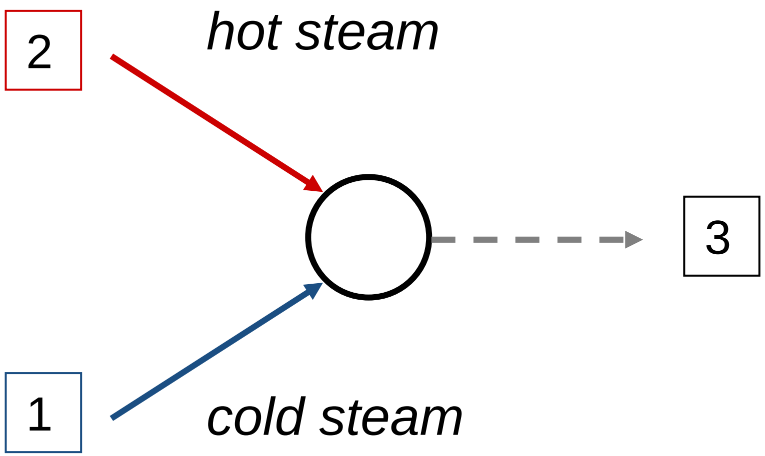
Expander

$$\dot{H}_1 - \dot{H}_2 = \dot{W}_{EX}$$

$$\dot{E}_P = \dot{W}_{EX} + \left(\dot{E}_2^T - \dot{E}_1^T\right)$$

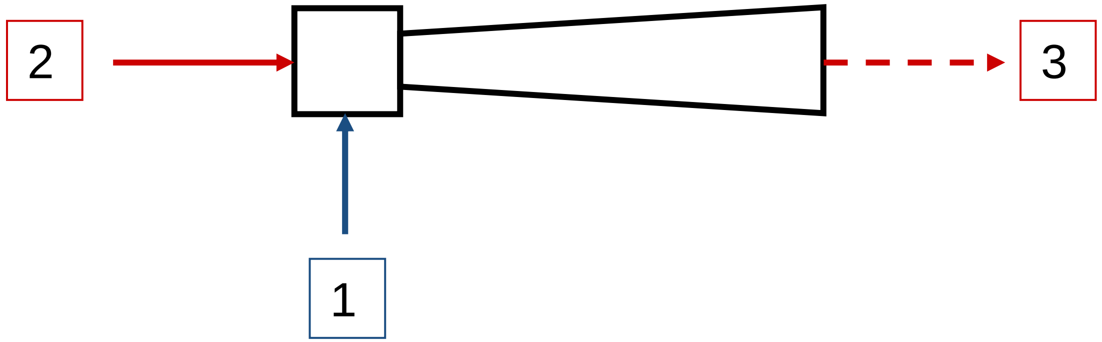
$$\dot{E}_F = \dot{E}_1^M - \dot{E}_2^M$$

Exergetic Efficiency: Mixing Unit



$$\dot{E}_P = \dot{m}_1 (e_3 - e_1)$$
$$\dot{E}_F = \dot{m}_2 (e_2 - e_3)$$

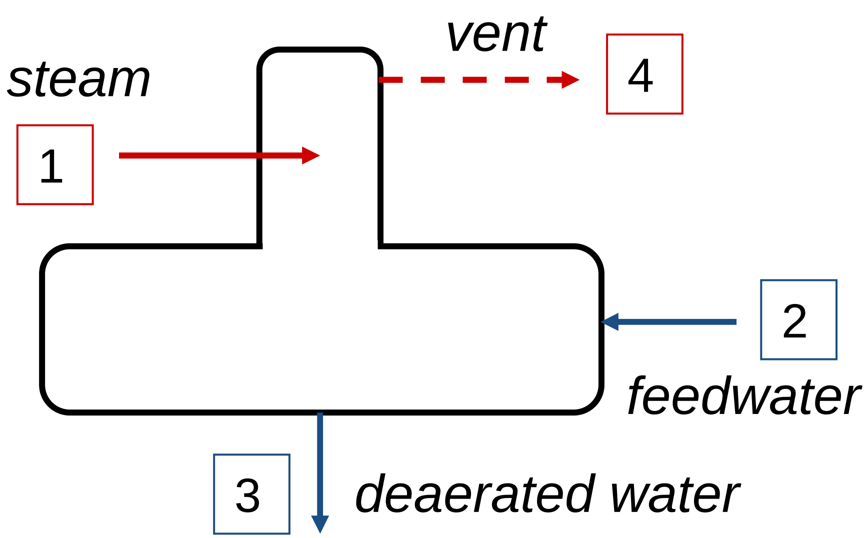
Exergetic Efficiency: Ejector



$$\dot{E}_P = \dot{m}_1 (e_3 - e_1)$$

$$\dot{E}_F = \dot{m}_2 (e_2 - e_3)$$

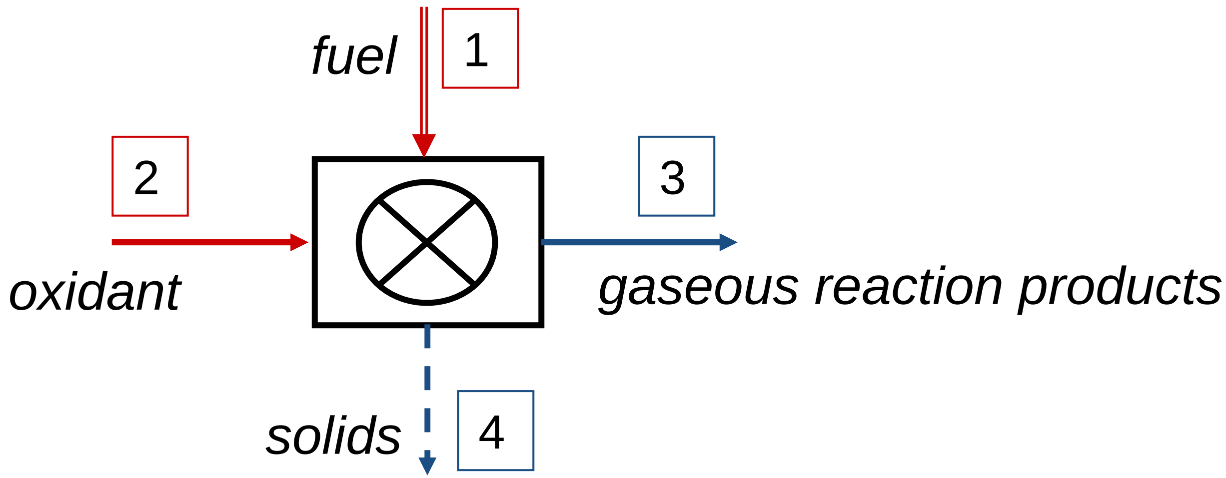
Exergetic Efficiency: Deaerator



$$\dot{E}_P = \dot{m}_2 \left(e_3 - e_2 \right)$$

$$\dot{E}_F = \dot{m}_1 e_1 - \left(\dot{m}_1 - \dot{m}_4 \right) e_3 - \dot{m}_4 e_4$$

Exergetic Efficiency: Combustion Chamber

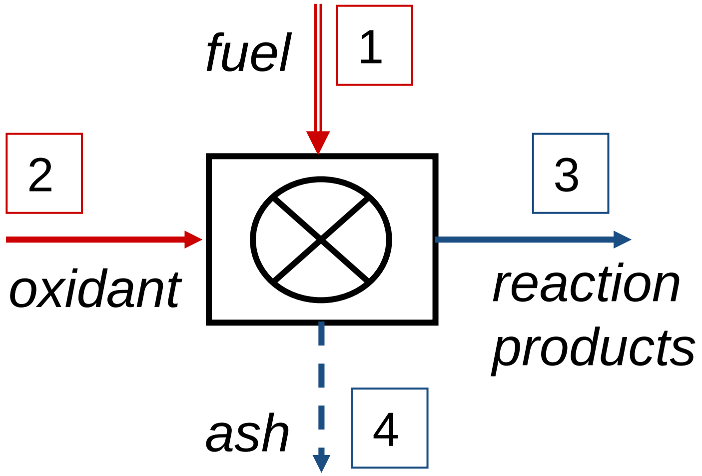


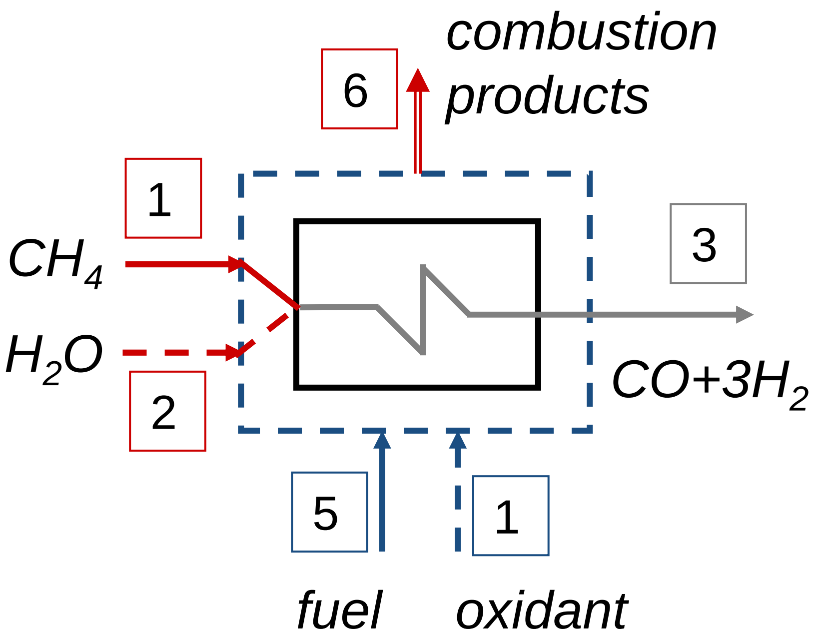
$$\dot{E}_P = \dot{E}_3 - \dot{E}_2$$
$$\dot{E}_F = \dot{E}_1 - \dot{E}_4$$

or

$$\dot{E}_P = \dot{E}_3^{PH} + \dot{E}_4^{PH} - \dot{E}_1^{PH} - \dot{E}_2^{PH}$$
$$\dot{E}_F = \dot{E}_1^{CH} + \dot{E}_2^{CH} - \dot{E}_3^{CH} - \dot{E}_4^{CH}$$

Exergetic Efficiency: Gasifier and Steam Reformer





$$\dot{E}_P = \dot{E}_3 - \dot{E}_2 \; ; \quad \dot{E}_F = \dot{E}_1 - \dot{E}_4$$

or

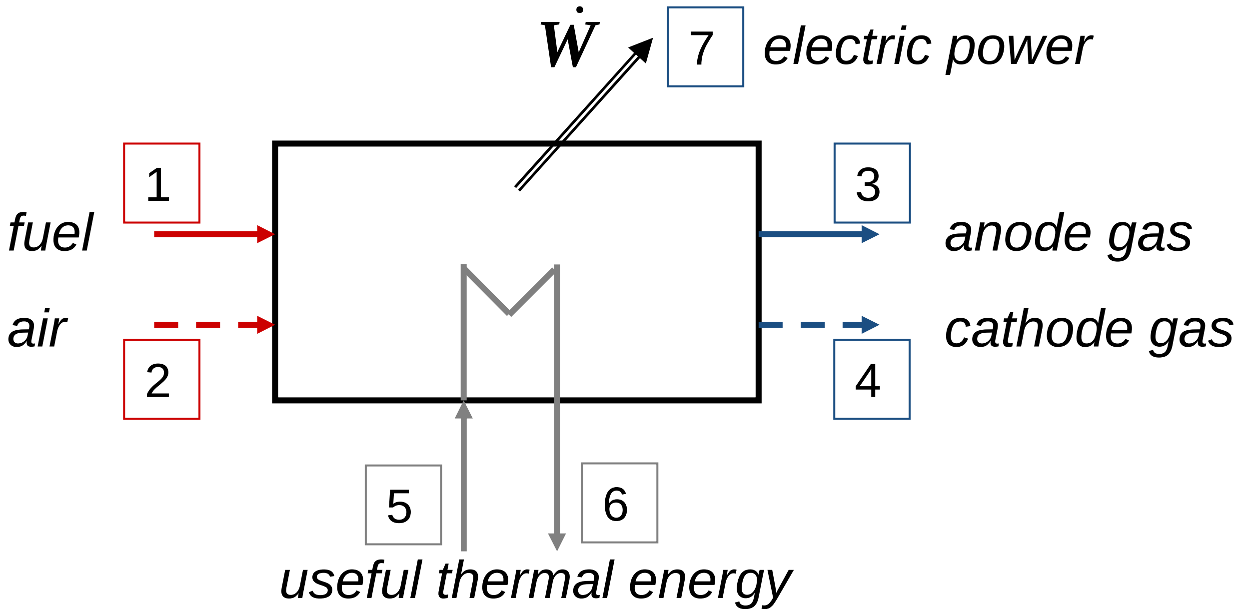
$$\dot{E}_P = \dot{E}_3^{CH} + \left(\dot{E}_3^{PH} + \dot{E}_4^{PH} - \dot{E}_2^{PH} - \dot{E}_1^{PH}\right)$$

$$\dot{E}_F = \dot{E}_1^{CH} + \dot{E}_2^{CH} - \dot{E}_4^{CH}$$

$$\dot{E}_P = \dot{E}_3 - \dot{E}_1 - \dot{E}_2$$

$$\dot{E}_F = \dot{E}_4 + \dot{E}_5 - \dot{E}_6$$

Exergetic Efficiency: Fuel Cell



$$\dot{E}_P = \dot{W} + \left(\dot{E}_6 - \dot{E}_5\right)$$

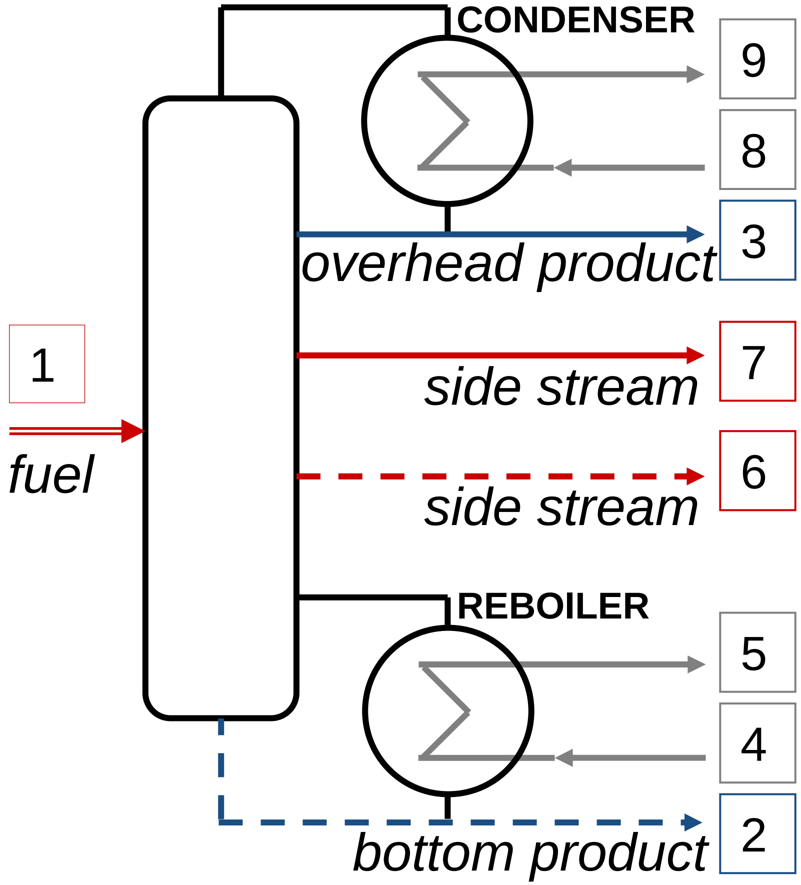
Fuel cell as part of the system

$$\dot{E}_F = \left(\dot{E}_1 + \dot{E}_2\right) - \left(\dot{E}_3 + \dot{E}_4\right)$$

Stand-alone fuel cell

$$\dot{E}_F = \dot{E}_1 + \dot{E}_2$$

Exergetic Efficiency: Distillation Column



$$\dot{E}_P = \dot{E}_2^{CH} + \dot{E}_3^{CH} + \dot{E}_6^{CH} + \dot{E}_7^{CH} - \dot{E}_1^{CH} + \dot{m}_6\left(e_6^{PH} - e_1^{PH}\right) + \dot{m}_2\left(e_2^{PH} - e_1^{PH}\right)$$

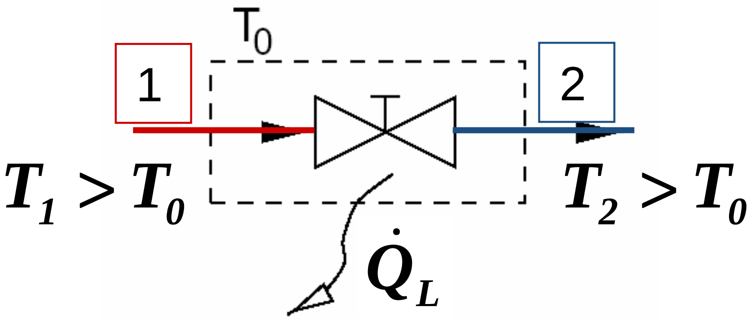
$$\dot{E}_F = \left(\dot{E}_4 - \dot{E}_5\right) + \dot{m}_7\left(e_1^{PH} - e_7^{PH}\right) + \dot{m}_3\left(e_1^{PH} - e_3^{PH}\right)$$

Here, it is assumed that $e_j^{CH} > e_1^{CH}$ $(j=2,3,6,7)$, $e_2^{PH} > e_1^{PH}$, $e_3^{PH} < e_1^{PH}$, $e_7^{PH} < e_1^{PH}$

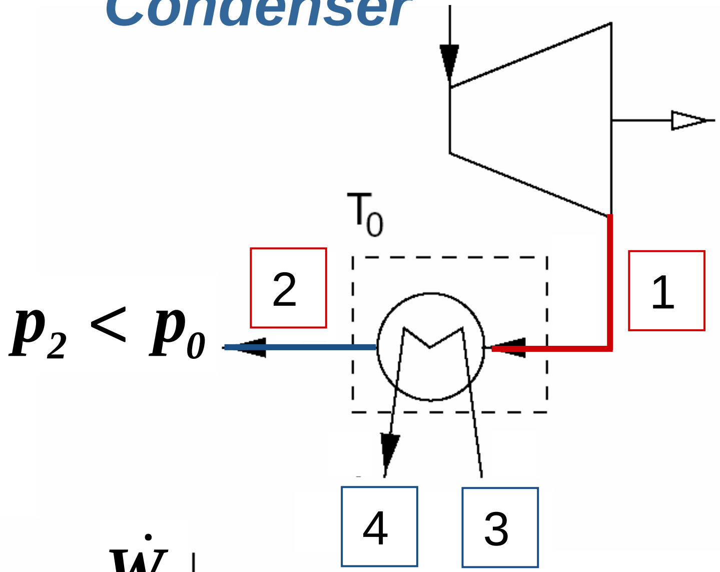
Dissipative Components

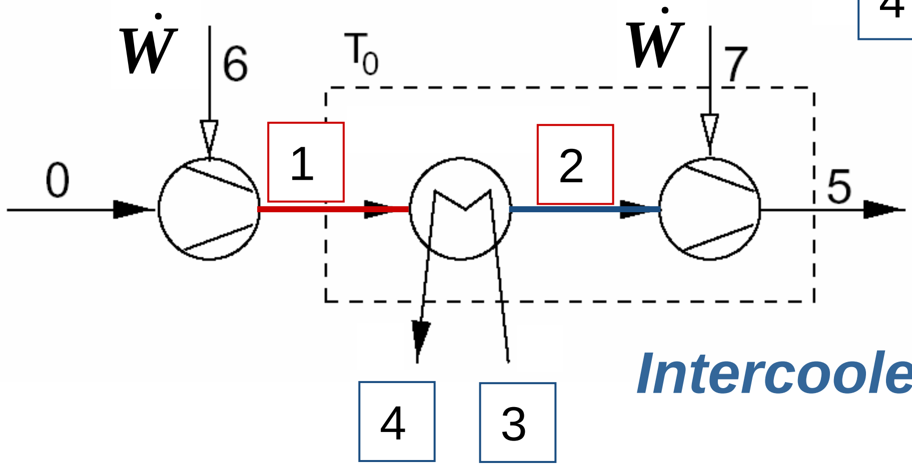
Throttling valve at $T > T_0$

$$p_2 < p_1, h_1 = h_2$$



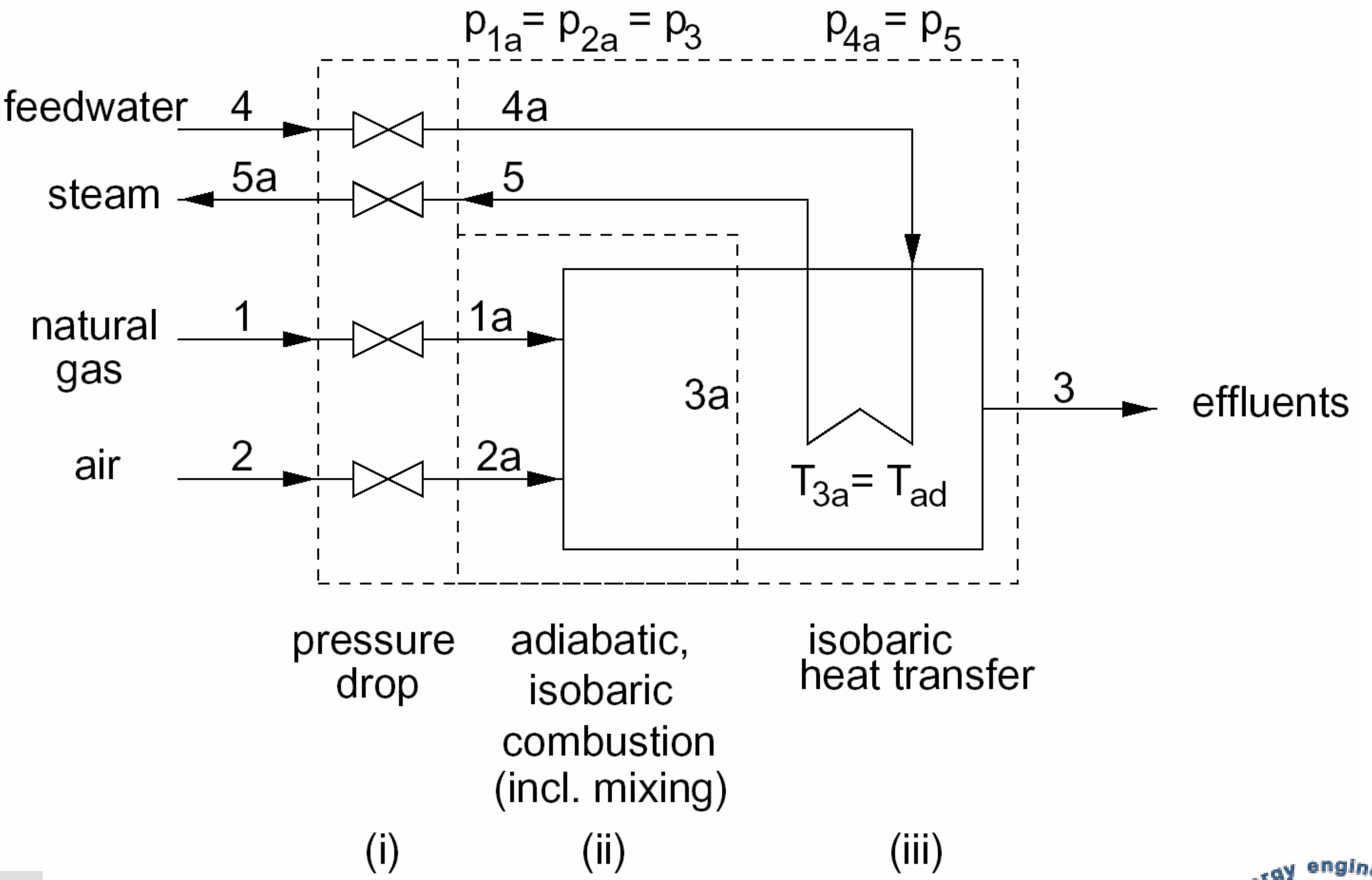
Condenser





Intercooler

Gas-Fired Steam Generator



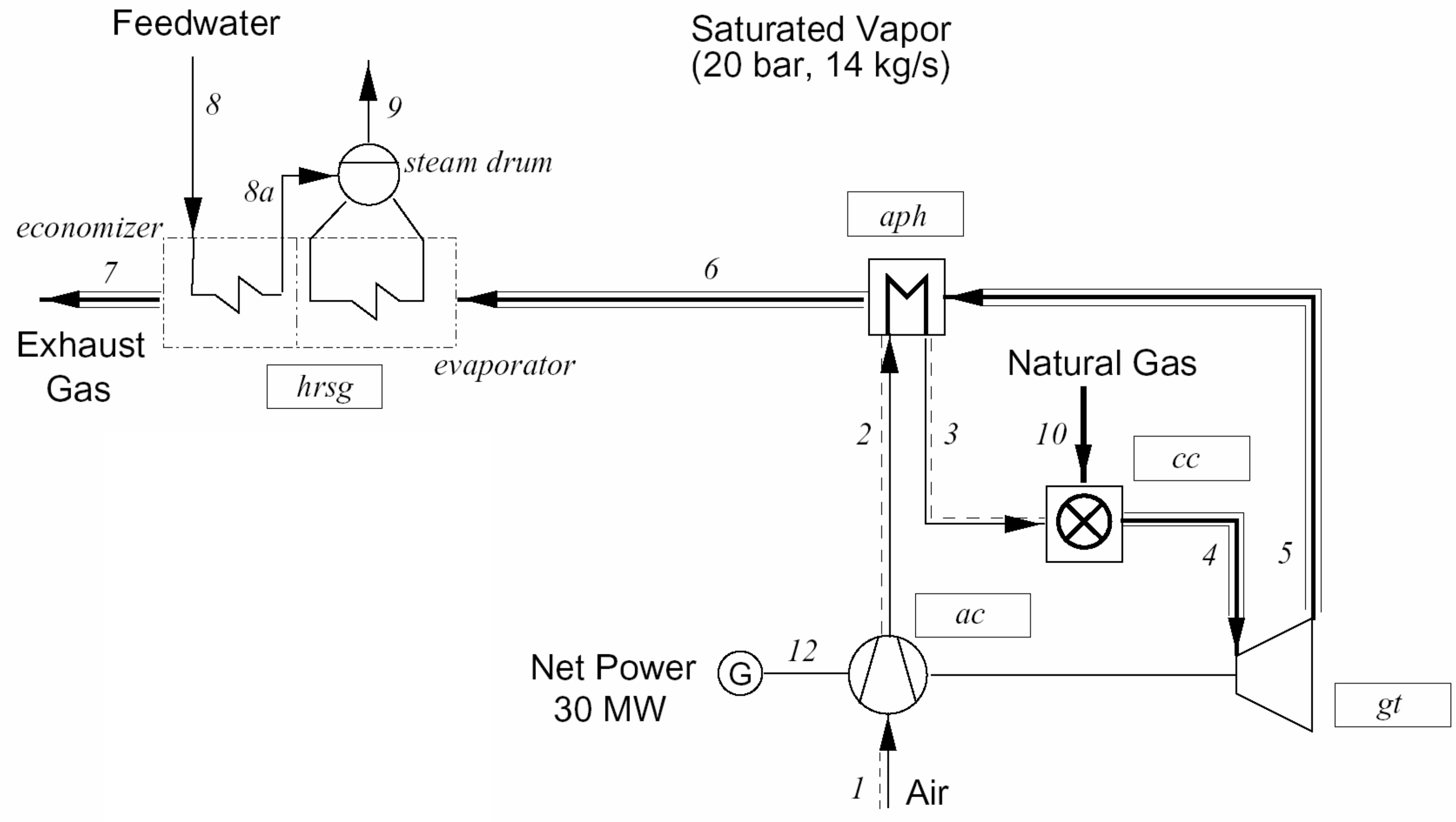
Gas-Fired Steam Generator: Steam Data

Stream	$\dot{m}_j$ [kg/s]	T_j [K]	p_j [bar]	$\dot{H}_j$ [MW]	$\dot{S}_j$ [MW/K]	$\dot{E}_j^{PH}$ [MW]	$\dot{E}_j^{CH}$ [MW]	$\dot{E}_j$ [MW]
1	0.376	326.00	1.200	-1.731	4.406	0.011	19.379	19.390
1a	0.376	326.00	1.013	-1.731	4.439	0.002	19.379	19.381
2	6.763	293.15	1.200	-0.034	46.111	0.095	0.024	0.120
2a	6.763	293.15	1.013	-0.034	46.441	0.000	0.024	0.024
3a	7.139	2252.30	1.013	-1.766	69.954	13.662	0.247	13.909
3	7.139	415.00	1.013	-19.626	54.175	0.349	0.247	0.595
4	6.000	380.00	97.000	-93.095	29.349	0.361	0.015	0.376
4a	6.000	380.09	92.150	-93.095	29.357	0.359	0.015	0.374
5	6.000	780.00	92.150	-75.413	61.107	8.892	0.015	8.907
5a	6.000	775.64	82.935	-75.413	61.379	8.814	0.015	8.829

Gas-Fired Steam Generator: Exergy Destruction

Process	$\dot{E}_{D,k}$ [MW]	$y_{D,k}$ [%]
Pressure drop (i):		
- natural gas (1→1a)	0.010	0.05
- air (2→2a)	0.095	0.50
- feedwater (4→4a)	0.002	0.01
- steam (5→5a)	0.078	0.41
Sum(i)	0.185	0.98
Combustion (ii):		
- mixing	0.189	1.00
- chemical reaction	5.307	28.06
Sum(ii)	5.496	29.06
Heat transfer from the combustion gas (iii):		
- to water/steam	4.648	24.57
- to the surroundings	0.133	0.70
Sum(iii)	4.781	25.27
Steam generator total (i + ii + iii):	10.462	55.31

Cogeneration System



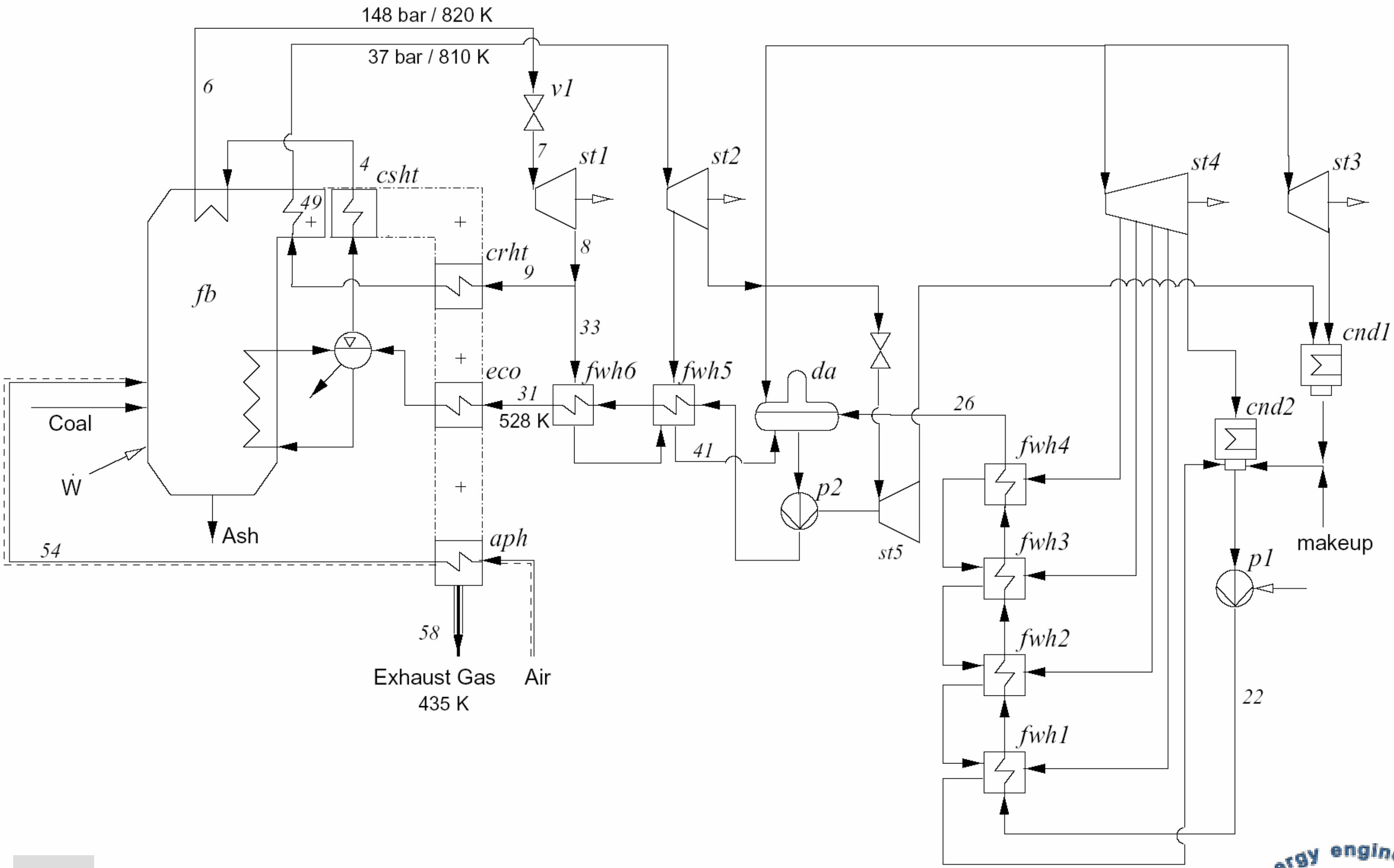
Cogeneration System: Steam Data

Nr.	$\dot{m}_j$ [kg/s]	T_j [K]	p_j [bar]	$\dot{E}_j^{PH}$ [MW]	$\dot{E}_j^{CH}$ [MW]	$\dot{E}_j$ [MW]
1	91.50	298.15	1.013	0.000	0.000	0.000
2	91.50	644.82	12.156	30.964	0.000	30.964
3	91.50	800.00	11.548	39.726	0.000	39.726
4	93.14	1470.00	10.971	97.916	0.362	98.278
5	93.14	929.73	1.099	31.835	0.362	32.197
6	93.14	787.54	1.066	21.380	0.362	21.742
7	93.14	424.87	1.013	2.322	0.362	2.684
8	14.00	298.15	20.000	0.027	0.035	0.062
9	14.00	485.52	20.000	12.775	0.035	12.810
10	1.64	298.15	20.000	0.747	84.127	84.874
11						33.195
12						30.000

Cogeneration System: Exergy Analysis

System component k	$\dot{E}_{F,k}$ [MW]	$\dot{E}_{P,k}$ [MW]	$\dot{E}_{D,k}$ [MW]	$y_{D,k}$ [%]	ε_k [%]
Combustion chamber	84.87	58.55	26.32	31.01	69.0
Heat-recovery steam generator	19.06	12.75	6.31	7.43	66.9
Gas turbine expander	66.08	63.20	2.89	3.40	95.6
Air compressor	33.20	30.96	2.23	2.63	93.3
Air preheater	10.46	8.76	1.69	1.99	83.8
Overall system	84.87	42.75	39.44	46.47	50.4

400 MW Coal-Fired Subcritical Power Plant



Institute for Energy Engineering

400 MW Coal-Fired Subcritical Power Plant

Component	ID	$\dot{E}_{F,k}$ [MW]	$\dot{E}_{P,k}$ [MW]	ε_k [%]	$\dot{E}_{D,k}$ [MW]	$y_{D,k}$ [%]
Fossil boiler	fb	775.63	328.59	42.4	447.04	42.78
Convective superheater	$csht$	118.22	88.76	75.1	29.45	2.82
Air preheater	aph	42.75	25.58	59.8	17.18	1.64
Economizer	eco	54.55	43.13	79.1	11.42	1.09
Convective reheater	$crht$	36.40	28.59	78.5	7.81	0.75
LP steam turbine	$st3$	132.96	125.83	94.6	7.14	0.68
HP steam turbine	$st1$	118.98	113.07	95.0	5.91	0.57
Generator	gen	407.84	402.54	98.7	5.30	0.51
IP steam turbine	$st2$	101.55	97.03	95.5	4.52	0.43
LP steam turbine	$st4$	75.88	71.92	94.8	3.96	0.38
Deaerator	da	18.99	16.57	87.3	2.42	0.23
LP feedwater heater	$fwh2$	10.48	8.10	77.3	2.38	0.23
HP feedwater heater	$fwh6$	29.84	28.05	94.0	1.79	0.17
Steam turbine	$st5$	10.05	8.31	82.7	1.74	0.17
LP feedwater heater	$fwh4$	12.46	11.00	88.3	1.46	0.14
HP feedwater heater	$fwh5$	11.99	10.88	90.7	1.11	0.11
Feedwater pump	$p2$	8.31	7.52	90.5	0.79	0.08
LP feedwater heater	$fwh1$	2.23	1.66	74.2	0.57	0.06
LP feedwater heater	$fwh3$	5.42	5.10	94.2	0.32	0.03
Condensate pump	$p1$	0.73	0.63	85.9	0.10	0.01
Overall plant	tot	1044.86	400.13	38.3	552.86	52.91

Exergy-Based Thermodynamic Analysis

An exergy-based thermodynamic analysis identifies the location, the magnitude, and the causes of thermodynamic inefficiencies in a thermal system, which are the *exergy destruction* within the system, and the *exergy loss* (exergy transfer to the environment).