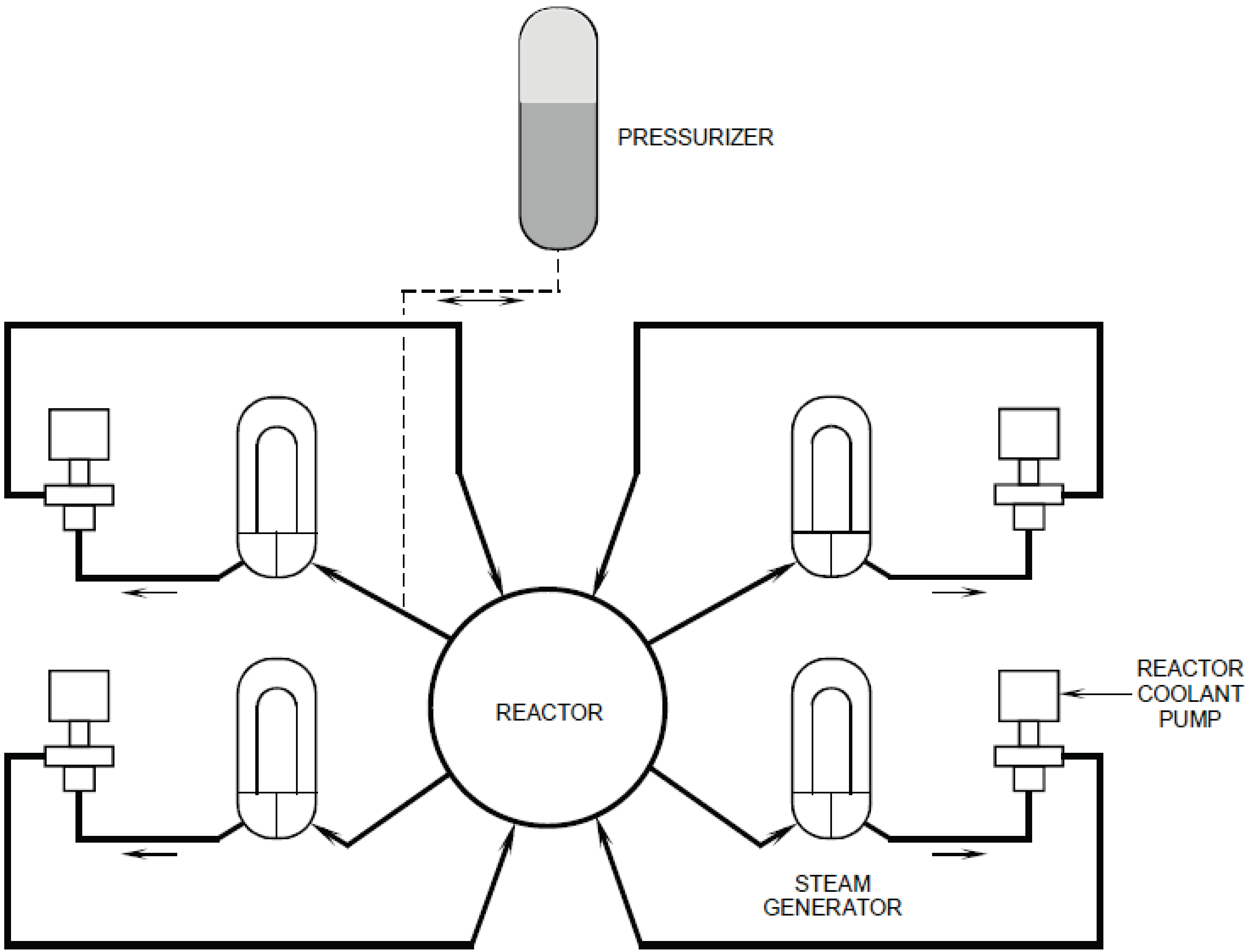
SH2702
Nuclear Reactor Technology

Exercise Session 02

Primary system of PWR



Steam Generator Analysis

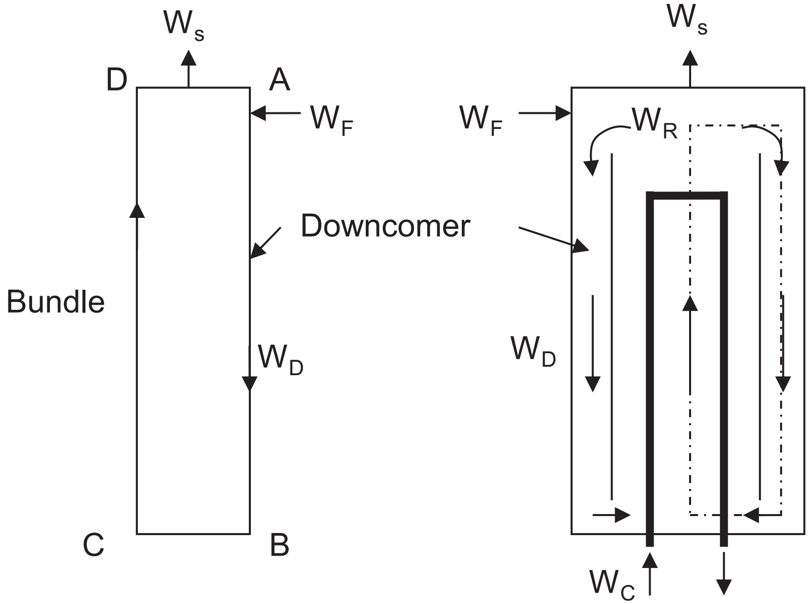
- Steam generator is a special case of heat exchanger, where water is evaporated to generate steam

- The performance of the steam generator is given by the recirculation ratio:

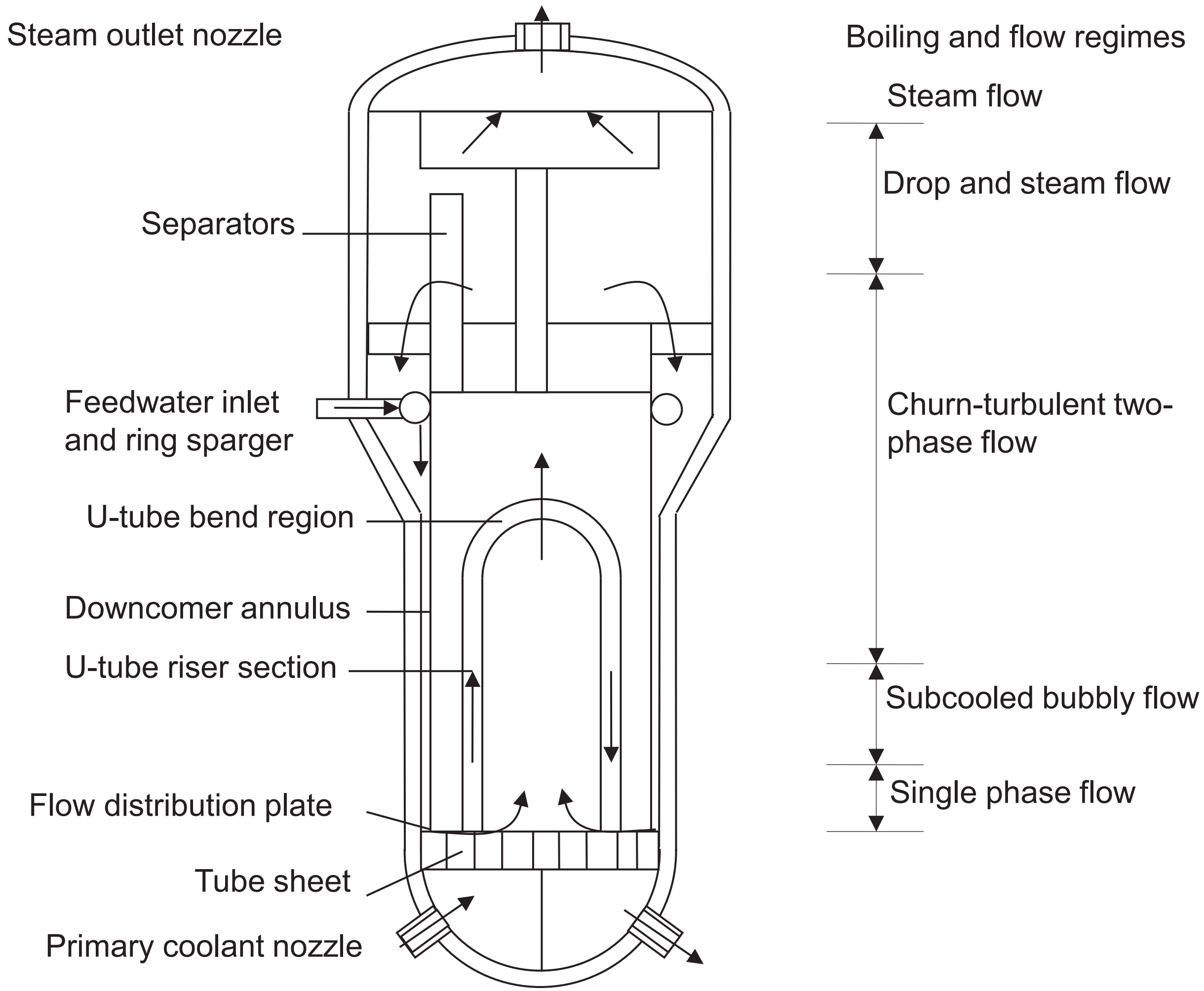
$$R = \frac{W_D}{W_F}$$

Total mass flow rate in downcomer

Feedwater flow rate



Steam Generator Schematic

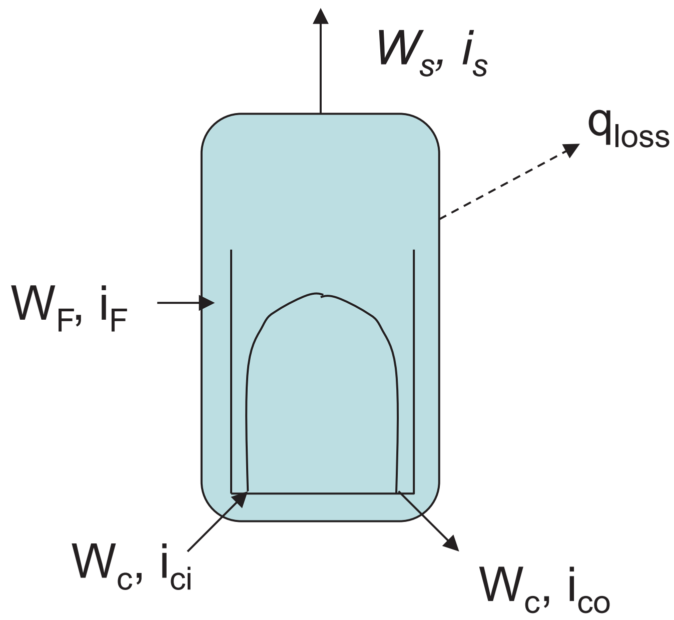
- 

Steam Generator Energy Balance

- The steam mass flow rate from the steam generator is found from the energy balance as follows:

$$W_s(i_s - i_F) + q_{loss} = q_t = W_C(i_{co} - i_{ci})$$

In steady-state: $W_s = W_F$



Exit steam from steam generator is wet due to the carryover fraction Fco.

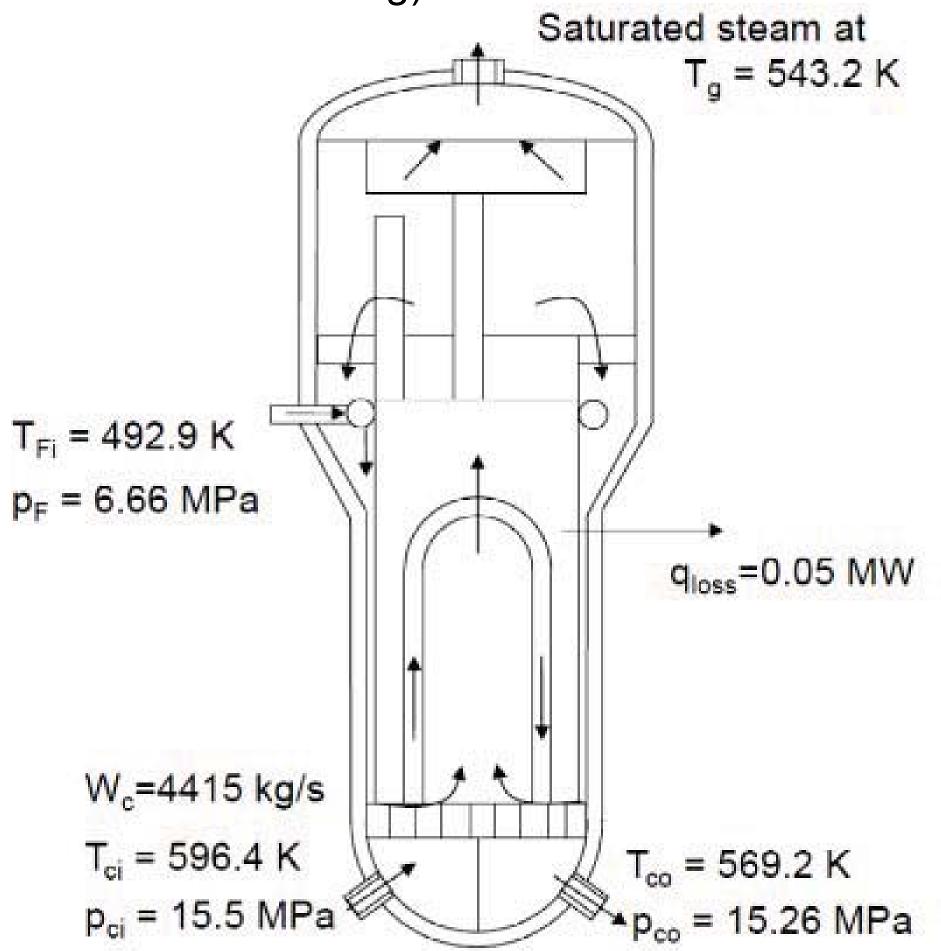
Thus, the wet steam enthalpy is:

$$i_s(p, F_{co}) = i_f(p)F_{co} + i_g(p)(1 - F_{co})$$

here i_f, i_g are specific enthalpies of saturated liquid and vapor, respectively

E01_P01

- A steam generator works at conditions indicated in the following figure. Calculate the mass flow rate of steam produced in the steam generator.
  - (Specific enthalpy of water at 15.5 MPa and 596.4 K is 1.4731×10^6 J/kg;
  - Specific enthalpy of water at 15.26 MPa and 569.2 K is 1.3164×10^6 J/kg;
  - Specific enthalpy of water at 6.66 MPa and 492.9 K is 0.9437×10^6 J/kg;
  - Saturation pressure of water at temperature 543.2 K is 5.507 MPa;
  - Specific enthalpy of saturated steam at 5.507 MPa is 2.7896×10^6 J/kg)



E01_P01

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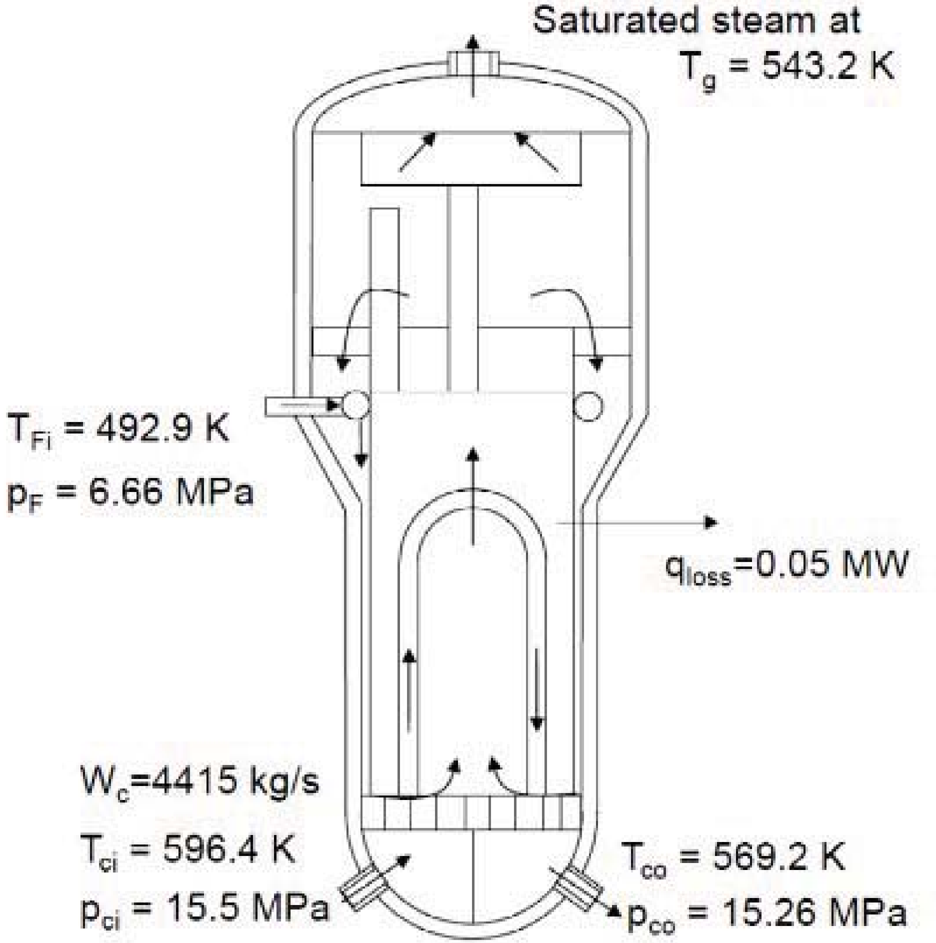
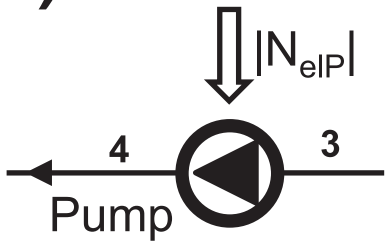
- Solution

$$q_t = W_c \left(i_{ci} - i_{co} \right) = 691.78\ MW$$

$$W_s = \frac{q_t - q_{loss}}{i_s - i_{fw}} = 374.73\ kg/s$$

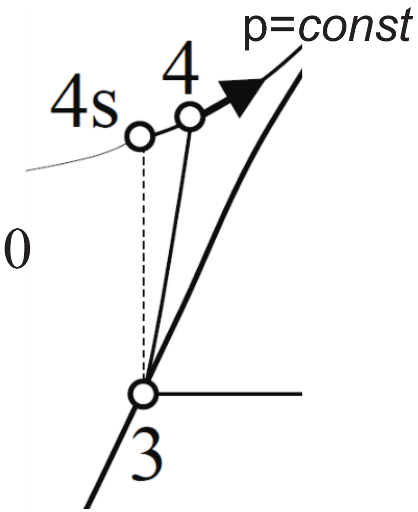


Pumping Power (1)



- To increase pressure from 3 to 4 pumping power $|N_{iP}|$ has to be supplied
- From the energy conservation principle for steady-state ($dE_T/dt=0$) we have

$$\frac{dE_T}{dt} = q - N_{iP} + W_3\left(i_3 + e_{P3} + e_{K3}\right) - W_4\left(i_4 + e_{P4} + e_{K4}\right) = 0$$

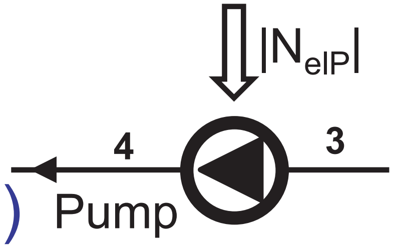


  - here we have to supply power to the system thus $-N_{iP} = |N_{iP}|$, no heat is added thus q = 0, we also neglect kinetic and potential energy changes and from mass conservation we have $W_3=W_4=W$

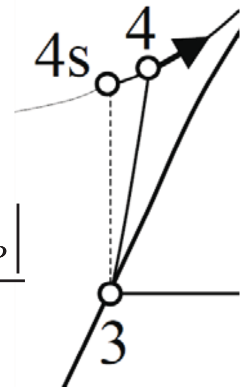
$$|N_{iP}| = W\left(i_4 - i_3\right) = W\left(\underbrace{e_{I4} - e_{I3}}_{\text{internal energy increase}} + \frac{p_4 - p_3}{\rho_e}\right) = \underbrace{W\frac{p_4 - p_3}{\rho_e}}_{N_{uP}=\text{useful pumping power}} + \underbrace{W\Delta e_I}_{\text{internal energy increase}}$$

Here ρ_e is an equivalent fluid density for process 3-4. Typically we assume $\rho_e \approx \rho_3 \approx \rho_4$ (incompressible)

Pumping Power (2)



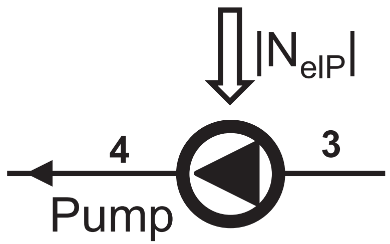
- The pumping power $|N_{thP}|$ is a theoretical pumping power (used in ideal cycle analyses)
- For real process 3-4, we obtain the pumping power $|N_{iP}|$ from energy conservation as $|N_{iP}| \equiv W\left(i_4 - i_3\right)$ and call this internal power
- Due to internal losses, internal power is: $|N_{iP}| = \dfrac{|N_{uP}|}{\eta_{iP}}$
- We also define an effective pumping power, N_{effP}, due to pump mechanical efficiency η_{mP}: $|N_{effP}| = \dfrac{|N_{iP}|}{\eta_{mP}}$
- Finally, the electric motor power for pumping is found as: $|N_{elP}| = \dfrac{|N_{effP}|}{\eta_{EM}}$

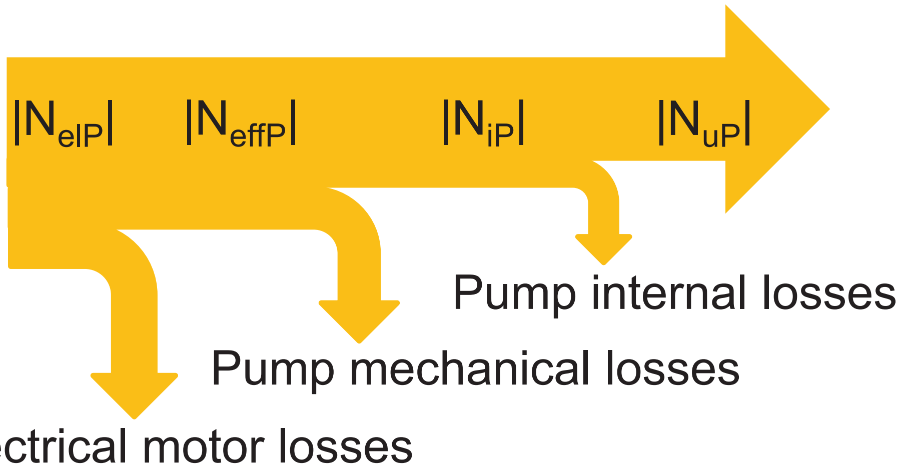


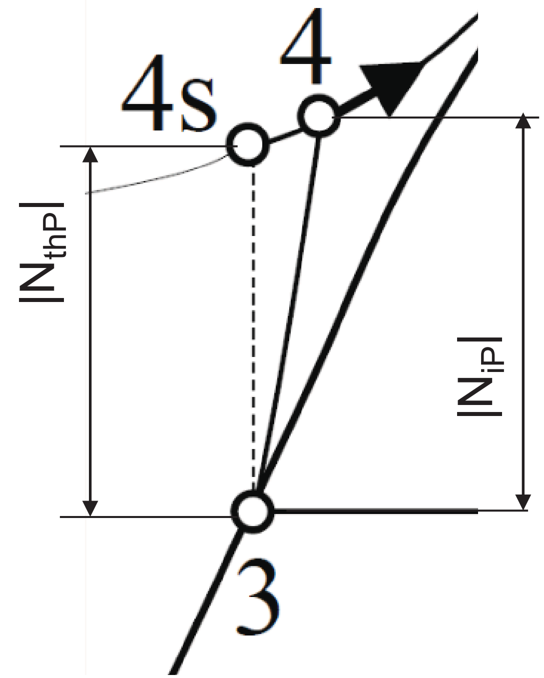
N_{uP} – useful pumping power

Here η_{EM}: is the electrical motor efficiency

Pumping Power (3)







1) $$\left|N_{elP}\right| = W\,\frac{p_4 - p_3}{\eta_{iP}\eta_{mP}\eta_{EM}\rho_e}$$

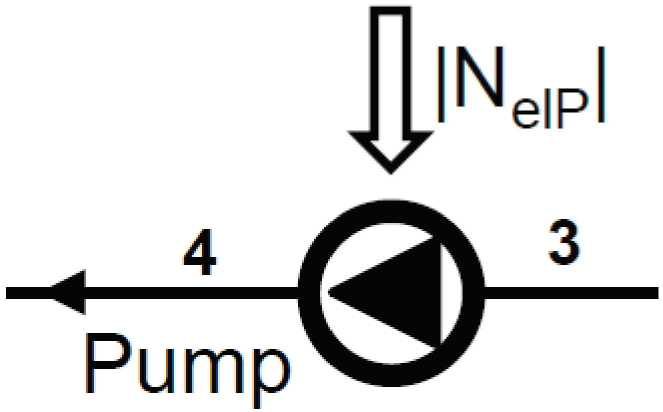
2) $$i_4 - i_3 = \frac{\eta_{mP}\eta_{EM}\left|N_{elP}\right|}{W}$$

3) $$i_4 - i_3 = \frac{p_4 - p_3}{\rho_e \eta_{iP}}$$

Typical tasks: (**1**) calculate required electrical power to produce given pressure difference; (**2**) calculate specific enthalpy at pump discharge for given electrical power; (**3**) the same as in (**2**) for given pressure drop

E01_P02

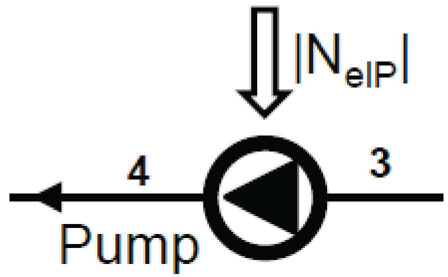
- Calculate the useful pumping power required in a primary loop of a PWR where the total pressure losses are 0.47 MPa and the coolant flow rate is 4410 kg/s. The reference pressure and temperature in the pump are 15.3 MPa and 286^{o}C, respectively.



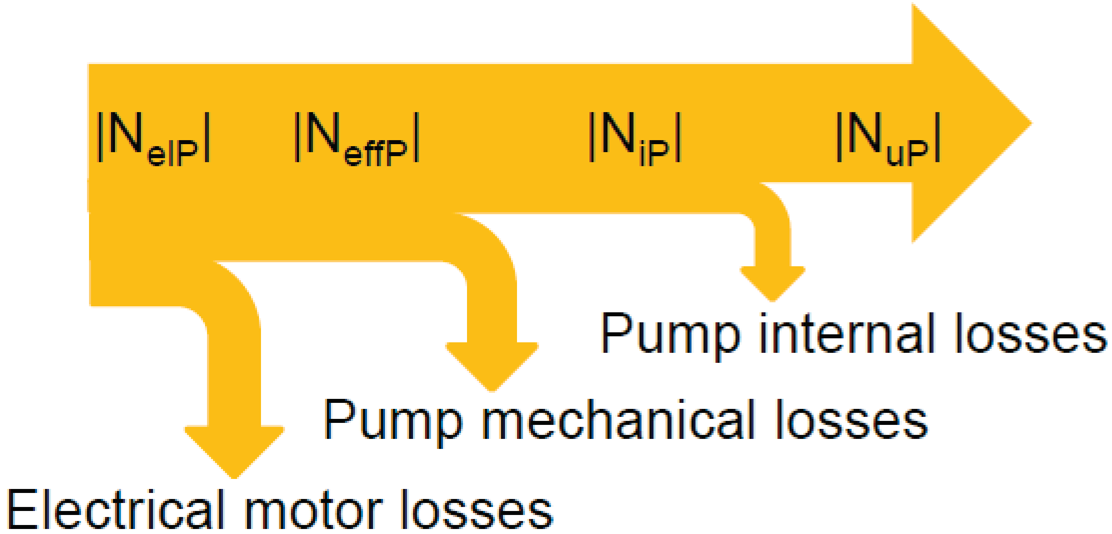
E01_P02

- Calculate the useful pumping power required in a primary loop of a PWR where the total pressure losses are 0.47 MPa and the coolant flow rate is 4410 kg/s. The reference pressure and temperature in the pump are 15.3 MPa and 286°C, respectively.

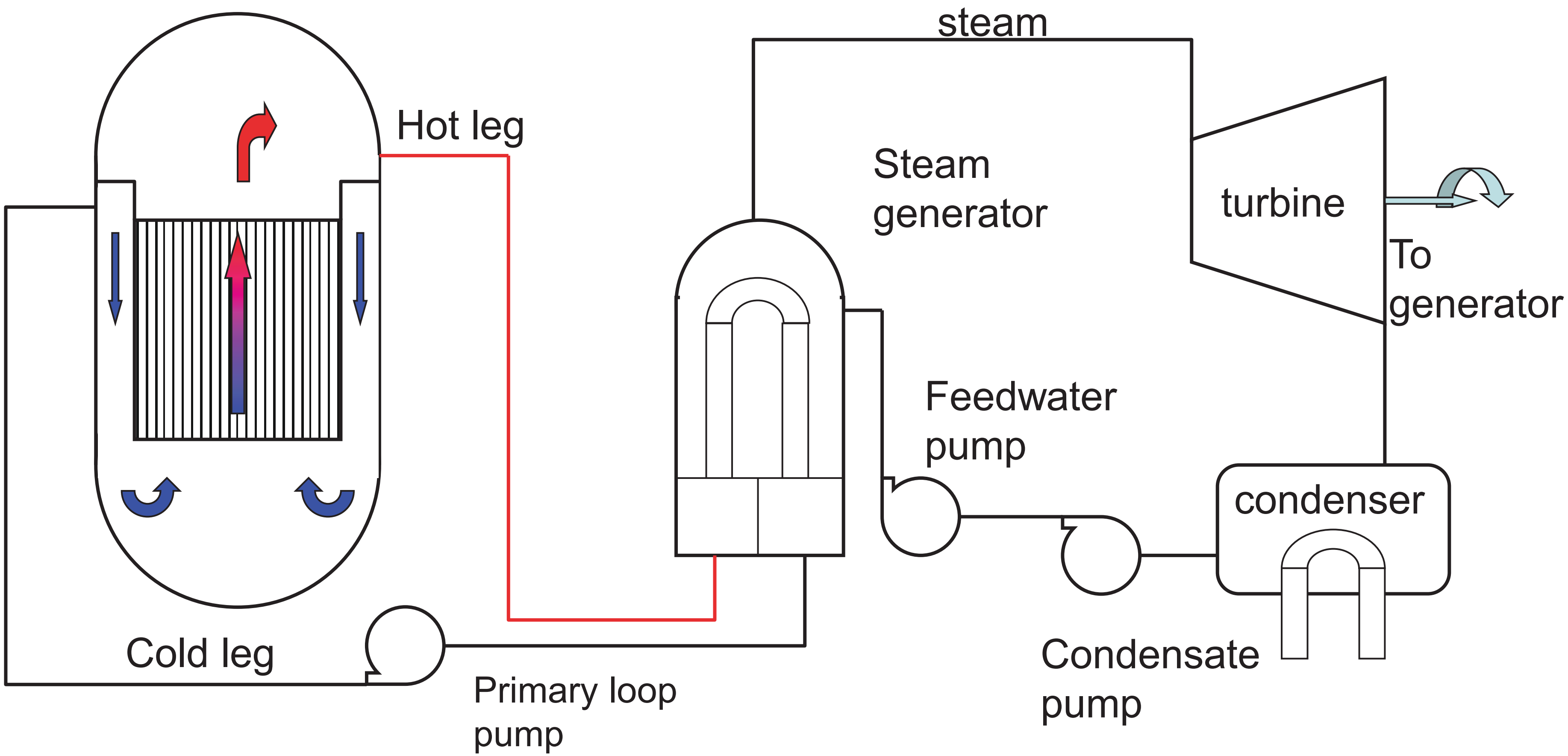
- Solution
  NuP = W dp / rhoe
  = 4410 * 0.47*106 / 753.3
  = 2.75 (MW)



$$\left|N_{elP}\right| = W \frac{p_4 - p_3}{\eta_{iP}\eta_{mP}\eta_{EM}\rho_e}$$



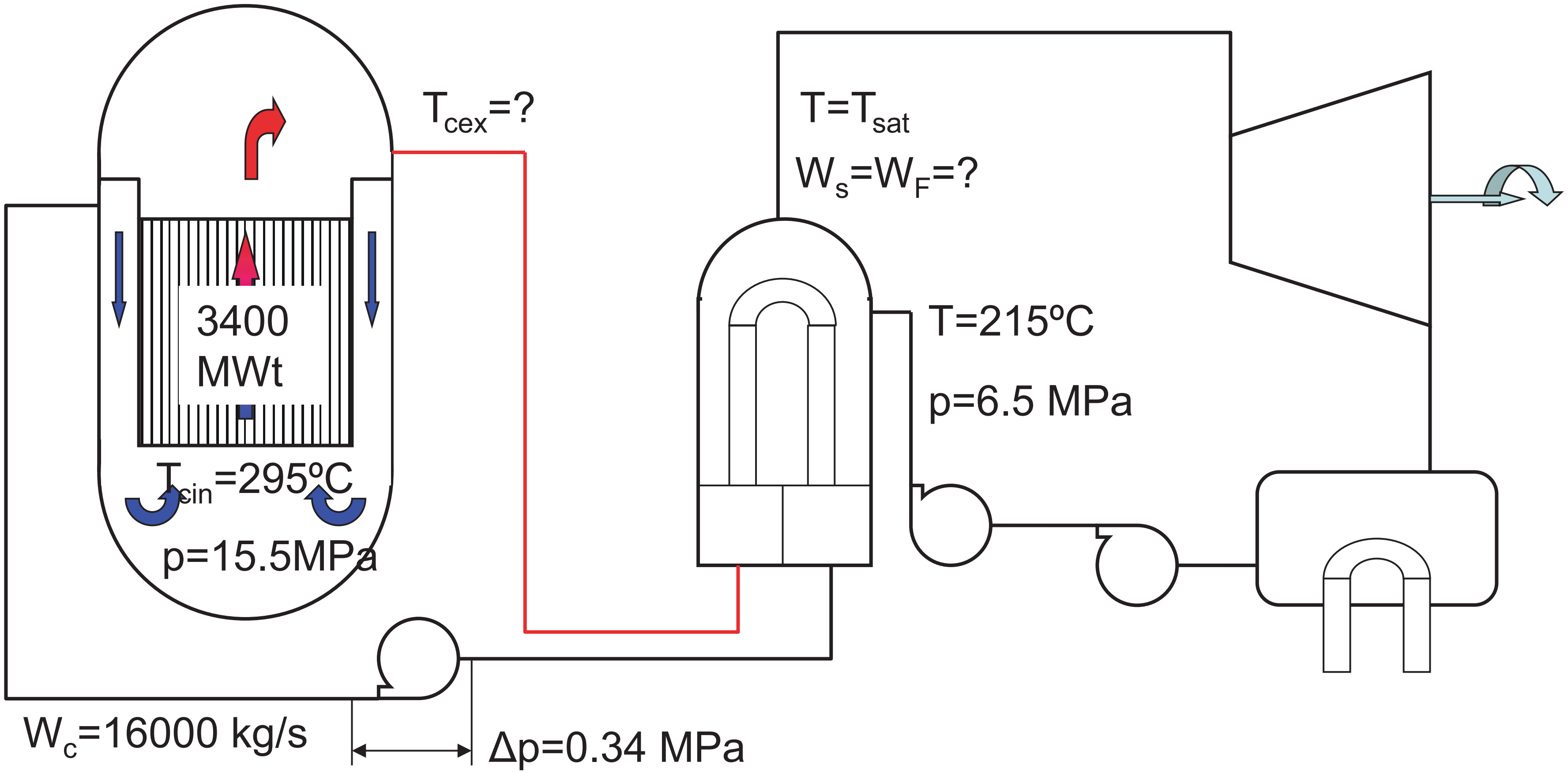
Schematic of PWR Plant



E01_P03

- Assume a PWR operating at steady-state with the following parameters:
  - Thermal core power q_c = 3400 MWt
  - Total coolant mass flow rate W_c = 16000 kg/s
  - Core inlet temperature T_{cin} = 295 °C
  - Reference pressure in the primary system 15.5 MPa
  - Total pump pressure drop in the primary system 0.34 MPa
  - Inlet temperature of feed water to steam generator T_{fwin} = 215 °C
  - Pressure in the secondary system 6.5 MPa
- Calculate
  - Core outlet temperature
  - Mass flow rate of saturated steam leaving the steam generator

E01_P03



T_{cex}=?
T=T_{sat}
W_s=W_F=?
3400
MWt
T=215ºC
p=6.5 MPa
T_{cin}=295ºC
p=15.5MPa
W_c=16000 kg/s
Δp=0.34 MPa

Energy Balance in the Core

- The inlet enthalpy of coolant is found as $i_{cin} = f(p, T_{cin})$ from water property tables: $i_{cin} = 1310.6$ kJ/kg
- For the reactor pressure vessel the energy conservation equation is as follows:

$W_c*i_{cex} = W_c*i_{cin} + q_c$ *(we neglect heat losses)*

thus

$i_{cex} = i_{cin} + q_c/W_c$ = 1310.6 + 3400000/16000 = 1310.9 + 212.5 = 1523.1 kJ/kg

Coolant Temperature

- From water property tables, the saturation enthalpy at p = 15.5 MPa is found as i_f = 1629.9 kJ/kg
- It is thus clear that there is a subcooled water at the outlet from the reactor core
- Its temperature is found from tables as $T_{cex} = \mathrm{f}(p, i_{cex})$ = 330.9 ºC
- The coolant temperature increase in the reactor core is thus 330.9 – 295 = 35.9 ºC

Energy Balance in Primary Loop

- Next step is to calculate the energy transferred to steam in the steam generator (SG)
- The total energy entering SG from the primary side consists of
  - Thermal energy generated in the reactor core per unit time: q_c = 3400 MW
  - Work done by pumps on surroundings: $P_p = W_c(i_1 - i_2)$

for incompressible and isentropic process: $di = dp/\rho$ => $i_1 - i_2 = (p_1 - p_2)/\rho$

pumping power = **pressure drop/coolant density * mass flow rate**

Assuming that coolant temperature in pump is 295 ºC and the mean pressure 15.33 MPa, the coolant density in the pump is found from water property tables as: 736.3 kg/m^3

Pumping Power

- Hence, the work per unit time done by pumps is (neglecting losses),

  $-3.4\ 10^5$ (Pa) / 736.3 (kg/m^3) * 16000 (kg/s) = -7.39 MW

- Thus, the total energy per unit time entering the SG on the primary side is

  3400 –(-7.39) = 3407.39 MW

- The same amount of energy is transferred to the secondary side of the SG

Energy Balance in SG (1)

- The energy balance for the SG is thus

  $q_{SG} = W_F{}^*(i_s - i_F)$

  here:

  q_{SG} – total thermal power provided to steam generator
  W_F – total mass flow rate of feed-water in the SG: from the mass conservation principle, it is equal to the mass flow rate of the generated steam, W_s
  i_s – outlet enthalpy of steam from SG
  i_F – inlet enthalpy of feed water to SG

Energy Balance in SG (2)

- The energy balance yields

$$W_F = q_{SG} / (i_s - i_F)$$

and from steam-water property tables:

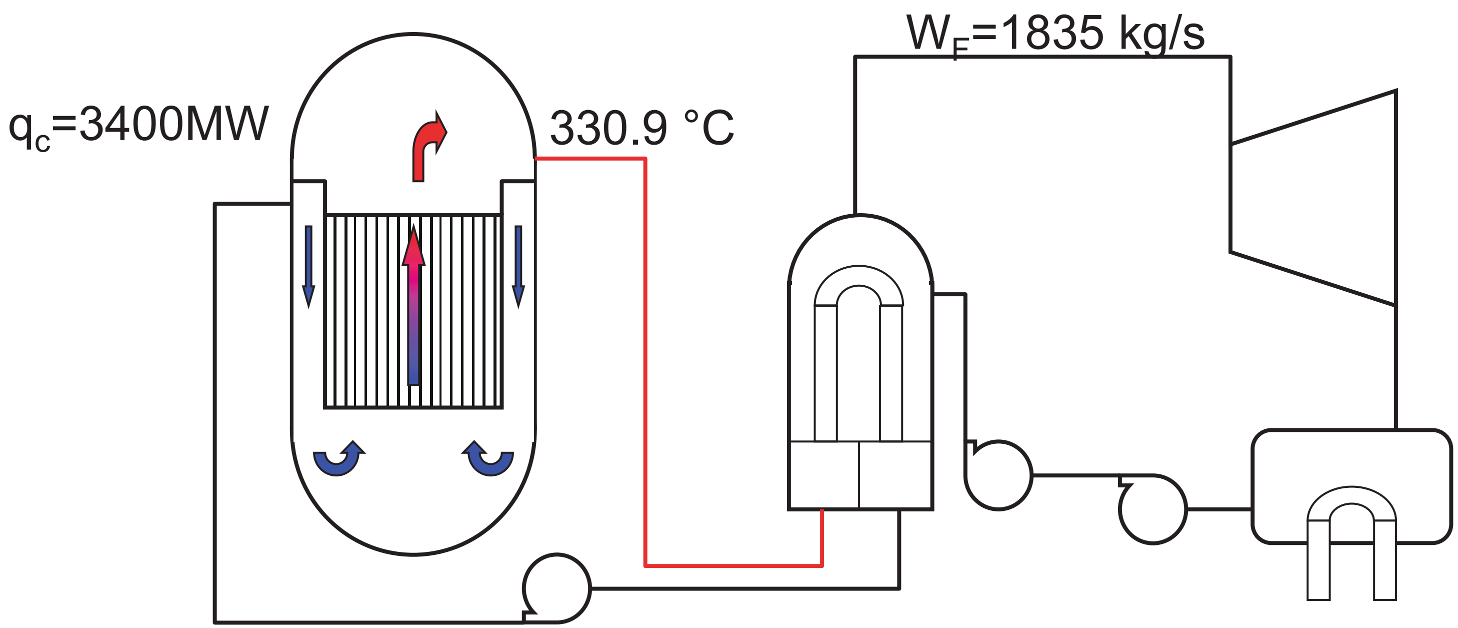
i_s = (saturated steam at 6.5 MPa pressure) = 2778.8 kJ/kg (Note: we assume dry steam, F_{co} = 0)

i_F = (subcooled water at 6.5 MPa and 215 ºC) = 921.9 kJ/kg

Thus: $W_F = 3407.39 * 10^6 / [(2778.8 - 921.9) * 10^3] = 1835$ kg/s

Summary of Results

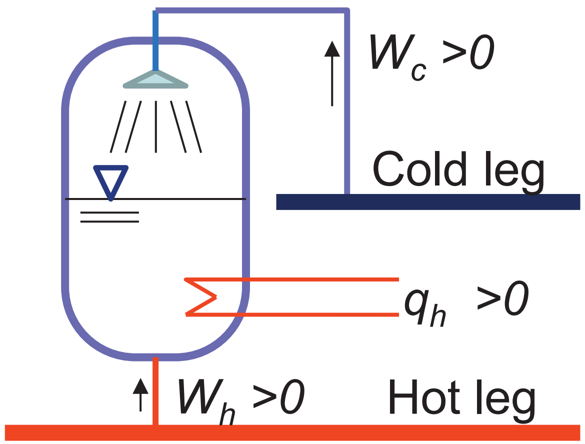
- Coolant temperature at the outlet from reactor: 330.9 °C
- Mass flow rate of saturated steam: 1835 kg/s



Pressurizer Operation

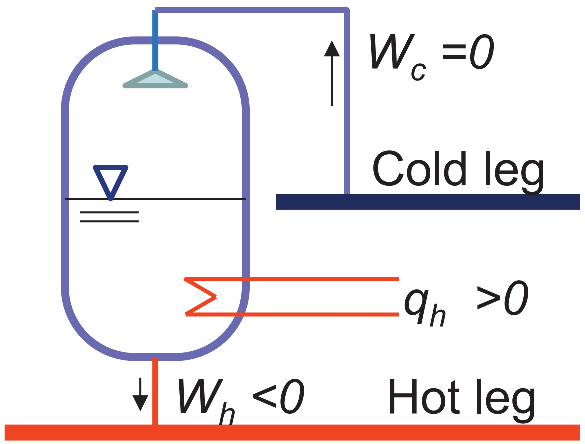
Insurge

- When pressure in the primary system is too high, water from cold leg is sprayed into pressurizer's part filled with vapor. As a result, the following occurs:
  - vapor is condensing and its volume is decreasing
  - water flows into pressurizer from the hot leg
  - heaters are switched on to bring water in pressurizer to saturation level
  - pressure in the primary system decreases



Pressurizer Operation
Outsurge

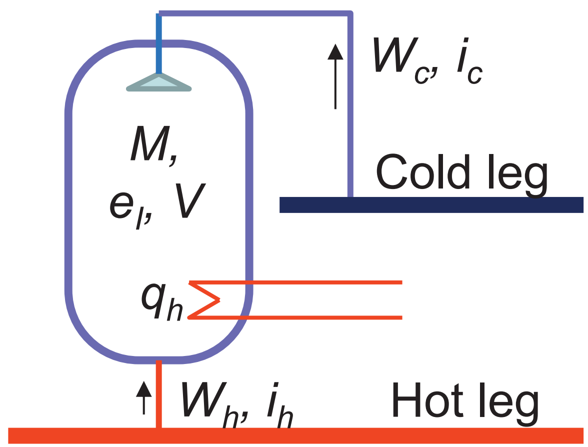
- When pressure in the primary system is too low, heaters are switched on to boil the saturated water. As a result, the following occurs:
  - vapor is generated and its volume is increasing
  - water flows out of the pressurizer into the hot leg
  - pressure in the primary system increases



HEM of Pressurizer

- For a simple transient, homogeneous equilibrium model (HEM) of pressurizer, it is assumed:
  - both phases are in the thermodynamic equilibrium
  - whole volume is filled with a saturated homogeneous mixture
- The following conservation equations can be formulated:
  - mass $$\frac{dM}{dt} = W_h + W_c$$
  - energy $$\frac{d(Me_I)}{dt} = W_h i_h + W_c i_c + q_h$$
  - volume $$\frac{dV}{dt} = 0$$

M – total mass in pressurizer
***e**$_l$* – total specific internal energy in pressurizer
V – total volume of the pressurizer
***W**$_h$* – insurge flow rate
***W**$_c$* – spray flow rate
***i**$_h$* – insurge specific enthalpy
***i**$_c$* – spray specific enthalpy
***q**$_h$* – heater power



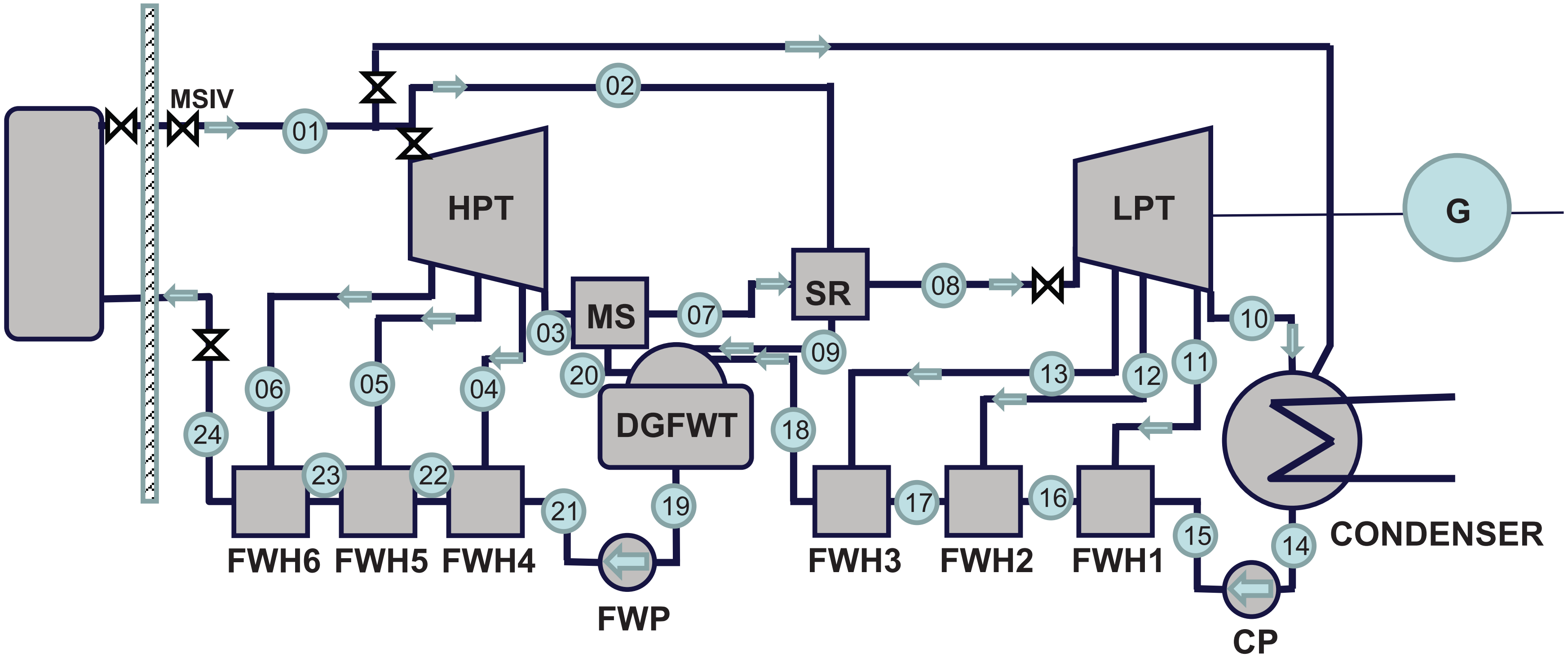
HEM of Pressurizer

- The model has:
  - five input parameters: W_c, i_c, W_h, i_h, q_h,
  - three unknowns: M, e_l and V,
  - three equations.

- The model provides the time variations of $M(t)$ and $e_l(t)$, whereas V = const = V_0 (initial volume).

- The pressure in the pressurizer can be found from HEM assumptions as $p = p(M, e_l)$, provided that the initial pressure is known.

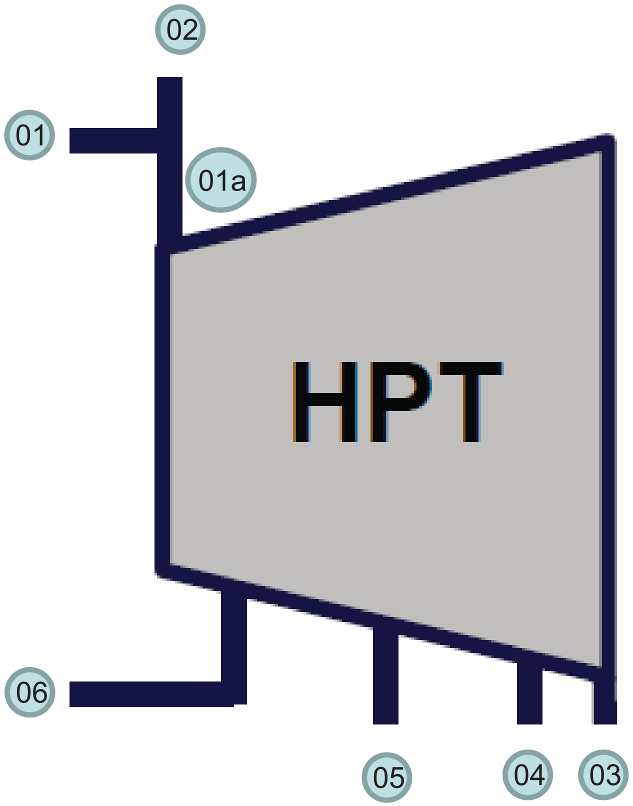
Schematic of BOP



HPT – high pressure turbine
LPT – low pressure turbine
G – generator
MS – moisture separator
SR – steam reheater

DGFWT – degasifier and feedwater tank
FWH – feed water heater
FWP – feed water pump
CP – condensate pump
MSIV – main steam isolation valve

HPT – Mass&Energy Balance



Mass balance for the turbine:

$$W_{1a} - W_3 - W_4 - W_5 - W_6 = 0$$

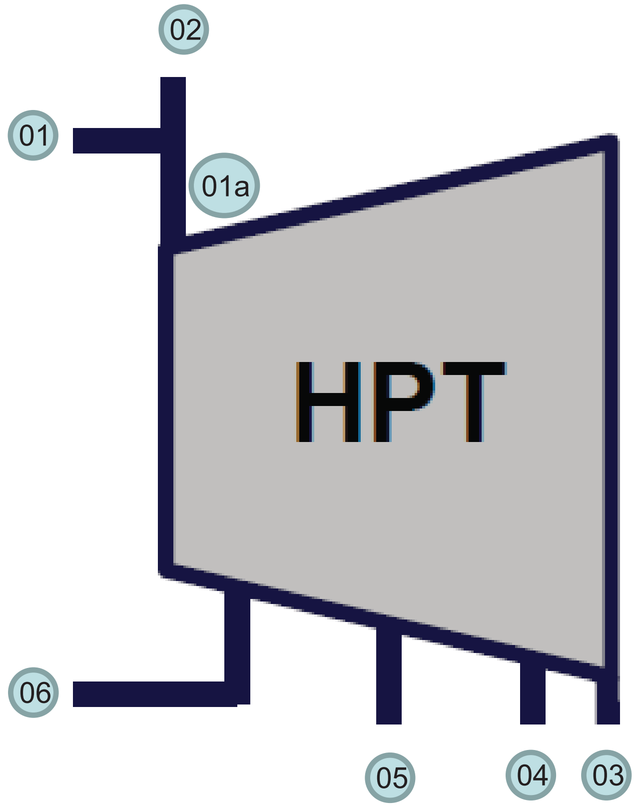
Energy balance for the turbine:

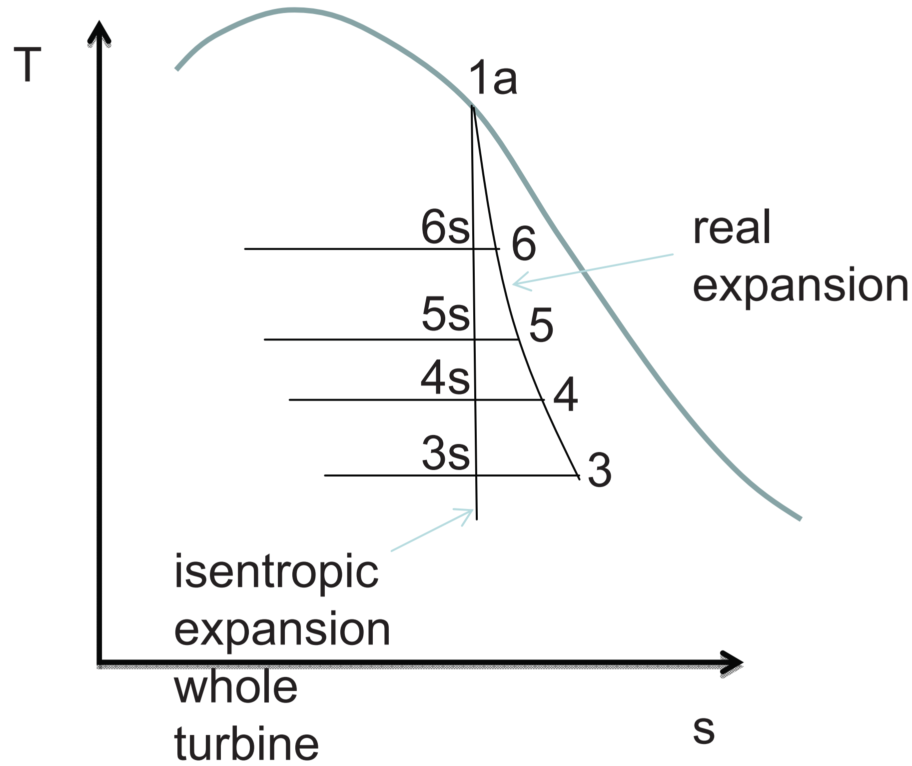
$$W_{1a} i_{1a} - W_3 i_3 - W_4 i_4 - W_5 i_5 - W_6 i_6 - N_{HPT,i} = 0$$

W_k – mass flow rate of stream k
i_k – enthalpy of stream k
$N_{HPT,i}$ – internal power of HPT

1- steam from reactor, 1a – steam to turbine, 2- steam to SR, 3- exit steam from turbine, 4- third steam extraction, 5- second steam extraction, 6 – first steam extraction

HPT – T-s Diagram





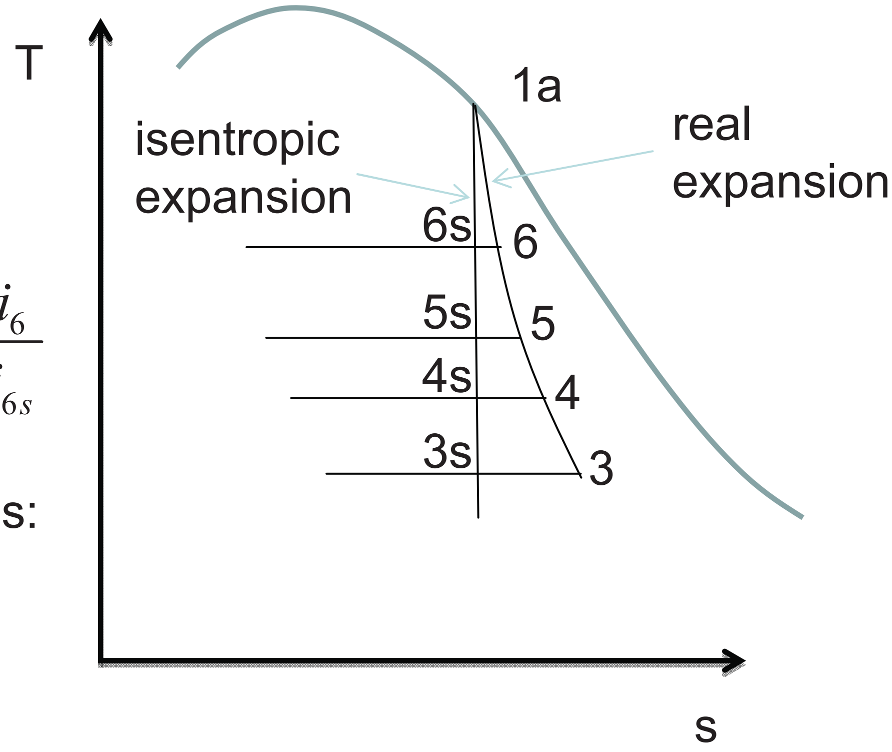
HPT – First Extraction

From inlet to the first extraction we have:

$$\eta_{HPT1,i} \equiv \frac{N_{HPT1,i}}{N_{HPT1,th}} = \frac{W_{1a}\left(i_{1a} - i_6\right)}{W_{1a}\left(i_{1a} - i_{6s}\right)} = \frac{i_{1a} - i_6}{i_{1a} - i_{6s}}$$

Thus, the enthalpy at the first extraction is:

$$i_6 = i_{1a} - \eta_{HPT1,i}\left(i_{1a} - i_{6s}\right)$$



Here we define the internal efficiency (called also isentropic efficiency) as:

$$\eta_{HPT1,i} \equiv \frac{N_{HPT1,i}}{N_{HPT1,th}}$$

The specific enthalpy at point 6s is found from property tables as $i(p_6, s_{1a})$

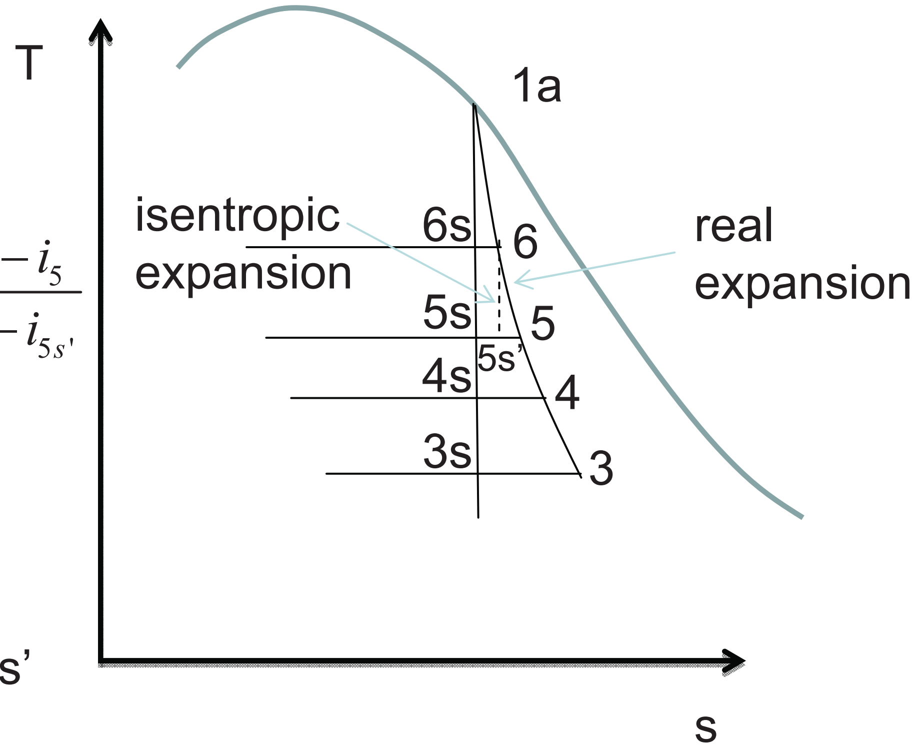
HPT – Second Extraction

The internal efficiency of the turbine between the first and the second extraction is given as:

$$\eta_{HPT2,i} \equiv \frac{N_{HPT2,i}}{N_{HPT2,th}} = \frac{(W_{1a} - W_6)(i_6 - i_5)}{(W_{1a} - W_6)(i_6 - i_{5s'})} = \frac{i_6 - i_5}{i_6 - i_{5s'}}$$

$$i_5 = i_6 - \eta_{HPT2,i}(i_6 - i_{5s'})$$

Where the specific enthalpy at point 5s' is found from property tables as $i_{5s'} = i(p_5, s_6)$



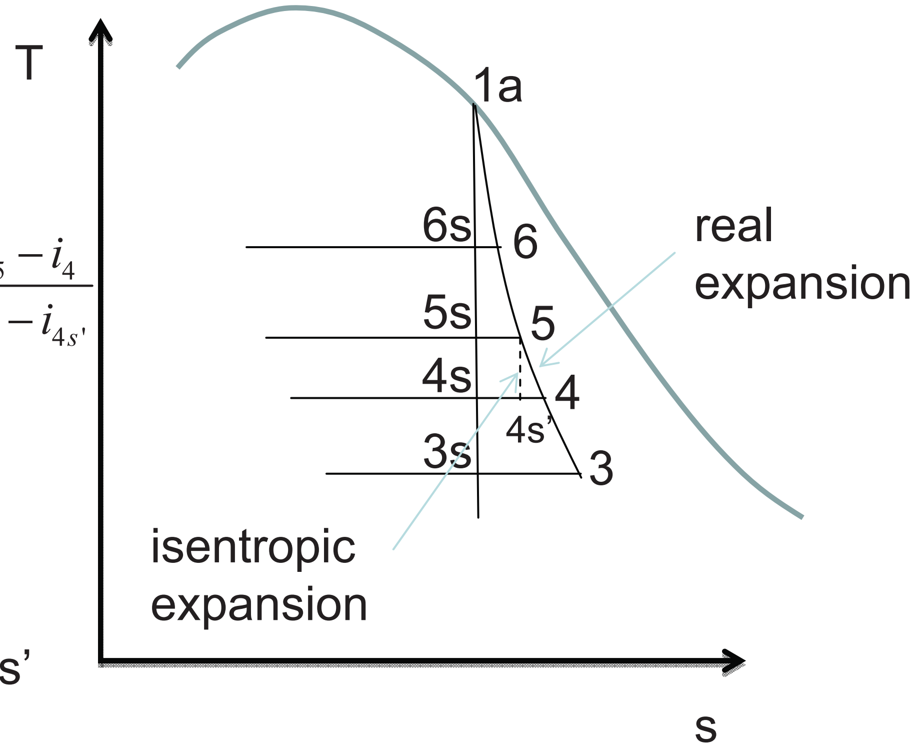
HPT – Third Extraction

The internal efficiency of the turbine between the second and the third extraction is given as:

$$\eta_{HPT3,i} \equiv \frac{N_{HPT3,i}}{N_{HPT3,th}} = \frac{(W_{1a} - W_6 - W_5)(i_5 - i_4)}{(W_{1a} - W_6 - W_5)(i_5 - i_{4s'})} = \frac{i_5 - i_4}{i_5 - i_{4s'}}$$

$$i_4 = i_5 - \eta_{HPT3,i}\left(i_5 - i_{4s'}\right)$$

Where the specific enthalpy at point 4s' is found from property tables as $i_{4s'} = i(p_4, s_5)$



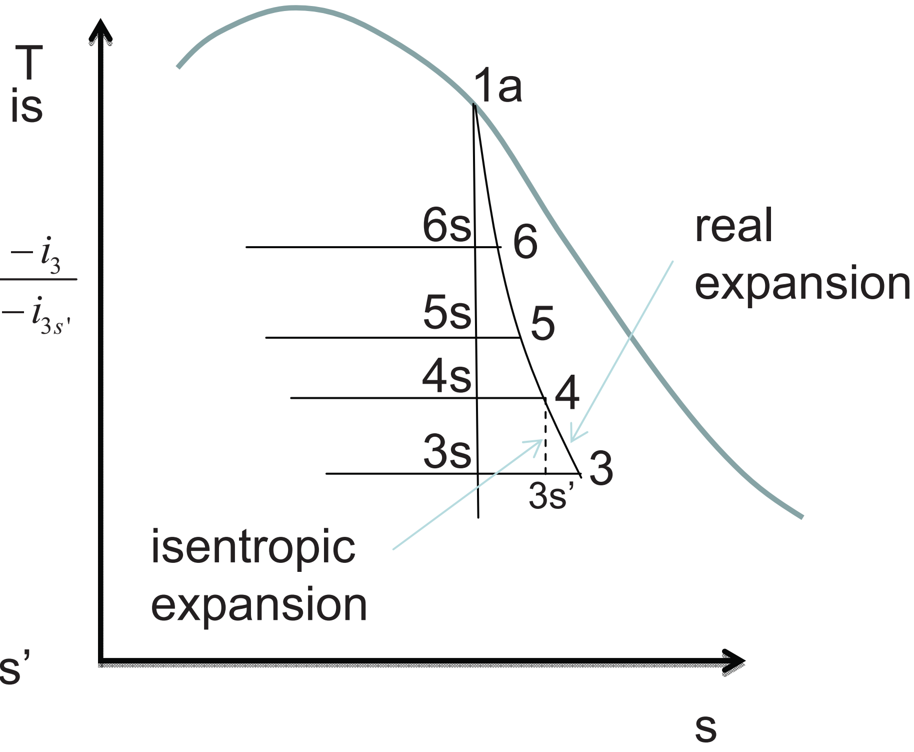
HPT – Exit

The internal efficiency of the turbine between the third extraction and the exit is given as:

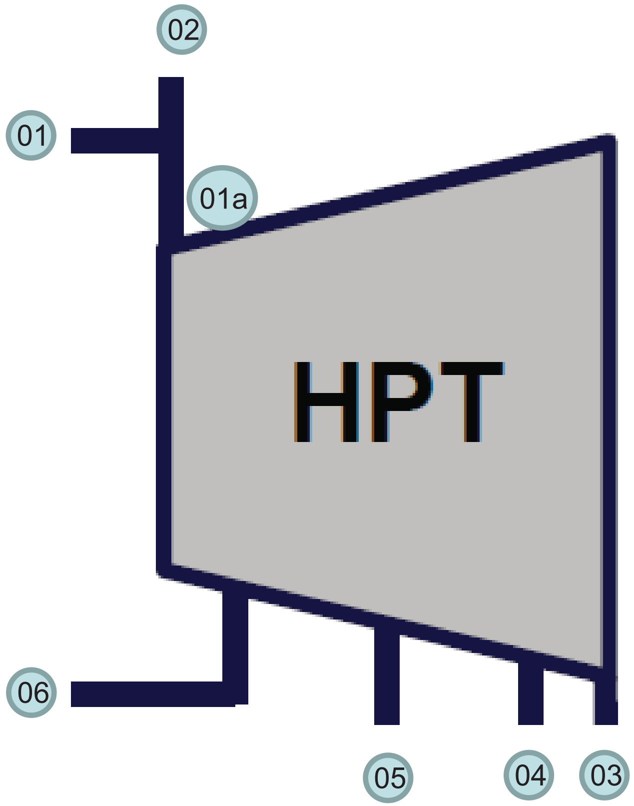
$$\eta_{HPT4,i} \equiv \frac{N_{HPT4,i}}{N_{HPT4,th}} = \frac{(W_{1a} - W_6 - W_5 - W_4)(i_4 - i_3)}{(W_{1a} - W_6 - W_5 - W_4)(i_4 - i_{3s'})} = \frac{i_4 - i_3}{i_4 - i_{3s'}}$$

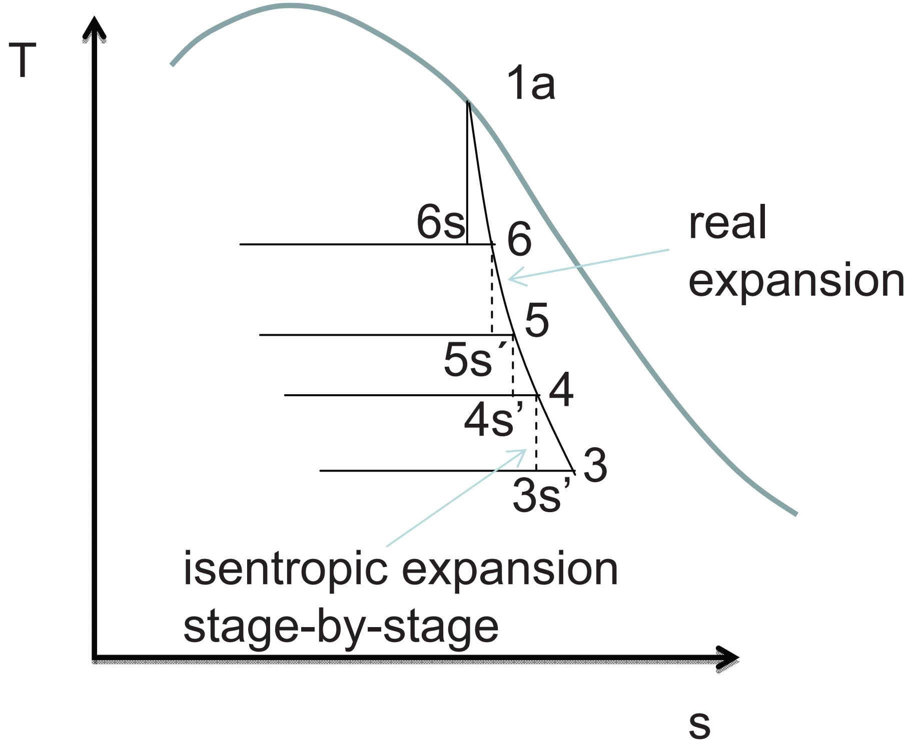
$$i_3 = i_4 - \eta_{HPT4,i}(i_4 - i_{3s'})$$

Where the specific enthalpy at point 3s' is found from property tables as $i_{3s'} = i(p_3, s_4)$



HPT – Total Internal Power





The total Internal power:

$$N_{HPT,i} = W_{1a}\left(i_{1a} - i_6\right) + \left(W_{1a} - W_6\right)\left(i_6 - i_5\right) + \left(W_{1a} - W_6 - W_5\right)\left(i_5 - i_4\right) + \left(W_{1a} - W_6 - W_5 - W_4\right)\left(i_4 - i_3\right)$$

Turbine Efficiency

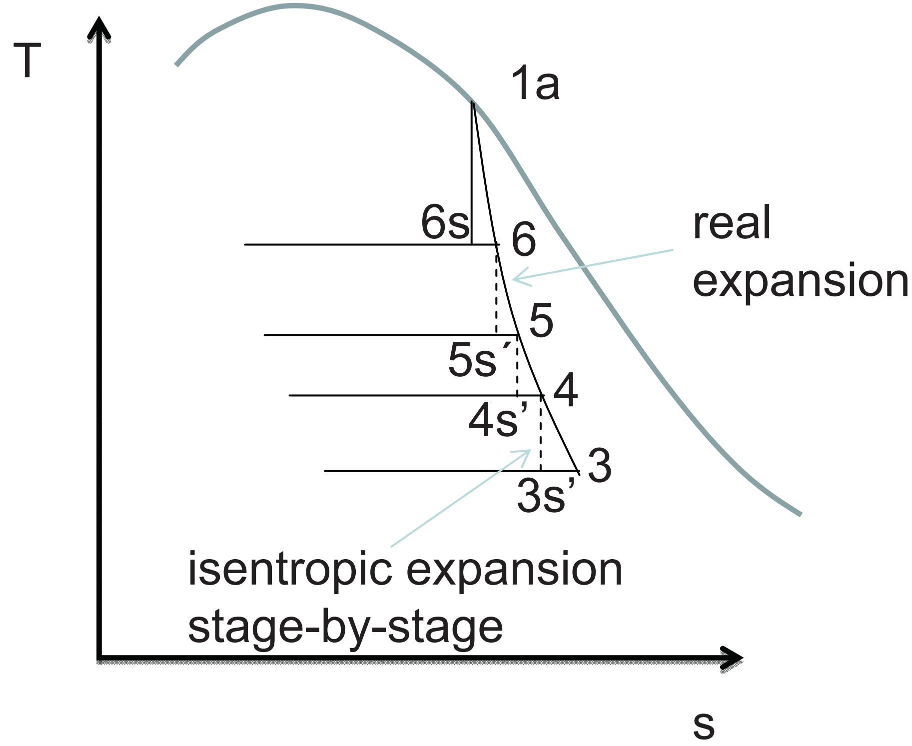
Internal efficiency:

$$\eta_{HPT,i} \equiv \frac{N_{HPT,i}}{N_{HPT,th}}$$

Mechanical efficiency:

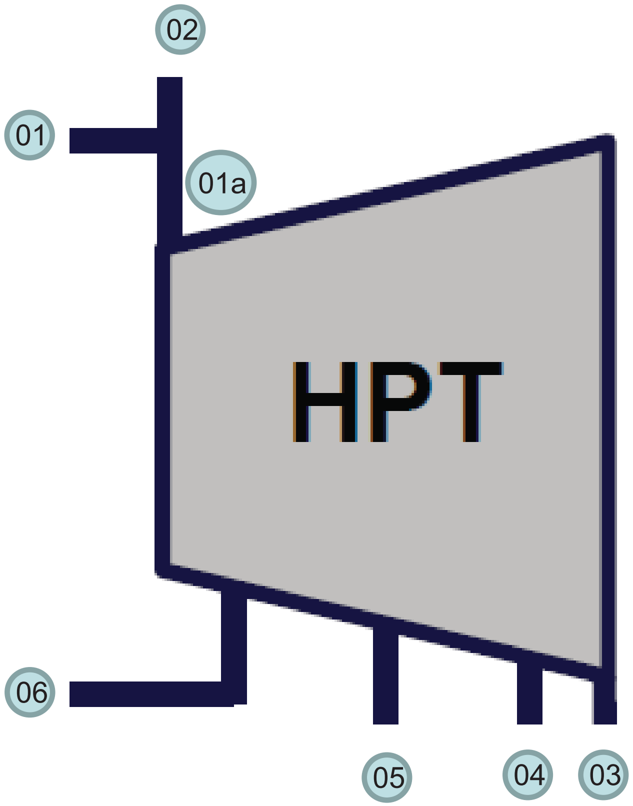
$$\eta_{HPT,m} \equiv \frac{N_{HPT,m}}{N_{HPT,i}}$$

Effective efficiency:



$$\eta_{HPT,e} \equiv \eta_{HPT,m}\eta_{HPT,i} = \frac{N_{HPT,m}}{N_{HPT,i}} \cdot \frac{N_{HPT,i}}{N_{HPT,th}} = \frac{N_{HPT,m}}{N_{HPT,th}}$$

HPT – Example



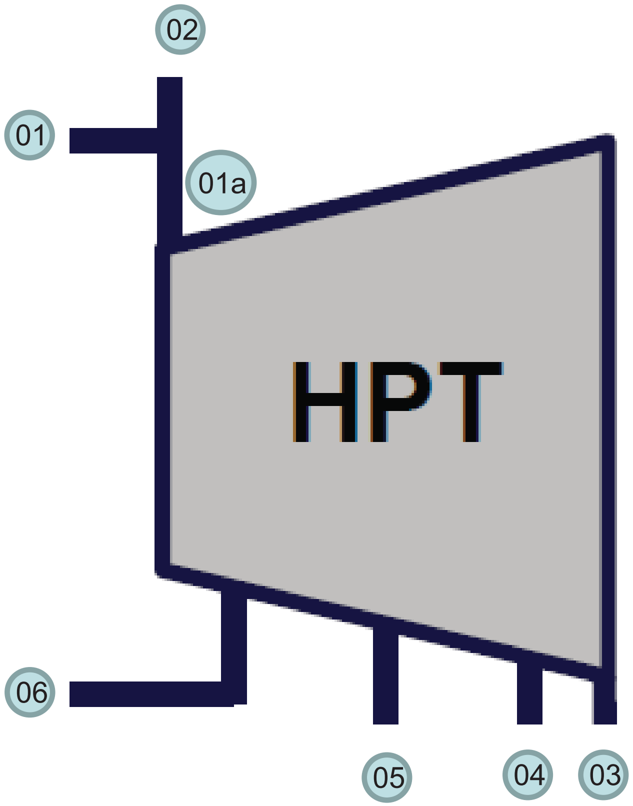
Calculate enthalpy distribution in HPT.

Known:

p_{1a} = 60 bar (sat. steam)
p_3 = 8 bar
p_4 = 23 bar
p_5 = 38 bar
p_6 = 50 bar
$W_{1a} = 0.91W_1$
$W_4 + W_5 + W_6 = 0.15W_1$

$$\eta_{HPT1,i} = \ldots = \eta_{HPT4,i} = 0.88$$

HPT – Solution



Calculated enthalpy distribution in HPT.

Found:

$i_{1a} = i_g(60 \text{ bar}) = 2784.6$ kJ/kg

$s_{1a} = s_g(60 \text{ bar}) = 5.89$ kJ/kg/K

$i_{6s} = i(p_6, s_{1a}) = 2749.3$ kJ/kg

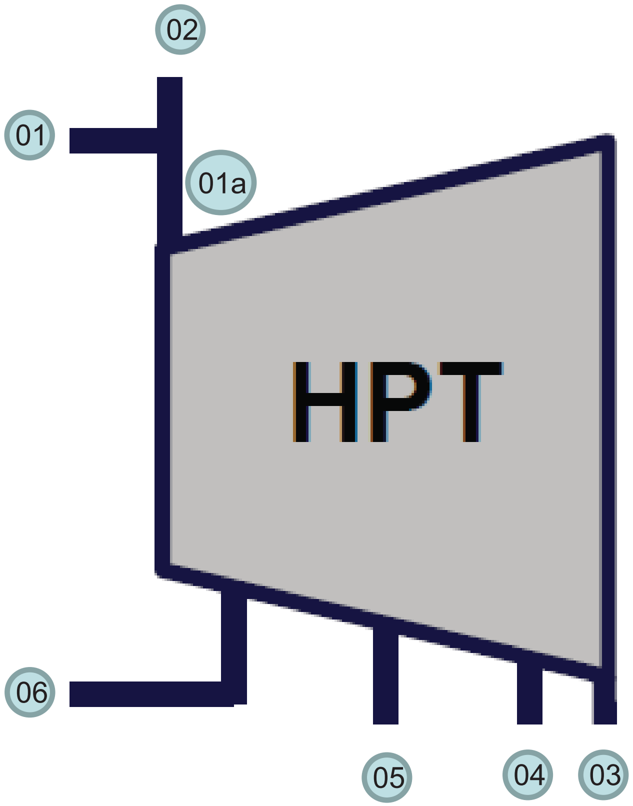
$i_6 = i_{1a} - \eta_1(i_{1a} - i_{6s}) = 2753.5$ kJ/kg

$i_5 = 2707.6$ kJ/kg

$i_4 = 2626.1$ kJ/kg

$i_3 = 2466.7$ kJ/kg

HPT – Solution



Flow distribution in HPT.

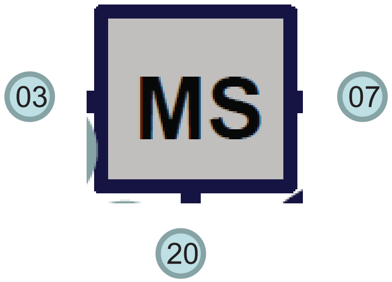
Typical values:

$W_{1a} = 0.91W_1$; $W_2 = 0.09W_1$

$W_4 + W_5 + W_6 = 0.15W_1$

$W_3 = 0.76W_1$

MS – Mass&Energy Balance



03 – wet steam from exit of HPT
07 – saturated steam to steam reheater
20 – moisture (saturated water)

Mass balance:

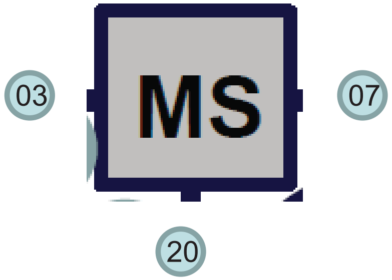
$$W_3 - W_7 - W_{20} = 0$$

Energy balance:

$$W_3 i_3 - W_7 i_7 - W_{20} i_{20} = 0$$

$$i_7 \approx i_g(p_7) \qquad i_{20} \approx i_f(p_{20})$$

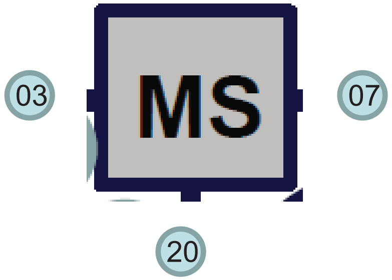
MS – Example



Known:
p_{20} = 8 bar ≈ p_7
i_3 = 2466.7 kJ/kg
Find fraction of flow y_7 and y_{20}:

$$y_7 \equiv \frac{W_7}{W_3};\ y_{20} \equiv \frac{W_{20}}{W_3} = 1 - y_7$$

MS – Example



Known:
p_{20} = 8 bar ≈ p_7
i_3 = 2466.7 kJ/kg
Find fraction of flow y_7 and y_{20}:

$$y_7 \equiv \frac{W_7}{W_3};\ y_{20} \equiv \frac{W_{20}}{W_3} = 1 - y_7$$

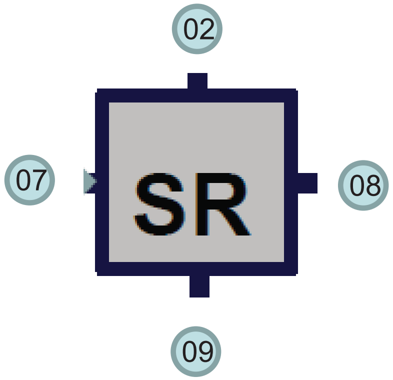
Energy balance gives:

$$i_3 - \frac{W_7}{W_3} i_7 - \frac{W_{20}}{W_3} i_{20} = i_3 - y_7 (i_7 - i_{20}) - i_{20} = 0 \quad \Rightarrow \quad y_7 = \frac{i_3 - i_{20}}{i_7 - i_{20}}$$

Found: i_7 = 2768.3 kJ/kg
i_{20} = 721.0 kJ/kg
y_7 = 0.853

The fraction of moisture separated in MS is y_{20} = 0.147. (In reality, not all moisture is separated.) Thus W_{20} ≈ 0.11$W_1$and W_7 ≈ 0.65W_1

SR – Mass&Energy Balance



02 – saturated steam from reactor
08 – steam to LPT inlet
09 – wet steam to DGFWT
07 – saturated steam from MS

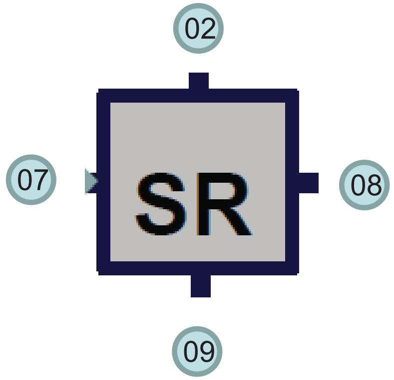
Mass balance:

$$W_2 = W_9 \quad W_7 = W_8$$

Energy balance:

$$W_2\left(i_2 - i_9\right) = W_7\left(i_8 - i_7\right)$$

SR – Example



Known:

i_7 = 2768.3 kJ/kg, $W_7 \approx 0.65W_1$, p_3 = 8 bar $\approx p_7 \approx p_8$

$i_2 = i_{1a} = i_g$(60 bar)= 2784.6 kJ/kg,

$W_2 = 0.09W_1$

Mass balance:

$$W_2 = W_9 \quad W_7 = W_8$$

From energy balance:

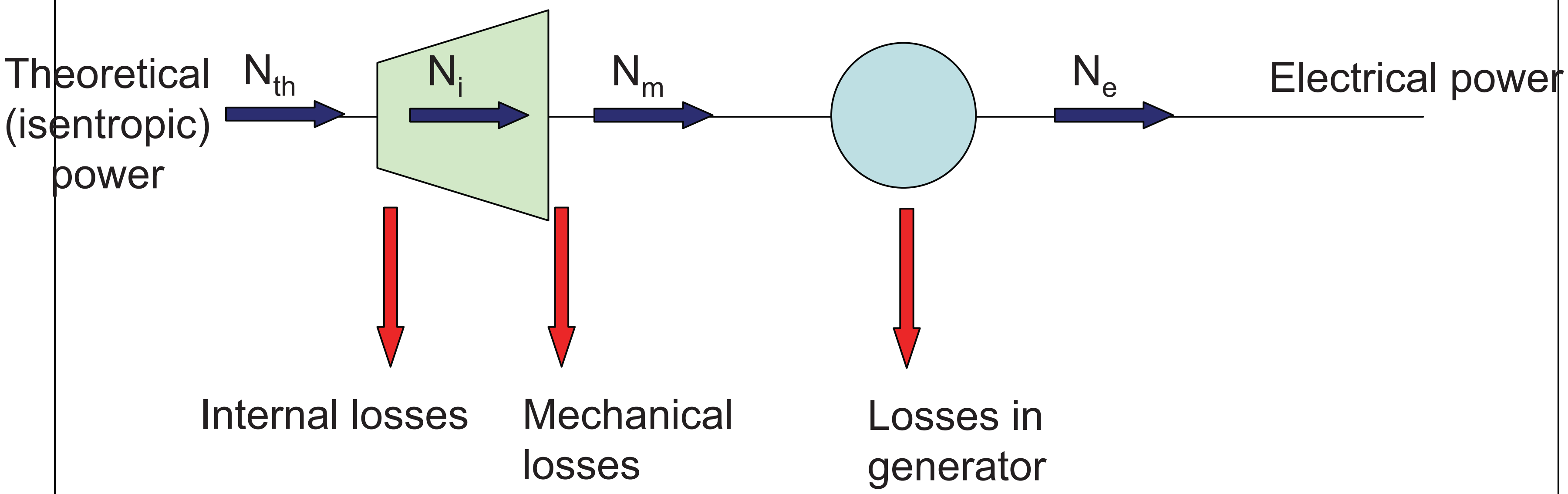
$$i_8 = i_7 + \frac{W_2}{W_7}\left(i_2 - i_9\right)$$

Assuming saturated liquid at 09, $i_9 = i_f$(60 bar) = 1213.7 kJ/kg; thus i_8 = 2985.8 kJ/kg; we note that t_9 = tsat(60 bar) = 275.6 °C and t_8 = tv(8 bar,2985.8 kJ/kg) = 266.4 ° C. So $t_9 > t_8$ as it should be.

Power Losses

- Power losses in a turbine set and generator are as follows:

$$N_i = \eta_i N_{th} \quad N_m = \eta_m \eta_i N_{th} \qquad N_e = \eta_g \eta_m \eta_i N_{th}$$



Plant Energy Efficiency

Reference efficiency: $$\eta_{Ref} \equiv \frac{\sum N_{Turb,i}}{q_{th}} = \frac{total\ internal\ power\ of\ turbines}{Reactor\ power}$$

Equivalent definitions

Internal power is sometimes called "actual useful" power

Thermodynamic efficiency:

$$\eta_{th} \equiv \frac{\sum N_{Turb}}{q_{th}} = \frac{total\ useful\ power\ of\ turbines}{Reactor\ power}$$

Gross efficiency:

$$\eta_{Gross} \equiv \frac{\sum N_{g}}{q_{th}} = \frac{total\ power\ of\ generators}{Reactor\ power}$$

Net efficiency:

$$\eta_{Net} \equiv \frac{\sum N_{g} - \sum N_{own}}{q_{th}} = \frac{total\ power\ of\ generators - own\ needs}{Reactor\ power}$$