Flexware®

Turbomachinery Engineers

A Veteran & Employee Owned Company

Practical Steam Turbine Performance Calculations

(using Flex Live's Steam Flex routine or by manual methods)

A steam turbine's power and/or efficiency can be quickly and accurately calculated using Flexware's Steam Flex steam properties program. It will be necessary to obtain the following operating data from the field.

- Inlet steam pressure
- Inlet steam temperature
- Inlet steam flow rate
- Extraction steam pressure (if extraction type)
- Extraction steam temperature (if extraction type)
- Extraction steam flow rate (if extraction type)
- Exhaust steam pressure
- Exhaust steam temperature (if the exhaust steam is dry & saturated or superheated)
- Shaft power (necessary for non-condensing or condensing turbines with wet exhaust steam)
- See Figure 1 for typical units used for the calculations.

Note the efficiency and/or power can also be calculated manually using a steam Mollier chart and steam tables such as Keenan and Keyes.

Go to Figure 1, page 12 for the descriptions of the various symbols used.

Basic calculations (manually or by Steam Flex).

- **Method 1** - Exhaust steam is dry & saturated or superheated. Can be used for non-condensing type turbines and the high-pressure section of an extraction steam turbine plus it may be possible to use for the non-condensing low-pressure section of an extraction turbine. See Figures 2, 3 or 4.
    - Overall efficiency (η) = Actual enthalpy / Isentropic enthalpy.
    - Actual enthalpy = Inlet enthalpy (h_1) – Exhaust enthalpy (h_2)
    - Isentropic enthalpy = Inlet enthalpy (h_1) – Exhaust enthalpy (h_{2i}). Note – the exhaust enthalpy is calculated using the inlet entropy (s_1)
    - Overall efficiency (η) = $(h_1 - h_2)/(h_1 - h_{2i})$
    - Steam Power = $(h_1 - h_2)$ x steam flow rate $(M_2)/C_1$ (for turbines with dry & saturated or superheated exhaust steam.
    - Shaft power = Steam Power - mechanical losses (journal and thrust bearing losses).

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- **Method 2** - Exhaust steam is wet. Can be used for condensing steam turbines and for the low-pressure section of extraction steam turbines. See Figure 3 or 4.
  - Shaft Power Known (generator, torque meter coupling or the driven unit's power)
    - Overall efficiency (η) = Actual enthalpy / Isentropic enthalpy
    - Isentropic enthalpy = Inlet enthalpy (h_1) – Exhaust enthalpy (h_{2i}) - the exhaust enthalpy is calculated using the inlet entropy(s_1)
    - Steam power = Shaft power plus mechanical losses (journal and thrust bearing losses).
    - ($h_1 – h_2$) = Steam power x C_1/Steam flow rate (M_2)
    - Overall efficiency (η) = ($h_1 – h_2$)/($h_1 – h_{2i}$)

  - Shaft Power Unknown
    - Do a heat balance on the steam condenser to determine the turbine exhaust enthalpy. See Figure 5
    - $h_2 = h_c + (h_{cw2} – h_{cw1})$ x M_{cw}/M_2
    - If the cooling water flow rate is in volume flow (GPM or m^3/hr), convert to mass flow - cooling water mass flow (M_{cw}) = cooling water volume flow rate x C_2
    - Overall efficiency (η) = ($h_1 – h_2$)/($h_1 – h_{2i}$)
    - Steam power = ($h_1 – h_2$) x Steam Flow Rate/C_1
    - Shaft power = Steam power minus mechanical losses (journal and thrust bearings)
    - **Warning** – the cooling water temperature rise is very low, so accurate temperature measures are critical for reliable results.

- Special notes for extraction steam turbines
  - High pressure section
    - Use Method 1 for the inlet conditions
    - Use the extraction steam pressure, temperature and enthalpy for the exhaust conditions.
    - Use in the inlet steam flow rate (M_1) for the steam flow.
  - Low pressure section
    - Use the extraction steam pressure, temperature and enthalpy for the inlet conditions. The steam flow is the inlet steam flow rate (M_1) minus the extraction steam flow rate M_{ex}).
    - Use Method 1 or Method 2 for the exhaust depending on the exhaust steam conditions.

Steam Turbine Performance Examples

Example 1 – Non-condensing steam turbine using Steam Flex

Input Data:

Inlet steam pressure	600 psia
Inlet steam temperature	700 ^{o}F
Exhaust steam pressure	140 psia
Exhaust steam temperature	430 ^{o}F
Inlet steam flow rate	75,000 lb/hr

Results:

Steam Power	3,339 HP
Overall efficiency	76.6%

Notes:

- Inlet steam flow is used. If the steam leakage for the seals is known, it can be deducted to give a more accurate result.
- Shaft power can be determined by subtracting the Mechanical Losses (if known) from the Steam Power.
- See Example 1 Steam Flex below for the summary of results

Example 1 - Steam Flex Data Summary

Flex Live ® Steam Turbine Field Test

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Description: Example 1 Steam Flex

Inputs	Units	Value
Inlet Pressure	psia	600.00
Inlet Temperature	°F	700.00
Inlet Flow	lb/hr	75,000
Exhaust Pressure	psia	140.00
Exhaust Temperature	°F	430.00
Speed	RPM	7,500.0

Results	Units	Value
Inlet Specific Volume	ft³/lb	1.0732
Inlet Enthalpy	Btu/lb	1,351.1
Inlet Entropy	Btu/lb °R	1.5875
Inlet Saturation Temperature	°F	486.21
Inlet Superheat	°F	213.79
Exhaust Enthalpy	Btu/lb	1,237.8
Exhaust Temperature	°F	430.00
Exhaust Power	HP	3,338.9
Exhaust Moisture	%	0
Theoretical Steam Rate	lb/HP hr	17.207
Steam Rate	lb/HP hr	22.463
Efficiency	%	76.601

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Example 1 – Non-condensing steam turbine using Mollier method and/or steam tables

Input Data:

Inlet steam pressure	600 psia
Inlet steam temperature	700 ^{o}F
Exhaust steam pressure	140 psia
Exhaust steam temperature	430 ^{o}F
Inlet steam flow rate	75,000 lb/hr

From Steam Tables:

inlet enthalpy (h_1)	1,351.1 BTU/lb
Inlet entropy (s_1)	1.5875 BTU/lb ^{o}R

Read vertically down on Mollier chart to get the isentropic exhaust enthalpy

Isentropic exhaust enthalpy (h_{2i}) 1202.5 BTU/lb. (Mollier chart)

This value can also be obtained from the steam tables by interpolation using the inlet entropy

Isentropic exhaust enthalpy (h_{2i}) 1203.2 BTU/lb. (steam tables)

Actual exhaust enthalpy can be obtained from the steam tables

Exhaust enthalpy (h_2) 1,237.8 BTU/lb

Efficiency:

Efficiency (η) = $(h_1 – h_2)/(h_1 – h_{2i})$

Efficiency = (1,351.1 – 1,202.5)/(1,351.1 – 1,237.8) = 76.2% using Mollier chart

Efficiency = (1,351.1 – 1,203.2)/(1,351.1 – 1,237.8) = 76.6% using steam tables

Steam Power:

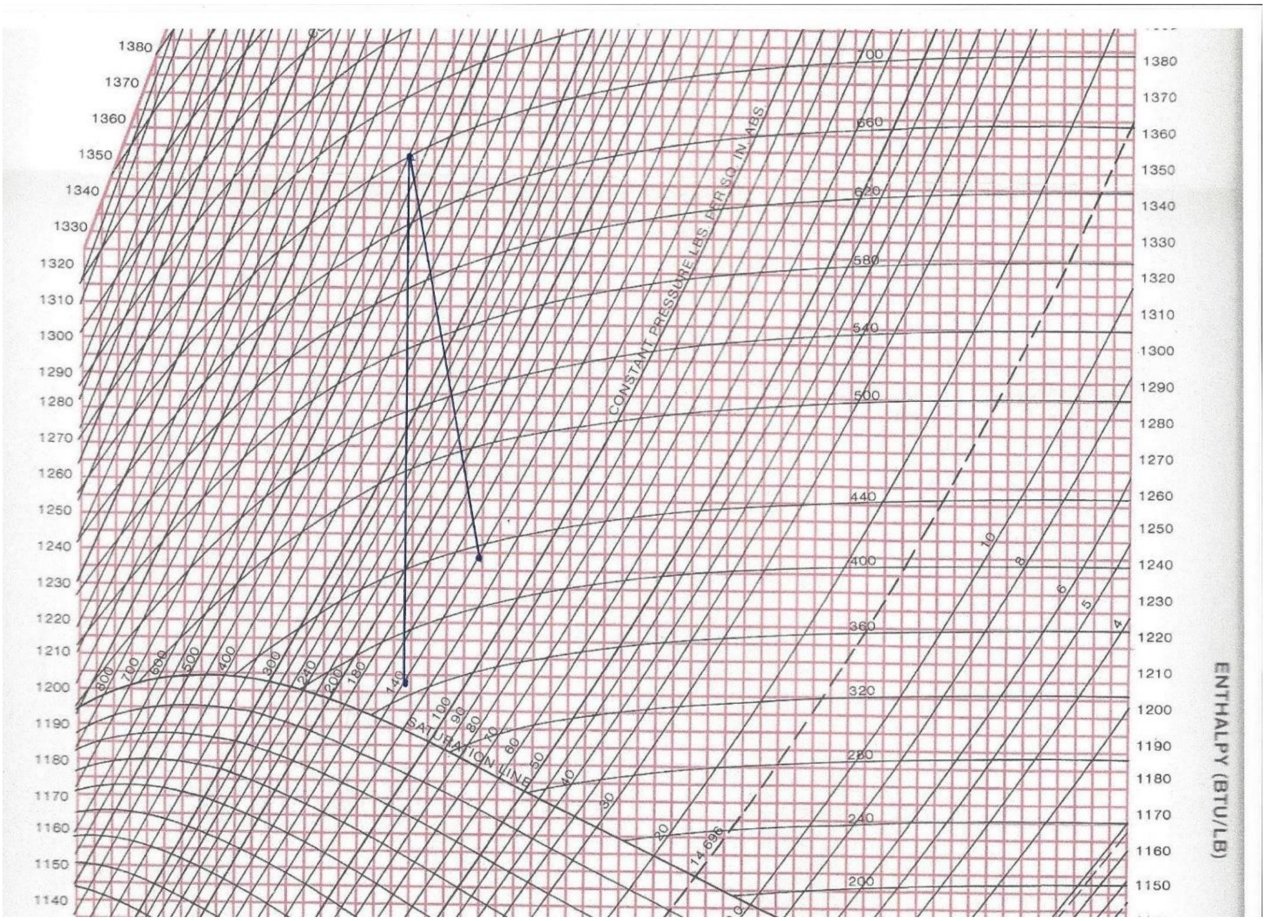
Steam Power = $(h_1 – h_2)$ x steam flow rate $(M_2)/C_1$

Steam Power = (1,351.1 – 1,237.8) x 75,000/2,545 = 3,339 HP

Notes:

- Inlet steam flow is used. If the steam leakage for the seals is known, it can be deducted to give a more accurate result.
- Shaft power can be determined by subtracting the Mechanical Losses (if known) from the Steam Power
- Using the steam tables is generally more accurate than using a Mollier chart.

Example 1 - Mollier Chart Results



Example 2 – Condensing steam turbine (Power Known) using Steam Flex

Input Data:

Inlet steam pressure	300 psia
Inlet steam temperature	500 ^{o}F
Exhaust steam pressure	4 in Hg a
Steam power	4,600 HP
Inlet steam flow rate	45,000 lb/hr

Results:

Overall efficiency	75.0%
Exhaust moisture	11.6%

Notes:

- Inlet steam flow is used. If the steam leakage for the seals is known, it can be deducted to give a more accurate result.
- Shaft power can be determined by subtracting the Mechanical Losses (if known) from the Steam Power.
- See Example 2 Steam Flex below for the summary of results

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Example 2 - Steam Flex Data Summary (Power Known)

Flex Live ® Steam Turbine Field Test

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Description: Example 2 Steam Flex

Inputs	Units	Value
Inlet Pressure	psia	300.00
Inlet Temperature	°F	500.00
Inlet Flow	lb/hr	45,000
Exhaust Pressure	in Hg a	4.0000
Power	HP	4,600.0
Speed	RPM	5,000.0

Results	Units	Value
Inlet Specific Volume	ft³/lb	1.7675
Inlet Enthalpy	Btu/lb	1,257.6
Inlet Entropy	Btu/lb °R	1.5701
Inlet Saturation Temperature	°F	417.33
Inlet Superheat	°F	82.670
Exhaust Enthalpy	Btu/lb	997.44
Exhaust Temperature	°F	125.54
Exhaust Power	HP	4,600.0
Exhaust Moisture	%	11.592
Theoretical Steam Rate	lb/HP hr	7.3323
Steam Rate	lb/HP hr	9.7826
Efficiency	%	74.953

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Example 2 – Condensing steam turbine (Power Known) using Mollier method and steam tables

Input Data:

Inlet steam pressure	300 psia
Inlet steam temperature	500 ^oF
Exhaust steam pressure	4 in Hg a
Steam Power	4,600 HP
Inlet steam flow rate	45,000 lb/hr

From Steam Tables:

Inlet enthalpy (h_1)	1,257.6 BTU/lb
Inlet entropy (s_1)	1.5701 BTU/lb ^oR

Read vertically down on Mollier chart to get the isentropic exhaust enthalpy. This value cannot be determined from the steam table because the exhaust is wet.

isentropic exhaust enthalpy (h_{2i})	910 BTU/lb

Exhaust Enthalpy:

$(h_1 – h_2)$ = Steam power x C_1/Steam flow rate (M_2)

$(h_1 – h_2) = 4{,}600 \times 2{,}545/45{,}000 = 260.2$ BTU/lb

$h_2 = 1{,}257.6 – 260.2 = 997.4$ BTU/lb

Efficiency:

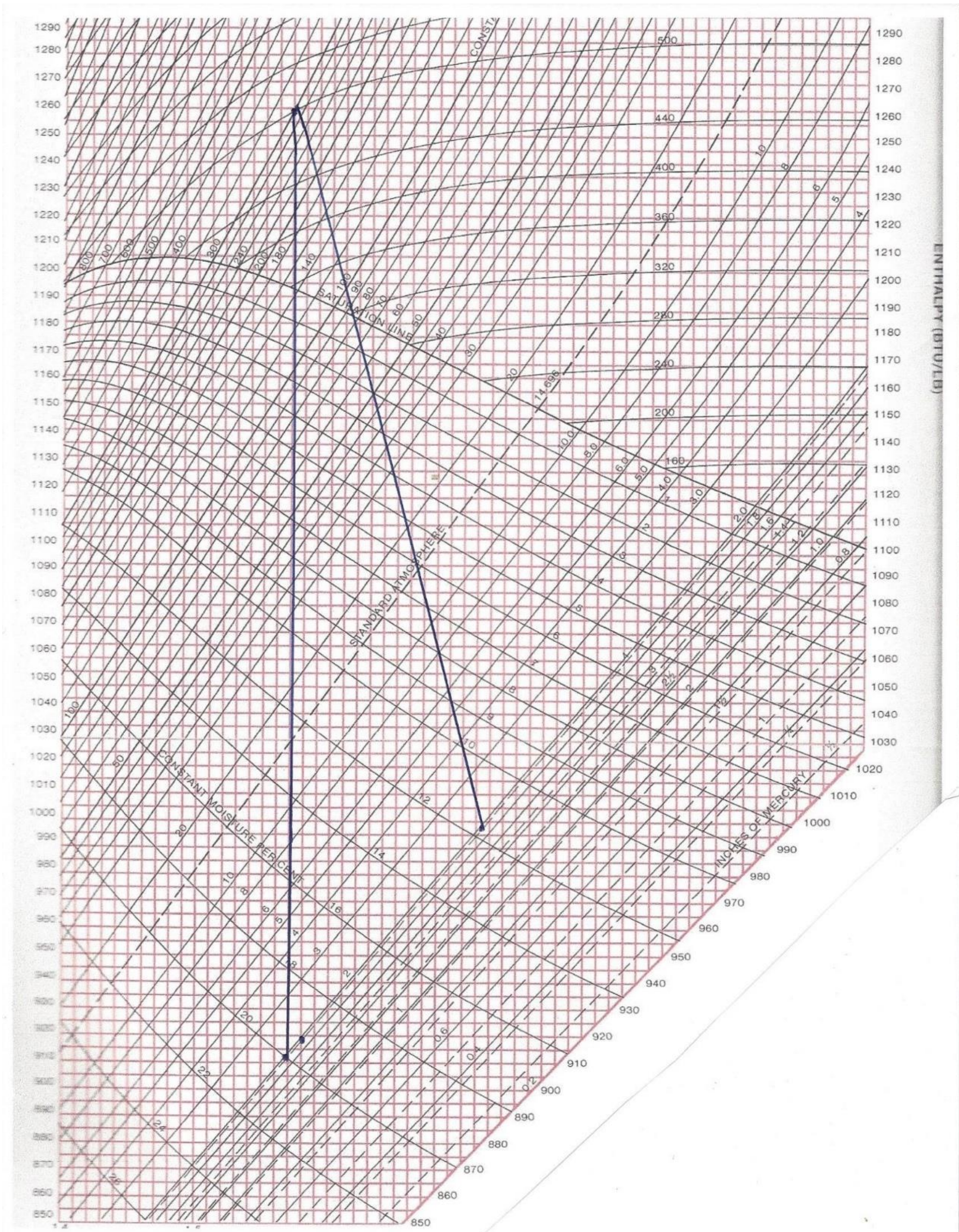
Efficiency $(\eta) = (h_1 – h_2)/(h_1 – h_{2i})$

Efficiency = 260.2/(1257.6 – 910) = 74.9%

Notes:

- Inlet steam flow is used. If the steam leakage for the seals is known, it can be deducted to give a more accurate result.
- Shaft power can be determined by subtracting the Mechanical Losses (if known) from the Steam Power

Example 2 - Mollier Chart Results



Example 2 – Condensing steam turbine (Power Unknown) – Steam Flex cannot be used

<u>Input Data:</u>

Inlet steam pressure	300 psia
Inlet steam temperature	500 ^{o}F
Exhaust steam pressure	4 in Hg a
Inlet steam flow rate	45,000 lb/hr
Cooling water flow rate	6,290 GPM
Cooling water inlet temperature	85.0 ^{o}F
Cooling water discharge temperature	98.0 ^{o}F
Condensate temperature	123 ^{o}F

(Note, condensate temperature is usually depressed by 2 ~ 3 ^{o}F below saturation (125.4 ^{o}F) to avoid flashing)

<u>Steam Condenser Heat Balance:</u>

Liquid enthalpy for condensate (h_c)	90.91 BTU/lb (from steam tables)
Cooling water inlet enthalpy (h_{cw1})	53.00 BTU/lb (from steam tables)
Cooling water discharge enthalpy (h_{cw2})	65.97 BTU/lb (from steam tables)

<u>Exhaust Enthalpy:</u>

$h_2 = h_c + (h_{2cw} – h_{1cw}) \text{ x } C_2 \text{ x } M_{cw}/M_2$

h_2 = 90.91 + (65.97 – 53.00) x 500 x 6,290/45,000 = 997.4 BTU/hr

<u>Efficiency:</u>

$\eta = (h_1 – h_2)/(h_1 – h_{2i})$

h_{2i} = 910 BTU/lb (from Example 2 Mollier Method above)

Efficiency = (1,257.6 – 997.4)/(1257.6 – 910) = 74.9%

<u>Steam Power:</u>

Steam power = $(h_1 – h_2)$ x Steam Flow Rate/C_1

Steam power = (1,257.6 – 997.4) x 45,000/2,545 = 4,601 HP

Figure 1

Typical Units				
		English/Imperial	**Technical Metric**	**SI**
Inlet pressure	P_1	psia	kg/cm^2 a	bar a kPa a MPa a
Extraction pressure	P_{ex}	psia	kg/cm^2 a	bar a kPa a MPa a
Exhaust pressure	P_2	psia in Hg a (condensing)	kg/cm^2 a mm Hg a (condensing)	bar a kPa a mm Hg a (condensing)
Inlet steam temperature	T_1	^{o}F	^{o}C	^{o}C
Extraction steam Temperature	T_{ex}	^{o}F	^{o}C	^{o}C
Exhaust steam temperature **(if superheated)**	T_2	^{o}F	^{o}C	^{o}C
Inlet steam flow rate	M_1	lb/hr	kg/hr	kg/h
Extraction steam flow rate	M_{ex}	lb/hr	kg/hr	kg/h
Exhaust steam flow rate	M_2	lb/hr	kg/hr	kg/h
Cooling water temperature	T_{cw1} T_{cw2}	^{o}F	^{o}C	^{o}C
Cooling water flow rate **(Volume)**	M_{cw}	GPM	m^3/hr	m^3/h
Cooling water flow rate **(Mass)**	M_{cw}	lb/hr	kg/hr	kg/h
Condensate flow rate	M_{cond}	GPM lb/hr	m^3/hr kg/hr	m^3/h kg/h
Enthalpy	h	BTU/lb	kcal/kg	kJ/kg
Power		HP	kW	kW
Steam constant	C_1	2,545 BTU/hr/HP	859.85 kcal/kg/kW	3,600 kJ/kg/kW
Cooling water constant **(fresh water)**	C_2	500 lb/hr/GPM	1,000 kg/m^3	1,000 kg/m^3

Note: All pressures must be in absolute units. If field data is in gauge then add the barometric pressure to the gauge values.

Steam Flex can accept temperature units in ^{o}F, ^{o}R, ^{o}C or ^{o}K. If the manual system is used, then temperatures must in ^{o}F or ^{o}C.

Figure 2 – Back Pressure Steam Turbine

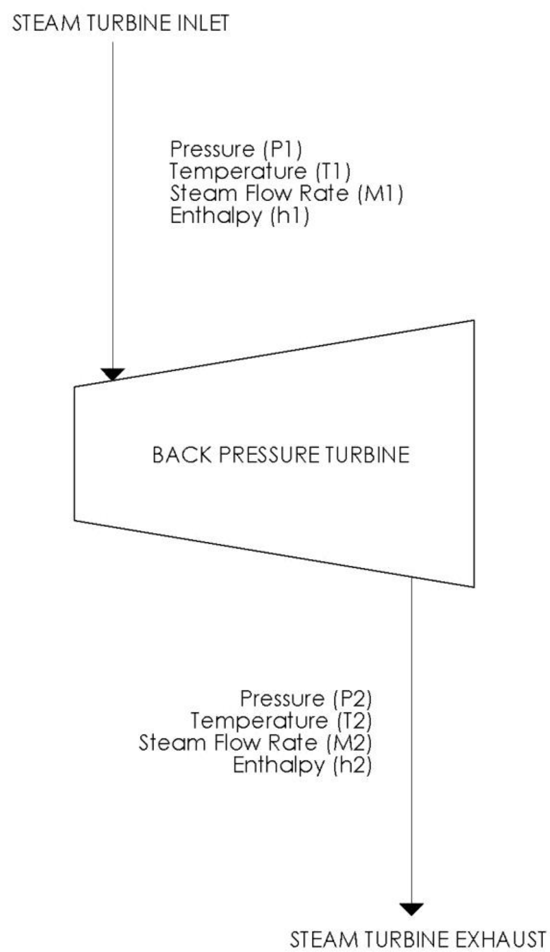


Figure 3 – Condensing Steam Turbine

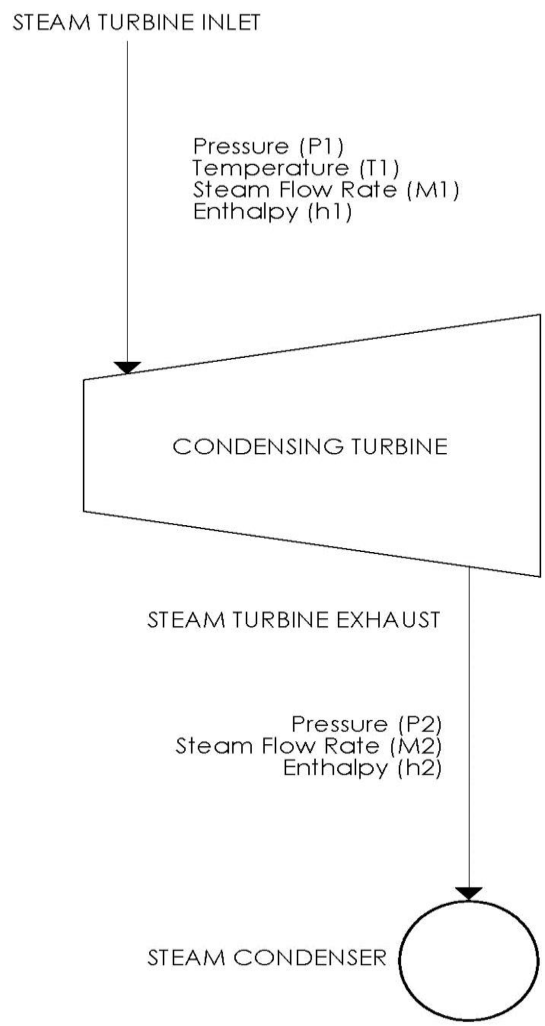


Figure 4 – Extraction Steam Turbine

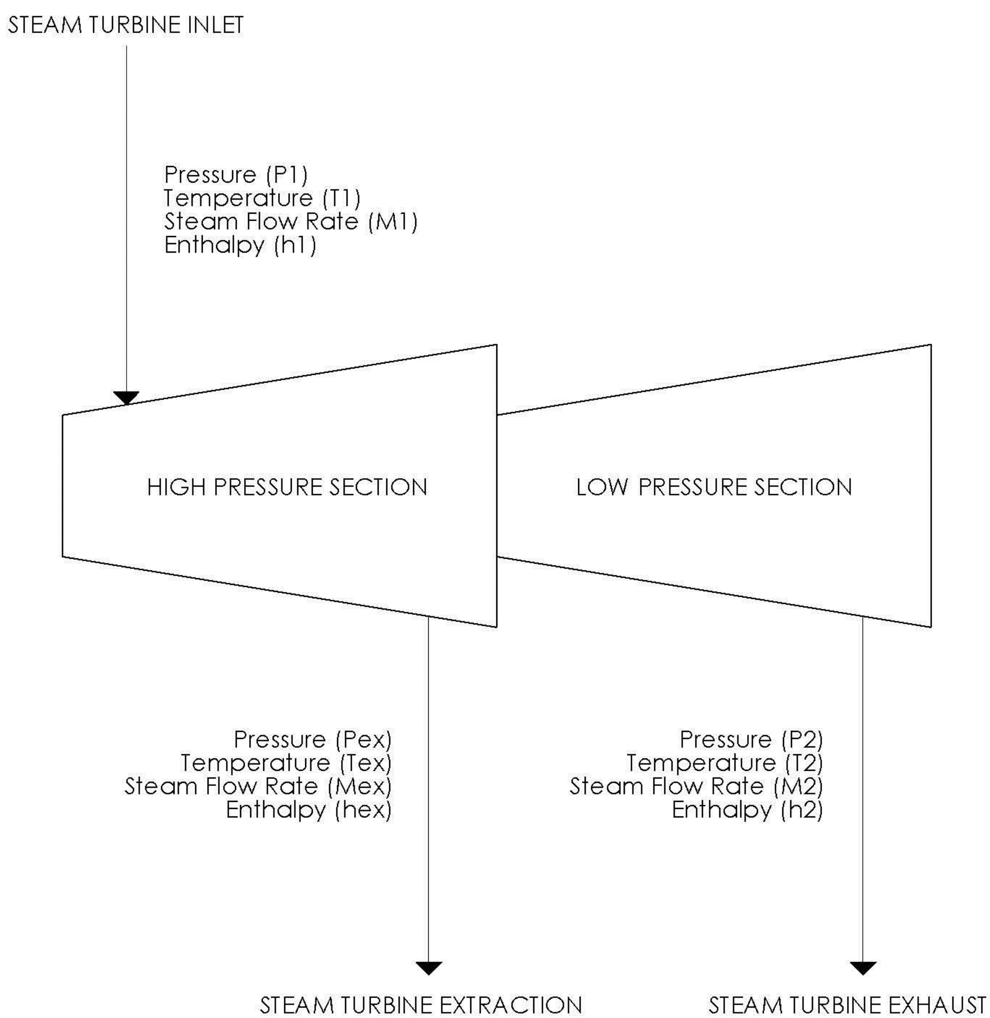


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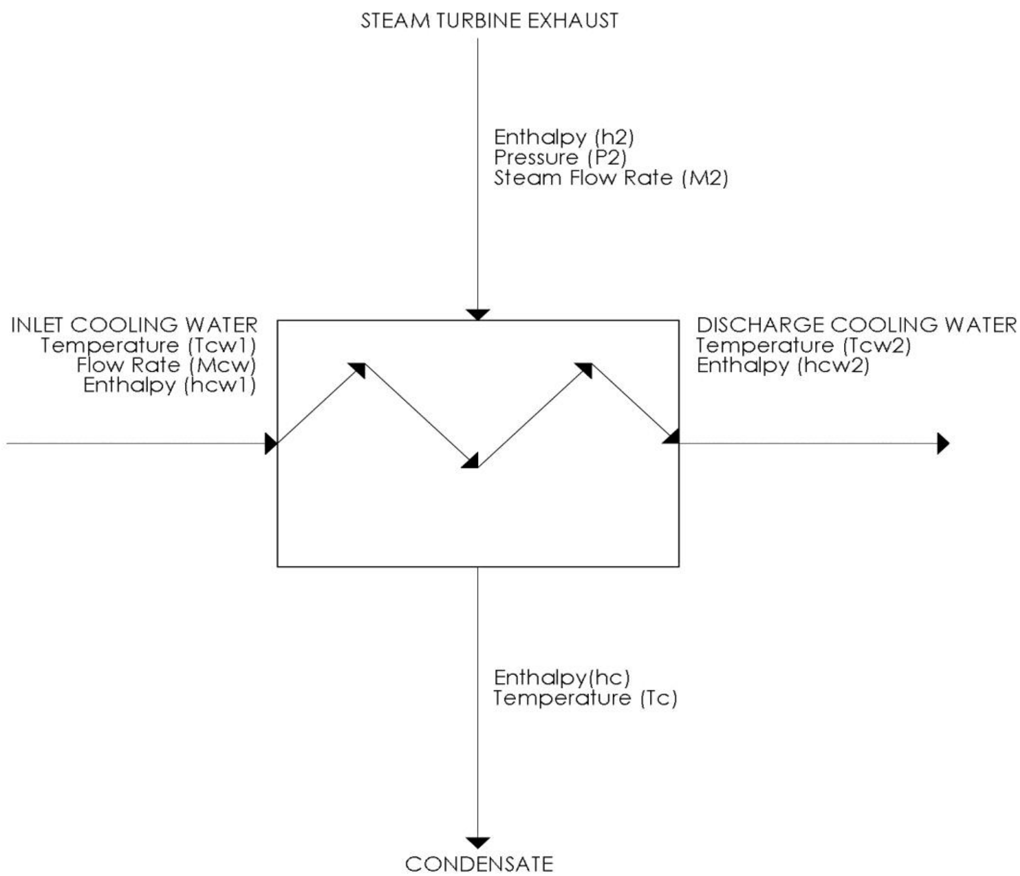
Figure 5 – Steam Condenser



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