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 ($\eta$) = 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 ($\eta$) = ($h_1 - h_{2i}$)/($h_1 - h_2$)
  - 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).
• **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 ($\eta$) = Actual enthalpy / Isentropic enthalpy
    • Isentropic enthalpy = Inlet enthalpy ($h_1$) – Exhaust enthalpy ($h_2$) - 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 ($\eta$) = $(h_1 - h_2)/(h_1 - h_2i)$

• Shaft Power Unknown
  • Do a heat balance on the steam condenser to determine the turbine exhaust enthalpy. See Figure 5
  • $h_2 = h_e + (h_{cw2} - h_{cw1}) \times M_{cw}/M_2$
  • 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 ($\eta$) = $(h_1 - h_2)/(h_1 - h_2i)$
  • Steam power = $(h_1 - h_2) \times$ 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 °F
- Exhaust steam pressure: 140 psia
- Exhaust steam temperature: 430 °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

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Pressure</td>
<td>psia</td>
<td>600.00</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>°F</td>
<td>700.00</td>
</tr>
<tr>
<td>Inlet Flow</td>
<td>lb/hr</td>
<td>75,000</td>
</tr>
<tr>
<td>Exhaust Pressure</td>
<td>psia</td>
<td>140.00</td>
</tr>
<tr>
<td>Exhaust Temperature</td>
<td>°F</td>
<td>430.00</td>
</tr>
<tr>
<td>Speed</td>
<td>RPM</td>
<td>7,500.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Specific Volume</td>
<td>ft³/lb</td>
<td>1.0732</td>
</tr>
<tr>
<td>Inlet Enthalpy</td>
<td>Btu/lb</td>
<td>1,351.1</td>
</tr>
<tr>
<td>Inlet Entropy</td>
<td>Btu/lb*R</td>
<td>1.5875</td>
</tr>
<tr>
<td>Inlet Saturation Temperature</td>
<td>°F</td>
<td>486.21</td>
</tr>
<tr>
<td>Inlet Superheat</td>
<td>°F</td>
<td>213.79</td>
</tr>
<tr>
<td>Exhaust Enthalpy</td>
<td>Btu/lb</td>
<td>1,237.8</td>
</tr>
<tr>
<td>Exhaust Temperature</td>
<td>°F</td>
<td>430.00</td>
</tr>
<tr>
<td>Exhaust Power</td>
<td>HP</td>
<td>3,338.9</td>
</tr>
<tr>
<td>Exhaust Moisture</td>
<td>%</td>
<td>0</td>
</tr>
<tr>
<td>Theoretical Steam Rate</td>
<td>lb/HP hr</td>
<td>17.207</td>
</tr>
<tr>
<td>Steam Rate</td>
<td>lb/HP hr</td>
<td>22.453</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>76.601</td>
</tr>
</tbody>
</table>
Example 1 – Non-condensing steam turbine using Mollier method and/or steam tables

**Input Data:**
- Inlet steam pressure: 600 psia
- Inlet steam temperature: 700 °F
- Exhaust steam pressure: 140 psia
- Exhaust steam temperature: 430 °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 °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 \( \eta \) = \( \frac{h_1 - h_2}{h_1 - h_{2i}} \)
- Efficiency using Mollier chart: \( \frac{1,351.1 - 1,202.5}{1,351.1 - 1,237.8} = 76.2\% \)
- Efficiency using steam tables: \( \frac{1,351.1 - 1,203.2}{1,351.1 - 1,237.8} = 76.6\% \)

**Steam Power:**
- Steam Power = \( (h_1 - h_2) \times \text{steam flow rate} \times \frac{M_2}{C_1} \)
- Steam Power = \( (1,351.1 - 1,237.8) \times 75,000/2,545 = 3,339 \) 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 °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
Example 2 - Steam Flex Data Summary (Power Known)

Flex Live ® Steam Turbine Field Test

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Pressure</td>
<td>psia</td>
<td>300.00</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>°F</td>
<td>500.00</td>
</tr>
<tr>
<td>Inlet Flow</td>
<td>lb/hr</td>
<td>45,000</td>
</tr>
<tr>
<td>Exhaust Pressure</td>
<td>in Hg a</td>
<td>4,0000</td>
</tr>
<tr>
<td>Power</td>
<td>HP</td>
<td>4,800.0</td>
</tr>
<tr>
<td>Speed</td>
<td>RPM</td>
<td>5,000.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Specific Volume</td>
<td>ft³/lb</td>
<td>1.7575</td>
</tr>
<tr>
<td>Inlet Enthalpy</td>
<td>Btu/lb</td>
<td>1,257.6</td>
</tr>
<tr>
<td>Inlet Entropy</td>
<td>Btu/lb °R</td>
<td>1,5701</td>
</tr>
<tr>
<td>Inlet Saturation Temp</td>
<td>°F</td>
<td>417.33</td>
</tr>
<tr>
<td>Inlet Superheat</td>
<td>°F</td>
<td>82.870</td>
</tr>
<tr>
<td>Exhaust Enthalpy</td>
<td>Btu/lb</td>
<td>997.44</td>
</tr>
<tr>
<td>Exhaust Temperature</td>
<td>°F</td>
<td>125.54</td>
</tr>
<tr>
<td>Exhaust Power</td>
<td>HP</td>
<td>4,600.0</td>
</tr>
<tr>
<td>Exhaust Moisture</td>
<td>%</td>
<td>11.592</td>
</tr>
<tr>
<td>Theoretical Steam Rate</td>
<td>lb/HP hr</td>
<td>7.3323</td>
</tr>
<tr>
<td>Steam Rate</td>
<td>lb/HP hr</td>
<td>9.7826</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>74.953</td>
</tr>
</tbody>
</table>

Flex Live ®: Turbomachinery Monitoring Software
www.flexwareinc.com

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

**Input Data:**
- Inlet steam pressure: 300 psia
- Inlet steam temperature: 500 °F
- 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 °R

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:**
\[
(h_1 - h_2) = \text{Steam power} \times C_1/\text{Steam flow rate} \times (M_2)
\]
\[
(h_1 - h_2) = 4,600 \times 2,545/45,000 = 260.2 \text{ BTU/lb}
\]
\[
h_2 = 1,257.6 - 260.2 = 997.4 \text{ BTU/lb}
\]

**Efficiency:**
\[
\text{Efficiency} = \frac{(h_1 - h_2)}{(h_1 - h_{2i})}
\]
\[
\text{Efficiency} = \frac{260.2}{(1257.6 - 910)} = 74.9\%
\]

**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

**Input Data:**
- Inlet steam pressure: 300 psia
- Inlet steam temperature: 500 °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 °F
- Cooling water discharge temperature: 98.0 °F
- Condensate temperature: 123 °F

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

**Steam Condenser Heat Balance:**
- 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)

**Exhaust Enthalpy:**
$$h_2 = h_c + (h_{2cw} - h_{1cw}) \times C_2 \times M_{cw}/M_2$$
$$h_2 = 90.91 + (65.97 - 53.00) \times 500 \times 6,290/45,000 = 997.4 \text{ BTU/hr}$$

**Efficiency:**
$$\eta = (h_1 - h_2)/(h_1 - h_{2i})$$
$$h_{2i} = 910 \text{ BTU/lb (from Example 2 Mollier Method above)}$$
$$\text{Efficiency} = (1,257.6 - 997.4)/(1257.6 - 910) = 74.9\%$$

**Steam Power:**
Steam power = $(h_1 - h_2) \times \text{Steam Flow Rate}/C_1$
Steam power = $(1,257.6 - 997.4) \times 45,000/2,545 = 4,601 \text{ HP}$
### Figure 1

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

**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 °F, °R, °C or °K. If the manual system is used, then temperatures must in °F or °C.
Figure 2 – Back Pressure Steam Turbine

STEAM TURBINE INLET

Pressure (P1)
Temperature (T1)
Steam Flow Rate (M1)
Enthalpy (h1)

BACK PRESSURE TURBINE

Pressure (P2)
Temperature (T2)
Steam Flow Rate (M2)
Enthalpy (h2)

STEAM TURBINE EXHAUST
Figure 3 – Condensing Steam Turbine

STEAM TURBINE INLET

Pressure (P1)
Temperature (T1)
Steam Flow Rate (M1)
Enthalpy (h1)

CONDENSING TURBINE

STEAM TURBINE EXHAUST

Pressure (P2)
Steam Flow Rate (M2)
Enthalpy (h2)

STEAM CONDENSER
Figure 4 – Extraction Steam Turbine

STEAM TURBINE INLET

Pressure (P1)
Temperature (T1)
Steam Flow Rate (M1)
Enthalpy (h1)

HIGH PRESSURE SECTION

Pressure (Pex)
Temperature (Tex)
Steam Flow Rate (Mex)
Enthalpy (hex)

LOW PRESSURE SECTION

Pressure (P2)
Temperature (T2)
Steam Flow Rate (M2)
Enthalpy (h2)

STEAM TURBINE EXTRACTION

STEAM TURBINE EXHAUST
Figure 5 – Steam Condenser