12.0 Efficiency

If we plan to build an installation to produce electricity, then the starting point is always to burn as little fuel as possible while generating as much electricity as possible. And if we succeed in accomplishing that, we can say that the efficiency of the installation is high. But what exactly do we mean by efficiency? Take the case of a very simple installation as shown in illustration 1.

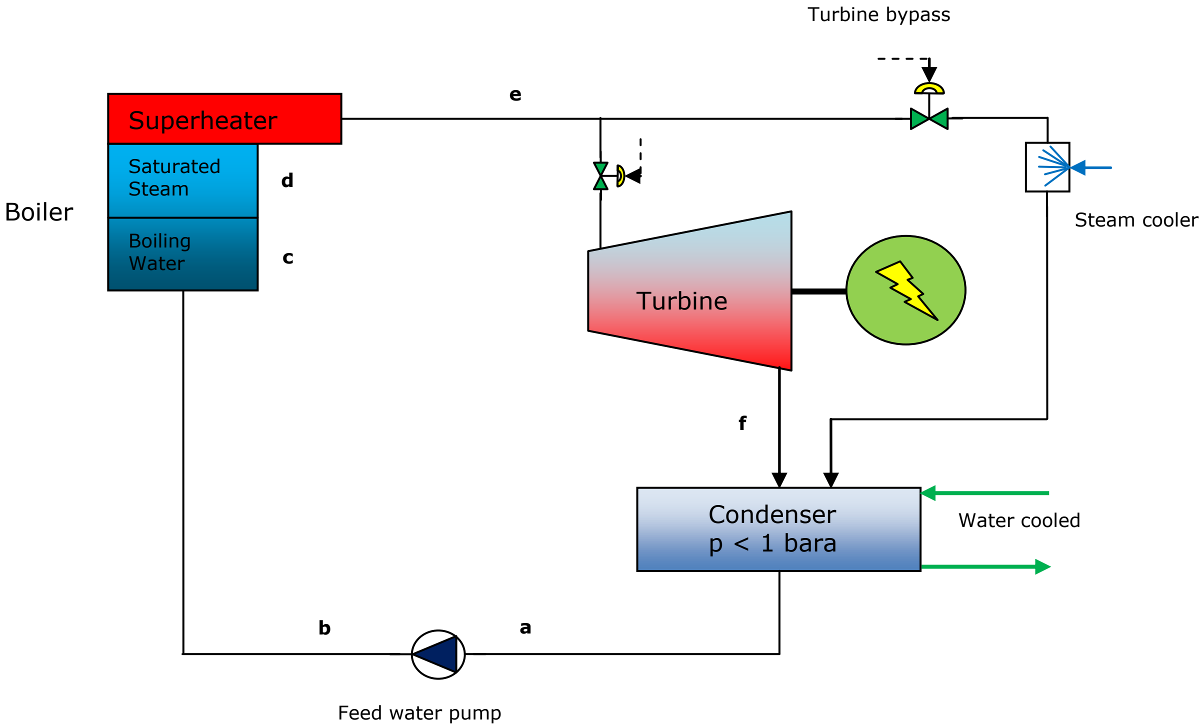

Illustration 1. Condensation turbine installation without a preheater.

In which:

a	: Boiling water from the condenser, at the condenser pressure
b	: Feed water at the boiler pressure.
c	: Boiling water in the boiler.
d	: Saturated steam in the boiler drum.
e	: Superheated steam
f	: Wet steam after the turbine

a → b	: Pressure increase due to feed water pump condenser pressure to boiler pressure.
b → c	: Heat is supplied to the boiler, the feed water is brought to a boiling temperature. The pressure remains constant.
c → d	: Heat is supplied in the boiler, the boiling water evaporates into saturated steam. The pressure remains constant.
d → e	: Heat is supplied to the boiler, saturated steam is converted into superheated steam in the superheater. The pressure remains constant.
e → f	: Expansion in the turbine, work is generated.
f → a	: The wet steam from the turbine is compacted in the condenser into water at a boiling temperature. Heat is discharged by means of the cooling water.

We will show the process, as shown in illustration 1, in the h-s and in the T-s diagram. See illustrations 2 and 3.
We will assume in this example that the steam in de turbine expands isentropically. Which implies that the entropy remains constant and that no heat is exchanged with the environment.

Rankine

This is also referred to as a Rankine process. The point k represents the critical point.

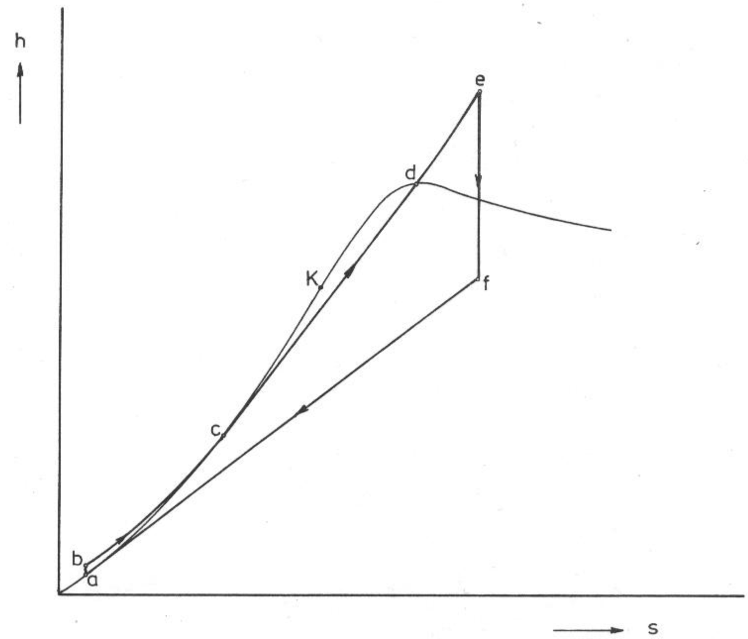

Illustration 2. The Rankine process in the h-s diagram.

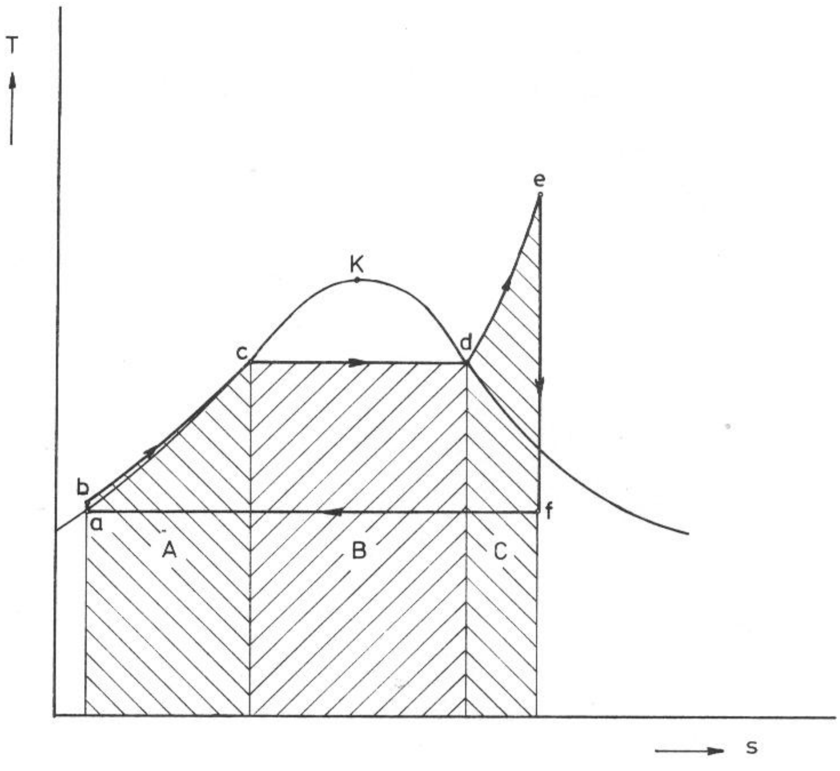

Illustration 3. The Rankine process in the T-s diagram.

It is clear from illustrations 1, 2 and 3 that heat must be supplied in order to get from point a to point e. We can therefore state that the difference in enthalpy between point e and point a represents the heat that is supplied during the process. The supplied heat naturally comes from the fuel.
We then find:

$$Q_{Supplied} = h_e - h_a \quad [kJ / kg]$$

An isentropic drop in heat occurs in the turbine from point e → f, which generates work (W). Of course, this is the work that is theoretically generated. The difference in enthalpy between e and f yields the theoretical work.
We then find:

$$W_{Theoretical} = h_e - h_f \quad [kJ / kg]$$

Finally, there remains the process from point f → a. Here, the steam that is led from the turbine into the condenser is compacted into water. Condensation occurs here; the pressure and temperature remain constant during this process. Heat is discharged. The difference in enthalpy between point f and a represents this discharged heat. This is also called the condenser loss.
We then find:

$$Q_{Disch\arg ed} = h_f - h_a \quad [kJ / kg]$$

The following applies to each level of efficiency:

$$\text{Efficiency} = \frac{\text{Goal}}{\text{Offer}} \cdot 100\% \quad [\%]$$

The following then applies to the efficiency of the Rankine process, also called the thermal efficiency of the installation:

$$\text{Thermal efficiency} = \frac{\text{Goal}}{\text{Offer}} \cdot 100\% \quad [\%]$$

$$\eta_{Thermal} = \frac{W_{Theoretical}}{Q_{Supplied}} \cdot 100\% \quad [\%]$$

It can be demonstrated that:

$$\text{W}_{\text{Theoretical}} = \text{Q}_{\text{Supplied}} - \text{Q}_{\text{Discharged}}$$

$$Q_{Supplied} - Q_{Disch\arg ed} = (h_e - h_a) - (h_f - h_a) \quad [kJ / kg]$$

$$Q_{Supplied} - Q_{Disch\arg ed} = h_e - h_a - h_f + h_a \quad [kJ / kg]$$

$$Q_{Supplied} - Q_{Disch\arg ed} = h_e - h_f \quad [kJ / kg]$$

$$W_{Theoretical} = h_e - h_f \quad [kJ / kg]$$

$$\eta_{Thermal} = \frac{W_{Theoretical}}{Q_{Supplied}} \cdot 100\% \quad [\%]$$

$$\eta_{Thermal} = \frac{h_e - h_f}{h_e - h_a} \cdot 100\% \quad [\%]$$

The total efficiency of the installation that includes a steam boiler and a turbine, and in our case no heating of the feed water, is:

$$\text{Total efficiency} = \text{Boiler efficiency} \cdot \text{Thermal efficiency} \cdot \text{Turbine efficiency}$$

$$\eta_{Total} = \eta_{boiler} \cdot \eta_{Thermal} \cdot \eta_{Turbine}$$

12.1 Example

Given:
This example concerns a condensation turbine that operates at a low steam pressure. It will become clear later on why we will work with increasingly higher pressures and temperatures. The system does not include a preheater.

Pressure superheated steam : p_{os} = 40 bara
Temperature superheated steam : t_{os} = 460 °C
Enthalpy superheated steam : h_{os} = 3354.0 kJ/kg
Entropy superheated steam : s_{os} = 6.9702 kJ/(kg·K)

Condenser pressure : p_c = 0.05 bara
Enthalpy saturated water from condenser: h_{vw} = 137.77 kJ/kg
Enthalpy saturated steam : h_{vs} = 2561.6 kJ/kg
Entropy saturated water from condenser: s_{vw} = 0.4763 kJ/(kg·K)
Entropy saturated steam : s_{vs} = 8.3960 kJ/(kg·K)

The boiler efficiency : η_{boiler}= 97 %
The turbine efficiency : $\eta_{Turbine}$ = 86 %

We furthermore assume that the steam in the turbine expands isentropically.
The energy that the feed water pump releases to the water due to a pressure increase is considered negligible.

Required:
Calculate the Thermal efficiency and the total efficiency of the installation.

Solution:
We will first plot the process in the h-s diagram; this is shown in illustration 4.

All of the points have been plotted in the h-s diagram, except for the enthalpy of the boiling water and the entropy of the boiling water.

The diagram shows us that point B, which is the state of the steam upon leaving the turbine, is in the wet steam area. We must now calculate the enthalpy of the wet steam. This is actually the unknown factor in the equation. It would be easier, although less accurate, to look up the value of this enthalpy in a h-s diagram.

Calculation of the enthalpy of the wet steam, h_{ns} or h_b.

We will first calculate the vapour content of the steam in point B. Once we have calculated this, we can then calculate the enthalpy of the wet steam in point B.

Note: the entropy in point B equals that of point A. This is a case of isentropic expansion.

$$s_{ns} = s_w + x \cdot (s_{vs} - s_w) \quad [kJ/(kg \cdot K)]$$

$$6.9702 = 0.4763 + x_B \cdot (8.3960 - 0.4763)$$

$$x_B = \frac{6.9702 - 0.4763}{8.3960 - 0.4763} = 0.8199$$

$$x_B = 81.99\ \%$$

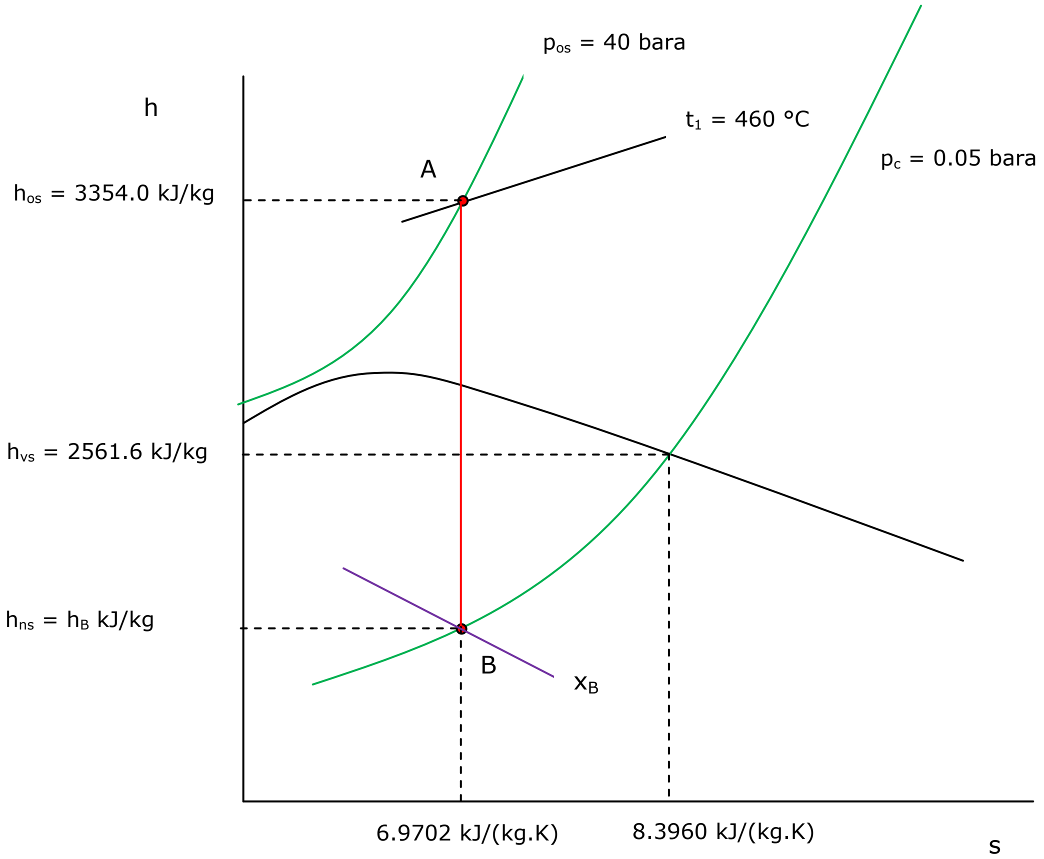

Illustration 4. The process in the h-s diagram.

We can now calculate the enthalpy of the wet steam in point B in the same way.

$$h_{ns} = h_w + x \cdot (h_{vs} - h_w) \quad [kJ/kg]$$
$$h_{ns} = 137.77 + 0.8199 \cdot (2561.6 - 137.77)$$
$$h_{ns} = 2125.06 \quad kJ/kg$$

We now find the following for the thermal efficiency:

$W_{theoretical} = h_a - h_b$ [kJ/kg]
$W_{theoretical} = h_{os} - h_b$ [kJ/kg]

$Q_{Supplied} = h_{os} - h_{vw}$ [kJ/kg]

$$\eta_{Thermal} = \frac{W_{Theoretical}}{Q_{Supplied}} \cdot 100\% \quad [\%]$$

$$\eta_{Thermal} = \frac{h_a - h_b}{h_{os} - h_w} \cdot 100\% \quad [\%]$$

$$\eta_{Thermal} = \frac{3354.0 - 2125.06}{3354.0 - 137.77} \cdot 100\%$$

$$\eta_{Thermal} = 38.21 \quad \%$$

And so the total efficiency comes to:

$$\text{Total efficiency} = \text{Boiler efficiency} \cdot \text{Thermal efficiency} \cdot \text{Turbine efficiency}$$

$$\eta_{Total} = 0.97 \cdot 0.3821 \cdot 0.86$$

$$\eta_{Total} = 0.3187$$

$$\eta_{Total} = 31.87 \quad \%$$

It is immediately evident that the effect of the thermal efficiency is a decisive factor in terms of the total efficiency. Despite the fact that the boiler efficiency and the turbine efficiency are relatively high, the value of the total efficiency is brought down by the low value of the thermal, or Rankine, efficiency.

If we wish to achieve a higher total efficiency, then we will have to improve the thermal efficiency.

12.2 Heat savings via insulation using valves

The next chapter examines improving the efficiency. You will see that this involves quite a lot of calculating. An aspect that is not referred to specifically, but that is very important, concerns the insulation of steam valves and steam pipes. Table 1 illustrates the savings on an annual basis if valves are indeed insulated. As you can see, there is much to be gained here. These may seem to be but small amounts, but the total can be quite considerable if one considers the large number of valves in a steam plant. This too can help to improve the efficiency.

Savings per year and per insulated valve at an ambient temperature of 25 °C and 8760 operational hours per year								
Pressure	**Unit**	**Type of valve**						
Bara		**DN 50**	**DN 65**	**DN 80**	**DN 100**	**DN 125**	**DN 150**	**DN 200**
5	kWh/year	2840	3663	4298	5580	6862	8300	10,801
5	Tonnes steam per year	4.02	5.19	6.09	7.91	9.73	11.76	15.31
9	kWh/year	3526	4548	5337	6928	8519	10,305	13,410
9	Tonnes steam per year	4.95	6.39	7.49	9.73	11.96	14.47	18.83
16	kWh/year	4433	5718	6711	8712	10,713	12,958	16,862
16	Tonnes steam per year	6.18	7.97	9.36	12.15	14.94	18.07	23.51
21	kWh/year	4869	6280	7370	9568	11,766	14,231	18,520
21	Tonnes steam per year	6.77	8.73	10.24	13.30	16.35	19.78	25.74

Table 1. Savings on annual basis due to insulation of valves