Stack

In a stack flue gas is being cooled down and released to the environment which is accompanied by an energy loss. The value of this loss depends upon the environment chosen and the perspective taken for the calculation. Different values of energy loss occur when the calculation is dependent on the enthalpy, the Higher Heating Value or on the Lower Heating Value. In this chapter an explanation of these differences is given in section 2.2 and calculations of the differences are shown in section 2.3. The model used in this chapter is that of the simple heat exchanger as discussed in chapter 1.

2.1   Plot of the used system

Because the calculations for this situation have already been done in the chapter of the simple heat exchanger the plots and calculations are just copied in here.

As can be seen in the plot flue gas with a mass flow of 130.364 kg/s and an enthalpy value of –2825.93 kJ/kg is flowing through the stack into the environment.
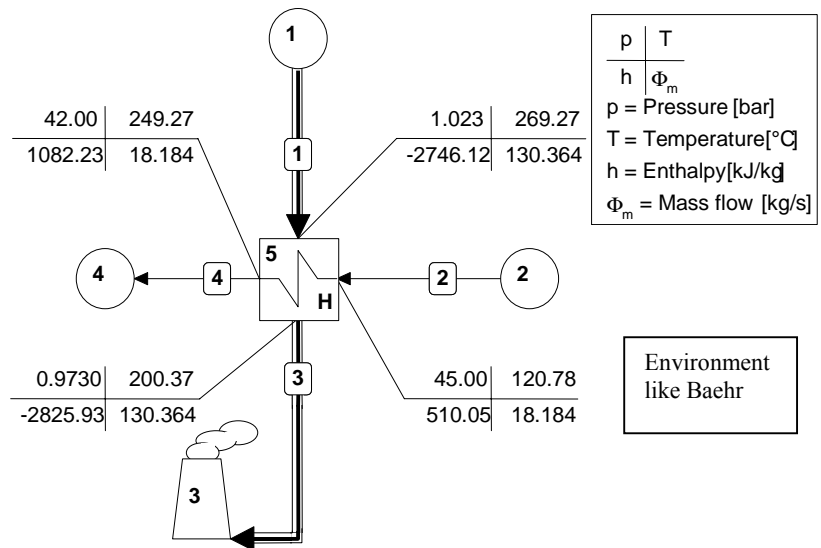

Figure 1: Plot of the system

2.2   The energy loss in the stack

Before calculations of the stack can be made the energy balance must be known first. The results from this balance are shown in table 1. Only the values of the stack from the energy balance are shown because only these are of interest. The table shows three different values of energy loss in the stack. And even an fourth different value of the energy loss exists and can be derived from the Q,T-diagram. These four differences are caused by the used calculation method and will be discussed here.
The first three differences are shown in table 1.

Table 1: Energy balance

No.	Name	Type	Energy loss (enthalpy) [kW]	Energy loss (HHV) [kW]	Energy loss (LHV) [kW]
3	Stack	10	-368,399.84	65,463.83	25,741.25

1. The energy loss with respect to the <u>enthalpy</u> can be calculated by multiplying the enthalpy value and the mass flow, both shown in figure 1 at the flue gas outlet of the heat exchanger.

2. The value of the energy loss with respect to the Higher Heating Value (<u>HHV</u>) corresponds with the heat that will be released if the flue gas is cooled down to the environment conditions, assuming that all of the H_2O is condensed.

3. The amount of energy which is lost with respect to the Lower Heating Value (<u>LHV</u>) is equal to the heat released when the flue gas is cooled down to environment conditions, assuming that none of the H_2O is condensed and that all of the water in the flue gas leaves the stack as a vapor.

4. As said before, not only the table of the energy balance shows values of the heat loss to the environment but also the Q,T-diagram of the stack does. Because the transmitted heat in the stack is exchanged with the environment it can be considered as an energy loss. And therefore, the transmitted heat on the x-axis of the Q,T-diagram indicates the amount of the energy loss of the stack into the environment. A plot of the Q,T diagram is shown in figure 2.
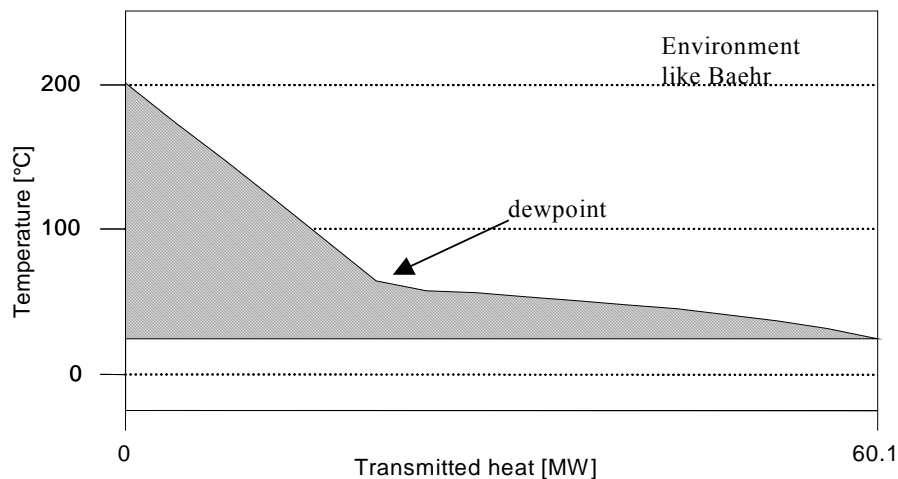

Figure 2: The Q,T diagram

The value of the transmitted heat of the stack is equal to 60.0686 MW. This value is somewhere between the value of the HHV and the LHV. The reason for this is that in reality the flue gas of a stack does not contain entirely condensed H_2O, according to the HHV, nor does it contain entirely vaporized H_2O, according to the LHV. In fact some of the H_2O will be condensed and the other part will release the stack as a vapor dependent on the dewpoint of the flue gas. The Q,T diagram reckons with this situation and a calculation of the vapour fraction still present in the flue gas after leaving the stack will be considered in subsection 2.3.3.

2.3   Calculations of the energy loss differences

In this section some of the differences stated in the previous section will be calculated. For the convenience of the reader in table 2 the four different values of the energy loss are given again.

Table 2: The four different values of energy loss

Energy loss with respect to:			
enthalpy [kW]	HHV [kW]	LHV [kW]	Q,T-diagram [kW]
-368,399.84	65,463.83	25,741.25	60,068.6

2.3.1   The energy loss according to the enthalpy

The energy loss with respect to the enthalpy is calculated by multiplying the enthalpy with the mass flow:

$$\Phi_{\Delta E,H} = h * \Phi_m \qquad [kW]$$
$$-368,399.84 = -2825.93 * 130.364$$

2.3.2.   The difference in the HHV and LHV

The difference in the higher and lower heating value depends on the phase (liquid or vapor) the water is in. Consequently, the difference between the higher and the lower heating value is equal to the evaporation heat of water at the environment temperature. In this example the environment temperature is set on 25° C which can also be seen in figure 2 where the bottom line of the gray area is situated at this temperature.
Now the difference in HHV and LHV can be calculated by multiplying the mass fraction of the water in the flue gas with the evaporation heat.

$$HHV - LHV = \xi_{H_2O} * \Phi_m * (h_{vapour} - h_{liquid}) \qquad [kW]$$
$$65463 - 25741 = 0.1248 * 130.364 * (2547.28 - 104.77)$$

2.3.3.   The difference in the HHV and the Q,T-diagram

If a gas mixture, which also contains water vapor, is cooled down below the dew point (see figure 1) condensation of at least a part of the water in the flue gas takes place. Before this condensation can be determined some detailed information of the flue gas must be known. These details are shown in tables 2 and 3. The molar mass and the mole fractions which contains in the flue gas are taken from Cycle-Tempo. With this information the mass fractions are calculated manually and put in the same table. In table 3 the part of interest of the data for all pipes of Cycle-Tempo is shown.

Table 3: Composition of the flue gas

	M	Flue gas		
	M (kg/kmol)	Mole % y_{fg}	Mass/mole	Mass % ξ_{fg}
Ar	39.948	0.82%	3.276E-01	1.182%
CO_2	44.01	9.50%	4.181E+00	15.087%
H_2O	18.0153	19.19%	3.457E+00	12.475%
N_2	28.0134	70.49%	1.975E+01	71.256%
O_2	31.9988			
Totaal		100%	2.771E+01	100%

Table 4: Data of the flue gas

Medium	Mass flow [kg/s] Φ_m	Mole flow [kmol/s] Φ_{mole}	Volume flow [m3/s] Φ_v	Pressure [bar] p	Temperature [°C] T
Flue gas mix	130.364	4.704	181.01	1.023	200.38
Flue gas mix	130.364	4.704	95.068	1.023	25

The volume flow of the flue gas at 25˚ has been found by making a system for flue gas at 1.023 bars and 25 degrees in Cycle-Tempo.

To perform calculations of the condensation in the flue gas it is of importance to draw a distinction between the water vapor in the flue gas (called vapor in the calculations following) and the rest of the composites of the flue gas (called dry flue gas). In the calculations following the subscript "fg" stands for dry flue gas and "v" for vapor.

The amount of dry flue gas in the flue gas mixture is equal to:

$$\xi_{fg} = 100\% - 12.475\% = 0.875 \qquad \text{kg/kg}$$
$$y_{fg} = 100\% - 19.19\% = 0.8081 \qquad \text{mole/mole}$$

The partial pressure of the flue gas at 25° C. can be found with the equation for an ideal gas:

$$p_{fg} = \frac{\xi_{fg} * m_a * (\overline{R}/M_a)T}{V} = \frac{y_{fg} * n_a * \overline{R} * T}{V} = \frac{y_{fg} * \Phi_{mole} * \overline{R} * T}{\Phi_v} \qquad [kPa]$$

$$99.179 = \frac{80.81\% * 4.707 * 8.314 * (25 + 273.15)}{95.068}$$

So now with the partial pressure of the flue gas known the partial pressure of the vapor can be calculated with the next formula.

$$p_v = p - p_{fg} \qquad [kPa]$$
$$3.12 = 102.3 - 99.18$$

The humidity ratio is now equal to:

$$x_{rh} = \frac{M_v * p_v}{M_{fg} * p_{fg}} \qquad [-]$$

$$0.02 = \frac{18.02 * 3.12}{27.71 * 99.18}$$

So now, the mass fraction of water vapor in the flue gas mixture can be calculated with:

$$\xi_v = x_{rh} * \xi_{fg} \qquad [-]$$
$$0.0175 = 0.02 * 0.875$$

This mass fraction represents the amount of water that has not been condensed and exists in the flue gas as a vapor. Therefore, the evaporation heat of this water is equal to the difference in the value of the HHV and the value according to the Q,T-diagram.

$$HHV - Q,Tvalue = \xi_v * \Phi_m * \left(h_{vapour} - h_{liquid}\right) \quad [kW]$$
$$65463.8 - 60068.6 \cong 0.0175 * 130.364 * (2547.28 - 104.77)$$

The difference between the two values is about 3% which can be allocated to rounding off in the calculation. The calculations made by Cycle-Tempo are much more accurate than the hand-made calculations. But, these calculations are just for the understanding of the calculations Cycle-Tempo performs.

2.4 Calculations of the energy loss differences for Baehr at 15°

In this section the calculations done in the previous chapter will be done again, but now with the environment like Baehr at 15°. The plot of the system is shown below.

Figure 3: The system for Baehr at 15 degrees

Table 5: Energy balance

No.	Name	Type	Energy loss (enthalpy) [kW]	Energy loss (HHV) [kW]	Energy loss (LHV) [kW]	Q,T-diagram [kW]
3	Stack	10	-368,399.84	67,282.75	27,176.43	64,394.1

2.4.1 The energy loss according to the enthalpy

The energy loss according to the enthalpy is equal to that in section 2.3.1 because this calculation is based on the enthalpy of the flue gas, which is not influenced by the environment.

$$\Phi_{\Delta E,H} = h * \Phi_m \qquad [kW]$$
$$-368,399.84 = -2825.93 * 130.364$$

2.4.2. The difference in the HHV and LHV

The values of the HHV and LHV are different to that in section 2.3.2. Also the evaporation heat is different because now the evaporation heat at 15° is needed.

$$HHV - LHV = \xi_{H_2O} * \Phi_m * (h_{vapour} - h_{liquid}) \qquad [kW]$$
$$67282.75 - 27176.43 = 0.1248 * 130.364 * (2529.05 - 62.94)$$

2.4.3. The difference in the HHV and the Q,T-diagram

For the convenience of the reader table 3 is copied here.

Table 6: Composition of the flue gas

	M	Flue gas		
	M (kg/kmol)	Mole %	Mass/mole	Mass %
		y_{fg}		ξ_{fg}
Ar	39.948	0.82%	3.276E-01	1.182%
CO_2	44.01	9.50%	4.181E+00	15.087%
H_2O	18.0153	19.19%	3.457E+00	12.475%
N_2	28.0134	70.49%	1.975E+01	71.256%
O_2	31.9988			
Totaal		100%	2.771E+01	100%

Table 7: Data of the flue gas

Medium	Mass flow	Mole flow	Volume flow	Pressure	Temperature
	[kg/s]	[kmol/s]	[m3/s]	[bar]	[°C]
	Φ_m	Φ_{mole}	Φ_v	p	T
Flue gas mix	130.364	4.704	181.01	1.023	200.38
Flue gas mix	130.364	4.704	90.548	1.023	15

With the data above the calculation can be done in just the same way. And again in the calculations following the subscript "fg" stands for dry flue gas and "v" for vapor.

The amount of dry flue gas in the flue gas mixture is equal to:

$$\xi_{fg} = 100\% - 12.475\% = 0.875 \qquad \text{kg/kg}$$
$$y_{fg} = 100\% - 19.19\% = 0.8081 \qquad \text{mole/mole}$$

The partial pressure of the flue gas at 15° C. can be found with the equation for an ideal gas:

$$p_{fg} = \frac{\xi_{fg} * m_a * (\overline{R}/M_a)T}{V} = \frac{y_{fg} * n_a * \overline{R} * T}{V} = \frac{y_{fg} * \Phi_{mole} * \overline{R} * T}{\Phi_v} \qquad [kPa]$$

$$100.64 = \frac{80.81\% * 4.707 * 8.314 * (15 + 273.15)}{90.548}$$

So now with the partial pressure of the flue gas known the partial pressure of the vapor can be calculated with the next formula.

$$p_v = p - p_{fg} \qquad [kPa]$$
$$1.66 = 102.3 - 100.64$$

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The humidity ratio is now equal to:

$$x_{rh} = \frac{M_v * p_v}{M_{fg} * p_{fg}} \qquad [-]$$

$$0.0107 = \frac{18.02 * 1.66}{27.71 * 100.64}$$

So now, the mass fraction of water vapor in the flue gas mixture can be calculated with:

$$\xi_v = x_{rh} * \xi_{fg} \qquad [-]$$

$$0.00936 = 0.0107 * 0.875$$

This mass fraction represents the amount of water that has not been condensed and exists in the flue gas as a vapor. Therefore, the evaporation heat of this water is equal to the difference in the value of the HHV and the value according to the Q,T-diagram.

$$HHV - Q,Tvalue = \xi_v * \Phi_m * \left(h_{vapour} - h_{liquid} \right) \qquad [kW]$$

$$67282.75 - 64394.1 \cong 0.00936 * 130.364 * (2529.05 - 62.94)$$

The difference between the left-hand side and the right-hand side is about 4% and can again be explained by rounding off within the calculations.

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Input summary for the stack at 15 degrees

Description

System data: NAPP=7, NLIN=5, NCYCLE=3, NPRINT=4

Apparatus: NO=1, TYPE=10, APNAME='Sink/Source', DELM= -130.364

Apparatus: NO=2, TYPE=10, APNAME='Sink/Source', DELM= -18.184

Apparatus: NO=3, TYPE=10, APNAME='Stack'

Apparatus: NO=4, TYPE=10, APNAME='Sink/Source'

Apparatus: NO=5, TYPE=6, APNAME='Heat Exchgr.', PIN1= 45, DELP1= 3,
              TIN1= 120.78, PIN2= 1.023, DELP2=0, TIN2= 269.27,
              DELTH= 20

Apparatus: NO=6, TYPE=10, APNAME='Sink/Source', POUT= 1.023,
              TOUT= 15, DELM= -130.364

Apparatus: NO=7, TYPE=10, APNAME='Sink/Source'

Medium: Pipe No = 1, Type = 'GASMIX'
              Standard Fluegas

Medium: Pipe No = 5, Type = 'GASMIX'
              Standard Fluegas

Medium: Pipe No = 2, Type = 'WATERSTM'

Environment: Default environment like Baehr, but 15°C
              Environment composition:
              Specie= AR   CO2   H2O   N2   O2
              Mole %= 0.91   0.03   1.68   76.78   20.6
              Environment pressure: 1.01325 bar
              Environment temperature: 15 °C
              Heating values calculated at 1 atm, 25 °C

Input summary for the stack at 25 degrees

Description

System data: NAPP=7, NLIN=5, NCYCLE=3, NPRINT=4

Apparatus: NO=1, TYPE=10, APNAME='Sink/Source', DELM= -130.364

Apparatus: NO=2, TYPE=10, APNAME='Sink/Source', DELM= -18.184

Apparatus: NO=3, TYPE=10, APNAME='Stack'

Apparatus: NO=4, TYPE=10, APNAME='Sink/Source'

Apparatus: NO=5, TYPE=6, APNAME='Heat Exchgr.', PIN1= 45, DELP1= 3,
              TIN1= 120.78, PIN2= 1.023, DELP2=0, TIN2= 269.27, DELTH= 20

Apparatus: NO=6, TYPE=10, APNAME='Sink/Source', POUT= 1.023,
              TOUT= 25, DELM= -130.364

Apparatus: NO=7, TYPE=10, APNAME='Sink/Source'

Medium: Pipe No = 1, Type = 'GASMIX'
              Standard Fluegas

Medium: Pipe No = 5, Type = 'GASMIX'
              Standard Fluegas

Medium: Pipe No = 2, Type = 'WATERSTM'

Environment: Default environment of Baehr
              Environment composition:
              Specie= AR   CO2   H2O   N2   O2
              Mole %= 0.9   0.03   3.12   75.65   20.3
              Environment pressure: 1.01325 bar
              Environment temperature: 25 °C
              Heating values calculated at 1 atm, 25 °C