# Heat-exchanger

## 1.1 Introduction

This chapter is written to give the user a better understanding in the use of heat exchangers in Cycle-Tempo. In section 1.2 the heat exchanger model is used to appoint the main parameter, U*A, of the heat exchanger from given design conditions. Besides, other results of interest are discussed. For a given heat exchanger with the U*A parameter given, the working conditions are calculated as off-design situation which will be discussed in section 3.

## 1.2 Design situation

To start a calculation for a heat exchanger some information about temperatures, massflow and the used medium must be known. In this example these parameter values are freely chosen although in reality these values are related with other apparatuses. In subsection 1, the input necessary to run a calculation will be singled out. In subsection 1.2.2 the results from this calculation run given by Cycle-Tempo are discussed.

### 1.2.1 Input for a design calculation

Flue gas with a temperature, mass flow and pressure of 269.27 degrees Celsius, 130.364 kg/s and 1.023 bar respectively, is exchanging heat with water at 120.78 degrees, 18.184 kg/s and 45 bar. The pinch point of the heat exchanger is set at 20˚ K. This is a chosen value based on financial arguments. If a smaller temperature difference is chosen the heat-exchanging area must be larger and the production costs will increase. The input parameters, which Cycle-Tempo needs to run a calculation, are shown in Table 1.

**Table 1: Input parameters**

| Input variable | Model 1 | Model 2 |
|---|---|---|
| | **Heat-exchanger (Nr 5)** | **Heat-exchanger (Nr 10)** |
| Eeqcod | 2 | 1 |
| Delp1 | 3 | 3 |
| Tout1 | | 249.27 |
| Delp2 | 0.05 | 0.05 |
| Tout2 | | 200.37 |
| Delth | 20 | |
| | **Sink/source (Nr 1)** | **Sink/Source (Nr 6)** |
| Pout | 1.023 | 1.023 |
| Tout | 269.27 | 269.27 |
| Delm | -130.364 | -130.364 |
| | **Sink/Source (Nr 2)** | **Sink/Source (Nr 7)** |
| Pout | 45 | 45 |
| Tout | 120.78 | 120.78 |
| Delm | -18.184 | |

It is easily seen that there are two major differences in the input parameters between the models. The first one is in the energy equation codes (or Eeqcod). In model 1 this code is set on 2, which means that the energy equation of the apparatus is used to calculate an enthalpy (or temperature) of outlet 1. The mass flow must be known in this situation and is therefore given at source 1. The negative value of the mass flow indicates that the mass flow is out of the source. In model 2 this code is set on 1 indicating that the energy equation is used to calculate a mass flow. In this situation, the temperatures are given and the mass flow of source 7 is to be calculated.
The second difference is less obvious and is concerning the “Tout1”. In model one the inlet temperature and the “Delth” are given at which the “Tout1” can be calculated with the relation:
Tout1 = Tin2 – Delth.

Please consider that Tin2 equals Tout from source 1 (or 6). In model 2 the “Tout2” is already given as in model 1 the Tout2 will be calculated from the energy balance.
Details of the input data are given in appendix A and B.

### 1.2.2 The results of the design calculation

When all of the necessary input parameters are filled up Cycle-Tempo can perform a calculation run. After the calculation has finished a plot of the system will be automatically shown. In this example also a Q-T diagram is created. The results of the plot and the diagrams will be discussed in the next subparagraphs.

#### 1.2.2.1 Plot of the system

After filling in all the input variables given in table 1 a calculation can be made and the basic results hereof are shown in Figure 1

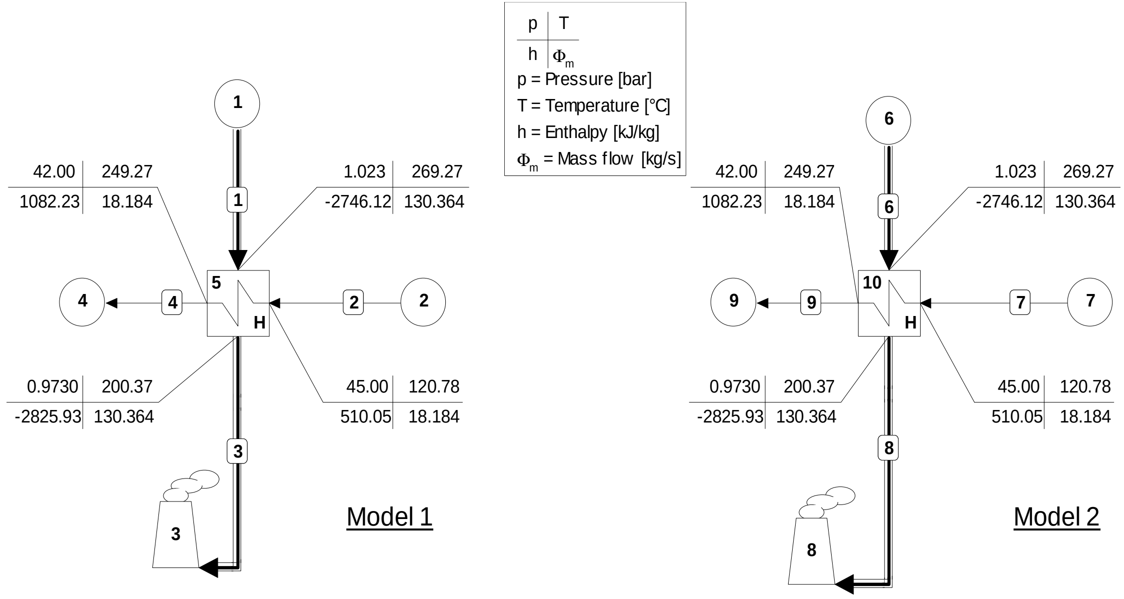

**Figure 1: The calculation output**

The two different models produce exactly the same results as expected, since the input data are taken from the same case.

#### 1.2.2.2 The Q-T diagram

For a simple heat exchanger, it is useful to look at the heat-transfer in a Q-T diagram. Because both models are identical in thermodynamic point of view there is no difference in calculated values or plots. In the Q-T diagram (Figure 2) it can be seen that the flue gas is cooling down and the water is warming up. The gray surface between the lines of this figure represents the (thermal) exergy loss in the heat exchanger due to the heat transfer.

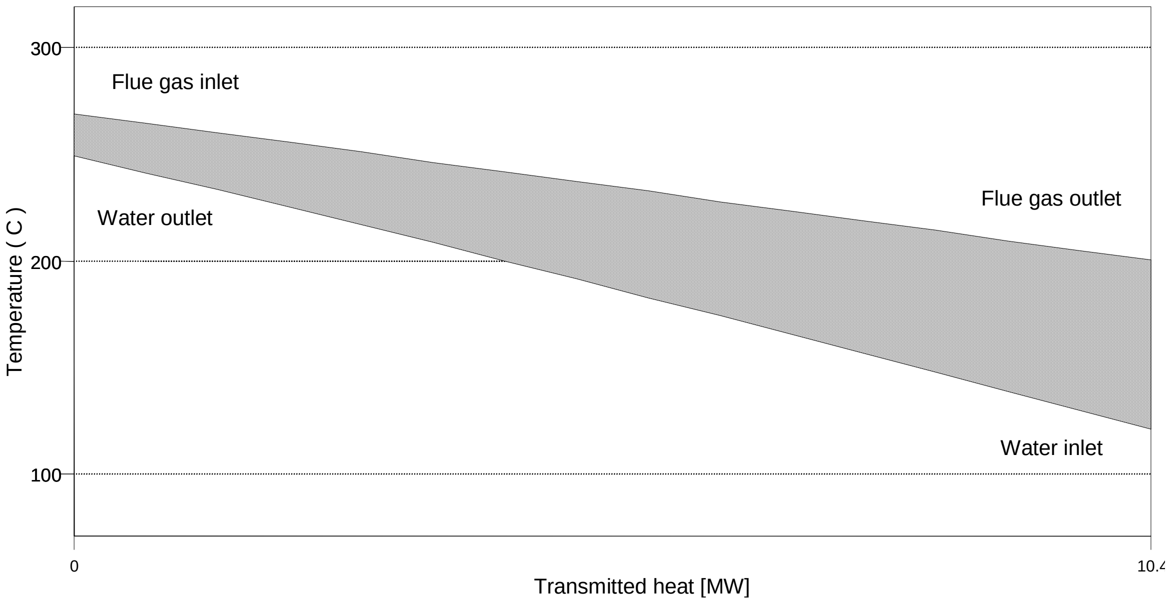

**Figure 2: Q-T Diagram**

### 1.2.2.3 Energy and exergy in the system

A table of the energy and exergy flows will be made after setting the environment definitions at the general data window (in menu bar). The exergy of a medium is relative to that of the environment chosen. Therefore the environment has to be set so that Cycle-Tempo can make this exergy calculation. For this example the environment is chosen to be like Baehr (at 25° Celsius).

**Table 2: Exergy values in the system**

| No. | Name | Exergy transmitted from system [kW] | | | Rel. Ex. Loss | Univ. Exergy eff. | Func. Exergy eff. |
|---|---|---|---|---|---|---|---|
| | | Total | Heat | Losses | [%] | [%] | [%] |
| 5 | Heat Exchgr. | 1268 | 0 | 1268 | 6.09 | 73.98 | 93.91 |
| 1 | Pipe | 0 | | 0 | 0 | | |
| 3 | Stack | 14914 | 0 | 14914 | 71.57 | | |
| 4 | Sink/Source | 4656 | 0 | 4656 | 22.35 | | |
| 1 | Sink/Source | -19787 | 0 | -19787 | -94.96 | | |
| 2 | Sink/Source | -1051 | 0 | -1051 | -5.04 | | |
| | Total: | 0 | 0 | 0 | 0 | | |

**Table 3: Energy and exergy flows**

| Pipe | Total Energy flow | Therm.Mec. Energy flow | Total Exergy flow | Therm.Mec. Exergy flow | Chemical exergy |
|---|---|---|---|---|---|
| no. | [kW] | [kW] | [kW] | [kW] | [kW] |
| 1 | 75868.36 | 75868.36 | 19787.91 | 12274.19 | 7513.71 |
| 2 | 7368.02 | 7368.02 | 1051.28 | 1051.28 | 0 |
| 3 | 65463.83 | 65463.83 | 14914.21 | 7400.49 | 7513.71 |
| 4 | 17772.55 | 17772.55 | 4656.84 | 4656.84 | 0 |

In the Cycle-Tempo manual in chapter 5 (technical notes) paragraph 5.2.3 definitions are given of exergy-efficiencies. For this example the efficiencies are calculated in the following.
The universal exergy efficiency:

$$\eta_{Ex,u} = \frac{\Phi_{Ex,out}}{\Phi_{Ex,in}} = \frac{\Phi_{Ex,3} + \Phi_{Ex,4}}{\Phi_{Ex,1} + \Phi_{Ex,2}} = \frac{14914.21 + 4656.84}{19787.91 + 1051.28} = 93.91\%$$

In which the numbers in the subscripts refer to the pipe numbers.
And the functional exergy efficiency:

$$\eta_{Ex,f} = \frac{\Delta\Phi_{Ex,product}}{\Delta\Phi_{Ex,source}} = \frac{\Phi_{Ex,primairy,out} - \Phi_{Ex,primairy,in}}{\Phi_{Ex,secundairy,in} - \Phi_{Ex,secundairy,out}} = \frac{\Phi_{Ex,4} - \Phi_{Ex,2}}{\Phi_{Ex,1} - \Phi_{Ex,3}} = \frac{4656.84 - 1051.28}{19787.91 - 14914} = 73.98\%$$

A graphical perception of the universal and functional exergy is shown in figure 5-3 of the user manual.

## 1.3 Off-design calculations

In this paragraph a closer look will be taken at the results from the off-design calculations. Again, the two models are used and the calculations made by Cycle-Tempo are worked out. For calculations in an off-design situation it is important to know if the heat transfer rate in the off-design situation depends upon the mass flow on the primary or on the secondary side. In subsection 1.3.1 an off-design calculation in which the outlet temperatures are unknown will be treated while in subsection 1.3.2 one outgoing temperature and one massflow is unknown. In subsection 1.3.3 the method of calculating the heat transfer rate (UA) will be explained.

### 1.3.1 Off-design with two unknown temperatures

In this section the off-design massflows are known and the outlet temperatures are to be calculated. In model 1 the heat transfer rate depends on the mass flow of the water as in model 2 the UA-value is calculated from the flue gas mass flow. The off-design mass flows are freely chosen and the other parameters are according to the design situation. The input parameters for this situation are shown in the following table:

**Table 4: input parameters in off-design if massflow is fixed**

| Inputvariable | Model 1 | Model 2 |
|---|---|---|
| | **Heat-exchanger (Nr 5)** | **Heat-exchanger (Nr 10)** |
| Eeqcod | 2 | 2 |
| Delp1 | 3 | 3 |
| Delp2 | 0.05 | 0.05 |
| | **Off-design** | **Off-design** |
| Dsmas1 | 18.184 | |
| Dsmas2 | | 130.364 |
| UA (at design point) | 241.149 | 241.149 |
| Etha | 0.8 | 0.8 |
| | **Sink/Source (Nr 1)** | **Sink/Source (Nr 6)** |
| Pin | 1.023 | 1.023 |
| Tin | 269.27 | 269.27 |
| Delm | -65 | -65 |
| | **Sink/Source (Nr 2)** | **Sink/Source (Nr 7)** |
| Pin | 45 | 45 |
| Tin | 120.78 | 120.78 |
| Delm | -15 | -15 |

And after a calculation run of Cycle-Tempo the results for the off-design situation are shown in the plot following:

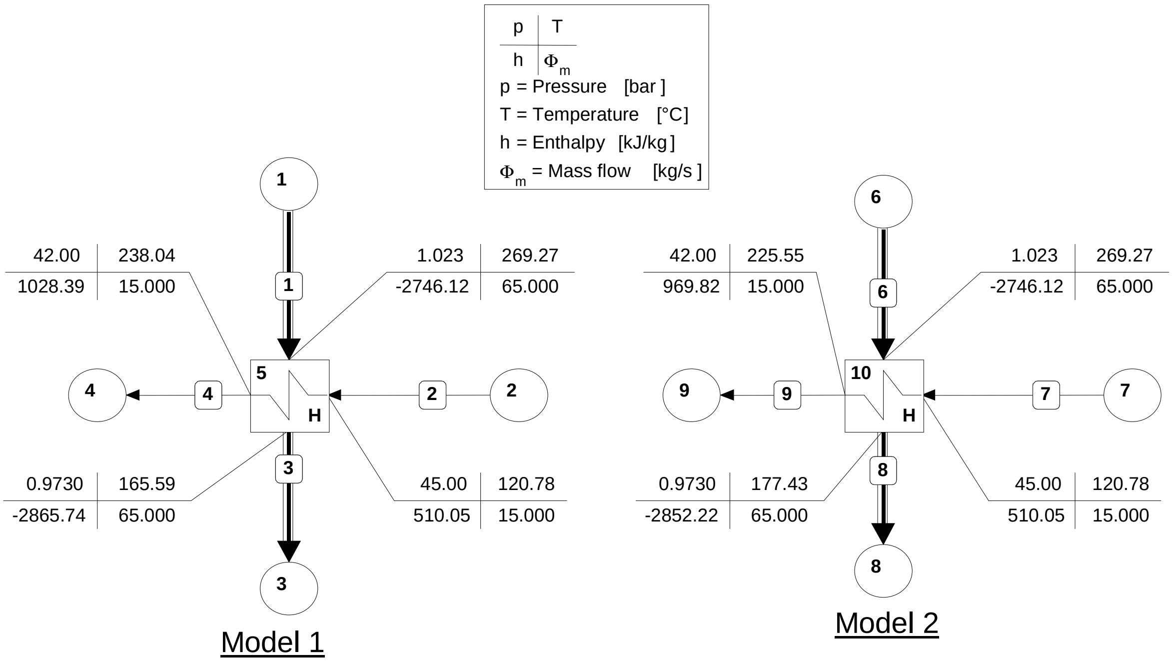

**Figure 3: Off-design situation with fixed massflows**

As shown in the figure the massflows are equal. The difference in outlet temperatures is caused by the choice of the DSMAS, for primary or secondary medium. An extended explanation is given in subsection 1.3.3.

### 1.3.2 Off-design with one unknown massflow and one unknown temperature

Suppose now that the flue gas massflow is fixed and that the outlet temperature of the water after passing through the heat exchanger also must be constant at 249.27 °C like in the design situation. To reach this value the massflow of the water must be controlled. The massflow can be calculated by Cycle-Tempo by stating Eeqcod = 1 for the heat exchanger.
In model 3 the heat transfer capacity rate is depending on the water like in model 1 and in model 4 this value depends on the flue gas like in model 2. The inputparameters are now according to table 5

**Table 5: input parameters in off-design if one massflow and temperature is fixed**

| Inputvariable | Model 3 | Model 4 |
|---|---|---|
|  | **Heat-exchanger (Nr 5)** | **Heat-exchanger (Nr 10)** |
| Eeqco | 1 | 1 |
| Delp1 | 3 | 3 |
| Delp2 | 0.05 | 0.05 |
| Tout1 | 249.27 | 249.27 |
|  | **Off-design** | **Off-design** |
| Dsmas1 | 18.184 |  |
| Dsmas2 |  | 130.364 |
| UA | 241.149 | 241.149 |
| Etha | 0.8 | 0.8 |
|  | **Sink/Source (Nr 1)** | **Sink/Source (Nr 6)** |
| Pin | 1.023 | 1.023 |
| Tin | 269.27 | 269.27 |
| Delm | -65 | -65 |
|  | **Sink/Source (Nr 2)** | **Sink/Source (Nr 7)** |
| Pin | 45 | 45 |
| Tin | 120.78 | 120.78 |

The Cycle-Tempo results from this input are shown in figure 4.

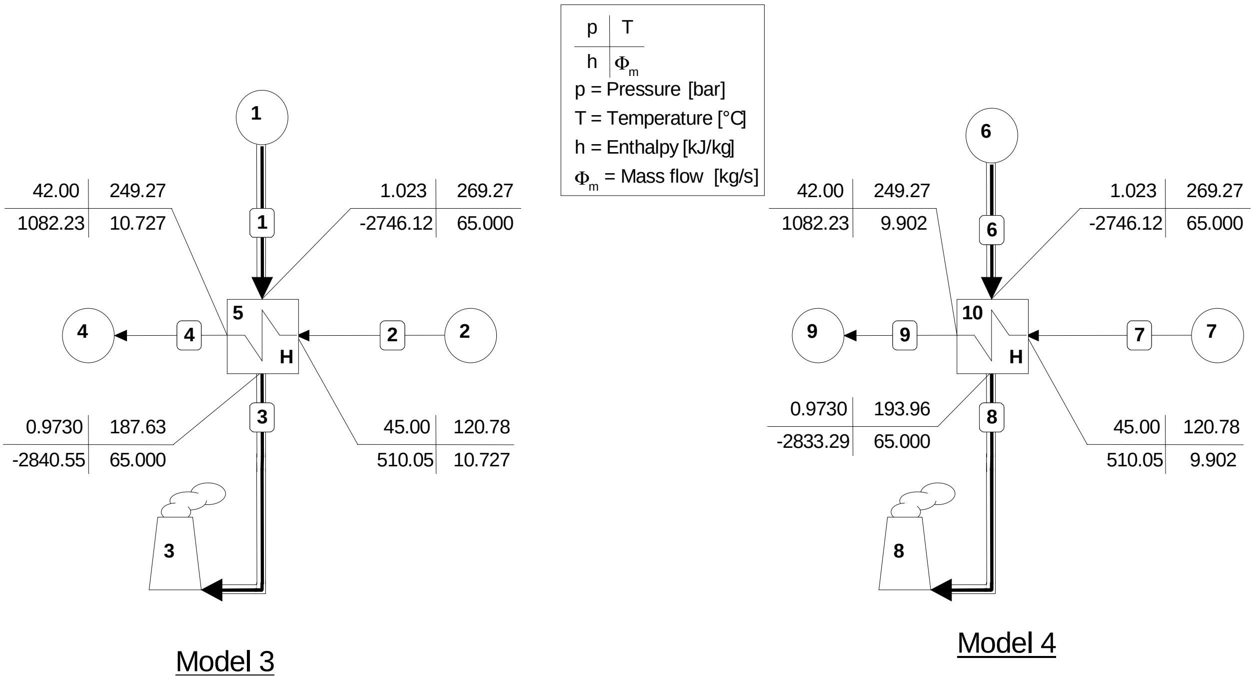

**Figure 4: Off-design situation with one unknown massflow and one unknown temperature**

As shown in the figure the outlet temperature of the water is constant at 249.27 degrees. The difference in massflow between the models is caused by the choice of the DSMAS, for the primary or the secondary medium, influencing the U*A value as discussed in subsection 1.3.3.

### 1.3.3 Calculation of the UA-value for working conditions

For off-design calculations Cycle-Tempo uses the heat transfer capacity rate of a surface heat exchanger, UA. In the design calculation this value of UA can be calculated from the calculated heat transfer that takes place. After this (design) value is known the UA value for the off-design can be calculated. For the design situation the UA value is equal to:

$$\Phi_H = UA * \Delta T_{\ln} \qquad [kW]$$

Subsequently, in the off-design situation the (off-design) UA'-value is formed with the equation:

$$UA' = UA * \left( \frac{\Phi_{m,prim}}{DSMAS1} \right)^{\eta} \qquad [kW/K]$$

Or when DSMAS2 is specified this value will be used instead of DSMAS1. The formula then changes to:

$$UA' = UA * \left( \frac{\Phi_{m,\sec}}{DSMAS2} \right)^{\eta} \qquad [kW/K]$$

In which DSMAS1 is the design mass flow of the primary side of the heat exchanger and DSMAS2 is the secondary side respectively. Please note that the formula could be given as:

$$U' = U * \left( \frac{\Phi_{m,prim}}{DSMAS1} \right)^{\eta} \qquad [kW/m^2K]$$

as A is a constant surface area.

With this (off-design) UA'-value an iterative process can be started to find the proper heat-transfer and the unknown temperatures and/or massflows.
From the difference in results between models 1 and 2 and between 3 and 4 it becomes clear that the influence of the choice for DSMAS1 or DSMAS2 can be significant. The value U in the formula can be calculated with:

$$\frac{1}{U} = \frac{1}{\alpha_{fg}} + \frac{t}{\lambda} + \frac{1}{\alpha_w} \qquad [m^2K/kW]$$

in which:

| | |
|---|---|
| α | heat transfer coefficient (fl: flue gas; w: water) |
| λ | heat conduction coefficient |
| t | thickness of the tube wall |

As $\alpha_{fg} << \alpha_w$ and $\lambda$, the value of U is dominated by $\alpha_{fg}$. So usually it is advised to give DSMAS2 for heat exchangers in a boiler.

### *Example 1: The calulation of the UA-value in design situation*

In the following example the UA-value for the design situation will be calculated. To do so, the transmitted heat and temperatures have to be known. These data are shown in table 6.

**Table 6 : Heat exchanging equipment**

| App. no. | Name | Type | Low end Temp diff [K] | High end temp diff [K] | Transmitted heat flow [kW] |
|---|---|---|---|---|---|
| 5 | Heat Exchgr. | 6 | 79.59 | 20 | 10404.53 |
| 10 | Heat Exchgr. | 12 | 79.59 | 20 | 10404.79 |

Before the data from table 6 can be used in the formula:

$$\Phi_H = UA * \Delta T_{\ln} \qquad [kW]$$

the logarithmic-mean temperature difference, $\Delta T_{\ln}$, must be calculated. This can be done with the following formula:

$$\Delta T_{\ln} = \frac{\Delta T_h - \Delta T_l}{\ln\left(\frac{\Delta T_h}{\Delta T_l}\right)} = \frac{20 - 79.59}{\ln\left(\frac{20}{79.59}\right)} = 43.15 \;\; [K]$$

And therefore:

$$\Phi_H = UA * \Delta T_{\ln} \qquad [kW]$$
$$10404 = UA * 43.15$$
$$UA = 214 \qquad [kW]$$

With the UA value in design situation known the UA-value in off-design situation can easily be calculated with the formulas stated earlier in this subsection.

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## Appendix A: Model 1

Description
System data: NAPP=5, NLIN=4, NCYCLE=2, NPRINT=4

Apparatus: NO=1, TYPE=10, APNAME='Sink/Source', POUT= 1.023, TOUT= 269.27, DELM= -130.364
Apparatus: NO=2, TYPE=10, APNAME='Sink/Source', POUT= 45, TOUT= 120.78, 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.', DELP1= 3, DELP2=0.05, DELTH= 20

Medium: Pipe No = 1, 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

## Appendix B: Model 2

Description
System data: NAPP=5, NLIN=4, NCYCLE=2, NPRODF=1, NPRINT=4

Apparatus: NO=6, TYPE=10, APNAME='Sink/Source', POUT= 1.023, TOUT= 269.27, DELM= -130.364
Apparatus: NO=7, TYPE=10, APNAME='Sink/Source', POUT= 45, TOUT= 120.78
Apparatus: NO=8, TYPE=10, APNAME='Stack'
Apparatus: NO=9, TYPE=10, APNAME='Sink/Source'
Apparatus: NO=10, TYPE=12, APNAME='Heat Exchgr.', DELP1= 3, TOUT1= 249.27, DELP2=0.05, TOUT2= 200.37

Medium: Pipe No = 6, Type = 'GASMIX'
Standard Fluegas

Medium: Pipe No = 7, 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