This document contains Chapter 4 from the book by Chemplant

Data Validation and Reconciliation in Practice

Recon Demo Examples

Heat and Energy Balancing

Index

5 Models of thermal unit operations

In the previous chapter, we have given several examples of mass and species balances. With the energy balances, the situation is more complicated for a number of reasons. Besides the unavoidable energy losses into the environment, there is another problem. It is the modeling of the mass streams enthalpy dependency on the state variables; indeed, our knowledge about these dependencies is never perfect. That's why already the name of the chapter speaks of models.

Further, we'll describe models of basic heat operations. From such “bricks”F one can then set up the models of more complex systems. The present chapter will enable the reader to create simple models in the program RECON and check himself the results.

The structure of all sections is as follows:

1. BALANCING SCHEME. It is a copy of the scheme created in the graphical editor of the RECON program. To individual streams are in addition written identifiers of state variables (T for temperature, P for pressure and X for wetness) .If a given variable is denoted by these letters, unmeasured variables are given in italics. Details can be found in the part INPUT DATA of the example.
2. INPUT DATA. This is a somewhat abridged extract of data for the task F

3. created in program RECON – menu *Flowsheet – Data review - Brief*. It comprises all information needed for the task configuration.

4. PANEL OF THE NODE MODEL PARAMETERS DEFINITION. It is the panel, where the node parameters for energy balance are defined. In case of more complex schemes, there can be more such panels.

5. RESULTS. It is an abridged extract from the results for the user's inspection, created in program RECON – menu *Calculate – Results*. All examples in this chapter are without gross errors, so the sum of squares of adjustments thus Q_{min}. values are not given.

Although this manual is not conceived as a substitute for instructions to the RECON program, let us still indicate a procedure to be maintained by the reader when creating the tasks.

1. Enter the name of the task, which is simultaneously the name of the file for the model to be created.
2. Enter the text of the file title (long name).
3. In the further panel, change physical units (when necessary). The units chosen in individual cases are given in part INPUT DATA.
4. Enter the component name. It is recommended to enter H2O and not to fill in the full name.
5. The graphical editor surface turns up. Before one starts drawing, it is recommended to enter the state variables values (temperatures, pressures and wetnesses) in the menu *Accessories*. Names, types and values can be found in part INPUT DATA. In the standard manner are given beforehand the wetnesses STEAM (wetness = 0) and WATER (wetness = 100).
6. The set up of models including energy balance is a little bit more difficult than for models with a mass balance only. It is recommended to start with the mass balance part of the model, which is usually a basis of energy balancing. After checking the mass balance part of the model, energy balance functions can be added gradually.
7. The scheme drawing proper is recommended to be started by drawing all nodes; the latter are to be conveniently placed on the screen (at later changes in size and placing, one can disturb the streams already drawn). At the nodes, one fills in only Name (it is in the scheme) and Description (invent some).
8. Then draw the streams. Their short names are given in the scheme, a description is again invented. The types of streams, values and possible errors (for measured variables) can be found in part INPUT DATA. If one deals with an energy stream, this must be marked in the panel of the stream on the right above. Thereby, the definition of the task concerning the mass balance is complete.
9. In order to create the energy balance equation for the given node, we must designate this node on its panel as a *heat node* (square on the right above). In this manner, one makes the center of the panel accessible for the configuration of heat functions, temperatures, pressures and wetnesses. **At this moment, these state variables must naturally be already defined.** Let us recall that one

fills in only those state variables that are relevant for the given heat function. So as to explain this important part, all panels are figured in the text.

10. Having finished the configuration of all heat nodes, one can carry out the computation.

Let us still explain certain abbreviations used in the RECON program.

dT	mean temperature difference in a heat exchanger
F	type of variable - fixed variable (known as errorless)
HTC	heat transfer coefficient
M	type of variable - Measured variable
MC	type of variable – Measured variable, adjustable (Corrected by data reconciliation)
MN	type of variable – measured variable, nonadjustable
MPag	unit of pressure (final g means pressure difference against atmospheric pressure, the same for further pressure units)
N	type of variable – uNmeasured variable
NO	type of variable – uNmeasured variable, Observable
NN	type of variable – uNmeasured variable, uNobservable (non-observable)
Q	heat flow

Let us note in addition that certain examples have null degree of redundancy and one deals then only with solving the set of equations. For simple cases formed by one or several nodes, this is typical in practice. Redundancy arises just by connecting simple unit operations in larger systems.

For the majority of examples given in this chapter the reader will have at hand also their model solutions, i.e. files with respective models. Names of the files correspond to numbers of sections in this chapter. E.g. to example from Section 5.1 coresponds Example E-1, to example from Section 5.2 example E-2, etc.

Important note: If the heat balance concerns different forms of water only (water, steam, wet steam) without chemical reactions, we recommend to use only one chemical species denoted for example H2O. In this case Components (menu *Accessories/Components*) need not be linked with chemical component in the database of physical properties (column *Chemical name*).

If chemical reactions take place (typical for burning of fuels), we must be careful. Heats of formation of water and steam differ due to the latent heat of water vaporization. Different forms of H2O (water, steam) must be distinguished around nodes with chemical reactions. On the other hand side in nodes without chemical reactions (for example a condenser) distinguishing between water and steam would require to make this node the chemical reactor which is not practical. In such cases it is possible to use around nodes without chemical reaction only one form of H2O (water or steam) irrespective of the real state of H2O. See also the Note at the end of Subsection 5.16.

5.1 *Mixer of thermal streams*

Mixing two or several streams is a basic unit operation. The model generates two balance equations – the mass and energy balances. From the model, one can compute two unmeasured variables at most, e.g. the outlet flowrate and temperature.

The following example is that of mixing two streams of water with different temperatures. Before creating the scheme in the graphical editor, the user must define 3 temperatures and 1 pressure (menu *Accessories*). The pressure in the whole system is that of the atmosphere, and with respect to the temperatures, the water is below the saturation line. The model is formed by two equations (mass and energy balances). Because all variables are measured, the task has two degrees of redundancy.

Start by drawing the flowsheet for mass balance only (node M1 and streams S1, S2 and S3). At this moment the color of the node will be gray. After checking the box *Heat node* on the node's panel, fill in heat functions and their parameters. After that the color of the node will change, showing that the heat balance is active.

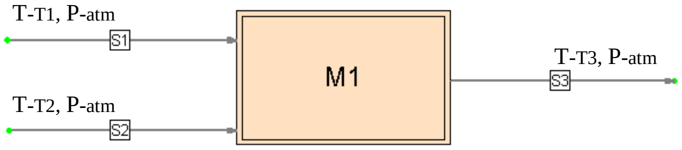
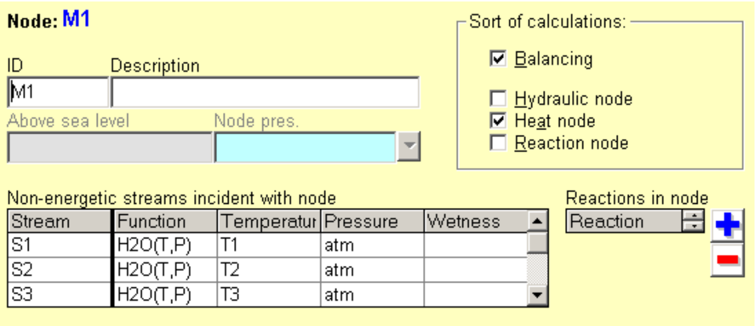


Fig. 5.1-1: Balance scheme (demo Example E-1)

INPUT DATA

```
NAME         TYPE                VALUE      MAX.ERROR

M A T E R I A L   S T R E A M S     [KG/S]

S1            M               60.0000      1.0000
S2            M               40.0000      2.0000
S3            M              102.0000      2.0000

T E M P E R A T U R E S     [C]

T1            M               60.0000      1.0000
T2            M               40.0000      1.0000
T3            M               51.0000      1.0000

P R E S S U R E S     [KPA]

atm           F              101.3250
```



Node: M1

ID: M1

Description:

Above sea level:

Node pres.:

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
S1	H2O(T,P)	T1	atm	
S2	H2O(T,P)	T2	atm	
S3	H2O(T,P)	T3	atm	

Reactions in node

Reaction

Fig. 5.1-2: Panel of node model definition

RESULTS (abbreviated)

```
G L O B A L   D A T A

  Degree of redundancy                           2
  Number of equations                            2
  Qmin                                   3.764E+00
  Qcrit                                  5.974E+00

V A R I A B L E S

  Name      Type       Inp.value     Rec.value      Max. error
  S T R E A M S    [KG/S]
  S1         MC          60.000        60.148         0.938
  S2         MC          40.000        41.053         1.472
  S3         MC         102.000       101.201         1.484
  T E M P E R A T U R E S    [C]
  T1         MC          60.000        59.653         0.880
  T2         MC          40.000        39.769         0.946
  T3         MC          51.000        51.589         0.600
  P R E S S U R E S    [KPA]
  atm        F          101.325       101.325
```

The mixer is a basic node type. In practice, it can have several inlets, and also more outlets. For a mixer in proper sense, all outlet streams should be in the same thermodynamic state.

5.2 Simple heat exchanger

This kind of exchanger is characterized by the fact that it has only two streams, which exchange heat. One stream is so-called *hot* and the other *cold* stream. This model generates just one equation (heat balance). It is worth mentioning that with this model, one gives the heat exchange area and number of passes. From the model one then computes, besides the heat flow in the exchanger, also the overall heat transfer coefficient.

In our example, one deals with the heating/cooling of water with temperature below the saturation line and under atmospheric pressure. Before creating the scheme in graphical editor, one has to enter 4 temperatures and 1 pressure.

After that draw both streams. You will be warned that these streams are loops going from Environment to environment. This is allowed for heat exchangers only. After that draw the exchanger E1 on the crossing of streams.

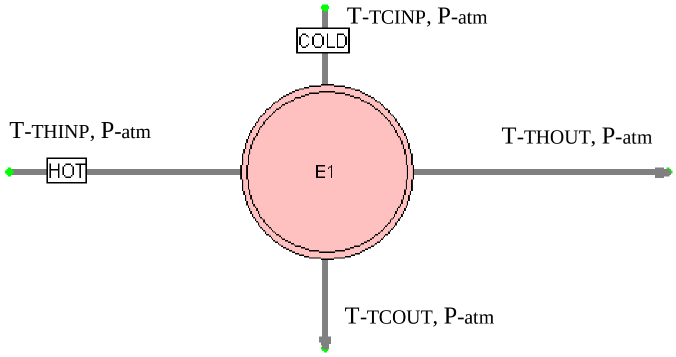
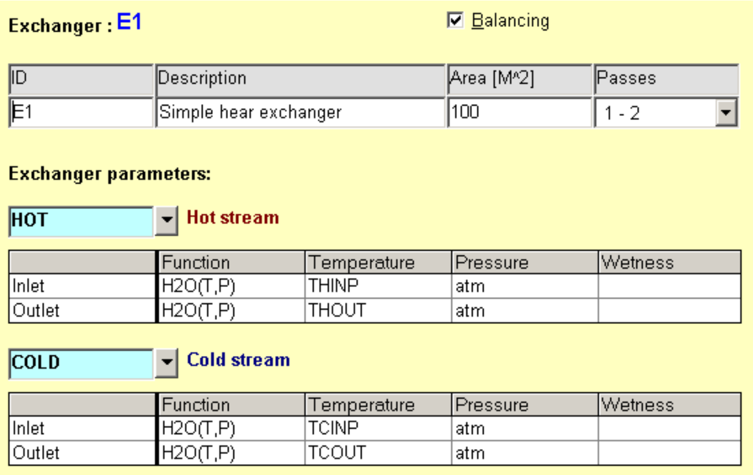


Fig. 5.2-1: Balance scheme (demo Example E-2)

INPUT DATA

```
NAME       TYPE           VALUE      MAX.ERROR

M A T E R I A L  S T R E A M S    [t/h]
COLD        M            20.0000     2.0000 %
HOT         M            10.0000     2.0000 %
T E M P E R A T U R E S    [C]
TCINP       M            20.0000     1.0000
TCOUT       M            39.0000     1.0000
THINP       M            90.0000     1.0000
THOUT       M            50.0000     1.0000
P R E S S U R E S    [KPA]
atm         F           100.0000


E X C H A N G E R S    [M^2]
NAME      Stream      End     Function  Temperature  Pressure     Wetness      Area

E1         HOT         Inlet    H2O(T,P)   THINP        atm                         100
                       Outlet   H2O(T,P)   THOUT        atm
           COLD        Inlet    H2O(T,P)   TCINP        atm
                       Outlet   H2O(T,P)   TCOUT        atm
```



Exchanger : E1

☑ Balancing

ID	Description	Area [M^2]	Passes
E1	Simple hear exchanger	100	1 - 2

Exchanger parameters:

HOT — Hot stream

	Function	Temperature	Pressure	Wetness
Inlet	H2O(T,P)	THINP	atm	
Outlet	H2O(T,P)	THOUT	atm	

COLD — Cold stream

	Function	Temperature	Pressure	Wetness
Inlet	H2O(T,P)	TCINP	atm	
Outlet	H2O(T,P)	TCOUT	atm	

Fig. 5.2-2 Panel of the model parameters definition

RESULTS

```
G L O B A L   D A T A

  Degree of redundancy                             1
  Number of equations                              1
  Qmin                                     1.481E+00
  Qcrit                                    3.841E+00

V A R I A B L E S

  Name       Type      Inp.value      Rec.value      Max.error
  S T R E A M S    [t/h]
  COLD       MC           20.000         20.056          0.389
  HOT        MC           10.000          9.970          0.194
  T E M P E R A T U R E S    [C]
  TCINP      MC           20.000         19.629          0.802
  TCOUT      MC           39.000         39.370          0.803
  THINP      MC           90.000         89.814          0.954
  THOUT      MC           50.000         50.185          0.955
  P R E S S U R E S    [KPA]
  atm        F           100.000        100.000


 E X C H A N G E R S    [MJ/h],  [C],  [MJ/h/M^2/C]

  Name           Q(hot)       Q(cold)         Q(rec)         dT        HTC
  E1            1675.797      1588.655       1655.290     39.672      0.417
```

Here, Q(hot) and Q(cold) mean transferred heats calculated from hot and cold streams separately, while Q(rec) is heat resulting from reconciled values.

5.3 *General heat exchanger*

A general heat exchanger differs from the simple one mainly by the fact that it can comprise more than two streams. It is formed by two balancing nodes, one of which represents the hot side, the other one the cold side of the exchanger. Both nodes are connected by an energy stream representing the heat flow from the hot to the cold side through the heat exchange surface. This arrangement makes possible to model situations, for the description of which the simple exchanger does not suffice.

The model generates altogether 4 balance equations – the mass and energy balances around both of the nodes. If compared with the simple exchanger, it has now three unknowns – the heat flow through the exchanger and two unknown flowrates at the outlets from both nodes. One degree of redundancy is available for the reconciliation, so long as the other variables are known (thus in the same manner as in the case of a simple exchanger).

Let us start from the preceding example, i.e. the heating/cooling of water with temperature below the saturation line at atmospheric pressure. In addition, let us consider the heat loss from the cold side, say QLOSS estimated a priori as 20 MJ/h; the error of this estimate is assumed to be 4 MJ/h.

Before drawing the scheme, it is necessary to define 4 temperatures and 1 pressure.

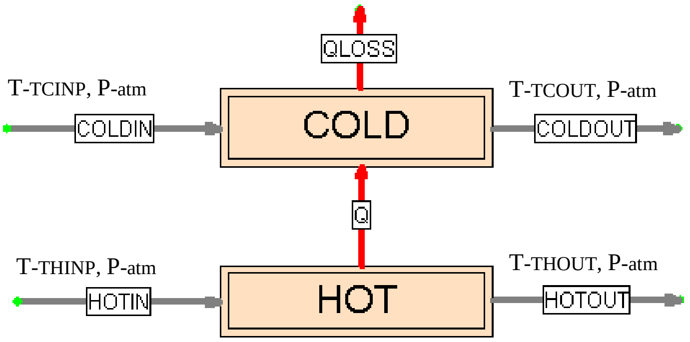


Fig. 5.3-1: Balance scheme (demo Example E-3)

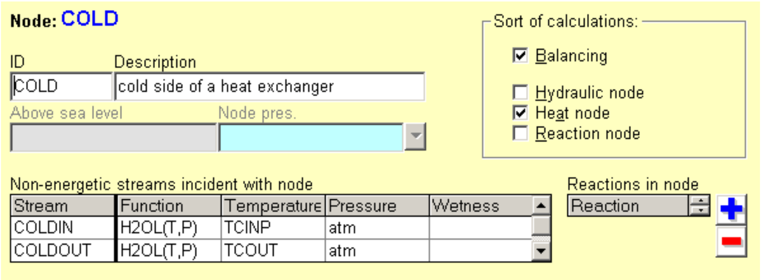
Comparing with a simple exchanger, we see that both parts of the exchanger have now two incident streams – inlet and outlet. If some of the flowrates is measured then only once, e.g. at the inlet. The outlet flowrate is then calculated from the mass balance.

INPUT DATA

```
 NAME       TYPE          VALUE      MAX.ERROR

 M A T E R I A L   S T R E A M S    [t/h]
 COLDIN      M            20.0000      2.0000 %
 COLDOUT     N            20.0000
 HOTIN       M            10.0000      2.0000 %
 HOTOUT      N            10.0000

F L O W S  O F  E N E R G Y   [MJ/h]
 Q           N          1000.0000
 QLOSS       M            20.0000       4.0000
 T E M P E R A T U R E S    [C]
 TCINP       M            20.0000      1.0000
 TCOUT       M            39.0000      1.0000
 THINP       M            90.0000      1.0000
 THOUT       M            50.0000      1.0000
 P R E S S U R E S     [KPA]
```

```
atm          F           100.0000
```

PANELS OF THE MODEL PARAMETERS DEFINITION



Node: COLD

ID	Description
COLD	cold side of a heat exchanger

Above sea level

Node pres.

Sort of calculations:

☑ Balancing

☐ Hydraulic node
☑ Heat node
☐ Reaction node

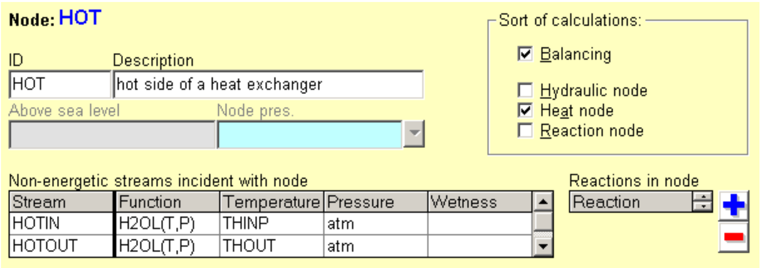
Non-energetic streams incident with node

Stream	Function	Temperature	Pressure	Wetness
COLDIN	H2OL(T,P)	TCINP	atm	
COLDOUT	H2OL(T,P)	TCOUT	atm	

Reactions in node

Reaction

Fig. 5.3-2: Cold side of exchanger



Node: HOT

ID	Description
HOT	hot side of a heat exchanger

Above sea level

Node pres.

Sort of calculations:

☑ Balancing

☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperature	Pressure	Wetness
HOTIN	H2OL(T,P)	THINP	atm	
HOTOUT	H2OL(T,P)	THOUT	atm	

Reactions in node

Reaction

Fig. 5.3-3: Hot side of exchanger

RESULTS

```
G L O B A L   D A T A

  Degree of redundancy                              1
  Number of equations                               4
  Qmin                                      8.792E-01
  Qcrit                                     3.841E+00

V A R I A B L E S

  Name        Type          Measured      Reconciled   Max.error of reconciled val.

  S T R E A M S     [t/h]
  COLDIN      MC            20.000         20.043         0.389
  COLDOUT     NO            20.000         20.043         0.389
  HOTIN       MC            10.000          9.977         0.194
  HOTOUT      NO            10.000          9.977         0.194
  F L O W S   O F   E N E R G Y       [MJ/h]
  Q           NO          1000.000       1659.996        59.427
  QLOSS       MC            20.000         20.055         3.998
  T E M P E R A T U R E S      [C]
  TCINP       MC            20.000         19.714         0.802
  TCOUT       MC            39.000         39.285         0.803
  THINP       MC            90.000         89.857         0.954
  THOUT       MC            50.000         50.143         0.955

  P R E S S U R E S     [KPA]
  atm         F            100.000        100.000
```

The results can be compared with the preceding example of a simple exchanger. The only difference is here the energy loss stream. In the case of a general heat exchanger, the mean temperature difference is no longer computed, nor the overall heat transfer coefficient. If the user needs these values, he must define them himself with the aid of user defined equations.

5.4 *Steam generator*

In practice, steam can be generated in different manners (e.g. by hot combustion products, other steam of higher pressure, or a hot heat exchanging medium). The thermodynamic state at the boiling proper inside the generator can be defined by temperature or pressure. One here assumes phase equilibrium between liquid and vapor phases.

This unit operation can be, according to its complexity, modeled as a simple or general heat exchanger. As the steam generator in a nuclear power plant will be the subject of a more extensive case study below, let us now prepare this model for further use.

Heat is supplied to the steam generator (SG) by high-pressure hot water circulating between the nuclear reactor and the high pressure water part of the SG. Into the steam part is supplied feed water; steam and blowdown water form the outlets. The steam contains a small amount of liquid phase. Because we here have more than 2 streams, let us apply the general heat exchanger model.

In this model, altogether 4 balance equations are generated. If we measure the flowrates of all mass streams connected with the steam space and the hot water flowrate at the inlet into the high-pressure water space, we have altogether 2 unknown streams, viz. hot water outlet and heat flow. If we further measure all temperatures and pressures, two degrees of redundancy are available for reconciliation and data validation.

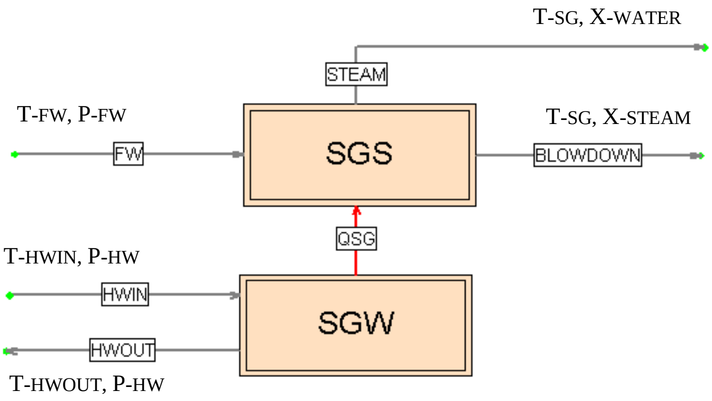


Fig. 5.4-1: Balance scheme (demo Example E-4)

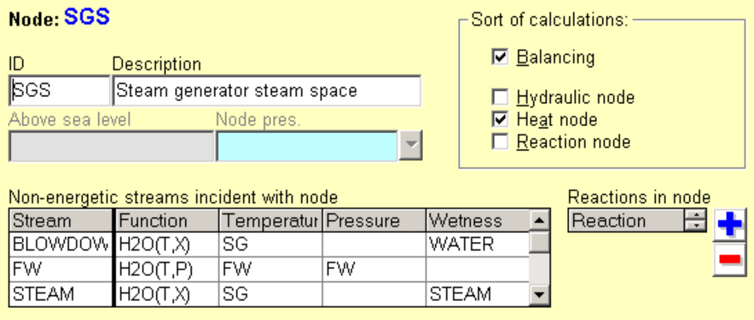
INPUT DATA

Besides the mass and heat flowrates, the task involves 4 temperatures (hot water temperatures HWIN and HWOUT, temperature in steam generator SG , equal for outlet steam and blowdown, and temperature of feed water FW). Further involved are two pressures (FW for feed water and HW for hot water). In addition, we here have two wetness values for liquid water (WATER) and (wet) steam (STEAM).

```
NAME         TYPE          VALUE        MAX.ERROR

 M A T E R I A L    S T R E A M S     [KG/S]
 BLOWDOWN     M            6.1200       5.0000 %
```

```
FW          M          444.5000      2.0000 %
HWIN        M         5650.0000      5.0000 %
HWOUT       N         5000.0000
STEAM       M          445.0000      2.0000 %
E N E R G Y    F L O W S    [KJ/S]
QSG         N       800000.0000
T E M P E R A T U R E S     [C]
HWIN        M          295.2000      1.0000
HWOUT       M          265.8000      1.0000
SG          M          257.6000      1.0000
FW          M          221.6000      1.0000
P R E S S U R E S    [KPA]
FW          M        10000.0000      0.5000 %
HW          M        10000.0000      0.5000 %

W E T N E S S E S    [%]
STEAM       F            0.2500
WATER       F          100.0000
```

PANELS OF MODEL PARAMETERS DEFINITION



Node: SGS

ID: SGS
Description: Steam generator steam space

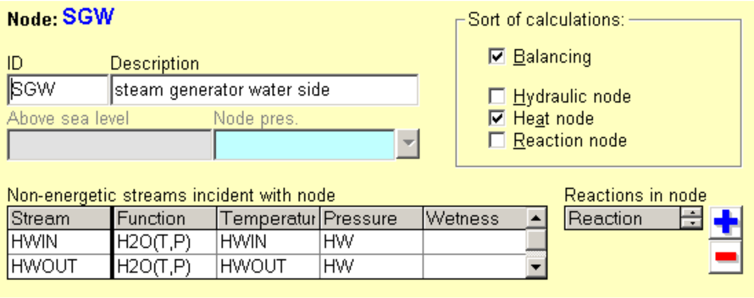
Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
BLOWDOW	H2O(T,X)	SG		WATER
FW	H2O(T,P)	FW	FW	
STEAM	H2O(T,X)	SG		STEAM

Reactions in node

Fig. 5.4-2: Steam space



Node: SGW

ID: SGW
Description: steam generator water side

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
HWIN	H2O(T,P)	HWIN	HW	
HWOUT	H2O(T,P)	HWOUT	HW	

Reactions in node

Fig. 5.4-3: Water space

RESULTS

```
G L O B A L   D A T A
Degree of redundancy                                2
Number of equations                                 4
Qmin                                        4.001E+00
Qcrit                                       5.974E+00

V A R I A B L E S

Name      Type       Inp.value      Rec.value      Max.error

S T R E A M S    [KG/S]
BLOWDOWN    MC           6.120          6.115          0.306
FW          MC         444.500        448.863          6.172
HWIN        MC        5650.000       5471.834        200.270
HWOUT       NO        5000.000       5471.834        200.270
STEAM       MC         445.000        442.748          6.172
E N E R G Y  F L O W S    [KJ/S]
QSG         NO      800000.000     816004.219      11530.738
```

```
T E M P E R A T U R E S    [C]
FW          MC         221.600        221.570          0.999
HWIN        MC         295.200        294.745          0.863
HWOUT       MC         265.800        266.161          0.890
SG          MC         257.600        257.597          1.000
P R E S S U R E S    [KPA]
FW          MC       10000.000       9999.995         50.000
HW          MC       10000.000      10000.159         50.000
W E T N E S S E S    [%]
STEAM       F            0.250          0.250
WATER       F          100.000        100.000
```

The steam generator balancing is very important in practice. This example will again be scrutinized from other points of view in one of the Case studies below.

5.5 Condensation of steam

During the condensation, steam transfers its condensation heat to the cold stream, which is mostly liquid of lower temperature. So long as just this heating is the purpose, the whole apparatus is called heater. The steam in the condenser changes to condensate, which can be water at the saturation line, possibly also somewhat subcooled (in this section, sub-cooling will not be considered for simplicity). The difference between the inlet steam and outlet condensate enthalpies determines the amount of heat transferred.

The state at the condensation proper inside the exchanger can be defined either by temperature or by pressure. One here assumes phase equilibrium between steam and condensate. A heat exchanger with condensation can be, according to its complexity, modeled as a simple or general exchanger. Let us further use the general form of exchanger.

The example describes a high-pressure heater of feed water heated by steam withdrawn as side stream from a high-pressure turbine. With this arrangement, only feed water flowrate is usually measured. One further measures the withdrawn steam (STEAM) pressure (which approximates the pressure in the steam space of the heater) and the feed water temperatures before (FW-IN) and after (FW-OUT) the heater. Further known is also the wetness of the steam withdrawn.

This model generates 4 balance equations, but simultaneously we here have 4 unknowns (flowrates of steam, condensate and outlet feed water, and the heat flow. The degree of redundancy is 0 and no data reconciliation takes place. At this measurement constellation, the model is only able to compute all the unmeasured variables.

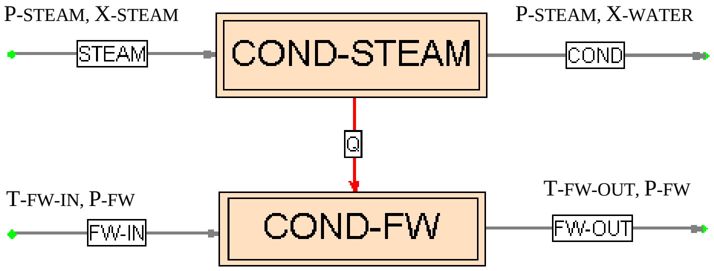


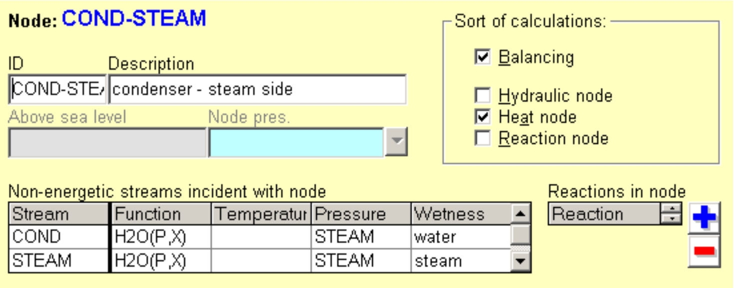
Fig. 5.5-1: Balance scheme (demo Example E-5)

INPUT DATA

```
NAME         TYPE            VALUE        MAX.ERROR

M A T E R I A L   S T R E A M S    [T/H]
 COND         N            60.0000
 FW-IN        M          1320.0000      2.0000 %
 FW-OUT       N          1300.0000
 STEAM        N            60.0000
 E N E R G Y   F L O W S    [GJ/H]
 Q            N            60.0000
 T E M P E R A T U R E S    [C]

 FW-IN        M           191.0000      1.0000
 FW-OUT       M           223.0000      1.0000
```

```
P R E S S U R E S     [MPAG]

FW          M            6.5000      0.1000
STEAM       M            2.8400    2.000E-2

W E T N E S S E S     [%]

steam       F            4.6000
water       F          100.0000
```

PANEL OF MODEL PARAMETERS DEFINITION



Node: COND-STEAM

ID	Description
COND-STE/	condenser - steam side

Above sea level
Node pres.

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

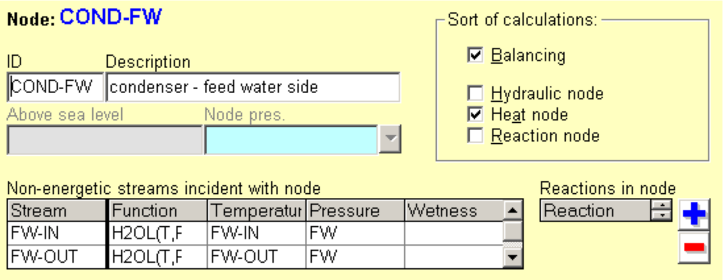
Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
COND	H2O(P,X)		STEAM	water
STEAM	H2O(P,X)		STEAM	steam

Reactions in node

Reaction

Fig. 5.5-2: Steam side



Node: COND-FW

ID	Description
COND-FW	condenser - feed water side

Above sea level
Node pres.

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
FW-IN	H2OL(T,F	FW-IN	FW	
FW-OUT	H2OL(T,F	FW-OUT	FW	

Reactions in node

Reaction

Fig. 5.5-3: Feed water side

RESULTS

```
G L O B A L   D A T A

  Degree of redundancy                                 0
  Number of equations                                  4
  Qmin                                         0.000E+00
  Qcrit                                        0.000E+00

V A R I A B L E S

  Name        Type        Inp.value      Rec.value      Max.error

  S T R E A M S     [T/H]
  COND        NO           60.000         110.800          5.383
  FW-IN       MN         1320.000        1320.000         26.400
  FW-OUT      NO         1300.000        1320.000         26.400
  STEAM       NO           60.000         110.800          5.383

  F L O W S   O F   E N E R G Y     [GJ/H]

  Q           NO           60.000         190.266          9.243

  T E M P E R A T U R E S     [C]

  FW-IN       MN          191.000         191.000          1.000
  FW-OUT      MN          223.000         223.000          1.000

  P R E S S U R E S     [MPAG]

  FW          MN            6.500           6.500          0.100
```

```
STEAM      MN           2.840          2.840          0.020

W E T N E S S E S    [%]

steam      F            4.600          4.600
water      F          100.000        100.000
```

In this case, one has not dealt with data reconciliation, but only with direct computation (the degree of redundancy was 0). It is obvious that the values of all measured variables before and after the procedure must remain the same. However, this does not hold for the unmeasured ones. Quite often, at the task configuration the values of unmeasured variables are not known even approximately. There then arises the question, what the software will do with bad initial guesses of the unmeasured variables.

Special attention is required in cases where the enthalpy function does not uniquely determine the temperature or pressure (the enthalpy of steam as dependent on temperature or pressure passes through the maximum and two values of temperature or pressure can correspond to one enthalpy value).

5.6 Expander

Expanders serve for reducing the pressure of hot water to a lower value (frequently as part of a cascade of condensate from the steam system). Some part of the heat energy then gives rise to steam phase by evaporation. Then from one liquid stream, two streams are formed – water and steam. We here assume that the two streams are in the state of thermodynamic equilibrium. In addition the situation is complicated by the fact that the steam phase can contain some portion of liquid as a consequence of imperfect water droplet separation (this depends on the construction of the expander).

The following example will be simple – condensate on the saturation line expands from higher to lower pressure. The condensate is defined by the temperature, in the expander proper is maintained constant pressure. The arising steam contains 0.2 % liquid phase. From the flowrates, only inlet into the expander is measured.

The model generates two balance equations and we here have two unmeasured outlet flowrates. The degree of redundancy is thus 0. The model only serves for computing the phase distribution in the expander.

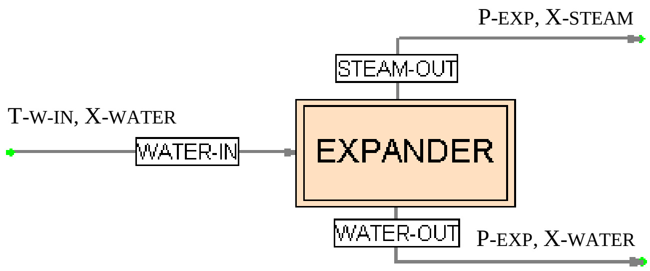
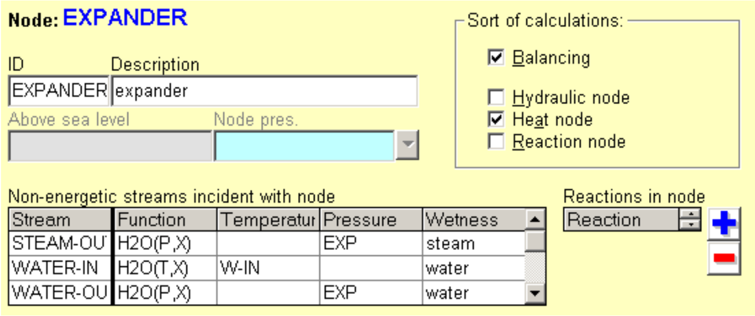


Fig. 5.6-1: Balance scheme (demo Example E-6)

INPUT DATA

```
NAME          TYPE            VALUE         MAX.ERROR

 M A T E R I A L   S T R E A M S    [T/H]

 STEAM-OUT    N              2.0000
 WATER-IN     M             26.0000        5.0000 %
 WATER-OUT    N             20.0000

 T E M P E R A T U R E S     [C]

 W-IN         M            258.0000        1.0000

 P R E S S U R E S     [MPAG]

 EXP          M              0.6600      5.000E-3

 W E T N E S S E S     [%]

 steam        F            0.200E+0
 water        F            100.0000
```



Node: EXPANDER

ID	Description
EXPANDER	expander

Above sea level

Node pres.

Sort of calculations:

☑ Balancing

☐ Hydraulic node

☑ Heat node

☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
STEAM-OU	H2O(P,X)		EXP	steam
WATER-IN	H2O(T,X)	W-IN		water
WATER-OU	H2O(P,X)		EXP	water

Reactions in node

Reaction

Fig. 5.6-2: Panel of the model parameters definition

RESULTS

```
G L O B A L   D A T A
  Degree of redundancy                             0
  Number of equations                              2
  Qmin                                     0.000E+00
  Qcrit                                    0.000E+00

V A R I A B L E S

  Name       Type         Measured    Reconciled    Max.error of reconciled val.

  S T R E A M S    [T/H]

  STEAM-OUT  NO             2.000          5.236          0.269
  WATER-IN   MN            26.000         26.000          1.300
  WATER-OUT  NO            20.000         20.764          1.041

  T E M P E R A T U R E S    [C]

  W-IN       MN           258.000        258.000          1.000

  P R E S S U R E S    [MPAG]

  EXP        MN             0.660          0.660        5.00E-3

  W E T N E S S E S    [%]

  steam      F            0.00E+0        0.20E+0
  water      F            100.000        100.000
```

5.7 *Throttling of steam*

Throttling of steam is an adiabatic process, where the steam pressure is reduced by an obstacle in the flow. The throttling organ can have a fixed cross section area (e.g. an orifice), or a variable one (control valve). If heat loss into the environment is neglected, one can model in this way also pressure drop in flow of fluids in a pipeline.

The model generates 2 balance equations (mass and energy balances). In the following example, we'll have 2 unknown variables – flowrate and wetness of the steam at the throttling organ outlet. One will thus again deal with mere solution of the model equations without data reconciliation.

Concerning the stream energies, also their kinetic components may play a role (due to the pressure drop, also the stream velocity is changed). In case of wet steam, also wetness is changed. Although the operation is simple, the results of computation need not be trivial as the following examples will show.

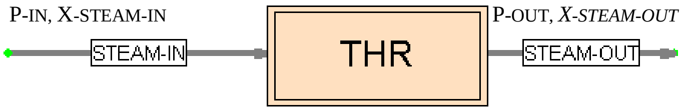
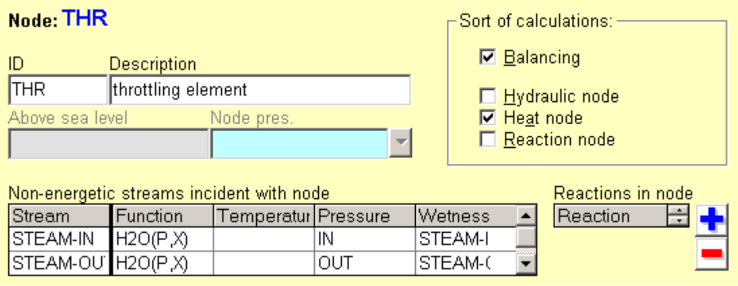


Fig. 5.7-1: Balance scheme (demo Example E-7)

INPUT DATA

```
NAME          TYPE            VALUE       MAX.ERROR
 M A T E R I A L   S T R E A M S    [T/H]

 STEAM-IN      M           440.0000      4.0000 %
 STEAM-OUT     N           400.0000

 P R E S S U R E S     [MPAG]

 IN            M             2.6500    5.000E-2
 OUT           M             2.3500    5.000E-2

 W E T N E S S E S      [%]

 STEAM-IN      F             0.2500
 STEAM-OUT     N             0.2500
```



Node: THR

ID	Description
THR	throttling element

Above sea level
Node pres.

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
STEAM-IN	H2O(P,X)		IN	STEAM-I
STEAM-OU	H2O(P,X)		OUT	STEAM-(

Reactions in node

Reaction

Fig. 5.7-2: Panel of model parameters definition

RESULTS

```
G L O B A L   D A T A
```

```
  Degree of redundancy                          0
  Number of equations                           2
  Qmin                                  0.000E+00
  Qcrit                                 0.000E+00

V A R I A B L E S

  Name      Type       Inp.value      Rec.value      Max.error
  ____________________________________________________________

  S T R E A M S    [T/H]

  STEAM-IN   MN         440.000        440.000         17.600
  STEAM-OUT  NO         400.000        440.000         17.600

  P R E S S U R E S    [MPAG]

  IN         MN           2.650          2.650          0.050
  OUT        MN           2.350          2.350          0.050

  W E T N E S S E S    [%]

  STEAM-IN   F            0.250          0.250
  STEAM-OUT  NO           0.250          0.187          0.016
```

One can see that due to throttling, the steam wetness has been lowered.

We have done still one computation with higher pressures of the steam; the values of other variables have remained the same.

```
P R E S S U R E S    [MPAG]
 IN         M            4.6500    5.000E-2
 OUT        M            4.3500    5.000E-2
```

The resulting wetnesses now are

```
W E T N E S S E S    [%]
  STEAM-IN   F            0.250          0.250
  STEAM-OUT  NO           0.250          0.373          0.029
```

In this case, the wetness of the outlet steam has increased from the value 0.187 % obtained in the preceding example, to the value 0.373 %. The, as it seems to be contradiction of the two results follows from the saturated steam enthalpy dependency on pressure. While in the first case enthalpy increased with pressure, with higher pressures in the second example we have already got into the region where with increasing pressure, saturated steam enthalpy decreases (see the *p-i* diagram for water vapor). The dividing point is ca. 235 deg C, resp. 3.06 MPa. In the neighborhood of this point (of the respective values on the saturation line), the temperature resp. pressure dependency of the saturated steam enthalpy is very flat and passes through the maximum. This fact is quite relevant for the precision of balancing calculations and will be documented with more details in one of the case studies.

5.8 Wetness separator

The separator of wetness (small water droplets) serves for separating the liquid phase from the wet steam. Since the steam wetness is difficult to measure, one usually starts from the assumptions of given (fixed) inlet wetness and separation efficiency expressed e.g. by the steam wetness at the outlet from the separator. The model generates 2 equations. Input variables can then be for example inlet steam flowrate and steam wetnesses at the inlet and outlet. It is then possible to compute for example the flowrate of the liquid phase separated and that of steam at the outlet from the separator. In the following example, we'll assume that the whole separator works under one pressure.

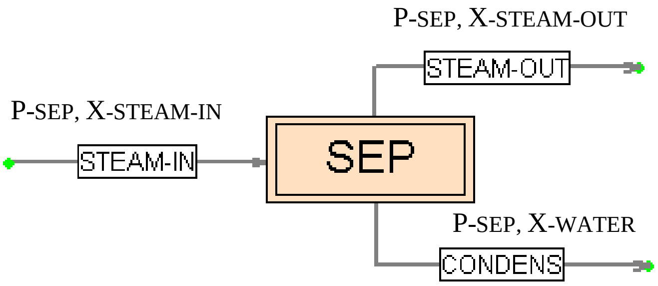
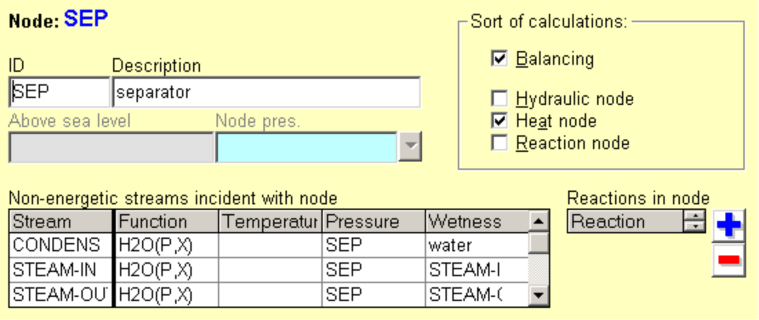


Fig. 5.8-1: Balance scheme (demo Example E-8)

INPUT DATA

```
NAME          TYPE              VALUE         MAX.ERROR

 M A T E R I A L    S T R E A M S    [T/H]

 CONDENS        N             10.0000
 STEAM-IN       M             64.2000       4.0000 %
 STEAM-OUT      N             40.0000

 P R E S S U R E S    [KPAG]

 SEP            M              0.6600     5.000E-3

 W E T N E S S E S    [%]

 STEAM-IN       F              6.2000
 STEAM-OUT      F              0.3000
 water          F            100.0000
```



Node: SEP

ID: SEP
Description: separator
Above sea level:
Node pres.:

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
CONDENS	H2O(P,X)		SEP	water
STEAM-IN	H2O(P,X)		SEP	STEAM-I
STEAM-OU	H2O(P,X)		SEP	STEAM-(

Reactions in node
Reaction

Fig. 5.8-2: Panel of the model parameters definition

RESULTS

```
G L O B A l   D A T A

  Degree of redundancy                          0
```

```
  Number of equations                              2
  Qmin                                     0.000E+00
  Qcrit                                    0.000E+00

V A R I A B L E S

  Name      Type      Inp.values     Rec.values      Max.error

  S T R E A M S    [T/H]

  CONDENS    NO           10.000          3.799          0.152
  STEAM-IN   MN           64.200         64.200          2.568
  STEAM-OUT  NO           40.000         60.401          2.416

  P R E S S U R E S    [KPAG]

  SEP        MN            0.660          0.660        5.00E-3

  W E T N E S S E S    [%]

  STEAM-IN   F             6.200          6.200
  STEAM-OUT  F             0.300          0.300
  water      F           100.000        100.000
```

5.9 *Input / output of energy (pump)*

One frequently meets with the need to supply / withdraw energy into / from the system. An example can be e.g. withdrawing heat into the environment or work performed on the shaft of a turbine. Such kind of problems will be illustrated by the energy balance of a pump.

The pump serves for enhancing the pressure of the fluid stream. The necessary energy is usually supplied by an electrical motor. The whole input power is transferred to the pump with certain efficiency (e.g. 95 %). The remaining part of electric energy is transformed to heat withdrawn into the environment by the cooling of the motor. The part that enters the pump energy balance is only energy transferred by the shaft connecting the motor and the pump.

Mechanic energy is transformed in the pump proper to enthalpy thus pressure and heat energies (heating of the fluid). The ratio of the two energies depends on the construction of the pump, its mechanical state and the working régime.

We'll further describe the energy balance of the pump proper. The input mechanic energy (power) is measured by the electric energy input multiplied by its efficiency.

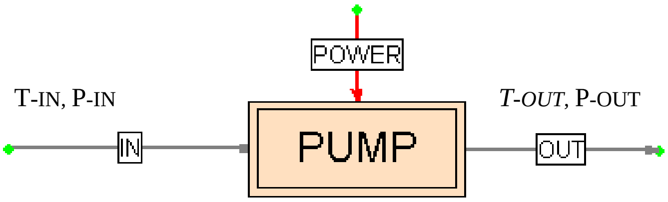
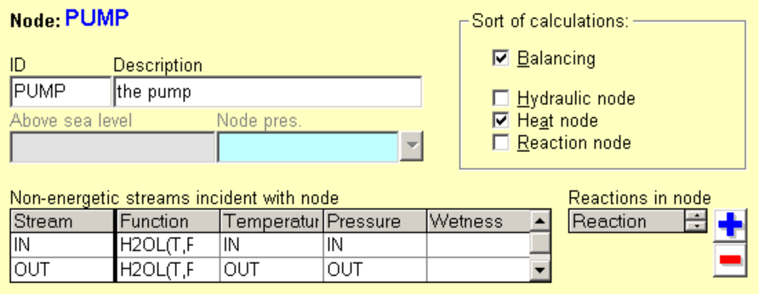


Fig. 5.9-1: Balance scheme (demo Example E-9)

INPUT DATA

```
NAME       TYPE           VALUE      MAX.ERROR

 M A T E R I A L   S T R E A M S    [T/H]

 IN          M           836.0000      3.0000 %
 OUT         N           800.0000

 F L O W S   O F   E N E R G Y    [MWH/H]

 POWER       M             0.5500     10.0000 %

 T E M P E R A T U R E S    [C]

 IN          M            38.8000      1.0000
 OUT         N            38.0000

 P R E S S U R E S    [MPAG]

 IN          M             1.0800    1.000E-2
 OUT         M             1.9800    1.000E-2
```



Node: PUMP

ID: PUMP
Description: the pump
Above sea level:
Node pres.:

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☑ Heat node
☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperatur	Pressure	Wetness
IN	H2OL(T,F	IN	IN	
OUT	H2OL(T,F	OUT	OUT	

Reactions in node

Reaction

Fig. 5.9-2: Panel of the model parameters definition

RESULTS

```
G L O B A L   D A T A

  Degree of redundancy                                  0
  Number of equations                                   2
  Qmin                                          0.000E+00
  Qcrit                                         0.000E+00

V A R I A B L E S

  Name       Type          Inp.value     Rec.value    Max.error

  S T R E A M S     [T/H]

  IN          MN         836.000       836.000         25.080
  OUT         NO         800.000       836.000         25.080

  F L O W S   O F   E N E R G Y     [MWH/H]

  POWER       MN           0.550         0.550          0.055

  T E M P E R A T U R E S     [C]

  IN          MN          38.800        38.800          1.000
  OUT         NO          38.000        39.176          1.002

  P R E S S U R E S     [MPAG]

  IN          MN           1.080         1.080          0.010
  OUT         MN           1.980         1.980          0.010
```

This simple example has shown a simple interconnection of the energy system with the 'ambient world'. At the mechanic energy, one dealt only with a rough estimate (the 10 % uncertainty can even be too optimistic). On the other hand we have obtained the temperature increase after the pump by less than 0.4 deg C, which is certainly inside the limits of uncertainty at temperature measurement. Fortunately, the heat equivalent of mechanic work is small.

5.10 Turbine segment

For the needs of balancing, the turbine segment (TS) is defined as a part of the turbine, endowed with just one side steam extraction. The thus defined TS can comprise one or several circulating wheels, which is however irrelevant for the balancing. The main goal of the TS balance is to find the work (power) exerted on the turbine shaft, which is directly unmeasurable variable.

Let us further suppose that we know the pressure and temperature of steam at the inlet to TS. In the TS, steam exerts work and gets on into the following segment (or out of the turbine), while some part of it is withdrawn as a side stream (extracted). For the outlet streams, we also suppose the knowledge of pressure and temperature. If some of these variables were not known, observability problems could arise with the unmeasured variables. Because the turbine is part of a larger system, the observability can be improved by the integration of the TS model into the whole model.

In the following example, we put together the models of TS and the model of the feed water preheating. The steam extracted from the turbine condenses in the exchanger and preheats thereby the feed water. From this preheating, the balance enables us to compute the unmeasured amount of extracted steam.

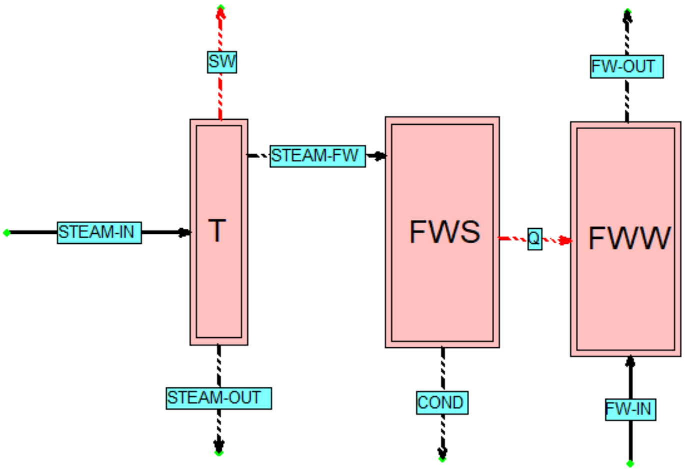


Fig 5.10-1: Balance scheme (demo Example E-10)

The following symbols are to be interpreted:

T	turbine segment
FWS	feed water preheating – steam side of exchanger
FWW	feed water preheating – water side of exchanger
STEAM-IN	saturated steam going into TS, defined by temperature (X = 0).
STEAM-OUT	steam leaving TS and going into further TS, with wetness 3.6 %
STEAM-FW	extracted steam heating the feed water heater. Its state is the same as in stream STEAM-OUT

SW	work (power) on the turbine shaft (Shaft Work)
COND	condensate from STEAM-FW
Q	heat transferred in feed water heater
FW-IN	inlet feed water
FW-OUT	outlet feed water

INPUT DATA

MATERIAL STREAMS

ID	Type	Value	Max.error	
COND	N	100.0000		T/H
FW-IN	M	1350.0000	2.0000%	T/H
FW-OUT	N	1300.0000		T/H
STEAM-FW	N	100.0000		T/H
STEAM-IN	M	1320.0000	3.0000%	T/H
STEAM-OUT	N	1250.0000		T/H

ENERGY STREAMS [MW]

ID	Type	Value	Max.error
Q	N	50.0000	
SW	N	30.0000	

TEMPERATURES [C]

ID	Type	Value	Max.error
FW-IN	M	191.0000	1.0000
FW-OUT	M	223.0000	1.0000
STEAM-IN	M	233.0000	1.0000
STEAM-OUT	M	148.0000	1.0000

PRESSURES [MPAG]

ID	Type	Value	Max.error
FW	M	6.6000	5.000E-2
STEAM-IN	M	0.4260	5.000E-3
STEAM-OUT	M	0.1230	5.000E-3

AUXILIARIES

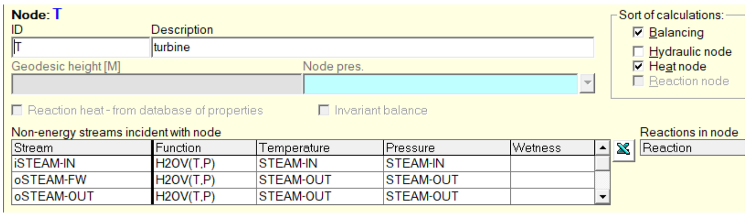
ID	Type	Value	Max.error	
IEE	N	80.0000		1

USER EQUATIONS

```
IEE          Turbine T: Isentropic efficiecy                              Model
               [V<IEE>]-[IEE([F<H2OV:STEAM-IN:STEAM-IN:>];[F<H2OV:STEAM
               -OUT:STEAM-OUT:>])]
```

There is one Auxiliary variable – the isentropic turbine efficiency.

PANELS OF MODEL PARAMETERS DEFINITION



Node: T

ID: T

Description: turbine

Geodesic height [M]

Node pres.

Sort of calculations:

☑ Balancing

☐ Hydraulic node

☑ Heat node

☐ Reaction node

☐ Reaction heat - from database of properties

☐ Invariant balance

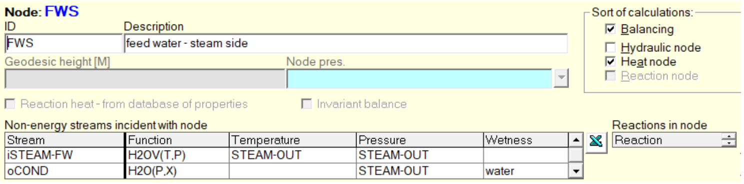
Non-energy streams incident with node

Stream	Function	Temperature	Pressure	Wetness
iSTEAM-IN	H2OV(T,P)	STEAM-IN	STEAM-IN	
oSTEAM-FW	H2OV(T,P)	STEAM-OUT	STEAM-OUT	
oSTEAM-OUT	H2OV(T,P)	STEAM-OUT	STEAM-OUT	

Reactions in node

Reaction

Fig. 5.10-2: Turbine segment



Node: FWS

ID: FWS

Description: feed water - steam side

Geodesic height [M]

Node pres.

Sort of calculations:
- ☑ Balancing
- ☐ Hydraulic node
- ☑ Heat node
- ☐ Reaction node

☐ Reaction heat - from database of properties

☐ Invariant balance

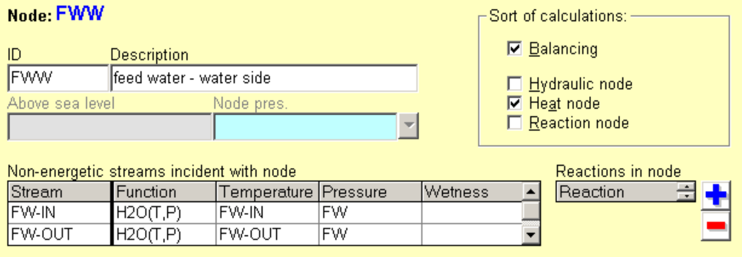
Non-energy streams incident with node

Stream	Function	Temperature	Pressure	Wetness
iSTEAM-FW	H2OV(T,P)	STEAM-OUT	STEAM-OUT	
oCOND	H2O(P,X)		STEAM-OUT	water

Reactions in node

Reaction

Fig. 5.10-3: Preheater – steam side



Node: FWW

ID: FWW

Description: feed water - water side

Above sea level

Node pres.

Sort of calculations:
- ☑ Balancing
- ☐ Hydraulic node
- ☑ Heat node
- ☐ Reaction node

Non-energetic streams incident with node

Stream	Function	Temperature	Pressure	Wetness
FW-IN	H2O(T,P)	FW-IN	FW	
FW-OUT	H2O(T,P)	FW-OUT	FW	

Reactions in node

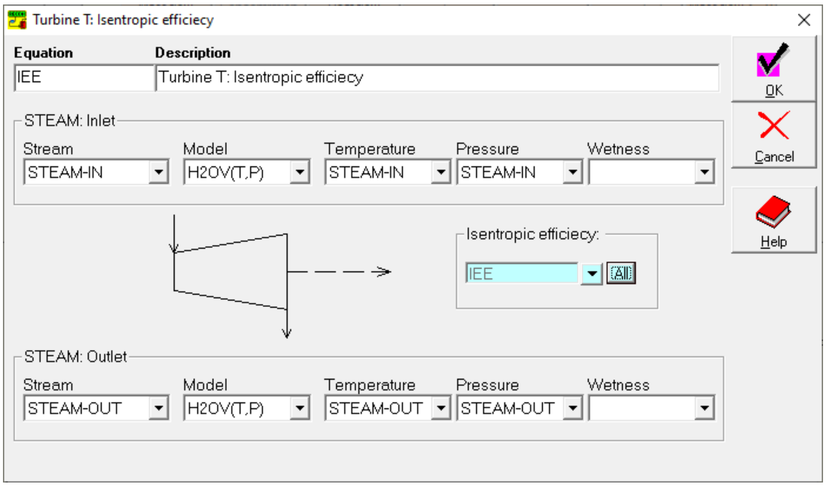
Reaction

Fig. 5.10-4: Preheater – water side

RESULTS

```
G L O B A L   D A T A

 Degree of redundancy                                   0

 M A S S   F L O W R A T E S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 COND             NO          100.000         86.753          4.217  T/H  condensate
 FW-IN            MN         1350.000       1350.000         27.000  T/H  feed water IN
 FW-OUT           NO         1300.000       1350.000         27.000  T/H  feed water OUT
 STEAM-FW         NO          100.000         86.753          4.217  T/H  staem to FW preheat
 STEAM-IN         MN         1320.000       1320.000         39.600  T/H  staem IN
 STEAM-OUT        NO         1250.000       1233.247         39.824  T/H  steam OUT

E N E R G Y   S T R E A M S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 Q                NO           50.000         54.046          2.625  MW  heat to FW
 SW               NO           30.000         59.252          2.090  MW  shaft work

T E M P E R A T U R E S

 Name               Type      Inp.value      Rec.value      Abs.error
 --------------------------------------------------------------------
 FW-IN              MN          191.000        191.000          1.000  C  feed water IN
 FW-OUT             MN          223.000        223.000          1.000  C  feed water OUT
 STEAM-IN           MN          233.000        233.000          1.000  C  steam to turbine
 STEAM-OUT          MN          148.000        148.000          1.000  C  steam out of turbine


 P R E S S U R E S

 Name               Type      Inp.value      Rec.value      Abs.error
 --------------------------------------------------------------------
 FW                 MN            6.600          6.600          0.050  MPAG  feed water
 STEAM-IN           MN            0.426          0.426      5.0000E-3  MPAG  steam IN
 STEAM-OUT          MN            0.123          0.123      5.0000E-3  MPAG  steam OUT

 A U X I L I A R I E S

 Name               Type      Inp.value      Rec.value      Abs.error
 --------------------------------------------------------------------
 IEE                NO           80.000         91.272          3.003  isentropic efficiency
```

Let’s look at the panel for configuration of the isentropic turbine efficiency:



Turbine T: Isentropic efficiecy

Equation	**Description**
IEE	Turbine T: Isentropic efficiecy

STEAM: Inlet

Stream	Model	Temperature	Pressure	Wetness
STEAM-IN	H2OV(T,P)	STEAM-IN	STEAM-IN	

Isentropic efficiecy: IEE

STEAM: Outlet

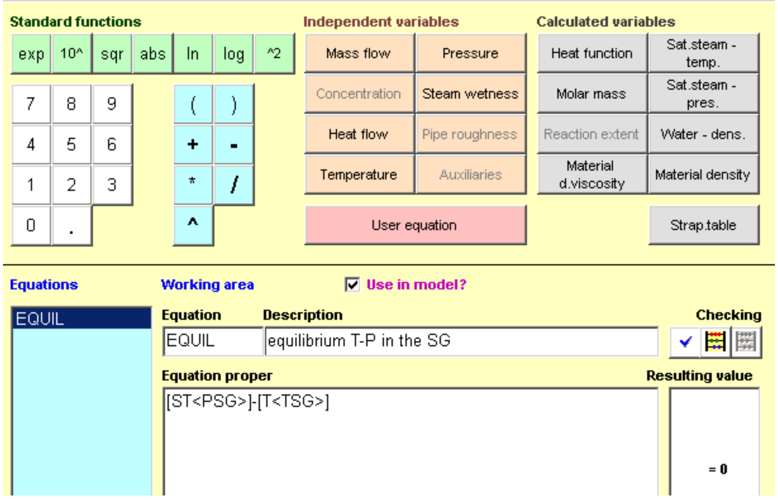
Stream	Model	Temperature	Pressure	Wetness
STEAM-OUT	H2OV(T,P)	STEAM-OUT	STEAM-OUT	

5.11 Phase equilibrium water – water vapor

Data reconciliation with the aid of phase equilibrium will be illustrated by the model of a steam generator (SG), which has been already given with details in Section 5.4. The model created in the graphical editor remains unchanged and the reader is referred to the section mentioned above. Further described will be the enlarging of the model by the phase equilibrium equation.

Let us now suppose that besides the temperature, also pressure has been measured in the SG. The relation between temperature and pressure is not given in the graphical editor, but in the editor of user defined equations. There are now two possibilities – either express temperature as function of pressure, or pressure as function of temperature. The result should, however, be practically independent of this choice.

In the original model, altogether 4 balance equations are generated, the phase equilibrium assumption generates the fifth. There are two unmeasured variables in the task, so three degrees of redundancy are at hand for data reconciliation and validation.



☑ Use in model?

Equations: EQUIL

Equation: EQUIL

Description: equilibrium T-P in the SG

Equation proper: [ST<PSG>]-[T<TSG>]

Resulting value: = 0

Fig. 5.11-1: Editor of user defined equations (demo Example E-11)

Equation EQUIL represents here the relation between measured temperature *T* and equilibrium temperature *T**, which is function of pressure.

$$T^* = \mathrm{T}(P) \qquad (5.11\text{-}1)$$

In the editor, the equation is of the form

[ST<PSG>-[T<TSG>] , (5.11-2)

which is Eq. (5.11-1) rewritten with zero right-hand side. Function ST (Saturated Temperature) called by button „Saturated steam – temp.“ has the argument of measured pressure PSG. The second term in the equation is measured temperature TSG.

INPUT DATA

In addition to the flowrates of streams, we here have 4 temperatures (those of hot water HWIN and HWOUT, the temperature in steam generator TSG valid for outlet steam and blowdown, and temperature of feed water FW). Further, we here have three pressures (pressure in steam generator PSG, for feed water FW and for hot water HW). New are two wetnesses for liquid water (WATER) and steam (STEAM).

```
NAME         TYPE           VALUE      MAX.ERROR

 M A T E R I A L    S T R E A M S    [KG/S]

 BLOWDOWN    M            6.1200      5.0000 %
 FW          M          444.5000      2.0000 %
 HWIN        M         5650.0000      5.0000 %
 HWOUT       N         5000.0000
 STEAM       M          445.0000      2.0000 %

 F L O W S  O F   E N E R G Y    [KJ/S]

 QSG         N       800000.0000

 T E M P E R A T U R E S    [C]

 HWIN        M          295.2000      1.0000
 HWOUT       M          265.8000      1.0000
 SG          M          257.6000      1.0000
 FW          M          221.6000      1.0000

 P R E S S U R E S    [KPA]

 FW          M           10.0000      0.5000 %
 HW          M           10.0000      0.5000 %
 PSG         M            4.5400      1.0000 %

 W E T N E S S E S    [%]

 STEAM       F            0.2500
 WATER       F          100.0000
```

PANELS OF MODEL PARAMETERS DEFINITION

Both panels are the same as in Section 5.4.

RESULTS

```
G L O B A L   D A T A
  Degree of redundancy                            3
  Number of equations                             5
  Number of user defined equations                1
  Qmin                                    4.409E+00
  Qcrit                                   7.842E+00


V A R I A B L E S

  Name       Type          Inp.values      Rec.values   Max.error

  S T R E A M S    [KG/S]

  BLOWDOWN   MC           6.120           6.115           0.306
  FW         MC         444.500         448.864           6.172
  HWIN       MC        5650.000        5471.657         200.269
  HWOUT      NO        5000.000        5471.657         200.269
  STEAM      MC         445.000         442.749           6.172

  F L O W S  O F  E N E R G Y    [KJ/S]

  QSG        NO       800000.000      815954.273       11528.935

  T E M P E R A T U R E S    [C]

  FW         MC         221.600         221.570           0.999
```

```
HWIN        MC          295.200         294.744            0.863
HWOUT       MC          265.800         266.162            0.890
TSG         MC          257.600         257.876            0.522

P R E S S U R E S    [MPA]

FW          MC           10.000          10.000            0.050
HW          MC           10.000          10.000            0.050
PSG         MC            4.540           4.532            0.039

W E T N E S S E S    [%]

STEAM       F             0.250           0.250
WATER       F           100.000         100.000
```

Note: If we created a user defined equation for phase equilibrium and temperature or pressure were unmeasured, this would only serve for computing the unmeasured variable without changing the degree of redundancy. In this case, RECON would only serve as a calculator for equilibrium temperature or pressure. Let us note in addition that in the panel „Node balance“, the unmeasured temperatures resp. pressures under phase equilibrium conditions are available for the user automatically, even without defining any user defined equation. ♦

5.12 Steam cooling

There are two notions connected with steam cooling – *desuperheating* and *attemperature*. While these terms are often used interchangeably, there is a small difference: desuperheating means bringing the superheated steam to its saturation temperature, attemperature is more general and means simply lowering its temperature closer to the saturation temperature. The most frequent way how to do it is the injection of water. In this example we will deal with cooling the superheated steam in a boiler by injection of the feed water to limit its temperature to a desired level.

Let us further consider a stream cooler with two inlet and one outlet streams.

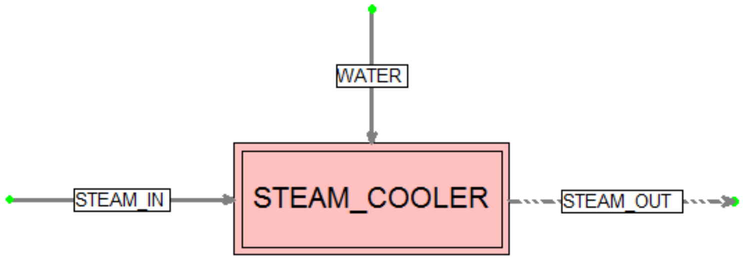


Fig. 5.12-1: Steam cooler (Demo example E-12)

For this node, we can write the mass balance equation

$$m_{steam\_in} + m_{water} = m_{steam\_out} \qquad (5.12\text{-}1)$$

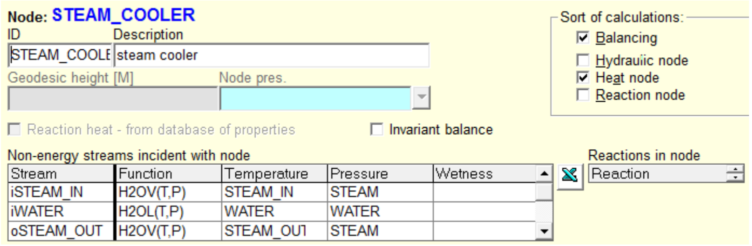
where the m_i are flowrates,

further the energy balance

$$m_{steam\_in}\, h_{steam\_in} + m_{water}\, h_{water} = m_{steam\_out}\, hsteam\_out \qquad (5.12\text{-}2)$$

where the h_i are specific enthalpies of the streams.

Let's suppose that flows of both input streams are measures as well as all temperatures and pressures. The configuration of the mode STEAM_COOLER is shown on the next Fig.



Node: STEAM_COOLER

ID: STEAM_COOLE

Description: steam cooler

Geodesic height [M]

Node pres.

☐ Reaction heat - from database of properties

☐ Invariant balance

Sort of calculations:

☑ Balancing

☐ Hydrauiic node

☑ Heat node

☐ Reaction node

Non-energy streams incident with node

Stream	Function	Temperature	Pressure	Wetness
iSTEAM_IN	H2OV(T,P)	STEAM_IN	STEAM	
iWATER	H2OL(T,P)	WATER	WATER	
oSTEAM_OUT	H2OV(T,P)	STEAM_OUT	STEAM	

Reactions in node

Reaction

It is supposed that both steam streams are superheated and the water is the subcooled liquid. There are 2 equations and one unknown (the flowrate of the outlet steam), the degree of redundancy is 1.

Results of data reconciliation are shown in the next table:

```
Task: E-14 (Steam cooler)

 G L O B A L   D A T A

 Number of measured variables                               7
 Number of non-measured variables                           1
 Number of equations                                        2
 Degree of redundancy                                       1

 Mean residue of equations                         2,6453E-04
 Qmin                                              1,6416E+00
 Qcrit                                             3,8400E+00
 Status (Qmin/Qcrit)                                 0,427509

 S T R E A M S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 STEAM_IN         MC          100,000        100,327          1,939  KG/S
 STEAM_OUT        NO          100,000        110,491          1,962  KG/S
 WATER            MC           10,200         10,165          0,198  KG/S

 T E M P E R A T U R E S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 STEAM_IN         MC          408,000        409,117          2,541  C
 STEAM_OUT        MC          349,000        347,562          1,917  C
 WATER            MC          218,000        218,078          1,997  C

 P R E S S U R E S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 STEAM            MC            9,400          9,401          0,050  MPA
 WATER            MC           10,200         10,200          0,050  MPA

 End of results
```

5.13 Preheat of a crude oil

Crude oil distillation consumes a lot of energy and systems for energy regeneration used in practice are very elaborated. The system described in this example is not very complex, its task is only to show typical techniques used in setting up the mass and heat balance of such system (a real industrial system is presented in one of case studies). The flowsheet is shown in the next figure.

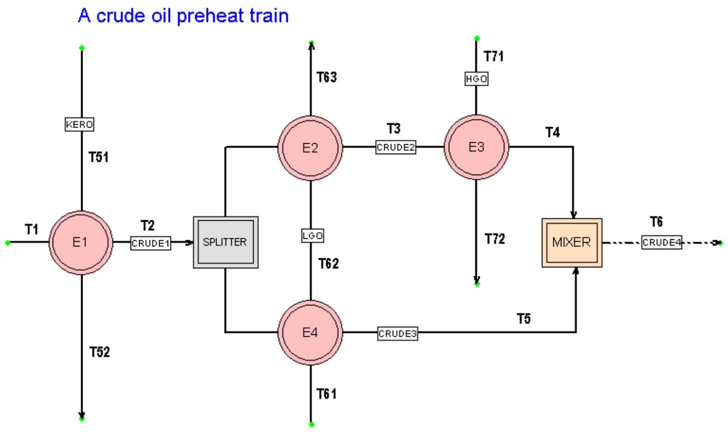


Fig. 5.13-1: Pre-heating crude oil (demo Example E-13)

Crude oil is preheated by contact with several hot product streams. In the first exchanger E1 (stream CRUDE1) it meets with kerosene (stream KERO). After that the crude stream splits in two streams (CRUDE2 and CRUDE3). Stream CRUDE2 is heated by contact with light gas oil (stream LGO) and heavy gas oil (HGO). Stream CRUDE3 meets only with LGO. After that both streams of crude are mixed to form stream CRUDE4. It is worth noting that the heat balance is not set up around the SPLITTER node (see the previous Section). All flows are measured, except of stream CRUDE4.

The input data are as follows:

INPUT DATA

MATERIAL STREAMS [KG/S]

ID	TYPE	VALUE	MAX.ERROR
CRUDE1	M	99.0000	1.0000 %
CRUDE2	M	60.0000	5.0000 %
CRUDE3	M	40.0000	5.0000 %
CRUDE4	N	100.0000	
HGO	M	5.0000	2.0000 %
KERO	M	15.0000	2.0000 %
LGO	M	20.0000	2.0000 %

HEAT FUNCTIONS [kJ, kg, C]

ID	TYPE	A	B	C	Plus H
FnCRUDE	2	0.8600	11.9500	0.000E+0	0.000E+0
FnKERO	2	0.8100	11.7000	0.000E+0	0.000E+0
FnLGO	2	0.8600	11.7700	0.000E+0	0.000E+0
FnHGO	2	0.8900	11.8300	0.000E+0	0.000E+0

```
T E M P E R A T U R E S    [C]

ID        TYPE        VALUE   MAX.ERROR

 T1          M          25.0000      1.0000
 T2          M          45.0000      1.0000
 T3          M          70.0000      1.0000
 T4          M          90.0000      1.0000
 T5          M         110.0000      1.0000
 T51         M         200.0000      2.0000 %
 T52         M         100.0000      2.0000 %
 T6          M         100.0000      2.0000 %
 T61         N         280.0000
 T62         M         180.0000      2.0000 %
 T63         M         110.0000      2.0000 %
 T71         M         335.0000      2.0000 %
 T72         M         150.0000      2.0000 %
```

```
 E X C H A N G E R S

ID       Stream    End     Function   TemperaturePressure   Wetness      Area

 E1         KERO      Inlet    FnKERO     T51                              200
                      Outlet   FnKERO     T52
            CRUDE1    Inlet    FnCRUDE    T1
                      Outlet   FnCRUDE    T2
 E2         LGO       Inlet    FnLGO      T62                              100
                      Outlet   FnLGO      T63
            CRUDE2    Inlet    FnCRUDE    T2
                      Outlet   FnCRUDE    T3
 E3         HGO       Inlet    FnHGO      T71                              100
                      Outlet   FnHGO      T72
            CRUDE2    Inlet    FnCRUDE    T3
                      Outlet   FnCRUDE    T4
 E4         LGO       Inlet    FnLGO      T61                               50
                      Outlet   FnLGO      T62
            CRUDE3    Inlet    FnCRUDE    T2
                      Outlet   FnCRUDE    T5
```

For modeling of enthalpies of crude oil and its fractions we have used Type 2 enthalpy function – so called Berghoff's correlation

Berghoff's correlation is convenient for hydrocarbon mixtures (crude oil fractions). In the SI system of units it reads

$$Cp = 4.1868\ (0.403 + 0.00045*t)*(0.054*KW + 0.35)/d\hat{}(1/2)$$

where

Cp specific heat capacity in kJ/(kg.C)

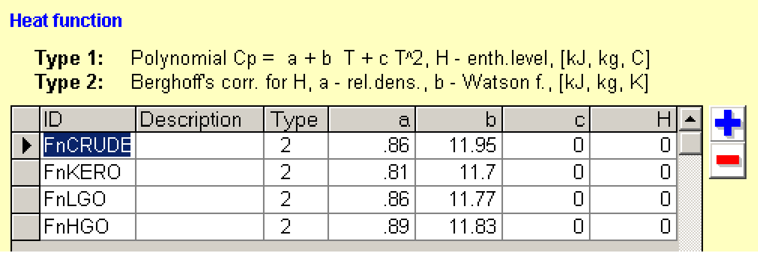
t temperature in centigrade

d relative density at 15.6 C (related to the density of the water at the same temperature)

KW "Watson's characteristic factor" defined by KW = ((1.8*Tb)^(1/3))/d, where Tb is the mean boiling point of the mixture in the absolute scale (Kelvin)

Here, the constant a stands for d in the Berghoff's correlation and the constant b stands for KW.

Parameters of Berghoff’s correlation are entered in a special RECON panel (menu *Accessories – Functions)*.



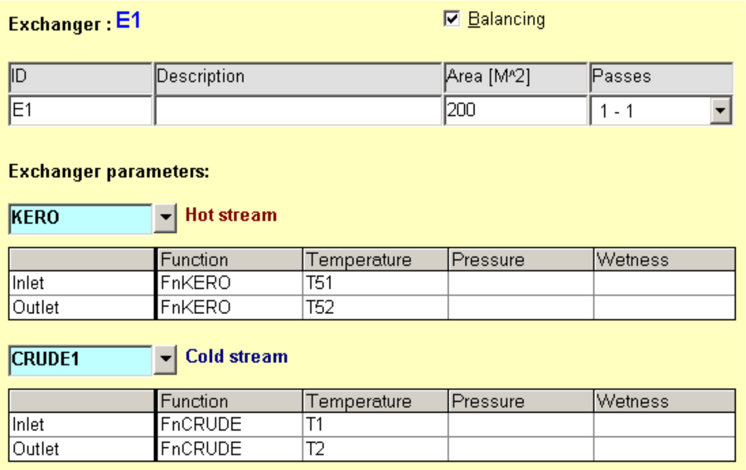
Heat function

Type 1: Polynomial Cp = a + b T + c T^2, H - enth.level, [kJ, kg, C]
Type 2: Berghoff's corr. for H, a - rel.dens., b - Watson f., [kJ, kg, K]

ID	Description	Type	a	b	c	H
FnCRUDE		2	.86	11.95	0	0
FnKERO		2	.81	11.7	0	0
FnLGO		2	.86	11.77	0	0
FnHGO		2	.89	11.83	0	0

Fig. 5.13-2: Panel for definition of enthalpy functions

For illustration here is also example of configuration of one of heat exchangers:



Exchanger : E1

☑ Balancing

ID	Description	Area [M^2]	Passes
E1		200	1 - 1

Exchanger parameters:

KERO **Hot stream**

	Function	Temperature	Pressure	Wetness
Inlet	FnKERO	T51		
Outlet	FnKERO	T52		

CRUDE1 **Cold stream**

	Function	Temperature	Pressure	Wetness
Inlet	FnCRUDE	T1		
Outlet	FnCRUDE	T2		

Fig. 5.14-3: Panel for configuration of exchanger E1

Results are as follows:

```
G L O B A L   D A T A

  Number of nodes                                 2
  Number of heat nodes                            1
  Number of exchangers                            4
  Number of streams                               7
  Number of components                            1
  Number of heat functions                        4
  Number of temperatures                         13
  Number of measured variables                   18
  Number of adjusted variables                   18
  Number of non-measured variables                2
  Number of observed variables                    2
  Number of non-observed variables                0
  Number of free variables                        0
  Number of equations                             7
  Number of independent equations                 7
  Number of user equations                        0

  Degree of redundancy                            5
  Mean residue of equations              1.0154E-09
  Qmin                                   7.8246E+00
  Qcrit                                  1.1081E+01
  Status (Qmin/Qcrit)                      0.706148
```

STREAMS [KG/S]

Name	Type	Inp.value	Rec.value	Abs.error
CRUDE1	MC	99.000	99.126	0.929
CRUDE2	MC	60.000	59.615	1.508
CRUDE3	MC	40.000	39.510	1.501
CRUDE4	NO	100.000	99.126	0.929
HGO	MC	5.000	5.000	0.097
KERO	MC	15.000	15.021	0.292
LGO	MC	20.000	19.912	0.390

TEMPERATURES [C]

Name	Type	Inp.value	Rec.value	Abs.error
T1	MC	25.000	25.183	0.813
T2	MC	45.000	44.412	0.756
T3	MC	70.000	70.428	0.747
T4	MC	90.000	90.243	0.792
T5	MC	110.000	110.176	0.982
T51	MC	200.000	200.618	3.483
T52	MC	100.000	99.869	1.956
T6	MC	100.000	98.275	0.707
T61	NO	280.000	280.088	5.020
T62	MC	180.000	177.838	2.768
T63	MC	110.000	110.717	2.062
T71	MC	335.000	335.059	5.959
T72	MC	150.000	149.991	2.963

EXCHANGERS [KJ/S], [C], [KJ/S/M^2/C]

Name	Q(hot)	Q(cold)	Q(rec)	dT	HTC
E1	3716.585	3898.313	3751.282	110.478	0.170
E2	3351.218	3090.906	3195.294	85.212	0.375
E3	2542.931	2582.835	2544.183	147.028	0.173
E4	5473.941	5569.634	5563.876	150.934	0.737

5.14 *Combustion of natural gas – the flame temperature*

The target is to set up a model of burning natural gas (NG) in air at the atmospheric pressure. The NG composition is in the next table:

Component	**Name**	**Vol.%**
CH_4	methane	98.60
C_2H_6	ethane	1.05
N_2	nitrogen	0.35

There are 2 chemical reactions describing the combustion process:

$$CH4 + 2O2 = CO2 + 2H2O \tag{5.14-1}$$

$$C2H6 + 3.5O2 = 2CO2 + 3H2O \tag{5.14-2}$$

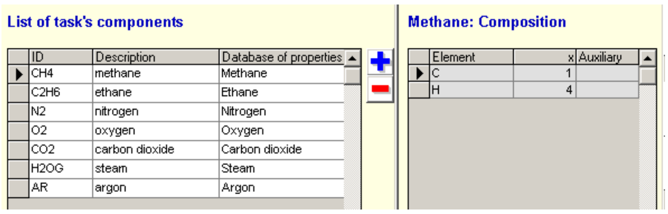
We will not model these two reactions directly but we will use the *reaction invariant method* which models the balance on the basis of conservation of chemical elements.

The following 7 components plays role in this system, which must be linked to the RECON database of physical data for calculating heats of reaction and thermal properties of gases:

```
ID          Description                     Database of properties
-----------------------------------------------------------------
CH4         methane                         Methane
C2H6        ethane                          Ethane
N2          nitrogen                        Nitrogen
O2          oxygen                          Oxygen
CO2         carbon dioxide                  Carbon dioxide
H2OG        steam                           Steam
AR          argon                           Argon
```

The procedure of model building is as follows:

- Select balance in mass units (kilograms, seconds)
- Define components and link them with the database of physical properties:



List of task's components

ID	Description	Database of properties
CH4	methane	Methane
C2H6	ethane	Ethane
N2	nitrogen	Nitrogen
O2	oxygen	Oxygen
CO2	carbon dioxide	Carbon dioxide
H2OG	steam	Steam
AR	argon	Argon

Methane: Composition

Element	x	Auxiliary
C	1	
H	4	

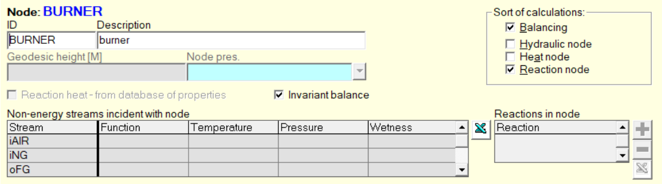
- Create model for mass balance with chemical reactions:

Fig. 5.14-1: Burning natural gas (demo Example E-14)

The stream parameters are (only nonzero values are shown). Note that while composition of air and natural gas is known (fixed), only the concentration of oxygen in the flue gas is measured (3 %).

```
M A T E R I A L   S T R E A M S

 ID          Component   Type         Value     Max.error
 ------------------------------------------------------

 AIR         Flowrate    M       1930.0000      5.0000%    KG/S
             N2          F         75.470000               %wt
             O2          F         23.200000               %wt
             AR          F          1.330000               %wt

 FG          Flowrate    N       1000.0000                 KG/S
             N2          N         70.000000               %wt
             O2          M          3.000000    0.100000   %wt
             CO2         N         10.000000               %wt
             H2OG        N         20.000000               %wt
             AR          N          1.000000               %wt

 NG          Flowrate    M        100.0000      2.0000%    KG/S
             CH4         F         98.600000               %wt
             C2H6        F          1.050000               %wt
             N2          F          0.350000               %wt
```

- The panel for configuration of the node BURNER follows:



Node: BURNER
ID: BURNER
Description: burner
Geodesic height [M]
Node pres.
☐ Reaction heat - from database of properties
☑ Invariant balance

Sort of calculations:
☑ Balancing
☐ Hydraulic node
☐ Heat node
☑ Reaction node

Non-energy streams incident with node

Stream	Function	Temperature	Pressure	Wetness
iAIR				
iNG				
oFG				

Reactions in node

Reaction

The *Reaction node* and *Invariant balance* must be ticked.

- This configuration enables one to calculate the mass balance. It is data reconciliation with one degree of redundancy. This task has its ID E-13M in the Demo task set. Below are selected results of this task:

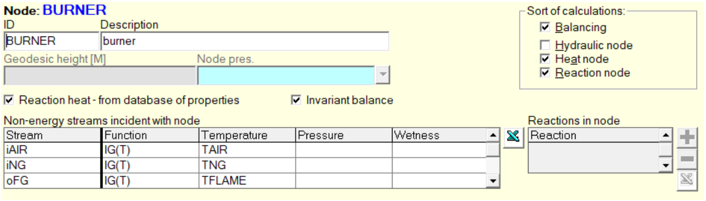
```
RECON 11.8.8-Pro  [ChemPlant Technology s.r.o.]
Task: E-14 (Combustion of natural gas - mass balance)

Balance: [24.09.2019 16:00; 24.09.2019 17:00)

I T E R A T I O N S

Iter            Qeq            Qx              Qy            Qmin
-----------------------------------------------------------------
START     2.1610E+01
   1      7.7173E-01    1.4415E+01      1.4017E+01      9.0856E-01
   2      1.2991E-03    1.1291E-01      6.2789E-01      9.2287E-01
   3      3.0605E-12    1.6361E-06      1.4930E-06      9.2287E-01
```

```
Legend:

Qeq   mean residual of equations
Qx    mean increment of measured variables in iteration
Qy    mean increment of non-measured variables in iteration
Qmin  least-square function


G L O B A L   D A T A

Number of nodes                                        1
Number of streams                                      3
Number of components                                   7
Number of reactions                                    2
Number of react. nodes                                 1

Number of measured variables                           3
Number of adjusted variables                           3
Number of non-measured variables                       5
Number of observed variables                           5
Number of non-observed variables                       0
Number of free variables                               0
Number of equations                                    6
Number of independent equations                        6
Number of user-defined equations                       0

Degree of redundancy                                   1

Mean residue of equations                     3.0605E-12
Qmin                                          9.2287E-01
Qcrit                                         3.8400E+00
Status (Qmin/Qcrit)                             0.240330


S T R E A M S

Stream: AIR  (From node ENVIRON -> To node BURNER)
    M = 28.965 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
-----------------------------------------------------------------
    Flowrate   MC         1930.000       1973.596         37.677  KG/S
  3 N2         F            75.470         75.470                 %wt
  4 O2         F            23.200         23.200                 %wt
  7 AR         F             1.330          1.330                 %wt

Stream: FG  (From node BURNER -> To node ENVIRON)
    M = 27.894 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
-----------------------------------------------------------------
    Flowrate   NO         2000.000       2073.227         39.463  KG/S
  3 N2         NO           70.000         71.860          0.018  %wt
  4 O2         MC            3.000          2.995          0.100  %wt
  5 CO2        NO           10.000         13.146          0.065  %wt
  6 H2OS       NO           20.000         10.732          0.053  %wt
  7 AR         NO            1.000          1.266        3.15E-4  %wt

Stream: NG  (From node ENVIRON -> To node BURNER)
    M = 16.146 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
-----------------------------------------------------------------
    Flowrate   MC          100.000         99.631          1.852  KG/S
  1 CH4        F            98.600         98.600                 %wt
  2 C2H6       F             1.050          1.050                 %wt
  3 N2         F             0.350          0.350                 %wt

End of results

Calculations lasted             00:00:0.274
```

- Define temperatures needed for the heat balance specified in the next table:

```
T E M P E R A T U R E S    [C]

 ID      Description  Type           Value   Max.error
 ---------------------------------------------------
 TAIR    air input      M          20.000E+01
 TFLAME  flue gases     N          2000.0000
 TNG     natural gas    M          20.000E+01
```

- Now fill the Heat node checkbox and configure the heat balance:



Node: BURNER

ID: BURNER

Description: burner

Geodesic height [M]

Node pres.

Sort of calculations:

☑ Balancing

☐ Hydraulic node

☑ Heat node

☑ Reaction node

☑ Reaction heat - from database of properties

☑ Invariant balance

Non-energy streams incident with node

Stream	Function	Temperature	Pressure	Wetness
iAIR	IG(T)	TAIR		
iNG	IG(T)	TNG		
oFG	IG(T)	TFLAME		

Reactions in node

Reaction

The burning takes place at the atmospheric pressure so that the enthalpy function for ideal gas IG(T) was chosen.

This task has its ID E-13E in the Demo task set. Below are selected results of this task:

```
RECON 11.8.8-Pro  [ChemPlant Technology s.r.o.]
 Task: E-13E (Combustion of natural gas - energy balance)

 Balance: [24.09.2019 16:00; 24.09.2019 17:00)

 I T E R A T I O N S

 Iter            Qeq             Qx              Qy             Qmin
 -----------------------------------------------------------------
 START     1.5711E+08
    1      7.0131E+06     1.4415E+01      2.6560E+01      9.0856E-01
    2      8.6175E+03     1.1291E-01      5.3786E-01      9.2287E-01
    3      4.6736E+00     1.6361E-06      5.6715E-04      9.2287E-01
    4      1.2943E-06     3.7702E-14      1.8643E-06      9.2287E-01

 Legend:

 Qeq   mean residual of equations
 Qx    mean increment of measured variables in iteration
 Qy    mean increment of non-measured variables in iteration
 Qmin  least-square function


 G L O B A L   D A T A

 Number of nodes                                       1
 Number of heat nodes                                  1
 Number of streams                                     3
 Number of components                                  7
 Number of temperatures                                3
 Number of reactions                                   2
 Number of react. nodes                                1

 Number of measured variables                          5
 Number of adjusted variables                          3
 Number of non-measured variables                      6
 Number of observed variables                          6
 Number of non-observed variables                      0
 Number of free variables                              0
 Number of equations                                   7
 Number of independent equations                       7
 Number of user-defined equations                      0

 Degree of redundancy                                  1
```

```
Mean residue of equations                    1.2943E-06
Qmin                                         9.2287E-01
Qcrit                                        3.8400E+00
Status (Qmin/Qcrit)                            0.240330


S T R E A M S

Stream: AIR  (From node ENVIRON -> To node BURNER)
    M = 28.965 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   MC         1930.000       1973.596         37.677  KG/S
  3 N2         F            75.470         75.470                 %wt
  4 O2         F            23.200         23.200                 %wt
  7 AR         F             1.330          1.330                 %wt

Stream: FG  (From node BURNER -> To node ENVIRON)
    M = 27.894 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   NO         2000.000       2073.227         39.463  KG/S
  3 N2         NO           70.000         71.860          0.018  %wt
  4 O2         MC            3.000          2.995          0.100  %wt
  5 CO2        NO           10.000         13.146          0.065  %wt
  6 H2OS       NO           20.000         10.732          0.053  %wt
  7 AR         NO            1.000          1.266        3.15E-4  %wt

Stream: NG  (From node ENVIRON -> To node BURNER)
    M = 16.146 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   MC          100.000         99.631          1.852  KG/S
  1 CH4        F            98.600         98.600                 %wt
  2 C2H6       F             1.050          1.050                 %wt
  3 N2         F             0.350          0.350                 %wt


T E M P E R A T U R E S

Name              Type      Inp.value      Rec.value      Abs.error
------------------------------------------------------------------
TAIR              MN           20.000         20.000          1.000  C
TFLAME            NO         2000.000       1856.127          7.384  C
TNG               MN           20.000         20.000          1.000  C

End of results

Calculations lasted            00:00:0.405
```

Discussion:

The mass balance version of the model has one degree of redundancy (DoR). This is due to that flowrates of both input flows (NG and air) are measured and the concentration of oxygen in the flue gas is measured too. This means that for example the air input flowrate is redundant. Adding the heat balance adds one equation more but there is also the unmeasured flame temperature. So, the DoR is not changed.

5.15 Combustion of coal

This example is the continuation of the example presented in Section 4.10 Burning of a coal (task MC-10). Now we suppose that the task of the mass balance is already solved. The next task – completing the heat balance – is named E-15. Recall the coal combustion flowsheet:

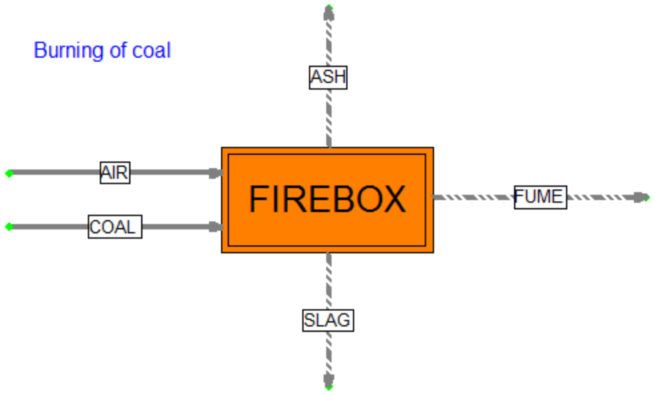


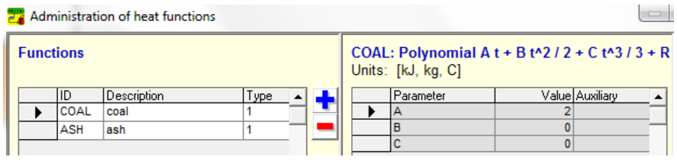
Fig. 5.15-1: Burning coal (demo Example E-15)

To complement this model by enthalpy balance, the following information must be supplied:

- Temperatures of the individual streams

```
T E M P E R A T U R E S    [C]

ID          Type            Value   Max.error
 ------------------------------------------
 AIR         M            300.0000      3.0000
 ASH         M            200.0000      2.0000
 COAL        M             35.0000      1.0000
 FUME        N           1700.0000
 SLAG        M            800.0000      5.0000
```

- Enthalpies of the air and of the fume are modeled as ideal gas on the basis of physical properties bank in RECON. Enthalpies of coal, slag and ash streams were approximated by empirical functions defined in the panel of the administration of heat functions (functions for ash and slag were supposed to be the same).



Functions

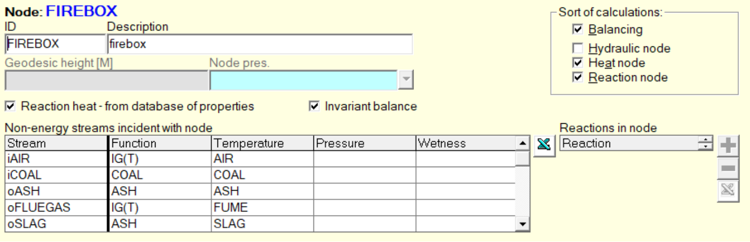
	ID	Description	Type
▶	COAL	coal	1
	ASH	ash	1

COAL: Polynomial A t + B t^2 / 2 + C t^3 / 3 + R
Units: [kJ, kg, C]

	Parameter	Value	Auxiliary
▶	A	2	
	B	0	
	C	0	

In both cases the polynomials of the first order were used with A parameters 2 for the coal and 0.89 for the ash.

The node FIREBOX configuration panel then looks like this:



Node: FIREBOX

ID: FIREBOX

Description: firebox

Geodesic height [M]:

Node pres.:

☑ Reaction heat - from database of properties

☑ Invariant balance

Sort of calculations:

☑ Balancing

☐ Hydraulic node

☑ Heat node

☑ Reaction node

Non-energy streams incident with node

Stream	Function	Temperature	Pressure	Wetness
iAIR	IG(T)	AIR		
iCOAL	COAL	COAL		
oASH	ASH	ASH		
oFLUEGAS	IG(T)	FUME		
oSLAG	ASH	SLAG		

Reactions in node

Reaction

Final results of the calculation follows:

```
RECON 11.8.8-Pro  [ChemPlant Technology s.r.o.]
 Task: E-14 (Combustion of the soft coal)

 Balance: [25.09.2019 15:00; 25.09.2019 16:00)

 I T E R A T I O N S

 Iter            Qeq            Qx              Qy            Qmin
 -----------------------------------------------------------------
 START     6.3833E+04
    1      1.5666E+04    2.0074E-02      2.0772E+00      3.1737E+00
    2      2.5210E+01    3.8439E-04      7.0178E+00      2.5622E+00
    3      4.6789E-02    2.6995E-06      3.9517E-02      2.5670E+00
    4      1.1874E-08    5.8712E-15      8.7390E-06      2.5670E+00

 Legend:

 Qeq   mean residual of equations
 Qx    mean increment of measured variables in iteration
 Qy    mean increment of non-measured variables in iteration
 Qmin  least-square function


 G L O B A L   D A T A

 Number of nodes                                        1
 Number of heat nodes                                   1
 Number of streams                                      5
 Number of components                                  11
 Number of heat functions                               2
 Number of temperatures                                 5
 Number of react. nodes                                 1

 Number of measured variables                          10
 Number of adjusted variables                           6
 Number of non-measured variables                       7
 Number of observed variables                           7
 Number of non-observed variables                       0
 Number of free variables                               0
 Number of equations (incl. UDE)                       10
 Number of independent equations                       10
 Number of user-defined equations (UDE)                 1

 Degree of redundancy                                   3

 Mean residue of equations                     1.1874E-08
 Qmin                                          2.5670E+00
 Qcrit                                         7.8100E+00
 Status (Qmin/Qcrit)                             0.328682


 S T R E A M S

 Stream: AIR  (From node ENVIRON -> To node FIREBOX)
     M = 28.964 KG/KMOL

 No. Name     Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
```

```
    Flowrate   MC            5.000          5.071          0.240  KG/S
 11 AIR        F           100.000        100.000                 %wt

Stream: ASH  (From node FIREBOX -> To node ENVIRON)
    M = 100 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   NO            0.050          0.042        2.07E-3  KG/S
  8 AH         F           100.000        100.000                 %wt

Stream: COAL  (From node ENVIRON -> To node FIREBOX)
    M = 46.384 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   MC            1.000          0.901          0.045  KG/S
  2 H2OL       F            25.400         25.400                 %wt
  8 AH         F            30.720         30.720                 %wt
 10 COAL       F            43.880         43.880                 %wt

Stream: FLUEGAS  (From node FIREBOX -> To node ENVIRON)
    M = 29.3 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   NO            6.000          5.695          0.269  KG/S
  1 H2OV       NO           10.000          6.810          0.106  %wt
  3 O2         MC            5.000          5.012          0.284  %wt
  4 N2         NO           50.000         67.303          0.128  %wt
  5 AR         NO            1.000          1.191        2.29E-3  %wt
  6 CO2        MC           19.000         19.359          0.304  %wt
  7 CO         MC            0.050          0.050        5.00E-3  %wt
  9 SO2        MC            0.260          0.275        4.29E-3  %wt

Stream: SLAG  (From node FIREBOX -> To node ENVIRON)
    M = 100 KG/KMOL

No. Name       Type      Inp.value      Rec.value      Abs.error
----------------------------------------------------------------
    Flowrate   NO            0.200          0.235          0.012  KG/S
  8 AH         F           100.000        100.000                 %wt


T E M P E R A T U R E S

Name             Type      Inp.value      Rec.value      Abs.error
------------------------------------------------------------------
AIR              MN          300.000        300.000          3.000  C
ASH              MN          200.000        200.000          2.000  C
COAL             MN           35.000         35.000          1.000  C
FUME             NO         1700.000       1636.617         18.269  C
SLAG             MN          800.000        800.000          5.000  C

End of results
```

Discussion:

This task showed using different enthalpy functions: ideal gas for air and flue gases and empirical functions for coal, ash and slag. Even better could be to calculate coal enthalpy as a function of moisture of the coal which influences its enthalpy significantly. But the coal temperature is quite close to the standard temperature and thus its influence on the Heat Rate is not significant.

Adding the heat balance did not changed redundancy of the task. One heat balance equation was compensated by one unknown – the flue gas temperature.

5.16 Coal fired steam generator with air preheat

This example is the continuation of the previous example presented in Section 5.15 Burning of a coal (task E-15). Now we suppose that the task of the coal burning is already solved. The next task will complete the coal burning by other nodes needed for the steam generation.

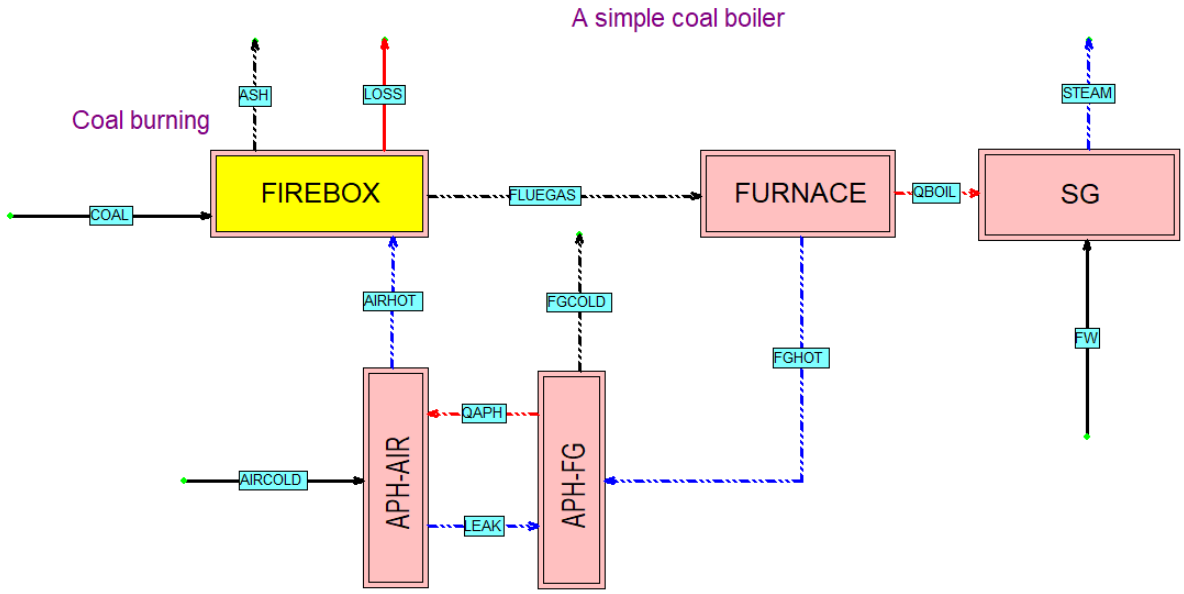


Fig. 5.16-1: Burning coal and the steam generation (demo Example E-16-1)

The following two couples of nodes are added:

1. Boiler and the Steam generator (SG)
2. Air preheater (air and flue gas sides of the rotary air preheater APH-AIR and APH-FG).

There are 3 energy streams:

1. Radiation and convection heat losses LOSS
2. Heat exchanged between flue gases and the feed water QBOIL
3. Heat exchanged between air and flue gases QAPH.

There is the air leak stream LEAK from air to flue gases in APH.

Input data for this task follows. Data for dependent streams (blue streams in Fig. 5.16-1) are not shown.

```
Task: E-16 (Simplified soft coal boiler II)

 Balance: [25.09.2019 15:00; 25.09.2019 16:00)

 G L O B A L   D A T A

 Number of nodes                                         5
 Number of heat nodes                                    5
 Number of streams                                      13
 Number of energy streams                                3
 Number of components                                   10
 Number of heat functions                                2
 Number of temperatures                                 10
 Number of pressures                                     2
 Number of auxiliaries                                   7
 Number of react. nodes                                  1


 C O M P O N E N T S

 ID         Description                    Chemical name
 -------------------------------------------------------
 H2OV       steam                          Steam
 H2OL       water                          Water
 O2         oxygen                         Oxygen
 N2         nitrogen                       Nitrogen
 AR         argon                          Argon
 CO2        carbon dioxide                 Carbon dioxide
 CO         carbon monoxide                Carbon monoxide
 AH         ash                            Ash
 SO2        sulphur dioxide                Sulfur dioxide
 COAL       soft coel flammable part       Soft coal
S T R E A M S

 ID         From node  To node    Master stream  Description
 -----------------------------------------------------------
 AIRCOLD    ENVIRON    APH-AIR                   air at APH inlet
 AIRHOT     APH-AIR    FIREBOX    AIRCOLD        air at APH outlet
 ASH        FIREBOX    ENVIRON                   ash
 COAL       ENVIRON    FIREBOX                   soft coal input
 FGCOLD     APH-FG     ENVIRON                   FG at APH exit
 FGHOT      BOILER     APH-FG     FLUEGAS        FG at APH inlet
 FLUEGAS    FIREBOX    BOILER                    Flue Gas at firebox exit
 FW         ENVIRON    SG                        Feed Water
 LEAK       APH-AIR    APH-FG     AIRCOLD
 LOSS       FIREBOX    ENVIRON                   boiler radiatin and convection loss
 QAPH       APH-FG     APH-AIR                   APH heat flux
 QBOIL      BOILER     SG                        boiler useful heat flux
 STEAM      SG         ENVIRON    FW             steam generated

 M A T E R I A L   S T R E A M S

 ID         Component   Type        Value     Max.error
 ------------------------------------------------------

 AIRCOLD    Flowrate    M       1730.0000      3.0000%    T/HR
            H2OV        F          1.360000               %wt
            H2OL        F        0.00000E+0               %wt
            O2          F         22.880000               %wt
            N2          F         74.470000               %wt
            AR          F          1.240000               %wt
            CO2         F        5.00000E-2               %wt
            CO          F        0.00000E+0               %wt
            AH          F        0.00000E+0               %wt
            SO2         F        0.00000E+0               %wt
            COAL        F        0.00000E+0               %wt

 AIRHOT     Flowrate    N       1731.4264                 T/HR
            (Master stream = AIRCOLD)

 ASH        Flowrate    N         98.7989                 T/HR
            H2OV        F        0.00000E+0               %wt
            H2OL        F        0.00000E+0               %wt
            O2          F        0.00000E+0               %wt
            N2          F        0.00000E+0               %wt
```

```
            AR        F        0.00000E+0               %wt
            CO2       F        0.00000E+0               %wt
            CO        F        0.00000E+0               %wt
            AH        F        100.000000               %wt
            SO2       F        0.00000E+0               %wt
            COAL      F        0.00000E+0               %wt

 COAL       Flowrate    M        325.0000      5.0000%    T/HR
            H2OV      F        0.00000E+0               %wt
            H2OL      F         25.400000               %wt
            O2        F        0.00000E+0               %wt
            N2        F        0.00000E+0               %wt
            AR        F        0.00000E+0               %wt
            CO2       F        0.00000E+0               %wt
            CO        F        0.00000E+0               %wt
            AH        F         30.720000               %wt
            SO2       F        0.00000E+0               %wt
            COAL      F         43.880000               %wt

FGCOLD     Flowrate    N       1996.9639                 T/HR
            H2OV      N          8.140798               %wt
            H2OL      F        0.00000E+0               %wt
            O2        M          4.800000    0.400000   %wt
            N2        N         66.224582               %wt
            AR        N          1.101647               %wt
            CO2       N         19.754648               %wt
            CO        M        5.00000E-2  2.50000E-3   %wt
            AH        F        0.00000E+0               %wt
            SO2       N          0.279564               %wt
            COAL      F        0.00000E+0               %wt

FGHOT      Flowrate    N       1954.2384                 T/HR
            (Master stream = FLUEGAS)

 FLUEGAS    Flowrate    N       1954.2384                 T/HR
            H2OV      N          8.289047               %wt
            H2OL      F        0.00000E+0               %wt
            O2        M          4.000000    0.400000   %wt
            N2        N         66.044313               %wt
            AR        N          1.098622               %wt
            CO2       N         20.185451               %wt
            CO        M        5.00000E-2  2.50000E-3   %wt
            AH        F        0.00000E+0               %wt
            SO2       N          0.285676               %wt
            COAL      F        0.00000E+0               %wt

 FW         Flowrate    M       1600.0000      1.0000%    T/HR
            H2OV      F        0.00000E+0               %wt
            H2OL      F        100.000000               %wt
            O2        F        0.00000E+0               %wt
            N2        F        0.00000E+0               %wt
            AR        F        0.00000E+0               %wt
            CO2       F        0.00000E+0               %wt
            CO        F        0.00000E+0               %wt
            AH        F        0.00000E+0               %wt
            SO2       F        0.00000E+0               %wt
            COAL      F        0.00000E+0               %wt

 LEAK       Flowrate    N         42.7255                 T/HR
            (Master stream = AIRCOLD)

 STEAM      Flowrate    N       1595.9000                 T/HR
            (Master stream = FW)

 E N E R G Y   S T R E A M S    [MW]

 ID         Type           Value   Max.error
 -------------------------------------------
 LOSS       M               5.0000     5.0000%
 QAPH       N            143.6246
 QBOIL      N            939.6163



 F U N C T I O N S    [kJ, kg, C]
```

```
 ID          Type           A          B          C     Plus H
 -------------------------------------------------------------
 ASH         1         0.8900   0.000E+0   0.000E+0   0.000E+0
 COAL        1         2.0000   0.000E+0   0.000E+0   0.000E+0

T E M P E R A T U R E S    [C]

 ID         Type           Value   Max.error
 -------------------------------------------
 AIRCOLD    M            30.0000      1.0000
 AIRHOT     M           315.0000      3.0000
 AIRLEAK    N           172.4177
 ASH        M           200.0000      2.0000
 COAL       M            35.0000      1.0000
 FGCOLD     M           125.0000      1.0000
 FGHOT      M           360.0000      3.0000
 FLAME      N          1687.3698
 FW         M           305.0000      2.0000
 STEAM      M           600.0000      2.0000

 P R E S S U R E S    [MPA]

 ID         Type           Value   Max.error
 -------------------------------------------
 FW         M            31.0000      1.0000%
 STEAM      M            27.0000      1.0000%

 A U X I L I A R I E S

 ID         Type           Value   Max.error
 -------------------------------------------
 BOILEFFIO  N            85.3505               kJ/kWh
 COALC      M            76.4200      1.0000%  1
 COALH      M             4.5000      1.0000%  1
 COALHHV    M      28080000.0000      0.2000%  J/kg
 COALN      M             0.9000      1.0000%  1
 COALO      M            16.2000      1.0000%  1
 COALS      M             1.9800      1.0000%  1


 H E A T   N O D E S

 ID         Stream     Function    TemperaturePressure   Wetness
 -------------------------------------------------------------------

 APH-AIR    AIRCOLD    IG(T)       AIRCOLD
            AIRHOT     IG(T)       AIRHOT
            LEAK       IG(T)       AIRLEAK

 APH-FG     FGHOT      IG(T)       FGHOT
            FGCOLD     IG(T)       FGCOLD
            LEAK       IG(T)       AIRLEAK

 BOILER     FLUEGAS    IG(T)       FLAME
            FGHOT      IG(T)       FGHOT

 FIREBOX    COAL       COAL        COAL
            FLUEGAS    IG(T)       FLAME
            ASH        ASH         ASH
            AIRHOT     IG(T)       AIRHOT

 SG         FW         H2O(T,P)    FW         FW
            STEAM      H2O(T,P)    STEAM      STEAM

 U S E R   E Q U A T I O N S

 ID         Description                                                 Remark
            Programmatic code
 ---------------------------------------------------------------------------------
 AIRLEAK    airleak temperature                                         Model
            [T<AIRLEAK>]-([T<AIRCOLD>]+[T<AIRHOT>])/2

 BOILEFFIO                                                              Model
            [V<BOILEFFIO>]-[S<QBOIL>]/([S<COAL>]*[V<COALHHV>]
            *[C<COAL:COAL>])*100
```

Note 1: Air leak temperature is calculated as the average of input and output air temperature.

Note 2: Use equation BOILEFFIO calculates the Input – Output boiler efficiency BOILEFFIO.

Main results of calculation follows:

```
Task: E-16 (Simplified soft coal boiler II)

 I T E R A T I O N S

 Iter            Qeq            Qx             Qy            Qmin
 -----------------------------------------------------------------
 START     2.0396E+05
    1      9.1841E+01    3.7335E+02      1.8222E+03      6.7120E+00
    2      1.6977E-02    5.7714E-02      3.4372E+01      6.7150E+00
    3      3.1590E-05    1.0490E-05      7.3858E-03      6.7150E+00

 Legend:

 Qeq   mean residual of equations
 Qx    mean increment of measured variables in iteration
 Qy    mean increment of non-measured variables in iteration
 Qmin  least-square function


 G L O B A L   D A T A

 Number of nodes                                        5
 Number of heat nodes                                   5
 Number of streams                                     13
 Number of energy streams                               3
 Number of components                                  10
 Number of heat functions                               2
 Number of temperatures                                10
 Number of pressures                                    2
 Number of auxiliaries                                  7
 Number of react. nodes                                 1

 Number of measured variables                          24
 Number of adjusted variables                          24
 Number of non-measured variables                      22
 Number of observed variables                          22
 Number of non-observed variables                       0
 Number of free variables                               0
 Number of equations (incl. UDE)                       27
 Number of independent equations                       27
 Number of user-defined equations (UDE)                 2

 Degree of redundancy                                   5

 Mean residue of equations                     3.1590E-05
 Qmin                                          6.7150E+00
 Qcrit                                         1.1100E+01
 Status (Qmin/Qcrit)                              0.60496

 F L O W R A T E S   &   C O N C E N T R A T I O N S

 Stream: AIRCOLD  (From node ENVIRON -> To node APH-AIR)
     M = 28.727 KG/KMOL

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   MC        1730.000       1773.601         33.988  T/HR  air at APH inlet
   1 H2OV       F            1.360          1.360                 %wt  Steam
   3 O2         F           22.880         22.880                 %wt  Oxygen
   4 N2         F           74.470         74.470                 %wt  Nitrogen
   5 AR         F            1.240          1.240                 %wt  Argon
   6 CO2        F            0.050          0.050                 %wt  Carbon dioxide
```

```
 Stream: AIRHOT  (From node APH-AIR -> To node FIREBOX)
     M = 28.727 KG/KMOL; Master stream = AIRCOLD

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   NO         1731.426       1731.330         43.183  T/HR  air at APH outlet

 Stream: ASH  (From node FIREBOX -> To node ENVIRON)
     M = 100 KG/KMOL

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   NO           98.799         98.801          1.067  T/HR  ash
   8 AH         F           100.000        100.000                 %wt  Ash

 Stream: COAL  (From node ENVIRON -> To node FIREBOX)
     M = 46.384 KG/KMOL

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   MC          325.000        321.618          3.473  T/HR  soft coal input
   2 H2OL       F            25.400         25.400                 %wt  Water
   8 AH         F            30.720         30.720                 %wt  Ash
  10 COAL       F            43.880         43.880                 %wt  Soft coal

 Stream: FGCOLD  (From node APH-FG -> To node ENVIRON)
     M = 29.091 KG/KMOL

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   NO         1996.964       1996.418         35.073  T/HR  FG at APH exit
   1 H2OV       NO            8.141          8.143          0.106  %wt  Steam
   3 O2         MC            4.800          4.444          0.288  %wt  Oxygen
   4 N2         NO           66.225         66.222          0.129  %wt  Nitrogen
   5 AR         NO            1.102          1.102      2.1610E-3  %wt  Argon
   6 CO2        NO           19.755         19.761          0.308  %wt  Carbon dioxide
   7 CO         MC            0.050          0.049      1.8493E-3  %wt  Carbon monoxide
   9 SO2        NO            0.280          0.280      4.3630E-3  %wt  Sulfur dioxide

 Stream: FGHOT  (From node FURNACE -> To node APH-FG)
     M = 29.099 KG/KMOL; Master stream = FLUEGAS

 No. Name       Type      Inp.value      Rec.value      Abs.error

 Stream: FLUEGAS  (From node FIREBOX -> To node FURNACE)
     M = 29.099 KG/KMOL

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   NO         1954.238       1954.147         44.249  T/HR  Flue Gas at firebox
exit
   1 H2OV       NO            8.289          8.290          0.139  %wt  Steam
   3 O2         MC            4.000          4.045          0.378  %wt  Oxygen
   4 N2         NO           66.044         66.044          0.169  %wt  Nitrogen
   5 AR         NO            1.099          1.099      2.8344E-3  %wt  Argon
   6 CO2        NO           20.185         20.187          0.405  %wt  Carbon dioxide
   7 CO         MC            0.050          0.051      1.8809E-3  %wt  Carbon monoxide
   9 SO2        NO            0.286          0.286      5.7273E-3  %wt  Sulfur dioxide

 Stream: FW  (From node ENVIRON -> To node SG)
     M = 18.015 KG/KMOL

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   MC         1600.000       1595.944         15.217  T/HR  Feed Water
   2 H2OL       F           100.000        100.000                 %wt  Water

 Stream: LEAK  (From node APH-AIR -> To node APH-FG)
     M = 28.727 KG/KMOL; Master stream = AIRCOLD

 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   NO           42.725         42.270         46.823  T/HR

 Stream: STEAM  (From node SG -> To node ENVIRON)
     M = 18.015 KG/KMOL; Master stream = FW
```

```
 No. Name       Type      Inp.value      Rec.value      Abs.error
 ----------------------------------------------------------------
     Flowrate   NO         1595.900       1595.944         15.217  T/HR  steam generated
   2 H2OL       F           100.000        100.000                 %wt  Water

 E N E R G Y   S T R E A M S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 LOSS             MC            5.000          4.998          0.250  MW  boiler radiatin and
convection loss
 QAPH             NO          143.625        143.605          2.854  MW  APH heat flux
 QBOIL            NO          939.616        939.652         10.151  MW  boiler useful heat
flux

 T E M P E R A T U R E S

 Name               Type      Inp.value      Rec.value      Abs.error
 --------------------------------------------------------------------
 AIRCOLD            MC           30.000         30.033          0.984  C  air cold
 AIRHOT             MC          315.000        314.811          2.485  C  air hot
 AIRLEAK            NO          172.418        172.422          1.392  C  airleak
 ASH                MC          200.000        199.997          2.000  C  ash
 COAL               MC           35.000         35.005          1.000  C  coal in
 FGCOLD             MC          125.000        124.959          0.976  C  flue gas cold
 FGHOT              MC          360.000        360.232          2.178  C  flue gas hot
 FLAME              NO         1687.370       1687.459         23.846  C  FG flame
 FW                 MC          305.000        305.245          1.978  C  feed water
 STEAM              MC          600.000        599.855          1.992  C  main steam

 P R E S S U R E S

 Name               Type      Inp.value      Rec.value      Abs.error
 --------------------------------------------------------------------
 FW                 MC           31.000         30.999          0.310  MPA  feed water
 STEAM              MC           27.000         27.008          0.270  MPA  main steam

A U X I L I A R I E S

 Name               Type      Inp.value      Rec.value      Abs.error
 --------------------------------------------------------------------
 BOILEFFIO          NO           85.350         85.352          0.106  boiler IO Efficiency
[kJ/kWh]
 COALC              MC           76.420         76.420          0.166
 COALH              MC            4.500          4.500          0.045
 COALHHV            MC     28080000.000   28083359.052      56013.301  coal HHV [J/kg]
 COALN              MC            0.900          0.900      8.9994E-3
 COALO              MC           16.200         16.200          0.158
 COALS              MC            1.980          1.980          0.020

 End of results
```

Note: Please recall the Note at the introductory part of this Section. In the node FIREBOX the input stream COAL contains H2O in the state of H2OL (water) and the stream FLUEGAS contains H2O is in the state H2OV (vapor). This respects the fact that moisture from coal in the FIREBOX vaporizes.

In the node SG both streams has H2O in state H2OL. This is because the water and steam enthalpy functions used in the configuration of heat balance of the SG node already count with the proper state of input and output streams.