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Modeling a 3-zone Feedwater Heater

Author: *Frantisek Madron*

Ústí nad Labem *November 2013*

ChemPlant Technology s.r.o.
Vinařská 1015/4
400 01 Ústí nad Labem

Tel.: +420 474 527 221

E-mail: support@chemplant.cz

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Summary

1. The present report describes modeling of a 3-zone Feedwater Heater.
2. The model is based on a detailed mass and energy balance complemented by user defined equations defining KPIs.
3. The following KPIs were calculated:
    - TTD – Terminal Temperature Difference
    - DCA – Drain Cooler Approach
    - HTCs – Heat Transfer Coefficients in individual zones
4. The following results of calculation were discussed:
    - Precision (uncertainty) of the desuperheating zone heat duty
    - Precision (uncertainty) of the desuperheating zone heat transfer coefficient.

1. Introduction

Feedwater heaters (FWH) are used in conventional and nuclear plants to preheat boiler feed water. The source of heat is the extraction steam from turbines. The main objectives are to

- improve the thermodynamic efficiency of the steam cycle (so called Carnotization of the cycle)
- lower the thermal shock to the boiler when feedwater enters the boiler
- disburden the LP turbine load.

This report describes modeling and KPI monitoring of a 3-zone feedwater heaters in the program RECON. There are several important subjects which must be mastered in this direction, mainly

- There are a lot of unmeasured streams in the system (uncontrolled extractions, stream parameters, …) so that a detailed mass and energy balance model must be set up to observe all important parameters
- Thermodynamic analysis of 3-zone Feedwater heaters
- Performance monitoring based on TTD and DCA values.
- Monitoring heat transfer in 3 heat exchangers.

Further it will be modeled a typical large size feedwater heater which is an auxiliary of a condensation turbine.

2. A 3-zone Feedwater Heater (FWH)

2.1. FWH description

Arrangement of a typical feedwater heater, which will be further modeled, is shown in the Fig. 2.1.

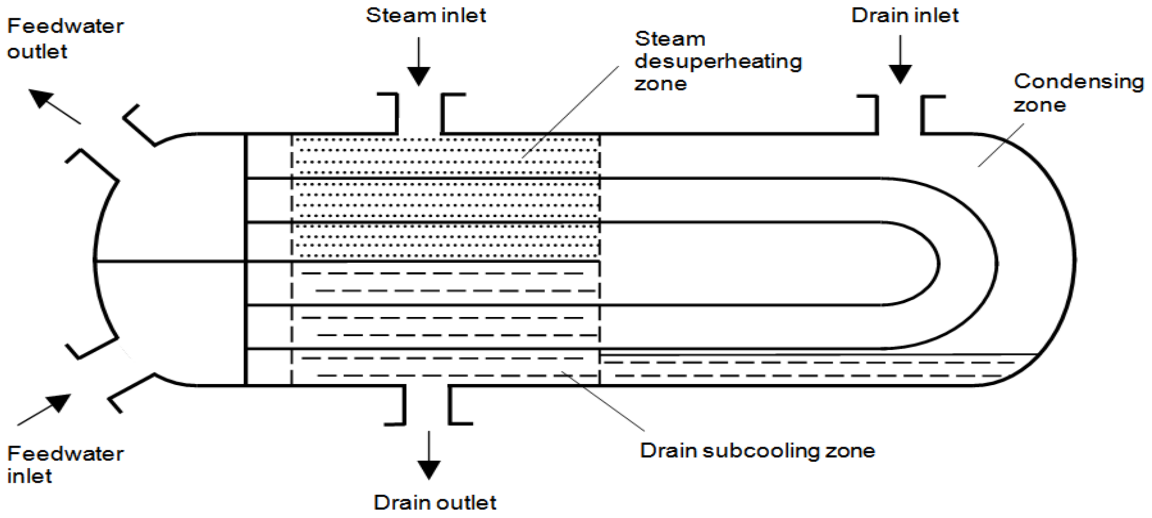

Fig. 2.1: Typical schematic arrangement of a 3-zone feedwater heater

A FWH is usually a shell and tube heat exchanger (condenser) where cold feed water in the tube space of FWH is heated by a contact with superheated steam which is consecutively cooled to the saturation temperature, condenses and the condensate is later subcooled by the fresh feed water.

The FWH consists of 3 zones (sections):

- The steam desuperheating section where the superheated steam is cooled in a contact with dry tubes of the U-tube bundle to the saturation temperature.
- The condensing zone where steam condenses in a contact with tubes. Some FWHs have also inlet of a condensate (drain) from a neighbor FWH. As this drain has higher pressure than is in the condensing zone, it flashes and releases some additional saturated steam.
- The subcooling zone which is flooded by the condensate, where subcooling occurs. Condensate leaves FWH at the bottom (drain).

All zones are equipped with baffles to promote heat transfer. There is therefore some pressure loss, especially in the desuperheating zone, which causes decrease of pressure (and also the saturation temperature) in the condensing zone. The pressure in the condensing zone is important for the performance analysis of FWHs and further will be supposed that this pressure is either measured or can be estimated from parameters of the extraction steam.

2.2. Temperature profiles in a FWH

Temperature profiles in a FWH are shown in the next Fig. 2.2

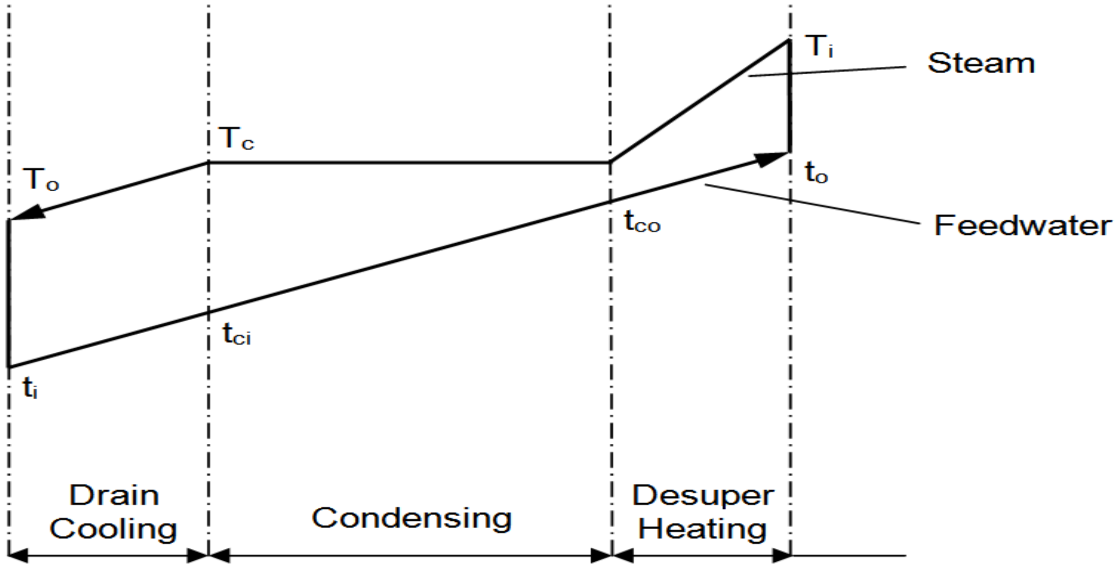

Fig. 2.2: Temperature profiles in a FWH

In practice, in modern power plants all input and output temperatures (indices i and o) are measured. Further there is usually measured pressure in the shell side of the condensing zone. This pressure then defines the saturation temperature T_c because the saturation conditions can be supposed in the condensing zone.

$$T_c = T_{sat}(P_c) \qquad (2\text{-}1)$$

where P_c is the pressure in the shell side of the condensing zone.

The remaining temperatures can be calculated on the basis of mass and heat balances.

2.3. Method of solution

At the beginning a mass and heat balance of the FWH must be set up. While this can be a problem for a separated FWH, in a real flowsheet of a power plant there should not be significant problems. Especially, flows of the condensate and the drain from the neighboring FWH are known from the mass and heat balance of the whole steam cycle. Moreover, modeling of equilibrium between water and steam in the condensing zone will add another equation (see later).

The performance of FWHs is in practice frequently characterized by two simple characteristic temperature differences – TTD and DCA:

TTD (Terminal Temperature Difference)

$$TTD = T_c - t_o \qquad (2\text{-}2)$$

DCA (Drain Cooler Approach)

$$DCA = T_o - t_i \qquad (2\text{-}3)$$

While the DCA must be always positive, TTD can be both positive or negative, depending on steam superheating.

The other (more important) characteristics of 3-zone FWHs are heat transfer coefficients (HTCs) in the individual zones.

Heat transfer in heat exchangers is usually defined by the following equation:

$$Q = U\,A\,dT \qquad (2\text{-}4)$$

Where Q = heat flux
U HTC
A heat transfer area
dT mean temperature difference.

In FWHs the heat transfer area of individual zones is not easy to determine. Moreover, the borders between individual zones need not be fixed, depending on load, FWH degradation, etc. Anyway, it is sufficient to identify the product

$$HTCA = U\,A \qquad (2\text{-}5)$$

The Equation (2-4) then reads

$$Q = HTCA\,dT \qquad (2\text{-}6)$$

where the heat transfer area is hidden.

Another problem is a definition of dT. An analytical solution for a single phase flow in simple heat exchangers is available but the situation in practice is frequently more difficult. The most frequent model is the Logarithmic Mean Temperature Difference (LMTD), which is the optimal solution for countercurrent heat exchangers. The following equations (2-7) and (2-8) hold for the subcooling zone.

$$\mathrm{LMTD} = \frac{(T_o - t_i) - (T_c - t_{ci})}{\ln\frac{T_o - t_i}{T_c - t_{ci}}} \tag{2-7}$$

In the case of FWH the situation is quite simple for the condensing zone where the use of LMTD is justified. On the other hand side, the remaining two zones have very complicated flow patterns. We still think that the LMTD is applicable even in this case.

The temperature difference can be calculated also as the arithmetic average of temperature differences at exchanger's ends.

For example, in the case of the subcooling zone the temperature difference can calculated as follows:

$$\mathrm{dT} = \frac{(T_o - t_i) + (T_c - t_{ci})}{2} \tag{2-8}$$

To summarize, for subcooling and desuperheating zones both LMTD and arithmetic average temperature difference are available and easily applicable in Recon models. It should be noted that the arithmetic average method is more suitable from the numerical point of view. Also, from the Eq. (2-7) it is clear that LMTD is not defined for equal temperature differences at both sides of a heat exchanger (numerical problems can occur even in the vicinity of such case). In this case the LMTD in Recon is replaced by the arithmetic average.

2.4. Modeling the FWH in Recon

2.4.1 Basic considerations

A detailed balancing flowsheet of a FWH is shown in Fig. 2.3 (compare with Fig. 2.1.).

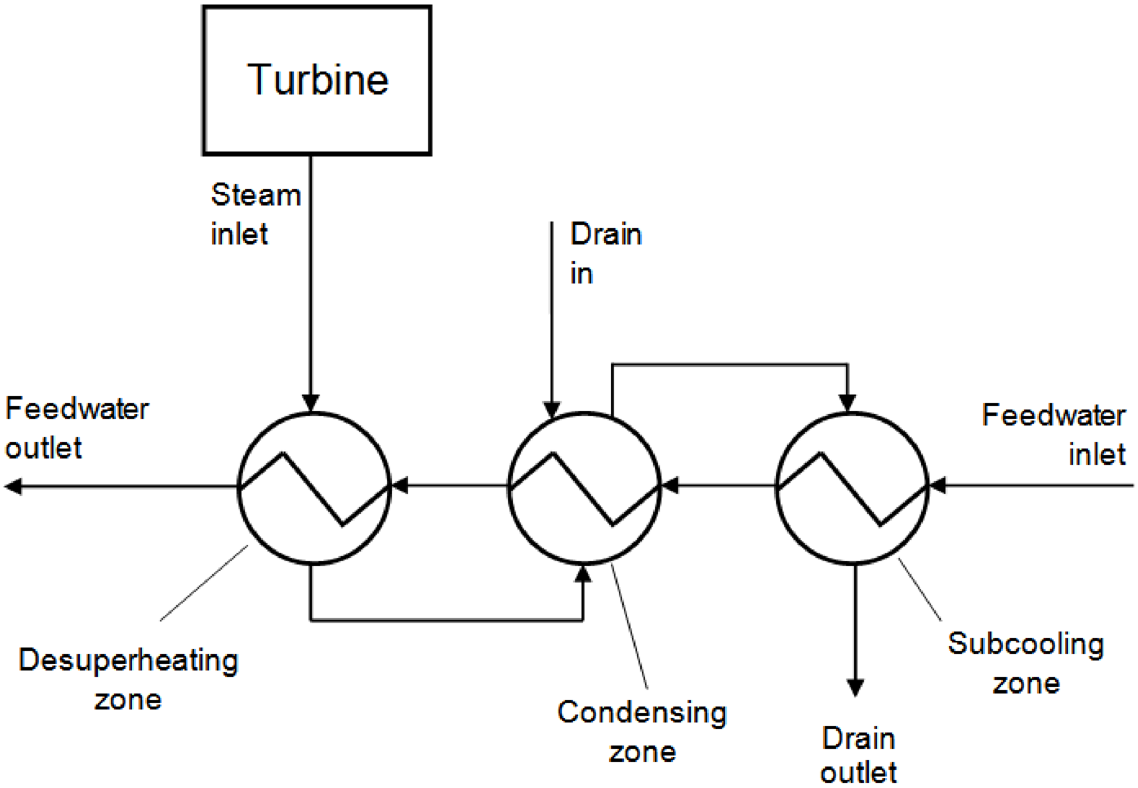

Fig. 2.3: Feedwater Heater – a balancing flowsheet.

The flowsheet created in Recon is shown in the next Fig. 2.4 where is also shown the instrumentation used in the model configuration.

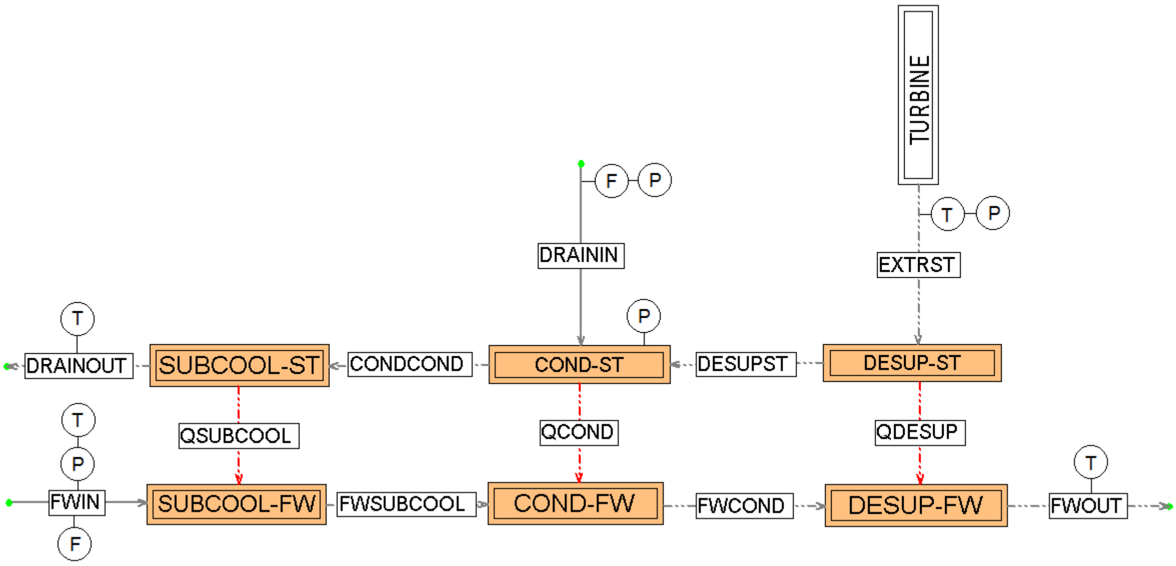

Fig. 2.4: Feedwater Heater – a balancing flowsheet in Recon.

It is supposed that flows of entering feedwater (FWIN) and the drain from the neighboring FWH (DRAININ) are known. In practice these flows are not measured but are known from the overall balance of the feedwater preheat train. The measured temperatures concern inlet and outlet streams of the FWH (extraction steam, drain input and output and feedwater). In practice these values are usually available.

Pressures of the feedwater are sometimes unmeasured but can be estimated (the influence of a variable pressure on feedwater enthalpy is only marginal).

Aside of mas streams there are also energy streams QSUBCOOL, QCOND and QDESUP representing heat duties (fluxes) in individual zones.

2.4.2 Modeling heat nodes

The configuration of mass and energy balances is illustrated on an example of steam side of the desuperheater DESUP-ST, see the next Fig. 2.5.

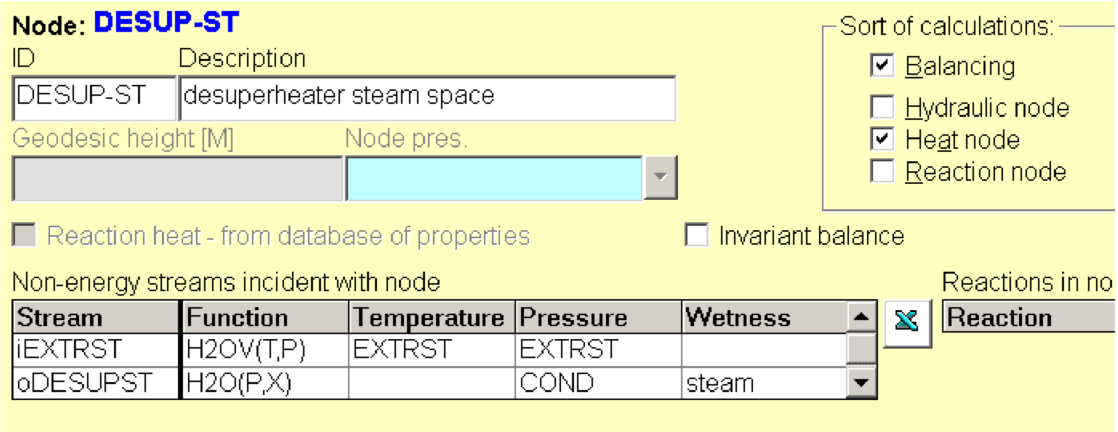

Fig. 2.5: Configuration the DESUP-ST node

There are 2 mass streams incident with this node. The enthalpy of the inlet extraction steam EXTRST is calculated by function H2OV(T,P) (superheated vapor defined by temperature and pressure). The outlet stream DESUPST is modeled by function H2O(P,X) (saturated steam at pressure in the condensing zone).

2.4.3 Modeling Key Performance Indicators of the FWH

The performance of the whole FWH is usually characterized by TTD and DCA, the individual zones are characterized by heat transfer coefficients (HTC). In our model we will use HTCA – a product of HTC and the heat transfer area, se Eq. (2-5).

At the beginning there is the calculation of the condensing steam saturated temperature, see Eq. (2-1). This temperature is configured in the editor of User Defined Equations – Model supplements.

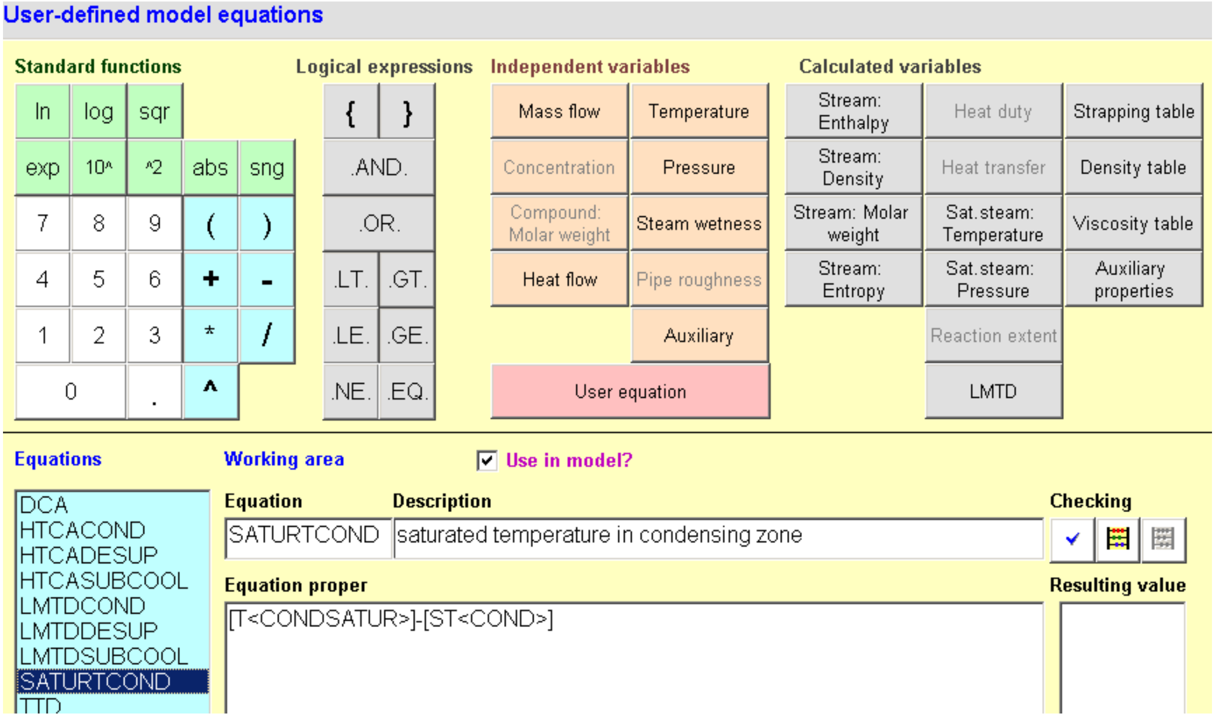

Fig. 2.6: Definition of the saturated temperature in the condensing zone

The saturated temperature CONDSATUR is calculated by function [ST<COND>] where COND is the pressure in the condensing zone. The ST<> function is invoked by the button *Sat.steam Temperature* on the panel.

TTD and DCA are defined also by User Defined Equations. The example of TTD (see Eq. (2-2) is shown in the next Fig. 2.7.

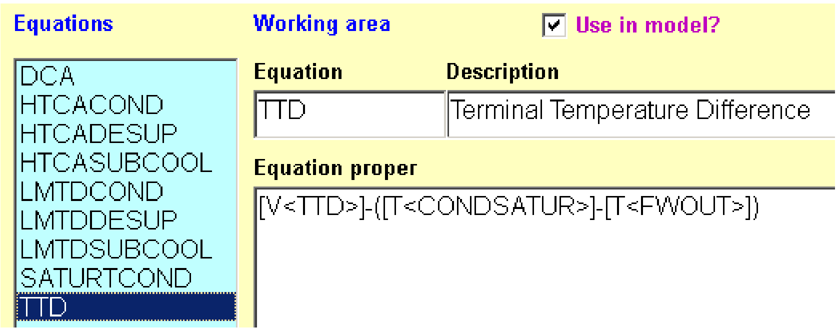

Fig. 2.7: Definition of the Terminal Temperature Difference

Also HTCAs are defined with the aid of User Defined Equations, the example of desuperheater's HTCA follows:

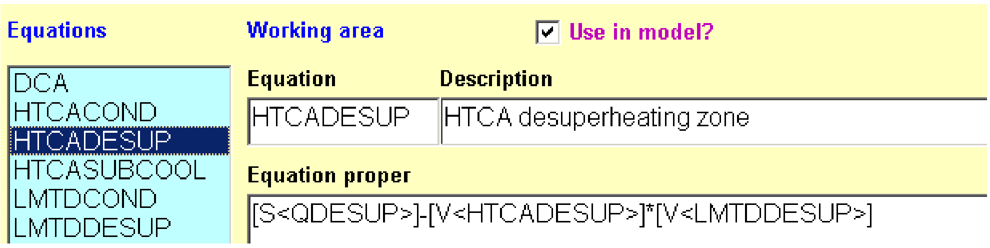

Fig. 2.8: Definition of the desuperheater's HTCA

The Equation defining HTCA (see Eq (2-7)) is in the implicit form. The temperature difference LMTDDESUP is the auxiliary variable defined by the following user defined equation:

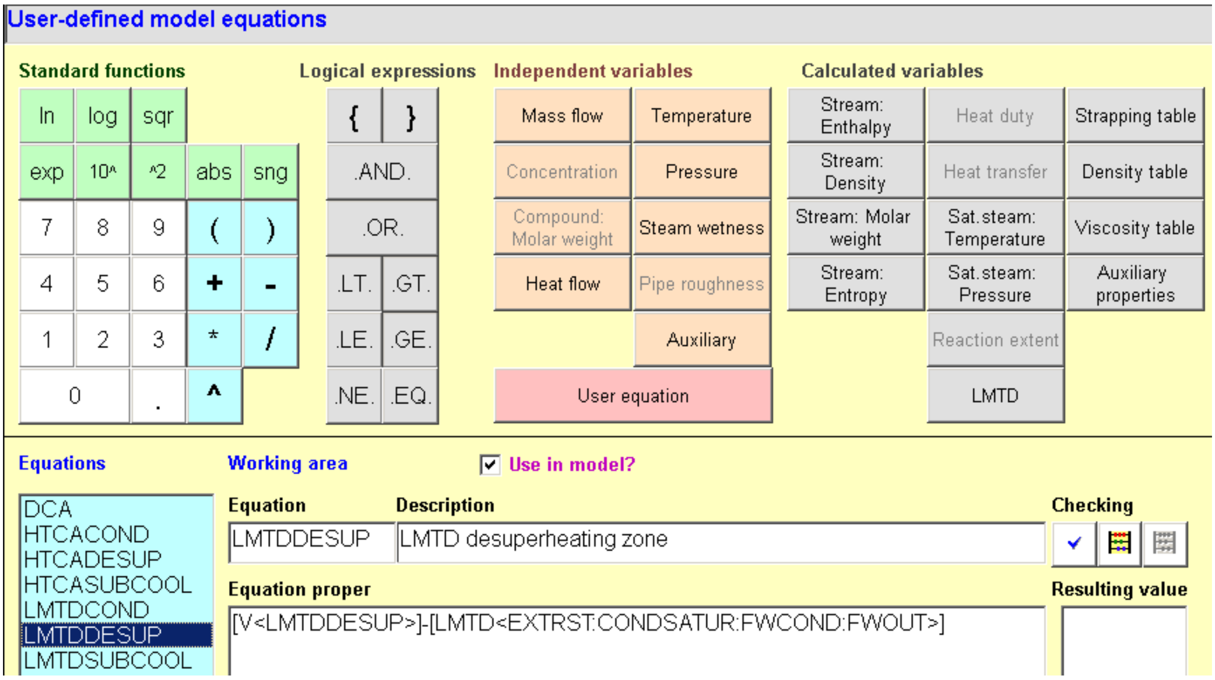

Fig. 2.9: Definition of the LMTD for the desuperheater.

The LMTD function [LMTD<EXTRST:CONDSATUR:FWCOND:FWOUT>] is invoked by the LMTD button on the panel.

3. Results of modeling

Input data of the task are presented in the Apendix 1, complete results of calculation are in the Appendix 2 (RECON's output file). It is supposed that the reader is familiar with basics of Data Reconciliation in the extent of report [4]. Here are some excerpts of main results:

In the input data it is worth mentioning the uncertainties of measured variables. The uncertainties of measured flows were supposed to be 2 % of measured values and temperature's uncertainties were supposed to be 2 ^{o}C.

The iterative calculation proper required 3 iterations. The calculation lasted 0.3 second on a standard desktop PC. The main global characteristics are

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

 Number of nodes                                             7
 Number of heat nodes                                        6
 Number of streams                                          12
 Number of energy streams                                    3
 Number of components                                        1
 Number of temperatures                                      8
 Number of pressures                                         4
 Number of auxiliaries                                       8

 Number of measured variables                               11
 Number of adjusted variables                                0
 Number of non-measured variables                           21
 Number of observed variables                               21
 Number of non-observed variables                            0
 Number of free variables                                    0
 Number of equations (incl. UDE)                            21
 Number of independent equations                            21
 Number of user-defined equations (UDE)                      9

 Degree of redundancy                                        0

 Mean residue of equations                          6.0412E-09
 Qmin                                                        0
 Qcrit                                                       0
 Status (Qmin/Qcrit)                                         0
```

There is no redundancy in this task, just solution of a system of 21 equations in 21 unknown variables. No data validation and no gross errors can be detected.

There are several important KPIs which belong to auxiliary variables (TTD, DCA and HTCAs). For information there are also temperature differences LMTDs.

A U X I L I A R I E S

Name	Type	Inp.value	Rec.value	Abs.error
DCA	NO	3.900	3.900	2.828
HTCACOND	NO	4168891.129	4136670.915	679761.487
HTCADESUP	NO	326315.384	323455.477	57472.358
HTCASUBCOOL	NO	1192145.222	1186238.525	347172.538
LMTDCOND	NO	16.782	16.755	1.901
LMTDDESUP	NO	29.959	29.906	3.052

```
LMTDSUBCOOL      NO           13.776         13.784         3.781
TTD              NO            3.136          3.136         2.026
```

(NO = Nonmeasured Observable variable, Inp.value = first guess, Abs.error = uncertainty)

TTD, DCA and LMTDs are in centigrades, HTCAs are in W/°C.

Heat duties of heat exchangers are in the next table:

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

Name	Type	Inp.value	Rec.value	Abs.error	
QCOND	NO	251.862	249.515	21.644	GJ/H
QDESUP	NO	35.194	34.824	3.495	GJ/H
QSUBCOOL	NO	59.124	58.864	3.801	GJ/H

We can ask a question, which variables are influencing the uncertainty of important variables? The next tables present shares of important variables on the variance of the heat flux QDESUP and HTCA of the desuperheater HTCADESUP (the vector of shares):

```
REPORT ABOUT PROPAGATION OF ERRORS
==================================
Type Variable
 -------------
  HF  QDESUP

 THE VARIANCE OF GIVEN VARIABLE IS CAUSED MAINLY BY:

 Type Variable                 Share
 -----------------------------------
  MF  FWIN                       6 %
  T   EXTRST                     4 %
  T   FWIN                      42 %
  T   FWOUT                     47 %

  Sum                           98 %


 Type Variable
 -------------
  V   HTCADESUP

 THE VARIANCE OF GIVEN VARIABLE IS CAUSED MAINLY BY:

 Type Variable                 Share
 -----------------------------------
  T   FWIN                       9 %
  T   FWOUT                     88 %

  Sum                           97 %

 Legend:
  MF  Mass flow
  T   Temperature
```

The vector of Shares informs how much the individual primary variables influence the Efficiency's variance. In the case of the heat duty QDESUP it is clear that there are 2 variables which together represent 89 % of the QDESUP variance:

Temperature FWIN (feed water inlet)
Temperature FWOUT (feed water outlet)

These variables represent the bottleneck of this heat duty precision. These instruments should be therefore carefully maintained. It should be noted that the uncertainties of temperatures were set as 2 °C.

Literature

[1] ANSI/ASME PTC 12.1 -2000 (R2005): Closed Feedwater Heaters

[2] IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam. International Association for the Properties of Water and Steam. ASME PRESS, NY 1998

[3] Gay R.R., Palmer C.A., Erbes M.R.: Power Plant Performance Monitoring. Tech Books International, New Delhi 2006

[4] Process data validation in practice. Applications from chemical, oil, mineral and power industries. Report CPT 229-07. Usti nad Labem 2007

Appendix 1: RECON's input data

```
RECON 11.1.6-Pro  [CHemPlant]
Task: FWH-3PARTS (3 sectional feed water heater)

G L O B A L   D A T A

 Number of nodes                                          7
 Number of heat nodes                                     6
 Number of streams                                       12
 Number of energy streams                                 3
 Number of components                                     1
 Number of temperatures                                   8
 Number of pressures                                      4
 Number of auxiliaries                                    8


 C O M P O N E N T S

 ID         Description                    Database of properties
 ----------------------------------------------------------------
 H2O


 N O D E S

 ID         Description                    Remark
 ------------------------------------------------
 ENVIRON    Environment                    unbalanced
 COND-FW    condensing zone - feed water si
 COND-ST    condenser steam space
 DESUP-FW   desuperheater Feed Water side
 DESUP-ST   desuperheater steam space
 SUBCOOL-FW subcooler Feed Water space
 SUBCOOL-ST subcooler steam side
 TURBINE    turbine extraction segment     unbalanced


 S T R E A M S

 ID         From node  To node    Description
 -------------------------------------------
 CONDCOND   COND-ST    SUBCOOL-ST condensate from condensing zone
 DESUPST    DESUP-ST   COND-ST    steam from desuperheater
 DRAININ    ENVIRON    COND-ST    drain from the previous heater
 DRAINOUT   SUBCOOL-ST ENVIRON    drain out
 EXTRST     TURBINE    DESUP-ST   extraction steam
 FWCOND     COND-FW    DESUP-FW   Feed Water from condenser
 FWIN       ENVIRON    SUBCOOL-FW feed water inlet
 FWOUT      DESUP-FW   ENVIRON    Feed Water outlet
 FWSUBCOOL  SUBCOOL-FW COND-FW    Feed Water from sucooler
 QCOND      COND-ST    COND-FW    heat flux condenser
 QDESUP     DESUP-ST   DESUP-FW   heat flux desuperheater
 QSUBCOOL   SUBCOOL-ST SUBCOOL-FW heat flux subcooler


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

 ID         Type           Value   Max.error
 ------------------------------------------
 CONDCOND   N           334.4571              T/H
 DESUPST    N           139.4571              T/H
 DRAININ    M           195.0000      2.0000%  T/H
 DRAINOUT   N           334.4571              T/H
 EXTRST     N           139.4571              T/H
 FWCOND     N          2023.2000              T/H
 FWIN       M          2023.2000      2.0000%  T/H
 FWOUT      N          2023.2000              T/H
 FWSUBCOOL  N          2023.2000              T/H


 E N E R G Y   S T R E A M S    [GJ/H]

 ID         Type           Value   Max.error
 ------------------------------------------
```

QCOND	N	251.8621
QDESUP	N	35.1945
QSUBCOOL	N	59.1237

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

ID	Type	Value	Max.error
CONDSATUR	N	271.2358	
DRAININ	M	274.9000	2.0000
DRAINOUT	M	235.1000	2.0000
EXTRST	M	349.0000	2.0000
FWCOND	N	264.4097	
FWIN	M	231.2000	2.0000
FWOUT	M	268.1000	2.0000
FWSUB	N	237.6904	

P R E S S U R E S [BAR]

ID	Type	Value	Max.error
COND	M	56.1000	0.5000%
DRAININ	M	85.0000	0.5000%
EXTRST	M	60.0000	1.0000%
FWIN	M	302.0000	0.5000%

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

ID	Type	Value	Max.error
steam	F	0.000E+0	
water	F	100.0000	

A U X I L I A R I E S

ID	Type	Value	Max.error
DCA	N	3.9000	
HTCACOND	N	4168891.1293	
HTCADESUP	N	326315.3845	
HTCASUBCOOL	N	1192145.2221	
LMTDCOND	N	16.7818	
LMTDDESUP	N	29.9595	
LMTDSUBCOOL	N	13.7762	
TTD	N	3.1358	

H E A T N O D E S

ID	Stream	Function	Temperature	Pressure	Wetness
COND-FW	FWSUBCOOL	H2OL(T,P)	FWSUB	FWIN	
	FWCOND	H2OL(T,P)	FWCOND	FWIN	
COND-ST	DRAININ	H2O(P,X)		DRAININ	water
	DESUPST	H2O(P,X)		COND	steam
	CONDCOND	H2O(P,X)		COND	water
DESUP-FW	FWCOND	H2OL(T,P)	FWCOND	FWIN	
	FWOUT	H2OL(T,P)	FWOUT	FWIN	
DESUP-ST	EXTRST	H2OV(T,P)	EXTRST	EXTRST	
	DESUPST	H2O(P,X)		COND	steam
SUBCOOL-FW	FWIN	H2OL(T,P)	FWIN	FWIN	
	FWSUBCOOL	H2OL(T,P)	FWSUB	FWIN	
SUBCOOL-ST	CONDCOND	H2O(P,X)		COND	water
	DRAINOUT	H2OL(T,P)	DRAINOUT	COND	

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

```
ID          Description                                                 Remark
            Programmatic code
-----------------------------------------------------------------------------------
DCA         Drain Cooler Approach                                       Model
            [V<DCA>]-([T<DRAINOUT>]-[T<FWIN>])

HTCACOND    HTCA condensing zone                                        Model
            [S<QCOND>]-[V<HTCACOND>]*[V<LMTDCOND>]

HTCADESUP   HTCA desuperheating zone                                    Model
            [S<QDESUP>]-[V<HTCADESUP>]*[V<LMTDDESUP>]

HTCASUBCOOL HTCA subcooler                                              Model
            [S<QSUBCOOL>]-[V<HTCASUBCOOL>]*[V<LMTDSUBCOOL>]

LMTDCOND    LMTD condensing zone                                        Model
            [V<LMTDCOND>]-[LMTD<CONDSATUR:CONDSATUR:FWSUB:FWCOND>]

LMTDDESUP   LMTD desuperheating zone                                    Model
            [V<LMTDDESUP>]-[LMTD<EXTRST:CONDSATUR:FWCOND:FWOUT>]

LMTDSUBCOOL LMTD subcooling zone                                        Model
            [V<LMTDSUBCOOL>]-[LMTD<CONDSATUR:DRAINOUT:FWIN:FWSUB>]

SATURTCOND  saturated temperature in condensing zone                    Model
            [T<CONDSATUR>]-[ST<COND>]

TTD         Terminal Temperature Difference                             Model
            [V<TTD>]-([T<CONDSATUR>]-[T<FWOUT>])
```

Appendix 2: RECON's output file

```
RECON 11.1.6-Pro  [ChemPlant]
 Task: FWH-3PARTS (3 sectional feed water heater)

 Balance: [29.10.2013 10:00; 29.10.2013 11:00)

 I T E R A T I O N S

 Iter           Qeq           Qx              Qy            Qmin
 -----------------------------------------------------------------
 START     3.9382E+04
    1      4.1897E+01    0.0000E+00      3.1653E+04      0.0000E+00
    2      8.8289E-05    0.0000E+00      2.8344E+00      0.0000E+00
    3      6.0412E-09    0.0000E+00      3.5774E-05      0.0000E+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                                          7
 Number of heat nodes                                     6
 Number of streams                                       12
 Number of energy streams                                 3
 Number of components                                     1
 Number of temperatures                                   8
 Number of pressures                                      4
 Number of auxiliaries                                    8

 Number of measured variables                            11
 Number of adjusted variables                             0
 Number of non-measured variables                        21
 Number of observed variables                            21
 Number of non-observed variables                         0
 Number of free variables                                 0
 Number of equations (incl. UDE)                         21
 Number of independent equations                         21
 Number of user-defined equations (UDE)                   9

 Degree of redundancy                                     0

 Mean residue of equations                       6.0412E-09
 Qmin                                                     0
 Qcrit                                                    0
 Status (Qmin/Qcrit)                                      0


 S T R E A M S

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 CONDCOND         NO          334.457        332.988         13.935  T/H
 DESUPST          NO          139.457        137.988         13.559  T/H
 DRAININ          MN          195.000        195.000          3.900  T/H
 DRAINOUT         NO          334.457        332.988         13.935  T/H
 EXTRST           NO          139.457        137.988         13.559  T/H
 FWCOND           NO         2023.200       2023.200         40.464  T/H
 FWIN             MN         2023.200       2023.200         40.464  T/H
 FWOUT            NO         2023.200       2023.200         40.464  T/H
 FWSUBCOOL        NO         2023.200       2023.200         40.464  T/H

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

 Name             Type      Inp.value      Rec.value      Abs.error
 ------------------------------------------------------------------
 QCOND            NO          251.862        249.515         21.644  GJ/H
 QDESUP           NO           35.194         34.824          3.495  GJ/H
 QSUBCOOL         NO           59.124         58.864          3.801  GJ/H
```

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

Name	Type	Inp.value	Rec.value	Abs.error	
CONDSATUR	NO	271.236	271.236	0.321	C
DRAININ	MN	274.900	274.900	2.000	C
DRAINOUT	MN	235.100	235.100	2.000	C
EXTRST	MN	349.000	349.000	2.000	C
FWCOND	NO	264.410	264.449	1.780	C
FWIN	MN	231.200	231.200	2.000	C
FWOUT	MN	268.100	268.100	2.000	C
FWSUB	NO	237.690	237.662	1.851	C

P R E S S U R E S

Name	Type	Inp.value	Rec.value	Abs.error	
COND	MN	56.100	56.100	0.281	BAR
DRAININ	MN	85.000	85.000	0.425	BAR
EXTRST	MN	60.000	60.000	0.600	BAR
FWIN	MN	302.000	302.000	1.510	BAR

W E T N E S S E S

Name	Type	Inp.value	Rec.value	Abs.error	
steam	F	0.00E+0	0.00E+0		%
water	F	100.000	100.000		%

A U X I L I A R I E S

Name	Type	Inp.value	Rec.value	Abs.error
DCA	NO	3.900	3.900	2.828
HTCACOND	NO	4168891.129	4136670.915	679761.487
HTCADESUP	NO	326315.384	323455.477	57472.358
HTCASUBCOOL	NO	1192145.222	1186238.525	347172.538
LMTDCOND	NO	16.782	16.755	1.901
LMTDDESUP	NO	29.959	29.906	3.052
LMTDSUBCOOL	NO	13.776	13.784	3.781
TTD	NO	3.136	3.136	2.026

End of results

Calculations lasted 00:00:0.301
Report created 12.11.2013 12:20:07