Trnsys User Manual

TYPE 402

Compressor Heat Pump Including Modulation, and Frost and Cycle Losses

Version 2.0, November 2022

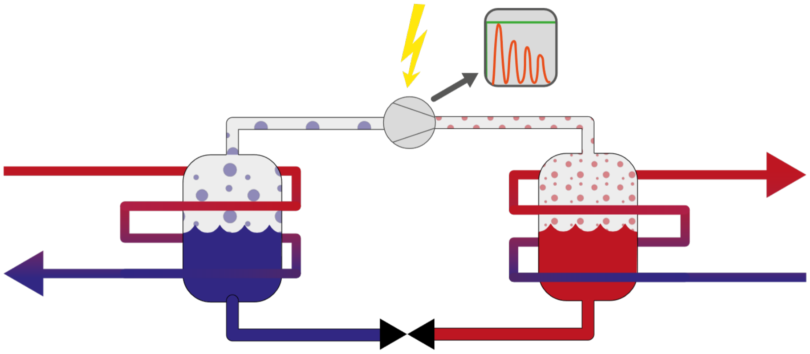

Table of Contents

1. Nomenclature

τ - Time constant
Δ - Difference
A - Constant for frost/defrost loss
B - Constant for frost/defrost loss
bp - Polynomial coefficient for compressor power
bq - Polynomial coefficient for condenser power
C - Constant for frost/defrost loss
c - Specific heat capacity
COP - Coefficient of performance
D - Constant for frost/defrost loss
E - Constant for frost/defrost loss
f - Scaling factor for heat pump power
m - Mass flow
P - Electrical power
Q - Heating power
T - Temperature
t - Time
Y - Modulation speed

Subscripts

c - Condenser
corr - Corrected
e - Evaporator
f - Fictive
hp - Heat pump
ice - Icing/defrosting
icycle - Including cycle losses
in - Inlet
lb - Lower boundary
m - Mean value
n - Normalized

nom	-	Nominal value
off	-	Off
on	-	On
out	-	Outlet
plug	-	Power at the electrical terminals
ss	-	Steady state
ub		Upper boundary
wol		Without losses

2. Introduction

This component is an update of Type 401 by Dr. Thomas Afjei (INFEL Zürich) and Michael Wetter (ZTL Luzern). The original component was created on behalf of the Swiss Federal Institute of Energy: Low temperature low-cost heat pump heating system, and modeled a single speed compressor heat pump including frost and cycle losses. For Type 402, the component was extended by Arno Dentel (Technische Hochschule Nürnberg) to include a modulation of compressor speed in the model.

2.1. Installation

For using Type402 the recent 64-bit TRNSYS Version (TRNSYS 18.04.) has to be installed. The provided installation copies files in the appropriate directories:

\TRNSYS18\Documentation\Nostand

\TRNSYS18\Examples\Nostand

\TRNSYS18\SourceCode\Nostand

\TRNSYS18\Userlib\

\TRNSYS18\Studio\Proformas\Nostand\

\TRNSYS18\Tools\

2.2. Citation

To cite this document and the associated software, please use:

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3. Trnsys Component Configuration

3.1. Description of Parameters

Par. no.	Symbol	Description	Unit
1	ce	**Specific heat of evaporator fluid**	kJ/kg
2	cc	**Specific hat of condenser fluid**	kJ/hr
3	Pcar	**Power of carter heating**	°C
4	loprth	**Set point of low-pressure thermostat (temperature)**	°C
5	hiprth	**Set point of high-pressure thermostat (temperature)**	-
6	airhp	**Flag for evaporator icing/defrosting** airhp = 0 ⇒ No icing/dforsting is calculated airhp = 1 ⇒ Icing/defrosting is calculated	-
7	COPcorr1	**1st COP correction value on straight line of frost curve**	-
8	COPcorr2	**2nd COP correction value on straight line of frost curve**	-
9	COPcorr3	**Maximum COP correction on Gauss curve** (not on the superposition of the Gauss curve and the straight line!)	°C
10	Tdbcorr1	**Outside air temperature at 1st COP correction value**	°C
11	Tdbcorr2	**Outside air temperature at 2nd COP correction value**	°C
12	Tdbcorr3	**Outside air temperature at maximum of Gauss curve**	°C
13	Tdbcorr4	**Width (temperature) of the gauss curve on the half height of the Gauss maximum**	hr
14	tauon	**Heat-up constant, related to the mean operation power**	hr
15	tauoff	**Cool-down constant** Related to evaporator inlet temp. +7°C and condenser outlet temp. +35°C	-
16	nchangemax	**Maximal number of changes of the heat pump mode during a TRNSYS timestep**	-
17	LUNhpd	**Logical unit number of file that contains the polynomial coefficients of the condenser and compressor power**	-

Note:

assign *filename LUNhpd*

The heat pump data file contains the coefficients of both, the condenser power and the compressor power. To generate these coefficients, the EES executables which are included in the installation can be used. Existing data files from version 1.0 can be converted to the new format using a conversion tool included in the installation. (See more in section 4. Getting Started)

3.2. Description of Inputs

Input no	Symbol	Description	Unit
1	Tein	**Inlet temperature evaporator**	°C
2	mdote	**Mass flow evaporator**	kg/hr
3	Tcin	**Inlet temperature condenser**	°C
4	mdotc	**Mass flow condenser**	kg/hr
5	yhp	**Control signal for heat pump** yhp = 0 ⇒ off yhp = 1 ⇒ on	-
6	ycar	**Control signal for carter heating** ycar = 0 ⇒ off ycar = 1 ⇒ on	-
7	Yn	**Modulation speed** Compressor speed of the heat pump	-

3.3. Description of Outputs

Out. no	Symbol	Description	Unit
1	Teout	**Evaporator outlet temperature**	°C
2	mdote	**Evaporator mass flow rate**	kg/hr
3	Tcoutc	**Condenser outlet temperature**	°C
4	mdotc	**Condenser mass flow rate**	kg/hr
5	Qdotmc	**Mean condenser power over the timestep**	kJ/hr
6	Qdotme	**Mean evaporator power over the timestep**	kJ/hr
7	Pcomp	**Compressor power**	kJ/hr
8	Pcar	**Carter heating power**	kJ/hr
9	(Pcomp+Pcar)	**Sum of compressor and carter heating power**	kJ/hr
10	COPc	**Coefficient of performance**	-
11	deltCOP	**Relative COP reduction due to icing/defrost losses**	-
12	hpmode	**Operation mode of heat pump** hpmode = 100 ⇒ heat pump on, usual operation hpmode = 200 ⇒ Heat pump switched off due to signal from external controller (yhp=0) hpmode = 210 ⇒ Low-pressure error. Evaporator inlet temperature lower than low-pressure thermostat hpmode = 220 ⇒ Low-pressure error. Evaporator outlet temperature lower than low-pressure thermostat hpmode = 230 ⇒ Low-pressure error. No mass flow through evaporator	-

		hpmode = 250 ⇒ High-pressure error. Condenser inlet temperature higher than high-pressure thermostat hpmode = 260 ⇒ High-pressure error. Condenser outlet temperature higher than high-pressure thermostat hpmode = 270 ⇒ High-pressure error. No mass flow through condenser	
13	switch	**Number of times heat pump switched on since start of simulation**	-
14	timeint	If the heat pump is changed from not running to running in the current time step: **Time difference between the last switch on signal and the current time step,** Otherwise: timeint = 0.	hr

4. Getting Started

4.1. Updating existing Models with Type 402

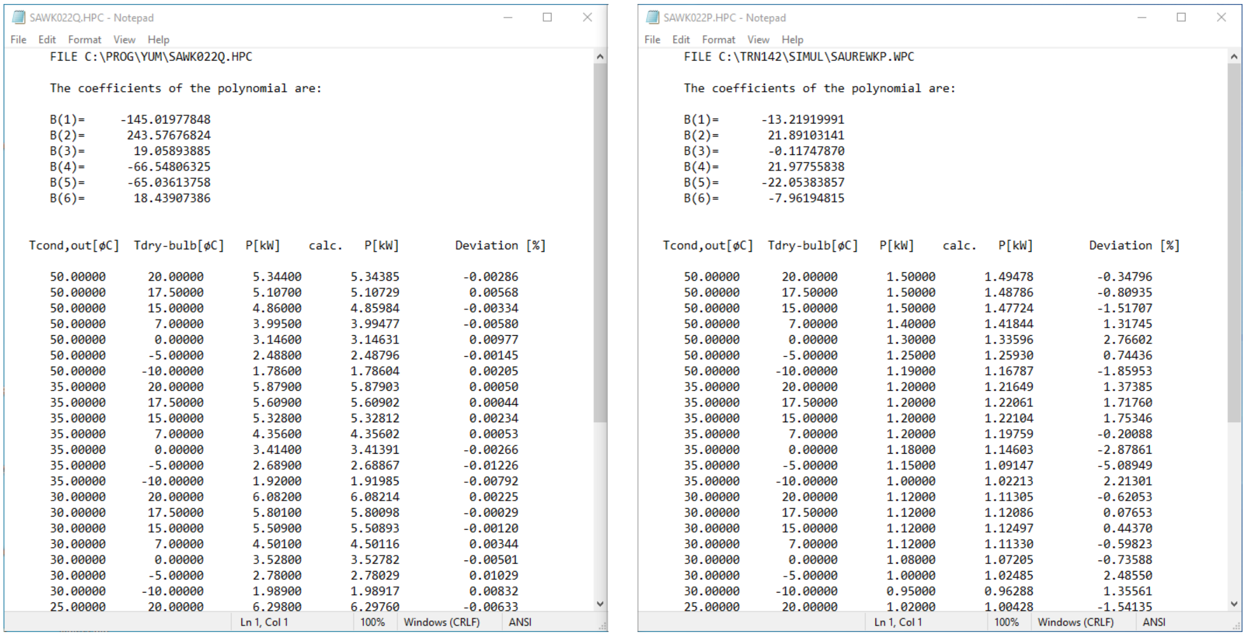
Simulation projects that have been created with the previous version Type 401, can be updated to use the new version Type 402 of the component.

Attention: The existing coefficients have been created for a single speed and therefore cannot be used to simulate a modulating heat pump. When using single speed coefficients, the modulation speed can only be 0/1.

Projects can be updated using the *Replace* function in Simulation Studio, however, there have been some changes to the component, so the user has to adjust a few details before running an updated simulation.

External Files

Converting the existing coefficient files to one new input file. For the existing version, two input files were used to specify the six coefficients each for the condenser polynom and the compressor polynom individually (see example files below).



```
     FILE C:\PROG\YUM\SAWK022Q.HPC

     The coefficients of the polynomial are:

     B(1)=     -145.01977848
     B(2)=      243.57676824
     B(3)=       19.05893885
     B(4)=      -66.54806325
     B(5)=      -65.03613758
     B(6)=       18.43907386


  Tcond,out[øC]  Tdry-bulb[øC]   P[kW]    calc.   P[kW]        Deviation [%]

     50.00000      20.00000      5.34400      5.34385       -0.00286
     50.00000      17.50000      5.10700      5.10729        0.00568
     50.00000      15.00000      4.86000      4.85984       -0.00334
     50.00000       7.00000      3.99500      3.99477       -0.00580
     50.00000       0.00000      3.14600      3.14631        0.00977
     50.00000      -5.00000      2.48800      2.48796       -0.00145
     50.00000     -10.00000      1.78600      1.78604        0.00205
     35.00000      20.00000      5.87900      5.87903        0.00050
     35.00000      17.50000      5.60900      5.60902        0.00044
     35.00000      15.00000      5.32800      5.32812        0.00234
     35.00000       7.00000      4.35600      4.35602        0.00053
     35.00000       0.00000      3.41400      3.41391       -0.00266
     35.00000      -5.00000      2.68900      2.68867       -0.01226
     35.00000     -10.00000      1.92000      1.91985       -0.00792
     30.00000      20.00000      6.08200      6.08214        0.00225
     30.00000      17.50000      5.80100      5.80098       -0.00029
     30.00000      15.00000      5.50900      5.50893       -0.00120
     30.00000       7.00000      4.50100      4.50116        0.00344
     30.00000       0.00000      3.52800      3.52782       -0.00501
     30.00000      -5.00000      2.78000      2.78029        0.01029
     30.00000     -10.00000      1.98900      1.98917        0.00832
     25.00000      20.00000      6.29800      6.29760       -0.00633
```

```
     FILE C:\TRN142\SIMUL\SAUREWKP.WPC

     The coefficients of the polynomial are:

     B(1)=      -13.21919991
     B(2)=       21.89103141
     B(3)=       -0.11747870
     B(4)=       21.97755838
     B(5)=      -22.05383857
     B(6)=       -7.96194815


  Tcond,out[øC]  Tdry-bulb[øC]   P[kW]    calc.   P[kW]        Deviation [%]

     50.00000      20.00000      1.50000      1.49478       -0.34796
     50.00000      17.50000      1.50000      1.48786       -0.80935
     50.00000      15.00000      1.50000      1.47724       -1.51707
     50.00000       7.00000      1.40000      1.41844        1.31745
     50.00000       0.00000      1.30000      1.33596        2.76602
     50.00000      -5.00000      1.25000      1.25930        0.74436
     50.00000     -10.00000      1.19000      1.16787       -1.85953
     35.00000      20.00000      1.20000      1.21649        1.37385
     35.00000      17.50000      1.20000      1.22061        1.71760
     35.00000      15.00000      1.20000      1.22104        1.75346
     35.00000       7.00000      1.20000      1.19759       -0.20088
     35.00000       0.00000      1.18000      1.14603       -2.87861
     35.00000      -5.00000      1.15000      1.09147       -5.08949
     35.00000     -10.00000      1.00000      1.02213        2.21301
     30.00000      20.00000      1.12000      1.11305       -0.62053
     30.00000      17.50000      1.12000      1.12086        0.07653
     30.00000      15.00000      1.12000      1.12497        0.44370
     30.00000       7.00000      1.12000      1.11330       -0.59823
     30.00000       0.00000      1.08000      1.07205       -0.73588
     30.00000      -5.00000      1.00000      1.02485        2.48550
     30.00000     -10.00000      0.95000      0.96288        1.35561
     25.00000      20.00000      1.02000      1.00428       -1.54135
```

Figure 1: Old structure of external files for Type 401

For the updated version, the model uses new polynoms that include the effect of the modulation speed and need eight coefficients each instead of six. With a binary modulation speed of only 0/1, the existing coefficients can be used, but have to be assigned differently. The following equations show the function of the coefficients within the condenser polynom in both versions in comparison. The two new coefficients in the updated polynom (2) have to be set to zero and the index of the coefficients 4,5 and 6 shifted to 5,6,7 to match the equation. With these adaptations the new polynom will produce the same results for a single speed heat pump as the old model.

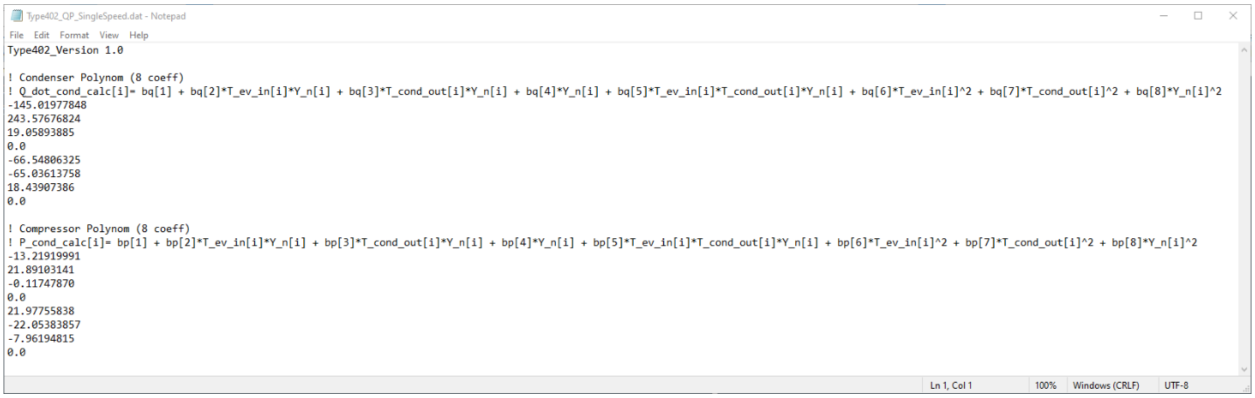
$Q_{ss,c,wol} =$

$$bq_1 + bq_2\, T_{n,e,in} + bq_3\, T_{n,c,out} + bq_4 T_{n,e,in}\, T_{n,c,out} + bq_5 T_{n,e,in}{}^2 + bq_6 T_{n,c,out}{}^2 \quad \textbf{(1)}$$

$$bq_1 + bq_2\, T_{n,e,in} \boldsymbol{Y_{n,i}} + bq_3\, T_{n,c,out} \boldsymbol{Y_{n,i}} + \boldsymbol{bq_4 Y_{n,i}} + bq_{\mathbf{5}} T_{n,e,in}\, T_{n,c,out} \boldsymbol{Y_{n,i}} + bq_{\mathbf{6}} T_{n,e,in}{}^2 + bq_{\mathbf{7}} T_{n,c,out}{}^2 + \boldsymbol{bq_8\, Y_{n,i}{}^2} \quad \textbf{(2)}$$

This applies to the compressor polynom in the same way. The resulting 16 coefficients are now stored in one unified external file for the heat pump with the following format:

- Version Statement: *Type402_Version 1.0*
- 8 polynomic coefficients for the condenser polynom
- 8 polynomic coefficients for the compressor polynom
- optional: rows starting with ! as *helptext*



```
Type402_Version 1.0

! Condenser Polynom (8 coeff)
! Q_dot_cond_calc[i]= bq[1] + bq[2]*T_ev_in[i]*Y_n[i] + bq[3]*T_cond_out[i]*Y_n[i] + bq[4]*Y_n[i] + bq[5]*T_ev_in[i]*T_cond_out[i]*Y_n[i] + bq[6]*T_ev_in[i]^2 + bq[7]*T_cond_out[i]^2 + bq[8]*Y_n[i]^2
-145.01977848
243.57676824
19.05893885
0.0
-66.54806325
-65.03613758
18.43907386
0.0

! Compressor Polynom (8 coeff)
! P_cond_calc[i]= bp[1] + bp[2]*T_ev_in[i]*Y_n[i] + bp[3]*T_cond_out[i]*Y_n[i] + bp[4]*Y_n[i] + bp[5]*T_ev_in[i]*T_cond_out[i]*Y_n[i] + bp[6]*T_ev_in[i]^2 + bp[7]*T_cond_out[i]^2 + bp[8]*Y_n[i]^2
-13.21919991
21.89103141
-0.11747870
0.0
21.97755838
-22.05383857
-7.96194815
0.0
```

Figure 2: Structure of external file for Type 402 containing condenser and compressor coefficients

To convert existing files from the old structure into the new one, the *DatFileConversion* tool can be used, which is included in the installation at C:\TRNSYS18\Tools\Type402\DatFile_Conversion\. The tool can be called from the command line or using a batch job and needs at least two arguments:

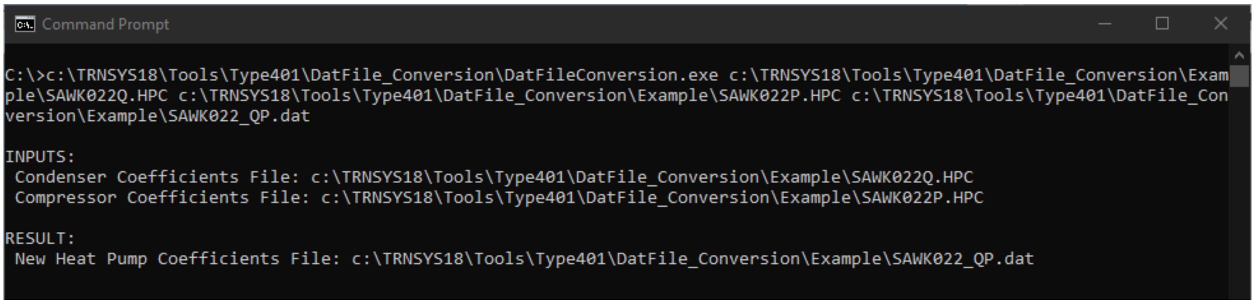
- File path of the condenser coefficients file
- File path of the compressor coefficients file

With an optional third argument, the desired name/ location of the output file can be specified.

DatFileConversion.exe %1 %2 %3
with
%1 File path of your condenser coefficients file
%2 File path of your compressor coefficients file
%3 File path of the converted result file (optional)

Example:

c:\TRNSYS18\Tools\Type402\DatFile_Conversion\DatFileConversion.exe c:\TRNSYS18\Tools\Type402\DatFile_Conversion\Example\SAWK022Q.HPC c:\TRNSYS18\Tools\Type402\DatFile_Conversion\Example\SAWK022P.HPC c:\TRNSYS18\Tools\Type402\DatFile_Conversion\Example\SAWK022_QP.dat



```
C:\>c:\TRNSYS18\Tools\Type401\DatFile_Conversion\DatFileConversion.exe c:\TRNSYS18\Tools\Type401\DatFile_Conversion\Exam
ple\SAWK022Q.HPC c:\TRNSYS18\Tools\Type401\DatFile_Conversion\Example\SAWK022P.HPC c:\TRNSYS18\Tools\Type401\DatFile_Con
version\Example\SAWK022_QP.dat

INPUTS:
 Condenser Coefficients File: c:\TRNSYS18\Tools\Type401\DatFile_Conversion\Example\SAWK022Q.HPC
 Compressor Coefficients File: c:\TRNSYS18\Tools\Type401\DatFile_Conversion\Example\SAWK022P.HPC

RESULT:
 New Heat Pump Coefficients File: c:\TRNSYS18\Tools\Type401\DatFile_Conversion\Example\SAWK022_QP.dat
```

Figure 3: Execution of DatFileConversion Tool with three arguments

If no file path for the result file is provided, the file is saved in the folder where the conversion tool is located and assigned a default name (Type402_QP_SingleSpeed.dat).

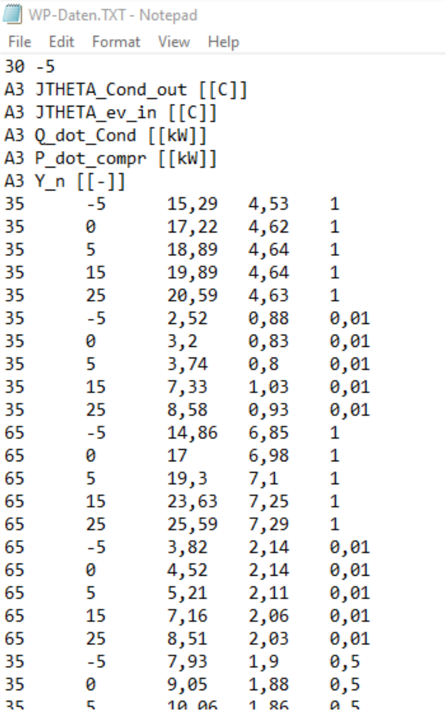
Finally, the new data file has to be assigned to the component in the External Files tab in Simulation Studio.

Inputs

The updated type uses one new input, that was not present in the old component, the modulation speed $\boldsymbol{Y_{n,i}}$. Because coefficients from Type 401 **cannot be used to model a modulation of the heat pump**, this input should not be used and just kept at the default value of 1. This way, the heat pump will be controlled through the control signal in input 5 as in the previous versions.

4.2. Create coefficients for Type 402

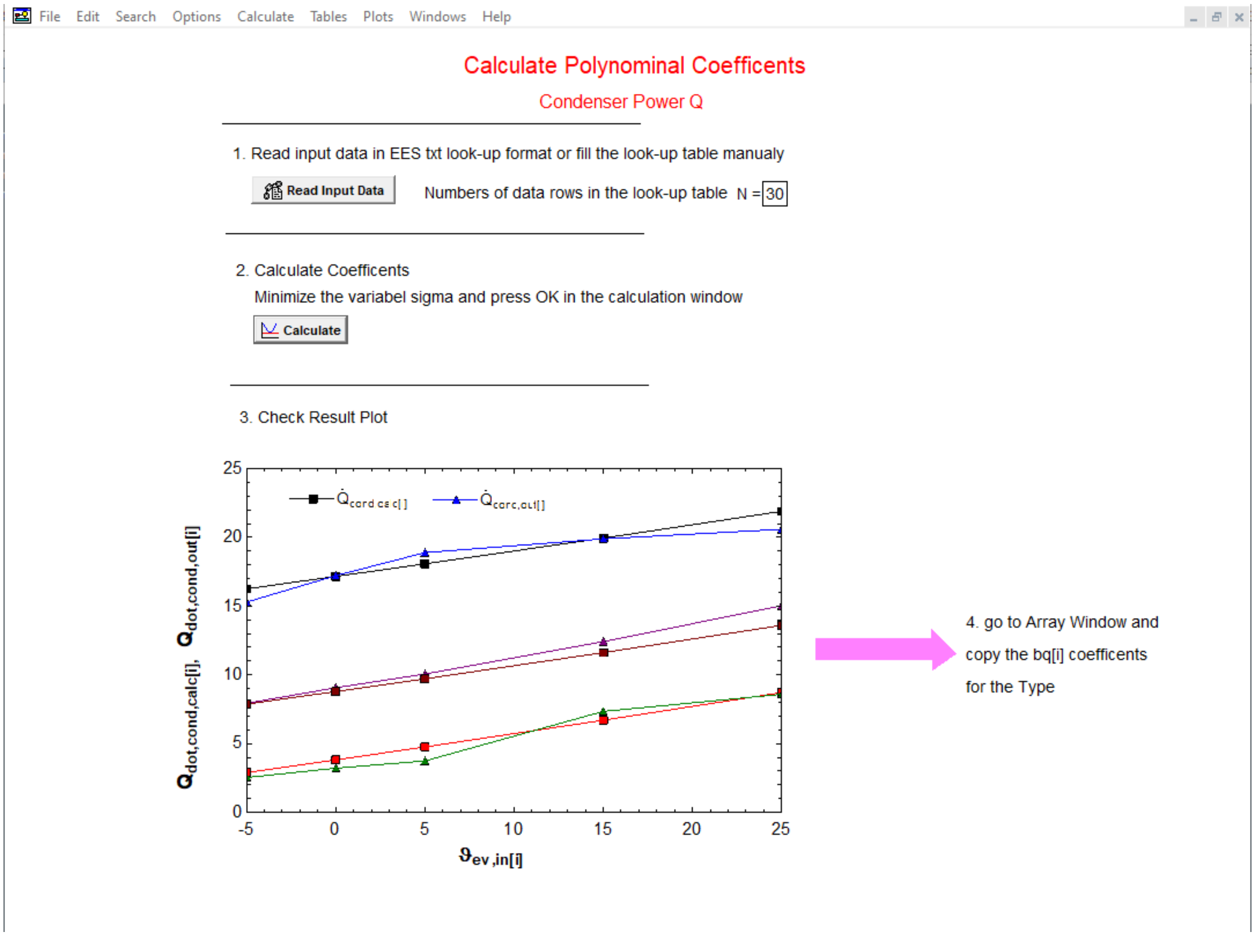
Creating the polynomial coefficients for condenser power and compressor power using the included EES executables (*WP_Model_P_Polynom.exe* and *WP_Model_Q_Polynom.exe*). For the use of the executables, no EES license is required. Create a file containing the manufacturer data in the format seen below. You can find a sample file in \TRNSYS18\Tools\Type402\WP_Daten.txt



```
30 -5
A3 JTHETA_Cond_out [[C]]
A3 JTHETA_ev_in [[C]]
A3 Q_dot_Cond [[kW]]
A3 P_dot_compr [[kW]]
A3 Y_n [[-]]
35      -5      15,29   4,53    1
35      0       17,22   4,62    1
35      5       18,89   4,64    1
35      15      19,89   4,64    1
35      25      20,59   4,63    1
35      -5      2,52    0,88    0,01
35      0       3,2     0,83    0,01
35      5       3,74    0,8     0,01
35      15      7,33    1,03    0,01
35      25      8,58    0,93    0,01
65      -5      14,86   6,85    1
65      0       17      6,98    1
65      5       19,3    7,1     1
65      15      23,63   7,25    1
65      25      25,59   7,29    1
65      -5      3,82    2,14    0,01
65      0       4,52    2,14    0,01
65      5       5,21    2,11    0,01
65      15      7,16    2,06    0,01
65      25      8,51    2,03    0,01
35      -5      7,93    1,9     0,5
35      0       9,05    1,88    0,5
35      5       10,06   1,86    0,5
```

Figure 4: Example/ structure of manufacturer data

Start the first executable, set the number of data rows according to the number of your input data points and use the *Read Input Data* button to select your input data file.



Calculate Polynominal Coefficents

Condenser Power Q

1. Read input data in EES txt look-up format or fill the look-up table manualy

Numbers of data rows in the look-up table N = 30

2. Calculate Coefficents

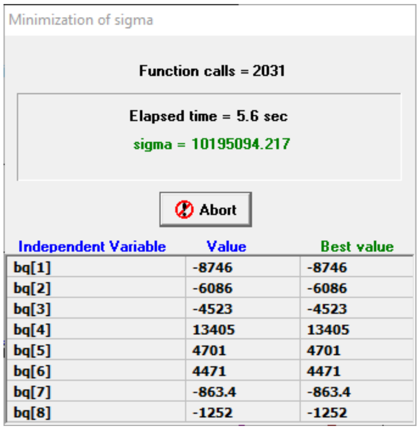
Minimize the variabel sigma and press OK in the calculation window

3. Check Result Plot

4. go to Array Window and copy the bq[i] coefficents for the Type

Figure 5: Interface of the EES executable for the Condenser power polynom

The calculate button will start a minimization of the sum of square errors *sigma* using the Nelder-Mead-Method

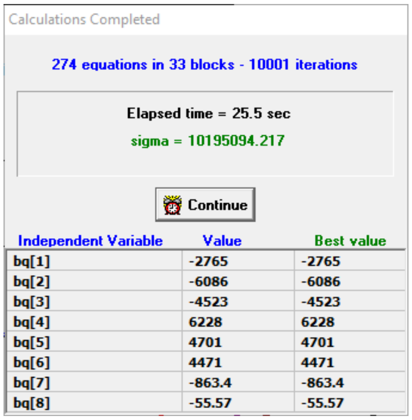


Function calls = 2031

Elapsed time = 5.6 sec

sigma = 10195094.217

Independent Variable	Value	Best value
bq[1]	-8746	-8746
bq[2]	-6086	-6086
bq[3]	-4523	-4523
bq[4]	13405	13405
bq[5]	4701	4701
bq[6]	4471	4471
bq[7]	-863.4	-863.4
bq[8]	-1252	-1252

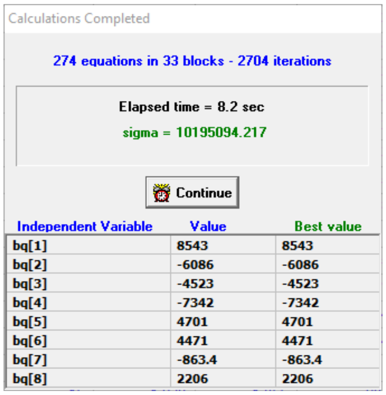


274 equations in 33 blocks - 10001 iterations

Elapsed time = 25.5 sec

sigma = 10195094.217

Independent Variable	Value	Best value
bq[1]	-2765	-2765
bq[2]	-6086	-6086
bq[3]	-4523	-4523
bq[4]	6228	6228
bq[5]	4701	4701
bq[6]	4471	4471
bq[7]	-863.4	-863.4
bq[8]	-55.57	-55.57



274 equations in 33 blocks - 2704 iterations

Elapsed time = 8.2 sec

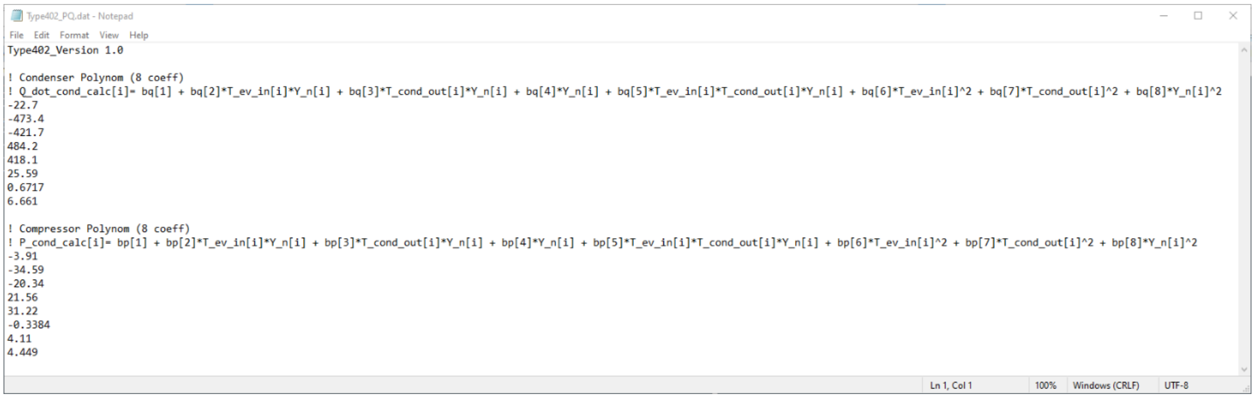
sigma = 10195094.217

Independent Variable	Value	Best value
bq[1]	8543	8543
bq[2]	-6086	-6086
bq[3]	-4523	-4523
bq[4]	-7342	-7342
bq[5]	4701	4701
bq[6]	4471	4471
bq[7]	-863.4	-863.4
bq[8]	2206	2206

The polynomial coefficients then can be copied into the external file. For example **Type402_PQ.dat** (c:\TRNSYS18\Examples\Nostand\Type402\Modulating\Type402_PQ.dat)

The format of these files must be the following:

- Version Statement: *Type402_Version 1.0*
- 8 polynomic coefficients for the condenser polynom
- 8 polynomic coefficients for the compressor polynom
- optional: rows starting with ! as *helptext*



```
Type402_Version 1.0

! Condenser Polynom (8 coeff)
! Q_dot_cond_calc[i]= bq[1] + bq[2]*T_ev_in[i]*Y_n[i] + bq[3]*T_cond_out[i]*Y_n[i] + bq[4]*Y_n[i] + bq[5]*T_ev_in[i]*T_cond_out[i]*Y_n[i] + bq[6]*T_ev_in[i]^2 + bq[7]*T_cond_out[i]^2 + bq[8]*Y_n[i]^2
-22.7
-473.4
-421.7
484.2
418.1
25.59
0.6717
6.661

! Compressor Polynom (8 coeff)
! P_cond_calc[i]= bp[1] + bp[2]*T_ev_in[i]*Y_n[i] + bp[3]*T_cond_out[i]*Y_n[i] + bp[4]*Y_n[i] + bp[5]*T_ev_in[i]*T_cond_out[i]*Y_n[i] + bp[6]*T_ev_in[i]^2 + bp[7]*T_cond_out[i]^2 + bp[8]*Y_n[i]^2
-3.91
-34.59
-20.34
21.56
31.22
-0.3384
4.11
4.449
```

Figure 6: Example Data file for Type 402

5. General Description

The heat pump is modeled as a black-box. The model is based on the one used in the YUM simulation program [1, 2]. The boundary conditions are the evaporator and condenser inlet temperature, the evaporator and condenser mass flow and the control signal of an external simulated controller.

The power of the condenser and the evaporator is calculated based on characteristic power curves which are usually supplied by the manufacturer of the heat pump. The curves show the condenser power and the electric power as a function of the evaporator inlet temperature and the condenser outlet temperature (see Fig. 1). These values are used to calculate coefficients of biquadratic polynomials.

	Relative error
Condenser energy	6.6%
Compressor energy	12.5%
COP	2.7%

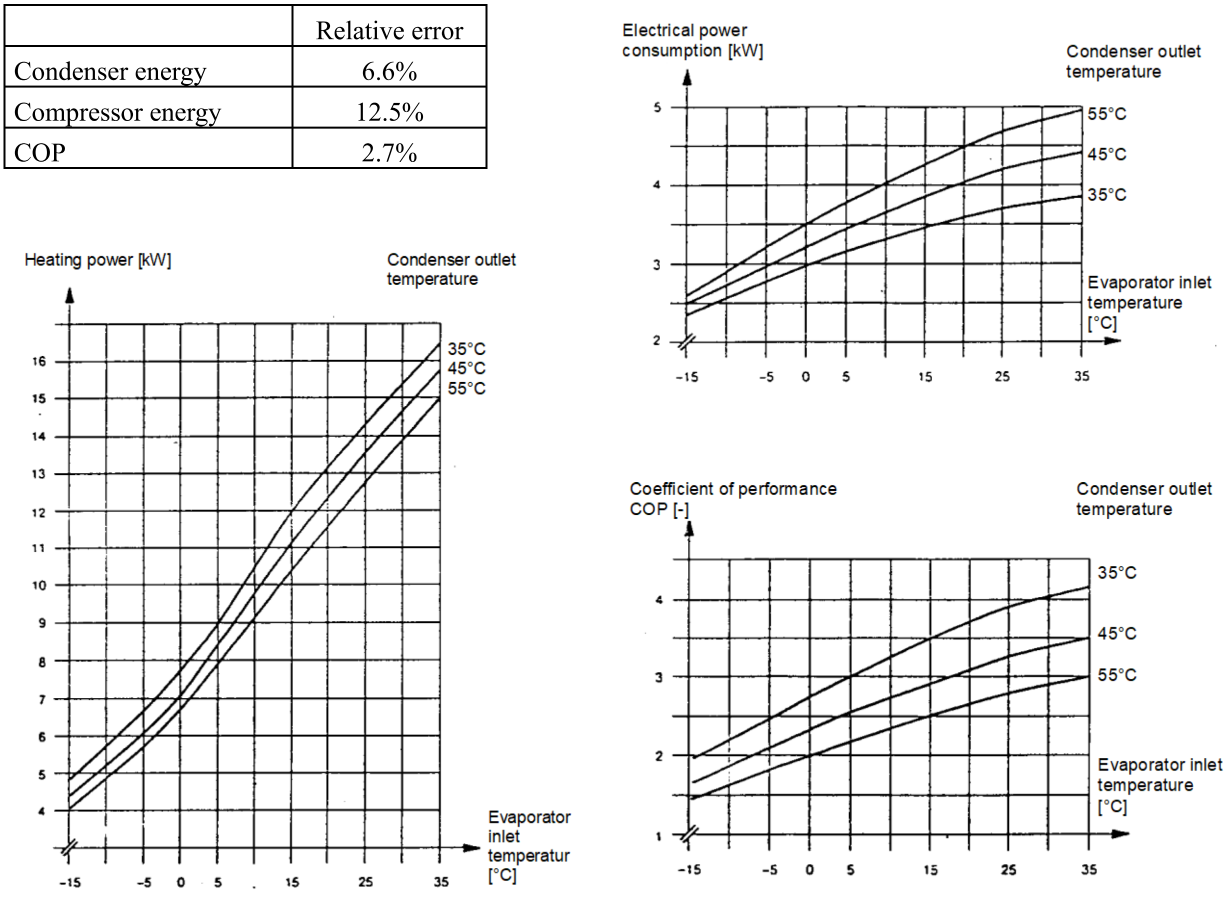


Figure 7: Power characteristics of a heat pump

6. Mathematical Description

Sign convention: Added power or energy is always positive, emitted always negative

6.1. Steady state condenser and compressor power

The biquadratic polynomial coefficients are read in from the heat pump data file specified in the external files tab.

The steady-state power is then computed with the biquadratic polynomial:

$$\begin{aligned} Q_{ss,c,wol} = {} & bq_1 + bq_2\, T_{n,e,in} Y_{n,i} + bq_3\, T_{n,c,out} Y_{n,i} + bq_4 Y_{n,i} \\ & + bq_5 T_{n,e,in}\, T_{n,c,out} Y_{n,i} + bq_6 {T_{n,e,in}}^2 \\ & + bq_6 {T_{n,c,out}}^2 \; + bq_8\, {Y_{n,i}}^2 \end{aligned} \tag{2}$$

$$\begin{aligned} Q_{ss,c,wol} = {} & bp_1 + bp_2\, T_{n,e,in} Y_{n,i} + bp_3\, T_{n,c,out} Y_{n,i} + bp_4 Y_{n,i} \\ & + bp_5 T_{n,e,in}\, T_{n,c,out} Y_{n,i} + bp_6 {T_{n,e,in}}^2 \\ & + bp_6 {T_{n,c,out}}^2 \; + bp_8\, {Y_{n,i}}^2 \end{aligned} \tag{3}$$

In the polynomial, normalized temperatures according to the formula

$$T_n = \frac{T[°C]}{273.15} + 1.0 \tag{4}$$

are used.

6.2. Iteration of condenser outlet temperature

The condenser outlet temperature is used as an independent variable in Eq. 2 and Eq. 3. Since the condenser outlet temperature is also dependent of the result of Eq. 2 and Eq. 3, it must be calculated iteratively. The iteration is carried out with the Van Wijngaarden-Decker-Brent algorithm [3]. This algorithm combines the stability of the bisection with the calculation speed of the inverse quadratic interpolation.

6.3. Cycling losses

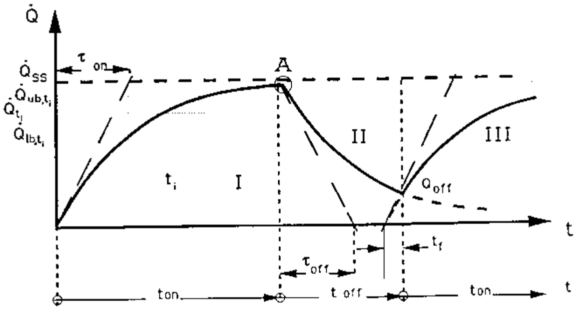


Figure 8: Cycling losses shown with an example of a discrete time step

After the heat pump is switched on, the machine has to be heated up and the pressure difference between the evaporator and the condenser must be built up. This leads to a power reduction during the heat-up process. The power reduction during the heat-up process of a completely cooled down heat pump (area **I**) can be written with

$$\Delta\dot{Q}_{on,c} = \dot{Q}_{ss,c}\, e^{-\frac{t_{on}}{\tau_{on}}} \tag{5}$$

In the case that the heat pump has not cooled down completely, the switch-on time can be transformed according to Fig. 2 (area **III**). Eq. 5 can therefore be written as:

$$\Delta\dot{Q}_{on,c} = \dot{Q}_{ss,c}\, e^{-\frac{t_f+t_{an}}{\tau_{on}}} \tag{6}$$

The effective condenser power (without icing and defrosting losses) can then be calculated according to:

$$\dot{Q}_c = \dot{Q}_{ss,c} - \Delta\dot{Q}_{on,c} = \dot{Q}_{ss,c}\left(1 - e^{-\frac{t_f+t_{on}}{t_{on}}}\right) \tag{7}$$

The time shift t_f is computed every time the heat pump is switched on. Because the running time ton is equal to 0 when the heat pump is switched on (border of area **II** and area **III**), the time shift t_f can be calculated according to

$$\dot{Q}_{lb,c} = \dot{Q}_{ss,c}\left(1 - e^{-\frac{t_f}{t_{on}}}\right) \tag{8}$$

Eq. 8 solved for the required time shift t_f is

$$t_f = -\tau_{on} \ln\left(1 - \frac{\dot{Q}_{lb,c}}{\dot{Q}_{ss,c}}\right) \tag{9}$$

If the heat pump is not running, its energy is assumed to decrease exponentially. Therefore, the starting point of the cool-down function must be known (Fig. 2, point A). For calculating the starting point of the cool-down curve, the power at the upper boundary of the current time interval must be calculated at every time step during the operating phase using the expression

$$\dot{Q}_{ub,c} = \dot{Q}_{ss,c}\left(1 - e^{-\frac{t_f+t_{on,ub}}{t_{on}}}\right) \tag{10}$$

The cool-down curve in Fig. 2 (area **II**) is calculated analogously to the heating reduction described previously:

$$\dot{Q}_{loss,c} = \dot{Q}_{ss,c,nom}\, e^{\frac{t_f+t_{off}}{\tau_{off}}} \tag{11}$$

The cool-down process is assumed to be proportional to the nominal power of the heat pump (at 7°C evaporator inlet temperature and 35°C condenser outlet temperature). Therefore, the time constant for the cool-down process which is derived from measurement data has to be based on this nominal power. The time shift t_f is analogously to the approach of Eq. 8**Error! Bookmark not defined.**, but with a decreasing exponential function:

$$\dot{Q}_{lb,c} = \dot{Q}_{ss,c,nom}\; e^{-\frac{t_f}{\tau_{off}}} \tag{12}$$

$$t_f = -\tau_{off}\ ln\left(1 - \frac{\dot{Q}_{lb,c}}{\dot{Q}_{ss,c,nom}}\right) \tag{13}$$

The power at the lower boundary of the interval of the current time step t is equal to the power at the upper boundary of the last time step t-Δt. The latter is already computed with Eq. 10.

Therefore, the cycle loss at the upper boundary of the current time interval is given by

$$\dot{Q}_{ub,c} = \dot{Q}_{ss,c,nom}\ e^{-\frac{t_f + t_{ub}}{\tau_{off}}} \tag{14}$$

where tub is the difference between the upper boundary of the current time interval and the shut-down time.

This value will be used if the heat pump is switched on again in the next time step.

The mean condenser power over the current time step is calculated using the integral of the power (Eq. 7) over the time step

$$\dot{Q}_{m,c} = \frac{1}{\Delta t}\int_{t_{l_b}}^{t_{ub}} \dot{Q}_c dt = \dot{Q}_{ss,c}\left(1 + \frac{\tau_{on}}{\Delta t} e^{-\frac{t_f}{\tau_{on}}}\left(e^{-\frac{t_{ub}}{\tau_{on}}} - e^{-\frac{t_{lb}}{\tau_{on}}}\right)\right) \tag{15}$$

The COP is therefore, taking the cycling losses into account:

$$COP_{icycle} = -\frac{\dot{Q}_{m,c}}{P_{plug}} \tag{16}$$

6.4. Icing and defrosting of the evaporator

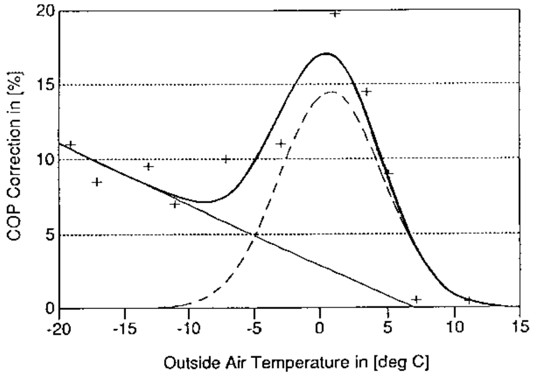


Figure 9: COP reduction due to icing and defrosting of the evaporator. (Dots indicate measurement data)

The relative variation of the COP due to frosting and defrosting of the evaporator is described by a modified Gauss curve [4] (see Fig. 3).

The curve results from a superposition of a Gauss curve with a straight line. The Gauss approximation represents the maximal frost occurrence between 0°C and +5°C (high absolute air humidity). The straight line stands for the energy input for defrosting, which increases with decreasing outside air temperature. This energy is used for heating up the metal of the evaporator, the refrigeration in the evaporator and the heating up and melting of the ice.

The relative variation of the COP can therefore be calculated according to:

$$\begin{aligned} &For \quad A + BT_{e,in} > \ 0: \\ &\Delta COP_{ice} = A + BT_{e,in} + Ce^{-\frac{\left(T_{e,in}-D\right)^2}{E}} \\ &For \quad A + BT_{e,in} \leq \ 0 \\ &\Delta COP_{ice} = Ce^{-\frac{\left(T_{e,in}-D\right)^2}{E}} \end{aligned} \qquad \textbf{(17)}$$

The COP in consideration of all losses (cycle loss, icing and defrosting) can be computed with:

$$COP_{corr} = COP_{icycle}\ (1 - \Delta COP_{ice}) \qquad \textbf{(18)}$$

6.5. Condenser and evaporator power

With the corrected coefficient of performance COP$_{corr}$, the condenser and evaporator power can be calculated according to

$$\dot{Q}_{m,c} = -COP_{corr}\ P_{plug} \qquad \textbf{(19)}$$

$$\begin{aligned} &For \quad -\left(\dot{Q}_{m,c} + P_{comp}\right) > 0 \\ &\quad \dot{Q}_{m,e} = -\left(\dot{Q}_{m,c} + P_{comp}\right) \\ &For \quad -\left(\dot{Q}_{m,c} + P_{comp}\right) \leq 0 \\ &\quad \dot{Q}_{m,e} = 0 \end{aligned} \qquad \textbf{(20)}$$

Finally, the outlet temperature of the condenser and evaporator can be computed with:

$$T_{c,out,corr} = T_{c,in} - \frac{\dot{Q}_{m,c}}{\dot{m}_c c_c} \qquad \textbf{(21)}$$

$$T_{e,out,corr} = T_{e,in} - \frac{\dot{Q}_{m,e}}{\dot{m}_e c_e} \qquad \textbf{(22)}$$

7. References

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