

# Module 8 :: Solar heating and cooling

This Module is related to the simulation of solar-driven heating and cooling systems. Starting from the behavior of single components like water- and air-based solar collectors, heat exchangers, storage tanks, sorption wheels, evaporative humidifiers and closed absorption cooling machines, more and more complex systems are developed. These systems reach from simple water-based solar heating systems to complete solar-driven open or closed desiccant cooling systems.

The solar collector data base (static models) includes over 300 market-available water based flat plate and evacuated solar collectors, some market available absorption cooling machines are included in the data base, too.

## 8.1 Solar collectors

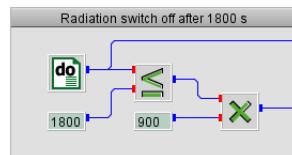
**Air collectors** We start with the utilization and behavior analysis of two types of solar air collector models, implemented in the SCAIRC and SCAIRCD blocks. The model of the SCAIRC block is a quite simple static model without consideration of the collector heat capacity and a very fast algorithm. The more complex dynamic model of the SCAIRCD block considers the thermal mass of the solar air collector.

The decision which one of the two models should be used depends on the purpose of the simulation. If only the annual energy production is calculated in hourly time steps, the simple static model is normally sufficient. For detailed analysis of measurement data with sampling times in the range of several minutes or even seconds, for example, the static model won't deliver sufficient results. In this case the utilization of the dynamic model is the right decision.

**Exercise 8.1** Plot the outlet air temperature of the static and the dynamic solar air collector for a time period of 3600 s with a time step of 5 s for an inlet and ambient temperature of 20 °C, an air flow rate of  $0.3 \text{ m}^3 \text{s}^{-1}$ ,  $900 \text{ W m}^{-2}$  solar irradiation on the collector plane, which is switched off after 1800 s and a wind speed close to the collector of  $1 \text{ m s}^{-1}$ . The collector parameters are given in Table 8.1 for both collector types.

**Hint** You'll find the solar air collector blocks in the category *Thermal energy – Collectors*. Use the DO block for the time period and logical blocks from *Mathematics – Logics* to switch off the solar irradiation after 1800 s.

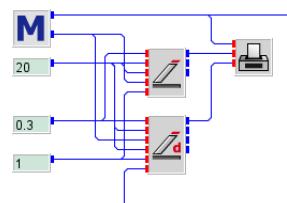
**Solution** At first, we create a macro for the time and radiation data.



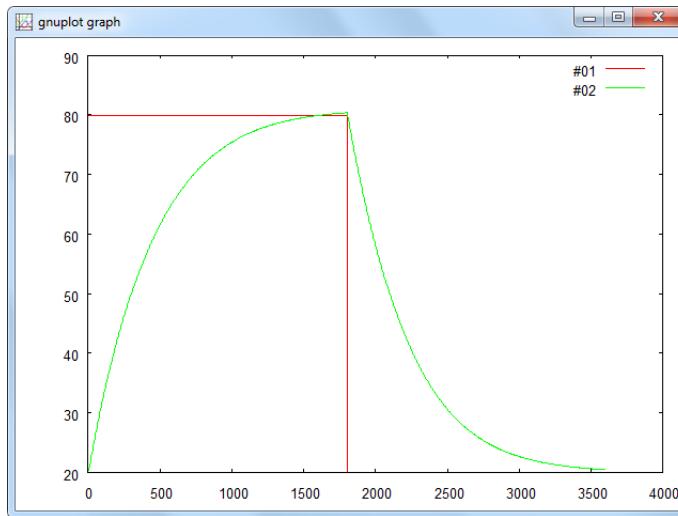
Parameters	
Numbers of collectors in series	3
Numbers of collectors in series	1
Collector tilt angle / °	34
Collector length / m	12.5
Collector width / m	0.96
Channel height / m	0.095
Channel width / m	0.060
Number of channels	16
Plate thickness / m	0.0014
Optical efficiency ( $\tau\alpha$ )	0.80
Insulation thickness / m	0.06
Insulation heat conductivity / $\text{W m}^{-1}\text{K}^{-1}$	0.04
Absorber heat conductivity / $\text{W m}^{-1}\text{K}^{-1}$	238
Emissivity glas cover	0.88
Emissivity absorber front	0.16
Emissivity absorber back	0.085
Emissivity channels	0.085
Distance absorber/ front cover	0.025
Thickness back cover material / m	0.002
Density back cover material / $\text{kg m}^{-3}$	3500
Density absorber material / $\text{kg m}^{-3}$	2702
Specific heat back cover material / $\text{J kg}^{-1}\text{K}^{-1}$	500
Specific heat absorber material / $\text{J kg}^{-1}\text{K}^{-1}$	500

Table 8.1: Parameters for the static and dynamic solar air collector simulation.

The rest of the model is trivial then.



This is the result:



The  $x$ -axis shows the time in s, the  $y$ -axis shows the air temperature at the collector outlet in °C. As expected, the curves show that the static model reacts immediately to the change in radiation while the thermal mass of the collector leads to a steady decrease in collector outlet temperature.

#### Water collectors

For water-based collectors so far only a static model SCETA **stimmt nicht mehr!** is included in the inselST library, which is used for both flat plate and evacuated collectors. The collector performance and efficiency is described by the four parameters, absorber area, maximum efficiency, linear and quadratic heat loss coefficient. This information is normally given on the data sheet of each market available solar collector.

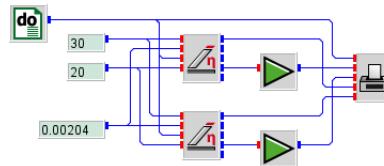
**Exercise 8.2** Plot the collector efficiency in per cent and the outlet temperature in °C of a flat plate and an evacuated collector as a function of the solar irradiation on the collector plane, starting from  $100 \text{ W m}^{-2}$  to  $1000 \text{ W m}^{-2}$ , with a temperature of  $20^\circ\text{C}$  for both, water inlet and ambient air temperature. The collector parameters are given in Table 8.1 for both collector types.

**Hint** Use the DO block for the variation of the solar irradiation with an increment of  $1 \text{ W m}^{-2}$ . Use GAIN blocks from the *Mathematics – Basics* category to multiply the collector efficiency with 100 to get the value in per cent.

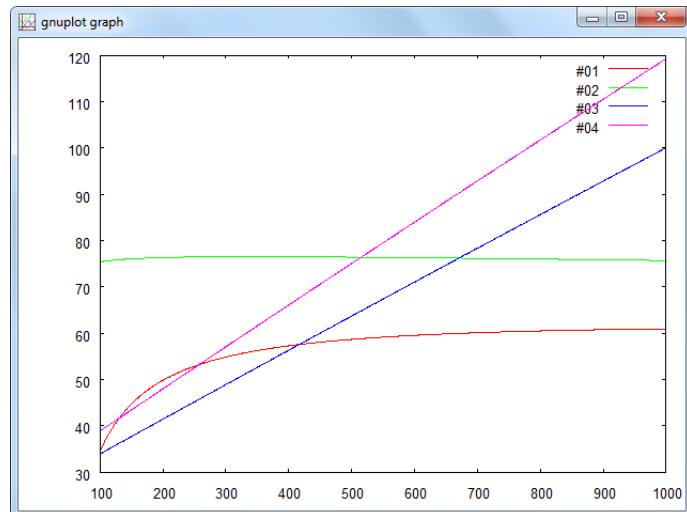
**Solution** The solution is not difficult.

Parameters	Flat plate	Vacuum tube
Absorber area / m <sup>2</sup>	0.9141	0.9141
Maximum efficiency $\eta_0$	0.806	0.794
Linear heat loss coefficient / m <sup>2</sup> K W <sup>-1</sup>	3.666	0.132
Quadratic heat loss coefficient / m <sup>2</sup> K <sup>2</sup> W <sup>-1</sup>	0.0155	0.010
Sp. heat capacity of collector fluid / J kg <sup>-1</sup> K <sup>-1</sup>	3900	3900
Number of collectors in series	1	1
Number of collectors in parallel	1	1
Temperature mode	inlet temp.	inlet temp.

Table 8.2: Collector parameters.



This is the result:



The  $x$ -axis shows the solar radiation in the collector plane in  $\text{W m}^{-2}$ , the  $y$ -axis shows the collector efficiency in % and the temperature in  $^{\circ}\text{C}$ . Line 1 and 2 refer to the collector efficiency and line 3 and 4 show the outlet temperature of the flat plate and the evacuated collector.

## 8.2 Storage tanks

Two types of storage tanks are available in the *Thermal energy – Tanks* category, a fully mixed (block TANKFM) and a stratified storage tank (block TANKST). Both tank models can be used for heat and cold storage as well.

### Full mixed or stratified

The characteristics of the storage tanks with respect to their size and heat losses are described by six parameters in case of the fully mixed tank. In case of the stratified storage tank two more parameters are necessary to define the effective vertical heat conductivity and the number of nodes  $N$ , in which the storage volume shall be divided. The maximum number of nodes is limited to 200. However, in normal cases, depending on the storage size, 5 to 20 nodes are sufficient for nearly all calculations.

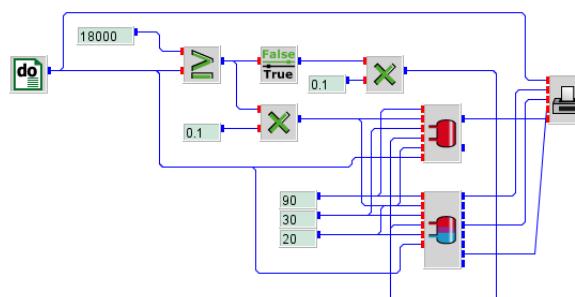
The temperature of all  $N$  nodes (tank sections) are connected to an output. Output number  $N + 1$  is connected to the energy content of the storage tank  $Q$  in joule. Since the default number of outputs is set to 5, the number of outputs has to be adapted to the number of nodes increased by one for the energy content output.

### Exercise 8.3

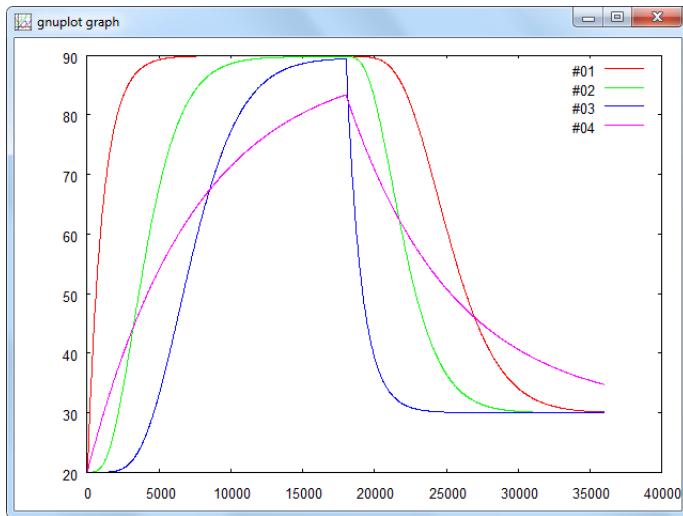
To analyze how the two storage tank types perform, use both blocks with the default parameters and load them by a heat source with a constant temperature of 90 °C and a mass flow rate of  $0.1 \text{ kg m}^{-2}$  over a time period of 18 000 s. Afterwards, both tanks shall be unloaded with an inlet temperature of 30 °C and a mass flow rate of  $0.1 \text{ kg m}^{-2}$  for another 18 000 s. Divide the stratified storage tank into 7 layers, plot the output temperature of outputs 1, 4 and 7 and the output temperature of the fully mixed tank in one graph over the whole time period of 36 000 s.

**Hint** Use a DO block for the time period of 36 000 s with an increment of 20 s.

**Solution** The solution is straight forward again.



And the graph is:



The  $x$ -axis shows the time in s, the  $y$ -axis shows the output temperature in  $^{\circ}\text{C}$ . Line 1, 2 and 3 refer to the output temperature of the stratified storage tank on node 1, 4 and 7. Line 4 shows the output temperature of the fully-mixed storage tank.

As clearly visible from the graph, the temperature of the stratified storage tank increases and decreases much faster and reaches a much higher maximum temperature as in case of the fully mixed storage tank. The reason for this difference in the loading behavior is obvious.

If the fact is considered, that in the stratified storage tank always the medium with the lowest/hottest temperature is exchanged by the hot/cold medium of the heating source/load, whereas in case of the fully mixed storage tank always the higher/lower temperature of the mixed medium is exchanged. Due to the greater temperature difference between heating source/load and the return temperature from the stratified storage tank more energy is stored/extracted in the same time period as in the fully mixed tank.

### 8.3 Heat exchangers

All together three different types of heat exchangers are currently available in the thermal tool box. In the simple heat exchanger models for parallel, counter and cross flow heat exchangers the heat transfer efficiency is simply calculated from the overall heat-transfer coefficient  $UA$  in  $\text{W K}^{-1}$ , the specific heat of the two fluids  $c_p$  in  $\text{J kg}^{-1}\text{K}^{-1}$  and their mass flows rates in  $\text{kg s}^{-1}$ . These heat exchanger models can be used for all kind of fluids like air, water, oil, etc.

### 8.3 Heat exchangers

The constant efficiency heat exchanger is a very simple model simulating a heat exchanger with constant heat recovery efficiency, which can be defined by the user as parameter. However, the effect of changing mass flow rates is not considered in this block. Additionally, the nominal electricity can be defined for the calculation of the electricity consumption of rotating heat exchangers. The input of the rotation speed has no influence on the calculated results as long as the rotation speed is greater than zero. This function can be used to consider operation modes without heat exchanging function, e.g. when the heat exchanger is bypassed or in case of a rotation heat exchanger, if there is no rotation.

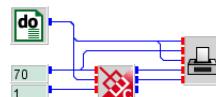
The third available heat exchanger is a real physical model of an air based cross-flow heat exchanger, which considers despite of different mass flow rates of the two air streams also condensation and icing effects within the heat exchanger, including the transferred condensation and latent enthalpy. With its 20 parameters the block can be adapted to the size of each cross-flow heat exchanger, even if heat transfer ribs are included between the heat exchanger plates. However, the construction details of the heat exchanger have to be known.

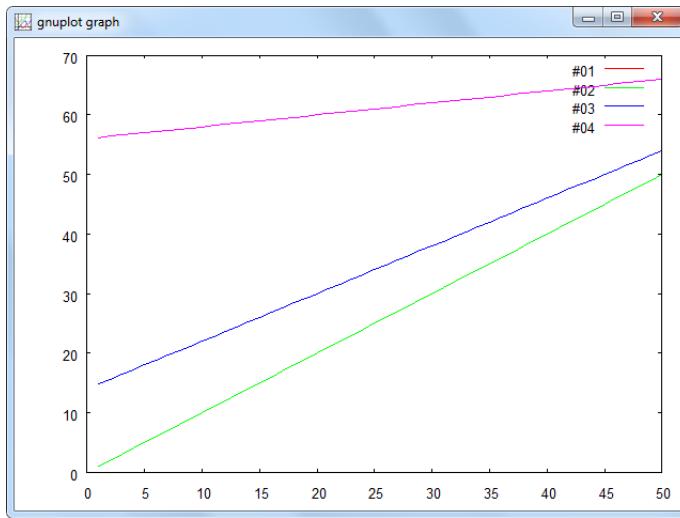
Further heat exchanger models for earth heat exchangers and water sprayed cross flow heat exchangers for evaporative cooling are currently under development.

**Exercise 8.4** Use the constant efficiency heat exchanger with a heat recovery efficiency of 0.8, an air inlet temperature on the hot side of 70 °C and an air inlet temperature on the cold side which is increased from 1 °C to 50 °C. Set the rotations speed to a value grater than zero and print the two inlet and the two outlet temperatures.

**Hint** Use the DO block to increase the temperature of the air at the cold side inlet.

**Solution**





The  $x$ -axis shows the calculation steps, the  $y$ -axis shows the inlet and output temperature in  $^{\circ}\text{C}$ . Line 1 and 2 refer to the input temperatures on the hot and cold side, line 3 and 4 show the temperatures at the heat exchanger outlet.

To demonstrate how a heat exchanger block can be integrated in a model for heat transfer between two systems, a complete model of a solar based heating system will be developed in the next exercise, consisting of evacuated solar collectors and a stratified heat storage tank .

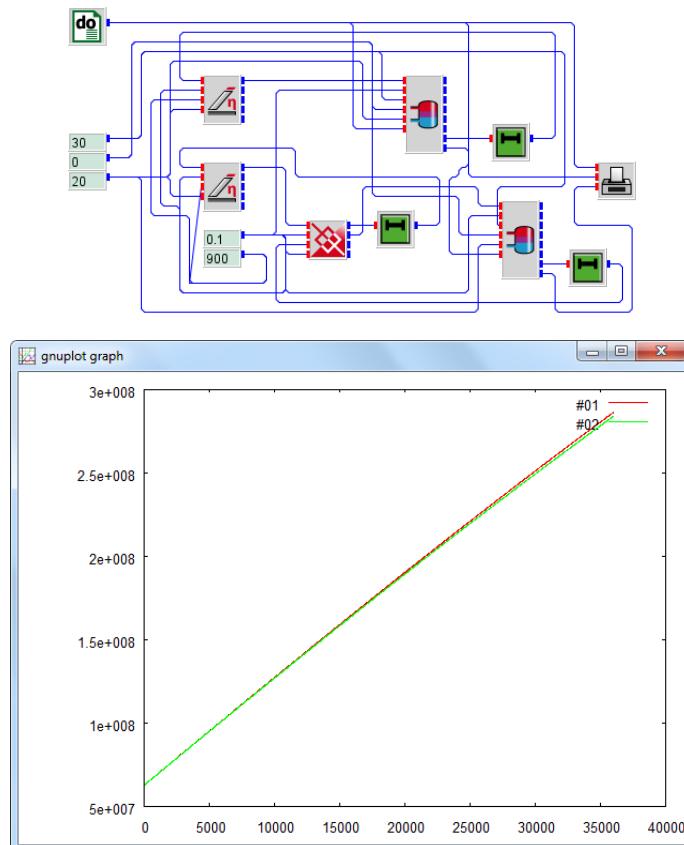
**Exercise 8.5** Use the evacuated solar collector and the stratified storage tank as described in the collector and storage tank exercise. Analyze two cases, in the first one, connect the evacuated solar collector directly to the storage tank. In the second case, integrate a counter flow heat exchanger from Thermal – Heat exchangers – Simple heat exchangers with the default parameters between the evacuated collector and the stratified storage tank. Print the energy content of the storage tank for both cases in one graph for a time period of 36 000 s with a time step of 20 s, a solar irradiation on the collector plane of  $900 \text{ W m}^{-2}$  and an ambient temperature of  $20 ^{\circ}\text{C}$ . Since the tanks are not unloaded, set the mass flow of the load to zero and the load temperature e.g. to  $30 ^{\circ}\text{C}$ .

**Hint** For this example it is necessary to connect the output temperature of the storage tank and/or the heat exchanger to the input temperature of the collector/heat exchanger. However, at calculation start the output temperatures of the components are not known, therefore DELAY blocks form Math – Loops have to be integrated between the outputs and the inputs. A DELAY block always outputs the calculated value of the previous time step. Therefore, an initial value has to be defined as parameter, to provide an output value for the first calculation

### 8.3 Heat exchangers

time step. In case of the storage tank and heat exchanger the initial value can be set to the initial temperature of the storage tank of 20 °C.

#### Solution

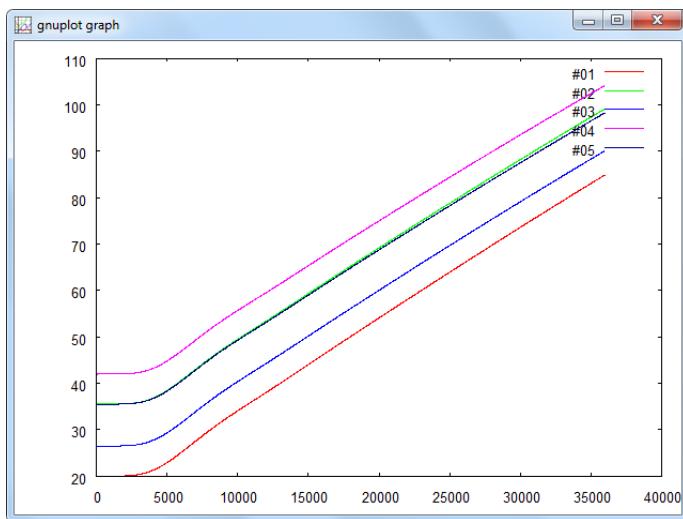


The *x*-axis shows the time in s, the *y*-axis shows the energy content of the storage tank in joule. Line 1 refers to the energy content of the storage tank which is directly connected to the collector and line 2 shows the energy content of the storage tank, which is connected to the heat exchanger.

As visible from the graph, there is only a marginal difference between the energy content of the two storage tanks. This means, it doesn't matter if a heat exchanger is included in the system or not, although the heat exchanger has only a heat transfer efficiency of about 70 %.

**Exercise 8.6** To analyze this effect, print for the same boundary conditions the input and output temperatures of the two collectors and the input temperature of the storage tank, which is connected to the output of the heat exchanger.

### Solution



The  $x$ -axis shows the time in s and the  $y$ -axis shows the temperature in °C. Line 1 and 2 refer to the input and output temperature of the collector without heat exchanger. Line 3 and 4 show the input and output temperature of the collector with heat exchanger and line 5 the input temperature of the storage tank, which is connected to the output of the heat exchanger.

As visible from the graph, the input and output temperatures of the collector with heat exchanger are much higher than the input and output temperatures of the collector, which is directly connected to the storage tank. However, the input temperature of the storage tank, which is connected to the heat exchanger (line 5), is nearly equal to the input temperature of the storage tank, which is directly connected to the collector. This means, that the integration of a heat exchanger just leads to a temperature lift in the collector circuit. This causes some higher collector losses, which are visible in the marginal differences between the storage tank input temperatures and the stored energies.

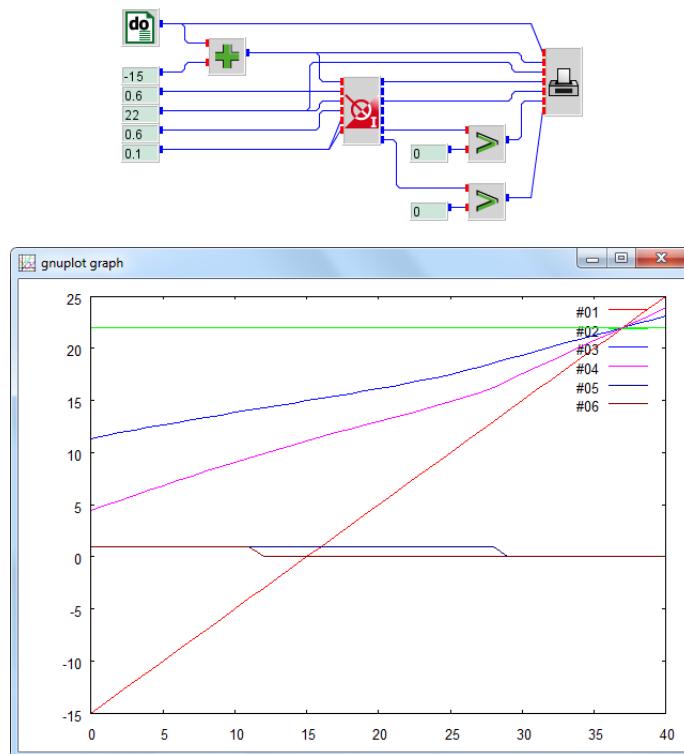
**Exercise 8.7** Use the cross-flow heat exchanger with condensation and icing with the default parameters. Plot the input and output temperatures of the heat exchanger for a cold air inlet temperature, which is increased from  $-15^{\circ}\text{C}$  to  $25^{\circ}\text{C}$  with a constant relative humidity of 60 %, a warm air inlet temperature of constant  $22^{\circ}\text{C}$  with a relative humidity of 60 % and an air volume flow of  $0.1 \text{ m}^3 \text{s}^{-1}$  on both sides. Print in the same graph indicators showing if condensation and icing occurs within the heat exchanger.

**Hint** Use the DO block to increase the cold air input temperature, but be aware that negative values are not allowed in this block. To built indicators for condensation

### 8.3 Heat exchangers

and icing use logical blocks from the Math menu, which output a 1 if the condensed water or ice mass is greater than zero and a 0 if no condensation or no icing occurs.

#### Solution



The  $x$ -axis shows the calculation step, the  $y$ -axis shows the temperature in °C. Line 1 and 2 show the input temperature of the cold and warm air stream, line 3 and 4 show the output temperatures of the two air streams. Line 5 and 6 are the indicators for condensation and icing. As clearly visible from the graph, the output temperatures do not increase linear with the increase of the cold air inlet temperature, as long as icing and/or condensation occurs.

**Exercise 8.8** To analyze how the heat transfer efficiency of the heat exchanger is influenced by condensation and icing effects, calculate the heat transfer efficiency for the warm and the cold air stream using the following equations:

Cold air stream

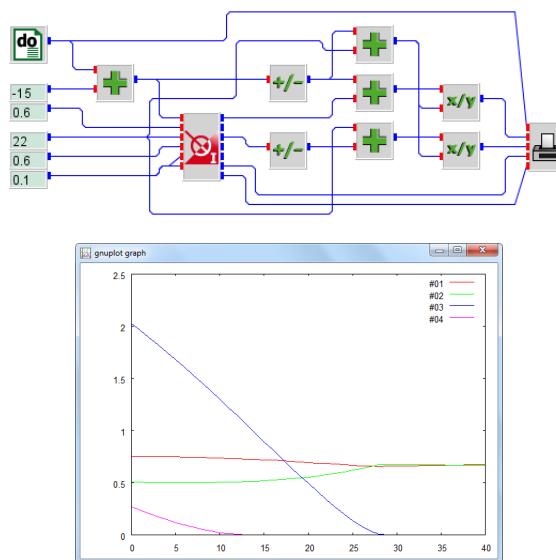
$$\phi = \frac{T_{\text{cold,out}} - T_{\text{cold,in}}}{T_{\text{warm,in}} - T_{\text{cold,in}}}$$

Warm air stream

$$\phi = \frac{T_{\text{warm,in}} - T_{\text{warm,out}}}{T_{\text{warm,in}} - T_{\text{cold,in}}}$$

Print the calculated heat exchanger efficiencies together with the condensed water mass and the ice mass in one graph for the same boundary conditions as described above.

Solution



The  $x$ -axis shows the calculation step, the  $y$ -axis shows the heat exchanger efficiency and the condensed water and ice mass in  $\text{kg h}^{-1}$ . Line 1 and 2 show the calculated heat transfer efficiency calculated for the cold and warm air stream. Line 3 and 4 refer to the condensed water mass and the ice mass.

As visible from the graph, the heat exchanger efficiency of the cold air stream decreases with decreasing condensed water mass from about 70 to 63 % and remains constant for conditions without condensation. The increase in the heat exchanger efficiency with increasing condensed water mass results from the condensing and latent enthalpy, which is set free during the condensing and icing process. However, the heat exchanger efficiency calculated from the warm air stream increases with decreasing condensed water mass from about 48 to 63 %. This antithetic behavior results from the fact, that a part of the condensing enthalpy is also transferred to the warm air stream which leads to higher outlet temperatures and therefore to a lower heat exchanger efficiency.

*... to be continued*